The mystery of the quantum world

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Real are the dreams of Gods

John Keats
Lamia, I, 127

Adam Hilger Ltd
Bristol and Boston

British Library Cataloguing in Publication Data

Squires, Euan
The mystery of the quantum world.
1. Quantum theory
I. Title
530.1'2 QC174.12

ISBN 0-85274-565-6
ISBN 0-85274-566-4 Pbk

Published by Adam Hilger Ltd
Techno House, Redcliffe Way, Bristol BS1 6NX, England
PO Box 230, Accord, MA 02018, USA

Typeset by Mathematical Composition Setters Ltd, Salisbury
Printed in Great Britain by J W Arrowsmith Ltd, Bristol

Preface

This book is about physics. Within the limitations of our present knowledge, I believe that what it says about physics is correct. More particularly, it is about quantum physics; about the mysterious behaviour of the micro-world, and the strange properties of the quantum theory which predicts this behaviour. In an endeavour to understand the quantum world, we are led beyond physics, certainly into philosophy and maybe even into cosmology, psychology and theology. Here I am not sure that there are clear criteria of what it means to be 'correct', and even if there are, I have less confidence that what is said will always satisfy these criteria. I have ventured into these areas because the issues raised by quantum physics are relevant, important and interesting.

Quantum phenomena challenge our primitive understanding of reality; they force us to re-examine what the concept of existence means. These things are important, because our belief about what *is* must affect how we see our place within it, and our belief about what we are. In turn, what we *believe* we are ultimately affects what we *actually* are and, therefore, how we behave. Nobody should ignore physics.

E J Squires

Acknowledgments

I have had useful discussions with many people during the writing of this book. In particular, I would like to thank Peter Collins, Peter Rowe, Barry Gower and Timothy Squires, all of whose comments on earlier attempts have contributed significantly to the final version.

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Chapter One

Reality in the Quantum World

1.1 The quantum revolutions

Quantum mechanics, created early this century in response to certain experimental facts which were inexplicable according to previously held ideas (conveniently summarised by the title 'classical physics'), caused three great revolutions. In the first place it opened up a completely new range of phenomena to which the methods of physics could be applied: the properties of atoms and molecules, the complex world of chemical interactions, previously regarded as things given from outside science, became calculable in terms of a few fixed parameters. The effect of this revolution has continued successfully through the physics of atomic nuclei, of radioactivity and nuclear reactions, of solid-state properties, to recent spectacular progress in the study of elementary particles. In consequence all sciences, from cosmology to biology, are, at their most fundamental level, branches of physics. Through physics they can, at least in principle, be understood. Indeed, on contemplating the success of physics, it is easy to be seduced into the belief that 'everything' is physics—a belief that, if it is intended to imply that everything is understood, is certainly false, since, as we shall see, the very foundation of contemporary theoretical physics is mysterious and incomprehensible.

The second revolution was the apparent breakdown of *determinism*, which had always been an unquestioned ingredient and an inescapable prediction of classical physics. Note that we are using the word 'determinism' solely with regard to physical systems, without at this stage worrying about which systems can be so described; that is, we are not here concerned with such concepts as free will. In a deterministic theory the future behaviour of an isolated physical system is uniquely determined by its present state. If, however, the world is correctly described by quantum theory, then, even for simple systems, this deterministic property is not valid. The outcome of any particular experiment is not, even in principle, predictable, but is chosen at random from a set of possibilities; all that can be predicted is the probability of particular results when the experiment is repeated many times. It is important to realise that the probability aspects that enter here do so for a different reason than, for example, in the tossing of a coin, or throw of a dice, or a horse race; in these cases they enter because of our lack of precise knowledge of the orginal state of the system, whereas in quantum theory, even if we had complete knowledge of the initial state, the outcome would still only be given as a probability.

Naturally, physicists were reluctant to accept this breakdown of a cherished dogma—Einstein's objection to the idea of God playing dice with the universe is the most familiar expression of this reluctance—and it was suggested that the apparent failure of determinism in the theory was due to an incompleteness in the description of the system. Many attempts to remedy this incompleteness, by introducing what are referred to as 'hidden variables', have been made. These attempts will form an important part of our later discussion.

