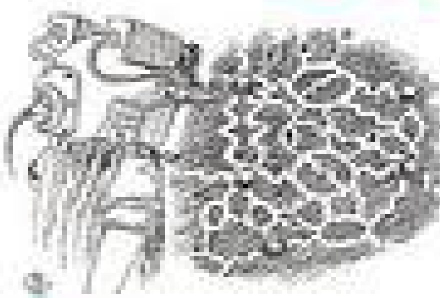
AN ALLEGORY OF QUANTUM PHYSICS

Alice in Quantumland



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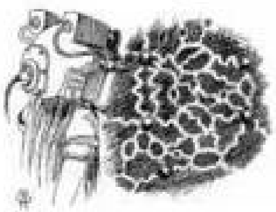

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 Published in the United States by Copernicus Books, an imprint of Springer-Verlag New York, LLC by arrangement with Birkhauser Boston. A member of Springer Science+Business Media Copernicus Books 37 East 7th Street New York, NY 10003

www.copernicusbooks.com Library of Congress Cataloging-in-Publication Data Gilmore, Robert, 1938Alice in Quantumland : an allegory of quantum physics / Robert Gilmore p. cm. Includes bibliographical references and index. ISBN 0-387-91495-1 (acid-free paper) 1. Quantum theory-Fiction. I. Title PS3557.14595A45 1995 813 x.54- dc20 95-10163

Manufactured in the United States of America. Printed on acid-free paper. 19 18 17 16 15 14 13 12 11 ISBN 0-387-91495-1 SPIN 10992432

Preface

In the first half of the twentieth century, our understanding of the Universe was turned upside down. The old classical theories of physics were replaced by a new way of looking at the world-quantum mechanics. This is in many ways at variance with the ideas of the older Newtonian mechanics; indeed, in many ways it is at variance with our common sense. Nevertheless, the strangest thing about these theories is their extraordinary success in predicting the observed behavior of physical systems. However nonsensical quantum mechanics may at times appear to us, that seems to be the way that Nature wants it-and so we have to play along.

This book is an allegory of quantum physics, in the dictionary sense of "a narrative describing one subject under the guise of another." The way that things behave in quantum mechanics seems very odd to our normal way of thinking and is made more acceptable when we consider analogies to situations with which we are familiar, even though the analogies may be inexact. Such analogies can never be very true to reality as quantum processes are really quite different from our normal experience.

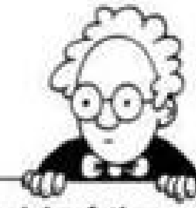
An allegory is an extended analogy, or series of analogies. As such, this book follows more in the footsteps of Pilgrim's Progress or Gulliver's Travels than of Alice in Wonderland. "Alice" appears the more suitable model, however, when we examine the world that we inhabit.

The Quantumland in which Alice travels is rather like a theme park in which Alice is sometimes an observer, while sometimes she behaves as a sort of particle with varying electric charge. This Quantumland shows the essential features of the quantum world: the world that we all inhabit.

Much of the story is pure fiction and the characters are imaginary, although the "real-world" notes described below are true. Throughout the narrative you will find many statements that are obviously nonsensical and quite at variance with common sense. For the most part these are true. Neils Bohr, the father figure of quantum mechanics in its early days, is said to have remarked that anyone who did not feel dizzy when thinking about quantum theory had not understood it.

Seriously, Though . . .

The description of the world that is given by quantum mechanics is undoubtedly interesting and remarkable, but are we seriously expected to believe that it is true? Amazingly, we find that we must. To underline this assertion, throughout this book you will find brief notes which emphasize the importance of quantum mechanics in the real world. The notes look like this:



These notes summarize the relevance to our world of the quantum topics Alice encounters in each chapter. They should be sufficiently unobtrusive that you may ignore them as you read the story of Alice's adventures, but when you wish to discover the real significance of these adventures, the notes are conveniently nearby.

There are also some longer, end-of-chapter, notes. These amplify some of the trickier points in the text and are denoted thus:

See end-of-chapter note 1

Much of the way that quantum theory describes the world may seem at first sight to be nonsense-and possibly it may seem so at the second, third, and twenty-fifth sight as well. It is, however, the only game in town. The old classical mechanics of Newton and his followers is unable to give any sort of explanation for atoms and other small systems. Quantum mechanics agrees very well with observation. The calculations are often difficult and tedious, but where they have been made, they have agreed perfectly with what has really been seen.

It is impossible to stress too strongly the remarkable practical success of quantum mechanics. Although the outcome of one measurement may be random and unpredictable, the predictions of quantum theory agree consistently with the average results obtained from many measurements. Any large-scale observation will involve very many atoms and thus very many observations on the atomic scale. We again find that quantum mechanics is successful, in that it automatically agrees with the results of classical mechanics for large objects. The converse is not true.

Quantum theory was developed to explain observations made on atoms. Since its conception, it has successfully been applied to atomic nuclei, to the strongly interacting particles which derive from the nucleus, and to the behavior of the quarks of which these are composed. The application of the theory has been extended over a factor of some hundred thousand million. The systems considered have both decreased in size and increased in energy by this factor. This is a long way to extrapolate a theory from its original conception, but so far quantum mechanics appears to be quite able to deal with these extreme systems.

Insofar as it has been investigated, quantum mechanics appears to be of universal applicability. On a large scale, the predictions of quantum theory lose their random aspect and agree with those of classical mechanics, which works very well for large objects. On a small scale, however, the predictions of quantum theory are consistently borne out by experiment. Even those predictions, which seem to imply a nonsensical picture of the world, are supported by experimental evidence.

Intriguingly, as is discussed in Chapter 4, quantum mechanics would appear to be in the strange position of agreeing with all observations made, while disputing that any observations can actually be made at all. It seems that the world is stranger than we imagine and perhaps stranger than we can imagine.

For the present, however, let us accompany Alice as she begins her journey into Quantumland.

Robert Gilmore

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CHAPTER

1 Into Quantumland

Alice was bored. All her friends were on holiday or visiting relations and it was raining, so that she was marooned indoors watching television. So far that afternoon she had watched part five of a series on introductory Esperanto, a program on gardening, and a paid political broadcast. Alice was really bored.

She looked down at the book lying on the floor beside her chair. It was a copy of *Alice in Wonderland*, which she had been reading earlier and had dropped there when she finished it. "I do not know why there cannot be more cartoons and interesting programs on the television," she wondered idly to herself. "I wish I could be like that other Alice. She was feeling bored and then she found her way to a land full of interesting creatures and strange happenings. If I could shrink down somehow and float through the television screen perhaps I might find all sorts of fascinating things."

She stared in frustration at the screen, which at that moment carried a picture of the Prime Minister telling her how, all things considered, everything was really far better than it had been three years ago, even if it didn't always seem that way. As she watched she was mildly surprised to see the picture of the Prime Minister's face slowly break apart into a mist of bright dancing speckles which all seemed to be rushing inward, as if they were beckoning her. "Why," said Alice, "I do believe that they want me to follow them in!" She leapt to her feet and started toward the television, but tripped on the book which she had discarded so untidily on the floor and fell headlong.

As she fell forward she was amazed to see the screen grow enormously, and she found herself in among the swirling speckles, rushing with them down into the picture. "I cannot see anything with these dots swirling all around me," thought Alice. "It is just like being lost in a snowstorm; why I cannot even see my feet. I wish I could see just a little. I could be anywhere."

At that moment Alice felt her feet strike something solid and she found herself standing on a hard, flat surface. All around her the swirling dots were fading away and she found that she was surrounded by a number of vague shapes.

She looked more closely at the one nearest to her and observed a small figure, coming roughly up to her waist. It was exceedingly difficult to make out, as all the time it kept hopping rapidly to-and-fro, moving so fast that it was very difficult to see at all clearly. The figure seemed to be carrying some sort of stick, or possibly a rolled umbrella, which was pointing straight up in the air. "Hello," Alice introduced herself politely. "I am Alice. May I ask who you are?"

"I am an electron," said the figure. "I am a spin-up electron. You can readily tell me apart from my friend there who is a spin-down electron, so, of course, she is quite different." Under his breath he added something which sounded rather like "*Vive la difference!*" As far as Alice could see, the other electron looked very much the same, except that her umbrella, or whatever it was, was pointing down toward the ground. It was very difficult to tell for sure, as this figure also was jigging to-and-fro as rapidly as the first.

Particles at the atomic level differ from large-scale objects. Electrons are very small and show no distinguishing features, being all completely identical to one another. They do have some form of rotation, although what it is that is rotating you cannot say. A peculiar feature is that every electron is rotating at exactly the same speed, no matter in what direction you choose to measure the rotation. They only difference is that some rotate in one direction and some in the other. Depending on their direction of rotation, the electrons are known as *spin-up* or *spin-down*.

"Oh please," said Alice to her first acquaintance. "Would you be good enough to stand still for a moment, as I really cannot see you at all clearly?"

"I am good enough," said the electron, "but I am afraid there is not *room* enough. However I will try." So saying he slowed his rate of jiggling. But as he moved more slowly, he began to expand sideways and become more and more diffuse. Now, although he was no longer moving at all quickly, he looked so fuzzy and quite out of focus that Alice could no more see what he looked like than she had been able to before. "That is the best I can do," he panted. "I am afraid that the more slowly I move, the more spread out I become. That is the way things are here in Quantumland: The smaller the space you occupy, the faster you have to move. It is one of the rules, and there is nothing I can do about it."

"There isn't really room to slow down here," continued Alice's companion as he began once more to leap rapidly around. "The platform is becoming so crowded that I have to be more compact." Sure enough, the space in which Alice stood had now become very crowded indeed, being closely packed with the small figures, each dancing feverishly to-and-fro.

"What strange beings," thought Alice. "I do not think I shall ever be able to see quite what they look like if they will not stand still for a minute, and there does not seem to be much chance of that." Since it did not look as if she could get them to slow down she tried another topic. "Would you tell me please what sort of platform we are on?" she asked.

"Why a railway platform, of course," replied one of the electrons cheerfully (it was very hard for Alice to say which had spoken; they really did all look very much the same). "We are going to take the wave train to the screen you see. You will change there to the photon express I expect, if you want to go any farther."

"Do you mean the television screen?" asked Alice.

"Why of course I do," cried one of the electrons. Alice could have sworn that it was not the same one which had just spoken, but it was very difficult to be certain. "Come on! The train is here and we have to get on."

The *Heisenberg uncertainty principle* says that no particle can have well-defined values for both position and speed. This means that a particle cannot be stationary in a given position, since a stationary particle has a well-defined speed of zero.

Sure enough, Alice could see a line of small compartments drawn up at the platform. They were very small. Some were empty, some had one electron in, and some two. All of the empty compartments were filling rapidly-in fact there did not seem to be any left-but Alice noticed that not one of the compartments held more than two electrons. As they passed by any of these compartments, the two occupants would cry out "No room! No room!"

"Surely you could squeeze more than two into a compartment, seeing as the train is so crowded?" Alice asked her companion.

"Oh no! Never more than two electrons together, that is the rule."

"I suppose we shall have to get into different compartments then," declared Alice regretfully, but the electron reassured her.

"There's no problem there for you, no problem at all! You can get into any compartment that you want, of course."

"I am sure that I do not see why that should be," Alice replied. "If a compartment is too full to hold you, then it must surely be too full for me as well."

"Not at all! The compartments are only allowed to hold two electrons, so almost all the places for *electrons* may be taken up, but you are not an electron! There is not a single other *Alice* on the train, so there is plenty of room for an Alice in any of the compartments."

This did not seem to follow so far as Alice could see, but she was afraid that the train would start to move off before they got seats, so she began looking for an empty space that could take another electron. "How about this one?" she asked her associate. "Here is a compartment with only one other electron already in it. Can you get in here?"

"Certainly not!" he snapped, sounding quite horrified. "That is another spin-up electron. I cannot share a compartment with another spin-up electron. What a suggestion! It is quite against my principle."

"Don't you mean against your principles?" Alice asked him.

"I mean what I say, against my principle, or rather Pauli's principle. It forbids any two of us electrons from doing exactly the same thing, which includes being in the same space *and* having the same spin," he responded crossly.

Electrons are absolutely identical and obey the Pauli exclusion principle (see Chapter 5), which prevents there being more than one electron in each state (or two, when you include the different possible spin directions).

Alice did not really know why she had upset him, but she looked around hastily to find another compartment which might suit him better. She managed to find one that held a single electron who was of the *spin-down* variety, and Alice's companion leaped into this one readily enough. Alice was surprised to find that although the tiny compartment now seemed full there was somehow enough room for her to fit in quite easily.

No sooner were they settled in than the train moved off. The journey was uneventful and the scenery not very interesting, so Alice was rather glad when the train began to slow down. "This must be the screen, I suppose," thought Alice. "I wonder what will happen here."

As they alighted at the screen there was an enormous bustle everywhere. "Whatever is going on?" Alice wondered aloud. "Why does everyone seem to be so excited?" Her questions were answered by an announcement which appeared to come from the air all around her.

"The screen phosphor is presently being excited by the incoming electrons, and we shall be having photon emission soon. Stand by for the departure of the photon express." Alice looked around to see if she could see the express arriving, when there was a rush of bright shining shapes across the platform. Alice was caught up in the middle of the crowd and carried along with them as they all crowded into one compartment. "Well, they do not seem to be worried by any principle, Pauli or otherwise," thought Alice as they crowded in around her. "These ones are certainly not worried about all being in the same place. I suppose the express is going to start soon. I wonder where ...

"... we shall end up," she concluded as she stepped out onto the platform. "My, that was certainly a fast journey. Why, it seemed to take no time at all." (Alice was quite right about this. The journey did indeed take no time at all, as time is effectively frozen for anything which is traveling at the velocity of light.) Once again she found herself surrounded by a crowd of electrons, all rushing away from the platform.

"Come along!" one of them cried to her as it rushed off. "We must get out of the station now if we are to get anywhere."

"Excuse me," Alice asked it tentatively, "are you the same electron that I was talking to before?"

"Yes I am," answered the electron as it darted off down a side passage. Alice was swept along by the crowd of electrons and carried through the main gateway from the platform.

"I declare, this is really too irksome," said Alice. "Now I have lost the only person I know at all in this strange place and have no one to explain what is happening."

"Don't worry Alice," said a voice from about knee level. "I will show you where to go." It was one of the electrons.

"How do you know my name?" asked Alice in surprise.

"That's simple. I am the same electron that spoke to you before."

"You cannot be!" exclaimed Alice. "I saw that electron go off in a different direction. Perhaps he was not the same one I was talking to before?"

"Certainly he was."

"Then you cannot be the same one," said Alice reasonably. "You cannot both be the same one you know."

"Oh yes we can!" replied the electron. "He is the same. I am the same. We are all the same, you know, exactly the same!"

"That is ridiculous," argued Alice. "You are here beside me, while he has run off somewhere over there, so you cannot both be the same person. One of you must be different."

"Not at all," cried the electron, jumping up and down even faster in its excitement. "We are all identical; there is no way whatsoever that you can tell us apart, so you see that he must be the same and I am the same too."

At that point the crowd of electrons which surrounded Alice all began to cry out, "I am the same," "I am the same too," "I am just the same as you are," "I am too, just the same as you." The tumult was dreadful, and Alice closed her eyes and put her hands over her ears until the noise died down again.

When it was quiet again Alice opened her eyes and lowered her hands. She found there was no sign of the crowd of electrons which had been clustering around her and that she was walking out of the station entrance all alone. Looking around she found herself in a street which at first sight seemed quite normal. She turned left and began to walk along the sidewalk.

Before she had gone very far she came across a figure standing dejectedly in front of a doorway and searching though his pockets. The figure was short and very pale. His face was difficult to make out distinctly, as was the case for everyone Alice had met recently, but he did look, Alice thought, rather like a rabbit. "Oh dear, oh dear, I am late and I cannot find my keys anywhere. I *must* get inside straightaway!" So saying he stepped back a few paces and then ran quickly toward the door.

He ran so very fast that Alice was not able to see him in any one position, but saw instead a string of afterimages which showed him at all the different positions he passed through along his path. These extended from his starting point to the door, but there, instead of stopping as Alice would have expected, they continued on *into* the door, getting smaller and smaller until they were too small to be seen. Alice had scarcely had time to register this strange series of images when he rebounded backward just as rapidly, once again leaving a series of images. This time they ended abruptly with the unfortunate person sprawled on his back in the gutter. Apparently in no way discouraged, he picked himself up and raced toward the door again. Again there was the series of afterimages, shrinking away into the door, and again he bounced off and ended up on his back.

As Alice hurried toward him he repeated this action several more times, throwing himself at the door and then falling back again. "Stop, stop," cried Alice. "You must not do that; you will surely hurt yourself."

The person stopped his running and looked at Alice. "Why, hello my dear. I must do this I'm afraid. I am locked out and I must get inside quickly, so I have no choice but to try and *tunnel* through the barrier."

Alice looked at the door, which was very large and solid. "I do not think you have much chance of getting through that by running at it," she said. "Are you trying to break it down?"

"Oh no, certainly not! I do not want to destroy my beautiful door. I just want to tunnel through it. I am afraid that what you say is true, though. The probability of my managing to get through is indeed not very high at all, but I have to try." As he said this he charged at the door again. Alice gave him up as a bad job and walked off, just as he came staggering back once more.

After she had walked a few paces, Alice could not resist looking back to see if by any chance he had abandoned his efforts, and she saw again the series of images rushing toward the door and shrinking down when they got to it. She waited for the rebound. Previously this had followed immediately after, but this time it did not happen. The door stood there looking solid and rather deserted, but there was no sign of her acquaintance. After a few seconds had passed with nothing happening, Alice heard a rattling of bolts and chains from behind the door and then it swung open. Her vanished companion looked out and waved to her. "I was really in luck!" he called. The probability of penetrating a barrier this thick is very small indeed, and I was amazingly fortunate to get through so quickly." He closed the door with a solid thump and that seemed to end the encounter, so Alice walked on up the street.

A little farther along she came to an empty plot by the side of the road, where a group of builders was clustered around a pile of bricks. Alice assumed they were builders, as they were unloading more bricks from a small cart. "Well at least these people seem to be behaving in a sensible manner," she thought to herself. Just then another group came running around a corner carrying what looked like a very large rolled-up carpet and proceeded to spread it out on the site. When it was unrolled Alice could see that it was some sort of building plan. It did seem to be rather a large plan since it covered most of the available space. "Why, I do believe it must be exactly the same size as the building they are going to put up," said Alice, "but how will they manage to build anything if the plan is already taking up all the room?"

The builders had finished easing the plan into position and had retreated to the pile of bricks. They all picked up bricks and began throwing them at the plan, apparently quite at random. All was confusionsome fell in one place, some in another-and Alice could see no purpose in it at all. "What are you doing?" she asked a person who was standing to one side. He appeared to be doing nothing, and she assumed him to be the foreman. "You are just making untidy piles of bricks. Aren't you supposed to be putting up a building?"

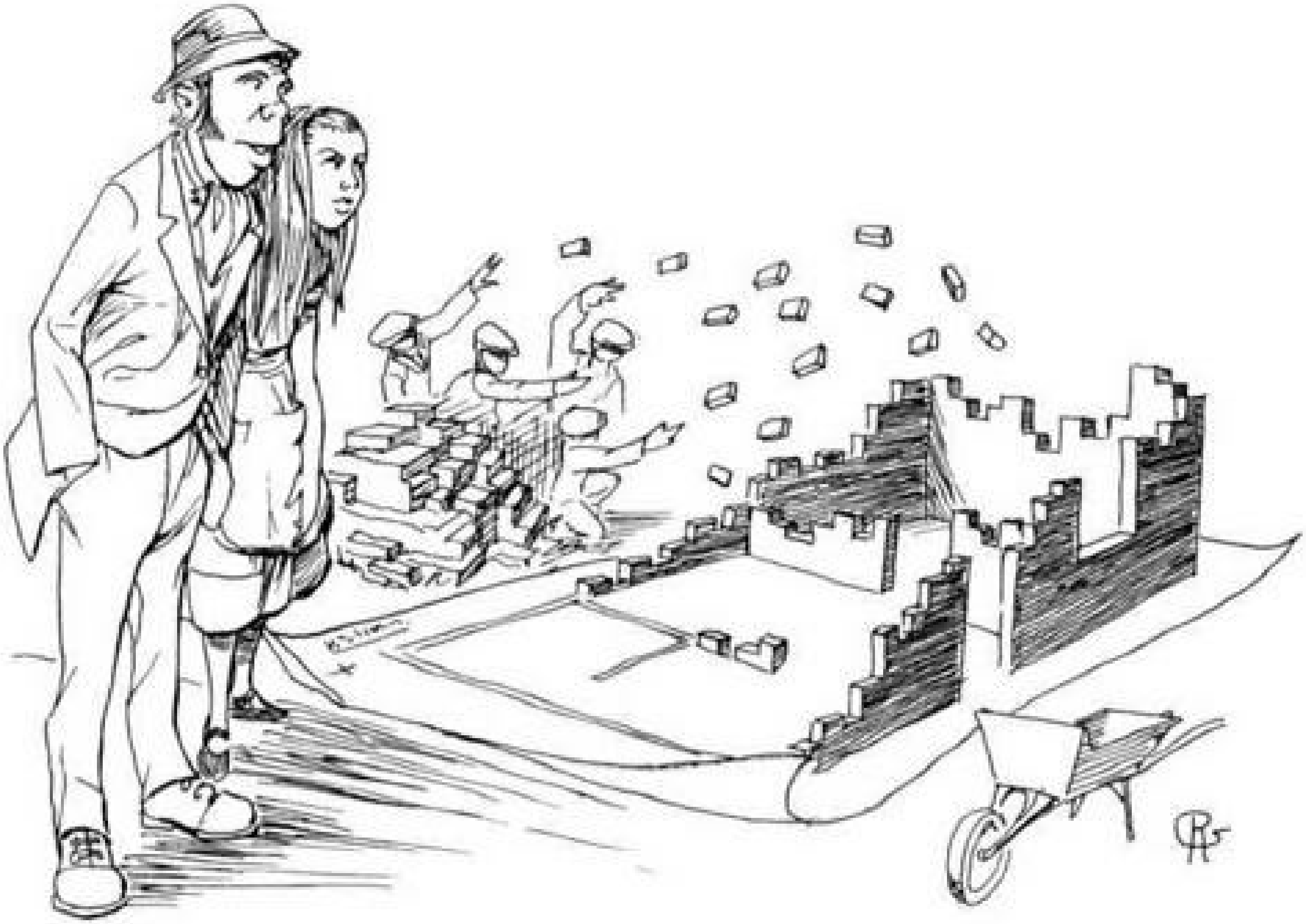
Quantum theory describes the behavior of particles in terms of *probability distributions*, and the actual observation of individual particles will occur at random within these. The probabilities may include classically forbidden processes, such as the penetration of particles through a thin energy barrier.

"Ah, sure, and we are, me darling," answered the foremen. "It's true so it is that the random fluctuations are still large enough to hide the pattern, but since we have laid down the probability distribution for the result we are after needing, we'll be getting there, never fear."

Alice felt that this display of optimism was not very convincing, but she kept her peace and watched as the shower of bricks continued to descend onto the site. Gradually, to her amazement, she noted that more bricks were falling in some regions than in others, and she could begin to make out the patterns of walls and doorways. She watched in fascination as the recognizable shape of rooms began to appear out of the initial chaos. "Why, that is amazing," she cried. "How have you managed to do that?"

"Well now, haven't I already told you," smiled the foreman. "You watched us lay down the probability distribution before we began. This specifies where there should be bricks and where there should be none. We must do this before we start bricklaying as we cannot tell where each brick will go when we throw it, you know," he continued.

"I do not see why!" Alice interrupted him. "I am used to seeing bricks being laid in place one after another in neat lines."



"Well now, that is not the Quantum way. Here we cannot control where each individual brick goes, only the probability that it will go one place or another. This means that when you have only a few bricks, they can go almost anywhere and seem to have no sort of pattern at all. As the number becomes large, however, you find that there are bricks only where there is some probability that they should be there, and where the probability is higher, there you get more bricks. When you have large numbers of bricks involved it all works out very nicely in the end, so it does."

Alice found this all very peculiar, although the foreman spoke so definitely that it sounded as if it might make some sort of strange sense. She did not ask any more questions at this time, as his answers only made her feel more confused than ever, so she thanked him for his information and went on down the road.

Before long she came to a window in which was displayed a large notice:

> Are you dissatisfied with your State?
> Would you like to move up to a higher level?
> We will help you to make the Transition for only 10 eV.
> (Offer subject to normal Pauli exclusion limitation)

"That all sounds very enticing I am sure, but I have no idea what it is talking about, and if I were to ask someone I am sure the answer would leave me even worse off than I am now," exclaimed

Alice in desperation. "I have not really understood anything that I have seen so far. I wish I could find someone to give me a good explanation of what is going on around me."

She had not realized that she had spoken aloud, until she was answered by a passerby. "If you want to understand Quantumland you will need to find someone to explain to you about quantum mechanics. For that you ought to go to the Mechanics Institute," she was advised.

"Oh, will they be able to help me understand what is happening here?" cried Alice in delight. "Will they be able to explain all the things I have seen, such as that notice in the window there, and to tell me what these eV' are?"

"I should think the Mechanics will be able to give you an explanation for most of it," answered her informant, "but as 'eV' are units of energy you had probably best start by asking about them at the Heisenberg Bank, particularly as it is just across the road there."

Alice looked across where he was pointing and saw a large building with a very formal frontage, obviously designed to impress. It had a tall portico with stone pillars and over the top, in large letters, was carved the name THE HEISENBERG BANK. Alice crossed the road, climbed the long flight of stone steps which led up to the lofty doorway, and passed through.

CHAPTER

2 The Heisenberg Bank

When Alice stepped through the doorway she found herself in a large pillared hall with marble walls. It looked much like other banks that she had seen only more intensely so, as it were. There was a line of cashiers' windows along the far wall, and the vast floor area was divided up by portable tape barriers so that the customers would be guided into regular lines as they waited to be served. At the moment however the place appeared to be quite empty of any customers at all. Apart from the cashiers behind their counters and a bank guard standing by the door, Alice did not see anyone.

As she had been advised to ask for information at the Bank, she began to walk purposefully toward the distant line of windows. "Now just you wait a minute!" called the guard by the door. "Where do you think you are going, young miss? Can't you see that there is a line?"

"I am sorry," replied Alice, "but actually I *can't* see a line. There are no people here."

"There certainly are, and a lot of them!" answered the guard emphatically. "We seem to have quite a rush of 'no people' today. Usually though we refer to them as *virtual*. I have seldom seen quite so many virtual particles waiting to get their energy loans."

Alice had a by-now-familiar feeling that things were not going to become all that much clearer very quickly. She looked over at the windows and saw that, although the room still appeared to be quite empty, the cashiers were all very busy. As she watched, she saw bright figures appear, one at a time, in front of one till or another and then rush quickly from the Bank. At one till she saw a pair of figures materialize together in front of a grill. One she recognized as an electron; the other was very similar, but was a sort of photographic negative of the first, opposite in every way to the electrons she had seen previously.

"That is a positron, an *antielectron*," murmured a voice in her ear. Alice looked around and saw a severe-looking, smartly dressed young woman.

"Who are you?" she asked.

"I am the Bank Manager," replied her companion. "I am in charge of the distribution of energy loans to all the virtual particles here. Most of them are photons, as you can see, but sometimes we get pairs of particles and antiparticles who come along together to ask for a loan, like the electron and positron pair that you were looking at just now."

"Why do they need an energy loan?" asked Alice. "And why can't I see them before they get it?"

"Well you see," replied the Manager, "in order for a particle to exist properly, so that it can be a *free* particle and able to move around and be observed normally and so on, it has to have, at the very least, a certain minimum energy which we call its *rest mass energy*. These poor virtual particles do not have even that energy. Most of them have no energy at all, so they do not really exist. Fortunately for them, they can get a loan of energy here at the Bank and this allows them to exist for a little while." She pointed to a notice on the wall, which read:

CONDITIONS OF LOAN

$$\Delta E\, \Delta t = \hbar/2$$

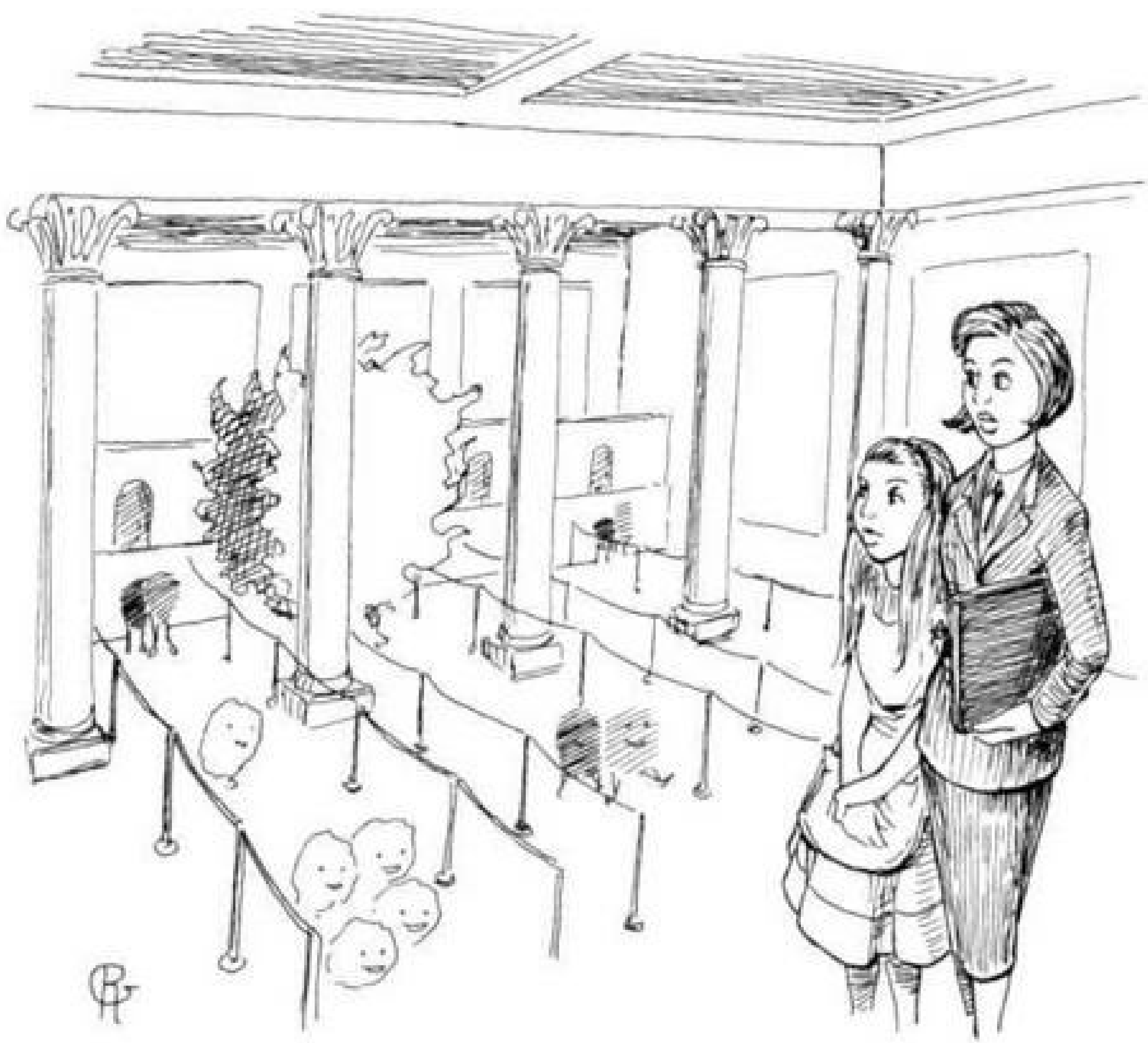
Prompt repayment
would be appreciated.

"That is called the Heisenberg relation. It governs all our transactions. The value $\hbar$ is called Planck's constant, the correctly reduced value, of course. The relation gives the rate of exchange for our energy loans. The quantity ΔE is the amount of energy which is borrowed, and Δt is the period for which the loan is made you see."

"You mean," said Alice, trying to follow what the Manager was saying, "that it is like an exchange rate between different types of money, so that the more time there is, the more energy they can have?"

"Oh no! Quite the reverse! It is the energy and time *multiplied together* which are constant, so the greater the amount of energy, the *shorter* the amount of time they are allowed to keep it. If you want to see what I mean just look at that exotic particle and antiparticle which have just taken out a loan at window #7."

Alice looked where she was directed and observed a striking sight. In front of the window was a pair of figures; one was the opposite of the other, in much the same way as for the electron and positron that she had seen earlier. This pair, however, were bright, flamboyant figures, taking up so much space with their presence that they quite obscured the cashier behind them. Alice could not but be impressed by the extravagance of the two, but as she opened her mouth to make a comment they grew hazy and then vanished completely.



Most particles have a rest mass, and this is the equivalent of a lot of energy. Virtual particles with no initial energy can still exist for a brief period by "borrowing" the energy that they need for their rest mass as a quantum fluctuation.

"That is an illustration of what I was saying," continued the Manager calmly. "That pair took out an enormous energy loan to support the huge rest mass that they needed for their lifestyle. Because the loan was so large, the repayment time was very short indeed, so short that they did not even manage to leave the counter before it had to be repaid. Because such heavy particles cannot get very far before they have to repay their energy loan, they are known in the trade as *short-range particles*," she added.

"Is the relation between time and energy the same for everyone then?" asked Alice, who felt that she might have discovered something definite at last.

"Yes indeed! The Planck constant is always the same whenever and wherever it applies. It is what is called a *universal constant*, which simply means it is always the same everywhere.

"We deal with energy at the Bank here," continued the Manager, "because energy acts as the currency here in Quantumland. As you would express your currency in pounds or dollars, the unit of energy that we use most of the time is called the *eV*. How much energy a particle has determines what it is able to do; how fast it can go, what state it can get into, how much it will be able to affect other systems, these all depend on the energy it has.

"Not all particles are completely destitute like the ones that are lining up. Many of them do have sufficient energy of their own, and in that case they can keep it for as long as they like. Those are the ones which you may see moving around outside. Any particle which needs to have a mass has to have energy just to exist at all."

She pointed at another framed notice on the wall, which read:

Mass Is Energy.
Energy Is Mass.

"If a particle wants to have mass then it must find the energy to support it somehow. If it has any energy left over then it can use it to do other things. Not that all particles bother with mass," she added. "There are some free-and-easy, bohemian particles which do not have any rest mass at all.

They are not tied down like most particles who have to provide for their mass, so they can make use of even small amounts of energy. Photons are a case in point. A photon has no rest mass, so a photon at rest would not weigh anything at all. Mind you, you do not normally find photons at rest; they are forever rushing about at the speed of light, as photons *are* what light is made of you see. Light is not a smooth continuous stream. It is made up of a lot of *quanta*, little packets of energy, so that the flow of light is lumpy. These quanta, or particles, of light are called photons. Practically everything comes in quanta of some size. This gives quantum physics its name, you know. Look at all those photons leaving the Bank now. Basically photons are all the same, exactly like one another in the way that electrons are all the same, but you may notice that many of these photons seem quite different. That is because they have different amounts of energy. Some of them have very little energy, like those radio frequency photons going out now."

Alice looked down at a crowd of photons which were rushing past her, flowing around her feet and on out through the door. As they went, she heard snatches of music, dramatic voices, and something about "doing lunch on Thursday." "I didn't know that radio waves were made up from photons," admitted Alice. "Oh yes indeed. They are very long wavelength photons of course, with low frequency and very little energy. They are very gregarious because if they are to have any noticeable effect you need a lot of them at once. Friendly little fellows aren't they?" smiled Alice's companion. "Visible photons now, the ones which make up the light that people use to see by, they have higher frequency and more energy. One of those can have quite a noticeable effect. The really affluent ones though, the big spenders, are the X-ray and gamma photons. Each one of those carries a lot of energy around with it and they can really make their presence felt on their surroundings if they choose to interact."

"That is certainly very interesting," said Alice, not entirely untruthfully, "but I still feel confused about the whole idea of energy. Can you tell me what energy actually *is*?"

"Well now," replied the Manager with satisfaction, "that is a very sensible question to ask. Unfortunately it is not a very easy one to answer. Come into my office and I will try to give you an explanation."

The Manager led Alice briskly across the tiled floor of the main hall and through an unobtrusive but rather forbidding door in one corner. Within was a large modern office. Motioning Alice to sit on a deep comfortable chair placed in front of the wide desk, the Manager went round and sat in the chair behind it.

"Well," she began, "energy is a little bit like money in your world and it is not too easy to say exactly what that is either."

"I should think that was quite easy," responded Alice. "Money is coins, like my pocket money, or it can be bank notes."

"That is *cash*, which is certainly one form of money, but money does not have to be in notes and coins. It can be in a savings account, for example, or in stocks and shares, or even invested in a building. In much the same way energy can take many forms, which seem quite different from one another.

"The most obvious form is *kinetic energy*," said the Manager, as she settled more comfortably into her chair and her voice took on the complacent tone of someone who is about to give a long lecture to a captive audience.

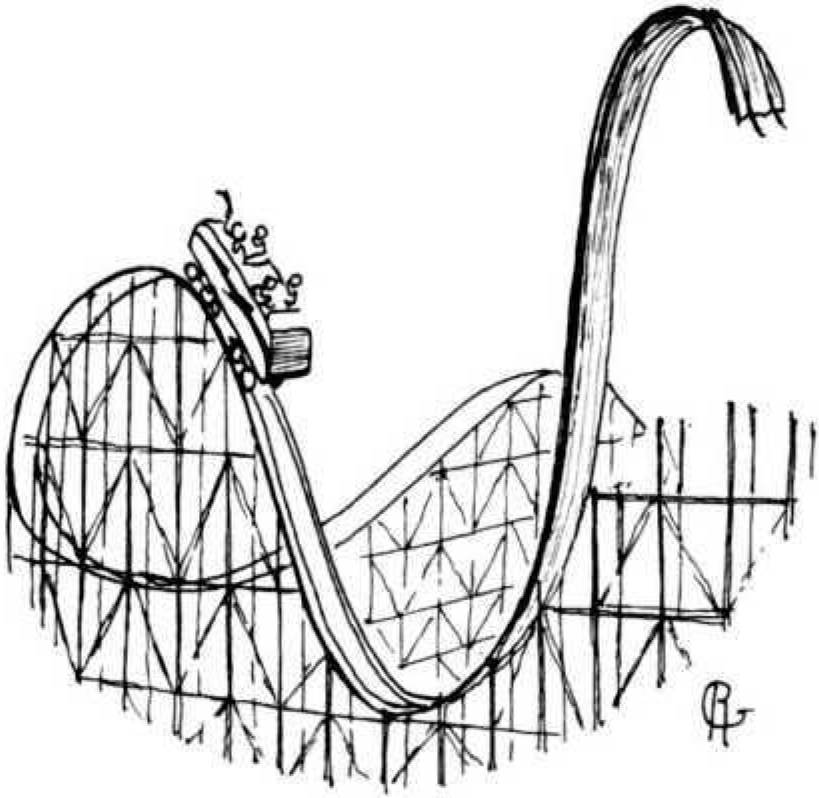
"A particle, or any other object for that matter, will have kinetic energy if it is moving about. Kinetic just means moving, you know. There are other forms of energy as well. There is *potential energy*, such as the gravitational energy which a stone has if it is up a hill and so is in a position to roll down it. You can also have electrical energy, or chemical energy, which is just potential energy which the electrons have when they are inside atoms. Then, as I have already mentioned, there is the *rest mass energy* which many particles must have just to exist, so that they can have some mass. One form of energy can *convert* into another, just as you can pay cash into your deposit account. I can illustrate that for you if you will just look through the round window." She leaned over and pressed a button on her desk, and a round window on the wall in front of Alice opened up. Through it Alice could see a fairground roller coaster. As she watched, a carriage climbed to the top of one hump and paused there momentarily before it rushed down the far side.

