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The Quantum World

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What does it mean?

If you thought that science was invariably characterised by clarity of vision you may have found the quantum world unexpectedly murky. The brilliant calculational successes can seem a little brittle when they are coupled with the degree of conceptual confusion still present. What does quantum mechanics really have to say about the nature of the physical world? We have to confess that we are at a stage of understanding where any answer must be to some extent tentative.

There are two possible lines of attack, of either positivist or realist tone. The positivist approach lays stress on perceptions which can be inter-subjectively agreed; its tests of meaning and truth rely upon the specification of observable procedures. Such content as it attaches to physical reality is to be interpreted in terms of the experience of an observer; its quest is for the harmonisation of such experience. The world it presents is populated by pointers on scales and marks on photographic plates. The observer disposes the apparatus and takes the readings. His is the central role.

It is a curiously unreal state of affairs, a world that none of us lives in outside the study. As Feynman has said, we are asked to believe that the historian who makes a statement about Napoleon simply means that there are books in libraries which make assertions similar to his own. There is no past; there are only sources.

The approach to quantum theory which is most positivist in its outlook is that of the Copenhagen school, with its emphasis on the role of classical measuring instruments. The very choice by an observer of the disposition of these instruments is considered fundamental to the nature of what is going on, as we saw when we considered Bohr's understanding of the EPR experiment (p. 72). In his public utterances Bohr was always very cautious about committing himself to what it is that actually *is*. He never made ontological

pronouncements. He preferred to think of quantum theory as a calculational procedure, writing that†

> The entire formalism is to be regarded as a tool for deriving predictions, of definite or statistical character, as regards information obtainable under experimental conditions described in classical terms.

However, in private conversation with a friend, Aage Petersen, he went further and declared

> There is no quantum world. There is only an abstract quantum physical description. It is wrong to think that the task of physics is to find out how nature *is*. Physics concerns what we can say about nature.

The austerity of the positivist programme may at first sight seem highly scientific, with its rigid adherence to what can be measured and its banishing of all that is not the immediate fruit of experience. In fact, it is more characteristic of natural history than of science to be content with the patient observation of phenomena without seeking an underlying understanding of the originating reality. If in the end science is just about the harmonious reconciliation of the behaviour of laboratory apparatus, it is hard to see why it is worth the expenditure of effort involved. I have never known anyone working in fundamental science who was not motivated by the desire to understand the way the world is. The point has been well put by Bernard D'Espagnat in his book *Conceptual Foundations of Quantum Mechanics*. Speaking of the activities of elementary particle physicists, he writes that

> whereas the activity appears essential as long as we believe in the independent existence of fundamental laws that we can still hope to know better, it loses practically its whole motivation as soon as we believe that the sole objective of the scientists is to make their impressions mutually consistent. These impressions are not of a kind that occur in our daily life. They are extremely special, are produced at great cost, and it is doubtful that the mere pleasure their harmony gives to a selected happy few is worth such large public expenditure.

Or, I would add, were the positivist view correct, the dedication and toil of those involved. Let us see then whether realism can offer a more fruitful alternative.

A realist approach lays stress on the belief that the world has an

† This and the subsequent quotation are culled from the plentiful stock provided by Max Jammer in *The Philosophy of Quantum Mechanics*.

existence independent of any observer; that it stands over against us as an entity in its own right. The content it attaches to physical reality makes the natural world autonomous; its quest is to determine what *is*. The world it presents is populated by entities such as electrons and quarks. By observation we can probe this world and attempt to discern the laws which regulate it. The observer has to submit himself to the way things are.

Unquestionably such a view corresponds to the motivation of science and the way that scientists talk about their discoveries. However we have seen that quantum theory places considerable restraint on a plain man's objectivist view of the natural world. The states of motion permitted to its particles cannot be characterised by straightforward assignment of position and momentum. These states of motion are subject to instantaneous change through the act of measurement, in a process for which we cannot claim to have discovered an exhaustive and convincing interpretation. Despite the atomising tendency of fundamental physics, with its motto 'divide and rule', we have found that the EPR experiment points to a surprisingly integrationist view of the relationship of systems which have once interacted with each other, however widely they may subsequently separate. Even the classical certainties of laboratory apparatus present us with a mystery when we recognise that we do not fully comprehend how they arise from the quantum substrate of which they are composed.