We are accustomed to regarding the behaviour, at least of simple mechanical systems, as being completely deterministic, so if the breakdown of determinism implied by quantum mechanics is genuine, it is an important discovery which must affect our view of the physical world. Nevertheless, our belief in determinism arises from experience rather than logic, and it is quite possible to conceive of a certain degree of randomness entering into mechanics; no obvious violation of 'common sense' is involved. Such is not the case with the third revolution brought about by quantum mechanics. This challenged the basic belief, implicit in all science and indeed in almost the whole of human thinking, that there exists an objective reality, a reality that does not depend for its existence on its being observed. It is because of this challenge that all who endeavour to study, or even take an interest in, reality, the nature of 'what is', be they philosophers or theologians or scientists, unless they are content to study a phantom world of their own creation, should know about this third revolution.

To provide such knowledge, in a form accessible to non-scientists, is the aim of this book. It is not intended for those who wish to learn the practical aspects of quantum mechanics. Many excellent books exist to cover such topics; they convincingly demonstrate the power and success of the theory to make correct predictions of a wide range of observed phenomena. Normally these books make little reference to this third revolution; they omit to mention that, at its very heart, quantum mechanics is totally inexplicable. For their purpose this omission is reasonable because such considerations are not relevant to the success of quantum mechanics and do not necessarily cast doubt on its validity. In 1912, Einstein wrote to a friend, 'The more success the quantum theory has, the sillier it looks.' [Letter to H Zangger, quoted on p 399 of the book *Subtle is the Lord* by A Pais (Oxford: Clarendon 1982).] If it is true that quantum mechanics is 'silly', then it is so because, in the terms with which we are capable of thinking, the world appears to be silly. Indeed the recent upsurge of interest in the topic of this book has arisen from the results of recent experiments; results which, though they beautifully confirm the predictions of quantum mechanics, are themselves, quite independent of any specific theory, at variance with what an apparently convincing, common-sense, argument would predict (see Chapter 5, especially §§5.4 and 5.5, for a complete discussion of these results).

We can emphasise the essentially observational nature of the problem we are discussing by returning to the experimental facts we mentioned at the start of this section, and which gave birth to quantum mechanics. Although, by abandoning some of the principles of classical physics, quantum theory *predicted* these facts, it did not *explain* them. The search for an explanation has continued and we shall endeavour in this book to outline the various possibilities. *All involve radical departures from our normal ways of thinking about reality.*

On almost all the topics which we shall discuss below there is a large literature. However, since this book is intended to be a popular introduction rather than a technical treatise, I have given very few references in the text but have, instead, added a detailed bibliography. For the same reason various *ifs* and *buts* and qualifying clauses, that experts might have wished to see inserted at various stages, have been omitted. I hope that these omissions do not significantly distort the argument.

I have tried to keep the discussion simple and non-technical, partly because only in this way can the ideas be communicated to non-experts, but also because of a belief that the basic issues are simple and that highly elaborate and symbolic treatments only serve to confuse them, or, even worse, give the impression that problems have been solved when, in fact, they have merely been hidden. The appendices, most of which require a little more knowledge of mathematics and physics than the main text, give further details of certain interesting topics.

Finally, I conclude this section with a confession. For over thirty years I have used quantum mechanics in the belief that the problems discussed in this book were of no great interest and could, in any case, be sorted out with a few hours careful thought. I think this attitude is shared by most who learned the subject when I did, or later. Maybe we were influenced by remarks like that with which Max Born concluded his marvellous book on modern physics [*Atomic Physics* (London: Blackie 1935)]: 'For what lies within the limits is knowable, and will become known; it is the world of experience, wide, rich enough in changing hues and patterns to allure us to explore it in all directions. What lies beyond, the dry tracts of metaphysics, we willingly leave to speculative philosophy.' It was only when, in the course of writing a book on elementary particles, I found it necessary to do this sorting out, that I discovered how far from the truth such an attitude really is. The present book has arisen from my attempts to understand things that I mistakenly thought I already understood, to venture, if you like, into 'speculative philosophy', and to discover what progress has been made in the task of incorporating the strange phenomena of the quantum world into a rational and convincing picture of reality.