Energy comes in many forms. It may appear as the rest mass energy of a particle, as the kinetic energy which is involved in the movement of any object and as various types of potential energy. One form of potential energy is the gravitational potential energy of an object which decreases when the object falls.

"That carriage, as you can see, is not moving at the moment, so it has *no* kinetic energy, but it is high up so it has potential energy because of its position. Now as it starts to fall down into the dip it is losing height, so it loses some of that potential energy. This is converted to kinetic energy, so as it falls it goes faster and faster." Alice could vaguely hear the happy excited shrieks of the distant passengers in the carriage as it thundered down the track.

"If the track were very smooth and the wheels ran without friction," the lecturer continued dispassionately, "then the carriage would come to rest again at exactly the same height." She leaned over and fiddled with something on her desk again. The distant figures on the roller coaster cried out in surprise as the next hump in the track suddenly surged up before them to a much greater height. Their carriage slowed and came to a complete stop before it had reached the top. "How did you do that?" exclaimed Alice in amazement. "Never underestimate the influence of a bank," muttered her companion. "Now see what happens."

The carriage began to roll backward down the track, accompanied by more shrieks, still excited but not quite as happy as last time. It gathered speed until it shot through the lowest point and then climbed the opposite slope, slowing as it went. It came to rest just at the peak where Alice had first seen it and then began to slip back down once again.



"This will go on indefinitely now, with the energy of the carriage changing from potential energy to kinetic energy and hack again, but you get the idea." The Manager pressed another button on her desk and the window closed on the scene.

"That is the sort of obvious way in which you see energy in ClassicWorld. It will change from one form to another in a smooth continuous manner. You saw how the carriage got steadily faster as it rolled steadily down the slope, with no big jumps, and there are no obvious restrictions on the exact amount of energy which any object *might have*. Here in Quantumland it is often not like this. In many situations a particle is only allowed to have one of a restricted set of values and it can only accept or give up energy in large lumps, which we call *quanta*. In ClassicWorld all energy payments are made on the installment plan, with very frequent and very very tiny payments, but here they often have to be made as a lump sum.

"As you saw, kinetic energy is a dramatic, showoff sort of energy—something which a body has just because it is moving. The more massive it is the more kinetic energy it has, and the faster it moves the more kinetic energy it has, but the amount does not depend at all on the *direction* in which it is moving, only on the speed. In this respect it is different from another important quantity which tells us how a particle moves. This is something we call momentum. *Momentum* is a sort of measure of a particle's obstinacy. Every particle is determined that it is going to keep on moving in exactly the same way as it was before, without any change at all. If something is moving fast it takes a lot of force to slow it down. It also takes a lot of force to make it move in a different *direction*, even if its speed does not change. Now a change in direction does not cause a particle to lose any of its precious kinetic energy, as this depends only on how fast it is traveling, but it still does not want to change because its momentum would have to be different. Particles are rather *conservative* that way.

In quantum theory it is as important to consider energy and momentum as it is to consider position and time. Rather more important in fact, as it is easier to measure the energy of an atom than to determine where it is. Energy is in a sense the physical world's equivalent of money. Energy is defined classically as the "capacity for doing work," and it is necessary for particles to have energy in order to do something: to make transitions from one state to another. Momentum is a quantity more like velocity. It is going in a specific direction while energy has only a size. When you have said how *much* energy there is, then there is nothing left to say about it. Electrons moving from right to left and from left to right at the same speed have the same kinetic energies, but opposite momenta.

"It is all a question of what we call *parameters*," continued the Manager enthusiastically. "When you want to describe a particle, you have to use the right parameters. If you want to say where it is you must talk about its position and time, for example."

"I would have thought that you would just need to say what its position was," objected Alice. "That will tell you where it is, surely?"

"No, certainly not. You must give the time as well as the position. If you want to know where something is now, or where it will be tomorrow, it is no good my only telling you a position if that is where it was last week. You must know the position *and* the time, as things tend to move around you know. Just as if you want to know what a particle is *doing* you must describe that in terms of its momentum and energy, in general you need to give both position and time if you want to know where a particle is."

There are many varieties of energy. Kinetic energy is directly due to movement: A moving cannonball has energy which a stationary one does not have. Rest mass energy is another form. The rest mass energy of any object is large. In Newtonian mechanics there was no need to consider rest mass energy because it never changed, so it did not affect any energy transfer. In quantum processes the masses of particles often do change, and the change in rest mass energy may be released to other forms. A release of much less than 1 percent of the rest mass for a small fraction of the material occurs in a nuclear weapon, for example. This is not a large energy change per particle when compared to many processes investigated in particle physics, but it is devastating when it is released by a significant number of particles into our everyday world.

"Here in Quantumland the parameters tend to be related. If you try to see where something is then that has an effect on its momentum, how fast it is moving. It is another form of the Heisenberg relation which I pointed out to you in the Bank."

"Oh!" cried Alice, remembering a previous encounter. "Was that the reason that the electron I saw earlier could not stand still to let me see him without becoming all fuzzy?"

"Yes, undoubtedly. The uncertainty relations affect all particles that way. They always seem a bit indefinite, and you can never pin them down too precisely.

"I know what I shall do! I shall get the Uncertain Accountant to explain it to you," exclaimed the Manager. "His job is to try and balance the accounts, so he has to worry all the time about quantum fluctuations." She reached out an elegant finger and pressed yet another of the buttons with which her desk was so well supplied.

There was a short pause, and then one of the doors which were spaced around the room opened and a figure entered. He looked rather like a picture of Ebenezer Scrooge from an illustrated copy of *A Christmas Carol*, except that he had a rather bemused expression on his face and an uncontrollable nervous twitch. He was carrying an enormous ledger whose covers bulged, not to say wriggled as if the contents were in continuous motion.

"I believe I have done it," he cried triumphantly, twitching so violently that he almost dropped the book. "I have gotten the accounts to balance! Apart from the residual quantum fluctuations, of course," he added, less enthusiastically.

"Very good," answered the Manager absently. "Now I should like you to take this little girl, Alice, here and explain to her about quantum uncertainty and fluctuations in the energy of a system and all that sort of thing." With a wave of farewell to Alice, the Manager turned back to her desk and began doing something particularly complicated with all the buttons on it. The Accountant led Alice out quickly before anything further could happen.

It is convenient to talk about the Heisenberg *uncertainty* relations when describing the strange mixing of energy and time, of position and momentum, which occurs in quantum systems. The danger in such a description is that it promotes the belief that nature is, at bottom, quite uncertain, that nothing can reliably be predicted and, in fact, that *anything goes. This is not true!*

They came to a much smaller, more cluttered office which contained a tall, old-fashioned desk covered in ledgers and with scraps of paper piled all over the floor. Alice looked at one of the open ledgers. The page was covered with columns of figures, much like other accounts ledgers she had seen, except that in this one the figures were continually changing slightly as she looked at them.

"Right!" said the rather Victorian figure in front of Alice. "You want to know about Uncertainty do you, young lady?"

"Yes please, if it is not too much trouble," replied Alice politely.

"Well now," he began, seating himself at his desk. He steepled his fingers together in the traditional magisterial manner to increase the dignity of his appearance, but this was not a good idea as just then he gave such a particularly violent jerk that he got his fingers all tangled up, and he had to stop to unravel them.

"Well now," he repeated, thrusting his hands deep into his pockets for safety. "The thing you must remember about energy is that it is *conserved*, which is to say that there is always the same amount of it. It may convert from one form to another but the *total* amount is always the same. At least it is if you take the long view," he added wistfully and sighed, staring mournfully into the distance.

"Isn't it true in the short term then?" asked Alice, who felt that she should say something to keep the conversation going.

"Well no, not entirely. In fact, not at all, if the term is short enough. You saw the Heisenberg relation on the notice outside in the Bank didn't you?"

"Oh yes. I was told it gave the terms for the energy loans."

"Well, so it does, in a way, but where do you think the energy for the loans comes from?"

"Why, from the Bank of course."

"Dear me, no!" said the Accountant, looking slightly horrified. "Most certainly not! It would be a fine thing if the Bank started lending out energy from its own stock!

"No," he went on conspiratorially, looking around him carefully, "It is not widely known, but the energy does not come from the Bank. In fact it does not really *come from* anywhere. It is a quantum fluctuation. The amount of energy that any given system has is not absolutely definite, but will vary up and down, and the shorter the time over which you measure it the more it is likely to vary.

"In this respect energy is not really at all like money. Money is well conserved in the short term. If you want to have money for some purpose, you have to get it from somewhere, don't you? You may take it out of a bank account, or borrow it from someone, or you might even steal it!"

"I wouldn't do that!" cried Alice indignantly, but the Accountant continued, ignoring her.

"No matter where you get it, it has to come from somewhere. If you get more, then someone else has less. That is what happens in the immediate short term at any rate.

"In the long term it is different; you may get inflation and find there is more and more money about. Everyone has more, but it does not seem to buy as much as it did. Energy is quite the reverse in a way. In the long term it is conserved, the total amount stays the same, and you get nothing like economic inflation. Every year you will need the same amount of energy on average to transfer from one state in an atom to another. In the short term, though, energy is not well conserved. A particle can pick up the energy it needs for some purpose without it having to come from *anywhere* else; it just appears as a quantum fluctuation. These fluctuations are a consequence of the uncertainly relation: The amount of energy you have is *uncertain*, and the shorter the time you have it the more uncertain the amount you have."

"That sounds terribly confusing," said Alice.

"You do not have to tell me!" answered her companion emphatically. "It is! How would you like to be an accountant when the figures you are trying to balance are fluctuating all the time?"

"That sounds terrible," cried Alice sympathetically. "How do you manage?"

"Well, I usually try to take as long as I possibly can to do the accounts. That helps a bit. The longer the period of time that I spend the smaller the residual fluctuations, you see. Unfortunately people will get impatient and come to me asking if I am planning to take forever to balance the accounts. That would be the only way to do it, you see," he went on earnestly. "The longer I take, the smaller the energy fluctuations, so if I did take *forever*, why then there would be *no* fluctuations and my accounts would balance perfectly," he cried triumphantly. "Unfortunately they just won't let me alone. Everyone is much too impatient and anxious to be off making transitions from one state to another all the time."

Energy can be transferred from one form to another, but the total energy of a system is constant (as long as it does not transfer energy to or from its surroundings). This is absolutely true in classical mechanics. It is true in the long term in quantum systems, but in the short term the value of the energy fluctuates. The word *fluctuation* is better than the word *uncertainty* since there are real physical consequences. The barrier penetration during alpha decay of nuclei is one case; we will meet alpha decay in Chapter 8, and have already encountered barrier penetration in Chapter 1.

"That is another thing that I wanted to ask about," remembered Alice. "What are all these states that I keep hearing of? Would you explain them to me please?"

"I am not really the best person to do that. It is all part of Quantum Mechanics, so you really ought to go to the Mechanics Institute and ask them there."

"That is what I was told before," said Alice. "If that is the best place to ask, would you please tell me how I might get there?"

"I am afraid that I cannot actually *tell* you how to get there. That is not the way we do things here. But I can arrange that it is very *probable* that you will get there.

He turned to the far wall of his office, which was covered with a dusty curtain. When he drew this aside with a sudden jerk, Alice could see a row of doors spaced along the wall. "Where does each of those lead?" she asked. "Does one of them lead to this Institute you were talking about?"

Each of them could lead you almost anywhere, including, of course, to the Institute. But the point is that *all* of them will be *very* likely to lead you to the door of the Institute."

"I do not understand," complained Alice, with an all-too-familiar feeling of increasing confusion. "What is the difference? If each of them can lead almost anywhere, it is the same as saying that they all could lead almost anywhere."

"Not at all! It is a different thing entirely. If you were to go through any *one* door, why then you might end up almost anywhere, but if you go through them all at once then you will most probably end up where you want to be, at the peak of the interference pattern."

"What nonsense!" cried Alice. "I cannot possibly go through all the doors at once. You can only go through one door at a time you see."

"Ah, that is different! Of course, if I *see* you going through a door, then you will go through that door and no other, but if I do *not* see you, then it is quite possible for you to have gone through any door. In that case the general rule will apply."

With a wave of his hand he indicated a large, striking notice which was fixed on the wall in front of his desk, where he could not avoid seeing it. It read:

> What is not forbidden is
> compulsory!

"That is one of the most basic rules that we have here. If it is possible to do several things, you do not just do one of them, you have to do them all. That way it saves having to make your mind up very often. So off you go, just go out through all the doors and when you have, then set off in every direction at once. You will find it is quite easy and very soon you will have got to the right place."

"This is ridiculous!" protested Alice. " There is no way that I can go through several doors at once!"

"How can you say that until you have tried? Have you never done two things at the same time?"

"Well, of course I have" answered Alice. "I have watched television while I was doing my homework, but that is not the same thing at all. I have never gone in two directions at the same time."

"I suggest then that you try it," replied the Accountant, rather huffily. "You never know whether you can do something until you try. That is the sort of negative thinking which is always holding back progress. If you want to get anywhere here you have to do *everything* that you possibly can and do it all at the same time. You do not have to worry about where it will take you, the interference will take care of that!"

"How do you mean? What is interference?" cried Alice.

"No time to explain. The Mechanics will tell you all about that. Now off you go and they will explain when you arrive."

"This is really too bad!" thought Alice to herself. "Everyone I speak to rushes me on somewhere else and promises me that I will get an explanation as soon as I get there. I wish that someone would just explain things properly, once and for all! I am sure that I do not know how I can possible go several ways at the same time. It seems to me to be quite impossible, but he is so certain that I shall be able to manage it here that I had better try, I suppose."

Alice opened a door and stepped through.

Alice's Many Paths

Alice stepped through the left-hand door and found herself in a small cobbled square with three narrow alleys leading out of it. She walked down the left-hand alley. Before she had gone very far, she found herself on the edge of a broad paved area. In the center rose a tall dark building with no windows on the lower levels. It looked very forbidding.

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Alice stepped through the left-hand door and found herself in a small cobbled square with three narrow alleys leading out of it. She walked down the right-hand alley. Before she had gone very far she came to a park, with weed-choked gravel paths winding between dismal drooping trees. Tall iron railings surrounded the park and a dank mist obscured the scenery within.

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Alice stepped through the left-hand door and found herself in a small cobbled square with three narrow alleys leading out of it. She walked down the middle alley. Before she had gone very far she came to another small square, in front of a rather shabby-looking building.

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Alice stepped through the right-hand door and found herself in a narrow alleyway with two others branching off it. She walked down the left-hand alley. Before she had gone very far she found herself on the edge of a broad paved area. In the center rose a tall, dark building with no windows on the lower levels. It looked very forbidding, and she had a distinct feeling that she ought not to be there.

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Alice stepped through the right-hand door and found herself in a narrow alleyway with two others branching off it. She walked down the right-hand alley. Before she had gone very far she came to a park, with weed-choked gravel paths winding between dismal drooping trees. Tall iron railings surrounded the park and a dank mist obscured the scenery within. She had a very strong feeling that she ought not to be there.

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Alice stepped through the right-hand door and found herself in a narrow alleyway with two others branching off it. She walked on down the central alley. Before she had gone very far she came to another small square, in front of a rather shabby-looking building. Somehow it seemed to her that this was the right place to be.

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Alice stepped through the center door and found herself facing a wall with three arched gateways which led to alleys beyond. She walked down the left-hand alley. Before she had gone very far she found herself on the edge of a broad paved area. In the center rose a tall, dark building with no windows on the lower levels. It looked very forbidding. She now felt very strongly that she ought not to be there.

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Alice stepped through the center door and found herself facing a wall with three arched gateways which led to alleys beyond. She did not walk down the right-hand alley at all, as that route somehow seemed to be completely wrong.

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Alice stepped through the center door and found herself facing a wall with three arched gateways which led to alleys beyond. She walked through the gateway to the central alley. Before she had gone very far she came to another small square, in front of a rather shabby-looking building. She now felt quite sure that this was the place where she ought to be.

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Alice looked more closely at the building. On a faded board by the door she could make out the words "Mechanics Institute." This was indeed where she had intended to come!

Particles which may take different paths exist as a superposition (sum) of amplitudes. Each possible path contributes an amplitude, or option, for the particles' behavior, and the amplitudes are all present together. The different amplitudes may *interfere*, combining together so that they add in some regions to give a high probability of finding the particles there. Elsewhere they may cancel one another out to give a low probability of finding any particles. Amplitudes and interference are discussed in the next chapter.

CHAPTER

3 The Mechanics Institute

Alice examined the building in front of her. It was unremarkable, a plain brick structure now rather the worse for wear. In front of her was the board which stated that this was "The Mechanics Institute." Beside this was a wooden door on which someone had pinned a note: "Don't knock. Just come in." Alice tried the door and found it was not locked, so she opened it and walked through.

Inside she found herself in a large, dark room. In the middle of the room there was an area of light and clarity. Within this limited area it was possible to make out a reasonable amount of detail. Beyond this there was a seemingly limitless expanse of darkness within which nothing meaningful could be discerned. In the pool of light was a billiards table, with two figures moving around it. Alice walked toward them, and as she approached they turned to look at her. They were an oddly assorted couple. One was tall and angular. He wore a starched white shirt with a tall stiff collar, a narrow tie, and, rather to Alice's surprise, a boiler suit. His face was aquiline, with bushy side whiskers. He regarded her with a gaze of such piercing intensity that Alice felt he could clearly distinguish every tiniest detail in whatever he saw. His companion was smaller and younger. He had a round face decorated with large, round metal-rimmed glasses. Behind the glasses his eyes were strangely hard to see; it was difficult to say where he was looking, or even exactly where his eyes were. He was wearing a white laboratory coat, which was open to display beneath it a T-shirt with a picture of something vaguely atomic on the front. It was not easy to say exactly what it was meant to be as the colors appeared to have run in the wash.

"Excuse me, is this the Mechanics Institute please?" asked Alice, mostly for the sake of making conversation. She knew from the notice outside that it must be.

"Yes, my dear girl," said the taller and more impressive looking of the two. "I myself am a Classical Mechanic from ClassicWorld, and I am visiting my colleague here, who is a Quantum Mechanic. Whatever your problem is, I am sure that between us we will be able to assist you, if you would just wait a moment while we finish our shots."

Both men turned back to the billiards table. The Classical Mechanic took careful aim, clearly judging all the angles involved to within a tiny fraction of a degree. At last, he very deliberately played his shot. The ball bounced to and fro in a remarkable series of ricochets, ending in a collision with the red ball and knocking it squarely into the center of a hole. "There you are," he exclaimed with satisfaction as he retrieved the ball from the pocket. "That is the way to do it, you know; careful and exact observation followed by precise action. If you do things that way you can produce any result you choose."

His companion did not respond, but took his place at the table and made a vague stab with his cue. After her previous recent experiences Alice was not really surprised to discover that the ball shot off in every direction at once, so that there was no part of the table where she could say definitely that the ball had not gone, though equally she could in no way say where it actually was. After a moment the player went over and peered into one of the pockets, then reached in and drew out a red ball.

"If you do not mind my saying so," said Alice, "you do seem to play the game very differently."

"Quite so," replied the Classical Mechanic. "I hate the way he plays his shots like that. I like everything to be done very carefully and precisely and to be planned in every detail in advance. However," he added, "I imagine that you did not come here to watch us play billiards, so tell us what you wanted to know."

Alice recounted all her experiences since she came into Quantumland and explained how confusing she found it and how everything seemed so strange and somehow indefinite. "And I do not even know how I came to find this building," she finished. "I was told that the interference would probably bring me to the right place, but I do not understand what happened at all."

"Well now," began the Classical Mechanic, who seemed to have appointed himself as the spokesman for the two. "I cannot say that I really understand all of it either. As I have said, I like things to be clear-cut, with cause following effect in a sensible fashion and everything clear and predictable. If truth be told, not a lot that goes on here makes much sense to me," he whispered confidentially to her. "I am just visiting from ClassicWorld. That is a splendid place where everything happens with mechanical precision. Cause follows effect in a wonderfully predictable fashion, so it all makes sense and you know what is going to happen. What is more, the trains all run on time," he added as an afterthought.

See end-of-chapter note 1

"That sounds very impressive," said Alice politely. "If it is so well organized, is everything run by computers?"

"Well, no," answered the Classical Mechanic. " We do not use computers at all. In fact electronics will not work in ClassicWorld. We are bet ter with steam engines. I do not really feel at home in Quantumland. My friend here is much more familiar with quantum conditions.

"However," he went on more confidently, "I can tell you what interference is. That happens in classical mechanics as well. Just follow me and I shall demonstrate how it works."

He led Alice out through a door, down a short corridor, and into another room. This one was well illuminated, with a clear light which was equally bright everywhere and did not seem to come from any particular source. They stood on a narrow wooden walkway which ran around the edges of the room. The floor in the center was covered with some sort of shimmering grayish material, which did not look solid. It was shot through with random flashes of light, rather like a television set when there is no picture being received.

Her guide explained, "This is the *gedanken* room, which means a 'thinking room.' You know that many gentlemen's clubs have a writing room and a reading room. Well, we have a thinking room. In here one's thoughts can take on substance, so that anyone can look at them. It allows us to do *thought experiments*. These allow us to work out what would happen in various physical cases, and they are much cheaper than real experiments of course."

"How does it work?" asked Alice. "Do you just think of something and it appears?"

"That is correct; in essence that is all you have to do."

"Oh please, may I try?" asked Alice.

"Yes certainly, if you wish."

Alice thought very intensely at the shifting, flickering surface. To her surprise and delight, where there had before been a featureless area there was now a group of small furry rabbits hopping about.

"Yes, very pretty," said the Mechanic rather impatiently. "But this is not helping to explain interference." He made a gesture and all the rabbits vanished, all but one little one who remained unnoticed in a corner of the area.

"Interference," he began authoritatively, "is something which happens with waves. You can have all kinds of waves in physical systems, but it will be simplest to consider water waves." He stared hard at the floor, which turned before Alice's eyes into a sheet of water, with gentle ripples running over the surface. In the corner the rabbit vanished below the surface with a "plop" as the floor turned to water beneath it. It quickly struggled out again and glared at them. Then it shook itself, looked mournfully at its damp fur, and vanished.

"Now we want some waves," continued the Classical Mechanic, paying no attention to the unhappy rabbit. Alice obligingly thought at the floor and a long curling wave came sweeping across the surface and broke dramatically upon a beach at one end.

"No, that is not the sort of wave that we want. Those large breaking waves are too complicated. We want the sort of gentler ripple which spreads out when you throw a stone into water." As he spoke a series of circular ripples spread out from the middle of the water.

"But we need to think about what are called *plane waves* where they all move in the same direction." The circular ripples changed to a series of long, parallel furrows, like a wet plowed field, all moving across the floor from one side to the other.

"Now we put a barrier in the middle." A low fence sprang up across the center, dividing the floor in two. The waves flowed up to the barrier and lapped up and down against it, but there was no way for them to get through and the water beyond was now still and calm.

"Now we make a hole in the barrier, so that the waves can get through there." A neat little gap appeared just to the left of the fence's center point. Where the ripples struck this narrow gap they could pass through and spread out in circular ripples into the calm region beyond.

"And now, see what happens when we have two holes in the barrier," cried the Mechanic. Abruptly there were holes both to the right and to the left of the center. Circular ripples spread out from both of these. Where they crossed, Alice could see that in some places the water was surging up and down much more than it had when there was only one hole open, whereas in other places it hardly moved at all and was locally quite still.

"You can see what is happening if we freeze the motion. We can do that of course in a thought experiment." All motion on the water stopped, and the patterns of ripples were frozen into position, as if the whole area had turned abruptly to ice.

"Now we shall mark regions of maximum and minimum amplitude," continued the Classical Mechanic determinedly. "The amplitude is the amount by which the water moves from the surface level it had when calm." Two fluorescent arrows appeared, hanging in space above the surface. One was an apple green color and was pointing down at a point where the disturbance was greatest. The other was a pale red and pointed to a spot where the surface was almost undisturbed.

"You will be able to see what is happening if we now look at the effect of only one hole at a time," he said, with steadily increasing enthusiasm. One of the gaps in the fence vanished, and there were left only the circular ripples spreading out from the other one, though still frozen in position as if they were made from glass. "Now we will switch to the other hole." Alice could see very little difference when this happened. The position of the gap had moved and the pattern of circular ripples coming from it had moved very slightly, but overall it looked much the same. "I am afraid that I cannot understand what you are trying to show me," she said. "The two cases look just the same to me."

"It will help you to see the difference if we cut quickly from one case to the other." Now the gap in the fence leapt to and fro, first to the right, then to the left. As it moved, the pattern of ripples on the surface shifted slightly back and forth.

"Look at the wave patterns under the green arrow," cried the Mechanic, who seemed to Alice to have become quite unnecessarily excited about the subject. However, she did as requested and saw that at the point indicated there was a hump in the water in each case. "Each gap in the fence has produced a wave which is high at this particular point, so when both gaps are open the wave is twice as high here and the overall rise and fall of the water is much greater than it is for one gap alone. This is called *constructive* interference.

"Now look at the wave patterns under the red arrow." Here Alice saw that, while one gap gave rise to a hump at that point, the other produced a trough in the surface. "You can see that in this position the wave from one gap goes up and that from the other goes down, so when you have the two present together, they cancel one another out and you get no overall effect. This is called *destructive* interference.

"That is all there is to wave interference really. When two waves overlap and combine with one another, their amplitudes, the amounts by which they go up or down, combine with one another. In some places the contributing waves are all going in the same direction, so the disturbances add up and you get a large effect. At other positions they go in different directions and cancel one another out."

"Yes, I think that I follow that," said Alice. "So you are saying that the doors in the Bank acted rather like the gaps in the fence here and gave rise to some sort of large effect in the place where I needed to go and can - celed one another out in other positions. I do not see how that can apply to my case though. With your water wave you say that there is more of the wave in one place and less in another because of this interference, but the wave is spread out over the whole area, while I am always in just one place at any time."

"Exactly!" cried the Classical Mechanic triumphantly. "That is the problem. As you say, you are in one place. You are more like a particle than a wave, and particles behave quite differently in a sensible classical world. A wave is spread over a wide area and you look at only a small portion of it at any position. Because of interference you may get more or less of it at different positions, but it is only a small part of the whole wave wherever you look. A particle, on the other hand, is located at some point. If you look in various positions you will either find the whole particle or it is simply not there. In classical mechanics there is no question of particles showing interference effects, as we can show."

He turned to the floor of the *gedanken* room and stared firmly at it. The surface turned from water to a smooth area of steel armor, with armored barriers around the edges, high enough for them to hide behind. Across the middle of the floor, where the low fence had stretched across the water, was now a tall armored wall, with a narrow slit slightly to the left of center. "Now we can look at the same setup, but I have changed it so that we can look at fast particles. These are something like bullets from a gun, so that is what we will use."

He gestured toward one end of the room where there appeared an unpleasant-looking machine gun with many boxes of ammunition stacked beside it. "This gun has an unsteady mounting, so that it will not always shoot in the same direction. Some of the bullets will strike the gap in the wall and pass through, as part of the wave did in our last thought experiment. Most of them, of course, will hit the steel wall and bounce off. Oh that reminds me," he added abruptly. "We had better wear these in case we are struck by ricocheting bullets." He produced a pair of steel helmets and handed one to Alice.

"Do we really need these?" asked Alice. "If this is only a thought experiment, surely these are thought bullets, and can't do us any harm."

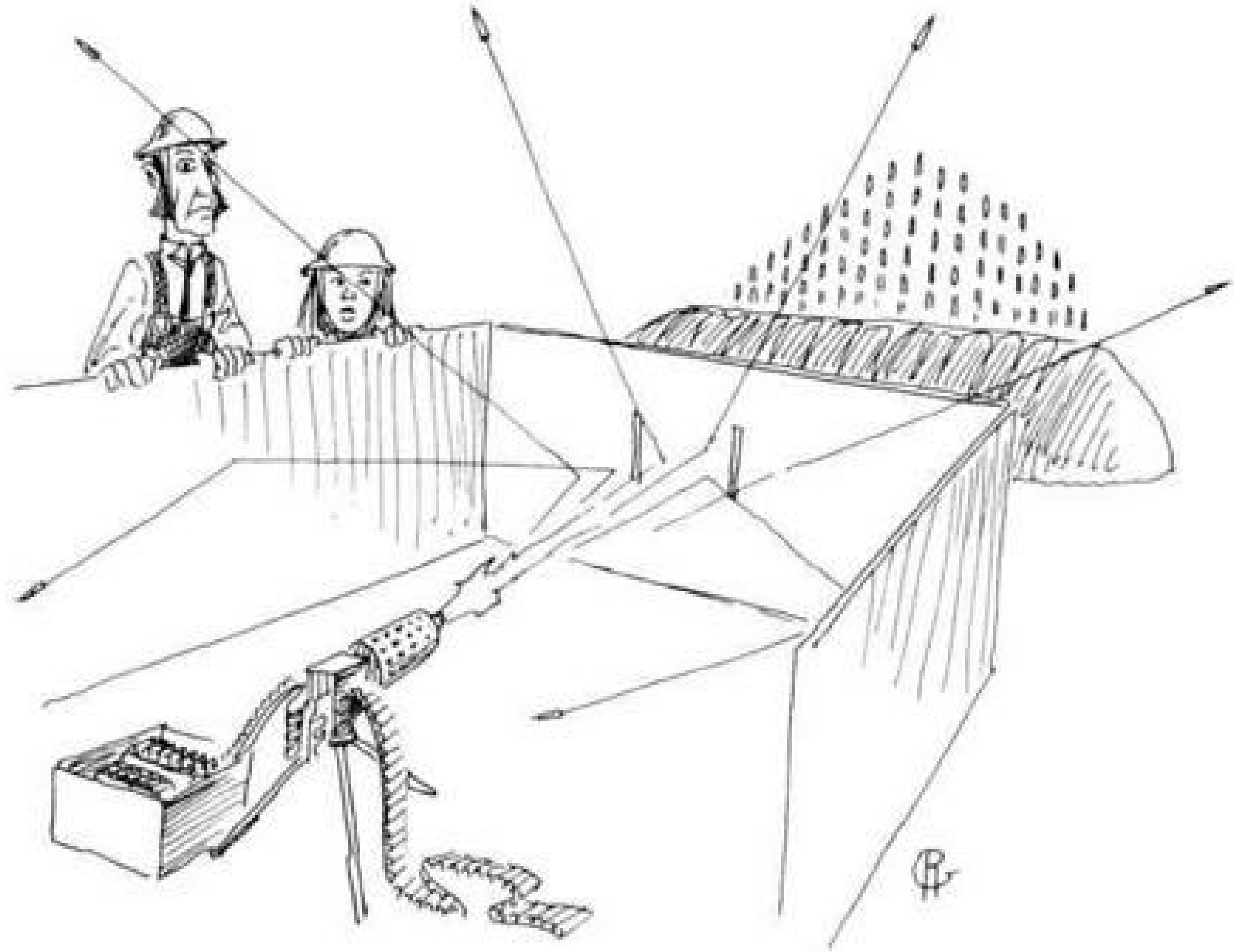
"Well, perhaps so. But you might still *think* that you had been hit by a bullet, and that would not be very nice you know."

Alice put the helmet on. She could not feel it on her head and did not think that it would be the least bit of use, but there did not seem to be much point in arguing any further. The Mechanic stood upright and gave an imperious wave of his hand, and the gun began firing very noisily. The bullets shot out in an unsteady stream; most hit the armored screen and whined off in all directions, but a few got through the slits in the barrier and hit the wall opposite. Alice was intrigued to note that when a bullet hit this wall, it immediately came to a stop and then rose slowly into the air to hang suspended in space, directly above the point where it had struck the wall.

Interference is classically a property of waves. It happens when amplitudes, or disturbances, from different sources come together, since they may add in some places and subtract or cancel in others. This will result in regions of intense or of low activity respectively. You can see such an effect in the pattern produced when the wakes left by two boats cross one another. Interference effects can also result in poor television reception when reflections from a building interfere with the direct signal. Interference requires extended, overlapping distributions. Classically particles are in one single position and do not interfere.

"As you can see, whereas the water wave was spread out all over the far wall, a bullet will hit it in one position only. However, in this experiment there is a greater *probability* that the bullet will strike the far wall opposite the slit in the screen than there is that it will bounce off the slit edge and end up a long way off to the side. If we wait for a little we will see how the probability varies for different points along the wall." As time passed and the air became full of flying bullets, the number which were suspended above the wall grew steadily. As she watched, Alice could make out a distinct trend developing.

"There, you see how the bullets which have passed through the slit are distributed along the wall," remarked the Mechanic as the gun fell silent. "Most have ended up directly opposite the hole, and the number falls off steadily on either side. Now see what happens when the slit is offset to the right." With another wave of his hand the hovering bullets dropped to the ground, and the gun began to fire again. Though the demonstration was noisy and rather unsettling, as far as Alice could see the end result was just the same as last time. Frankly, it was disappointing.



"As you can see," said the Mechanic with misplaced confidence, "the distribution is similar to the previous one, but displaced slightly to the right because the center is now opposite the new position of the slit." Alice could not see any difference at all, but she was prepared to take his word for it.

"Now," continued the Mechanic dramatically, "see what happens when *both* slits are open." As far as Alice could see it did not make the slightest difference, except that, since two slits were now open, more bullets got through to hit the far wall. This time she decided to comment. "I am afraid that it looks just the same to me each time," she said rather apologetically.

"Exactly!" replied the Mechanic with satisfaction. "Except that, as you will of course have observed, the center of the distribution is now centered between the two slits. We had one distribution for the probability that bullets will pass through the left-hand slit and another distribution for the probability that bullets will pass through the right-hand slit. When we have both slits open, then bullets may pass through either slit, so the overall distribution is given by the sum of the probabilities that we got for the two slits on their own, since the bullets must have passed through one *or* the other. They cannot have passed through *both* you know," he added, addressing the Quantum Mechanic, who had just come into the room.

"You say that," replied his colleague, "but how can you be so sure? Just look what happens when we repeat your *gedanken* experiment with electrons."

In his turn, the Quantum Mechanic waved his hand at the floor of the room. His gestures were not so decisive as his companion's, but they seemed to work just as well. The gun and the armored walls all disappeared. The floor returned to the shimmering material which Alice had first seen, but the now-familiar wall with two slits near its middle was still there, stretching across the center of the floor. At the far end of the floor was a wide screen with a greenish glow. "That is a fluorescent screen," muttered the Mechanic in her ear. "It gives a flash of light when an electron hits it, so it can be used to detect where they are."

At the opposite end of the floor, where the machine gun had been placed before, was another gun. This was a small stubby affair, like a very small version of the cannons from which people are sometimes shot during circus performances. "What is that?" asked Alice.

"Why, it's an *electron gun*, of course." As Alice looked more carefully, she could see a short flight of steps leading up to the mouth of the cannon and a line of electrons waiting to be fired from it. They seemed to be a great deal smaller than when she had last seen them. "But of course," she told herself, "these are only thought electrons."

As she looked at them, she was surprised to see the electrons all turn and wave to her. "I wonder how they know me?" she asked herself. "But then I suppose that they are *all* the same electron that I met before!"

"Commence firing!" commanded the Quantum Mechanic, and the electrons hurried up the steps into the gun and shot out in a steady stream. Alice could not make them out at all when they were in flight, but she saw a bright flash where each one hit the screen. As each flash died, it left a small glowing star which rose up the screen and remained behind to provide a marker for the position where the electron had landed.

As had been the case for the machine gun before it, the electron gun continued to fire out its stream of electrons and the stacks of little glowing stars began to build up a recognizable distribution. At first Alice could not be too sure what she was seeing, but as the number of little stars displayed became larger it was clear that their distribution was quite different from that represented by the previous stacks of bullets.

Instead of a slow, steady decrease from a maximum number in the center, the stars were now arranged in bands, with dark gaps between where there were few if any of the glowing markers. Alice realized that this was in a way like the case she had seen for the water waves, where there had been regions of high activity with calm areas in between. Now there were regions where many electrons had been detected, with very few in the areas between. It consequently came as no great surprise to her when Quantum Mechanic said, "There you see a clear interference effect. With the water waves you had regions of greater and lesser motion at the surface. Now each electron will be detected at one position only, but the *probability* of detecting an electron varies from one position to another. The distribution of different wave intensities which you saw before is replaced by a probability distribution. With one or two electrons such a distribution is not obvious, but when you use a lot of electrons you will find more of them in the regions of high probability. With one slit alone we would have seen that the distribution would decrease smoothly to either side, much as the bullets or the water waves did when there is only one slit. In this case we see that, when there are two slits open, the amplitudes from the two slits are interfering and are producing obvious peaks and troughs in the probability distribution. The behavior of the electrons is quite different from that of my friend's bullets."

"I do not understand," said Alice. This seemed to her to be the only thing she ever said. "Do you mean that there are so many electrons going through that somehow the electrons which go through one hole are interfering with the ones which go through the other?"

"No, that is not what I mean. Not at all. You shall now see what happens when there is only one electron in flight at any time." He clapped his hands and cried "OK! Let's do it again, but slowly this time." The electrons sprang into action or rather, to be strictly accurate, one climbed up into the cannon and shot off. The others continued to sit around where they were. A little later another electron climbed in and was fired on its way. This continued for some time, and Alice could see the same pattern of clumps and gaps appearing. These clumps and gaps were not so clear this time as they had been before because the slow rate at which the electrons were arriving meant that there were not very many in the clumps, but the pattern was clear enough. "There, you see that the interference effect works just as well even when there is only one electron present at any time. One electron on its own can show interference. It can go through both slits and interfere with itself, so to speak."

"But that is silly!" cried Alice. "One electron cannot go through both slits. As the Classical Mechanic said, it just isn't sensible." She went up to the barrier and peered more closely, to try and see where the electrons went as they passed through the slits. Unfortunately the light was poor and the electrons moved by so quickly that she could never quite make out which slit any one had passed through. "This is ridiculous," thought Alice. "I need more light." She had forgotten that she was in the "thinking room" and was startled when an intense spotlight mounted on a stand appeared by her elbow. Quickly she directed the light toward the two slits and was pleased to find that now there was a visible flash near one hole or the other when the electron passed through. "I have done it!" she cried. "I can see the electrons as they go through the slits, and it is just as I said it must be. Each one does go through just one slit."

The strongest experimental evidence for quantum behavior is given by the phenomenon of interference. When an observed result may come about in several ways, then an amplitude for each possible way will in fact be present. Further, if these amplitudes are in some way brought together then they can add or subtract and the overall probability distribution shows distinctive maxima and minima: alternating intense and empty bands. This effect is seen in practice wherever it might be expected. A form of interference produces the sets of distinct energy states which occur in atoms. Only those states which “fit neatly” within the potential will interfere positively to give a strong maximum in the probability. Any other states would cancel themselves out and hence do not exist.

"Aha!" replied the Quantum Mechanic meaningfully. "But have you looked to see what is happening to the interference pattern?" Alice looked back toward the far screen and was amazed to see that now the distribution of little stars fell smoothly from a central maximum, just like the distribution that she had seen for the classical bullets. It didn't seem fair somehow.

"That is how it always happens; there is nothing that you can do about it," said the Quantum Mechanic soothingly. "If you don't have any observation to show which hole the electrons go through, then you get interference between the effects of the two holes. If you do observe the electrons, then you find that indeed they *are* in one place or the other, not both, *but* in that case they also act as you would expect if they had come through one hole only and you do not get any interference. The problem is that there is no way in which you can look at the electrons without disturbing them, as when you shone that light on them, and the very act of making the observation forces the electrons to choose one course of action. It doesn't matter whether or not you make a note of which hole the electron came through. It does not matter whether you are aware which hole it came through. Any observation which *could* tell you this will disturb the electron and stop the interference. The interference effects only happen when there is no way that you could know which slit the electron went through. Whether or not you do know does not matter.