Perhaps some modest help can be obtained from reconsidering how it is that practitioners of quantum mechanics actually go about their trade. We tried in Chapter 3 to give an account of their procedures. The wavefunction (or state vector, in the more abstract language) plays a fundamental role. When a quantum mechanic thinks about what an electron is 'doing' he is thinking about what sort of wavefunction is associated with it. Now, we would all agree that the wavefunction is not a directly physical object in the sense that a billiard ball is a physical object. Indeed the rules of quantum theory do not even allot a unique wavefunction to a given state of motion, since multiplying the wavefunction by a certain factor (technically, a factor of modulus unity) does not change any physical consequence. However it is also difficult to think of a wavefunction as a *mere* calculational device, in the way that Bohr's words quoted above suggested. Its status is somehow intermediate. Heisenberg had something helpful to say on this question. He was a loyal member of the Copenhagen school but he displayed a greater

flexibility than most in the expression of his understanding. He once wrote

> In the experiments about atomic events we have to do with things and facts, with phenomena which are just as real as any phenomena in daily life. But the atoms or elementary particles are not as real; they form a world of potentialities or possibilities rather than one of things or facts.

Let us take the second half of his concluding sentence first. Here Heisenberg refers to a notion to which he often had recourse, that quantum mechanics had revived Aristotle's old idea of *potentia*. Quantum objects do not act as carriers of classical quantities such as position and momentum (their wavefunctions are not usually eigenstates of these observables) but they do carry the potentiality for such quantities (their wavefunctions are always superpositions of such eigenstates). It is as though the programme of Galileo and Locke, which involved discarding secondary qualities (colour, taste, etc.) in favour of primary qualities (the quantities of classical mechanics), had been carried a stage further and these primary qualities had themselves become secondary to the property of *potentia* in which they all lay latent.

The first part of Heisenberg's concluding sentence shows that he felt that such a view fell short of attributing reality to elementary particles. Perhaps that was too grudging a position. It may be that we can seek help from what to some of my readers might seem an unlikely source. A theologian, Eric Mascall, in his book *Christian Theology and Natural Science*, wrote about such problems that

> the point is that, although a physicist knows the objective world only through the mediation of sensation, the essential character of the objective world is not sensibility but intelligibility. Its objectivity is not manifested by observers having the same sensory experience of it, but by their being able, through their diverse sensory experiences to acquire a common *understanding* of it.

I think this emphasis on intelligibility as the clue to reality is very much to the point.

The wavefunction is the vehicle of our understanding of the quantum world. Judged by the robust standards of classical physics it may seem a rather wraith-like entity. But it is certainly the object of quantum mechanical discourse and, for all the peculiarity of its collapse, its subtle essence may be the form that reality has to take on the atomic scale and below. Anyone who has had to teach a mathematically based subject will know the difficulties which students encounter in negotiating a new level of abstraction. They have met the idea of a vector as a crude arrow. You now explain to them that it is better thought of as an object with certain transformation properties under rotations. 'But what is it *really*?' they say. You implore them to believe that it is an object with certain transformation properties under rotations. They do not believe you; they think that you are holding back some secret clue that would make it all plain. Time and experience are great educators. A year later the student cannot conceive why he had such difficulty and suspicion about the nature of vectors. Perhaps we are in the midst of a similar, if much longer drawn out, process of education about the nature of quantum mechanical reality. If we are indeed in such a digestive, living-with-it, period it would explain something which is otherwise puzzling. A great many theoretical physicists would be prepared to express some unease about the conceptual foundations of quantum mechanics – in particular, about Copenhagen orthodoxy – but only a tiny fraction of them ever direct serious attention to such questions. Perhaps the majority are right to submit themselves to a period of subliminal absorption.

I do not pretend that these notions can do more than offer a way of thinking about the quantum world with some hope of doing justice both to the idiosyncracy of its ways and also to the beautiful structure of the microworld which has been laid bare by the *discoveries* of elementary particle physics.

Appendix

Some mathematical knowledge, including an elementary grasp of the calculus, adds considerably to one's ability to understand the details of quantum theory. The following paragraphs present additional material accessible to readers with such a background.

A1 The Bohr atom

Consider an electron of charge $-e$ and mass m moving in a circle around a proton of charge e which is sufficiently massive to be treated as fixed. (The mass of the proton is 1836 times the mass of the electron so that this is a good approximation.) Let the radius of the circle be r and the velocity of the electron v. The electrostatic attraction between the electron and the proton must exactly match the electron's mass times its centrifugal acceleration in the circular orbit:

$$\frac{e^2}{r^2} = m\frac{v^2}{r}, \qquad \text{[A1.1a]}$$

or

$$e^2 = mv^2r. \qquad \text{[A1.1b]}$$

The energy of the electron is made up of its kinetic and electrostatic potential energies:

$$E = \frac{1}{2}mv^2 - \frac{e^2}{r}, \qquad \text{[A1.2]}$$

which, by [A1.1b], reduces to

$$E = -\frac{e^2}{2r}. \qquad \text{[A1.3]}$$