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The strange world of the quantum

What is quantum theory?

The word 'quantum' means 'a quantity' or 'a discrete amount'. On an everday scale we are accustomed to the idea that the properties of an object such as its size, weight, colour, temperature, surface area, and motion are all qualities which can vary from one object to another in a smooth and continuous way. Apples, for example, come in all manner of shapes, sizes and colours without any noticeable gradations in between.

On the atomic scale, however, things are very different. The properties of atomic particles such as their motion, energy and spin do not always exhibit similar smooth variations, but may instead differ in discrete amounts. One of the assumptions of classical Newtonian mechanics was that the properties of matter are continuously variable. When physicists discovered that this notion breaks down on the atomic scale they had to devise an entirely new system of mechanics – quantum mechanics – to take account of the lumpiness which characterizes the atomic behaviour of matter. Quantum theory, then, is the underlying theory from which quantum mechanics is derived.

Considering the success of classical mechanics in describing the dynamics of everything from billiard balls to stars and planets, it is not surprising that its replacement by a new system of mechanics on the atomic scale was considered to be a revolutionary departure. Nevertheless, physicists rapidly proved the value of the theory by explaining a wide range of otherwise incomprehensible phenomena, so much so that today quantum theory is often cited as the most successful scientific theory ever produced.

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Origins

Quantum theory had its first faltering beginnings in the year 1900, with the publication of a paper by the German physicist Max Planck. Planck addressed himself to what was still an unsolved problem of nineteenth-century physics, concerning the distribution of radiant heat energy from a hot body among various wavelengths. Under certain ideal conditions the energy is distributed in a characteristic way, which Planck showed could only be explained by supposing that the electromagnetic radiation was emitted from the body in discrete packets or bundles, which he called quanta. The reason for this jerky behaviour was unknown, and simply had to be accepted *ad hoc*.

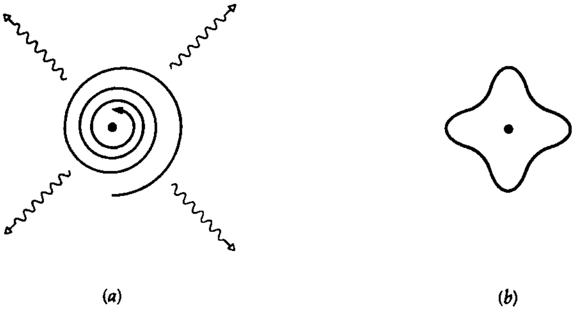
In 1905 the quantum hypothesis was bolstered by Einstein, who successfully explained the so-called photoelectric effect in which light energy is observed to displace electrons from the surfaces of metals. To account for the particular way this happens, Einstein was compelled to regard the beam of light as a hail of discrete particles later called photons. This description of light seemed utterly at odds with the traditional view, in which light (in common with all electromagnetic radiation) consists of continuous waves which propagate in accordance with Maxwell's celebrated electromagnetic theory, firmly established half a century before. Indeed, the wave nature of light had been demonstrated experimentally as long ago as 1801 by Thomas Young using his famous 'two-slit' apparatus.

The wave–particle dichotomy, however, was not restricted to light. Physicists were at that time also concerned about the structure of atoms. In particular, they were puzzled by how electrons could go round and round a nucleus without emitting radiation, since it was known from Maxwell's electromagnetic theory that when charged particles move along curved paths they radiate electromagnetic energy. If this were to occur continuously, the orbiting atomic electrons would rapidly lose energy and spiral into the nucleus (see Fig. 1).

In 1913 Niels Bohr proposed that atomic electrons are also 'quantized', in that they can reside without loss of energy in certain fixed energy levels. When electrons jump between the levels, electromagnetic energy is released or absorbed in discrete quantities. These packets of energy are, in fact, photons.

The reason why the atomic electrons should behave in this discontinuous fashion was not revealed, however, until somewhat later, when the wave nature of matter was discovered. The experimental work of Clinton Davisson and others and the theoretical work of Louis de Broglie led to the idea that electrons as well as photons can behave both as waves and as particles, depending on the particular circumstances. According to the wave picture, the atomic energy levels Bohr proposed correspond to stationary or standing wave patterns around the nucleus. Much as a cavity can be made to resonate at different discrete musical notes, so the electron waves vibrate with certain well-defined energy patterns. Only when the patterns shift, corresponding to a transition from one energy level to another, does an electromagnetic disturbance ensue, with radiation being emitted or absorbed.