1.2 External reality

As I look around the room where I am now sitting I *see* various objects. That is, through the lenses in my eyes, through the structure of the retina, through assorted electrical impulses received in my brain, etc, I experience sensations of colour and shape which I interpret as being caused by objects outside myself. These objects form part of what I call the 'real world' or the 'external reality'. That such a reality exists, independent from my observation of it, is an assumption. The only reality that I *know* is the sensations of which I am conscious, so I make an assumption when I introduce the concept that there are real external objects that cause these sensations. Logically there is no need for me to do this; my conscious mind could be all that there is. Many philosophers and schools of philosophy have, indeed, tried to take this point very seriously either by denying the existence of an external reality, or by claiming that, since the concept cannot be properly defined, proved to exist, or proved not to exist, then it is useless and should not be discussed. Such views, which as philosophic theories are referred to by words such as 'idealism' or 'positivism', are logically tenable, but are surely unacceptable on aesthetic grounds. It is much easier for me to understand my observations if they refer to a real world, which exist even when not observed, than if the observations are in fact everything. Thus, we all have an intuitive feeling that 'out there' a real world exists and that its existence does not depend upon us. We can observe it, interact with it, even change it, but we cannot make it go away by not looking at it. Although we can give no proof, we do not really doubt that 'full many a flower is born to blush unseen, and waste its sweetness on the desert air'.

It is important that we should try to understand why we have this confidence in the existence of an external reality. Presumably one reason lies in selective evolution which has built into our genetic make-up a predisposition towards this view. It is easy to see why a tendency to think in terms of an external reality is favourable to survival. The man who sees a tree, and goes on to the idea that there *is* a tree, is more likely to avoid running into it, and thereby killing himself, than the man who merely regards the sensation of seeing as something wholly contained within his mind. The fact of the built-in prejudice is evidence that the idea is at least 'useful'. However, since we are, to some extent, thinking beings, we should be able to find rational arguments which justify our belief, and indeed there are several. These depend on those aspects of our experience which are naturally understood by the existence of an external reality and which do not have any natural explanation without it. If, for example, I close my eyes and, for a time, cease to observe the objects in the room, then, on reopening them, I see, in general, the same objects. This is exactly what would be expected on the assumption that the objects exist and are present even when I do not actually look at them. Of course, some could have moved, or even been taken away, but in this case I would seek, and normally find, an explanation of the changes. Alternatively I could use different methods of 'observing', e.g. touch, smell, etc, and I would find that the same set of objects, existing in an external world, would explain the new observations. Thirdly, I am aware through my consciousness of other people. They appear to be similar to me, and to react in similar ways, so, from the existence of my conscious mind, I can reasonably infer the existence of real people, distinct from myself, also with conscious minds. Finally, these other people can communicate to me their observations, i.e. the experiences of their conscious minds, and these observations will in general be compatible with the same reality that explains my own observations.

In summary, it is the *consistency* of a vast range of different types of observation that provides the overwhelming amount of evidence on which we support our belief in the existence of an external reality behind those observations. We can contrast this with the situation that occurs in hallucinations, dreams, etc, where the lack of such a consistency makes us cautious about assuming that these refer to a real world.

We turn now to the scientific view of the world. At least prior to the onset of quantum phenomena this is not only consistent with, but also implicitly assumes, the existence of an external reality. Indeed, science can be regarded as the continuation of the process, discussed above, whereby we explain the experiences of our senses in terms of the behaviour of external objects. We have learned how to observe the world, in ever more precise detail, how to classify and correlate the various observations and then how to explain them as being caused by a real world behaving according to certain laws. These laws have been deduced from our experience, and their ability to predict new phenomena, as evidenced by the enormous success of science and technology, provides impressive support for their validity and for the picture of reality which they present.

This beautifully consistent picture is destroyed by quantum phenomena: Here, we are amazed to find that one item, crucial to the whole idea of an external reality, appears to fail. It is no longer true that different methods of observation give results that are consistent with such a reality, or at least not with a reality of the form that had previously been assumed. No reconciliation of the results with an acceptable reality has been found. This is the major revolution of quantum theory, and, although of no immediate practical importance, it is one of the most significant discoveries of science and nobody who studies the nature of reality should ignore it.

It will be asked at this stage why such an important fact is not immediately evident and well known. (Presumably if it had been then the idea of creating a picture of an external reality would not have arisen so readily.) The reason is that, on the scale of magnitudes to which we are accustomed, the new, quantum effects are too small to be noticed. We shall see examples of this later, but the essential point is that the basic parameter of quantum mechanics, normally denoted by $\hbar$ ('*h* bar') has the value 0.000 000 000 000 000 000 000 000 001 (approximately) when measured in units such that masses are in grams, lengths in centimetres and times in seconds. (Within factors of a thousand or so, either way, these units represent the scale of normal experience.) There is no doubt that the smallness of this parameter is partially responsible for our difficulty in understanding quantum phenomena—our thought processes have been developed in situations where such phenomena produce effects that are too small to be noticed, too insignificant for us to have to take them into account when we describe our experiences.

