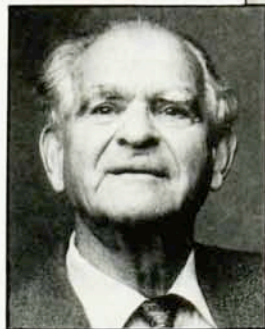




HERMAN FESHBACH

ASK A FOOLISH QUESTION...

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Quantum physics holds a unique position in intellectual history as the most successful framework ever developed for the understanding of natural phenomena. Devised more than 60 years ago, it has been used to study the world of the atom and the molecule, the physics of chemical reactions, the properties of the various forms of matter—liquids, solids and gases. Quantum mechanics has been applied to determine the structure of the nucleus and the nucleons, thus extending its range of validity from systems of macroscopic dimension to systems whose radii are of the order of 10^{-3} cm. Quantum electrodynamics, the study of the interaction of electromagnetic radiation with matter, has been verified to 10^{-16} cm. Yet one finds statements in the popular and not-so-popular literature, as well as by some philosophers, that quantum theory is not deterministic and that it is acausal. In a recent publication a writer states: "At the level of atoms and nuclear particles, quantum mechanics replaced surety with uncertainty. Researchers learned that events within that minuscule realm do not flow smoothly and gradually; rather they change abruptly and discontinuously. Nature became a game of probability."

That assessment is vastly exaggerated. Surely certain quantities can only assume discrete values, such as the angular momentum, or nearly discrete values, such as the energy of atomic states; surely some predictions

about certain quantities are sometimes probabilistic. It does not follow that the predictions of quantum mechanics are necessarily uncertain. In fact quantum mechanics leads to extremely accurate results; for example, it predicts the energy of the hydrogen atom in its ground state to one part in 10^{12} . Such results follow from the fundamental equation $i\hbar\psi = H\psi$, whose solutions are unique, continuous and incorporate the principle of causality. The wavefunction ψ of a given state incorporates all there is to know about the system in that state.

To make use of the fundamental equation one must relate the wavefunction to observations of the system. Quantum mechanics provides the rules for determining the initial wavefunction from the initial conditions and the rules for predicting the results of observations at a later time.

The proponents of an acausal interpretation will point to the Heisenberg uncertainty relation and to Born's probabilistic interpretation as examples of the indeterministic character of quantum theory. Let us now look at the significance of these consequences of quantum mechanics.

At the conceptual level, the most important issues that serve as the cornerstones of a physical theory are, What are the questions that make sense and thus can be answered? and its corollary, What are the relevant degrees of freedom? Ask a foolish question and you will get a foolish answer. It was the great discovery of Galileo and Newton that acceleration is the fundamental quantity of interest. From this followed the notions of inertial mass and force. Other characteristics, such as the shapes of the bodies under study, are of secondary importance. The sensible question posed by classical mechanics is, What is the position and velocity of a

particle at a certain time, given its position and velocity at an earlier time? Even in classical mechanics this question generally cannot be answered with complete precision. As we now know from the studies of deterministic chaos, for many mechanical systems two orbits whose initial conditions differ infinitesimally will separate exponentially with time. If under these circumstances one were asked to predict the position and velocity of a particle, the initial conditions would have to be given with an accuracy that cannot be achieved physically. Thus, for systems exhibiting chaos, a more sensible question is, Given the distribution of positions and velocities of a system at a time t , what is that distribution at another time separated by a finite amount from t ? Even in classical mechanics probability distributions are obtained in such cases.

Observations are formulated in the language of classical physics because that is the language used to record measurements with macroscopic instruments. That statement does not imply that the measuring instruments follow classical physics instead of quantum physics, a wrong opinion some writers ascribe incorrectly to Bohr. Instead our statement implies that the special nature, in particular the larger size, of measuring instruments allows the description of their behavior in classical terms. But classical physics concepts are not always appropriate for the description of atomic situations. Thus the results of measurements may not fully describe the atomic reality.

Quantum mechanics was discovered by Heisenberg when he realized that certain questions were not admissible even in principle. Designing an experiment that would measure simultaneously and precisely the po-

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sition and momentum of a particle is not possible. Quantum mechanics states that such proposals, and the equivalent for any pair of canonically conjugate variables, are not sensible. If one asks such an inappropriate question, quantum mechanics provides a probability distribution rather than a definite answer. The Heisenberg uncertainty relations are signposts saying: "You are allowed to use classical conjugate variables up to here, but go no further. The use of such variables beyond this limit is inappropriate. If you ask an inappropriate question, you get a probability distribution as a response." On the other hand, if an appropriate question is asked, quantum mechanics gives a crisp, precise answer such as the energy of a hydrogen atom in its ground state.