Fig. 1. Collapse of the classical atom. (a) *The theories of Newton and Maxwell predict that an orbiting atomic electron will steadily radiate electromagnetic waves, thereby losing energy and spiralling into the nucleus.* (b) *The quantum theory predicts the existence of discrete non-radiating energy levels in which the wave associated with the electron just 'fits' around the nucleus, forming standing wave patterns reminiscent of the notes on a musical instrument. (The wave must 'fit' in the radial direction too.)*



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It soon became apparent that not only electrons but all subatomic particles are subject to similar wavelike behaviour. Evidently the traditional laws of mechanics as formulated by Newton, as well as Maxwell's laws of electromagnetism, fail completely in the microworld of atoms and subatomic particles. By the mid-1920s, a new system of mechanics – quantum mechanics – had been developed independently by Erwin Schrödinger and Werner Heisenberg to take account of this wave–particle duality.

The new theory was spectacularly successful. It rapidly helped scientists to explain the structure of atoms, radioactivity, chemical bonding and the details of atomic spectra (including the effects of electric and magnetic fields). Further elaborations of the theory by Paul Dirac, Enrico Fermi, Max Born and others eventually led to satisfactory explanations of nuclear structure and reactions, the electrical and thermal properties of solids, superconductivity, the creation and annihilation of elementary particles of matter, the prediction of the existence of antimatter, the stability of certain collapsed stars and much else. Quantum mechanics also made possible major developments in practical hardware, including the electron microscope, the laser and the transistor. Exceedingly delicate atomic experiments have confirmed the existence of subtle quantum effects to an astonishing degree of accuracy. No known experiment has contradicted the predictions of quantum mechanics in the last 50 years.

This catalogue of triumphs singles out quantum mechanics as a truly remarkable theory – a theory that correctly describes the world to a level of precision and detail unprecedented in science. Nowadays, the vast majority of professional physicists employ quantum mechanics, if not almost unthinkingly, then with complete confidence. Yet this magnificent theoretical edifice is founded on a profound and disturbing paradox that has led some physicists to declare that the theory is ultimately meaningless.

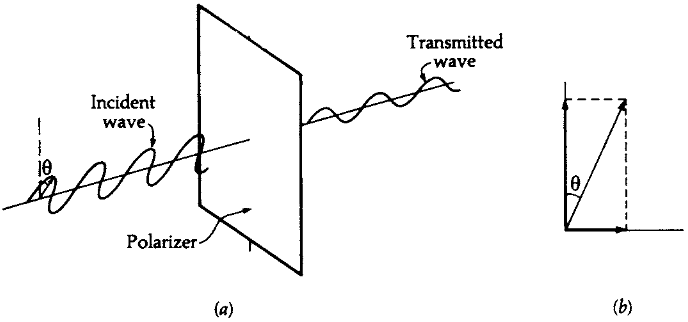
The problem, which was already readily apparent in the late 1920s and early 1930s, concerns not the technical aspects of the theory but its interpretation.

Waves or particles?

The peculiarity of the quantum is readily apparent from the way that an object such as a photon can display both wave-like and particle-like properties. Photons can be made to produce diffraction and interference patterns, a sure test of their wave-like nature. On the other hand, in the photoelectric effect, photons knock electrons out of metals after the fashion of a coconut-shy. Here, the particle model of light seems to be more appropriate.

The co-existence of wave and particle properties leads quickly to some surprising conclusions about nature. Let us take a familiar example. Suppose that a beam of polarized light encounters a piece of polarizing material (see Fig. 2). Standard electromagnetic theory predicts that if the plane of polarization of the light is parallel to that of the material, all the light is transmitted. On the other hand, if the angles are perpendicular, no light is transmitted. At intermediate angles some light is transmitted; for example, at 45° the transmitted light has precisely half the intensity of the original beam. Experiment confirms this.