1.3 The potential barrier and the breakdown of determinism

We now want to describe a set of simple experiments which demonstrate the crucial features of quantum phenomena. To begin we suppose that we have a flat table on which there is a smooth 'hill'. This is illustrated in figure 1. If we roll a small ball, from the right, towards the hill then, for low initial velocities, the ball will roll up the hill, slowing down as it does so, until it stops and then rolls back down again. In this case we say that the ball has been *reflected*. For larger velocities, however, the ball will go right over the hill and will roll down the other side; it will have been *transmitted*.

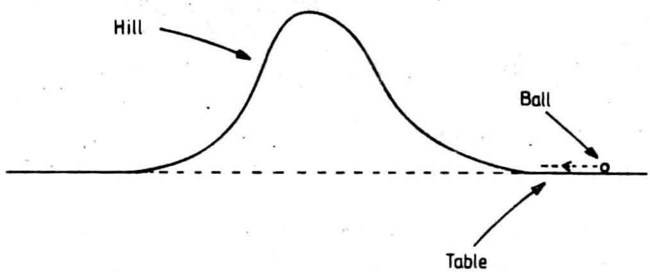

Figure 1 A simple example of a potential barrier experiment, in which a ball is rolled up a hill. The ball will be reflected or transmitted by the hill according to whether the initial velocity is less or greater than some critical value.

By repeating this experiment several times we readily find that there is a critical velocity, which we shall call V, such that, if the initial velocity is smaller than V then the ball will be reflected, whereas if it is greater than V then it will be transmitted. We can write this symbolically as

$$\begin{aligned} v < V&: \text{reflection} \\ v > V&: \text{transmission} \end{aligned} \tag{1.1}$$

where v denotes the initial velocity, and the symbols $<$, $>$ mean 'is less than', 'is greater than', respectively.

The force that causes the ball to slow down as it rises up the hill is the gravitational force, and it is possible to calculate V from the laws of classical physics (details are given in Appendix 1). Similar results would be obtained with any other type of force. What is actually happening is that the energy of motion of the ball (called kinetic energy) is being changed into energy due to the force (called potential energy). The ball will have slowed to zero velocity when all the kinetic energy has turned into potential energy. Transmission happens when the initial kinetic energy is greater than the maximum possible potential energy, which occurs at the top of the hill. In the general case we shall refer to this type of experiment as reflection or transmission by a *potential barrier*.

Now we introduce quantum physics. The simple result expressed by equation (1.1), which we obtained from experiment and which is in agreement with the laws of classical mechanics, is not in fact correct. For example, even when $v < V$ there is a possiblity that the particle will pass through the barrier. This phenomenon is sometimes referred to as *quantum tunnelling*. The reason why we would not see it in our simple laboratory experiment is that with objects of normal sizes (which we shall refer to as 'macroscopic' objects), i.e. things we can hold and see, the effect is far too small to be noticed. Whenever v is measurably smaller than V the probability of transmission is so small that we can effectively say it will never happen. (Some appropriate numbers are given in Appendix 4.)

With 'microscopic' objects, i.e. those with atomic sizes and smaller, the situation is very different and equation (1.1) does not describe the results except for sufficiently small, or sufficiently large, velocities. For velocities close to V we find, to our surprise, that the value of v does not tell us whether or not the particle will be transmitted. If we repeat the experiment several times, always with a fixed initial velocity (v) we would find that in some cases the particle is reflected and in some it is transmitted. The value of v would no longer determine precisely the fate of the particle when it hits the barrier; rather it would tell us the *probability* of a particle of that velocity passing through. For low velocities the probability would be close to zero, and we would effectively be in the classical situation; as the velocity rose towards V the probability of transmission would rise steadily, eventually becoming very close to unity for v much larger than V, thus again giving the classical result.

Before we comment on the implications of these results, it is worth considering a more readily appreciated situation which is in some ways analogous. On one of the jetties in the lake of Geneva there is a large fountain, the 'Jet d'eau'. The water from this tends