A word about quantum jumps. It is often said that an atom abruptly jumps from an excited state to a lower state, but the time of the jump is distributed according to a probability law. This is a response to an inappropriate question: When did the electron change its state? The energy of the excited state is reasonably well defined, and therefore the time of the quantum jump is correspondingly undefined within the lifetime of the state. The quantum state is given by the state function

$$\Psi = a(t)\psi_a + b(t)\psi_b$$

where ψ_a and ψ_b are the state functions of the upper state a and the lower state b . Ψ changes continuously. There is no jump; $a(t)$ is a decreasing and $b(t)$ is an increasing function of time. The probabilities of finding the atoms in a or b are $|a|^2$ and $|b|^2$. Thus the answer is probabilistic.

The same is true about a particle undergoing radioactive decay. Its energy is defined with great but not infinite accuracy. But the time at which the decay occurred is predictable only with wide margins. Asking for the exact time of decay is an inappropriate question. Quantum mechanics distinguishes questions that are appropriate for a given experimental situation from those that are not. The former will have an exact answer; the latter will have a probability distribution as a response. Once this is realized the paradoxes traditionally discussed are readily resolved.

Another source of misunderstanding is the attack on the superposition principle posed by the Schrödinger's cat paradox. The state vector describing the cat is a superposition of a state in which the cat is alive and one in which it is dead. This superposition

expresses the obvious fact that we are not sure whether the cat is alive or dead. The foolish question asks if there can be interference between the two states. There cannot be any since the two states are of such complexity that any overlap is negligible. However, such interferences are of importance in simpler macroscopic situations, such as the Josephson effect.

The Einstein-Podolsky-Rosen *gedanken* experiment provides another example. Two particles of spin $1/2$ are emitted in the spin-0 state from a source and move in opposite directions. Obviously the two spins are oriented opposite to each other. But it is typical of quantum mechanics that the question, In what direction are the spins opposed to each other? is inappropriate. The spins are distributed with equal probability over all directions, as one can show by using thoroughly tested properties of spin- $1/2$ particles. Only if the spin of one particle is measured and found to be $+1/2$ in the x direction can one conclude that the other particle must have opposite spin in the x direction. Quantum rules then predict the probabilities for the measurement of the spin of the second particle in any other direction. Had the spin of the first particle been measured in a different direction, the probability distribution of the second would be different. Thus the measurement of the spin of one particle is correlated with the probability distribution of the spin of the other, even if it is far away. It is highly improbable that any experiment testing these spin correlations would contradict the predictions of quantum mechanics since those predictions rest on well-established properties of spin- $1/2$ particles.

Perhaps deviations from quantum mechanical predictions will be uncovered eventually. But that will involve studies for a range of experimental parameters that have not yet been investigated. In the investigated ranges, quantum mechanics has been more than amply verified. It will not be easy to discover deviations since one's inclination will be to blame any observed deviation on the Hamiltonian employed rather than on the quantum mechanical framework. After all, quantum mechanics was created because of the striking inconsistencies with classical electromagnetic theory and classical mechanics posed by the photoelectric effect, the Compton effect, the properties of blackbody radiation, atomic spectra, the Franck-Hertz effect and so on. Such massive paradoxes do not exist at this time, and there is precious little evidence for a breakdown. ■

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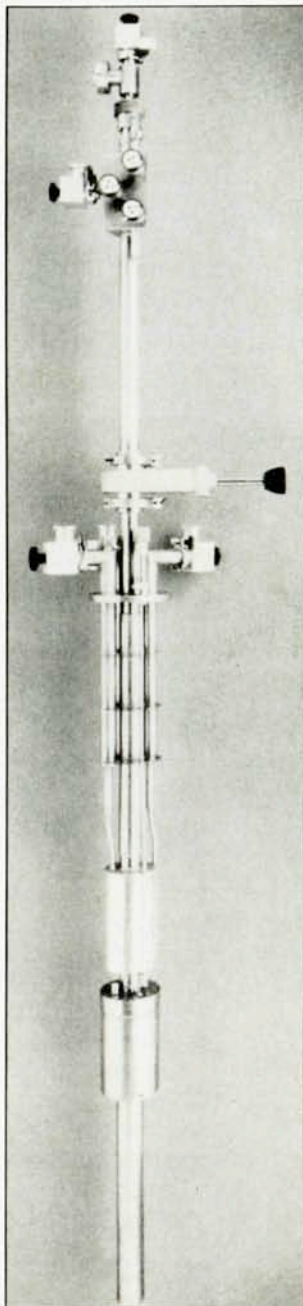
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