"So you see, when there is interference it seems as if each electron is going through both slits. If you try and check on this, you will find that the electrons go through only one slit, but then the interference vanishes. You can't win!"

Alice thought about this for a bit. "That is utterly ridiculous!" she decided.

"Certainly it is," replied the Mechanic with a rather smug smile. "Quite ridiculous I agree, but as it also happens to be how Nature works we have to go along with it. Complementarity, that's what I say!"

"Would you please tell me what you mean by *complementarity*?" asked Alice.

"Why of course. By complementarity I mean that there are certain things you cannot know, not all at the same time anyhow."

"Complementarity doesn't mean that," protested Alice.

"It does when I use it," replied the Mechanic. "Words mean what I choose. It is a question of who is to be master, that is all. Complementarity, that's what I say."

"You said that before," pointed out Alice, who was not entirely convinced by his last assertion.

In quantum mechanics a particle is like a wave and a wave is like a particle. They are the same thing. Electrons and light both show interference effects, but when detected they are detected as individual quanta and are each observed at one place. Interference between different paths which a particle might take will give a probability distribution with pronounced maxima and minima, where it is more *likely* that a particle will be detected in one position than another.

"No, I didn't," said the Mechanic. "This time it means that there are questions you cannot ask of a particle, such as where it is and, at the same time, how fast it is going. In fact it may not be really meaningful to talk about an electron *having* an exact position."

"That is a great deal for one word to mean!" said Alice tartly.

"Why, to be sure," answered the Mechanic, "but when I make a word do extra work like that I always pay it more. I am afraid that I cannot really explain what is happening to the electrons. An explanation is usually required to make sense in terms of things you already know about and quantum physics doesn't do that. It seems to make nonsense but it works. It is probably safe to say that no one really understands quantum mechanics, so I cannot *explain*, but I can tell you how we *describe* what goes on. Come into the back room and I will do my best."

See end-of-chapter note 2

They left the *gedanken* room, whose floor had returned to its original shimmering aspect, and walked down the corridor to another room furnished with scattered armchairs. When they had seated themselves, the Quantum Mechanic continued. "When we talk about a situation like the electrons passing through the slits, we describe it with an *amplitude*. This is something like the waves that you looked at, and indeed it is often called a *wave function* instead. The amplitude can pass through both the slits, and it is not always positive, like a probability. The lowest probability that you can have is zero, but the amplitude may be negative or positive, so the parts from different paths can cancel or add and give interference, again just like the water wave."

"So where are the particles?" asked Alice. "Which slit do they actually go through?"

"The amplitude doesn't really tell you about that. However if you *square* the amplitude, that is multiply it by itself so that it gives something that is always positive, then it gives you a *probability distribution*. If you choose any position this will tell you the probability that, when you observe a particle, you will find it at that position."

"Is that all it can tell you?" exclaimed Alice. "I must say that it sounds very unsatisfactory. You would never know where anything is going to be."

"Yes, that is true enough. For *one* particle you cannot tell where it will be found, except that it will not be at a position where there is zero probability of course. If you have a large number of particles, though, then you can be fairly sure that you will find more where the probability is high and far fewer where it is low. If you have a very large number of particles, then you can say quite accurately how many will end up where. That was the case with those builders you were telling us about. They knew what they would get because they used a large number of bricks. For really large numbers the overall reliability is very good."

See end-of-chapter note 3

"And there is no way you can say what each particle is doing until it is observed?" repeated Alice, just to get this clear.

"No, no way at all. When the thing that you actually observe could have come about in several different ways, then you have an amplitude for each possible way, and the overall amplitude is given by adding all of these together. You have a *superposition of states*. In some sense the particle is doing all the things which it could possibly be doing. It is not just that you do not *know* what the particle is doing. The interference shows that the different possibilities are all present and affect one another. In some way they are all equally real. Everything that is not forbidden is compulsory."

"Oh, I saw that on a notice in the Bank. It looked very stern."

"You had better believe it! It is one of the main rules here. Where there are several things which might happen, they all do. Look at the Cat, for example."

"What cat?," asked Alice, looking around her in confusion.

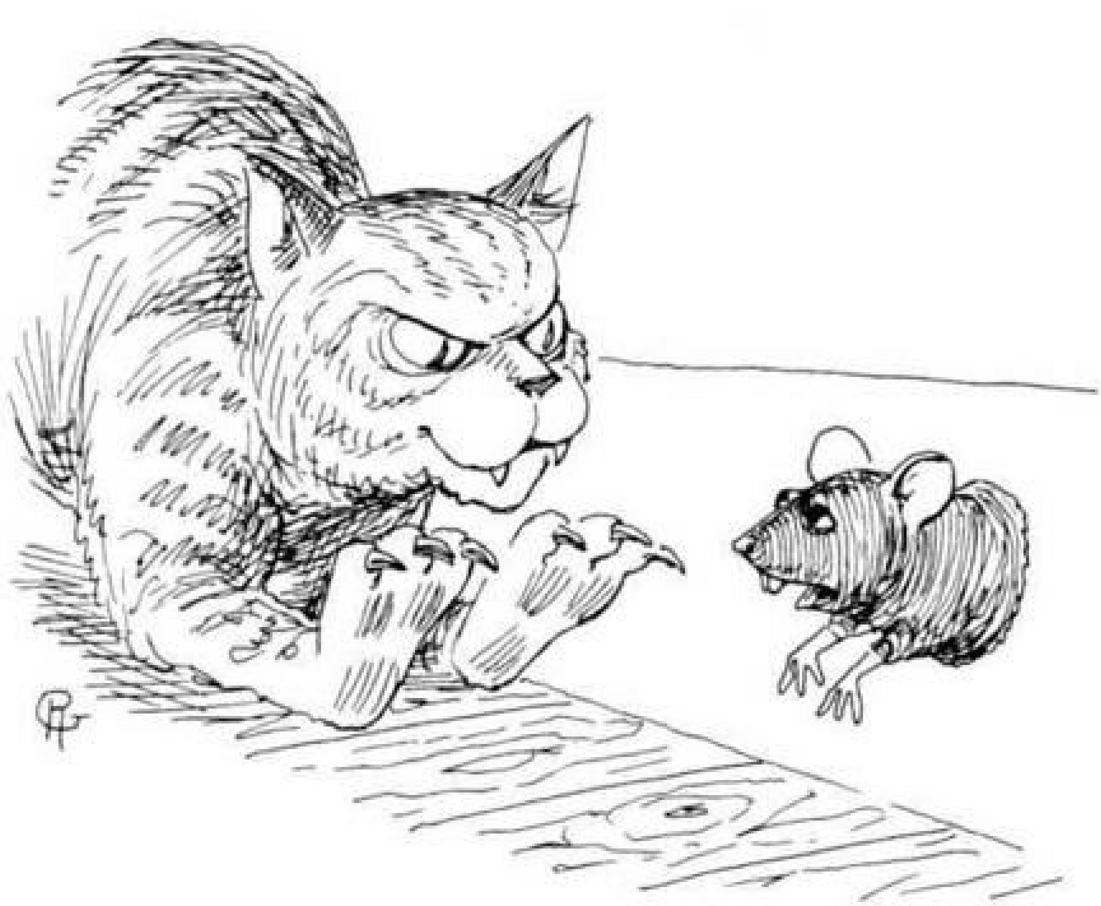
"Why Schrödinger's Cat over there. He left it with us to look after." Alice looked over in the corner where the Mechanic was pointing and saw a large tabby cat sleeping in a basket in the corner. As if awakened by hearing its name the cat stood up and stretched. Or rather, it did and it didn't. Alice could see that, as well as the slightly hazy figure of the cat standing with back arched in the basket, there appeared to be another identical cat which was still lying on the bottom. It was very stiff and motionless and lay in a rather unnatural position. From the look of it, Alice would have sworn that it was dead.

"Schrödinger devised a *gedanken* experiment in which an unfortunate cat was enclosed in a box, together with a flask of poison gas and a mechanism which would break the flask should a sample of radioactive material happen to decay. Now such a decay is definitely a quantum process. The material might or might not decay, so according to the rules of quantum physics you would have a superposition of states, in some of which the decay would have happened and in others it would not. Of course, for those states where a decay had happened the cat would have been killed, so you would have a superposition of cat-states, some dead and some alive. When the box was opened someone would observe the cat, and from that time on it would be either alive or dead. The question which Schrödinger posed was, 'What was the state of the cat before the box was opened?'"

"And what did happen when the box was opened?" asked Alice.

"Well actually, everyone was so engrossed in discussing the question that no one ever did open the box, which is why the Cat was left like that."

Alice peered closely into the basket, where one aspect of the Cat was busily licking itself. "He looks pretty lively to me," she observed. No sooner were the words out of her mouth than the Cat became fully solid and the dead version vanished. With a satisfied purr the Cat leapt out of the box and began to stalk a mouse which had just popped out of the wall. Alice noted that there was no mouse hole visible-the mouse had simply come out of the solid wall. The Quantum Mechanic followed the direction of her gaze. "Ah, yes. That is an example of barrier penetration; we get it happening all the time. Where you have a region that a particle could not enter at all according to classical mechanics, the amplitude does not necessarily stop abruptly at the boundary, though it does die away rapidly inside the region. If the region is very narrow, then there is still some small amplitude left at the other side, and this gives a slight probability that the particle may appear there, having apparently tunneled through an impassible barrier. It happens quite often."



Alice had been thinking through what she had seen and had noted a difficulty. "How is it that I was able to make an observation and fix the condition of the Cat if it was not able to do it for itself? What is it that decides when an observation is actually made and who is able to make one?"

"There you have a good question," replied the Quantum Mechanic, "but we are only mechanics after all, so we do not worry too much about such things. We just get on with the job and use ways that we know will work in practice. If you want someone to discuss the *measurement problem* with you, you will need to go somewhere more academic. I suggest that you go to a class at the Copenhagen School."

"And how do I get there?" asked Alice, resigned to being passed on somewhere else once again. In answer the Mechanic led her out into the corridor and opened yet another door. This did not lead into the alleyway from which she had entered, but into a wood.

Notes

1. Quantum mechanics is usually contrasted with classical or Newtonian mechanics. The latter covers the detailed description of moving objects which was developed before the early years of the

twentieth century and was based on the original work of Galileo, Newton, and others both before and since. Newtonian mechanics works very well on a large scale. The motion of the planets can be predicted over long times and with great accuracy. It works almost as well for artificial planets and the various exploratory space missions: Their positions may be predicted years ahead. It also works pretty well for falling apples.

In the case of a falling apple there will be significant resistance from the air that surrounds it. Classical mechanics describes this as the collision of vast numbers of air molecules bouncing off the apple. When you ask about air molecules you are told that they are small groups of atoms. When you ask about atoms there is an embarrassing silence.

Classical mechanics had virtually no success in describing the nature of the world on the scale of atoms. Things must somehow be different for small objects from how they seem to be for large ones. If you argue in this way, then you must ask: large or small relative to what? There must be some dimension, some fundamental constant which fixes the size at which this new behavior becomes obvious. It is a definite change in the way things are observed to behave, and it is universal. Atoms in the sun and in distant stars emit light with a spectrum which is like that from a lamp on a table beside us. The onset of quantum behavior is not something that just happens to take place locally; there is some fundamental property of Nature involved. This is given by the universal constant $\hbar$, which features in most equations of quantum mechanics. The world is *grainy* on the scale defined by this constant, $\hbar$. On this scale energy and time, position and momentum are blurred together. It need hardly be pointed out that, on the human scale of perception, $\hbar$ is very small indeed and most quantum effects are not at all obvious.

2. What the Heisenberg uncertainty relations are telling us is that we are looking at things in the wrong way. We have a preconception that we *ought* to be able to measure the position and momentum of a particle at the same time, but we find that we cannot. It is not in the nature of particles for us to be able to make such a measurement on them, and the theory tells us that we are asking the wrong questions, questions for which there is no viable answer. Neils Bohr used the word *complementarity* to express the fact that there may be concepts which cannot be precisely defined at the same time: such pairs of concepts as justice and legality, emotion and rationality.

There is, apparently, something fundamentally wrong with our belief that we *should* be able to talk about the position and momentum of a particle, or of its exact energy at a given time. It is not clear why it should be meaningful to talk simultaneously of two such different qualities, but it appears that it is not.

3. Quantum mechanics is not really about definite particles in the traditional classical sense; instead you talk about *states* and *amplitudes*. If you *square* an amplitude (i.e., multiply it by itself), then you get a probability distribution which gives the *probability* of obtaining various results when you make an observation or measurement. The actual value that you get for any one measurement appears to be quite random and unpredictable. So it does look as if the suggestion made earlier that nature is uncertain and "anything goes" must, after all, be true, does it not?

Well, no-if you make many measurements the *average* result is accurately predictable. Bookmakers do not know which horse will win each race, but they confidently expect to make a profit at the end of the day. They do not anticipate large surprise losses even though they have to work with rather small numbers, so that the averaging is not too reliable. The number of gamblers will be a mere few thousand people rather than the 1,000,000,000,000,000,000,000,000 or more atoms you will get in even a tiny speck of matter. This looks less like a number than a repetitive wallpaper pattern, but it is undeniably large. The overall statistical fluctuations to be expected for measurements made on such a large number of atoms are negligible, even though the result for each individual atom may be quite random.

Quantum-mechanical amplitudes may be calculated very accurately and compared with experiments. An often quoted result is for the magnetic moment of the electron. Electrons spin like little tops and they also have electrical properties: They behave rather like tiny bar magnets. The magnetic strength and the electron spin are related, and their ratio may be calculated using suitable units.

A classical calculation gives the result 1 (with rather arbitrary assumptions about the distribution of the electric charge in an electron).

The quantum calculation gives the result 2.0023193048 (±8) (the error is in the last decimal place).

A measurement has given the result 2.0023193048 (±4).

This is good agreement! The probability of getting by chance a value which is in such good agreement is similar to the probability of throwing a dart at random and hitting the bull's-eye on a dartboard-when the dartboard is as far away as the Moon. This particular result is often given as an example of the success of quantum theory. It is possible to calculate accurately the amplitudes for other processes just as accurately, but there are very few quantities which you can *measure* to this precision.

CHAPTER

4 The Copenhagen School

Alice entered the wood and made her way along a path which wound between the trees, until she came to a place where it forked. There was a signpost at the junction, but it did not appear very helpful. The arm pointing to the right bore the letter "A," that to the left the letter "B," nothing more. "Well, I declare," exclaimed Alice in exasperation. "That is really the most unhelpful signpost I have ever seen." She looked around to see if there were any clues as to where the paths might lead, when she was a little startled to see that Schrödinger's Cat was sitting on the bough of a tree a few yards off.

"Oh Cat," she began rather timidly. "Would you tell me please which way I ought to go from here?"

"That depends a good deal on where you want to get to," said the Cat.

"I am not really sure where.... " began Alice.

"Then it doesn't matter which way you go," interrupted the Cat.

"But I have to decide between these two paths," said Alice.

"Now that is where you are wrong," mused the Cat. "You do not have to decide, you can take all the paths. Surely you have learned that by now. Speaking for myself, I often do about nine different things at the same time. Cats can prowl around all over the place when they are not observed. Talking of observations," he said hurriedly, "I think that I am about to be obs..." At that point the Cat vanished abruptly.

"What a strange cat," thought Alice, "and what a strange suggestion. He must have been referring to that superposition of states that the Mechanic was talking about. I think that it must be something like the time that I left the Bank. Somehow I managed to go in many different directions that time, so I suppose I shall just have to try and do it again."

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State: Alice (A1)

Alice turned right at the sign and walked farther along the winding path, looking around her at the trees as she passed. She had not gone very far when she came to another fork in the path; this time the signpost had two arms, labeled "1" and "2." Alice turned to the right and continued on her way.

As she walked along, the trees thinned out and she found herself trudging up a steep, rocky track. It became steeper and steeper as she went on, until she found herself climbing the side of a lonely mountain. The track brought her along a narrow ledge running along the side of a precipitous cliff. This finally ended at a little grassy-floored area with vertical sides. Before her eyes was a yawning mouth in the cliff face, from which a passage led in and down.

The passage was very dark, but to her surprise Alice found herself creeping on down it. It had a smooth floor and sides and ran straight ahead, sloping gently downward toward a dimly visible distant glow. As she went, the light steadily became brighter and also redder, and the tunnel got hotter. Wisps of vapor floated past her, and she heard a sound like some vast animal snoring in its sleep.

At the end of the tunnel Alice peeped out into a great cellar. Its dark vastness could only be guessed dimly, but rising from close below her feet was a great glow. There lay a vast reddish-gold dragon fast asleep with his huge tail coiled around him. Beneath him, forming his bed, was an enormous pile of gold and silver, jewels, and marvelously carved objects, all red-stained in the ruddy light.

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State: Alice (A2)

Alice turned right at the sign and walked farther along the winding path, looking around her at the trees as she passed. She had not gone very far when she came to another fork in the path; this time the signpost had two arms, labeled "1" and "2." Alice turned to the left and continued on her way.

As she was walking along, she looked down and found that the path she was on had changed from a forest track to a narrow road paved with yellow bricks. She followed this through the trees until the wood opened out into a wide meadow. It was very wide, extending as far as Alice could see, and the whole field was covered with bright poppies. The yellow brick road ran through the middle of the meadow up to the gates of a distant city. From where she stood, Alice could see that the high walls of the city were a brilliant green and the gates were studded with emeralds.

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State: Alice (B1)

Alice turned left at the sign and walked farther along the winding path. There was nothing very remarkable to see as yet. She turned a corner and came to another fork in the path; this time the signpost had two arms, labeled 1 and 2. Alice turned to the right and continued on her way.

The undergrowth between the trees became thicker, and it was difficult to see anything that was at all far from the path, though the path itself was still quite clear as it wound between the closely packed trees. Alice turned a corner and came suddenly upon an open space. In the center of the clearing stood a little building with a steeply pitched roof and a small belfry at one end. The words

"Copenhagen School" were carved deeply into the stone lintel over the door.

"This must be the place I was told to go to," Alice remarked to herself. "I am not sure that I want to go to a school though! I spend quite enough time at school as it is. But maybe a school here will be quite different from the one that I am used to. I will go in and see!" Without knocking, she opened the door and went in.

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State: Alice (B2)

Alice turned left at the sign and walked farther along the winding path. There was nothing very remarkable to see as yet. She turned a corner and came to another fork in the path; this time the signpost had two arms, labeled 1 and 2. Alice turned to the left and continued on her way.

A little further along, the path began to rise, and Alice climbed up the side of a little hill. At the top of the hill she stood for some minutes looking out in all directions over the country-and a most curious country it was. There were a number of little brooks running across it from side to side, and the ground between was divided up into squares by a number of hedges, which reached from brook to brook.

"I declare. It's marked out just like a large chessboard," Alice said at last.

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"Ah, come in, my dear," a voice called softly, and Alice realized that she had been observed. She stepped through the door and looked around the schoolroom. It was quite a large room with high windows all round. There were rows of desks down the middle of the room. At one end there was a blackboard and a large table behind which stood the Master.

"It does look very much like an ordinary school," Alice admitted to herself as she turned to look at the children in the class. She found that the desks were not occupied by children, however, but by a most remarkable selection of beings who clustered around the front of the room. There was a mermaid, with long flowing hair and a scaly fish's tail. There was a uniformed soldier who, on closer examination, appeared to be made out of tin and a ragged little girl with a tray full of matches. There was a dramatically ugly duckling and a haughty looking man of regal bearing who for some reason was clad only in his underclothes.

Or is he?" Alice wondered to herself. As she looked again she fancied she could see him wearing rich embroidered garments and a thick flowing velvet robe. When she looked once more, however, all she could see was a rather portly man dressed in his undergarments.

"Hello, my dear," said the Master, who was a kindly looking avuncular figure with bushy eyebrows. "Have you come to join our discussion?"

"I am afraid that I do not know how I have come to be here," said Alice. "I seemed to be in several other places just a moment ago, and I am not at all sure why I have ended up here, rather than in one of the others."

"That is because we have observed you to be here, of course. You were in a superposition of quantum states, but once you had been observed to be here, why you were here, naturally. Obviously you were not observed in any of the other places."

"What would have happened if I had been?" asked Alice curiously.

"Why then your set of states would have collapsed to that other one. "You would not be here, but would instead be at the position where you had been observed to be, of course."

"I really do not see how that can be," replied Alice, who was once again feeling terribly confused. "What difference does it make whether I was observed or not? Surely I must be in one place or the other no matter who sees me."

"Not at all! After all, you cannot say what is happening in any system if you do not observe it. There may be a whole range of things that it might be doing and you could give a probability that it is or is not doing any one of them as long as you do not look. In fact the system will be in a mixture of states corresponding to all the things that it might be doing. That will be the situation up to the point when you look to see what it is doing. At that point of course one possibility is selected and the system will then be doing only that."

"Then what happens to all the other things it was doing?" asked Alice. "Do they just vanish?"

"Well, there are more things that it *may* be doing than things it was doing, but yes," answered the Master, beaming at her. "You have got it exactly. All the others states just vanish. The *land of maybe* becomes the *land that never was*. At that point all the other states cease to be in any way real. They become, if you like, just dreams or fantasies, and the observed state is the real one. This is called *reduction of the quantum states*. You will soon get used to it."

The "orthodox" picture of quantum mechanics is the *Copenhagen interpretation* (named after the Danish physicist Neils Bohr, not Hans Christian Andersen). Where different things might happen in a physical system, there will be present an *amplitude* for each, and the total state of the system is given by a sum, or superposition, of all these amplitudes.

When an observation is made it will find a value which corresponds to one of these amplitudes, and the excluded amplitudes will vanish, a process called *reduction of the amplitudes*.

"Does that mean that when you look at something you can choose what you will see?" asked Alice in some disbelief.

"Oh no, you do not get any choice in the matter. What you are *likely* to see is determined by the probabilities for the various quantum states. What you actually *do* see is a matter of random chance. You do not get to choose what will happen; the quantum amplitudes only give the probability of different results, but they do not fix what *will* happen. That is pure chance and only becomes fixed when an observation is made." The Master said this very earnestly, though so quietly that Alice had to strain to catch everything that he said.

"Making an observation seems to be very important then," Alice mused, half to herself. "But then who can make an observation? Obviously the electrons are not able to observe themselves as they go through the slits in an interference experiment, as they seem to go through both slits. Or should I say that amplitudes for both slits are present?" she corrected herself, copying the way of speaking which she had heard so much recently. "Apparently I did not observe myself properly when I was in a superposition of states just now.

"In fact," Alice said abruptly, struck by a sudden thought, "if quantum mechanics says that you must do everything you can do, then surely you must observe *all* the possible results of any measurement you make. If your quantum superposition principle is to work everywhere, then it is not possible to make measurements at all! Any measurement you tried to make could have several possible results. You might observe *any* of these results and, according to your rules, if you could observe any of them you would have to observe *all* of them. The results of your measurement would all be present in a new version of this superposition of states you talk about. You could never actually observe anything, or rather there would never be anything you could fail to observe."

Alice paused for breath, quite carried away with this new thought, and noticed that everyone in the room was staring at her intently. When she stopped they all stirred a little uneasily.

"Of course you have a very important point there," said the Master kindly. "It is known as the *measurement problem* and is the very subject that we have been considering in the class here."

See end-of-chapter note 1

The Master continued: "It is important to remember that it is a real problem. There must exist a mixture of amplitudes such as we describe for systems of one or two electrons, as in the two slit interference experiment you saw, because there is interference between the amplitudes. This is not just a way of saying that the electron may be in one state, but that you do not happen to *know* what state that is. That situation could not give any interference, so we are forced to accept that, in some sense, each electron is in *all* the states. I believe that it is not a proper question when you ask what the electron is really doing because there is no way you can ever find out. If you try to check you will alter the system, so that you are examining something different.

"As you point out, there seems to be a problem here. Atoms, and systems containing a small number of particles, always do everything they possibly can, and they never make any decisions. We, on the other hand, always do one thing or the other and do not observe more than one outcome from any given situation. The students have each prepared a short talk about the measurement problem. They consider at what point, if any, the quantum behavior which allows all states to be present at the same time ceases to operate, so that unique observations may be made. You might like to sit and listen to their presentations." This seemed to Alice to be a good opportunity, so she sat at one of the desks and leaned forward expectantly.

"The first talk," announced the Master, his quiet voice managing to quell the expectant buzz of comment from the students, "is from the Emperor." The portly gentleman in the tasteful purple underwear, whom Alice had noticed when she first entered the classroom, got up and walked to the front of the class.

See end-of-chapter note 2

The Emperor's Theory (Mind Over Matter)

"Our hypothesis," he began, with a haughty glance around the room, "is that it is all in the mind.

"The laws that are obeyed by quantum systems," he continued, "the description of physical states by amplitudes, and the superposition of these amplitudes when there is more than one possible condition-these laws apply to every material thing in the world. We say 'every material thing,'" he repeated, "as Our contention is that such a superposition is not experienced by the conscious mind. The physical world is governed at every stage by quantum behavior, and any purely material system, large or small, will always be in a combination of states, with an amplitude present for everything which might be or might have been. It is only when the situation comes to the attention of the sovereign will of a conscious mind that a choice is made.

"For the mind is a thing outside, or in Our case above, the laws of the quantum world. We are not tied by the need to do everything that might possibly be done; instead We are free to make selections. When We observe something, then that thing is observed; it knows that We have observed it, the Universe knows that We have observed it, and it remains thereafter in the condition in which We have observed it. It is Our very act of observation which imposes a unique and definite form upon the world. We may not have the choice to select what We will see, but whatever We do observe has become uniquely real at that point."

He paused and looked commandingly around the room once more. Alice found herself strangely impressed by his authoritative delivery, despite his purple underwear. "For example, when We look at Our magnificent new imperial clothing We observe that We are of course exquisitely attired." He looked down at himself and abruptly he was clad from head to foot in rich garments. His coat and waistcoat were smothered in fine embroidery and he wore a flowing velvet robe trimmed with ermine. "Now it is conceivable that, when Our attention was diverted from Our garments they might have been less tangibly real than they are now seen to be, but if that had been so, now that We have observed them they are seen by all to be of the finest cut and that is in reality what they are."

The Emperor raised his head again and looked out at the class. Alice was intrigued to note that, although his observation of the clothes had fully established their rich aspect, as soon as he had looked away they gradually became hazy-looking once more and his tastefully monogrammed underclothes began to show through.

"That then is Our thesis. The whole material world is indeed governed by the laws of quantum mechanics, but the human mind is outside the material world and not so restricted. We have the ability to see things uniquely. We cannot choose what We will see, but what We do see becomes reality in the world, at least for the time We observe it. When We have finished Our observation, then of course the world can once again begin to enter its customary set of mixed states."

He stopped and looked around with a satisfied air. "Thank you for an interesting talk," said the Master, "that was very, very interesting. Does anyone have any questions?"

Alice discovered that she did. Perhaps the school atmosphere was affecting her after all. She put her hand up. "Yes," said the Master, pointing to her, "what is the question that you would like to ask?"

"There is one thing that I do not understand," said Alice. (This was not strictly true, as there were many things that she did not understand, and the number was becoming larger at a most alarming rate, but there was one particular thing about which she wished to ask a question.) "You say the world is customarily in this strange mixture of different states, but it reduces to one unique condition when you, as a conscious mind, happen to look at it. I suppose that any person is able to make something become real in this way, so what happens about *other* people's minds?"

"We do not believe that We understand what you mean," replied the Emperor crushingly, but the Master cut in at this point.

"Perhaps I might enlarge on the young lady's question. We were talking earlier about electrons passing through two slits. Suppose I were to take a photograph which would show an electron in the act of passing through either one slit or the other. If I follow what you say, you would maintain that, as the photograph might show that the electron was in either slit, it would have to show that it was in both. The photographic plate has no conscious mind and would be unable to reduce the wave function, so a superposition of two different images would be present on the film. Now suppose that I were to make a number of copies of this photograph, without of course looking at any of them. Would you say that each print would now also have a mixture of different images on it, each corresponding to the different slits which the electron might have passed through?"

"Yes," replied the Emperor cautiously. "We believe that that would be the case."

"If that is so and if the prints were all posted to different people, then the first one to open his envelope and look at the picture would cause one image from the mixture to become the real one and all the others would vanish?" Again the Emperor agreed cautiously. "But in that case, the photographs which the other people received would then each have to reduce to the same image, even though they might be in different cities miles apart. We know from experience that copies of a photograph do indeed show the same thing as the original, and if it was the occasion when the first person looked at a copy which caused one possibility to become uniquely real, presumably this act affected all the other copies, as they must subsequently agree with the first one. So one person who looked at a copy in one city would make all the other copies in other cities all over the world suddenly change to show the same thing. It would turn into a peculiar sort of race, with the first person to open the envelope fixing the images on all the other people's prints before they opened them. I think that was what the young lady meant," he finished.

"Naturally such a consideration would not present any problem in Our case," responded the Emperor, "since no one would presume to look at such a photograph before We had examined it first. However, We see that such a situation might arise among people of the lower orders, and in that case the situation would indeed be as you describe."

Alice was so startled at having this apparently ridiculous argument accepted that she did not notice the Emperor return to his seat and the little mermaid come up. The mermaid was unable to stand in front of the class, as she did not have any feet, so she sat on the Master's table, swinging her tail in front of her. Alice's attention returned to the proceedings as the mermaid began to speak.

The Little Mermaid's Theory (Many Worlds)

"As you know," she began in a liquid, musical voice, "I am a creature of two worlds. I live in the sea and am equally at home upon the land. But this is as nothing compared with the number of worlds which we all inhabit, for we are all citizens of many worlds-many, many worlds.

"The previous speaker told us that the quantum rules apply to the whole world, apart from the minds of the people who live in it. I tell you that they apply to the whole world, to everything. There is no limit to the idea of the superposition of states. When an observer looks at a superposition of quantum states you would expect him or her to see all of the effects that are appropriate to the selection of states present. This is what does happen; one observer does see all the results, or rather the observer also is in a superposition of different states, and each state of the observer has seen the result that goes with one of the states, in the original mixture. Each state is simply extended to include the observer in the act of seeing that particular state.

"This is not the way that it *seems* to us, but that is because the different states of the observer are not aware of one another. When an electron passes through a screen with two slits in it, then it might pass through to the left or to the right. What you observe to happen is pure chance. You might see that the electron has gone to the left, but there will be another *you* that will have seen the electron go to the right. At the point at which you observe the electron, you split into two versions of yourself, one to see each possible result. If these two versions never get together again, then each remains totally unaware of the other's existence. The world has split into two worlds with slightly different versions of you in them. Of course, as these different versions of you will then talk to other people, you need different versions of them also, so what you have is a splitting of the entire universe. In this case it would split into two, but for a more complex observation it would split into a larger number of versions."

"But surely this would happen rather often," Alice could not help herself from saying, interrupting the flow of the mermaid's talk.

"It always happens," replied the mermaid calmly. "Whenever you have a situation where a measurement could give different results, then all the possible results *will* be observed, and the world will split into the appropriate number of versions.

"Mostly the split worlds would remain separate and would diverge without ever being aware of one another, but sometimes they will come together again at some point and give interference effects. It is the presence of these interference effects between the different states which shows that they can and do all exist together."

The mermaid stopped speaking and sat there combing the myriad strands of her long hair as they fell, side by side but separate, down over her shoulders.

"It must mean there are an awful lot of universes. There would have to be as many as there are grains of sand on all the beaches on Earth," Alice protested.

"Oh, there would be far more than that. Far more!" replied the mermaid dismissively. "Far, far more," she went on dreamily. "Far, far, far. . .."

"That theory," cut in the Master, "has the advantage of being rather economical with assumptions, but it is very extravagant with universes!" He went on to ask for the next speaker. This was the Ugly Duckling, who had to stand on top of the Master's table so that he could be more clearly seen.

The Ugly Duckling's Theory (It Is All Too Complicated)

The Duckling began his speech, and Alice observed that, as well as being very ugly, he appeared to be very cross as well. His speech was so full of quacks and spluttering that she was hard put to make out what he said. As far as she could tell he was saying that the superposition of different states only worked for rather small systems, with just a few electrons or atoms. He said that you need only argue that systems were often in mixtures of states because interference happened, since a single, unique, state would have nothing with which it could interfere.

He further argued that you do not actually know that interference does happen for objects which contain many particles. People know that interference and hence the superposition of states can occur for groups of a few particles, so they think the same must still be true for complicated things, like ducklings. He would be quacked if he believed that.

A duckling contains a lot of quacking atoms, he went on, and before any superimposed states can interfere, all the atoms in each separate state must combine exactly with the appropriate atom in the other states. There are so many atoms that this is not quacking likely. Any effects would average out, and you could not see any net result. So how, he asked, can you be so quacking sure that ducklings are ever in a superposition of states? Answer me that if you are so quacked clever. All this superposition of states is fine and quacking for a few particles at a time, but it stops well short of ducklings.

He went on to say that he quacking well knew when he saw something and when he quacking didn't. He knew that he was not in any quacking superposition of states, he was in only one, worse luck. So when he changed, he continued forcefully, he really changed from one definite state to another. The change was irreversible and there was no question of going back to combine with other states. Nothing was going to quacking interfere with him he concluded. At this point his quacking became so extreme that Alice could not follow him at all and was not really surprised when he became so angry that he fell off the table, out of her sight.

There was a pause and a moment of silence. This ended as a long graceful neck rose from behind the desk, followed by a snowy white feathered body. It was a swan.

"How beautiful!" exclaimed Alice. "May I stroke you?"

The swan hissed at her furiously and clapped his wings in a threatening manner. Alice decided that, though his change was certainly irreversible, it did not appear to have changed his temper very much.

At this point there was a disturbance at the back of the classroom, and Alice heard a voice shouting "Stop this charade, you are all wrong!" She looked across and saw a tall figure striding angrily down the space between the desks. It was the Classical Mechanic. His progress was considerable hampered by the fact that he was carrying a pinball machine, much as Alice had previously seen in cafes. (They might more often be found in bars, but of course Alice was too young to have seen them there.)

The Classical Mechanic's Theory (Wheels Within Wheels)

The Classsical Mechanic marched to the front of the room and set his machine down by the Master's table. It was labeled "Electron Interceptor" and had the form of a sloping table, with two slits at the top through which the particles would be fired and a row of pockets along the bottom which were alternately marked "Win" and "No Win." The surface of the table, though brightly painted, appeared strangely free of the usual selection of obstacles and flippers which Alice had previously seen on pinball machines.

"You are all deceiving yourselves," the Classical Mechanic announced firmly. "I have looked carefully at this device, which is basically a normal two-slit electron interference setup, and I believe I see what is really going on."

Alice could see that, apart from its garish decoration, it was indeed a smaller version of the experiment which she had been shown in the Mechanics' *gedanken* room. The Classical Mechanic quickly demonstrated its operation by firing a stream of electrons from the two slits. At least Alice presumed that they must have come through those slits as they were the only ones present, although she was not able to see clearly where the electrons actually were until their arrival registered along the bottom of the table. As she had by now come to expect, the electrons clustered in a series of heaps, with gaps between the heaps where very few were detected. Alice was intrigued to see that these gaps in the interference pattern corresponded closely with the pockets marked Win.

"You see that interference is produced and you would argue that this shows the electrons have somehow each come through both slits, so that the combination of the amplitudes for the two slits is producing the interference pattern we see. I tell you now that the electrons are in fact each going through just one slit, in a perfectly sensible way. The interference is due to *hidden variables!*"

Alice found it very hard to follow exactly what happened at that point. The best she could say afterward was that the Classical Mechanic seemed to pull from the pinball table a dust cover which had not apparently been there before. However it had happened, she now saw that the surface of the table was covered with a pattern of deep ridges and grooves, leading away from the two slits. "Behold, hidden variables!" cried the Mechanic.

"They are not very well hidden," remarked Alice, looking critically at the complicated surface now revealed.

"My contention," began the Classical Mechanic, pointedly ignoring Alice's remark, "is that electrons and other particles behave in a perfectly rational and indeed classical fashion, very much like the particles to which I am accustomed in ClassicWorld. The only difference is that here, as well as the normal forces which act upon particles, they are also affected by a special *quantum force*, or *pilot wave*. This causes the strange effects which you interpret as due to interference. In my demonstration with the electron pinball here each electron really does enter by one slit or the other. It then moves over the table in a respectable and predictable fashion. Any randomness in the setup comes from the different directions and speeds which the electrons happen to have initially. When the electrons cross over the dips that you see here in the quantum potential, then the quantum force will deflect them, like a bicycle wheel caught in a trolley rail, so that most of the electrons end up in clumps. This gives your so-called interference effects."

"Well now," said the Master, "that is certainly a very interesting theory-very, very interesting indeed. However, if you do not mind my saying so, you seem to have removed those difficulties you had with the electron's behavior at the expense of some very peculiar behavior for your *quantum potential*.

"Because your quantum force has to produce the effects which we say are due to interference, it must be affected by things that happen in quite different places. If a third slit were to open in your table, then the quantum forces on the particles would change, even if none of the particles had gone through that hole. It must do this because the interference for three holes is different from that for two, and your force has to reproduce all those interference effects that we know to occur. Further your quantum potential, or network of quantum forces, must be very complicated indeed. In this theory you have nothing like the reduction of the wave functions which occurs in the normal quantum theory, so your potential must be affected by all the possibilities of everything which might have happened—ever. It is like the Many Worlds theory in that way. In your theory you say that what is observed will depend on how the particles happened to be traveling when they were affected by your pilot wave, but the pilot wave itself will retain information from all the possible things which might have happened and there is no way of removing it. Your wave would have to be incredibly complicated, like the sum of *all* the worlds in the Many Worlds theory, even though most of it may not affect any particles for most of the time.

"The pilot wave in your theory affects what the particles do, but the way that the individual particles actually move has no effect on the wave. This depends only on what particles *might* have done. There is no symmetry of action and reaction between the particles and the pilot wave. As a Classical Mechanic this must be a worry to you. You would not want to contradict Newton's Law that action and reaction are always equal, would you now?"

At this point the Quantum Mechanic, who had followed the Classical Mechanic into the room but remained quietly in the background, came forward and took his colleague by the arm. "Come along," he said. "You surely do not want to get involved in a charge of Classical Heresy by denouncing Newton's Laws. All this academic discussion of what electrons may or may not actually be doing is not for the likes of us. We are Mechanics. As a Mechanic, my main concern is that the Quantum laws do work and work well. When I calculate an amplitude for some process, this tells me what is likely to happen. It gives me the probabilities of different results and it does it accurately and reliably. It is not my job to worry about what the electrons are doing when I do not look at them, as long as I can tell what they are likely to be doing when I do look. That is what people pay me to do."

He led his subdued colleague quietly to one side, then turned to Alice and asked, "Have you learned as much as you want to know about observers and measurements?"

"Well," began Alice, "to tell you the truth I feel more confused than I was before I came here."

There are various "answers" to the measurement problem, but no one of them is universally accepted.

In practice, quantum mechanics is normally used to work out the amplitudes and hence the various probabilities for some physical system and then to use these to predict the behavior of large *ensembles* of simple atomic systems, without worrying too much about what would happen for a single system. The results for the ensembles can be compared with measurements, again without worrying too much about how the measurements could have been made.

The practical response to this problem is to "close your eyes and calculate." The interpretation of quantum mechanics may be difficult, but there is no denying that it works very well.

"Right," interrupted the Quantum Mechanic emphatically. "I thought as much. You have learned quite as much as you want to. Come along with me now and see some of the *results* of quantum theory. Let me show you some of the features of Quantumland."

