Going Bohr's Way in Physics

Bohr's centennial: New moves in the debate over the nature of reality

By DIETRICK E. THOMSEN

Physics is supposed to deal with objective realities, these little hard things called matter. Everybody can see, feel and count them. They move around in time and space. Physics measures them and tells how they go.

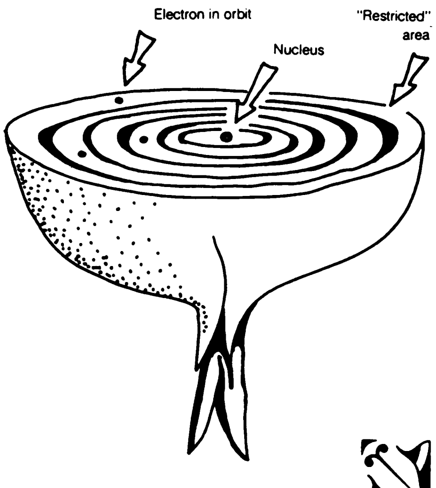
That is the classical view. In the third decade of this century the development of the physics of the microcosm shattered that view. It opened a new debate over the most essential of ontological questions: What is real? That is, what does "real" mean, and what, if anything, can be called real? Today, 60 years after physics reopened these questions, they are still with us, still vehemently debated, still unsolved.

That is not to say that there has not been movement. Indeed, it is only recently that experiments seem to be able to touch some of the questions involved. Some of the latest results were reported recently at "A Symposium Commemorating the Centennial of Niels Bohr," held at the American Academy of Arts and Sciences in Cambridge, Mass. Bohr, who was born Oct. 7, 1885, probably did more than anyone else to bring these philosophical matters to the world's attention, and these latest results seem to give a definite advantage to his side of the debate (see accompanying article). *If* the Bohrean view should prevail across the board — and the other side, whose tutelary genius is Albert Einstein, is busy making new suggestions — it would be a very serious philosophical revolution.

Physicists tend to regard Bohr as the tutelary genius of quantum theory and in general of the physics of the microcosm. He made the first applications of quantum theory to the structure of atoms and later to atomic nuclei. During the 40 years (1922-1962) he presided over the University Institute for Theoretical Physics in Copenhagen, he and a revolving company of mostly young physicists — over the years more than 600 from almost 40 countries — worked out much of the quantum theory as physics and also a philosophical and epistemological attitude that became known as the Copenhagen Interpretation. His pupils — collectively the Copenhagen school — spread these ideas throughout the world's physics community.

Bohr came on the scene at a propitious time, having completed his Ph.D. degree at the University of Copenhagen in 1911. "Bohr had the great luck to be born at that time," says Victor F. Weisskopf of the Massachusetts Institute of Technology. "The time had the great luck to have him."

Physicists were faced with a dilemma over the structure of the atom. It was known that the atom had a positively charged core around which negatively charged electrons orbited. According to classical electrodynamics, the electrons should radiate energy continually, and as they do so, their orbits should gradually collapse. The problem was that atoms do not radiate energy continuously, and they do not collapse.



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Atom as onion: A way of describing the microcosm with imagery familiar from the world of classical science.

Bohr, who was then working in England under the great Ernest Rutherford, seized on the idea of the quantum to solve the difficulty. In 1905, to solve some difficulties having to do with the radiation of blackbodies, Max Planck had proposed that energy is radiated in discrete packets called quanta rather than in a continuous stream. Bohr proposed that the electrons in an atom can exist only in certain orbits, a hierarchy characterized by *quantum numbers* and separated by discrete amounts from each other. In these orbits electrons *do not radiate.* They radiate only when they jump from orbit to orbit. The radiation comes in quanta; its frequency depends on the size of the jump.

