QUANTUM MECHANICS AND EXPERIENCE

DAVID Z ALBERT

Quantum Mechanics and Experience

• • • • • •

David Z Albert

Harvard University Press
• • •
Cambridge, Massachusetts
London, England

Printed in the United States of America

This book has been digitally reprinted. The content remains
identical to that of previous printings.

First Harvard University Press paperback edition, 1994

Library of Congress Cataloging-in-Publication Data
Albert, David Z
Quantum mechanics and experience / David Z Albert.
p. cm.
Includes bibliographical references and index.
ISBN 0-674-74112-9 (alk. paper) (cloth)
ISBN 0-674-74113-7 (pbk.)
1. Physical measurements. 2. Quantum theory. I. Title.
QC39.A4 1992
530.1'6—dc20 92-30585
CIP

Contents

Preface ix

1. Superposition 1

2. The Mathematical Formalism and the Standard Way of Thinking about It 17

3. Nonlocality 61

4. The Measurement Problem 73

5. The Collapse of the Wave Function 80

6. The Dynamics by Itself 117

7. Bohm's Theory 134

8. Self-Measurement 180

Appendix: The Kochen-Healy-Dieks Interpretations 191

Bibliography 199

Index 203

Preface

This book was written both as an elementary text and as an attempt to add to what we presently understand, at the most advanced level, about what seems to me to be the central difficulty at the foundations of quantum mechanics, which is the difficulty about *measurement.*

The first four chapters are a more or less straightforward introduction to that difficulty: Chapter 1 is about the idea of superposition, which is what most importantly distinguishes the quantum-mechanical picture of the world from the classical one, and which is where everything that's puzzling about quantum mechanics comes from. Chapter 2 sets up (in a way that presumes nothing at all, insofar as I understand how to do that, about the mathematical preparation of the reader) the standard quantum-mechanical formalism and outlines the conventional wisdom about how one ought to *think about* that formalism. Chapter 3 is about the Einstein-Podolsky-Rosen argument and how that argument was stunningly undercut by Bell (and it is urged there, by the way, that what Bell's discovery actually amounts to is very frequently misunderstood; it is urged that Bell discovered something not merely about hidden-variable theories but also about *quantum mechanics,* and also about *the world*). Finally, Chapter 4 explicitly sets up the measurement problem.

The rest of the book (which is the *bulk* of the book) is taken up with investigations of those ideas about what to *do* about the measurement problem which seem to me to have some possibility of being right: Chapter 5 is an account and a critique of the idea of the collapse of the wave function (with a detailed discussion of the recent breakthrough of Ghirardi, Rimini, and Weber). Chapter 6 is about a certain very confused but nonetheless (I want to argue) very interesting tradition of thinking about the measurement problem which is (misleadingly) called the "many-worlds" interpretation of quantum mechanics. Chapter 7 is about a completely deterministic replacement for quantum mechanics due to de Broglie and Bohm and Bell. And Chapter 8 is about what the mental lives of sentient observers can potentially be like, if either one of the proposals discussed in Chapters 6 and 7 should actually happen to pan out.

Lots of people helped me out with this. Let me mention a few.

Barry Loewer is the one who first suggested that this book be written, and he has (astonishingly) been willing to spend many hours of his time talking about it with me, and many of the original ideas in it are (as the reader will learn from the references) partly his; and if not for all that, it simply could not have come into being.

I've learned a great deal about the foundations of quantum mechanics from innumerable conversations, over many years, with (first and foremost) Yakir Aharonov, and also with Hilary Putnam, David Deutsch, Irad Kimchie, Marc Albert, Gary Feinberg, Lev Vaidman, Sidney Morgenbesser, Isaac Levi, Shaughn Lavine, and Jeff Barrett, and also with students in some classes I've taught.

I am much indebted to Andrea Kantrowitz for doing such a great job with the illustrations; and I am thankful to Lindsay Waters and Alison Kent and especially Kate Schmit of Harvard University Press, without whose help and understanding this would have been a much less valuable book.