Notes

1. The "measurement problem" is that the selection of one single possibility and the reduction of all the other amplitudes is quite unlike other quantum behavior, and it is not obvious how it can occur. The problem is stated most simply in the form: How can you ever actually measure *anything*? The conventional view of quantum mechanics is that, when there are several possibilities, there will be present an amplitude for each one, and the overall amplitude for the system is the sum, or superposition, of all of them together. For example, if there are several slits through which a particle might pass, then the overall amplitude for the system contains an amplitude for each slit, and you can have interference between the individual amplitudes. If the system is left to itself, then the amplitudes will change in a smooth and predictable way. When you make a measurement on a system which has a sum of amplitudes corresponding to different possible values of the quantity measured, then the theory says that you will, with some probability, observe one or another of these values. Immediately after the measurement the value is a known quantity (because you have just measured it), so the sum of eigenstates (see box on p. 76) reduces to a single one, the one for the actual value you have just measured.

2. The orthodox description of a measurement in quantum mechanics has the drawback that the process of making a measurement does not seem to be at all compatible with the rest of quantum theory. If the quantum theory is the true theory of atoms, as seems to be the case, and if the whole world is made of atoms, then presumably quantum theory should apply to the whole world and everything that is in it. That includes measuring instruments. Where a quantum system can give various values, its amplitude is a sum of states corresponding to each possible value. When the measuring device is itself a quantum system and there are various values which it *could* measure, it has no right to select just one of them. It ought to be in a state which is a sum of the amplitudes for all the possible results it *might* measure, and no unique observation could be made.

The conclusion you would draw from the above would seem to be either:

(a) We never actually observe anything

or

(b) Quantum theory is all nonsense.

Neither conclusion is really tenable (however tempting conclusion (b) might appear to be). We *know* perfectly well that we do observe things, but we cannot deny that quantum theory has an unbroken success rate at successfully describing all observations, while no alternative theory does as well. We cannot lightly abandon it.

CHAPTER

5 The Fermi-Bose Academy

Alice walked with the Quantum Mechanic along the path away from the school. As they traveled the path grew wider and gradually changed to a well-surfaced road.

"I think the most curious thing you have shown me," remarked Alice, "was the way that you got those interference effects even when there was only one electron present. Is it true then that it makes no difference whether there are many electrons or only one?"

"It is certainly true that you may observe interference whether you have many electrons or only one at a time. However you cannot say that it makes no difference. There are some effects which you only see when you have many electrons. Take the Pauli Principle, for example...."

"Oh, I have heard of that," interrupted Alice. "I heard the electrons talk about it when I first came here. Would you tell me what it is, please?"

"It is a rule which applies when you have a lot of particles which are all the same-completely identical in every respect. If you would like to know more about it, it would be best if we were to call in here, since we happen to be passing, and they are very experienced in many-particle behavior."

Alice looked around at these words and found that, as they had been talking, they had come to a tall stone wall which ran along one side of the road. Immediately opposite them was a wide gateway.

Impressive wrought-iron gates stood open between massive stone pillars with a coat-of-arms painted in the center of each. To the right of the gateway, visible above the wall, Alice saw a wooden board which carried the message:

Fermi–Bose Academy
For electrons and photons

In the center of the gateway stood an imposing figure, a large and exceedingly well-built man made even more massive in appearance by the flowing academic gown and the mortarboard which he wore. His round, florid face was copiously adorned with a bushy mustache and side whiskers. Firmly fastened in one screwed-up eye he wore a monocle on a wide black ribbon.

"That is the Principal," whispered the Mechanic into Alice's nearest ear.

"Do you mean the Pauli principle?" asked Alice rather wildly. She had been taken off-guard by his sudden appearance.

"No, no," hissed the Mechanic, "he is the Principal of the Academy. Though of course Pauli's principle is the principal principle of the Academy, he is its Principal." Alice wished that she had not asked.

They crossed the road and went up to this imposing personage. "Excuse me sir," began the Mechanic. "Would you be so kind as to tell my young friend here something about many-particle systems?"

"Of course, of course," boomed the Principal. "We have no shortage of particles here, dear me no. I shall be most happy to show you around."

He turned around with a billow of his flowing gown and led the way toward the Academy. As they walked up the drive Alice saw small figures dodging in and out among the shrubbery. At one point a figure popped above a bush and made a face at them. At least Alice thought it had. As usual it was very difficult to make out any detail. "Ignore him," growled the Principal. "That is only Electron Minor."

They arrived at the door of the Academy, which was housed in a dignified old house of vaguely Tudor appearance. Without pausing the Principal led them through the main door into a vaulted entrance hall and up a wide carved staircase. As they walked through the building, Alice could see small figures hiding behind the banister, dodging in and out of rooms, and running off down side corridors as they approached. "Ignore him," remarked the Principal again. "It is just Electron Minor. Particles will be particles!"

"But it cannot be Electron Minor if we saw him on the drive," protested Alice. "Surely it cannot be the one particle in both places. Are we talking about something like the case when an electron managed to go through both holes in your double-slit experiment?" she asked the Quantum Mechanic.

"No, it is not that; they do have many electrons here. But don't you see, the electrons are all exactly the same. They are completely identical to one another. There is no way to tell them apart, so naturally they are *all* Electron Minor."

"That is right," confirmed the Principal emphatically as he led them into his study, "and it is a problem, let me tell you. You may know how difficult it can be for teachers when they have two identical twins in their school and are unable to tell them apart. Well I have hundreds of completely identical particles. It makes checking the register a nightmare, I can tell you.

"The electrons are not so bad," he went on. "We just count them and see whether we have the correct total. At least the *number* of electrons is conserved, so we know how many we ought to have, but for the photons even that does not work. The photons are bosons, so they are not conserved you see. We may begin a class with thirty, say, and have fifty or more at the end of it. Or the number may drop to less than twenty-it is hard to predict. This all makes it very difficult for the staff."

Alice had spotted a new word in that remark. "Do you think you might explain that?" she asked hopefully. "Would you please tell me what a'boson' is?"

The Principal turned an even deeper red than he was before and spoke to the Mechanic. "I think it would be best if you took her to the beginners' Facts of Symmetry lesson, don't you? That should explain all about the Bosons and the Fermions."

"Right you are," replied the Mechanic. "Come along, Alice, I believe I can remember the way."

They walked down a corridor to a classroom and went in just as a lesson was beginning.

"Attention please," said the teacher. "Now as you well know, all you electrons are identical to one another and so are all you photons. This means that no one can tell when any two of you have changed places. As far as any observer could tell you *might* have changed places and so of course you will have to some degree. You all know that you have an associated wave function, or amplitude, and that this amplitude will be a superposition of all the things which you *might* be doing. Where there is no way of telling which things you are doing, then, as you know, you are doing all of them, or at any rate have an *amplitude* for every one of them. So you see, for any group of you it is impossible to tell when any two have changed places and this means that your overall wave function will be a superposition of all the amplitudes for which a different pair has swapped over. I hope that you have all made a note of that."

See end-of-chapter note 1

"Now the probability of making any observation is given by the *square* of your wave function, that is, the wave function multiplied by itself. As you are completely identical, it is obvious that when any two of you change places it can make no observable difference, so the square of your wave function cannot change. It might look as if there can be no change at all. Can anyone tell me what might change?"

One of the electrons put his hand up, or at least Alice assumed that was what had happened. She was not able to see at all clearly. "Please sir, the sign might change."

"Very good, that is an excellent answer. I would make a note in your record that you had answered so well, except that unfortunately I cannot tell you apart from the others. Yes, as you know your amplitudes do not have to be positive. They may be either positive or negative, so that two amplitudes may cancel one another out when you have interference. This means that there are two cases in which the square of your amplitude would not be changed. It may be that the amplitude does not alter at all when two of you change places. In such a case the particles are bosons, like you photons. However, there is another possibility. When two of you exchange places, the amplitude may *reverse*. It changes between positive and negative. In this case the square is still positive and the probability distribution is unchanged, because multiplying the amplitude by itself will give *two* reversals, resulting in no change at all. This is what happens with fermions, such as you electrons. All particles fall into one or other of these two classes: They are either fermions or bosons.

"Now you may think that it does not matter much whether your amplitude reverses or not, especially as the probability distribution remains unchanged, but in fact it is very important indeed, particularly for fermions. The point is that if any two of you are in exactly the same state-that is, in the same place and doing the same thing-then if you exchange places, it is not only an unobservable change; it really is *no change at all*. In this case neither the probability distribution *nor* the amplitude can change. This is no problem for bosons, but for fermions, which always have to reverse their amplitude, such a situation is not allowed. For such particles you get the Pauli exclusion principle, which says that no two identical fermions may be doing exactly the same thing. They all have to be in different states."

See end-of-chapter note 2

"For bosons," as I said, "it is not a problem. Their amplitudes do not have to change at all when two of them change places, so they may be in the same state. In fact I can go further; not only may they be in the same state, but they positively *like* to be in the same state. Normally when you have a superposition of different states and square the amplitude to give the probability of observation, the individual states in the mixture are squared separately and contribute much the same to the overall probability. If you have two bosons in the same state, then when you square the two you get four. The two have contributed, not twice as much as one, but four times as much. If you had three particles in the same state they would contribute even more. The probability is much higher when there is a large number of bosons in one state, so they tend to get into the same state if at all possible. This is known as *Bose condensation*.

"So, there you have the difference between fermions and bosons. Fermions are individualistic, no two will ever do exactly the same thing, while bosons are very gregarious. They love to go around in gangs where each one behaves in exactly the same way as the others. As you will see later, it is this behavior and the interaction between you two types of particles which are responsible for the nature of the world. In many ways you are the rulers of the world."

At this point the Quantum Mechanic led Alice out of the classroom. "There you are then," he said. "That is the Pauli principle. It rules that no two fermions of the same type can ever be doing the same thing, so you can have one and one only in each state. The principle applies to all fermions of whatever type, but not to bosons. This means, among other things, that the number of fermions must be conserved. Fermions cannot just appear and disappear in a casual fashion."

"I should think not!" Alice said. "That would be ridiculous."

"I do not think you can say that, you know, because bosons do appear and disappear. Their number is not conserved at all. You can argue that the number of fermions must be definite if there is one and only one in each state, since a particular number of occupied states implies that there is that particular number of fermions to occupy them. The argument does not hold for bosons, since you can have as many as you like in any state. In practice the number of bosons is not at all constant.

"If you just look out this window here," he said suddenly as they were passing, "you can see the difference between fermions and bosons quite well."

Alice gazed through the window and saw that a group of electrons and photons were being drilled on the Academy field. The photons were doing very well, wheeling and reversing in perfect synchronism with no differences between any of them. The group of electrons, however, were behaving in a manner which was obviously driving the drill sergeant to despair. Some were marching forward, but at different speeds. Some were marching to the right and to the left, or even backward. A few were jumping up and down or doing headstands and one was lying flat on his back, staring at the sky.

"He is in the ground state," said the Mechanic, looking over Alice's shoulder. "I expect the other electrons wish that they could join him there, but only one of them is allowed you see. Unless the other had an opposite direction of spin, of course-that would make a sufficient difference between them.

"You can clearly see the difference between the fermions and bosons here. The photons are bosons, so it is easy for them to do the same thing. Indeed, they positively like to be the same as one another, so they are very good at marching in step. The electrons, on the other hand, are fermions and so the Pauli exclusion principle stops any two of them from being in the same state. They have to behave differently from one another."

"You often talk about the electrons being in states," Alice remarked. "Would you please explain to me just what is a state?"

"Once again," responded the Mechanic, "the best way will be for you to sit in on one of the classes here. The Academy teaches world leaders, since it is the interaction of electrons and photons that rules the physical world, by and large. If they are to be world rulers, they have to go to Statecraft classes naturally. Come along and let us see one."

He led Alice down to a large low building at the back of the Academy. When they went inside Alice could see that it was some sort of workshop. A number of electrons were working away at different benches. Alice went over to watch one group, who were busily erecting a set of fences around the edge of the bench. Alice could see there were various structures on the bench, and as the students moved the fences around, these structures all changed.

"What are they doing?" Alice asked her companion.

"They are setting up the boundary conditions for the states. States are controlled largely by the constraints which hedge them in. In general, what you can do is governed by what you cannot do and the restrictions serve to define the possible states. It is very much like the notes you can get from an organ pipe. For a pipe of a given length you can produce only a limited number of notes. If you change the length of the organ pipe, then you will change the notes. Quantum states are given by the amplitude or wave function which the system can have, and this is much like the sound wave in an organ pipe.

"As you have already discovered, you usually cannot say what an electron is really doing, because if you observe it, to check you will select out one particular amplitude and reduce the amplitudes to that one alone. The only time when you can be really certain about your electron is when it has a single amplitude instead of a superposition and when your observation can give but one value. In that case the probability of your seeing that value from your measurement is 100 percent and for any other result the probability is zero-it won't happen. When you make the observation, then you will see the expected result. In such a case, the reduction of the amplitude to that for your observed result has made no difference at all, as you were already in such a state. The state is not changed by the observation, and it is called a *stationary state*. In this class electrons are setting up stationary states."

Alice walked around the table, looking at the states which the electrons were crafting. They looked to her like a series of boxes, eight in all. There was one very large one, one slightly smaller than the large one, and six tiny ones of much the same size. She turned a corner of the table and was surprised to see that the states had changed completely. Now they had the appearance of a number of stands, rather like cake stands, on tall pedestals. There were two which were much wider than the others; four of the same widths, but with successively taller pedestals; and two small ones. She walked quickly around another corner of the table. Now she saw that the center of the table was occupied with a large board to which were fastened a number of coat hooks. There were two rows of three and isolated single hooks top and bottom. "Goodness, whatever is happening?" she asked her companion. "I keep seeing the states quite differently when I look at them from different directions."

"Well, of course you do," replied the Quantum Mechanic. "You are seeing different *representations* of the states. The nature of a state depends on how you observe it. The very existence of a stationary state relies upon some observation for which it always produces a definite result, but a state cannot give definite results for *all* observations you can make. For example, the Heisenberg relations prevent you from seeing the position and the momentum of an electron at the same time, so a stationary state for one observation will not be a stationary state for the other. The observations which you use to describe the states are called its representation.

"The nature of a state may be very different, depending on how you observe it. Indeed the very identity of the different states can change. The states that you see in one representation may not be the same as the ones in another representation. As you may have noticed just now, the one thing which must remain constant is the *number* of the states. If you can put one of the electrons in each state then you must always have the same number of states to contain them all, even though the individual states may have changed."

A *state* describes the condition of a physical system. It is the basic concept in quantum theory—the best description of the real world which can be given. In general the amplitude for a state gives the probability for various possible results of any observation. For some states there may be only one possible outcome to a particular measurement. When a system is in one of these so-called stationary states any measurement of that quantity will give one and only one possible result. Repeated measurements will give the same result every time. Hence the name *stationary state*, or the frequently used German equivalent *eigenstate*.

"That seems very vague to me," complained Alice. "It sounds as if you cannot be at all sure what is really there."

"Right!" replied the Mechanic gaily. "Hadn't you noticed? We can talk quite confidently about *observations*, but what is really there to be observed, now that is quite another matter.

"Come along, though. It is time for the evening assembly of the Academy. You should find that quite interesting."

The Mechanic led her back into the main building and ushered her through the entrance hall into a huge room with a high vaulted roof. The great tiled floor was completely filled with a crowd of electrons, packed in as tightly as possible. Overhead, a wide ornate balcony ran around the edge of the vast hall, and on it Alice could see the vague distant figures of a few electrons hurrying to an exit. There was just one tiny space on the floor near the doorway by which they had entered, and an electron which had been following them darted in to it and immediately came to a halt, wedged in on every side by the dense crowd so that there was no room to move any farther.

There are certain quantities which cannot share the same stationary state; position and momentum are two examples. If you have an eigenstate which gives a definite value for the position of a particle, then a measurement of its momentum could give any result. This leads to the Heisenberg uncertainty relations. If you have a mixture of states which correspond to different values for the position, then a measurement of position might give any one of the appropriate values. The position has become "uncertain," though now the spread of momentum values may be reduced.

This spread is not caused by poor measurement technique; it is inherent in the physical state. The indefinite value of some physical quantity which may be inherent in a given state will allow such effects as barrier penetration, the exchange of heavy particles in nuclei, photons in electrical interactions, and indeed the existence of virtual particles in general. Virtual particles and particle exchange will be discussed in Chapters 6 and 8.

See end-of-chapter note 3

"Why is it so crowded here?" cried Alice, overcome by the scale of the scene before her. "This is the valence level," answered one of the helpful electrons. "All the spaces on the valence level are full because the valence level is always full of electrons. None of us can move at all, as there are no states free to move into, you see."

"That is terrible," cried Alice. "How can any of you possibly move across the floor to get out if it is so crowded?" "We can't," said the electron with cheerful resignation. "But you can if you want to. You can go anywhere on the floor because there are no other Alices here, so there are plenty of Alice states free for you to move into. You will have no Pauli Exclusion problems at all." This still sounded very strange to Alice, but she tried to push her way into the tightly packed crowd and found, just as she had when she had tried to get into the full railway compartment earlier, that somehow she could move through without any trouble.

Alice made her way through the crowd of electrons toward a raised platform at the far end of the hall. On it stood the Principal, impressive as always in his gown and mortarboard. As she came closer Alice could hear his mellow voice booming out over the packed room.

"I know that you have all had a busy day today, but I trust that I do not need to remind you what an important role you must be prepared to play in the world. You electrons, each taking your place in your proper state, form the very fabric of everything we know. Some of you will be bound in atoms and will have to work away in your various levels, controlling all the details of chemical processes. Some of you may find your place within a crystalline solid. There you will be relatively free of attachment to any particular atom and may move around as far as the Pauli Principle and your fellow electrons allow. You may be in a conduction band, where you can move freely, and it will then be your task to rush around carrying your electric charges as part of an electric current. On the other hand, you may be in a valence band within a solid. Perhaps you will feel trapped there as there will be no states free for you to enter. Do not become discouraged. Not every electron may be in the highest energy states, and remember that the lowest levels must also be filled."

See end-of-chapter note 4

"As for you photons, you are the movers and shakers. Left to themselves the electrons would stay complacently in their proper states, and nothing would ever be done. It is your task to interact with the electrons at all times and to produce the transitions between states, the changes which make things happen."

At this point in the Principal's address, Alice became aware of the bright shapes of photons rushing though the crowd of electrons and of occasional flashes from different parts of the room. She turned around to see what was happening. It was difficult for her to see very far, because she was closely surrounded by so many electrons.

"This is really too bad!" Alice could not help exclaiming as she looked at all the captive figures, held fixed in position by the crush around them. "Is there no way in which anyone can move at all?"

"Only if we should get excited to the higher level," a voice answered. Alice could not see who had spoken. "But it doesn't really matter," she thought to herself. "Since they are all the same, then the same one as always must have spoken, I suppose." Just then there was a flash nearby and Alice saw that a photon had come rushing through the crowd and crashed into an electron. The electron soared upward and landed on the balcony, where he began running furiously toward the exit.

Alice was staring so hard at the retreating electron that she did not observe another photon rushing in her direction. There was a brilliant flash and she felt herself rising in the air. When she looked around she saw that she was now standing on the balcony also, looking down on the mass of electrons below. "This must be what the electron meant by being excited to the higher level. It doesn't seem all that exciting to me, but at least there is a lot more room here." She looked over the edge of the balcony at the floor beneath and could see occasional little flashes here and there, each one followed by an electron floating up from the floor and landing on the balcony, where he or she immediately began to run at high speed toward the exit. One of them landed on the balcony close to where Alice was standing.

She looked down and could see a little electron-shaped hole where that electron had been a moment before. It was clearly visible, as the contrasting color of the tiled floor stood out sharply against the uniform background of closely packed electrons which covered the surface everywhere else. As she watched this space another electron nearby stepped smartly onto the gap which had just been created, although it could then move no further. Where this electron had been standing, however, there was now a hole and a more recently arrived electron stepped into that. "What a curious thing!" Alice said to herself. "I have become used to seeing electrons, but I did not expect to be able to see the presence of *no electron* quite so clearly!" She watched with interest as the movement along the balcony of the electron which had risen up to make the original hole was balanced by the movement of the electron-shaped hole as it progressed steadily across the floor in the other direction, toward the wide door by which she had originally come in.

See end-of-chapter note 5

When both electron and hole were out of sight, Alice herself walked along the balcony to the exit. She felt she had heard quite enough of the Principal's talk. She passed through the small door and found herself in a long corridor. Waiting for her by the door was the Quantum Mechanic. "How did you enjoy that?" he asked.

"Very well, thank you," replied Alice politely. She felt that it was expected of her. "It was most interesting to hear the Principal conducting the assembly."

"You say that," began the Mechanic, "but of course it was really the electrons which were doing the conducting, once they had been excited up to the conduction level. All electrons have an electric charge you know, so when they move around they cause an electric current to flow. The charge they carry happens to be negative, so the current flows in the opposite direction to the movement of the electrons, but that is a minor point. If all the states which any electron might reach are already full of electrons, as in the valence level, then there can be no movement and you have an electrical insulator. All the electrons and their charges are fixed in position in that case so there can be no electric current. In the present case you can get a current only when electrons have been carried up to the empty conduction level where they have plenty of room and can move easily. In that case you can get a current produced both by the electrons and by the holes they leave behind."

"But how can a *hole* give a current?" protested Alice. "A hole is something which isn't even there."

"First, you will agree that when the electrons are all present in the lower valence level, they cannot move and there is no current?" asked the Mechanic. The current is just the same as if there were no negatively charged electrons present."

"Well, yes," answered Alice. That sounded fair enough.

"Then you must admit that when there is one electron *less*, the current will look like that due to one less than *no* electrons. The hole in the valence level behaves as if it were a positive charge. You saw how the movement of the hole toward the door was actually due to a lot of electrons taking one step in the opposite direction. So the electric current produced by negatively charged electrons moving away from the door is the same as a positive charge moving toward the door would give. As I said, the photons produce a current both from the electrons they put into the conduction band and from the holes they leave behind."

"The photons seem to be rather a bother to the electrons," remarked Alice, deciding to change the subject.

"Well, they are certainly rather hyperactive, but then photons are naturally very bright. As the Principal says, particles will be particles. I expect that at the moment some of them are lasing electrons in the dorm."

"I am sorry," queried Alice, "but don't you mean *hazing*? I am sure that is the word that I have heard used to describe student pranks."

"No, it is definitely *lasing*. Come and see."

They walked on down the corridor to a door at the end. The Mechanic opened this door and they entered, closing the door behind them. They were now in a long room which was lined along both sides with bunk beds. Alice could see that many of the top bunks were occupied by electrons, but the lower bunks were for the most part empty. "You sometimes find them in the top bunks rather than the lower ones," remarked the Mechanic. "It is called *population inversion*. It is only when they are like that that lasing becomes practical."

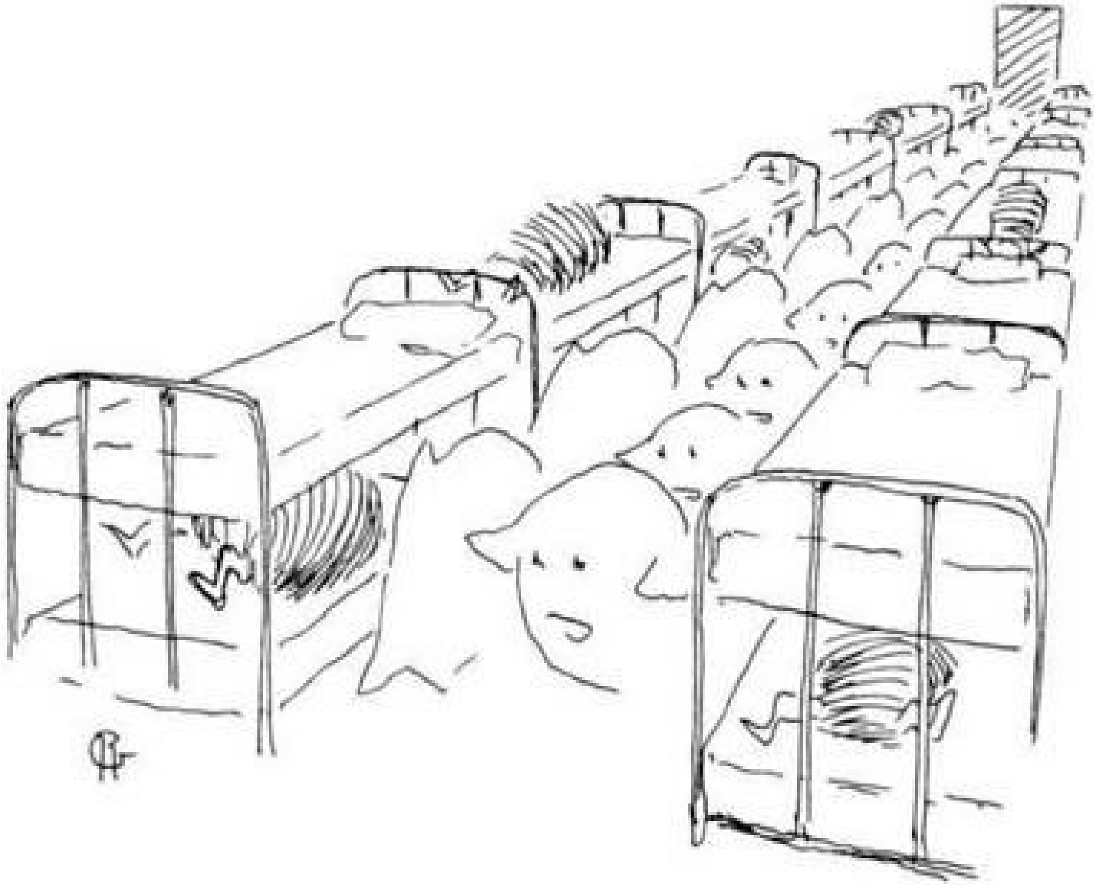
It was not very long before a lone photon came running into the room. He rushed to one of the bunks and careened into the electron which occupied that elevated position. With a thump the electron plummeted down to the lower bunk, and Alice was startled to see that there were now *two* photons rushing together around the room. They moved in perfect unison so that they almost seemed as one. "That is an example of *stimulated emission*," the Mechanic murmured in Alice's ear. "The photon has caused the electron to make a transition to a lower level, and the energy released has created another photon. Now just watch and see how the lasing develops."

The two photons rushed up and down the long room. One collided with an electron, and then there were three photons and another electron in a lower level. As Alice watched, the photons interacted with more electrons, producing more photons. Occasionally she noticed a photon collide with an electron which had fallen to a lower bunk. When this happened the electron shot up to the higher bunk and the photon vanished, but as there were initially very few electrons in the lower bunks this did not happen often to begin with.

See end-of-chapter note 6

Soon the room was crowded with a horde of identical photons, all rushing to-and-fro in perfect synchronism. There were now almost as many electrons in the lower bunks as in the upper ones, so that collisions were as likely to excite an electron to a higher position, with the loss of one of the photons, as to create a new one. The stream of photons poured out through the door at the end of the dormitory and down the corridor as a tight coherent beam of light. Before they had gone halfway down the corridor they collided with the massive form of the Principal who was walking toward them.

He immediately stopped, drew himself up to his full height, and spread his thick black gown to either side, so that he presented a dense black body, effectively blocking the corridor. The photons struck the inky black material and vanished completely. The Principal stood there for a moment, looking both hot and bothered and mopping the perspiration from his ruddy face with a handkerchief.



"I will not tolerate this sort of behavior," he puffed. "I have warned them before that any photons who carry on in this way will be instantly absorbed. It is hot work, though, since the energy released has to go somewhere, and it usually ends up as heat."

"Excuse me," said Alice. "Could you tell me where all those photons have gone?"

"Why, they have not gone anywhere, my dear. They have been absorbed. They are no more."

"Oh dear, how tragic," cried Alice, who felt sorry for the poor little photons who had been so abruptly snuffed out.

"Not at all, not at all. It is all part of being a nonconserved particle. Photons are like that. Easy come, easy go. They are always being created and destroyed. It is nothing very serious."

"I am sure that it must be for the photon," cried Alice.

"Well, I am not even so sure about that. I do not think it makes much difference to a photon how long it seems to *us* that it exists. They travel at the speed of light, you see, as after all they *are* light. For anything traveling at that speed, time will actually stand still. So, however long they seem to us to survive, for them no time at all will pass. The entire history of the universe would pass in a flash for a photon. I suppose that is why they never seem to get bored.

"As I said in the assembly, photons have many important parts to play in exciting electrons from one state to another and indeed in creating the interactions which make the states in the first instance. In order to do this, it is necessary that they be created and destroyed very frequently; it is part of the job, you might say. Creating interactions is more the task of virtual photons, though. We do not deal much with them here. If you are interested in states and how one goes about moving from one to another, then you should visit the State Agent. Your friend there will show you the way."

The Principal escorted them out of the Academy and back down the drive to the gate. As they walked on down the road, Alice turned back once to wave to the Principal, who was standing solidly in the center of the gateway where she had first seen him.

Notes

1. If you have many particles you will have some sort of amplitude for each of them and an overall amplitude which will describe the whole system of particles. If the particles are all different from one another then you know (or *can* know) the state each is in. The overall amplitude is just the product of the amplitudes for each particle separately.

If the particles are identical to one another, then things get more complicated. Electrons (or photons) are completely identical. There is *no way* to distinguish one from another. When you have seen one, you have seen them all. If two electrons were interchanged between the states they occupied, there is no way that you would ever be able to tell. The total amplitude is, as usual, a mixture of all the indistinguishable amplitudes, which now includes all those permutations in which particles have been interchanged between two states.

Interchanging two identical particles makes no difference to what you can observe, which means it makes no difference to the probability distribution that you get when you multiply the amplitude by itself. This could mean that the amplitude itself does not change either, or it *could* mean that the amplitude changes sign, for example, going from positive to negative. This is equivalent to multiplying the amplitude by -1. When you multiply the amplitude by itself to get the probability amplitude, then this factor -1 is also multiplied by itself to give a factor of +1, which produces no change in the probability. The change in sign sounds like a trivial academic point, but it has amazing consequences.

2. There is no obvious reason why an amplitude *should* change sign just because it cannot be shown that it may not, but Nature seems to follow the rule that anything not forbidden is compulsory and to take up all her options. There *are* particles for which the amplitude does change sign when two of them are interchanged. They are called fermions, and electrons provide an example. There are also particles for which the amplitude does not change in any way when two are interchanged. These are called *bosons*, and photons are of this type.

Does it really matter whether the sign of the amplitude for a system of particles does or does not change sign when two of them are interchanged between states? Surprisingly, it does. It matters a great deal.

You cannot have two fermions in the same state. If two bosons were in the same state and you happened to interchange them, then it really would make no difference at all-it could not give even a change of sign. Such amplitudes are not allowed for fermions. This is an example of the Pauli principle, which says that no two fermions may ever be in the same state. Fermions are the ultimate individualists; no two may conform completely.

The Pauli principle is extremely important and is vital for the existence of atoms and of matter as we know it. Bosons are not governed by the Pauli principle-quite the reverse, in fact.

If each particle is in a different state and you square the overall amplitude to calculate the probability distribution for the particles, then each particle separately contributes much the same amount to the total probability. If you have two particles in the same state and square that, you get four times the contribution from only two particles. Each has contributed proportionately more, so that having two particles in the same state is *more* probable than having each in a different state. Having three or four particles in the same state is even more probable, and so on. This increased probability for having many bosons in the same state gives the phenomenon of boson condensation: Bosons *like* to get together in the same state. Bosons are easily led; they are inherently gregarious.

Boson condensation is seen, for example, in the operation of a laser.

3. Electrical forces involving electrons can operate to hold atoms together, as discussed in Chapter 7, but they do not give rise to any repulsion which would push the atoms apart; so why do atoms

keep a fairly uniform distance from one another? Why are solids incompressible? Why are the atoms not pulled into one another, so that a block of lead would end up as one very heavy object of atomic size? Once again it is a consequence of the Pauli principle, which says that two electrons cannot be in the same state.

Since the atoms of a given type are all the same, each has the same set of states. Does this not put the equivalent electrons in each atom into the same state, which is not allowed? Actually, as the atoms are in different positions, the states are slightly different. If you were to superimpose the atoms, then the states *would* be the same, and the Pauli principle forbids this. The atoms are kept apart by what is known as Fermi pressure, but which is really the intense refusal of the electrons in one atom to be the same as their neighbor. Matter is incompressible because of the extreme individualism of electrons.

4. In a solid the electron states from the individual atoms have combined together to form a large number of electron states which belong to the solid as a whole. These states are grouped into energy bands, within which the energy levels of the states are so close together as to be almost continuous. Corresponding to the larger energy-level separations in the individual atoms, there are gaps in the energy bands of the solid. The lower bands are full of electrons which have come from the lower levels in the atoms. The highest of these full bands is called the valence band, and above it, separated by a band gap which contains no states, is another band: the conduction band. This band is either completely empty or, at most, only partly full.

In the valence band the electrons cannot move. Any electron movement requires that electrons should change from one state to another, and there are no empty states for the electrons to go into. If an electric potential was put across a material, it would apply a force to the electrons in the valence band, but they could not move. If there were no electrons in the conduction band, the material would act as an electrical insulator.

5. If an electron in the full valence band is given enough energy, either by collision with a photon or even by a chance concentration of thermal energy, then the electron may rise across the band gap into the higher conduction band. As there are plenty of empty states in this band the electron can now move around, and an electric potential will produce conduction. Further, there is now a free space in the valence level, where the electron used to be. Another electron may move into this hole, and so on. There will be a hole in the otherwise full valence band, and it will be moving in the opposite direction to the electron movement. This hole behaves very much like a particle with positive charge.

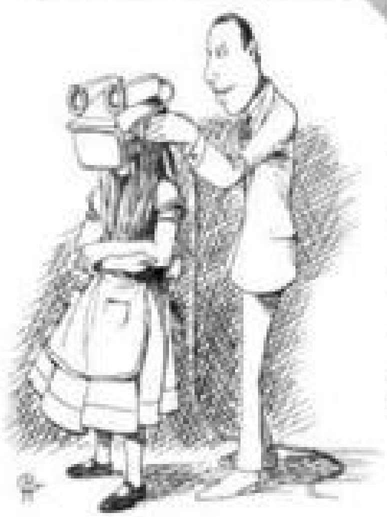
The above describes the behavior of semiconductor materials: materials such as silicon, which is widely used in electronics. Electric current is carried both by electrons in the conduction level and by *holes* in the valence level.

6. When a photon which has the correct energy interacts with an electron in an atom, it may produce a transition from one energy level to another, as described in Chapter 6. In most cases the transition will be from a lower to a higher energy level, since usually the lower levels will all be full. The photon is equally capable of producing a transition from a higher to a lower level, if the lower level is empty.

Should a substance happen to have a lot of electrons in a higher level, and a lower level is mostly empty (a condition known as *population inversion*), then a photon can cause an electron to transfer from a higher state to a lower one. This change releases energy and creates a new photon, in addition to the one which caused the transfer. This photon can in turn induce more electrons to fall to a lower state.

In a laser the light produced is reflected back-and-forth from mirrors at either end of the cavity, causing more photon emissions each time it passes repeatedly through the material. A little of this light escapes through the mirrors, which are not perfect reflectors, and gives an intense narrow beam: laser light. As the photons were emitted in direct response to the photons already present, the light is all "in step," or *in phase*, and has unique properties for producing interference effects on a large scale, as may be seen in holograms. (Not all holograms need laser light, but it helps.)

CHAPTER 6 Virtual Reality



The Quantum Mechanic led Alice down the road and through a wrought iron gate into an attractive park. Beautiful flower beds, full with an abundance of assorted blooms, lined both sides of the path, giving a most pleasing effect as they strolled along in the warm summer weather. In the sky the sun shone brilliantly, pouring out its light upon the idyllic scene. Beside the path colorful butterflies flitted from bright blossom to bright blossom and a small stream burbled downhill over a bed of rounded pebbles, while here and there along its path the water poured over a miniature waterfall. Alice thought it all very pretty and was looking around her in delight when she saw another figure approaching on a converging path.

The newcomer was plainly another little girl, but there was something very peculiar about her. She looked somewhat like Alice herself, but she resembled rather more the figure that Alice had occasionally seen in the negatives of her snapshots. Alice was reminded of the antielectrons which she had watched in the Bank. She noted to her surprise that, although the girl was coming toward her, she was facing in the opposite direction and walking along backward.

Alice was so absorbed in the remarkable appearance of this strange girl that she did not consider how quickly they were approaching one another. Before she had fully realized what was happening they had collided. There was a blinding flash which quite took her senses away. When she recovered from this she found herself walking alone down the path along which the other girl had come. Looking back she could see that the reverse-girl was walking away, still backward, along

Alice's original path. Now, however, she was accompanied by another negative figure which was companionably walking along backward beside her. This second figure resembled her previous companion, the Quantum Mechanic.

When she looked around her, Alice was startled to discover that her surroundings had altered every bit as dramatically. Everything seemed to be reversed. In the sky the sun glowered darkly, draining the light from the scene below. Beside the path, dull butterflies flitted backward from dark blossom to dark blossom and a small stream burbled uphill over a bed of round pebbles, while here and there the water soared to the top of a miniature waterfall. Alice had never experienced anything like this before.

She was so fascinated by this remarkable scene that she did not observe that once again a small girl was bearing rapidly down upon her in reverse. Alice looked around just as they collided, with yet another blinding flash. When she recovered from her shock, she saw the girl was backing away along the path by which Alice had just come. She noticed furthermore that the scenery had now returned to normal. "Curiouser and curiouser," said Alice to herself. "The first collision somehow managed to make the whole countryside reverse itself, while the second one has put it back to normal. I'm sure I do not see how that could possibly happen. How can my colliding with that girl, however violently, affect the stream and the sun? It does not make any sense at all." Alice continued to debate with herself about the meaning of her recent experience. It had been so very remarkable that she paid hardly any attention when she heard a sharp detonation to one side of her, while shortly after an extremely energetic photon rushed across the path.

Alice had not reached any satisfactory explanation of her recent experience when the path led her out of the park and onto a wide, level plain. This seemed devoid of any feature, apart from a large, utilitarian building which stood facing her a little way ahead.

When she got close she could see that the building had a name board mounted centrally on the front, a little above the level of Alice's head. At one end this sign bore the words "State Agent." at the other "Virtual Realtor." In the center of the vast blank frontage were a door and a small window, which was full of notices.

Genuine Amplitude Reductions for Quick Sale

Fine Periodic Features.

States situated in desirable Energy Band.

Attractively priced for early Transition.

As Alice could see no one outside, she opened the door and went in. Immediately inside the door was a short counter and behind this a huge room, almost empty apart from what seemed to be tiers of shelves rising up into the shadows in the distance. In the center of the room, a single figure was visible sitting at a desk and talking into a telephone. When he saw Alice he rose and hurried over.

He rested his hands on the counter and smiled widely in a toothy and rather insincere manner. "Come in, come in," he said, ignoring the fact that Alice had already come in. "What may I have the pleasure of showing you? Perhaps you are planning to move into your very first state? I am confident that we will be able to give you every satisfaction."

To tell you the truth," began Alice, not that she had been at all tempted to lie about it, "I am not actually looking for anything. I was told that you would be able to tell me something about how electrons and other particles move between states."

"Well, you have certainly come to the right place. We have long been established in the particle transition business. If you would care to come with me to one of our locations I will endeavor to clarify the situation to your complete satisfaction."

Alice understood this to mean that he would explain things, so she came around the counter and followed him to one of the sets of shelves, or whatever they were. Either they were a long way away and very large, or perhaps she and the State Agent shrank as they came closer, but however it happened Alice found as she drew near that they now looked much more like a tall block of apartment buildings. These bore a sign which read:

Periodic Mansions

They were very open at the front, and she could see electrons moving around on each level.