Fig. 2. Breakdown of predictability. (a) Classically, the polarized light wave will pass through the polarizer with a reduced intensity $\cos^2\theta$, emerging polarized in the 'vertical' direction. Viewed as a flux of identical photons, this phenomenon can be explained only by supposing that some photons are passed and others blocked, unpredictably, with probabilities $\cos^2\theta$ and $\sin^2\theta$, respectively. (b) Note that the incident wave could be regarded as a superposition of 'vertically' and 'horizontally' polarized waves.



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Now, if the intensity of the incoming beam is reduced so that only one photon at a time passes through the polarizer, we are faced with a puzzle. Because a photon cannot be divided up, any given photon must be either passed or blocked. With the angle set at 45°, on average half the photons must get through, while the other half are blocked. But which photons get through and which do not? As all photons of the same energy are supposed to be identical and hence indistinguishable, we are forced to conclude that the passage of photons is a purely random process. Although any given photon has a 50–50 chance (a probability of $\frac{1}{2}$) of getting through, it is impossible to predict in advance which particular ones will do so. Only the betting odds can be given. As the angle is varied so the probability can range from zero to one.

The conclusion is intriguing and yet disconcerting. Before the discovery of quantum physics the world was thought to be completely predictable, at least in principle. In particular, if identical experiments were performed, identical results were expected. But, in the case of the photons and the polarizer, one might very well find that two identical experiments produced different results, as one photon passed through the polarizer while another identical photon was blocked. Evidently the world is not wholly predictable after all. Generally we cannot know until after an observation has been made what the fate of a given photon will be.

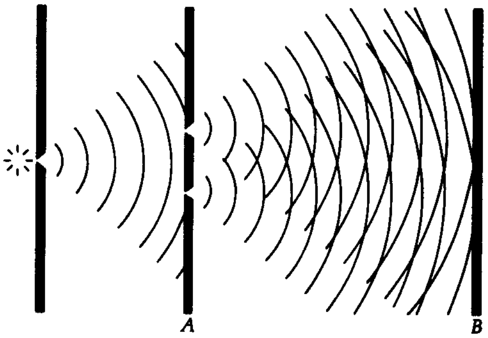
These ideas imply that there is an element of uncertainty in the microworld of photons, electrons, atoms, and other particles. In 1927 Heisenberg quantified this uncertainty in his famous uncertainty principle. One expression of the principle concerns attempts to measure the position and motion of a quantum object simultaneously. Specifically, if we try to locate an electron, say, very precisely, we are forced to forgo information about its momentum. Conversely, we can measure the electron's momentum accurately, but then its position becomes indeterminate. The very act of trying to pin down an electron to a specific place introduces an uncontrollable and indeterminate disturbance to its motion, and vice versa. Furthermore, this inescapable constraint on our knowledge of the electron's motion and location is not merely the result of experimental clumsiness; it is inherent in nature. Apparently the electron simply *does not possess* both a position and a momentum simultaneously.

It follows that there is an intrinsic fuzziness in the microworld that is manifested whenever we attempt to measure two incompatible observable quantities, such as position and momentum. Among other things, this fuzziness demolishes the intuitive idea of an electron (or photon, or whatever) moving along a distinct path or trajectory in space. For a particle to follow a well-defined path, at each instant it must possess a location (a point on the path) and a motion (tangent vector to the path). But a quantum particle cannot have both at once.

In daily life we take it for granted that strict laws of cause and effect direct the bullet to its target or the planet in its orbit along a precisely defined geometrical path in space. We would not doubt that when the bullet arrives at the target its point of arrival represents the end-point of a continuous curve which started at the barrel of the gun. Not so for electrons. We can discern a point of departure and a point of arrival, but we cannot always infer that there was a definite route connecting them.

Seldom is this fuzziness more apparent than in the famous

Fig. 3. Waves or particles? In this two-slit experiment electrons or photons from the source pass through two nearby apertures in screen A *and travel on to strike screen* B*, where their rate of arrival is monitored. The observed pattern of varying intensity indicates a wave interference phenomenon.*



two-slit experiment of Thomas Young (see Fig. 3). Here a beam of photons (or electrons) from a small source travels towards a screen punctured by two narrow apertures. The beam creates an image of the holes on a second screen. The image consists of a distinct pattern of bright and dark 'interference fringes', as waves passing through one hole encounter those from the other hole. Where the waves arrive in step, reinforcement occurs; where they are out of step, cancellation occurs. Thus is the wave-like nature of photons or electrons clearly demonstrated.