And maybe it ought to be mentioned that this book was written in the hope of finally being able to explain these matters to the reasonable satisfaction of my uncle, the physicist Arthur Kantrowitz, who first got me interested in science.

a bird is a bird
slavery means slavery
a knife is a knife
death remains death

—Zbigniew Herbert

... 1 ...

Superposition

Here's an unsettling story (the *most* unsettling story, perhaps, to have emerged from any of the physical sciences since the seventeenth century) about something that can happen to electrons. The story is true. The experiments I will describe have all actually been performed.[1]

The story concerns two particular physical properties of electrons which it happens to be possible to measure (with currently available technology) with very great accuracy. The precise physical definitions of those two properties don't matter. Let's call one of them the "color" of the electron, and let's call the other one its "hardness."[2]

It happens to be an empirical fact that the color property of electrons can assume one of only two possible values. Every electron which has thus far been encountered in the world has been either a black electron or a white electron. None have ever been

---

[1] As a matter of fact, not all of these experiments have actually been carried out on *electrons;* in some cases the particles involved were neutrons, and in other cases the "particles" were atoms of silver. Nonetheless, all the experiments described in this story have actually been carried out on one sort of particle or another; and as the reader shall see, the identities of the particles will turn out to be completely irrelevant to our concerns here.

[2] One of the properties I have in mind here is (as it happens) the angular momentum with which the electron is spinning about an axis which passes through its center and which runs along the x-direction, and the other one is the angular momentum with which the electron is spinning about an axis which passes through its center and which runs along the y-direction. But all that (as I said) doesn't matter. There are lots of different measurable properties of physical systems that could serve our purposes here just as well.

found to be blue or green. The same goes for hardness. All electrons are either soft ones or hard ones. No one has ever seen an electron whose hardness value was anything other than one of those two.

It's possible to build something called a "color box," which is a device for measuring the color of an electron and which works like this: The box (see figure 1.1) has three apertures. Electrons are fed into the box through the aperture on the left, and every black electron fed in through that aperture exits (along the indicated dashed line) through the aperture marked *b*, and every white electron fed in through that aperture on the left exits through the aperture marked *w*; and so the color of any electron which is fed in through that aperture on the left can later be inferred from its final position. It's possible to build "hardness boxes" too, and they work in just the same way (see figure 1.2).

Measurements with hardness and color boxes are repeatable, which is something we've grown accustomed to requiring, by definition, of a "good" measurement of a bona fide physical variable. If, say, a certain electron is measured with a color box to be black, and if that electron (without having been tampered with in the meantime) is subsequently fed into the left aperture of another