"There you have a good example of quality states built on wellspaced energy levels. Each one is occupied by the permitted number of electrons, up to the highest occupied level. Above that there are many vacant states, but there is currently no room for any more electrons on the lower levels. When an electron is a sitting tenant in a state, there is of course no room for another electron. Usually if he is left to himself an electron has no inclination to move from a state once he has settled into it. However, if we wait for a little we may be lucky and see some forced movement."

Alice stood and looked at the edifice, and after a short wait she saw a photon rush into the front. There was a commotion, and one of the electrons in the lowest level soared up and out of sight. Alice looked around to see where the photon had come from. Parked nearby there was a small truck with, painted on its side, the slogan:

Photon Removals
We make Light work of
Transitions.

"I am in luck," cried the State Agent joyfully. "A photon has given its energy to an electron in the lowest level and excited it right up to one of the vacant levels at the top. It is not so often that we get a removal from the ground state. That leaves a very attractive vacancy. I must see to it at once."

He rushed off and soon came back carrying a notice board on a post, which he planted in the ground. The notice read:

Vacant Possession!
Attractive State on Ground
Level.

Hardly had he got the board in position than one of the electrons in the second level gave a short cry and toppled down to the empty state. Once there he settled in and carried on as if nothing untoward had happened. As he fell Alice saw a photon rush out. Since the electron had not fallen very far, the energy carried by this photon was much less than the energy carried by the photon which had released the original electron.

The State Agent sighed, picked up a paintbrush from a pot he had brought out when he fetched the sign, and proceeded to cross out the word "Ground" and write "Second" in its place. The paint was hardly dry when Alice heard another sharp cry. An electron in the third level had fallen into the empty place in the second. The State Agent cursed and altered his board again to read "Third." He slammed the brush back into the paint pot and glared at the building.

There was another sharp cry. An electron from still higher up had fallen into the third level. The State Agent tore his notice from its post, flung it on the ground and stamped on it.

See end-of-chapter note 1

"Excuse me," said Alice, rather hesitant at interrupting this display of passion. "I had thought you said that the electrons would stay in their states indefinitely if they were left alone, but those ones appear to have fallen down quite spontaneously."

"So it may seem," replied the Agent, quite glad to be distracted from his momentary fit of temper. "Actually all of those electron transitions have in fact been stimulated by photons, but you did not notice them because they were *virtual* photons. Virtual photons play a very important part in all electron interactions. They not only give these apparently spontaneous transitions between states, but they also help to create the states themselves in the first instance. So you see, the very particles which keep an electron in its steady state are also the ones which force the electron to leave it.

"Before I tell you about virtual particles we ought to look at normal particles, the ones which are *not* virtual. They are commonly known as real particles. The distinctive thing about them is that there is a very strict relation between their particular masses and the energy and momentum that they can have. That is what the notice there is about."

The agent pointed to a small sticker, printed on fluorescent green paper, which was attached to the front of the building. It said:

Real particles do it on the Mass Shell.

Electrons may be excited by photons to make transitions in either direction, giving stimulated absorption and stimulated emission. Electrons which have been excited into a state of higher energy eventually decay back to a lower state if one is available, even if there are apparently no photons present. This is called *spontaneous decay*. Quantum mechanics maintains that all transitions are driven by something; they do not just happen. The apparently spontaneous decays are in fact caused by photons, but not by real photons. They are stimulated by virtual photons: quantum fluctuations in the vacuum.

Around any electric charge there is a cloud of virtual photons whose interaction with other charged particles produces an electric field. As they constitute the electric field, these virtual photons are always present in an atom and can produce the apparently spontaneous decays of electron states.

"They are certainly very fond of notices here," Alice thought to herself. "That one does sound rather suggestive, though I must admit that I do not know what it means."

"The mass shell," continued the agent, as if answering her thoughts, "is the region where energy and momentum are related in the strict way required for real particles. It is the straight and narrow path followed by conventional, hidebound particles.

"If you want to be a force in the community and to push things around, then you have to be able to transfer momentum. If you want something to move from where it is, or if you want to keep something from moving away, then you must transfer momentum. In each case you are concerned with moving, and moving means momentum. Whether you want to start a movement or to stop one makes little difference. It is changes in momentum which deflect objects from their paths and make things change, and it is control of momentum which makes particles take a particular path, for that matter.

"On the mass shell, you cannot have momentum without supplying the appropriate kinetic energy that befits your mass. A really massive particle, one with a lot of energy already invested in its rest mass, does not need so much extra kinetic energy to provide it with a given amount of momentum as would a lighter particle. All real particles must have the appropriate amount of energy if they are to have momentum. This is true even for photons, which do not have any rest mass at all."

The Agent reached into his pocket and took out a number of legallooking documents. "The conditions are quite precise. Provided that real particles obey them, they are free, free of any energy debt. They can move around as they wish, as far as they wish. They are quite free to come and go. You may have seen the rule: 'What is not forbidden is compulsory,'" he remarked.

"Yes, I did," replied Alice, anxious to air her knowledge. "I saw that in the Heisenberg Bank, and the manager told me about momentum and...."

"There is another rule," continued the agent enthusiastically, without actually stopping to listen to Alice's reply. "It says 'What *is* forbidden had better be done pretty quickly.' This is the rule followed by the virtual particles. These are not usually discussed much in polite, classical society, but they have a very important part to play in the world. Virtual particles behave in ways that classical laws say are simply not allowed."

"How can that be?" asked Alice, a little naively. "Surely if something is not allowed then no particle will be able to do it."

The agent heard her then and answered her question. It is the quantum fluctuations which permit it," he said. "If you have been to the Bank, you will remember that particles may have a loan of energy for a short time. The larger the amount of energy the shorter the time of course. You may have heard the expression The difficult we do immediately, the impossible takes a little longer.' Well, in quantum mechanics the impossible does not take a little longer, but it does last a little shorter. Virtual particles can enjoy all the benefits of energy which they do not possess, on a short-term free trial. This includes being able to transfer momentum."

"It must be a rather short free trial," said Alice thoughtfully.

"Oh, it is; it is. But it is something for nothing you see, so they all want it. You will have a better appreciation of virtual particles once you have seen them."

"But I can't see them," complained Alice. "Surely that is the point."

"You cannot see them at the moment," the Agent replied sternly, "but you will when you put on my *virtual reality* helmet." He walked quickly away in the direction from which they had come, and Alice hoped that she had not offended him. She was relieved when he returned soon after, carrying a large and highly technical looking helmet. This had a transparent visor which entirely covered the front, and there was a long cable attached to a socket at the back. The cable snaked away along the path by which he had come until it was lost from sight in the distance. "Here it is," he said triumphantly, "a marvel of modern technology. Just put this on, and you will see the world of virtual particles."

In quantum theory the concept of a particle is not so sharp as in classical physics. Particles carry and deliver energy in a quantized form, in discrete packets. In many cases they have definite masses which clearly distinguish them from other particles and can carry specific amounts of other quantities, such as electric charge. Photons have zero rest mass (which also is a definite value). Real particles, those with a long-term existence, have strict relations between the values of mass, energy, and momentum. Where particles may be created and destroyed and have but a fleeting existence, then they do not obey such strict rules and the quantum fluctuations in their energy may be large. This is particularly true for those particles which are exchanged to provide an interaction between other particles. The entire energy of such particles is a quantum fluctuation. They are created literally from nothing. The vacuum is not completely empty, but is a seething mass of these short-lived particles.

Alice felt a little nervous as she contemplated the helmet. It was large, and it looked *very* complicated and even, she felt, a little sinister. However, if this was going to reveal the virtual particles she had heard mentioned so often, she was prepared to try it. She put the helmet on her head. It was very heavy. The Agent reached across to the helmet and made some adjustment at the side of her head, where Alice was unable to see. The view through the visor clouded over with little sparkling dots and....

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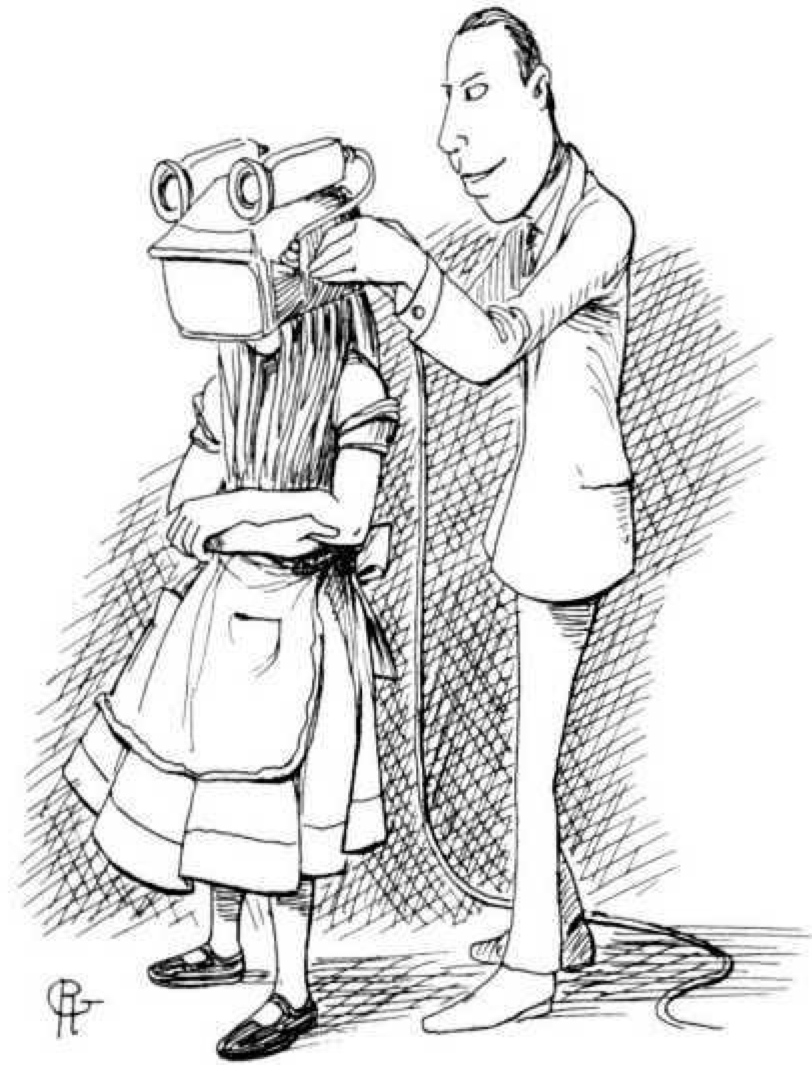
When her view through the visor cleared, it had dramatically changed. Alice could still see the electrons in their various levels, but now instead of their appearing to be within a tall building she saw them as enmeshed in a network of vivid lines which joined one electron to another, so that they looked as much as anything like flies caught in some great spider's web of shining strands. As she looked more carefully at these strands she could see that they were actually composed of photons, but photons distinctly different from the ones she had seen before at the Academy.

All the photons which she had met before had been moving very rapidly, but they had at least been moving in a normal fashion. They had started at one position and a little time later they were at a new position, even if their positions were never precisely defined, while in the intervening period they passed through all the points between the two positions. It had never occurred to Alice that it was possible to travel in any other way, but some of these virtual photons seemed to manage it. As she looked at them she found it very difficult to say in which direction they were moving, or indeed if they were moving at all in any normal fashion. A given strand in the net, which represented the behavior of one photon, would seem to appear at the same moment at the positions of both the electrons which it joined, without apparently moving in the normal way from one to another. This link would then fade while others appeared elsewhere in the great mesh of photons which coupled together the electric charges of all the electrons.



It was a really beautiful sight, if rather peculiar. The virtual photons were moving in every way conceivable, while some photons seemed to have mastered the art of traveling from one position to another without actually requiring any time to elapse between the two events.

As Alice was watching this strange scene with interest, the helmet emitted a whirring noise beside her ear, followed immediately by a loud "clunk." The view in front of her shimmered and returned to the mundane view she had seen before she put on the helmet. Alice exclaimed aloud in annoyance at losing the fascinating picture. "I am sorry," said the Agent. "I am afraid that there is a timer built into the mechanism. I had intended to make it coin-operated, you see."

Alice was still too much enthralled by the vision she had just been watching to pay much attention to the Agent's apology and tried to describe to him what she had seen. As with all the people she had met in this odd world, he immediately began a lengthy explanation.

> Particles in quantum theory are found to show properties which classically are associated with continuous waves. In a corresponding way, classical force fields are found to be composed of particles. The electrical interaction between any two charged particles is caused by the exchange of photons between them. These photons have a brief existence, which means they are well localized in time and so are uncertain in energy. They are *virtual particles*, whose energy and momentum may fluctuate well away from the values which would be normal for a long-lived particle.

"That is just another aspect of the way that virtual particles do things which real particles cannot. It is a bit like barrier penetration in a way. I expect you have seen some cases of barrier penetration by now."

"I was told that I had," answered Alice carefully. "I saw someone penetrate through a door when I first came here and I was told that he could do this because his wave function spread into and through the door, to give a small probability of his being observed on the other side."

"That is quite true. That part of his wave function allowed your friend to penetrate into a barrier which would have stopped a real classical particle. He did not have enough energy to cross the barrier, so when he was penetrating the door he was in a sort of virtual condition. There are very few particles, if any, which are entirely real. They almost all have some virtual aspects, though some are more virtual than others. The exchange photons you have just been looking at are almost totally virtual.

"It is the general rule that virtual particles do not obey the rules, even though they cannot manage to escape them for very long. This means that they can do things for which they do not actually have enough energy. These exchanged virtual particles, such as the photons you saw, produce interactions between other particles. They can penetrate through barriers which would stop a real classical particle, and this includes the barrier of time itself. They can move in a *spacelike* way, while real particles can only be *timelike*. This means that, although a real particle can sit at the same position while the time changes, it is unable to sit at the same time while its position changes. A virtual particle is able to do both. It can move sideways in time if it chooses."

"That sounds very curious indeed," said Alice. "I am not surprised that real particles are unable to do that and that they only move from the past to the future."

See end-of-chapter note 2

"Well, actually that is not quite true," said the Agent a little apologetically. "It is certainly true that most particles move forward in time, just as you suppose. However most particles become a little virtual on occasion, during collisions for example, so it is possible for a real particle to revert. One moment it is moving forward through time in a respectable, lawabiding way. The next moment it finds that it has been quite turned around and that it is moving backward toward the past. Though it might surprise you to hear me say so, this is an allowable way for a real particle to behave."

"Oh!" cried Alice suddenly, startling the Agent in the middle of his careful description. "I think that must have been what happened to me earlier. I could not imagine what had become of me when I was walking through the park and everything seemed to reverse around me, but now I see that it was not the stream and the butterflies which were going backward. It was I who was traveling backward in time!"

Alice told her companion all she could remember about the incident, and he agreed with her interpretation. "It certainly sounds to me like a clear case of antiparticle production," he said.

"Antiparticle!" exclaimed Alice. "I did not know that this had anything to do with antiparticles. I remember seeing them at the Heisenberg Bank, but I do not understand why they should have anything to do with the present case."

"I would have thought it was obvious," said the Agent, though Alice did not feel it was in the least obvious. "Why, don't you see that when a particle moves backward in time it appears to an onlooker to be something totally opposite, moving forward through time in the normal way. Take the case of an electron. It has a negative electric charge, so when it moves from the past to the future in the normal way it carries its negative charge into the future. If, on the other hand, it moves from the future into the past, then it carries this negative charge from the future to the past, which is like a *positive* charge going from the past, to the future. Either way it is making the overall charge in the future more positive. It looks to an outside observer like a positron, or antielectron.

"What happened to you would have appeared to the rest of the world as an unusually high-energy photon giving up its energy to create an Alice and an *anti-Alice*. The anti-Alice would travel along until it collided with an Alice and the two mutually annihilated one another, converting their energy back to photons."

"How can that be?" cried Alice in some dismay. "I do not see how this anti-Alice could ever have found a second Alice to collide with anyway. There is only one of me and I certainly haven't been annihilated," she concluded defiantly.

"Ah, but what I have just described is how it would appear *to the rest of the world*. How it would appear to you is quite different, quite different altogether. For you the annihilation would come before the creation of course."

"I do not see any 'of course' about it," answered Alice rather sharply. "How can anything be destroyed *before* it is created?"

"Why, that is the natural order of things when you are going backward in time. Normally, when you move forward in time you expect creation to come before destruction don't you?"

"Yes, of course I do," replied Alice.

"Well in that case, if you move *backward* in time you naturally expect the creation to come after destruction from your point of view. You are experiencing events in reverse order after all. I would have expected you to see that for yourself.

"In this case you were walking quietly along with the Quantum Mechanic and suddenly you collided with the anti-Alice. As far as your companion was concerned you and the anti-Alice were both utterly destroyed and your mass energy was carried off by high-energy photons."

"Oh dear! The poor Mechanic," exclaimed Alice. "He must believe that I have been destroyed then! How can I find him to set his mind at rest?"

"I shouldn't worry too much about that," the Agent assured her. "Naturally, the Quantum Mechanic knows about antiparticle annihilation, so he will know that you have simply gone back in time. He will no doubt expect to bump into you later, or perhaps earlier, depending on how far back you went. Anyway, the annihilation process converted you to an anti-Alice and you traveled backward in time until you were created, together with an Alice, by a high-energy photon. That is how it would have seemed to any onlooker. To you it just appeared that suddenly you were no longer traveling back in time, but had started to move forward as normal. You would not have seen the photon which caused this. You couldn't because it ceased to exist at the instant when you reversed your passage through time, so both as Alice and anti-Alice you were in a future which it never reached.

"You see now that, although anyone looking on would say that for a time there were three of you, two Alices and one anti-Alice, in fact they were all the same you. Because you had gone back in time you were living through the same period that you had already lived through as you walked along with the Quantum Mechanic. When you were returned to normal by the pair-creation process, you lived through the same period for a third time, now once again moving forward in time.

"That part of your life was rather like a road which zigzags up the side of a hill, climbing first to the east, then doubling sharply back to run toward the west before turning to the east again. If you climbed due north up the side of such a hill you might think that you crossed three different roads, while in fact you would have crossed the same road three times. It is the same sort of thing with antiparticle production. The antiparticle is a section of the road which goes the other way."

At that point there was a faint buzzing from the helmet and a small green light glowed in the corner of the visor. "I think the helmet is sufficiently recharged for another demonstration," said the Agent. "If you look carefully this time you should be able to make out some of the secondorder effects."

He adjusted the side of the helmet, and once again the view clouded over....

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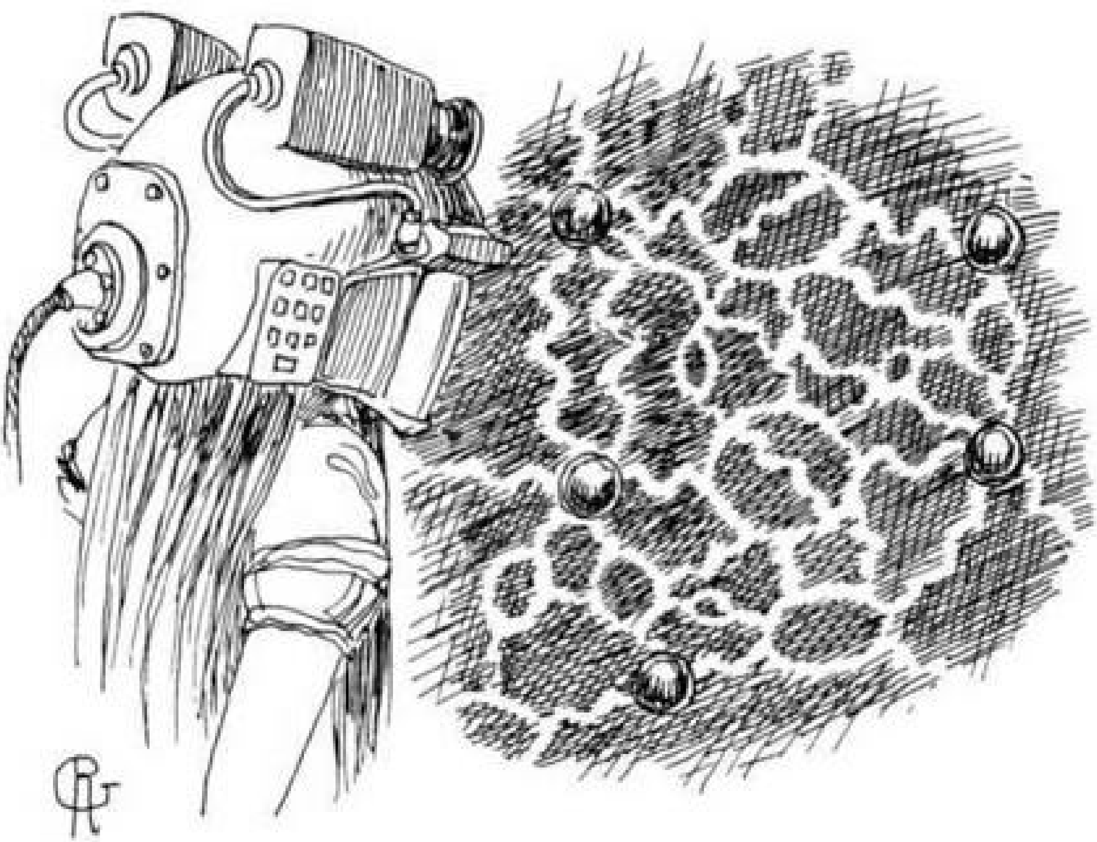
The view cleared again to reveal that the landscape everywhere was strung together by an all-pervading net of photon lines. When Alice looked more carefully at one particular region, she could see that a few of the bright links were interrupted. In the middle of a shining photon strand she could see a sort of loop, where the photon changed in midposition into what she could just recognize as an electron and a positron, an antielectron. These two combined together again almost immediately to form a photon strand which went on to attach itself to a real electron.

Peering still more closely, Alice could see another photon faintly issuing from the electron in the loop. Partway along the path of this photon she could see the dim outline of another electron-positron loop. From this emerged even fainter photons, and, if she peered really closely, she could just make out faint electron-positron loops along these. As far as she was able to distinguish she could see photons creating closed electronpositron loops and electrons or positrons emitting photons which created more electron-positron pairs. This went on and on, in apparently infinite profusion, but becoming fainter and fainter with each extra stage of complexity. Alice was becoming quite dizzy as she strained her eyes to try and see some end to this sequence. Finally an end came. She heard the whir and clunk from the helmet, and the entire pattern vanished from her sight.



"I thought that you said that electrons were joined by *photon* exchange," she said in a rather accusing tone. "I am sure that I saw electrons among the virtual particles. Quite a lot of them in fact."

"Oh yes, you would. The original real electrons act as the sources of the electric field, though it is more correct to say that the electric charges carried by the electrons are what produce the field. Photons do not really care about anything but electric charge, but wherever there is such a charge you will always get a cloud of virtual photons hanging about it. If another charged particle comes by, these photons are available to be exchanged and to produce a force between the two particles. Exchanged particles have to be created in order to be exchanged and they are destroyed afterward when they have been captured. Their number is obviously not conserved, so they have to be bosons.

"The relationship between photons and charge works both ways. Just as charged particles produce photons, so photons would like to produce charged particles, but they cannot produce just one charged particle because the amount of electric charge present is not allowed to change. That is another of the rules, and one that does not allow any uncertainty. What the photons can do however is to produce both an *electron* and an *antielectron*, or positron, at the same time. Since one has a negative charge and the other a positive one, the *total* charge in the universe has not changed. That was what you saw. The virtual photons produce virtual electron-positron pairs, which annihilate one another and return to being a photon. During the brief life of the pair, however, since they are both charged particles, they may produce more photons; those photons may produce more electron-positron pairs, and so on."

Not only can photons be created, but also particles such as electrons, though these have to be produced in company with their antiparticles so that there is no change in the total electric charge. Energy is required to create the rest masses of two such particles, but the necessary energy may be available briefly as an energy fluctuation. Such a fluctuation may occur even if there is no energy present initially, and the particles may be created literally from nothing. "Empty space" is, in fact, a seething brew of particle-antiparticle pairs.

"My goodness," said Alice. "It does sound excessively complicated. Where does it all end?"

"Oh, it doesn't. It goes on like that forever, getting more and more complicated. But the probability of an electron producing a photon, or of the photon producing an electron-positron pair, is rather small. This means that the more complicated amplitudes are weaker and eventually they are too weak to be noticeable. You must have seen that."

"Well," said Alice, whose head was spinning as she tried to follow what she had just observed and been told, "all I can say is that I have seen nothing like it before."

"You may well have done so," returned the Agent. "What you have just seen is like Nothing anywhere else. Though I am a little surprised that you have managed to see Nothing before you came here."

"I am sure that I wouldn't say that," replied Alice indignantly. "I may not have traveled very much, but I have still seen something, I would have you know."

"I have no doubt that you have," said the State Agent. "I am sure that you came from a very desirable location, but it is relatively easy to see Something, you know. It is much more difficult to see Nothing. I do not know how you could have done it without the aid of my virtual reality helmet."

"Just a minute," interrupted Alice, who had begun to suspect that they were talking at cross-purposes. "Would you tell me please what you mean by Nothing?"

"Why yes, certainly. I mean Nothing: the complete absence of any real particles whatever. You know: the Vacuum, the Void, the oblivion of all things, whatever you like to call it."

Alice was quite taken aback by the extent of this negative concept. "Would that look any different through your helmet? I should have thought that Nothing would look like nothing however you looked at it."

"Why, of course it makes a difference. The void is not the best neighborhood, perhaps, but there is plenty of undercover activity. Come and see for yourself."

The Agent set off at a smart pace and Alice followed him across the floor of his office. It was becoming increasingly difficult for her to believe that they were still inside an office, or a building of any sort, for it seemed remarkably large. They walked for some time, with Alice struggling under the weight of the helmet and of the cable which was still stretching out behind her. "I wonder how long this connection can be," she said to herself. "I am sure I must come to the end of it soon."

The Periodic Mansions, in which she had watched the electron states, were soon out of sight behind them, and still they marched on. Just as Alice was about to beg that they stop for a rest, she saw ahead of them what looked rather like the shore of a lake, or of a remarkably calm sea. As they came closer she could see that it was a very large lake, that is, if it was a lake. It stretched ahead of them as far as she was able to see, an apparently limitless expanse. But if it was the sea, it was the strangest seascape that Alice had ever seen. It was very calm, completely and utterly still apart from a faint, hardly seen, quivering around the surface. It was not blue, or green, or wine-dark, or any other color Alice had heard used to describe water. It was completely without color. It was like a deep, clear night but without the stars.

"What is that?" gasped Alice, overcome by the eye-devouring emptiness of the sight.

"Nothing," replied the Agent. "That is Nothing. It is the Void!"

"Come now," he continued. "Let me switch on the helmet, and you may observe the activity in the Void."

He reached out to the helmet and once again did whatever he had done before. Alice's view, her view of Nothing, clouded over....

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Her view cleared to reveal a scene very similar to the last one she had seen through the helmet. Once more she saw a mesh of glowing strands. This time, however, she did not see the strands ending on the real electrons, which before had seemed to be trapped in the web but were in reality its source. Now there were no real particles present, only the virtual ones. Photons created electron-positron pairs. Electrons and positrons produced more photons, just as she had seen before. Previously the network had originated from the real electrons, which were its source and anchor in the world of real particles. Where was its source now? The electron-positron pairs were produced by the photons; the photons were produced by the electron-positron pairs, which were produced by the photons. Alice tried to trace back along the lines of particles to find their source, but she found that she was going around and around in circles. She felt that she must have lost her thread and was trying again to follow the lines more carefully when she heard the familiar buzzing and the loud clunk, and the whole scene vanished.

Alice once more explained what she had seen to the Agent and told him how she had been unable to decide which particles had been creating which others. "I am not surprised," replied the Agent. "They all create one another, you know. It is a chicken and egg situation, with them all laying and hatching at the same time."

"How can that be?" asked Alice. "There must be a source. They cannot have come from nowhere."

"I am afraid that they can and they have," was the answer. "All that prevents particle-antiparticle production normally is the need to provide energy for the particles' rest mass, and virtual particles are not even inhibited by that. The whole thing is a great big quantum fluctuation."

"Is it real then?" asked Alice. "Are all those particles really there at all."

"Oh yes, they are quite real, even if not in the technical sense of *real particles*. They are just as vital a part of the world as anything else. I should think, though, you have now seen as much through the helmet as you need," he continued and lifted the heavy device from Alice's head. "We shall not be needing it any more, so I shall engage the cable rewind mechanism." He touched a button on its side and the helmet began to rewind itself along its cable, scuttling over the ground in the direction from which they had come, like a mechanical spider, until it vanished from sight.

Although the helmet had gone, Alice's head was still full of the remarkable sights she had seen and she turned them over in her mind as she walked in silence beside the State Agent, along the shore of the infinite Void.

Notes

1. Within atoms, the allowed states for electrons have widely spaced energy levels and electrons may occupy only these levels. An electron can only transfer from one of these states if it goes to another (empty) one and in so doing its energy changes by a definite amount, the difference in the energies of the two states. An atom in its normal, or *ground*, state has its lowest energy levels uniformly filled with electrons, but there are levels of higher energy which are normally empty. When an electron is excited from its initial position it will end up in one of these empty higher levels or leave the atom completely.

An electron which has been excited to a higher level can decay back to a level of lower energy if there is an empty state available. As the electron transfers to a level of lower energy, it must rid itself of the surplus energy, which it does by emitting a photon. This is how atoms come to give off light. Since the electrons all occupy definite states within the atom, any photon that is emitted can only have an energy equal to the difference of that possessed by the initial and final states of the electron. This gives a large number of possibilities, but nevertheless imposes a restriction on the energy which a photon may have. The photon energy is proportional to the frequency of the light and thus to its color, so the spectrum of the light produced by an atom consists of a set of colored "lines" of specific frequencies. The spectrum for a given type of atom is completely distinctive.

Classical physics can give no explanation for these spectra.

2. Virtual particles have a distinct fuzziness, both in time and in energy. This fuzziness shows itself as energy fluctuations, in which the particles behave as if they had more (or less) energy than they should. It can equally appear as an uncertainty in time. In a quantum system particles seem to be able to be in two places at the same time (or at least they have amplitudes which are).

The particles can even turn time around. The physicist Richard Feynman explains antiparticles as being "particles traveling backward in time."* This explains the way in which the properties of antiparticles are opposite to those of the particles: A negative electric charge carried backward in time is equivalent to a positive charge moving toward the future. In both cases the positive charge in the future is being increased, and a negatively charged electron traveling toward the past is seen as a positively charged positron, which is its antiparticle.

All particles have their antiparticles, as is to be expected if they are in effect the same particle behaving in a different way.

CHAPTER

7 Atoms in the Void

Alice walked with the State Agent along the edge of the Void, looking out over the shimmering tenuous surface which was continuously aboil with the activity of the virtual particles as they were born and died unnoticed.

A little way out from the shore Alice saw a disturbance in the surface, some sort of circular depression in the general uniform level. Further out she could see other pits, and many of them were clumped together into groups. Some of the groups were very small and contained just a couple of the circular objects. Other collections were more extensive. She could see one group which contained a ring made up of six of the objects arranged in a circle, while others were attached around the outside. In the distance she could see some enormous assemblies spread across the surface. The largest contained many hundreds of the circular things, whatever they might be.

As Alice watched, she saw photons soar intermittently from one or another of the shapes which were spread out before her. The brilliantly colored photons looked rather like flares fired from ships at sea.

The Agent followed the direction of her gaze. "I see that you are watching the atoms as they swim in the Vacuum. Atoms provide us with much of our work in the electron state business, one way or another. You can see from here the various molecular partnerships that they have set up between them. These range from small two-atom businesses to huge organic conglomerates. Each different type of atom has its own distinctive spectrum of colors for the photons which it emits, so the photons act as signals which help you to identify the different types of atoms."

See end-of-chapter note 1

"I was wondering about all those things way out there," admitted Alice candidly. "I cannot see them very clearly from here. Is it possible to get any closer?"

"If you want to look closely at atoms we ought to go along to Mendeleev Moorings. There you will see every type of atom on display, with all the different elements laid out in a regular order."

The Agent led Alice along the shore until they came in sight of an extremely long, narrow jetty, which stretched far out over the Void. At the shore end there was an arched gate on top of which was a sign which read:

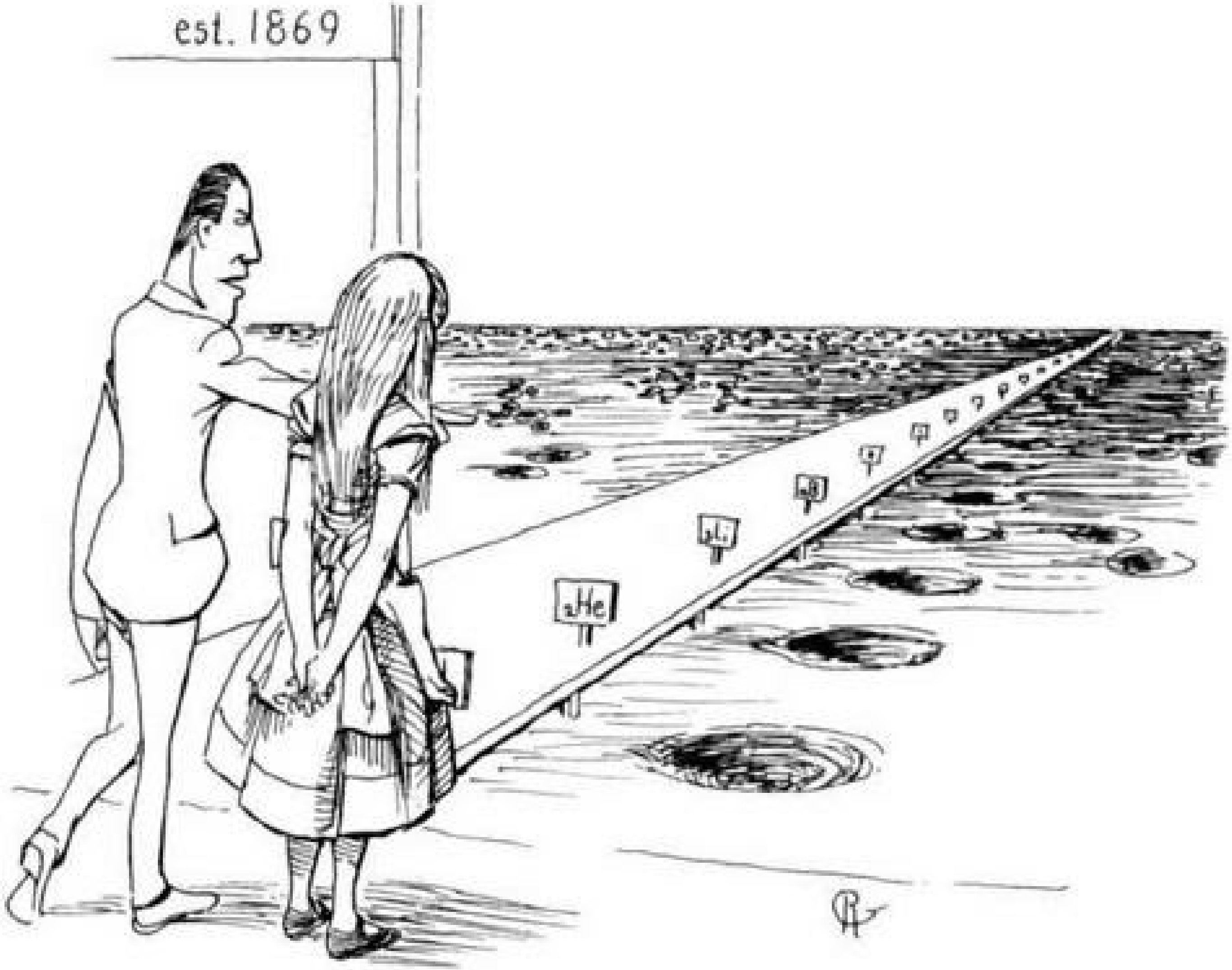
THE PERIODIC PIER
prop. D. I. Mendeleev.
Established 1869.

"There you are," announced the Agent. "That is where the atoms lie at dock before they set out to form their different chemical compounds. We usually call it the 'Mendeleev Marina' or the 'Atomic Pier,' though sometimes people talk of the 'Quay of the Universe.' You will find each different kind of atom represented here."

Together they walked beneath the sign and stepped onto the boards of the jetty. They strolled slowly out along the anchorage, while Alice looked at the long line of atoms moored in sequence to one side. Each of them appeared to her as a trumpet-shaped pit in the flat surface of the surrounding Void. The shape reminded her of the little whirlpool which she often saw forming over the drain whenever she emptied a bath, though these seemed to be quite still with no visible rotation. The surrounding surface of slick nothingness sloped down into each pit from the still flat level which stretched all around it. It sloped with almost imperceptible gradient at first, but ever more steeply as it funneled down toward the center. There were signs of activity taking place somewhere in the depths of the pit.

"Why is there such a deep hole?" Alice asked curiously. "As we are looking at Nothing, I would expect it to be all flat and featureless."

"That is a potential well," was the answer.



"What sort of well is that?" Alice continued curiously. "I know about garden wells which supply water and about oil wells, and I vaguely remember seeing something about a treacle well in a book I was reading recently, but what do you get in a *potential* well?"

"Why, the source of the potential, of course. You have to have a source to provide the water in a garden well. Here there is an electric charge as the source of electrical potential in the potential well. You should know by now what is in the well. It contains virtual photons. They provide the electrical attraction which would make the potential energy of a negative charge drop farther and farther below the surrounding vacuum level as it moves toward the potential source at the center of the atom. The potential source actually creates the well, you see."

The first pit was fairly shallow, but Alice could see that the others became successively deeper the farther they were positioned along the pier. The jetty stretched away ahead of her into the distance, with atom after atom moored along the side. Beside each one was a small notice to mark the mooring. The first of these read: ${}_1$H; the second, ${}_2$He; the third, ${}_3$Li. Each position had a different label. "Will these atoms all set out from here eventually to combine into groups like the ones already out on the surface of the Void?" asked Alice.

"Most of them will certainly, but there are a few which will not, like the one just here for example."

They paused beside an atom which carried the notice: $_{10}$Ne. "That is an atom of a Noble Gas element. They are an aristocratic lot and that means that they refuse to engage in commerce of any sort. They keep to themselves. They are perfectly satisfied with the way they are and will not mix with anyone else. They always travel around in splendid isolation. You never see them take part in any sort of compound."

They walked a little farther and the Agent explained that, even apart from the aloof Noble atoms, there was considerable variation in the enthusiasm with which different elements joined into compounds. "For example, this is a particularly active concern," he remarked, as they came to a notice which read: $_{17}$Cl.

Alice decided that it was time to examine one of these atoms more closely, so she tentatively extended one foot off the edge of the jetty. To her delight she did not sink. Her foot stood on a tiny dimple in the surface, rather like some pond-skating insects she had once watched. When she tried to walk toward the atom, however, she discovered that there was no friction in the void. The surface was *extremely* slippery, and she was quite unable to keep her footing. With a small cry she skidded down the increasingly steep slope and toppled into the deep pit.

As she fell, Alice found that she had plenty of time to look around her. The sides of the well became ever steeper as they closed in upon her, and she soon noticed that she was falling through the ghostly outline of a series of rooms which had low, closely spaced ceilings. The first few rooms were very low indeed, scarcely tall enough for a doll's house, but as she fell the rooms became steadily taller. Initially they were all completely empty and deserted, but then she came to a room which contained a large, round table surrounded by chairs. On the floor below this she could see desks and filing cabinets, as if she was passing through some sort of office.

The states which electrons may occupy within an atom tend to group into a set of levels which are separated by significant gaps in energy. If an atom has its outermost occupied level completely filled with all the electrons it can hold, then any extra electron added would have to go into a state of higher energy. It will usually have a lower energy than this if it stays in its original atomic state. Atoms of this type, whose outer shells are completely filled with electrons, form the noble gases and do not interact chemically with anything in the normal way.