But the beam can instead be considered as consisting of particles. Suppose the intensity is again reduced so much that only one photon or electron traverses the apparatus at a time. Naturally each arrives at a definite point on the image screen. It can be recorded as a little speck. Other particles arrive elsewhere leaving their own specks. The effect at first seems random. But a pattern begins to build up in a speckled kind of way. Each particle is directed not by an imperative to a particular place on the image screen but by the 'law of averages'. When a large number of particles has traversed the system, an organized pattern is created. This is the interference pattern. Thus, any given photon or electron does not make a pattern; it makes only a single spot. Yet each electron or photon, while apparently free to go anywhere, cooperates in such a way as to build up the pattern in a probabilistic fashion.

Now, if one of the two apertures is blocked, the average behaviour of the electrons or photons changes dramatically; indeed, the interference pattern disappears. Nor can it be reconstructed by superimposing the two patterns obtained by recording the images from each individual slit acting alone. Interference only presents itself when both apertures are open simultaneously. Hence, each photon or electron must somehow *individually* take account of whether both or only one hole is open. But how can they do this if they are indivisible particles? On the face of it, each particle can only go through one slit. Yet somehow the particle 'knows' about the other slit. How?

One way of answering this question is to recall that quantum particles do not have well-defined paths in space. It is sometimes convenient to think of each particle as somehow possessing an infinity of different paths, each of which contributes to its behaviour. These paths, or routes, thread through both holes in the screen, and encode information about each. This is how the particle can keep track of what is happening throughout an extended region of space. The fuzziness in its activity enables it to 'feel out' many different routes.

Suppose a disbelieving physicist were to station detectors in front of the two holes to ascertain in advance towards which hole a particular electron was heading. Could not the physicist then suddenly block the other hole without the electron 'knowing', leaving its motion unaltered? If we analyse the situation, taking into account Heisenberg's uncertainty principle, then we can see that nature outmanoeuvres the wily physicist. In order for the position of each electron to be measured accurately enough to discern the hole it is approaching, the electron's motion is so disturbed that the interference pattern defiantly vanishes! The very act of investigating where the electron is going ensures that the two-hole cooperation fails. Only if we decide not to trace the electron's route will its 'knowledge' of both routes be displayed.

A further intriguing consequence of the above dichotomy has been pointed out by John Wheeler. The decision either to perform the experiment to determine the electron's route, or to relinquish this knowledge and experiment instead with an interference pattern, can be left until *after* any given electron has already traversed the apparatus! In this so-called delayed-choice' experiment, it appears that what the experimenter decides now can in some sense influence how quantum particles shall have behaved in the past, though it must be emphasized that the inherent unpredictability of all quantum processes forbids this arrangement from being used to send signals backwards in time or to in any way 'alter' the past.

An idealized arrangement designed to carry out a related delayed-choice experiment (with photons rather than electrons) is shown in Fig. 4, and forms the basis of a practical experiment performed recently by Caroll Alley and his colleagues at the University of Maryland. Laser light incident on a half-silvered mirror *A* divides into two beams analogous to the two paths through the slits in Young's experiment. Further reflections at mirrors *M* redirect the beams so that they cross and enter photon detectors 1 and 2, respectively. In this arrangement a detection of a given photon by either 1 or 2 suffices to determine which of the two alternative routes the photon will have travelled.

If, now, a second half-silvered mirror *B* is inserted at the crossing point (see Fig. 4) the two beams are recombined, part along the route into 1 and part along the route into 2. This will cause wave interference effects, and the strengths of the beams going into 1 and 2 respectively will then depend on the relative phases of the two beams at the point of recombination. These phases can be altered by adjusting the path lengths, thereby essentially scanning the interference pattern. In particular it is possible to arrange the phases so that destructive interference leads to zero beam strength going into 1, with 100% of the light going into 2. With this arrangement the system is analogous to the original Young experiment, for which it is not possible to specify which of the two routes has been taken by any given photon. (Loosely speaking, each photon takes both routes.)

Fig. 4. Schematic diagram showing the layout of a practical version of Wheeler's delayed-choice experiment.