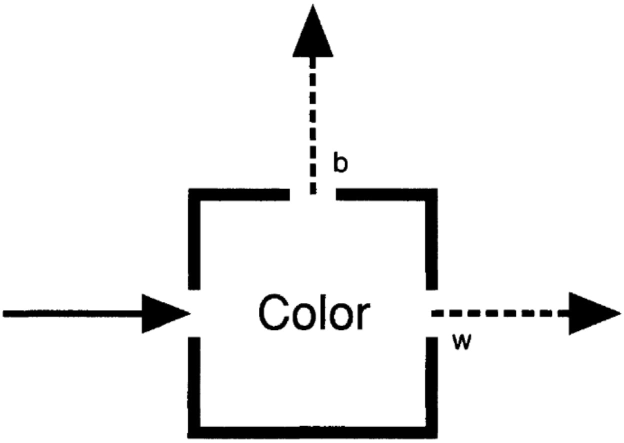

Figure 1.1

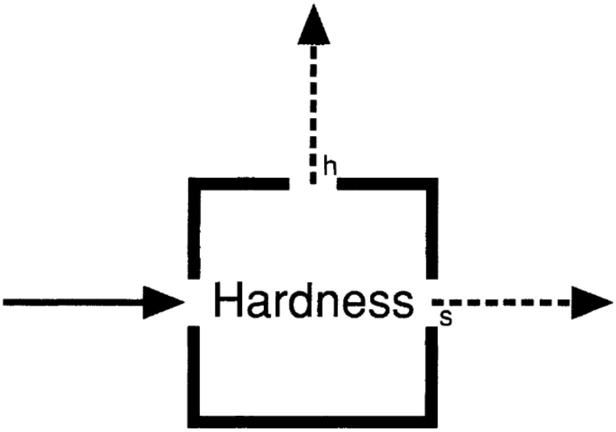

Figure 1.2

color box, then that electron will with certainty emerge from that second color box through the *b* aperture as well. The same goes for white electrons, and the same goes (with hardness boxes) for hard and soft electrons too. All that can be (and has been) confirmed by means of tests with those boxes.

Now, suppose that it occurs to us to be curious about the possibility that the color and hardness properties of electrons might somehow be related to one another. One way to look for such a relation might be to check for *correlations* between the values of the hardness and color properties of electrons. It's easy to check for correlations like that with our boxes; and it turns out (once the checking is done) that no such correlations exist. Of any large collection of, say, white electrons, all of which are fed into the left aperture of a hardness box, precisely half emerge through the hard aperture, and precisely half emerge through the soft one. The same goes for black electrons fed into the left aperture of a hardness box, and the same for hard or soft ones fed into the left apertures of color boxes. The color (hardness) of an electron apparently entails nothing whatever about its hardness (color).

Suppose we set up a sequence of three boxes. First a color box, say, then a hardness box, and then another color box. Consider an electron which emerges through the white aperture of the first color box, and thereafter (without having been tampered with)[3] is fed into the left aperture of the hardness box, and which happens to emerge from *that* box through the soft aperture (as half of such electrons will), and thereafter (once again with no tampering) is fed into the left aperture of the second color box. That electron, as it enters that third box, is presumably known to be both white and soft. As there has been no tampering between boxes here, we should expect that the electron will emerge from this third box through the white aperture, confirming the result of the first measurement. As a matter of fact, that isn't what happens. Precisely half of such electrons emerge from the white aperture of that third box, and the other half (the other half, that is, of those electrons which have been measured to be white and soft by the previous two boxes) emerge from the black aperture. The same goes for any other pair of results in the first two boxes, and the same goes if the color boxes in the above example are replaced with hardness boxes and the hardness box with a color one. Apparently (in the example we considered) the presence of the hardness box between the two color boxes *itself* constitutes some sort of color tampering. Indeed, that hardness box must be what's to blame for changing half of those white electrons to black ones, since we already know that two color measurements, without tampering between the boxes and without an intervening hardness measurement, will invariably produce identical results!

Perhaps the hardness box is poorly built, *crudely* built. It seems to do its job of measuring hardness (without disturbing the hardness in that process) well; but in the course of doing that job it apparently does disrupt color. That raises two questions. First, whether hardness boxes can be built less crudely; whether the job of measuring hardness can be accomplished more delicately, whether it can be accomplished without disrupting color. Second, in the case of this "crude" apparatus, this apparatus which changes the colors of fully half of the electrons whose hardnesses it mea-

---

[3] Exactly what constitutes "tampering" and what doesn't is (of course) something one learns, at first, by *experience.*

sures: what is it that determines precisely *which* electrons have their colors changed and which don't?

Let's talk about the second question first. The right way to discover precisely what it is that determines which electrons change color in passing through that intermediate hardness box and which don't would seem to be to monitor very carefully all of the measurable properties of all of the electrons which are fed into that first color box in the course of some particular experiment and which are at that point found to be, say, white; and to make very certain that the physical states of those three boxes are held perfectly and constantly fixed throughout that experiment; and to look for correlations between the measurable physical properties of those incoming electrons and their final positions as they emerge from the second color box. Well, it turns out that, in so far as we are presently able to tell, absolutely no such correlations exist. As a matter of fact, when we take whatever pains we know how to take to insure that all of the electrons in some particular experiment are fed into that first color box with precisely identical sets of physical properties, and to insure that the physical states of those boxes are indeed held precisely and constantly fixed throughout that experiment, the statistics of final outcomes remain precisely as they were described above. In so far as we are now able to determine, then, this second question has no answer. That is, in so far as we are now able to determine, those electrons whose color is changed by passage through a hardness box and those electrons whose color isn't changed by passage through a hardness box need not initially differ from one another in any way whatever.