As the time passed she became increasingly amazed to find that she was still falling, without any sign of reaching the bottom. Down, down, down; would the fall *never* come to an end?

An atom is contained by the electrical field which is generated by the positive charge on its nucleus. This charge produces a *potential well* around the nucleus, which in turn defines the states available for the electrons to occupy. The selection of states available is a form of interference effect, akin to the range of notes you can get from an organ pipe or a violin string. One pipe can give only a few notes, for which the wavelength of the sound waves fits the pipe. In a similar way the allowed electron states fit within the potential well. The allowed states are grouped together into distinct energy levels. Any other wave function which does not correspond to one of these states is eliminated by destructive interference.

Alice gradually began to realize that her fall was *not* going to come to an end. She had not reached the bottom of the hole, but she was not getting any lower. She was floating quite unsupported in the center of the funnel, on a level with one of the shadowy rooms. She looked around her and noted that she was not alone. Near her were two electrons who were involved in a hectic flurry of activity. Around them she could discern the faint outline of an extremely tiny and cramped office. "Excuse me," she called. "Do you think that you could stop for a moment and tell ine where I am?"

"No room, no room," they called.

"I beg your pardon, what do you mean?" cried Alice, to whom this reply did not seem particularly relevant.

"There is not enough room here for us to slow down at all, let alone *stop*," they answered her. "As you know, when the position of a particle is restricted, the Heisenberg relation forces its momentum to be large, and it is so cramped here that we have no choice but to keep moving. If we had as much room as they have on some of the higher levels we could afford to move in a more leisurely way, but not here. This is the lowest level, you see, so we must expect to be kept busy."

"Really?" inquired Alice. "What is it that you do that is so important?"

"We do not do anything in particular. No one is particularly interested in *what* the electrons in the ground state are doing, just as long as we keep moving."

"In that case, do you think you could tell me where I am, *without* stopping?" Alice asked. "For I do not know where I have come to. What is preventing any of us from falling farther down into the well."

"You are in the lowest level of a chlorine atom, as we have already told you. Here, we are so close to the potential source that there is very little room, so we have to move very quickly as our momentum is forced to be high. This means that our kinetic energy is also high. None of us is in a particularly virtual state, you see. Electrons have secure positions in atoms, with very good tenure. Most atoms have been around for a long time and the quantum energy fluctuations are small, so for us electrons the energy and momentum are properly related.

"You probably know that when an electron, or anything else, falls farther into a potential, it loses potential energy, and this will be converted to kinetic energy," they went on.

"Yes, that was explained to me when I visited the Heisenberg Bank," agreed Alice.

"Here in this potential well, though, when we get closer to the center, there is less and less room, so we need to have more kinetic energy. If we were to fall even closer we would need to have more kinetic energy than we can possibly get from converting potential energy, so we are unable to fall any further. In fact, paradoxically, we just do not have enough energy to be able to fall any lower and we cannot borrow the energy as a quantum fluctuation because we would need it for a long time.

"There are only two states on this level so there is only room for two electrons, one being in a spin-up and one in a spin-down state. There are more states available as you move up to higher energy levels, so you will find more electrons on the levels above. The next two levels can hold up to eight electrons on each level. In any atom, the lowest levels, the ones with the lowest potential energy, are the first to be filled. The Pauli principle allows only one electron in each state, so when all the states on one level already have an electron, any extra electrons have no choice but to move into levels higher up. The levels are filled from the bottom until all the electrons are accommodated. The highest level which contains any electrons is called the valence level. That is where the valence electrons live, though there are plenty of unoccupied states higher up in the attic. The valence electrons make all the decisions and control the compounds our atom can join. If you want to discover how an atom operates, your best plan would be to go up and talk to them."

See end-of-chapter note 2

"How shall I get up to that level from here?" asked Alice.

"Well, if you were an electron you would have to wait here until you were excited to the higher level by a photon which could give you the extra energy you would need. In your case, however, I expect that you can be carried up by the Ladder Operator."

"Don't you mean the elevator operator?" queried Alice. "I have been in an elevator in a large department store and it had an operator who took people from floor to floor, but I have never heard of a ladder that needed one."

When she looked around, however, she could see a sort of ladder with very widely separated rungs. Beside it stood a rather indistinct figure. "May I ask who you are?" said Alice curiously.

"I am the Ladder Operator. I am not a physical creature, but merely a mathematical construct. It is my job to transform a system from one state to a higher or lower one." He performed some complicated operation which Alice completely failed to understand but resulted in her being carried rung by rung up to the higher level.

In due course Alice arrived at the level on which she had seen the large, round table. This level contained more electrons than the first. She managed to count eight in all, though with some difficulty. As with all the electrons she had seen so far, they were moving energetically around. Several of them were circling around the table, some in one direction and some in the other. The others were not obviously rotating but were nonetheless in motion. None of them was sitting quietly on any of the chairs around the table, but they were leaping up and down, and some were stepping on and off the table. The electrons were never still, though on this level they were not moving quite so frantically as they had been on the lowest one.

"Hello Alice," they cried as she appeared. "Come, and let us show you how a reliable, medium-sized atom operates. The way in which Chlorine Corporation conducts its business is decided by us seven electrons in the valence level."

"But there are eight of you!" protested Alice.

"That is because we have entered into a partnership with another atom, Sodium Syndicate, to form a sodium chloride molecule. Working together in this way we like to think that we are the Salt of the Earth. An atom runs much more harmoniously when all of its levels that hold any electrons are filled completely. On our own we have only seven electrons in the valence level and Sodium has but the one, although there is room for eight. It helps both of us if the Sodium valence electron comes over here to sit on our valence level and give us a full board. This means of course that we now have an extra electron, and so we have a negative charge. The Sodium atom has an electron less than normal, which gives them a positive charge, and the electrical force between these opposite charges holds the two atoms together. That is known as *ionic bonding* between the atoms and is one of the common forms of corporate structure."

"That sounds very cooperative on both sides," agreed Alice tactfully. "Which of you is the electron that has come over from the Sodium atom then?" she asked.

"I am," they all cried, talking together. They paused for a moment and looked at one another. "No, he is the one," they now said, still speaking in perfect unison. Alice realized that there was absolutely no point in asking any question which tried to distinguish between the identical electrons.

"Could you explain to me, please, why you say that the sodium atom has a positive electric charge when it has lost one of its electrons," she asked instead. "Surely it still has quite a few electrons left, and they will presumably have negative charges also."

"That is quite true, all we electrons do have the same amount of negative charge, as we are all identical. Normally in an atom this charge is balanced and neutralized by an equal amount of positive charge carried by the Nucleus. Atoms are usually neutral, with no net electrical charge either way. So you see, when an atom has one electron more than usual, it will be negatively charged. It is known as a *negative ion*. If it has one electron fewer than normal, the positive charge on the Nucleus will dominate, and the atom becomes a positive ion."

"I see," said Alice thoughtfully, "but what is this Nucleus that you are talking about?"

"Every atom has one," was the evasive answer, "but you do not want to know too much about it. You really don't!" he added nervously.

At this point the conversation was interrupted by a faint cry which started somewhere below them, passed through the valence level close at hand, and finally stopped somewhere above. Alice looked up and saw that it was due to an electron which had apparently been excited by a photon from its position in a lower level and was now looking uncomfortably remote in one of the empty higher levels. The electron wandered rather slowly around the high wide level until eventually it gave a brief cry and toppled to the level below. As it did a photon rushed out of the atom, carrying away the energy released by the fall. Alice watched with interest as the electron fell in succession from one level to the next, in each case emitting a photon. As the lower energy levels were more widely separated than those above, each fall was farther than the one before, so the photons created had higher energy arising from each successive fall. As their energy increased, the color of the light moved farther toward the blue end of the spectrum.

Looking downward Alice saw that the space that had been left by the electron which was excited from the lower level had been filled and that one of her companions in the valence level was missing. Before long the electron falling from above had dropped to the valence level and filled the vacant place. The atom was now back to its original state. Two electrons had exchanged levels, but as they were identical that was no difference at all.

See end-of-chapter note 3

"You will have noticed all the different colors of the photons which I emitted," said one of the electrons proudly. This remark tended to suggest that it was the electron which had fallen that had just spoken, but Alice was now too experienced with the effects of electron identity to fall into that trap. "That is the way that atoms emit light you know: when electrons change from one level to another. All the photons were of different energy, and hence different color, because the levels are all different distances apart. They are very closely spaced at the top of the well but are farther and farther apart as you get lower down. This level spacing is different in atoms of different types, so the set of photon energies is completely distinctive for each type of atom-as distinctive as a human fingerprint."

Hardly had the eight electrons settled down, or got as settled as they could ever be while they were all in continuous frantic motion, when there was a tremor which seemed to run through the whole atom. "What was that!" cried Alice in some alarm.

"It was an interaction of some sort. We have been separated from our Sodium partner and are drifting through the void as a free negative ion. But do not worry. I do not anticipate that we shall drift about aimlessly for very long. We shall very soon be back in business if the Exchange is agreeable."

"What Exchange is that?" asked Alice. "Do you mean the Stock Exchange? I understand that controls business in my world."

"In our case we mean the Electron Exchange. All of our activities are governed by electron interactions of some sort, so it is electron exchange which is significant. Perhaps you would like to visit the Exchange?"

"Yes, I should think so," replied Alice. "How would I get there from here? Is it a long journey?"

"Oh no. Not really. In fact it is not really a journey at all. As you are in an interacting atom, you are already there in a sense; you just need a different representation. It is all a question of how you look at things. Just follow me."

As the electron had told her, they did not seem actually to go anywhere else, but still Alice found herself in company with an electron on the edge of a broad room. The floor was crowded with electrons which clustered around a large table in the middle of the room. It looked to Alice rather like one of the tables which she had seen in old war films, where commanders moved around various counters which represented aircraft, or ships, or armies. On this table also, she saw a great selection of counters which were being moved around into different groupings.

She looked more closely at some of these counters and saw that they bore the same labels as the atom moorings on the Periodic Pier. In fact, as she looked really closely, she was no longer so sure that they were merely counters. They looked like reduced versions of the atoms which she had seen along the side of that jetty. "Perhaps they are the same," she thought. "Maybe those are the same atoms which I am seeing differently. I suppose that instead of the Periodic Pier, that would make this the Periodic Table."

Around the side of the room, the walls carried rows of display screens on which she could see columns of numbers that changed as atoms were moved from group to group.

"Are those the prices for the various atoms?" asked Alice.

"Yes, after a fashion. Those numbers tell us the energies of the various electrons which are taking part in chemical combinations. They quote the *binding energies* of the electrons: the amount by which an electron's energy has been reduced below the value it would have if it were free. The larger is the value quoted, the lower is the potential energy that the electron has, and so the more stable and successful is the compound which it binds. The job of the Exchange is to make these binding energies as large as possible."

"And is this all done by moving electrons from one atom to another?" queried Alice, who remembered the explanation she had been given of ionic bonding in Sodium Chloride.

"Not always, no. Sometimes that is the most effective method and then the binding is done in that way. The Electron Exchange can get an advantage by moving electrons around because the electron states that are available within an atom are arranged in levels, or shells, with quite large gaps between. The binding energy for the last electron in a lower shell level is much greater than for the first electron that has to go into the next shell higher. This means that there is an easy method of improving the overall energy score for an atom which has only one electron in its highest shell. If this electron can move from its splendid but extravagant isolation into an almost full lower shell in some other atom, then there is almost certain to be an overall gain in binding energy.

"It is equally true that, when an atom has but one space remaining in its highest occupied shell, this state will have an unusually low energy, and any electron which transfers into it will be likely to improve its energy balance sheet. It is generally true that atoms with just one electron too many or too few are the most active—the most likely to take part in transactions and to form compounds. Atoms with two electrons alone in a high state and those with only two spaces left in a lower one may engage in similar electron transfers, but the gain in binding energy for the second electron is usually a lot less than for the first one, and it is much less effective."

"So what can an atom do if it has several electrons in its outer shell?" asked Alice, as this seemed to be expected of her.

If an atom has just one electron in its outer level, while another atom is one electron short of a full level, the two can achieve a lower energy overall by transferring the isolated electron of the one to the nearly full valence level of the other atom. This is chemistry: The electrons in their various energy levels bind the atoms together. The details of chemistry can get rather complicated in practice, but that is the principle.

An atom contains that number of electrons which is needed to neutralize the positive charge on the nucleus. These electrons fill the states of lowest energy, with one electron in each state. If one atom has a single space left unfilled in its highest filled level and another atom has a single electron which has had to go into a higher level, then the overall energy may be reduced by transferring this electron into the space left in the other atom. Both atoms now have a net charge and the resultant electrical attraction binds them together to form a chemical compound.

"Such an atom has to change to a different kind of binding, one which is known as a *covalent* bond. An atom such as carbon, for instance, has four electrons in its outer shell. This means it has four electrons too many to be an empty shell and four electrons too few to be a full one. It is too nicely balanced to gain anything by actually transferring electrons to or from another atom, so instead it *shares* them. It turns out that if the electrons from two atoms are in a superposition of states such that each may be in either atom, then the energy of the two atoms may be lowered and this serves to bind them together.

"The ionic bond, in which an electron is completely moved from one atom to another, can only work between very different atoms, one of which has an electron too many, the other an electron too few. The covalent bond, on the other hand, can work when both atoms are of the same type. The most remarkable example is given by the covalent bonding of carbon atoms, the basis of the huge Organic Conglomerates." Alice could sense an atmosphere of awed respect emanating from the electron manipulators around the table as the Organics were mentioned.

"A carbon atom has four electrons in its outer, or valence, level. If each of these electrons is combined with electrons from other atoms, then all of the eight electron states contribute to the superposition and the shell is effectively filled. In this way a carbon atom can attach itself to as many as four other atoms, which may also be carbon. The carbon atom may also exchange two of its electrons with another carbon atom to give a *double bond*, in which case it will not be connected to so many other atoms, though the connection will be stronger.

"The ionic bond at its strongest connects but one atom to one other, so it does not produce large molecules. Where there are two electrons to transfer, things can get more complex. Even then the situation does not compare with that of carbon, where one atom may connect to four others and each of those may be connected to several others. Carbon-based compounds can form into enormous organic molecules of great complexity, which may contain hundreds of atoms in all."

"Do all of the different atom types that I can see there form compounds in the ways you describe?" Alice asked.

"Yes, apart from the noble gases. With the noble gases, the atoms have filled valence shells already and so do not stand to gain by any electron transfers. All of the others do form compounds to a degree, though some are more active than others and some are encountered much more often. The chlorine atom which you visited, for example, is very active. It will form compounds with the simplest atom, hydrogen, which employs only one electron in total, and also with the largest natural element, uranium. That is a very large establishment indeed. It employs almost a hun dred electrons, but only the ones in the outer valence level really affect its chemical behavior. It is so large that there have been rumors that its Nucleus is unstable," he added confidentially.

"I wanted to ask about that," said Alice firmly. "You have mentioned the nucleus again. Please, would you tell me: What is the nucleus?"

All of the electrons looked somehow uncomfortable, but reluctantly answered. "The Nucleus is the hidden master of the atom. We electrons conduct all the business of forming chemical compounds and emitting light from the atom and so on, but it is the Nucleus which really controls the sort of atom we are. It makes the final policy decisions, and fixes the number of electrons that we can have and the levels that are available to put them in. The Nucleus contains the nuclear family, the hidden underground of Organized Charge."

Alarmed by this outburst of candor, the electrons around the room all tried to shrink unobtrusively into one corner, or at least as far as they were able without becoming too localized. Too late, the harm was done! Alice became aware of a new menacing presence nearby.

Amongst the scurrying electrons there was now a hulking shape, looming over Alice and her companions. She realized that it was a photon, but distinctly more massive than any she had seen before. Like all the photons she had seen it was glowing, but in a peculiarly dim and furtive way. Alice also noticed that, surprisingly for something which was itself the essence of light, this photon was wearing a pair of very dark glasses.

"It is a heavy virtual photon," gasped the electrons, "Very heavy, a long way off its mass shell. It is one of the enforcers for the Nucleus. Photons such as him transmit the Nucleus's electrical control to its client electrons."

"I hear that someone is asking questions," said the photon, in a menacing tone. "The nucleons are the sort of particles that do not like to hear that questions are being asked by any other person whatever. I am taking that same person for a little ride to meet certain parties, or rather certain particles. They want to meet her very badly indeed."

This did not sound like a very promising start for a new encounter, and Alice was considering whether she might safely refuse. She could never quite make out, in thinking it over afterward, how it was that they began: All she could remember was that they were running side by side and the photon was continuously crying "faster," and Alice felt that she could not go faster, though she had no breath left to say so. They rushed across the surface of the table and dived into one of the atoms represented on its surface. It was one of the uranium atoms and it grew enormously as it rushed up to meet them.

The most curious part of the experience once they were inside the atom was that the things around them never changed in position: However fast they went they never seemed to pass anything. What Alice did note was that her surroundings, the busy electrons and the outlines of the levels which contained them seemed to be getting steadily *larger* as she ran.

"Is everything really growing, or am I shrinking?" thought poor puzzled Alice.

"Faster!" cried the photon. "Faster! Do not try to talk."

Alice felt that she would never be able to talk again; she was getting so out of breath: and still the photon cried "Faster! Faster!" and dragged her along.

"Are we nearly there?" Alice managed to pant out at last.

"Nearly there!" the photon repeated. "Why, we are there all the time and no other place, but we are not sufficiently *localized*, not hardly. Faster!" They ran on for a time in silence, going faster and faster while the surrounding scene ballooned in size around them, spreading upward and outward until everything she had seen before was too large to be readily appreciated.

"Now! Now!" cried the photon. "Faster! Faster! Your momentum is now nearly so large as will localize you within the Nucleus." They went so fast that they seemed to skim through the air, until suddenly, just as Alice was getting quite exhausted, she found herself standing in front of a tall, dark tower which rose smoothly in front of her, curving up from the ground and narrowing steadily as it rose. It was dark and featureless at the lower levels, though somewhere at the top Alice could see that it finished in a confusion of turrets and battlements. The overall effect Alice found extremely forbidding.

"There you see Castle Rutherford, the home of the Nuclear Family," said the heavy virtual photon.

Notes

1. Atoms had been found to contain light negative electrons and, later, were found to contain a positively charged nucleus. This suggested that they might be tiny versions of the solar system, with planetary electrons in orbit around a nuclear sun. The notion gave rise to fantasies in which the electrons were indeed miniature planets, with still more miniature people living on them, and so on *ad infinitum*. Unfortunately for such schemes, the "solar system" picture is clearly wrong.

- The only reason planets do not fall directly into the sun is because they are orbiting around it. There is definite evidence that many electrons do not have any rotation the nucleus.

• According to classical physics, the orbiting electrons within atoms should radiate energy and their motion should run down. Something as small as an atom would do this rather quickly, in less than a millionth of a second, and atoms do not collapse in this way. (The solar system is, in fact, running down, but rather slowly, on a time scale of millions of years.)

2. Because of the Pauli principle you can have only one electron in each state. As electrons are available in *spin-up* and *spin-down* versions, this effectively doubles the number of states. Electrons will fall into the atomic states because they have lower energy there and it is a general rule that things tend to fall to lower energy levels (as you may discover by holding a cup over a tiled floor and releasing it). Any atom has a large number of levels which could hold electrons; in fact, the number of states is infinite, though the upper ones are very close together in energy. An atom will continue to attract electrons into its levels only until it contains the correct number to compensate the positive charge of its nucleus, after which the atom no longer has any surplus positive charge with which to attract further electrons. When an atom has reached its full complement of electrons, it will in almost all cases contain more than there are room for in the state of lowest energy. Some electrons must then be accommodated in states of higher energy.

3. When people looked at the light given off by atoms of a single type, they found that the spectrum was not a uniform spread of colors like a rainbow, but a set of sharp lines, each of a distinct color. Every type of atom showed these *line spectra*, which were a complete mystery to classical physics.

The set of energy levels for the electrons is unique to any given type of atom. When electrons transfer from one level to another they emit photons which have an energy that corresponds to the difference in the energy of the two levels. As the energy of photons is proportional to the frequency and color of the light, this gives an optical line spectrum for the atoms which is as distinctive as a fingerprint.

The explanation of the existence of a line spectrum was the first major success of the developing quantum theory. The theory fitted the observed line frequencies and predicted other line spectra which had not been seen. These where all found in due course and showed that the quantum theory could not readily be dismissed.

CHAPTER 8 Castle Rutherford

Alice stood gazing up at the dark heights of Castle Rutherford as it loomed overhead. "Where did that come from?" she asked her companion. "How did we get here from the atom's potential well?"

"I have to tell you that during no time are we going anywhere. We are remaining strictly in the vicinity of the atom, but are now somewhat localized in its center or indeed rather more than somewhat. What you see before you is the bottom of the same potential well. Do you not recognize that same item?"

"No, I certainly do not!" replied Alice emphatically. "The potential well was a *well*; it was a hole which went downward. This is a tower which goes upward. Quite a different thing."

"It is by no means so very different when you think about it," replied the photon. "The Nucleus is producing an electric field, and this same Nucleus gives a negative potential energy to any negative electrons which are in the locality. When you are mixing in such company, as with electrons and so on, you are naturally seeing the potential as a pit going downward. Nuclear particles like protons are such particles as carry a positive charge at all times, so if guys like these should come calling unexpectedly, they are liable to find their potential energy is rising more than somewhat as they approach the Nucleus. This will usually make characters like this keep a polite distance, and the field acts like a barrier. In fact, it is for this reason it is called the coulomb barrier. The nucleons are apt to hate having uninvited visitors. If you are mixing with characters of this sort, you are seeing what they are seeing, which is a high potential wall around the Nucleus."

"How shall I get in then?" asked Alice. "I do not think I shall be able to get over the wall. I am sure it will be very effective at making me keep a polite distance," she argued hopefully. She was still not at all sure that she wanted to meet the Nuclear Family.

At the center of each atom is a tiny atomic nucleus. This contains most of the mass of the whole atom, though it is only about one hundred-thousandth of its diameter. The nucleus carries a positive electric charge which attracts the negatively charged electrons and holds the atom together. This positive charge will, on the other hand, repel other positively charged particles and provide a barrier around the nucleus, the *coulomb barrier*, which keeps out protons and other nuclei.

"The coulomb barrier is acting to keep out only those same particles which have a positive electric charge. There are others that do not have any electric charge at all, and these particles can pass through easily. You are not carrying a charge at present, so you are liable to get in through the neutral particle entrance." He pointed toward a tall doorway in the bottom of the castle wall, which Alice had not noticed before. It was obligingly labeled: "Neutral Particles Only."

Alice and her escort went over to the door and knocked loudly. "What are the nuclear particles like?" asked Alice cautiously. Are they much the same as the electrons I have already met?"

"They are commonly considered by one and all to be bigger than any electrons and are known to be about two thousand times more massive." This answer did nothing at all to reduce Alice's feeling of nervousness as she heard slow, ponderous footsteps approaching the door from within. These grew louder until she fancied she could feel the ground tremble slightly with each footfall. Finally they stopped and the tall door began to swing slowly inward. Alice looked up nervously to catch her first sight of this monster which had summoned her. Finally the door was completely open and still she could see nothing. Were the nucleons invisible?

"Here I am," snapped an irritated voice, from somewhere below the level of Alice's knees. Startled, she looked down and there, standing in front of her, was a small figure. It looked not unlike the electrons she had seen before, except that somehow there was an aura of power about it and, like her companion, it was wearing dark glasses. However, when Alice remembered how far she had shrunk on her way to Castle Rutherford, she realized that this figure must be far, far smaller than the electrons had appeared to her before.

"I thought you told me that the nucleons were larger than the electrons!" she exclaimed, turning indignantly to the photon. She felt angry that she had been so deceived.

"Why, most informed citizens agree that they are indeed larger and I am sure you would not wish to question my word over so small a matter. Of course the nucleons are much heavier than the electrons and so they are inclined to be that much more localized. As they are two thousand times heavier, they naturally have two thousand times more rest mass energy, and it is widely accepted that they are in the region of two thousand times more localized, even when they are having the same energy as an electron type guy. This means that they are apt to occupy less space and so they may *seem* to be smaller than the electrons, but informed opinion is that they are in actual fact larger.

"Compared to the citizens of the Nucleus, the atomic electrons are such parties as have very little energy or momentum at all and are by no means well localized. They form considerable electron clouds which hang around in the vicinity of the nucleus and are very large indeed. They spread out over a volume which is hundreds of thousands of times farther across than the same nucleus." As Alice looked around she could see great gray clouds surrounding them, clouds which stretched away as far as the eye could see. It was strange to think that these were the electrons that she had seen so often before, but now seen from the viewpoint of a much more compact scale.

The neutron which had greeted them (for such it was) was becoming increasingly impatient with this exchange. "Don't just stand there, whoever you may be," it snapped querulously. "Come closer so that I can identify you."

"Why, he cannot see us," realized Alice. I do believe that he is blind!"

"All neutrons are in such condition, as most people admit," replied her escort. "These parties are not such as have any interaction with photons, or hardly any, having no electric charge of their own. Neutrons are citizens who do not have much long-range interaction whatsoever, being only given to interactions of very short range indeed. Such a party is not much at recognizing others until they are close enough to touch."

They moved up close to the neutron until he bumped into them. "Ah, there you are!" he exclaimed sharply. "Come in and let me shut the door. It is much cosier inside." He ignored the photon, of whom he was largely unaware. Alice was interested to note that the photon simply faded into the castle's fortifications, which were after all composed of the virtual photons emitted by the charge of the Nucleus.

Alice followed the neutron into the Castle while he felt his way down a rough stone corridor. This passage was very narrow, but seemed obligingly to widen at their approach so that there was always just enough room to pass through. Alice found this behavior rather eerie, but she was never sufficiently sure that it was actually happening to make any comment. Now that she had met him, the nucleon whom she was following did not seem as threatening as she had feared. Impatient yes, but not in any way *sinister*. He reminded Alice of a distant uncle of hers.

Together they entered a tall vaulted central chamber of bare stone. The walls rose sheer on every side and vanished into the shadows of the ceiling. Around the walls overhead were arched openings leading to various higher levels, vaguely reminiscent of the electron energy levels that Alice had seen in the atom outside. The floor area was of moderate size and was crowded with as many particles as it could contain, but as Alice and her companion entered she clearly observed that the massive stone walls drew back slightly to create just the right amount of extra space needed to accommodate the new occupants.

Alice was quite sure of what she had seen this time and commented on the movement. "That is the effect of the self-consistent field within the castle," she was told.

"Like electrons and all other particles, we nucleons have to occupy quantum states, and the available states here are controlled by the local potential well. In the case of the electrons in the atom, that potential well is provided by *us*. The electron states are fixed by the electrical potential and we control that potential. The atom is our territory and the potential energy of the electrons within it is controlled by their distance from the positive electric charge of the protons in the central Nucleus. By means of the electrical potential produced by this charge, we in the Nucleus control the electron states, and the electrons must fit into them as best they can. In our own case the situation is different. We ourselves provide the potential for our own nuclear states."

"If you provide the potential in both cases, surely that makes the two cases the same," protested Alice.

"No, it makes the two cases quite different. You see, in the atom the potential is provided mostly by the Nucleus so that the Nucleus controls the states although the nucleons do not themselves make use of them. The potential controls the states which give the probability distributions for the electrons, but the electrons which use them have little effect on the potential. The atomic potential is much the same wherever the electrons may happen to be."

"For the Nucleus, on the other hand, the potential that we are now in is produced by the collective effort of all the nucleons within it. We have a very democratic system ourselves, though we rule the electrons autocratically. Our collective potential fixes the states which are available for us nucleons to occupy and so controls our probability distribution. This distribution subsequently controls the potential, as I said at the beginning. It is a vicious circle, as you might expect for the Nuclear Family, and you can see that the states we inhabit will naturally change as the distribution of nucleons changes."

"Is the nuclear potential produced by the same electric charge as the potential which holds the electrons?" asked Alice, who thought that she should get this point clear in her mind.

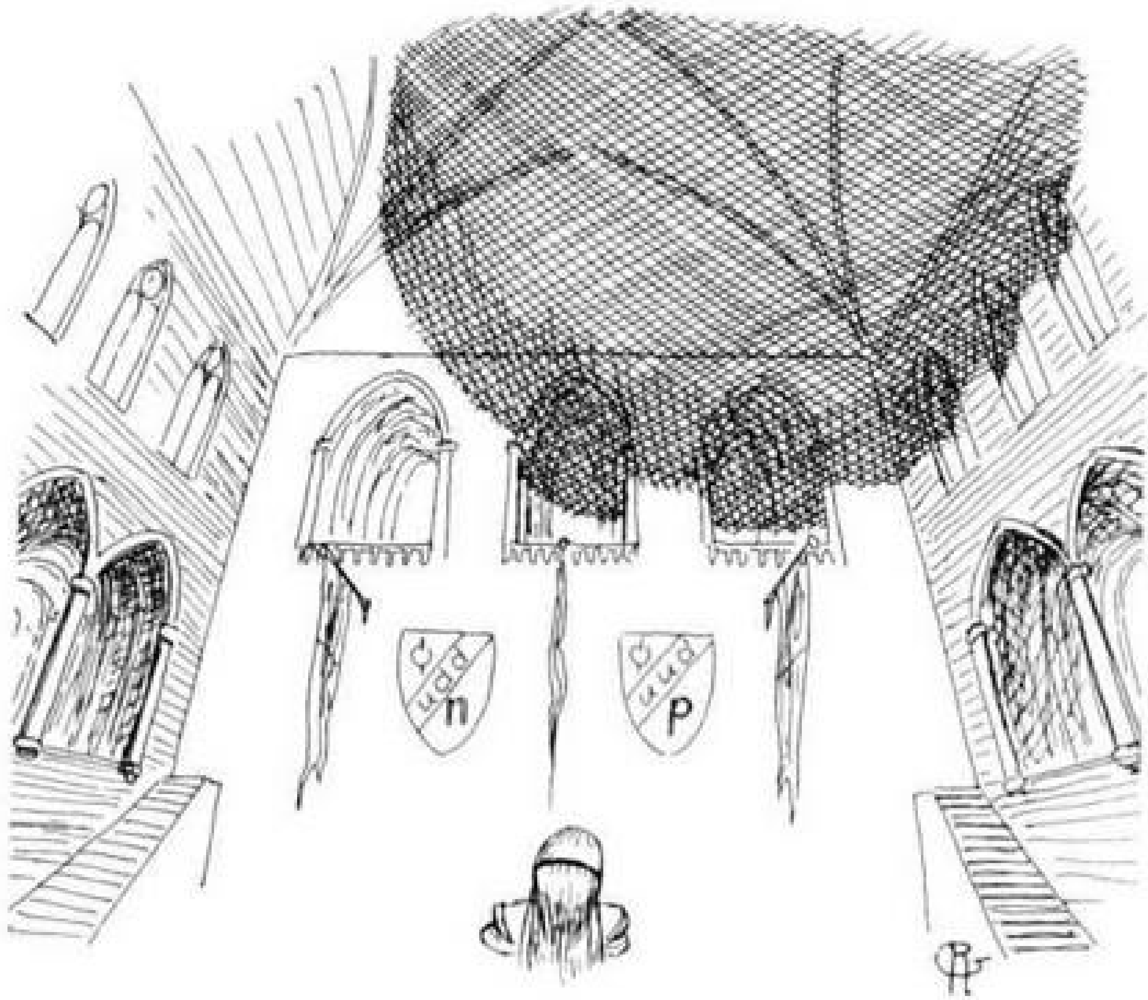
"Oh no, quite the reverse in fact. The electric charge in the nucleus is all carried by protons. You are bound to see some protons over there." He waved in the direction of the nearby particles. Alice glanced over and could see more neutrons, which looked just like her companion. Scattered among them were some other particles which looked distinctly more assertive. Where the neutron had been slightly irritable, these appeared to be in a state of barely suppressed fury. "The protons all carry positive charges, and particles which have the same sort of charge repel one another, you know. Protons are forever flying into a temper with each other and threatening to rush off. It is very difficult to keep them together, I can tell you."

"Don't the electrons have the same problem then? I should have thought that they would. If all electrons have a negative electric charge, then any two of them will have the same sort of charge and should repel one another."

"That is quite true; they do repel one another. However, you must realize that the electrons are relatively spread out and diffuse, and their charges are widely separated, so the repulsion they produce is fairly weak. The attractive force from the concentrated positive charge in the Nucleus is able to keep them in order. The protons in the Nucleus are crowded close together, so their repulsive force is very strong. The electrical forces threaten to tear the Nucleus apart."

See end-of-chapter note 1

"In that case what does keep you all together?" asked Alice reasonably.



"That is achieved by a completely different force, a strong force—in fact, the *strong nuclear interaction* is what it is called.

"The strong nuclear interaction is very powerful. It is able to overcome the disruptive electrical repulsion within the nucleus, even though it has no obvious effects outside the nucleus. It is a *short-range* force you see. Inside the Nucleus the nuclear forces are dominant, but outside there is little sign of them, and all that anyone sees is the electrical field due to the positive charges carried by the protons. We nucleons hold firmly onto our immediate neighbors when they are within reach, but we are not really aware of those farther away in the crowd and have very little effect on them."

Ever since she had entered the central hall of the castle, Alice had felt rather uncomfortable. Now she experienced a peculiarly eerie feeling and sensed that something was now in the chamber which had not been there just before. She looked around her and could see nothing. Then she looked upward toward the ceiling. She dimly perceived the great curved flank of some vast rounded shape which passed through the dim shadows of the soaring space above her head. It was obviously but a small part of some much larger object which looked vague and tenuous, like a ghost, and which was drifting through the surrounding walls as if they did not exist.

Alice exclaimed aloud, and then she had to describe what she was seeing to the neutron, who had not been able to see it of course. "Ah, that will be an electron," he said. "They fill the entire volume of the atom you know, which means that they pass through the Nucleus as well as elsewhere. Electrons are completely unaffected by the strong interaction, so they are not aware of us when they do pass through. The nucleus is a tiny part of the volume occupied by electrons, so we do not see very much of them here. Well, actually I do not see them at all, but you know what I mean."

"Is this strong interaction not caused by photons then?" Alice inquired. She had been told that photon exchange held atoms together, but she had understood that that was due to the interaction between electric charges, and she gathered that this was something quite different.

"You are right, it is nothing to do with photons. It *is* caused by particle exchange—all interactions are—but it involves a different sort of particle. The strong interaction is in fact caused by the exchange of many different particles, the most evident of these being called pions. These are of necessity bosons, as they are created and destroyed during the exchange process. Pions have much greater mass than photons. Indeed photons do not have any mass at all, which makes them quite inexpensive to create, in energy terms. Pions have a mass about three hundred times that of an electron. They may still be created using an energy fluctuation, as allowed by the Heisenberg relation, but the fluctuation must be very large to provide the rest-mass energy of the pion, so it cannot last for long. In the available time the pions cannot get far from their source, so they can only be exchanged with particles which are close at hand, almost touching in fact. The strong interaction is consequently of very short range."

At this point a disturbance broke out. Two of the protons had had a sudden and violent argument and were threatening to storm off in opposite directions. Neutrons rushed in to separate the contestants and keep them well apart, so diluting the strength of their mutual repulsion. While the neutrons crowded between the protons to increase their separation, they also grasped them firmly to hold them within the Nucleus.

"You see how we neutrons are necessary to hold the Nucleus together, particularly in the larger nuclei," remarked a neutron. "In a Nucleus every proton repels every other proton, not just those immediately next to them, as is the case for the strong interaction. The repulsion rises rapidly with the number of protons in the Nucleus, and this means that heavy nuclei, which have a large number of protons, need proportionately more neutrons to keep them well away from one another so that their repulsion does not overwhelm the attractive force exerted by their immediate neighbors.

"The Family of nucleons comes from two distinct clans, the protons and the neutrons. The lineage displayed on the wall over there shows how they combine." He indicated a large diagram hanging on the wall, among various other symbols and heraldic decorations. This showed a large and fanciful drawing of a proton and a neutron at the top two corners of the chart. Down the center were listed all the different nuclei in which the Family were involved. Alice saw that they were identified by the same labels that she had seen marking the different atoms at the Mendeleev Marina. On close examination she noted that the labels were slightly different: There was another number given for each one. Now the nuclei were given as, ${}_1H^1$, ${}_2He^4$, ${}_3Li^7$ and so on.

From the original proton and neutron at the top of the picture, lines were drawn to the various nuclei listed. There was one line from the proton to the $_1H^1$ nucleus and no line at all from the neutron. To the $_2He^4$ nucleus there were two lines from the proton and two from the neutron. Thereafter many nuclei had approximately equal numbers of lines from the proton and from the neutron. As Alice looked toward the bottom of the chart she saw that each nucleus depicted there had many more neutron lines than proton ones.

"That chart shows how the different nuclei are populated from the two distinct clans of nucleons. The first number tells you the number of protons involved. This is the same as the number of electrons which can be controlled and hence decides the chemical behavior of the atom. The second number gives the total number of nucleons which populate a given Nucleus.

"Lighter nuclei have the same numbers of protons as of neutrons. A carbon nucleus, for instance, contains six protons and six neutrons. The repulsion given by six protons, each repelled by every single one of the five other protons, is still not enough to overcome the attraction caused by the strong interaction. Here in our uranium Nucleus, on the other hand, we have 92 protons. The repulsive force between all the different pairs of protons is now very large, so a relatively large number of neutrons is needed to keep the protons apart and dilute their electrical repulsion. In our Nucleus we have all of 143 neutrons. The number of neutrons need not be quite the same in every uranium nucleus. For a given element the number of protons is always the same, since this fixes the number of electrons and hence the chemical behavior, but the number of neutrons does not have much effect on the chemistry of the atom and can vary slightly from one Nucleus to another. Nuclei of an element which have different numbers of neutrons are known as *isotopes*. We have 143 neutrons in this Nucleus, as I said, but many uranium nuclei have 146, which makes them a little more stable."

"I have heard of stability before," said Alice. "I thought that atoms were completely unvarying, and, although they might take part in different compounds, the atoms themselves last forever."

"Not entirely. The walls of the nuclear potential barrier serve to keep us inside, just as the coulomb barrier keeps other protons out. Occasionally, however, there is penetration, and the Nucleus is changed in some way. It works both ways; particles outside the Nucleus might break in, or some from among our complement may try to escape.

"The reason that protons and neutrons stay in the Nucleus is the same as the reason that electrons stay in the atom: because they require less energy where they are than they would if they were outside. The decrease in energy from the value they would have outside the Nucleus is called the nuclear *binding energy*, or BE. There are energy levels for nucleons within the Nucleus in much the same way as for electrons in the atom, and, as neutrons are not identical to protons, these levels may be filled with neutrons and with protons independently. Because the levelfilling process is the same for neutrons and protons, stable nuclei tend to have equal numbers of the two types. For the heavier nuclei, which have larger numbers of protons, the proportion of neutrons is greater, as I have described already. For all nuclei there is a ratio of protons to neutrons which gives the most stable atom. An excess of either type will give a tendency to instability and some form of decay. I am forced to admit that, in uranium, the repulsion between the protons is so great that the Nucleus is barely stable at the best of times. Any disruption of the balance between protons and neutrons could well be disastrous."

Suddenly an alarm trumpet sounded and a strident voice echoed through the vaulted chamber. "Alert! Alert! Condition Alpha. We have an escape attempt in process."

In large nuclei with many nucleons the repulsion between all the protons becomes proportionately stronger and the nuclei may be *unstable*. They may undergo *radioactive decay*, where the nucleus emits an α particle, which is a tightly bound group of two neutrons and two protons which penetrate through the coulomb barrier. Neutrons may also undergo β (beta) decay, where an electron is created within the nucleus and immediately escapes because electrons are not affected by the strong interaction. Nuclei may also emit Γ's (gammas), which are just high-energy photons.