Let's try the first question. Can hardness boxes be built less crudely? Well, hardness boxes can be built in a number of entirely different ways. We can try each one. It turns out that they all produce the statistics described above. All of those boxes change the color of (statistically) precisely half of the electrons which pass through them. We can try to be much more careful and much more precise in constructing our hardness boxes, but it turns out that that doesn't change anything either. What's striking here isn't that we are unable to build hardness boxes which don't disturb the color of electrons at all, but rather that we are unable to move the statistics of color disruption even so much as one millionth of one percentage point away from fifty-fifty, in either direction, no matter what we try. So long as the device at hand fulfills the *definitional* requirements of a hardness box (that is: so long as it's a device with which the hardnesses of electrons can be determined, repeatably), then the color randomization produced by that device has always, in our experience, been total; and all of the same goes for the effects of color boxes on hardness.

Suppose we wanted to build a color-*and*-hardness box; that is, a device with which both the color *and* the hardness of electrons could be determined. That box would need five apertures (see figure 1.3); one (on the left) where the electrons are taken in, one where white and hard electrons emerge, one where white and soft ones emerge, one where black and hard ones emerge, and one where black and soft ones emerge.

Consider how we could build a box like that. A box like that would seem to need to consist of a hardness box and a color box. But if the incoming electrons are made to pass first through, say, the hardness box, then their hardnesses might subsequently be