Alice looked around to see if she could see any cause for this alarm. Everything looked much as before. There was considerable movement among the assembled nucleons, but then they, like other particles which she had encountered, were always in continual agitation, so that was nothing new. As she watched carefully she noticed that a small group of particles, two protons and two neutrons, were moving together through the crowd, holding tightly to one another. They would rush up to the wall, collide with it and bounce back, and rush across the chamber to collide with the opposite wall. Alice was strongly reminded of the person she had seen trying to penetrate his locked door when she first arrived in Quantumland.

She commented on this to her companion, and he replied, "That is alpha particle clustering that you are describing. An alpha particle is a group of two protons and two neutrons which will bind together so tightly that they act as one particle. As it contains two protons the alpha particle is repelled by the overall positive charge of the protons and is trying to escape, but is prevented by the wall around the nucleus. The group is trying to *tunnel* out. They are planning to escape by barrier penetration, and sooner or later, of course, they will succeed."

"How long is it likely to take them to manage it?" asked Alice curiously.

"Oh a few thousand years, I should think."

"Don't you think it is a bit premature to sound the alarm then?" inquired Alice. "It sounds to me as if you have plenty of time to deal with such an escape without having to panic!"

"Ah, but we cannot be sure of that. It will *probably* take them thousands of years to escape, but they *might* get out at any moment. There is no way of being sure; it is all a matter of probability."

"Are all escapes from the Nucleus by barrier penetration then?" asked Alice.

"Not at all. Alpha emission is by barrier penetration, as I have just stated. We also get beta and gamma emission, and neither of those requires barrier penetration."

"What are they, then?" asked Alice dutifully. She suspected that she was about to be told whether or not she asked, but it seemed more polite to inquire.

"Gamma emission is photon emission, much as you get from the electrons in the atom. When an electron has been excited to a high state and then drops back to a lower one, it will emit a photon to carry off the energy released. The same thing happens when an excitation of the nucleus rearranges the charged protons: A photon is emitted when the nucleus returns to the state of lower energy. Because the interaction energies in the nucleus are so much greater than in the atom generally, the gamma photons have much higher energy than those from the atomic electrons. Indeed they will have some hundred thousand times more energy, but they are still photons.

"Beta emission is the emission of an electron from the Nucleus," her informant continued.

"I thought you said that there were no electrons in the Nucleus," protested Alice. "You said that the electrons were not aware of the strong interaction and just drifted through occasionally."

"That is quite true. There are no electrons in the Nucleus."

"If the Nucleus cannot hold electrons and there are no electrons in the Nucleus," said Alice patiently, "how can one escape from it? That does not make any sense. It cannot escape unless it is there to begin with."

"It is because the Nucleus cannot hold electrons that they *do* escape from it so readily. The electrons are produced right inside the Nucleus in a weak interaction, and, of course, as the Nucleus cannot hold them they immediately escape. It is quite straightforward when you think about it," said the neutron kindly.

"That may be," said Alice, who felt that it was not *at all* clear yet, "but what is a weak interaction? How do the electrons... ?"

Once again a trumpet sounded and a herald somewhere in the top of the chamber cried out. "Attention everyone. The Castle is under attack! We are besieged by a hot plasma of charged particles."

"Oh dear!" cried Alice. "That sounds serious."

"No, it isn't really," replied a nearby neutron soothingly. "None of the charged particles in the plasma are likely to have enough energy to breach our defenses. Come and see."

He led Alice up through the various galleries and energy levels within the Castle until they came to a position from which Alice could view the outside. She saw other nuclear castles in the distance and, spread across the plain, a number of protons moving quickly around. "Those protons are from a hot hydrogen plasma," Alice's companion told her. "In a plasma the atoms have lost some of their electrons and become positive ions with an overall positive charge. The nucleus of hydrogen contains only a single proton, so when a hydrogen atom loses its electron there is nothing left but a proton. Plasmas can be made very hot, and then the protons rush about with a lot of energy, but not enough for them to break in here," he finished complacently.

Alice watched as some protons came running toward a nucleus and on up the curving base of its wall. As they rushed upward they moved more and more slowly as they lost their kinetic energy, eventually coming to a halt a short way up the wall. From that point they slipped back down again and rushed off in a different direction than that from which they had come.

"You will see, even if I can't, that they are having no success at all at actually getting inside," continued Alice's guide.

"Could they not get in by barrier penetration then?" asked Alice.

"Well, yes. They could in *principle*, but they spend so little time near the Nucleus that it is really most unlikely."

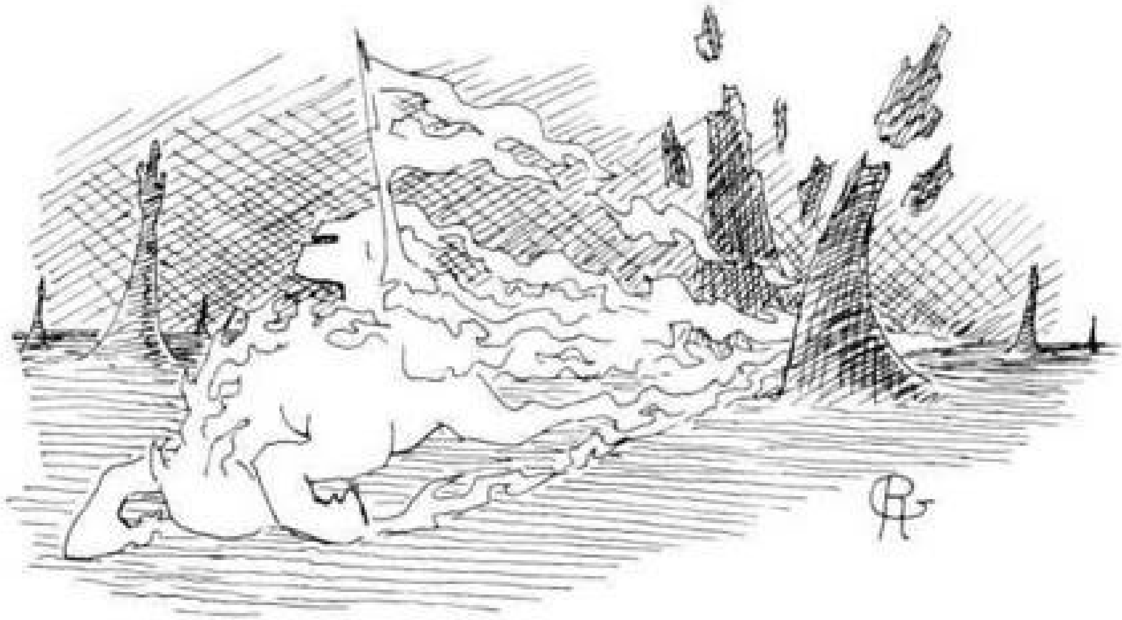
At this point Alice noticed a disturbance in the distance. Something was getting closer at a most remarkable speed. "What is that approaching?" she asked, rather anxiously.

"I have no idea," answered the neutron. "Is there something approaching?"

Alice realized that the neutron would naturally be unaware of the approach of the fast charged particle as it came galloping up, with plumes of scarcely seen virtual photons trailing from it in its whirlwind passage. As Alice was describing its appearance to the neutron, the newcomer arrived at a Castle in his path. With little apparent reduction in his mad onward rush, he ran up the barrier wall and over the top. A moment later Alice saw him galloping off into the distance, apparently little affected by his encounter. She could not say the same for the Nucleus he had entered. This had burst completely asunder, and large portions of it were flying off in different directions. Alice completed her description of the event.

"Ah, that would be a Cosmic Ray-der. We very occasionally get one passing by. They come from somewhere way outside our world and they have enormous energy. To them the energy needed to cross the coulomb barrier of a Nucleus is as nothing and it presents no barrier at all. We have no defense against them, but fortunately they are, as I said, very rare."

Looking down on the area outside Alice could make out a few unobtrusive figures moving quite slowly and stealthily about. "Oh look!" she cried, forgetting who her companion was. "There are some neutrons moving about out there."



"What?" cried the neutron by her side. "Are you sure? This is serious. Come, we must get down to the main hall at once."

He rushed Alice back down through the successive energy levels to the hall she had first entered, ignoring her protest that there had not been very many neutrons outside and that they had not had much energy at all, really.

Hardly had they arrived when, without warning, an invading neutron popped right through the wall and landed in the middle of the chamber, on top of all the other particles. This was not one of the normal occupants of the Nucleus, but one of the foreign neutrons which had come in from outside. Alice remembered that the virtual photon had told her how the coulomb barrier had no effect on neutral particles and how she herself had come in through the barrier without difficulty. In the same way this neutron had entered uninvited.

There was immediately a great bustle and panic among all the nucleons. They rushed to-and-fro in consternation, surging from one gallery to the next, calling out that the stability of the nucleus had been totally upset by the addition of this excess neutron. As they surged to-and-fro, Alice was much alarmed to discover that the whole room was shaking violently in sympathy. The massive stone walls were quivering like a vibrating drop of liquid. One moment the chamber would be square and compact, the next it would stretch out very long and thin. A narrow neck formed in the middle close to where Alice was standing, so that the room was almost separated in two. Back and forth the walls swung, and each time the room became narrower and narrower at the midpoint. The room stretched out for a last time. Alice saw the far walls rushing away in opposite directions while the nearer walls came closing in as if they were going to crush her and the particles which were in her vicinity. Previously the movement had always reversed before the gap closed, but this time the walls clashed together, just where Alice was standing together with a few neutrons.

The electrical potential of the nucleus gives a coulomb barrier which repels positively charged particles. Protons of low energy are unable to pass above this barrier. They could in principle pass *through* it by barrier penetrtation, but the probability of this is low as they are only passing by and have only a fleeting interaction with the nucleus. Some particles in cosmic radiation have sufficient energy to overcome the barrier and can readily pass through, giving enough energy to the nucleus in passing to disrupt it completely.

Neutrons do not have any electrical charge, so for them the barrier does not exist. A neutron which happens to collide with a nucleus can pass straight through.

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When the walls had moved through her, Alice found that she was back on the plain outside the Castle. She looked back toward it and saw that the tall, dark tower was split by a fissure which ran all the way down its middle. As she watched, the Castle was torn into two half towers, which slumped apart. Each one was shaking violently, its outer surface vibrating wildly like a bag full of jelly. High-energy photons soared from the two castles like some dramatic fireworks display as both of them shed their surplus energy. Gradually the shaking died down and both the irregular shapes flowed into the same tall soaring shape which she had first seen. Two smaller replicas of Castle Rutherford now stood before her, except that they did not stand but slid rapidly away from one another, driven by the positive charge which they had previously shared between them.

"Come, I am glad that is over. It was really rather frightening," Alice admitted to herself. As she looked around the now quiet landscape she could see a few neutrons which had been ejected with her from the Castle when it had split in two. They spread out over the plane, rushing off in random directions. As she watched, one arrived by chance at the distant shape of another nuclear castle and promptly dived into it through its side.

For a short time nothing appeared to happen. Then she could see this castle also begin to shake. The shaking increased until suddenly the castle split down the middle. "Oh no!" cried Alice in dismay as she saw the two halves thrust apart, spitting out energetic photons. Almost unnoticed, a fresh group of neutrons ran away from the scene of the catastrophe.

Before much time had passed, a couple of the neutrons which were now roaming aimlessly around the plain had chanced upon and entered other nuclei. Again the process repeated, ending once again with these nuclei splitting, more gamma photons pouring onto the scene, and more neutrons being ejected to roam around in confusion. Again and again the process was repeated. Soon there were four nuclei all in the pangs of separation, then ten, twenty, fifty. All around her, Alice could see nuclear castles falling apart in fiery fission, while overhead the scene blazed with the intense, vivid radiation of high-energy photons.

"This is terrible!" cried Alice in horror. "Whatever can be happening?"

"Do not worry, Alice," said a calm voice by her side. "It is only induced nuclear fission. A chain reaction, you know. It is nothing for you to worry about. It is just that you are standing in the middle of what, in your world, would be called a nuclear explosion."

Alice whirled around and saw the mild features of the Quantum Mechanic. "You do not have to worry," he said again. "The energies involved in a fission reaction are less than those you have already met within the Nucleus itself. The only problem is that they are no longer confined within the Nucleus. I have been looking for you," he continued, still calmly, "as I have an invitation to give you."

He presented Alice with a stiff, ornately engraved invitation card. "It is an invitation to the Particle MASSquerade, a party which is being held for all the elementary particles," he said.


We hereby Invite
Alice
to attend at a
Particle

Some nuclei may split into two smaller and more stable nuclei, a process known as *nuclear fission*. This may be caused by the addition of an extra neutron, which is not kept out by the coulomb barrier and is the "last straw" for an already unstable nucleus. The fission may release several other neutrons, leading to a *chain reaction*.

Notes

1. Almost everything in the physical world may be seen as caused by the interplay between electrons and photons, virtual or otherwise. The properties of solids, of individual atoms, and of the chemical behavior which comes from the interplay between atoms, all reduce to an electrical interaction between electrons. As well as the electrons which interact with the rest of the world, there is within the atom a positively charged nucleus. The nucleus is not held together by electrical forces, quite the reverse in fact.

The atomic nucleus contains neutrons, which have no electrical charge, and protons which are positively charged. Within the small space of the nucleus, whose radius is typically a hundred thousand times smaller than the overall size of an atom, the mutual repulsive force of the protons is enormous. This electrical force tends to tear the nucleus apart, so there must be an even stronger force which holds the nucleus together, one that, for some reason, is not evident elsewhere. Such a force exists, and it is called the *strong nuclear interaction*. Although it is strong, it has a very short range, so that its effects are not obvious outside the nucleus. This strong interaction is produced by the exchange of virtual particles, just as the electrical interaction is produced by photon exchange. Photons have no rest mass, but the exchanged particles in the strong interaction are relatively heavy. They must get their rest mass energy through a particularly large quantum fluctuation, which is only possible for a very short time. Such heavy virtual particles are very short-lived and unable to travel far from their source, so that the interaction they produce is consequently of short range.

CHAPTER

9 The Particle MASSquerade

Clutching her invitation, Alice climbed up the broad stone steps which led to the tall polished door. She could not remember how she had come to be there, though she remembered being given the invitation. "So I expect this is probably the right place for the MASSquerade, whatever that may be," she said to herself encouragingly. "I always seem to end up somehow where people want me to be."

She stopped outside the door and examined it. Its paint was very smooth and glossy, deep red in color. It had a shiny brass doorknob and an equally shiny brass knocker in the shape of a grotesque face. It was also closed and locked. Cheerful candlelight streamed from the keyhole and Alice could hear loud music being played within.

How was she to enter? The answer seemed obvious enough, so she firmly grasped the knocker and hammered loudly.

"Ow! Do you mind!" exclaimed an anguished voice from close at hand. Literally at hand, in fact. Alice stared in surprise at the door, to meet the furious glare of an irate door knocker.

"That was my nose!" it exclaimed indignantly. "What do you want anyway?"

"I am really sorry," said Alice, "but I thought that, as you *are* a door knocker, I might use you to knock at the door. How am I to get in if I do not knock?" she asked plaintively.

"There's no use in knocking," said the knocker huffily. "They are making such a noise inside no one could possibly hear you." And certainly there was a great deal of noise going on within: a buzz of conversation, a louder voice speaking above the rest, but still not quite audible through the door, and, above it all, the sound of the music.

"How am Ito get in then?" asked Alice, in some frustration.

"Are you to get in at all?" said the door knocker. "That's the first question, you know."

It was, no doubt, but Alice did not like to be told so. "It is really dreadful," she muttered to herself, "the way everyone will argue so." Raising her voice she addressed the knocker, though she felt a little self-conscious in talking to a door knocker at all. "I have an invitation," she said, holding it up in front of his face.

"So I see," replied the knocker. "That is an invitation to the Particle MASSquerade, which is a function for particles only. Are you a particle?"

"I am sure that I don't know," declared Alice. "I did not think that I was, but with all the things that have happened to me, I am beginning to feel that I must be."

"Well, let me see if you meet the requirements," said the knocker, rather more agreeably now that its nose felt recovered. "Let me just look at my notes for a moment." Alice did not see how a door knocker could keep notes, let alone look at them, but after a short pause the knocker continued. "Ah, yes. Here we are. The list of specifications to define a particle."

"One," it read out. "Whenever you are observed, are you invariably observed in a reasonably well-defined position?"

"Yes, I think so, as far as I know," answered Alice.

"That's fine," said the knocker encouragingly.

"Two. Do you have a unique and well-defined mass—apart from the normal fluctuations, of course."

"Well, yes. My weight has not changed very much for some time." That was what Alice believed, at any rate.

"Good, that is a very important requirement. All the different particles have their particular masses. It is one of their most distinctive features and very useful when it comes to telling one particle from another." Alice was rather taken with the notion that people might be identified by weighing them rather than looking at their faces, but she realized that particles did not on the whole have anything very definite in the way of faces.

"Three. Are you stable?"

"I beg your pardon?" said Alice, feeling distinctly affronted.

"I said, 'Are you stable?' It is a simple enough question. Or at least it ought to be: The requirement has become increasingly blurred recently. It used to mean quite simply, 'Do you decay to something else?' If you were likely to decay at any time in the future, then you were unstable, and that was that. But that wasn't good enough! People started to say, 'We cannot be sure that anything lives forever, so a distinct state that exists for a long enough time can be classed as a particle.' Then the question is, 'What counts as long enough?' Is it years, or seconds, or what? At the moment they accept lifetimes of less than a hundred million millionth of a second as being stable," he finished disgustedly. "So, I must now ask you: Do you expect to survive for longer than a hundred million millionth of a second?"

There are many strongly interacting particles as well as the proton and the neutron. It is not all that easy to distinguish one type of particle from another. Some have different electric charges, but there are many with the same charge. Particles are usually distinguished in practice by measuring their masses, which are fairly distinctive. Most of the particles are to some degree unstable: a heavier particle decaying into lighter ones. Outside of a nucleus even the neutron is unstable, with a mean lifetime of about 20 minutes.

"Oh yes, I should think so," answered Alice confidently.

"Good, then I can count you as a stable particle. You had better go inside. You may not have anything better to do than stand about out here, but I have," grumbled the door knocker. There was a click and the door swung open. Alice lost no time in passing through it.

Inside she walked through an elegant entrance hall, with pale paneled walls, chandeliers, and alcoves containing statues. As they were all statues of notable particles, it was rather difficult for Alice to make out much detail. She thought it was rather clever the way the sculptor had managed to make the features of a statue appear so vague and unlocalized. In fact, to the uninitiated, they looked much like shapeless pieces of stone.

Beyond the entrance hall Alice entered a large room, which seemed to be a main ballroom or salon. It was lit by ornamental chandeliers hanging from the ceiling, but somehow they did not give much light and the room was mostly in shadow. The shadows were made more intense by contrast with a few bright spotlights which spun around the room. One came to rest in a circle of light immediately in front of Alice. Into the center of this circle leaped a figure clad much like the joker in a pack of cards. His ridiculously cut costume was gaily striped in red, blue, and green. On closer examination, Alice saw that it was also striped in *antired*, *antiblue*, and *antigreen*. Alice had never seen such colors before. (Unfortunately this book does not have colored illustrations, so you cannot see what these colors look like.) His fantastic appearance was completed by a mask, which was set in an unbelievably wide permanent smile.

He addressed Alice. "Bon soir, mademoiselle. Guten Abend, Fraulein. Good evening, young lady. Willkommen. Bienvenue. Welcome. Welcome to the MASSquerade."

"Thank you," replied Alice. "But who are you and what is a MASSquerade?"

"I am the Master of Ceremonies for this MASSquerade," he replied, "which is the Masked Dance of the Particles. An evening of Revelry and Revelation. An Exploration of the Mystery behind the Mask. The particles all come here to whirl about in joyous dance and, at suitable occasions, they unmask. Your mask, if I may say so, is particularly inspired," he added.

"I am not wearing a mask," said Alice coldly.

"Ah, but can you be certain of that? We all wear masks of some sort. Why, tonight we have had two unmaskings already."

"I do not see how that can be," challenged Alice. "You can only unmask once. You are either wearing a mask or you are not, surely."

"Why, it depends how many masks you wear. Particles can wear many masks. At the beginning of the evening we had a group of atoms, and then these unmasked to reveal themselves as a crowd of electrons and a number of nuclei. Later in the evening we had a further time of unmasking and the nuclei shed their disguise to show that they were actually neutrons and protons, with a sprinkling of pions among them. I confidently anticipate that there will be further revelations before the night is over.

"But now," he cried out in a voice suddenly loud enough to carry throughout the whole room, "on with the festivities! Mesdames et Messieurs, Damen and Herren, Ladies and Gentlemen, I pray you to step lively in a Collider-Dance."

There was a bustle of movement and Alice saw that the assembled particles were beginning to circulate around the room. She could not truly say that they were dancing, but they were certainly going around and around, with ever-increasing speed. The main problem was that there seemed to be no general agreement on the *direction* in which they were to circulate, so some went round one way and some the other.

Faster and faster the circulating bunches of particles rushed through one another. Before long the inevitable happened and two particles collided with a great crash. Alice looked over in concern to see if they had been hurt in the collision. She could not really determine whether they had been hurt, but they were certainly not the same after their interaction. She saw several small pions rush away from the collision, which she did not believe had been there before, and the colliding particles themselves were changed into something quite new. They were larger and somewhat more exotic particles than they had been-definitely they were not the same.

The dance continued and there were further collisions, more and more as time went on. With every one which took place, relatively familiar nuclear particles changed to something new and strange. Soon there was a bewildering variety of different particles present-far more types than Alice had seen before or than she had imagined to exist.

"A marvelous sight, is it not?" inquired a voice by Alice's ear. It was the Master of Ceremonies, his grinning mask a mere arm's length away. "Such a fine hadronic assembly of particulate revelers. Such a splendor of baryonic variety. Why, I do believe that there are now no two of them the same!"

Alice did not understand many of the words he had used and felt that it was wisest not to ask about them. She wanted to know, as simply as possible, just what had been happening. "Where have all these new types of particles come from?" she asked.

Particles may be created in collision processes, the kinetic energy of the colliding particles being converted to produce the rest mass energy of the new particles. Very many such particles were discovered and were classified in various *symmetry groups*, but they are now known to be different combinations of quarks, rather as atoms are combinations of electrons with protons and neutrons in their nucleus. The fermions, or *baryons*, contain three quarks, while the bosons, or *mesons*, contain a quark and an antiquark.

"They have been created in the collisions, of course. As you saw, the particles were all circulating very quickly indeed, so they each had a large amount of kinetic energy. When they collided, this kinetic energy could be converted to rest mass energy, so that particles of higher mass could be created. In the different collisions which took place, different particles were produced. Each one has its own distinctive rest mass which serves conveniently to identify it, though there are also other, more subtle, differences. I expect that by now there are no two strongly interacting particles present here which have the same mass. That is what happens at a MASSquerade."

Once again his voice became loud as he addressed the whole room. "The dance is now finished. Please assemble in your appropriate multiplets."

At his request the assembled particles began to gather together into separate little clumps, scattered around the room. Alice saw that mostly they gathered into groups of eight particles, six arranged in the form of a hexagon around the outside and two together in the middle. A few groups contained ten particles in a triangular layout which had four of the particles spaced across its base.

"There you see the particles gathered into their symmetry groups," the Master of Ceremonies said quietly to Alice. "These groups are collections of particles which all have the same values for some property, such as spin. You can see that there is a striking regularity in all the different groupings. This provides an indication of an underlying similarity beneath the skin, or rather beneath the mask. You may recognize some of the members of that nearest group," he added.

Alice looked at the eight particles nearby and saw that the two on the top edge of the six-sided pattern were a proton and a neutron. The others, however, were unknown to her.

"That is a group of baryons which all have a spin of one-half," she was told. That meant nothing at all to Alice, but for the moment she was quite prepared to believe it.

"The neutron and proton I believe you have already met. In the next row you have the sigma particle, which can manifest with both positive and negative electric charge and also with no charge at all. It consequently appears as if it were three different particles. In the center of the pattern you have the lambda, which is a single particle with no charge. These are all strange particles," he added.

See end-of-chapter note 1

"They all seem very strange to me," agreed Alice, as she came over to look at them more closely.

"No, no. *Strangeness* is simply a property possessed by certain particles and which happens to have been given the *name* of strangeness. Rather like electric charge, you know—except that it is totally different," he added unhelpfully. "The remaining two particles are both the Cascade. It comes in two different charge states, so there are two of it," he explained. "It is doubly strange, of course."

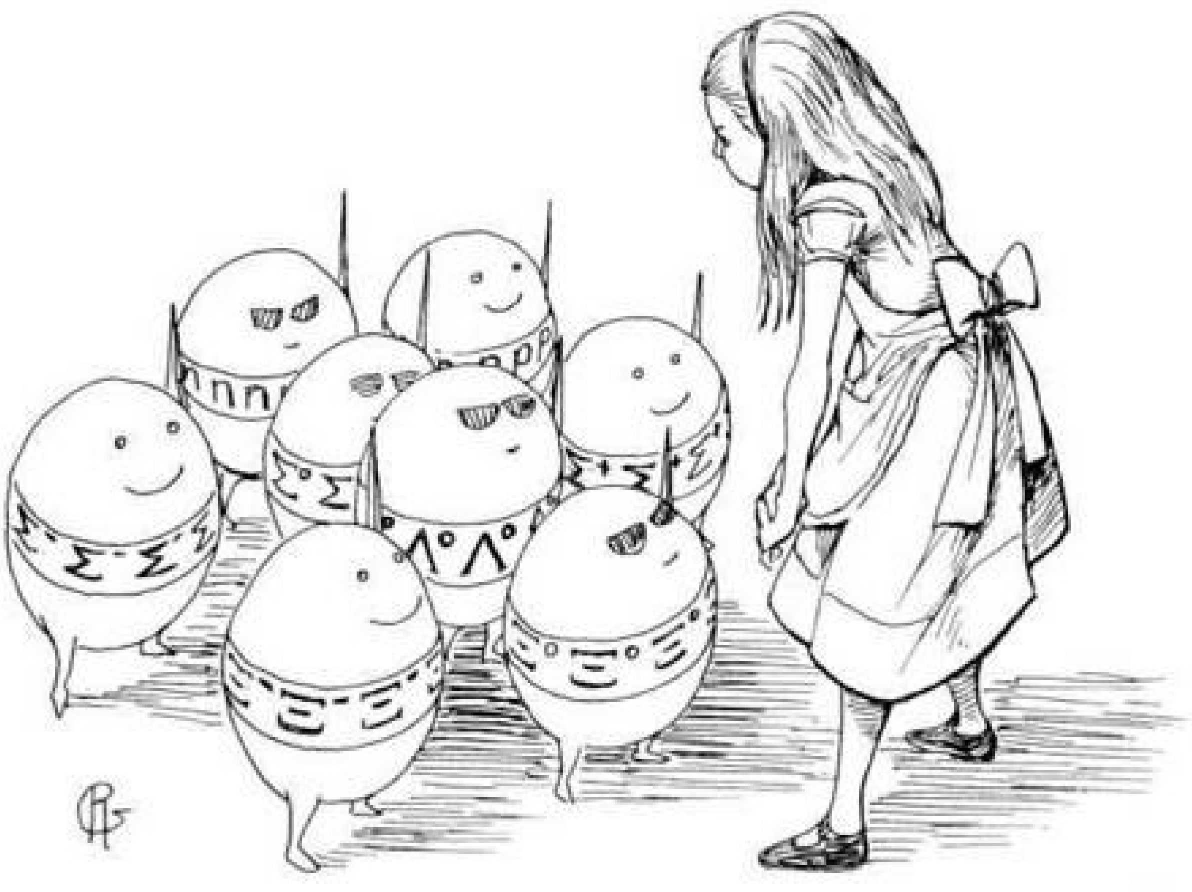
"Of course," echoed poor Alice.

"And now the time is upon us," he called out suddenly, speaking loudly and clearly so that his voice carried through the whole room. "Now is the time for the final unmasking of the evening. Mesdames et Messieurs, Damen and Herren, Ladies and Gentlemen, I bid you all. . . unmask!"

Just how it was done Alice could never quite decide, but all around her the aspect of the particles was changed. She looked at the particle nearest to her, which was the one the Master of Ceremonies had called the lambda. It no longer looked like a particle, but like a sort of bag, within which she could see three shapes. She came closer, to try to make them out more clearly, and felt herself being pulled within the enclosure. She tried to pull away, but despite her efforts she found herself sucked in.

Once inside, Alice found that there was not sufficient room for her to stand. She tried kneeling down on the floor, but the container still pressed in on her so closely that she tried lying down with one elbow on the floor and the other arm curled around her head.

In this awkward position she looked around and stared at the three small figures which she had dimly glimpsed from outside. Now that she could see them, she observed that they were different from any of the particles which she had so far encountered. Each one was colored in a distinctive shade. One was red, one was green, and one was blue. She noted that they were attached to one another with lengths of multicolored cable of some sort. It was variously striped in the three colors, together with the three anticolors which she had seen on the costume of the Master of Ceremonies.



Alice was so engrossed in studying these odd new particles that she was quite startled to hear a voice coming from one of them.

"If you think we are moving pictures," he said, "you ought to pay, you know. Moving pictures are not made to be looked at for nothing. No how!"

"Contrariwise," he added, "if you think that we are alive, you ought to say hello and shake hands."

"I am sorry," exclaimed Alice contritely as, with some difficulty, she held out her hand. She was not quite sure how it happened, but somehow she found that, instead of a hand, she was holding the large rubber bulb of an old motor horn. When she pressed it there was a loud honking noise.

"Well, who are you then?" she asked, a little irritated by this foolery.

"We need no introduction, so I shall perform it. We are the Three Quark Brothers," answered the spokesperson (spokesparticle?), wiggling heavy eyebrows at her. "I am Uppo, this is Downo, and that is Strangeo over there." Uppo was green, Downo red, and Strangeo blue.

"I hope you do not mind if I join you," said Alice, trying to make light of her awkward position.

"Why? We are not going to come apart," answered Uppo and they all laughed uproariously.

Alice was not amused; she had not found the joke very funny. In fact, on further consideration she was not sure that she had found it at all humorous. She looked at the three brothers in irritation and was struck by the fact that now Uppo was red and Downo was green.

Quarks are the most fundamental form of matter presently known. All of the strongly interacting particles are bound groups of quarks. The fermions each consist of three quarks, the bosons of a quark and an antiquark bound together. The binding is very strong and, like the electrical interaction, is due to the exchange of virtual particles.

"You have changed color," she announced in a tone that was almost accusing.

"Naturally," replied Uppo calmly, "we are usually off color. When I started I was quite green, then I felt a little blue, but now I am beginning to see red. You know that particles which have electric charge exchange photons?" he said abruptly.

"Yes, I was told about that," replied Alice.

"Well, we Quarks are colorful characters. We stick together by exchanging gluons. Through thick and thin, or rather through red, green, and blue. The gluons stick around when they see the color of our money; they monitor our color. Particles which have color all exchange gluons. The gluons hold them together in much the same way as photons do for particles with charge."

"But why do you change color?" asked Alice. "Charged particles do not change their electric charge when they exchange photons."

"No, but photons do not carry charge. There is no charge on a photon, which is why they are so popular. Gluons do carry color. When a colored gluon escapes from its source, then that hue is transferred to the Quark that catches it. It is a regular who's hue, I can tell you." As Uppo was speaking, Downo changed his hue to blue, and Strangeo became red, his curly hair taking on a particularly vivid shade.

See end-of-chapter note 2

Uppo indicated Strangeo. "There," he said, "that is a source of a different color!

"It is because we have such colorful gluons that we can never be separated. One for all and all for nothing. United we stand and divided we remain inseparable."

"I am afraid that I do not see what you mean at all," protested Alice.

"Well, we all know that opposite electric charges attract, but you can separate particles which are suffering from that sort of attraction. They are held together by photon exchange, but the photons have no charge."

"If there is-a no charge on photons then-a they free. They go wherever they want," said Downo suddenly.

"Right, because photons have no charge they are free, free to spread out as far as they want. They do not exchange other photons between themselves."

"If there is-a no change and no charge, then there is-a no transaction," added Downo. "These photons, they no do-a business together."

"Without charge the virtual photons have no business with one another, so they do not attract one another. No one gets a charge out of them. So they just spread out all over the place. The farther apart the source charges get, the more place there is for the photons to spread out over. The photons are spread out thin. They have a thin time of it, with less momentum to transfer."

"Last job, I get-a transfer," cut in Downo helpfully. "They say they going to give-a me a little momentum, but all they give-a me was the boot."

"And you felt the force of their argument," replied Uppo. "But with less momentum to give, the force gets weaker. You pull charges far apart, they lose touch, the attraction gets weaker and weaker, and eventually they get so out of touch that they don't even remember to write. Give them enough energy and you can pull them anywhere. They can get so far apart there is no attraction left to speak of. The charges are then quite independent. I expect you know what someone means by an 'independent charge,' or what I charge someone with independent means, for that matter?" he added.

"But enough about electric charges, we are here to talk about Quark charges."

"What's a Quark charge?" asked Alice curiously, always anxious to get as much clear as she could manage.

"Double rate on weekends and for up-Quarks," answered Downo. "But we-a very cheap. Our charge only a third of other particles' charge."

"One thing I do not understand," said Alice to Downo. (That was an understatement, as there were many things that she did not understand by now.) "Why do you try to talk as if you were Italian? I do not believe that you are."

Many particles have electrical charges, and it is a striking fact that the observed particles have charges which are all of the same size. Some particles have positive charge and some negative, but the *amount* is the same in each case. This amount is usually called the *charge on the electron*, simply because electrons were the first particles to be discovered. Estimates of the charges possessed by quarks require that they be different. A quark may have a positive charge which is *two-thirds* the size of the electron's charge, or it may have a negative charge which is *one-third* as large as an electron has. As quarks cannot escape from their bound groups, these fractional charges cannot be observed directly, but there is strong evidence that they are correct.

"It is because he is a fermion," replied Uppo on his behalf. "Enrico Fermi was Italian."

"But aren't you all fermions?" protested Alice.

"Certainly, one for all and all for Pauli. Which nobody can deny." All three Quarks stood to attention and saluted.

"We are one group indivisible. A Quark cannot escape from inside a proton or from any other particle. This is all because of the red, green, and blue. There's Old Glory for you."

"Pardon me," began Alice.

"Gesundheit!" answered Uppo, but Alice continued determinedly.

"I don't know what you mean by *glory*."

"Of course you don't-until I tell you. I meant, 'There's a nice knockdown argument for you!'"

"But *glory* doesn't mean that!" protested Alice.

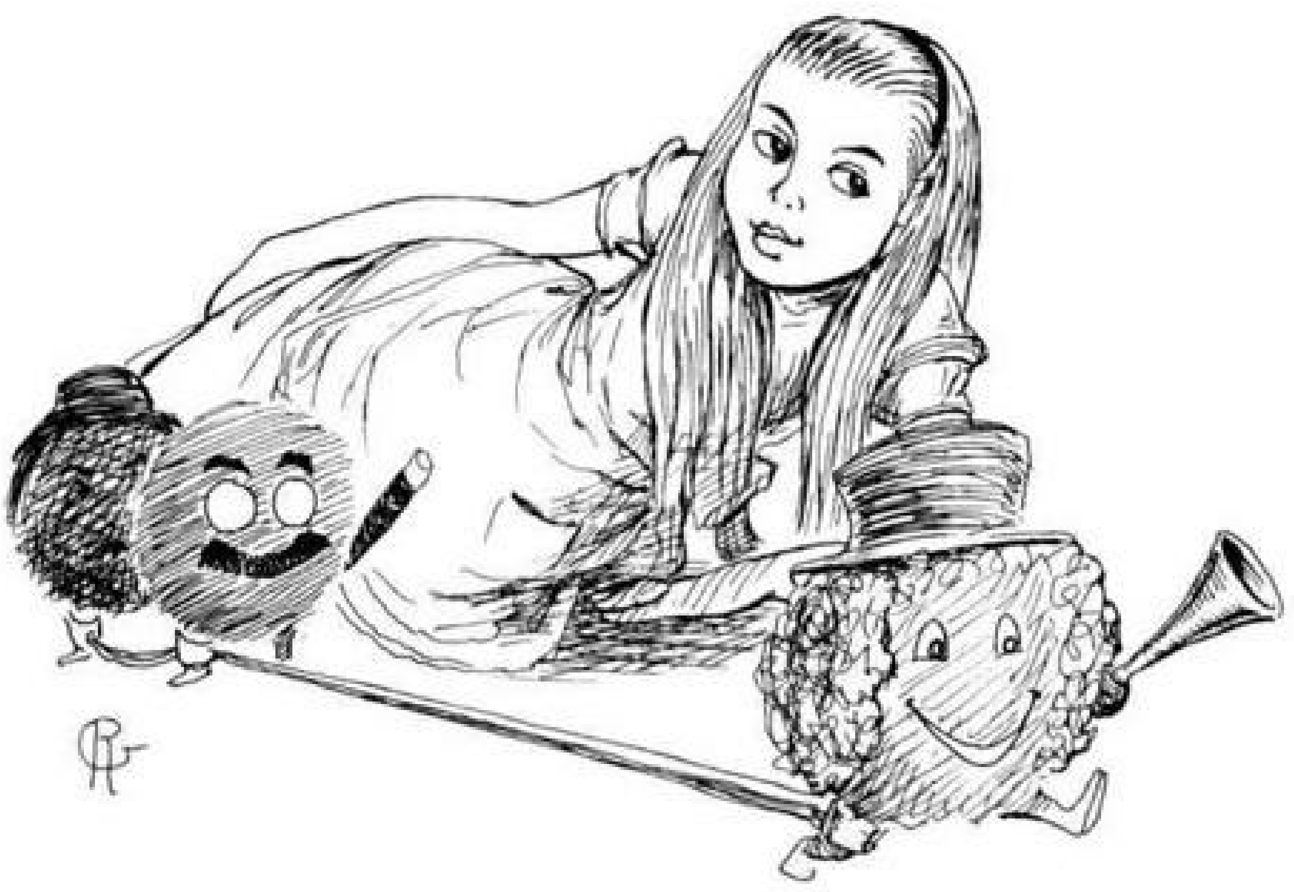
"When I use a word, it means just what I choose it to mean, neither more nor less. The question is, which is to be master-that's all. But it is another question with gluons," he added gloomily. "There is no mastering them, they never let go-not like the photons. The trouble is that the gluons are all colored. And color creates gluons like charge creates photons, so all the gluons emit other gluons, and those gluons emit more gluons. You start with just one or two, and you end up with hundreds. It's like having the wife's family stay. And because they are all exchanging gluons, they all stick together, just like the wife's family. Instead of spreading out in a wide fuzzy cloud like photons, they bunch up to form the tight, colored strings of virtual gluons that you see here. Because they are bunched up they are not free to spread out like the photons. There is no such thing as a free bunch."

The existence of three different types of color allows the gluons to be colored also. Each gluon is a mixture of color and anticolor. With photons a mixture of charge and anticharge gives a particle with no charge, but the gluons may mix different colors; a gluon may be blue and antigreen for example. Such a gluon is not neutral; it possesses color and may act as a source for other gluons. This means that the gluons also are bound to one another and form narrow strings joining the quarks together, rather than spreading widely as do photons.

"When one Quark moves away he soon comes to the end of his tether. If we have more energy, the gluons will give us more rope, but we are still hanging on the end of it. However far we roam, the gluon attraction pulls us home. We cannot break free, but we can still escape with a little help from our friends."

At that singularly appropriate moment, a photon of very high energy crashed into the little group of Quarks. Alice had had no warning as she had not seen it coming. In fact, as she now realized, photons move so fast that she had never yet seen one coming before it arrived. This photon collided with Strangeo, exciting him to a quite manic frenzy, and he rushed off, honking loudly on a horn. Behind him his tethering rope stretched out farther and farther. Alice could see that, however far it stretched, the rope was not becoming in any way thinner or weaker. It was obvious that it could go on stretching indefinitely and that the escaping Quark would soon run out of energy, with no chance of breaking free. But no sooner had Alice reached this conclusion than ... the rope broke!