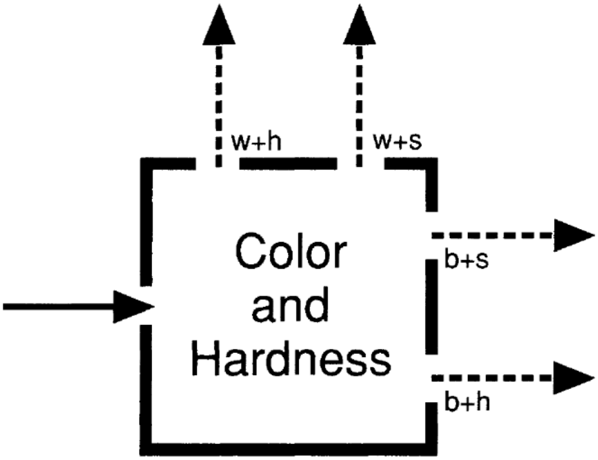

Figure 1.3

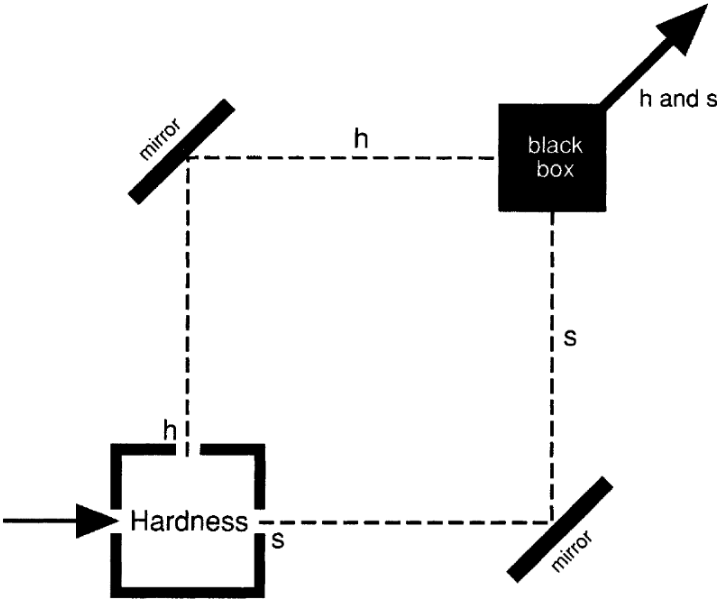

Figure 1.4

changed when they pass through the color box, and we would end up with reliable information only about the colors of the emergent electrons. If we put the color box first, we would end up with reliable information only about the hardnesses. Nobody's been able to think of any *other* ways to build a color-and-hardness box, and it's hard to imagine how, in principle, there could be other ways (other, that is, than building them out of color boxes and hardness boxes). So the task of putting ourselves in a position to say "the color of this electron is now such-and-such and the hardness of this electron is now such-and-such" seems to be fundamentally beyond our means.

That fact is an example of the *uncertainty principle.* Measurable physical properties like color and hardness are said to be "incompatible" with one another, since measurements of one will (so far as we know) always necessarily disrupt the other.

O.K. Let's get in deeper. Consider the rather complicated device

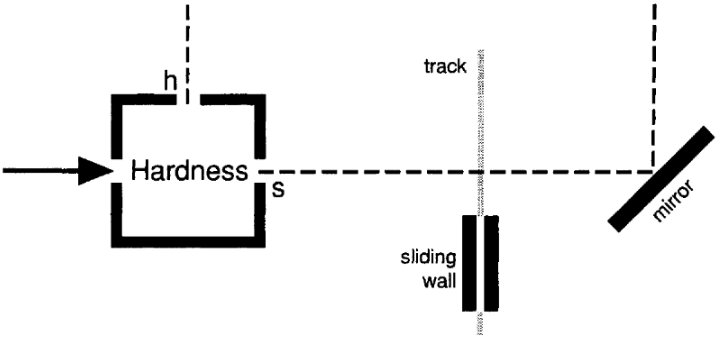

Figure 1.5

since we can easily verify that whether the wall is in or out of *s* can have no effect on the colors of electrons traveling along *h*, that implies that those remaining 50 percent should all be white.

What actually happens when we do the experiment? Well, the output is down by 50 percent, as we expect. But the remaining 50 percent is not all white. It's half white and half black. The same thing happens, similarly contrary to our expectations, if we insert a wall in the hard path instead.

Now we're in real trouble.

Consider an electron which passes through our apparatus when the wall is out. Consider the possibilities as to which route that electron can have taken. Can it have taken *h*? Apparently not, because electrons which take *h* (as we've just seen again) are known to have the property that their color statistics are fifty-fifty, whereas an electron passing through our device with the wall out is known to have the property of being white at *h and s*! Can it have taken *s*, then? No, for the same reasons. Can it somehow have taken *both* routes? Well, suppose that when a certain electron is in the midst of passing through this apparatus, we stop the experiment and look to see where it is. It turns out that half the time we find it on *h*, and half the time we find it on *s*. We never find two electrons in there, or two halves of a single, split electron, one on each route, or anything like that. There isn't any sense in which the electron seems to be taking both routes. Can it have taken neither route?

Certainly not. If we wall up *both* routes, nothing gets through at all.

So what we're faced with is this: Electrons passing through this apparatus, in so far as we are able to fathom the matter, do not take route *h* and do not take route *s* and do not take both of those routes and do not take neither of those routes; and the trouble is that those four possibilities are simply all of the logical possibilities that we have any notion whatever of how to entertain!

What can such electrons be doing? It seems they must be doing something which has simply never been dreamt of before (if our experiments are valid, and if our arguments are right). Electrons seem to have modes of being, or modes of moving, available to them which are quite unlike what we know how to think about.

The name of that new mode (which is just a name for something we don't understand) is *superposition.* What we say about an initially white electron which is now passing through our apparatus with the wall out is that it's not on *h* and not on *s* and not on both and not on neither, but, rather, that it's in a superposition of being on *h and* being on *s*. And what that means (other than "none of the above") we don't know. And some of what this book is going to be about are a number of attempts to (as it were) say something more about superposition than that.

Let's make the main point (which is that superpositions are *extraordinarily* mysterious situations) one or two more times.

Here's a second example. It's possible to construct boxes which I'd like to call "total-of-nothing" boxes. A total-of-nothing box is a box with two apertures. An electron which is fed into one aperture emerges from the other with all of its measurable properties (color, hardness, velocity, whatever) *unchanged;* and the time of passage through the box for any electron is equal to the time it would have taken for that electron to traverse an empty space the size of the box. Those are the defining properties of total-of-nothing boxes.

Clearly, there are lots of ways to build total-of-nothing boxes. A completely empty box with two holes in it is a total-of-nothing box. We can also imagine building boxes which do all sorts of violent things to the electrons fed into them but which subsequently *undo* all those things and finally eject those electrons, at the right times, at the right speeds, with all of their original physical properties. Every box like that will be a total-of-nothing box too.

Now, recall the two-path apparatus of figure 1.4. White electrons fed into that apparatus always come out white. It turns out to be possible to build a total-of-nothing box which, when inserted into either one of those two paths, will make all of those outgoing electrons black instead of white. If the box is removed from the path, the outgoing electrons will all go back to being white.[4] So, inserting such a box into one of those paths will change the color of an electron passing through this two-paths apparatus. But total-of-nothing boxes, by definition, change none of the properties of electrons which pass through them; and, of course, total-of-nothing boxes change none of the properties of electrons which *don't* pass through them! So it isn't possible that these electrons pass through the total-of-nothing box on one of the paths, since in that event their colors couldn't have been changed from white to black by the presence of the box; and it isn't possible that those electrons pass outside of the box, since in *that* event their colors couldn't have been changed either! And it isn't possible (by our earlier arguments) that those electrons pass both inside and outside of the box, and it isn't possible that they pass neither inside *nor* outside of the box.

Here's one final example, a very well-known one. Consider an arrangement such as is depicted in figure 1.6. On the left is a source of electrons. Electrons emerge from that source in a whole spectrum of possible directions, as shown. Slightly farther to the right is a screen which electrons cannot pass through, and that screen has two holes in it. Still farther to the right is a fluorescent screen, much like a television screen, which lights up, at the point of impact, whenever it is struck by an electron (that is, this fluorescent screen is a *measuring device* for the positions of electrons).

Suppose, first, that the top hole in the first screen is closed up, as in figure 1.6A. Electrons emerge, one by one, from the source,

---

[4] That there can be boxes like that was first predicted in a famous paper of Aharonov and Bohm (1959).

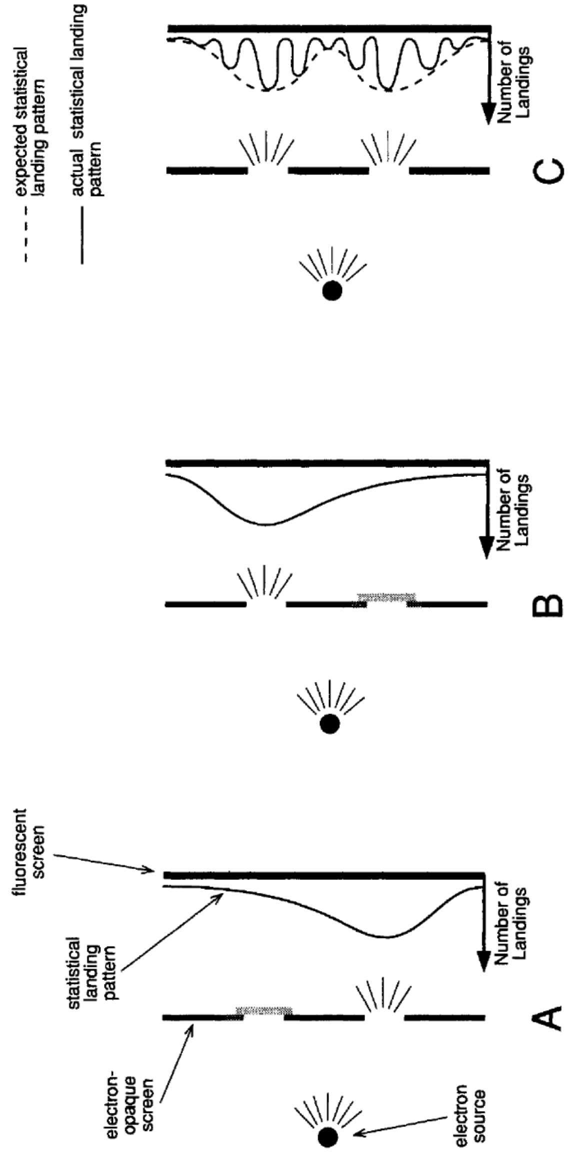
electron source
electron-opaque screen
statistical landing pattern
fluorescent screen
Number of Landings
A
Number of Landings
B
- - - expected statistical landing pattern
—— actual statistical landing pattern
Number of Landings
C