Where a moment before there had been one long and steadily lengthening cord which was soaking up all the energy that the photon had delivered, now there were *two* very short lengths with a large and steadily widening gap between them. On either side of this break had appeared a new Quark, each anchoring one of the fractured ends of the ropes. On the end of the rope which was still attached to the two Quarks who had remained with Alice was a Quark who looked exactly like Downo, apart from being a different color. The rapidly receding Strangeo was trailing his own short length of rope, to which was attached a reversed version of Downo. This Alice assumed correctly to be an anti-Quark. "Whatever has happened?" asked Alice in some confusion.



"You have just seen a Quark escape with the help of friends in low places. In the vacuum, in fact, and you can't get much lower than that. You cannot detach a gluon rope once it has seen the color of a Quark, so we have to fool it with something which looks just like a Quark."

"And what is that?" asked Alice.

"Another Quark, of course. When the gluon string has stretched long enough so that it now contains enough energy to create the rest masses of two Quarks, then we cut the string and work the switch. One end gets a new Quark, the other Not."

"There is-a knot in the string?" asked Downo (one of the Downos).

"That's right, there's a Quark at one end, Not-a-Quark at the other."

"What's a Not-a-Quark?" asked Alice.

"An anti-Quark. And if you believe that, you should see my uncle. Part of the original string has vanished rapidly into the distance, carrying off the energy and connecting the absent Strangeo to the new antiQuark. So, you see, absence makes the part go yonder."

"He may have escaped, but he still isn't free," protested Alice.

"With a bound he was free. He is free of us now, but he is still bound. With his anti-Quark he is bound into a boson. That's like a pion, but pions can be deceiving and in this case they have formed a kaon instead. You do not see a free Quark-or even free a Quark sea, but that's another kettle of fish."

"Are the fish in-a the Quark sea?" asked Downo.

"No, there's nothing fishy about the Quark sea. Its sole purpose is to hold virtual Quark-Antiquark pairs."

"The sole I understand, and the porpoise I understand, but why the pears in-a the sea?" argued Downo.

"Forget the sea," replied Uppo, "or we will all be at sea. The point is that you will never find a Quark on his own."

See end-of-chapter note 3

"Does that mean that you have to stay here forever with no chance of a change?" asked Alice in concern.

"Oh, we can have a change all right. They say a change is as good as a rest, but I feel quite at liberty to discuss the weak interaction."

"I heard that mentioned when I was visiting the Nucleus. I believe it had something to do with beta decay of nuclei, whatever that may be."

"It is the same thing. In fact it is a far, far beta thing. What happens is that a neutron inside the Nucleus changes into a proton and an electron, together with another particle called a neutrino. This neutrino has no charge, no mass, and no strong interaction. It doesn't do much of any thing really, like most of the folk I know. Anyway, that's the story we tell. What *really* happens is that a down Quark inside the neutron changes to an up Quark, an electron, and a neutrino. When the down Quark changes to an up Quark, then everything is on the up. It puts the charge up, the neutron becomes a proton, and there you are. Hang around, and you might get lucky."

Hardly had he spoken when, by a most convenient coincidence, one of the two Downos became blurred and began to change and lose his identity. After a fleeting moment of transition, Downo was no longer there and in his place stood a duplicate of Uppo. As he moved aside, Alice saw an electron rush away from the same spot. This was followed by yet another particle. Alice caught only the briefest glimpse of this one, something barely perceived and very hard to see at all. This she assumed to have been the neutrino, performing its usual role of ignoring and being ignored by everything and everybody.

The group of three Quarks now consisted of one Downo and two identical Uppos. Identical, that is, but for the fact that one was currently green and the other blue. "My," said Alice. "That was a most remarkable thing altogether."

Obediently the two Uppos replied, in perfect unison, "That was a most remarkable thing."

"But what can you expect," they added, "when the particles exchanged in an interaction have an electric charge? Photons don't have a charge, but this isn't the Charge of the Light Brigade. When a source emits one of these charged particles, it has to share the charge. There are no fluctuations allowed there, you know. When the particle's electric charge has changed then it counts as a different particle. You must have heard of charge accounts. That is how we Quarks get to change," they added.

"But where does the electron come from?" asked Alice, who felt that the explanation was a little lacking.

"The particles exchanged in the weak interaction are called W," began Uppo rather inconsequentially.

"What?" responded Alice, temporarily forgetting her manners. "Not 'What,' just W. It is not much of a name, but it is all they have, poor things. There are two of them, you know: One is W Plus, and one is W Minus. No one has ever asked them what the W stands for," he finished thoughtfully. "Anyhow," he continued, "these W's, as their friends call them, are very friendly types. They will mix with anyone. They interact with both leptons and hadrons, with electrons as well as strongly interacting particles. So when a down Quark decides it is time to change into an up Quark, it gets all charged up. The electric charge of the Quark has increased, so it gives out a W Minus particle to balance the books. This W in turn plays it by the book and interacts with a passing neutrino, which has no electric charge at all, turning it into an electron, which does have an electric charge. The electron finds itself in company with a lot of strongly interacting particles, where it has no right to be, and leaves as rapidly as it can."

See end-of-chapter note 4

"But where does the W find a neutrino which it can change into an electron?" asked Alice in some puzzlement. "I didn't think there had been a neutrino there before. I thought that it was emitted after the decay, along with the electron."

"Ah, that is where it fools you. You thought it should be there *before*, but instead it was there *after*. You are expecting it to arrive from the past, so it sneaks up on you, back from the future, and still arrives just when it is needed. Of course, because it came from the future, it is still around afterward, on its way to arrive. In this way it gets to be both the neutrino converted by the W and the one emitted after the decay. That cuts down on the overheads."

"But how can it arrive from the future?" asked Alice. As she spoke she had a distinct feeling that she already knew the answer to this question.

"It is an antineutrino, of course. One of my favorite anti's. Every particle has its antiparticle, which travels backward in time and so is opposite in every way. That's the great principle of antiparticles-' Whatever it is, I'm agin it.'"

"And is there no way any of you can ever get free?" asked Alice, to be quite sure on this point.

"No, no way at all," they assured her.

"Does that mean that I cannot escape either?" asked Alice in dismay, as she did not really wish to be trapped with them forever. "Not at all. You have no color so the gluons don't hold you. You are one of the most colorless people we have ever met, so there is nothing to keep you; you can leave whenever you wish. We won't even notice. You can get up and walk away. Just don't forget to leave a tip."

This sounded much too simple, but Alice tried it anyway. She stood up and found that indeed there had been nothing to prevent her from leaving the group at any time. She stretched after her cramped confinement in such a small space, looked around her, and found that she was standing face to mask with the Master of Ceremonies. His grinning mask was just a few feet from her face. She stared at him, hypnotized by his wide, fixed grin and the dark eyeholes above. Deep within their black depths where his eyes should have been, she thought she could see an intense blue spark, like a distant star on a clear, frosty night.

"And how did you enjoy your meeting with the Quarks?" he asked her merrily.

"It was very interesting," she replied truthfully. "They were most colorful characters, but I did find them rather changeable.

"Was that the last unmasking that will take place tonight," Alice continued, "or are there further layers to be stripped away before I can see what is really there?"

"Who can say?" he replied. "How can you ever know if you are finally looking on the naked face of Nature or if you are simply looking at yet another mask? Tonight however there is but one more unmasking to come. I have yet to remove my own mask."

As he was speaking, the bright spotlight which had followed him all through the evening began to dim, and the light from the chandeliers overhead became even fainter than it had been before. As the light died, the Master of Ceremonies lifted both hands to his face and slowly pulled off his mask.

In the rapidly fading light Alice looked at the face behind the mask. She could see nothing but a smooth oval, a total blank with no features of any sort discernible. She stared in astonishment at this enigmatic visage, and, as the last gleam of light died, she saw the *mask* wink at her.

Notes

1. The protons and neutrons which inhabit the nucleus (known collectively as nucleons) are examples of strongly interacting particles, also known as *hadrons*. There are many other hadrons, though not all particles interact strongly. The class of particles which are known as *leptons* do not feel the strong interaction at all. Electrons belong to this class and so are not bound inside the nucleus together with the nucleons. They are aware of the nucleus only as a positive electric charge which holds them loosely bound within the atom.

Experiments in high-energy physics have discovered hundreds of strongly interacting particles. This situation presents a fairly familiar scenario in physics. Whenever a class contains a very large number of members, they usually turn out to be built up as composites of something more basic. The various chemical compounds identified are all composed of atoms. There are 92 naturally occurring varieties of atoms that are stable, and they are all composed of electrons arranged in differing numbers around a central nucleus. Nuclei in turn are composed of neutrons and protons bound by the ex-change of pions. These are mentioned in the previous chapter. Now the neutron and proton are found to be just two members of a class with hundreds of others: K, ρ, ω, Λ, Σ, Ξ, Ω, Δ, and so on. These particles have now been shown all to be composed of quarks.

2. Quarks are held together by forces like, but yet unlike, the electrical interaction. These forces do not act on electrical charge, but on something else which is called *color charge* or just color. This has nothing to do with color as we normally understand it; it is just a name which has been given to something completely new. The fact that the word *color* is already in use is perhaps unfortunate, though it is not the first time that a word has had two different meanings.

The interaction between two electrically charged particles is due to the exchange of virtual photons. The interaction between quarks is caused by the exchange of a new class of particles which have been named *gluons*. There are differences between the interactions: Electrical charges come in only two forms, positive and negative, or charge and anticharge. The photons which are exchanged between electrical charges are themselves electrically neutral; they carry no charge and so do not emit more virtual photons in their own right.

The gluons exchanged between quarks are emitted by a form of charge carried by the quarks, but completely different from the normal electrical charge. It is called color charge, though it has nothing whatsoever to do with the colors that we can see. While there is only one form of electrical charge, together with its opposite, or anticharge, there are three different forms of color charge, given the names *blue*, *green*, and *red*. Again it should be stressed that these names are just conventions and have nothing to do with ordinary color. Associated with each color charge there is an anticolor, and there are two ways of producing color-neutral objects. With electrical charge you can only produce an electrically neutral object by combining charge and anticharge (positive and negative charge). There are two ways to produce color-neutral particles: a combination of color and anticolor (as in bosons) or a combination of all three colors of quarks (as in fermions).

3. When particles are bound together by the electrical interaction, the potential energy in the binding decreases rapidly as they move far apart. If a particle is given enough energy, it can break free

completely, as a rocket which has reached escape velocity has then enough energy to break free of the earth's potential. When a gluon string has already been stretched, however, it takes just as much energy to stretch it a little farther as it did initially. It is like stretching an elastic string; it does not get any easier the farther you stretch it. It is also like an elastic string in that, when you stretch it, it can break.

The gluon string is capable of absorbing more and more energy as the quarks separate and the string stretches. Eventually the energy in the string is more than is necessary to create a quark-antiquark pair. The string breaks and its broken ends are terminated on the color charges of the new quark and antiquark. In place of the original bound system of three quarks there are now two separate systems, one of three quarks and one of a quark and an antiquark. Instead of releasing a free quark the energy has created a new particle, a boson. This will always happen and free quarks are never produced.

4. Though the quarks cannot escape from the "particles" within which they are bound, they can change from one type to another. This is caused by a peculiar process called the *weak interaction*. The weak interaction is a broad-minded process which will interact with virtually everything. The electromagnetic interaction affects only particles that have electric charge. The strong interaction affects only the strongly interacting particles (or hadrons) and not leptons. The weak interaction will affect them all, though the effect is rather slow and weak because it is a *weak* interaction.

The weak interaction is peculiar in that it can change quarks. It can change either a *down* quark or a *strange* quark to an *up* quark. In the process, the electric charge of the quark is changed, with the surplus charge carried off by the "W boson," the type of particle which is exchanged in the weak interaction. This charge may then be handed over to newly created leptons, an electron and a massless electrically neutral lepton known as an antineutrino. This happens in the process of nuclear β decay, in which a radioactive nucleus emits a fast electron. This process had been known for many years, but was odd in that it was quite clear that there were not any electrons available within the nucleus to be so emitted. The electron is created in the decay process and, as it is not bound, leaves the nucleus immediately.

CHAPTER

10 The Experimental Physics Phun Phair

The darkness slowly cleared from about Alice. The shadows lifted from her eyes, which were immediately dazzled by a chaos of bright lights and colors. At the same time her ears were assaulted by an assertive cacophony of sounds. She looked around her and found that she was in the midst of a merry and diverse throng of people. There appeared to be all manner of folk present, in every kind of dress. She could see that some of them were wearing white coats, such as one imagines scientists to wear in their laboratories, while others in the crowd were dressed in very casual clothes or in formal suits. She could see costumes from countries all over the world and indeed from many different times in the past.

There were men in Victorian frock coats, with impressive bushy side whiskers, and others in burnooses, or traditional Chinese costume, with wide flowing sleeves and long pigtails. She saw one particularly hairy-looking individual who staggered past dressed in untreated animal skins and carrying what looked rather like a roughly formed wheel, which appeared to have been chipped out of stone. One the side of the wheel the words *Patent applied for* had been carefully chiseled. One man in particular caught her attention for some reason. She sensed some special quality about him, without being able to pin down exactly what it might be. He had a pale, intense face and was dressed in the breeches, waistcoat, and wide frock coat of the seventeenth century. He was walking along absentmindedly taking a large bite out of a bright red apple.

"Where am I?" she asked herself, speaking aloud but hardly expecting to be noticed in the hubbub which arose all around her.

"You are in the Experimental Physics Phun Phair," came the unexpected response. Alice looked to see who had spoken, and found that, once again, she was accompanied by the Quantum Mechanic, who was walking quietly by her side. He indicated a banner stretched across a gateway by which they had, apparently, just entered. It bore the slogan:

Experimental Physics Phun Phair

"It does seem to be spelled rather strangely," commented Alice, this being the first thing which struck her about it.

"Well, what do you expect? They are all scientists here, you know. This is the great carnival of empirical observation. Here you will find many demonstrations of physical phenomena and sideshows of experimental results."

Alice gazed around her and saw a splendid variety of tents and stalls, with here and there a more substantial looking building. They all carried large, brightly colored posters which vied with one another for the attention of the crowd. She read a few of them:

Enjoy the thrill of particle collisions.

Hunt the neutrino.

Knock out a quark and win a Nobel Prize.

There was a disturbance of some sort in the crowd nearby. Alice looked across and saw a balding bearded man wrapped in what appeared to be a large white bath towel. He was shouldering his way through the crowd, hampered by the fact that he was carrying a large posterboard in one hand and an incredibly long pole or lever of some sort in the other. She peered carefully at the notice he was carrying. At the top, roughly painted out, she could just make out the words:

Feel the Earth Move!

Below the erased words she read the modified message:

See Me Move the World!

"Who is that," asked Alice, "and what is he planning to do?"

"Oh, that is a well-known Greek philosopher. He is obviously intending to go into his old 'Moving the World' routine."

"Really?" exclaimed Alice. "Does he often move the world then?"

"Oh no, he never does. He can never find a fixed place to stand while he uses his lever, you see."

As this did not appear to offer much immediate entertainment, Alice looked around for something more promising. Her attention was attracted by a stall nearby which bore the name "Photoelectric Canon." There was a sort of stylized gun from which the player could direct a beam of light onto a metal surface. The light caused electrons to be emitted where it struck, and the idea, as explained by the stall's occupant, was to get the electrons to move a little distance to a sort of bucket, where they would be collected. This seemed easy enough to Alice, even when it was explained that, to make things a little more interesting, there was a weak electric field which resisted the passage of the electrons and turned them back just before they reached the collector. After all, as the stall owner explained, there was a control which would allow Alice to increase the intensity of the beam of light to many times its present value. However hard she tried, though, she found that she *could not* get any of the electrons to travel that last little distance. She turned the intensity of the light higher and higher. More and more electrons came streaming out, but every one was turned back at the last minute by the electric field.

"This is really too bad!" exclaimed Alice in frustration.

"I am afraid that it is what you have to expect," replied her companion sadly. "You see, you have only been given control of the *intensity* of the light and not its color. If light were a classical wave, then you would expect that as you increased its intensity, the associated disturbance would increase, and it would give more energy to the electrons that were emitted from the surface of the metal target. In fact, it is the color, or frequency, of the light that decides the energy of the individual photons which compose it. As you are not provided with any way to alter this, you cannot change the energy of the photons or for that matter the energy of the electrons which those photons will knock out of the metal surface. The stall has, of course, carefully been set up so that this energy is not *quite* enough to get through the retarding electric field. When you increased the intensity of the light, you directed more photons onto the surface, and these produced more electrons, but they all had the same energy, and in every case it was not quite enough for the electron to make it to the collector. I am afraid that you cannot win."

The quantum description of the world is hardly what we would have expected. The reason for believing in it is that its predictions agree with experimental results. It is the only theory that can give any sort of explanation for the behavior of matter on the atomic scale, and it does it remarkably well.

Alice felt somewhat cheated by her experience with this stall and looked around for something different to occupy her. Nearby was a small tent with a sign which read:

ROLL UP! ROLL UP!

See the largest collection of quarks in captivity.

The central features of quantum behavior are the detection of discrete particles and the observation of interference. The observation of quanta is shown by the photoelectric effect: the production of electrons by light falling on a metal surface. The only result of increasing the light intensity is to increase the number of photons present and consequently the number of electrons. Each photon still interacts on its own, so if the *frequency* of the light is unchanged as the *intensity* is altered, then each photon will still have the same energy, and the energies of any electrons produced will be the same, whatever the intensity of the light. This is quite different from the behavior expected for a classical wave, where a greater intensity should mean more energy delivered.

Alice and her companion slipped inside the tent, where the exhibitor was telling a small crowd how fortunate they were to see all six quarks captured and displayed for their entertainment. Alice looked at the exhibits. None of the quarks were present singly, of course. They were all assembled in pairs, each one bound unbreakably to his antiquark. Alice realized that this was as close to a collection of isolated quarks as it was possible to get. "And after all," she thought, "he did say that they were in captivity."

Alice looked at the assembled quark pairs. They were assembled on a platform which had various levels, with the heavier quark combinations standing on a higher energy level. She saw an *up* quark, wiggling his heavy eyebrows at her as before, a *down* quark, and, slightly higher up, a *strange* quark with flaming red curly hair.

As well as these three types, which she had already met at the MASSquerade, there were two others higher still. One projected a captivating personality, and she saw a quick flash of light as from a display of incredibly white teeth. "That is a *charm* quark," the Quantum Mechanic murmured in her ear. The other new quark was heavier yet. This one was placed quite high up, and Alice saw him even less clearly than other particles she had met, but she got the strangest impression that this one had a donkey's head. "That is a *bottom* quark," her companion informed her.

Alice now looked higher to see the sixth quark. There was the position on the platform, but it was empty. There was no sign of the sixth quark, which, she was informed, would be the *top* quark.

Other members of the audience also had noticed the absence of this sixth quark and were protesting noisily. "All right, all right!" said the exhibitor soothingly. "I know that he is in here somewhere. The top quark is the heaviest of them all, so we have to look for him at high energies, but he must be there." He picked up a large butterfly net which was leaning against a pole, climbed up a stepladder, and began making wide random sweeps of the net close beneath the roof of the tent.

During this, his audience became increasingly restless, with uncomplimentary remarks being made on all sides. Gradually, the mood of the crowd grew distinctly ugly and people began to slip away in order to write critical letters to their favorite technical journals. "Come away," said the

Quantum Mechanic to Alice. "This is no place for us now."

They went outside and Alice's attention was caught by another stall at which people were clustered, throwing balls at various prizes which they would win if only they were able to knock them from their stands. It looked very much like the sort of fairground stall which she had seen near her home, except that in this one there was a sort of fence of thin, uniformly spaced wires between the competitors and their targets.

Alice watched for a while and noted that, as soon as a ball was thrown, it became quite blurred and it was impossible to see exactly where it had gone until it hit some point along the back wall of the booth. She saw that most of the balls did just that; they hit the wall rather than any of the prizes. Gradually piles of balls built up where they had hit, and Alice could see that these piles were positioned neatly in the spaces between the prizes.

Recently, the existence of the top quark has been confirmed at a very high mass. The top quark joins the two earlier known types of quarks, charm and bottom quarks, in completing the picture. At present, it is believed that there are six and only six types of quarks, with a matching set of six leptons. Are the quarks in turn made of something more fundamental? There is, at present, no way of telling.

"Exactly right," said a voice by her ear, echoing her thoughts. "The regularly spaced wires are acting to produce an interference pattern, with much greater probability for the balls being observed in some places than in others. Naturally the minima, the places where the probability of finding a ball is at its lowest, are arranged to fall where the prizes are."

"That doesn't seem very fair," remarked Alice.

"Well no, perhaps not, but in the Phun Phair you do not expect it to be fair. After all, the man who runs the stall has to make a living, so he does not want to give out prizes too often. Of course, there is still *probability* of the ball being observed even at the minima, so *some* prizes do get won, but not too many."

Alice still felt that it was not quite right somehow, but before she said anything further, her attention was caught by a large pavilion a little way off. It was surmounted by a huge glowing sign which said:

THE GREAT PARADOXUS
Spooky action at a distance!

Below the sign there were a number of large posters strung across the front of the building:

Extraordinarily astounding!
Paradoxically incomprehensible!
Rather surprising on the whole!

Alice and her associate made their way to this exhibit and joined the crowd which was streaming in through the doorway. Within was a long, high-ceilinged enclosure with a raised platform in the center. On either side were a pair of short ramps leading up to doors at the two ends of the building. On each ramp stood a short metal cylinder with a pointed nose and stubby fins at the back.

On the central platform stood the Great Paradoxus, a tall figure with glossy black hair, a spiky waxed moustache, and a flowing black cloak. "Good evening, Ladies and Gentlemen," he greeted them. "Tonight I plan to conduct a little experiment on the reduction of amplitudes, which you may find to be of some interest. Here on the platform beside me," he continued, "you see a source of transitions, transitions which will release two photons in exactly opposite directions. As you know, if you were to measure the spin of the photons along some direction of your choice, you would find them to have a spin either *up* or *down*, with no intermediate choice possible." Alice had not known that, though she had heard talk of spin-up and spin-down electrons, but all the other people present were nodding their heads wisely, so she assumed it must be all right.

"As I say, *if* you were to measure the spin, you would find it to be spin-up or spin-down, but if you do *not* measure it, then there will be a mixture, a superposition of states having different directions for the spin. Only when you make a measurement of the spin will the amplitudes reduce. One will be selected, and one will no longer be present. Now," he said abruptly, "the source which you see here makes its transitions from states which have no spin at all, so the *total* spin of the two particles produced must also be zero. That means," he explained kindly, "that the spins of the two photons must be opposite: If one has spin-up then the other *must* have spin-down. But, mark you, the spin direction of the photons is only selected from the superposition of states when a measurement is made-that is the usual understanding. Thus, you see that when a measurement is made on one photon with the discovery, let us say, that it has spin-up, then the amplitude superposition for that photon will reduce to the appropriate state.

"However," Paradoxus continued, drawing himself up to his full height, "at the same time, the superposition for the *other* photon must reduce also, because we know that this photon must have the opposite spin. This must happen however far apart the photons might be at the time, even if they had arrived at different stars in the sky. In this demonstration we will not be making our measurements quite so far apart as that," he smiled at his audience. "I now call for two volunteers, two trusty and reliable experimenters who will agree to travel to the opposite ends of Quantumland and make our observations for us."

The central features of quantum behavior are the detection of discrete particles and the observation of interference. Particles, or quanta, are observed at one place rather than spread over a wide region like a classical wave. Despite this, particles seem to behave like waves, in that they show interference effects between the different amplitudes which describe all the things that a particle might be doing. Interference may be demonstrated by scattering electrons from a regular grid, as illustrated by the arrangement of atoms in a crystal, and may be performed at such a low intensity that only one electron will be present at a time.

See end-of-chapter note 1

There was a buzz of argument and discussion from the assembled crowd. Eventually, two people were pushed forward. Both were dressed in long frock coats and narrow trousers, and both had bushy side whiskers. Both wore waistcoats, each with a gold chain attached to a watch which its owner had obviously checked recently against a reliable standard clock. These two were not actually identical to one another, since only particles are completely identical, but they were certainly very much alike. They were obviously both honorable, honest, and reliable as well as being competent and conscientious observers. If they were to say that they had seen something, no one would dream of disputing it.

Paradoxus handed to each a polarimeter, a device with which they might measure the spin directions of the particles. With military precision each stripped the instrument he had been given, examined it to make sure that it had no unusual features, and quickly reassembled it. The showman then summoned two attractive female assistants, who escorted the volunteers to the metal cylinders and opened a door in the side of each. For some reason each of the two observers then put on a tall top hat before he squeezed himself into the cramped space within. The assistants closed the doors, lit a fuse at the rear of each cylinder, and stepped hastily back. With a roar the stubby rockets rushed up the ramps, through the doors at the end of the pavilion and arced over the horizon, making for the opposite ends of Quantumland.

"And now we wait for them to arrive," remarked the impresario. "As soon as each is in position he will send a message through his telegraph line." He indicated two bells which stood on small tables at either end of the platform. Everyone looked at them, waiting for them to ring as a signal that the show might proceed. It was a long wait.

"Everyone seems very patient," remarked Alice, who was beginning to feel a bit restless herself.

"They have to be," replied the Quantum Mechanic. "Experimental scientists all learn to develop patience."

Finally the bells rang, first one and then shortly after the other. This indicated that both observers were in position, and, with a dramatic gesture, Paradoxus opened windows at either end of his photon source. Two by two the photons went rushing off in opposite directions.

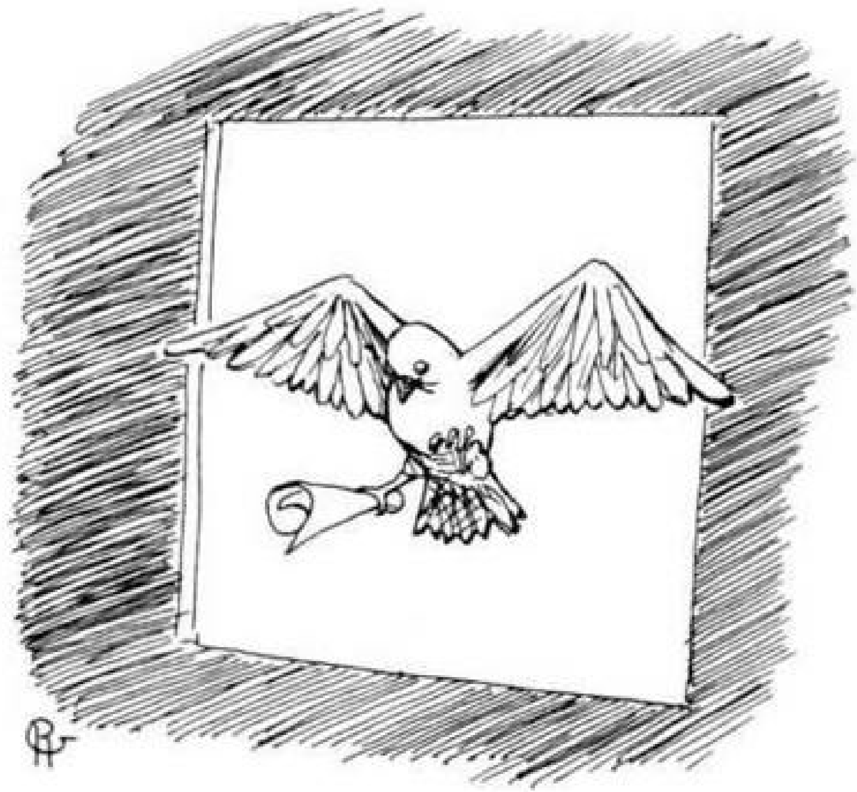
After some time he closed the windows again and there was another long pause. "I wonder what we are waiting for now," thought Alice, who felt that the entertainment might move just a *little* faster. There was a flapping of wings and through the door at one end of the building flew a carrier pigeon, which was expertly caught by one of the assistants. Not long after, a pigeon arrived through the other door, and the messages carried by both could be compared. Paradoxus displayed the two messages, which showed a perfect correlation, with a spin-up photon going to one side invariably accompanied by a spin-down version detected at the other, even though the two detectors were too far apart to have had time to exchange any information.

"That's no mystery!" shouted someone from the other side of the large room. The voice had come from a tall figure whom Alice could not see very clearly, but he did look *rather* like the Classical Mechanic. "It is obvious," he went on, "that the photons are not in fact completely uncertain whether they are really spin-up or spin-down when they leave the source. In some way they know which they will be, and they know also that the two of them must be opposite. It does not matter then how long they wait before they are detected; they will be found to have that spin direction which was already decided when they were emitted."

"That sounds a very reasonable argument, does it not?" beamed the impresario, looking not in the least dismayed. "We shall have to extend our demonstration a little. You say that it has been decided at the time of emission whether the photons shall have spin upward or downward, and they carry this information with them as they travel. What would happen if our two observers were to measure the spin in other directions, say to the left and to the right, or at some other angle in between? And what would happen if our observers were to rotate their polarimeters as and when they felt like it, without referring back to us or collaborating with one another? Would it be possible for the source to know in advance what information it should transmit along with the particles such that their spins would match properly *whatever* the angles our friends chose for their measurements? I think not!"

Quickly he wrote out new instructions for the observers, bound the notes to the pigeons' legs, and sent them back to whence they had come. After a pause the telegraph bells rang once more to show that the messages had been received and understood. Again, with a flourish, he opened the windows on the central source and let the photons stream outward. After a suitable period, he closed the windows again, and then it was back to waiting. Alice was feeling distinctly tired of waiting for something to happen when, at last, there was a rushing noise from both sides. This grew steadily louder, and then the two rockets came arcing back down through the doors at the two ends of the building and landed back on the ramps from which they had departed.

As the stubby cylinders sat smoking gently, the doors opened and from each vehicle descended one of the observers, still wearing his tall formal hat. They both marched over to the impresario, removed their hats, bowed, and presented him with their notes. As far as Alice could tell, everyone in the audience apart from herself immediately crowded around to try to be the first to get a glimpse of the results. There was a tremendous hubbub of discussion and argument, and they all began to make their own calculations. Alice saw people with tiny portable computers, with electronic calculators, and with slide rules. She also saw someone with a strange mechanical calculator which had scores of tiny cogwheels. The Chinese folk whom she had noticed earlier had each produced an abacus, and their deft fingers slipped the beads to-and-fro along the wires more quickly than her eyes could follow. Even the hairy gentleman in the animal skins was involved. He had abandoned his wheel and was going through some complicated procedure with several little piles of bleached knucklebones.



Finally the arguing groups quieted down and came together in a common conclusion. It was true, they said, that there was a quite inexplicable agreement between the spin directions of the two photons. Even when arbitrary changes were made in the directions along which the two spins were measured, the observed correlations were greater than could be explained by any information sent out along with the particles. It was all quite clear, they agreed; in fact, it was clear as a bell. It didn't look all that clear to Alice, but if everyone was agreed, she supposed it must be correct.

"That is a very interesting result," remarked the Quantum Mechanic as he returned from the middle of the crowd. Most of the other people present were still arguing excitedly, despite the fact that they were apparently all in agreement. "It shows that the behavior of the wave function in different places cannot be caused by messages passed from one position to the other. There simply isn't enough time for that. It presents a whole new Aspect of quantum nature."

See end-of-chapter note 2

Interesting it might be, but Alice felt that there had been too much sitting and waiting and that she would like more action, so they left the pavilion and went off to investigate the rides.

"You will have to behave as a charged particle if you want to take any of the rides," remarked the Quantum Mechanic. "The rides all operate by electrical acceleration, so they will only work for charged particles. As you are just a sort of honorary particle, I see no reason why you should not be a charged particle just as readily as an uncharged one."

They had come to a very long, narrow building on which was a sign reading:

RIDE THE WAVE!

Ride the electromagnetic wave for mile after mile.

(That makes two miles; count them: 2.)

There was an excited line of electrons outside, waiting their turn to get on, but Alice did not think that this was quite the ride she wanted at the moment. She would rather go on something like the Big Wheel, which she had ridden in a fair near her home.

She mentioned this to her companion, who said that he would take her to the circular machines. As they headed in that direction they were passed by a parade. There was a succession of little carts, on each of which was balanced a huge apparatus built around a vast iron magnet with copper coils wound around it and various intriguing devices embedded in its center. From all of these snaked great bundles of wires and cables.

"How do those little carts manage to support all that weight?" asked Alice. "Surely they should be squashed flat under such huge masses of metal?"

"Oh, they would be if the pieces of equipment were *real*, but this is the Experiment Funding Parade, so each one is only a proposal. They are rather like the experiments we did in our *gedanken* room. They are just ideas at the moment, not real at all, so they are not very heavy. In fact, most of them carry very little weight indeed."

Alice looked at the procession and observed that the second cart carried an apparatus exactly like the first, the third carried another exactly the same, so did the fourth, the fifth, the sixth, and on and on as far as the parade was visible. "There doesn't seem to be a great deal of variety," remarked Alice.

"That is because multiple copies of each proposal must be submitted," replied her associate. "There will be a different one along in due course."

As they watched the floats go by the air was filled with a snowstorm of irregular scraps of paper. "Torn-up unsuccessful grant applications," said the Quantum Mechanic before Alice could ask. "Come along, we had better find your ride."

They passed a succession of Big Wheels. They were all lying on their side instead of being upright as they would be in a normal fair, and Alice's companion told her that in the Phun Phair they called them rings rather than wheels. There was the Big Ring, the Much Bigger Ring, and the CERN Truly Enormous Ring. Alice decided that she would like to ride on this last one.

She lined up with a jostling bunch of protons, and soon she was entering the machine and being seated, or "injected" as they termed it, in a *beam bucket*. This was a sort of electrical enclosure which Alice shared with a large crowd of protons who were milling around excitedly in all directions. They moved off, accelerated forward by strong fields which pulled on their electric charges. As they gathered speed, the protons quieted down, and they all rushed forward together.

Faster and faster they went, guided around and around by magnetic fields. After some time, Alice began to notice that their speed was no longer increasing much, though she could still feel an acceleration. She asked one of the protons about this and was told that they were now going almost as fast as photons did and nothing could go much faster than that, but that their *kinetic energy* was still rising. This seemed odd to Alice and she was about to argue, when there was a sudden wrench and she felt herself flung out of the ring together with the protons.

Through the air she rushed at what now seemed an incredible velocity. Looking ahead, she was terrified to see a wall directly in front of her and to realize that she and the protons were headed straight toward it! She tensed for the collision as the wall rushed closer, but to her amazement the wall stopped her no more than would a fog or a dream.

It is part of the paradox of quantum physics that measurements on very small objects must be made with enormously large particle accelerators. Because of the *Heisenberg relation,* a small size is coupled with a large momentum, and it requires a large machine to accelerate particles up to the enormous energies needed. Most of the very high energy accelerators are circular and the particles travel around and around many times as they are accelerated. There are a few large linear accelerators, in which electrons are accelerated along a single straight path, such as the 2-mile-long "linac" at Stanford in California.

She looked around her and saw that, although the wall had had little effect on her, the reverse was far from true. She passed an atom some way off and it burst asunder, the electrons spilling out and the nucleus cast free to drift on its own. All around her she trailed a deadly train of virtual photons. These tore at the atoms she passed, which seemed as gossamer, ripped apart by the distant effect of her passage. She came close to a nucleus and it too was shattered, the protons and neutrons scattered in every direction. In dismay she recollected the Cosmic Ray-der whom she had seen from Castle Rutherford and who had so effortlessly destroyed a nuclear castle. Now she was horrified to realize that she had become as he, leaving a wide swath of destruction among the atoms and nuclei which she passed!

She saw a neutron straight ahead for just a moment before she plowed into it. Briefly she glimpsed its three quarks, who were thrown into a panic by her passage. They were not cast individually out of the neutron, because they were too firmly bound to one another, but their chains stretched and broke, stretched and broke, with the creation of a host of quark-antiquark pairs. Where previously the neutron had been standing was now a great jet of mesons carried forward by the wake of Alice's own enormous momentum.

Alice hid her eyes to blot out the image of the chaos about her, lest she should see some even more violent catastrophe. She had a brief sensation of falling and felt a slight bump.

The high-energy particles produced by accelerators can penetrate for considerable distances through normal matter. They have such high energy compared with that in the electronic bonds between atoms that these have little effect in slowing them. Such particles leave a swath of ionization and broken bonds along their path. If they pass close to the nucleus of an atom, they will split this apart also. Eventually these fast particles will lose all their energy through such processes, but they can go a long way.

Alice quickly opened her eyes, to find that she had fallen off the couch in her own front room and was lying on the floor. She got up quickly and looked around. The sun was shining cheerfully in through the window and the rain had cleared away. She turned to look at the television, which was still operating. The screen showed a group of rather serious folk sitting around a studio, arranged carefully on either side of a commentator, who informed Alice that they were about to have a studio discussion on the future of scientific planning in the country.

"Boring," said Alice. She switched off the television firmly and went outside into the sunshine.

Notes

1. There have been many attempts to set up an experiment which would contradict the more extreme predictions of quantum theory, but so far quantum mechanics has always been vindicated.

An example is the Aspect experiment to investigate a form of the *Einstein-Podolsky-Rosen* (EPR) paradox. There are various forms of this paradox, which involves measurements of particle *spin*, the strange quantized rotation possessed by elementary particles such as electrons and also photons. The paradox treats the case of a system which has no spin but which emits two particles that do have spin and which travel directly away from one another. The restrictions of quantum theory tell us that a measure of the spin of either particle can give only one of two values: *spin-up* or *spin-down*. If the original system has no spin, then the spins of the two particles must compensate; that is, if one is spin-up, the other *must* be spin-down, so that the sum of the two gives a total spin of zero. If no measurement is made of the particle spins, then quantum mechanics says that they will be in a superposition of spin-up and spin-down states. When a measurement is made on the spin of one, then *at that point* its spin will be definite, either up or down. But at the same time, the spin of the other particle becomes definite also, as the two must be opposite. This would be true no matter how far apart the particles have moved since they separated. This is in essence the EPR paradox.

2. It would seem reasonable to explain the EPR paradox by saying that in some way the spins were predetermined from the start: that, in some way, the particles *knew* which would be spin-up and which spin-down when they set out. In that case it would not matter how far they had traveled as they would bring the information with them. The limits of the information which it would be possible for the particles to fix in advance are considered in *Bell's theorem*, which treats what happens if the spin measurements are not made along one predetermined direction, but at a selection of different angles for the two particles. The calculation is rather subtle, but the outcome is that, in some cases, quantum mechanics predicts a greater correlation between the measurements on the two particles than could be arranged by any advance information which could be sent with the particles without prior knowledge of the directions along which the spins would be measured. Alain Aspect in Paris has measured this effect and found, as usual, that quantum mechanics appears to be correct. It seems to involve some sort of information which travels more quickly than the speed of light.

The Aspect result does not directly contradict the normal understanding of Einstein's special theory of relativity. This says that no information, no message, may travel more quickly than the speed of light. The effect considered in the EPR paradox cannot be used to send messages. If you could decide whether you would measure the particle spin as up or down, then the opposite spin of the other particle would convey information in a sort of Morse code, but you cannot do this. You have no control whatsoever of the result of a measurement on a superposition of quantum states; the result is completely random and no signal can be forced onto it.

Richard Feynman, *QED: The Strange Theory of Light and Matter,* Penguin, New York

General Science / Physics

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An imprint of
Springer-Verlag New York, Inc.
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ISBN: 0-387-91495-1

ISBN 0-387-91495-1
9 780387 914954

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