Figure 1.6

and move toward the first screen. Most of them run into the screen and are stopped there. Some get through the hole. Those latter land at various points on the fluorescent screen. The statistics of those landings (that is: how many land in any particular region) are shown in the figure. Figure 1.6B gives the same information for the case when the bottom hole is closed instead of the top one.

What sort of landing statistics should we expect when *both* holes are open? Well, all of the electrons which arrive at the fluorescent screen will have passed either through the top hole or through the bottom one. Those which pass through the bottom hole are known (by our first experiment with this apparatus) to give rise to the statistical landing pattern of figure 1.6A; and those which pass through the top hole are known to give rise to the statistical landing pattern of figure 1.6B; and so, in the event that both holes are open (and in the event that only one electron is allowed to pass through this apparatus at a time), we should expect a statistical landing pattern which is the direct sum of those two (as shown in figure 1.6C). But that (it will be no surprise by now) is not what happens. The statistical landing pattern which emerges on the fluorescent screen when both holes are open is markedly different from the direct sum of patterns A and B. So, it's inconsistent with these experimental results to suppose that an electron passing through this apparatus passes through the upper hole when both holes are open; and it is inconsistent with these experimental results to suppose that an electron passing through this apparatus passes through the lower hole when both holes are open. And the same sorts of experiments and arguments as were described above will entail that it also can't be maintained that such electrons pass through both holes, and that it also can't be maintained that they pass through neither hole.

These electrons are (then) in superpositions of passing through the upper hole and passing through the lower one; but (once again) we have no idea, or rather only a negative idea, of what that means.

All this stuff about superpositions, by the way, sheds a very curious light on the phenomena of uncertainty and incompatibility (be-

••• 2 •••

The Mathematical Formalism and the Standard Way of Thinking about It

There is an algorithm (and the name of that algorithm, of course, is quantum mechanics) for predicting the behaviors of physical systems, which correctly predicts all of the unfathomable-looking behaviors of the electron in the story in Chapter 1, and there is a standard way of interpreting that algorithm (that is, a way attempting to fathom those behaviors, a way of attempting to confront the fact of superposition) which can more or less be traced back to some sayings of Niels Bohr.[1] This chapter will describe that algorithm and rehearse that standard way of talking about it, and then it will apply them both, in some detail, to that story.

Mathematical Preliminaries

Let me say a few things, to begin with, about the particular mathematical language in which it is most convenient to write the algorithm down.

Let's start with something about vectors. A good way to think about vectors is to think about arrows. A vector is a mathematical object, an abstract object, which (like an arrow) is characterized by

---

[1] The story of the evolution of this standard way of thinking is a very long and complicated one, and it will be completely ignored here. The far more obscure question of what Bohr himself really thought about these issues will be ignored too. What will matter for us is the legacy which Bohr and his followers have left, by whatever route, and whatever they themselves may have originally thought, to modern physics. That legacy, as it stands now, can be characterized fairly clearly. The name of that legacy is the Copenhagen interpretation of quantum mechanics.