This was a radical, ad hoc theory that violated the tenets of classical mechanics and classical electrodynamics, and it left physicists generally flabbergasted. Martin Klein of Yale University says that Rutherford called it an ingenious mixture of Platonism and old physics, difficult to understand. And Rutherford asked: "How does an electron know which frequency to vibrate? It seems to know beforehand where to stop."

Rutherford's questions have never really been answered, but Bohr's theory works. It tells why different atoms radiate the colors of light they do, and why atoms are stable. It also gave Bohr a means, the famous *Aufbauprinzip* or principle of building up, by which he could arrive at a theory of the periodic table of the elements. Just as he was about to start his lecture on receipt of the 1922 Nobel Prize for physics, Bohr learned that back in Copenhagen this theory had passed a serious test as the Hungarian physicist George Hevesy discovered element 72 according to its prescriptions. Element 72 is called hafnium after the Latin name of Copenhagen.

This successful quantum theory demanded a quantum mechanics to go with it. The break with classical mechanics was too radical for that to extend to the atomic microcosm. As the new quantum mechanics developed, it forced physicists to radical departures from their previous ideas about the nature of things.

Contrary states of being seemed somehow — could one say hypostatically? — united in the same object. A thing is both a particle and a wave. A particle is something with a well-defined and relatively small extent in space — it is localizable. A wave cannot be localized. In principle it can extend from infinity to infinity. Classical physics can easily answer the question: Where is the planet Jupiter now? Quantum mechanics has no answer to the question: Where is the electron now?

From this conjunction of opposites follows the so-called uncertainty principle. The physical characteristics of objects come in pairs indissolubly linked together — for example, position and momentum, energy and time. The better you know one member of these pairs, the worse you know the other. Under this constraint what can measurement mean?

Yet in quantum mechanics you do make measurements. You make them perforce with objects that are macroscopic in size, that obey the laws of classical physics and that turn up numbers that have the appearance of classical measurements. This led Bohr to propose what is called the principle of correspondence, one of the main tenets of the Copenhagen Interpretation:

Basically our way into the quantum world is necessarily through classical physics. We must use classical language to describe the microcosm because we have no other terminology — even though the terminology is woefully inadequate and even misleading. We must use classical measuring devices, because these are the only kind we can handle. This point implies that somewhere there is a boundary between the quantum and the classical regimes, but it has proved an elusive boundary — wherever anyone searches for it, it refuses to be found.

It seems that somehow by this correspondence across this boundary, the physical attributes of objects and perhaps the objects themselves are translated from the uncertain, potential existence characteristic of the quantum domain to the actual, certain existence of the classical domain. The act of measurement somehow affects the reality of their existence.

Classical physics had taught that reality consists of independence. An object and its attributes are real if they exist in themselves independent of all observers. Otherwise how could everybody see them alike; how could everybody count the same number? Is anything in the quantum domain real in this sense? Bohr seemed to say that the phenomena that quantum mechanical measurement touches are real, but he was less clear whether behind them there is a thing-in-itself, a *Ding an sich* in the Kantian sense.

(Bohr was rarely clear about anything. His statements were full of the qualifiers that his mind immediately saw applying to any idea. "I do not choose to speak more clearly than I think," he once said.)

In any case this was not Einstein's *Ding*. One of Einstein's biographers, Abraham Pais of Rockefeller University in New York City, says that Einstein once turned to him and asked whether he [Pais] believed that the moon existed only when he looked at it. Although Einstein believed that quantum mechanics was the best theory available under the circumstances, he believed it was incomplete. According to him, there are aspects of the situation we do not see, so-called "hidden variables." If we could know the hidden variables, all these problems of reality and duality and uncertainty would fall away. On the contrary, Bohr insisted that quantum mechanics is all the theory there is, and physicists had better adjust their expectations and their attitudes toward reality to accommodate it. This is more or less the second tenet of the Copenhagen Interpretation.

Most of the foregoing questions arise from assuming that the waves that permeate the mathematical expressions of quantum mechanics refer to a physical reality. Indeed, Bohr chose as his motto *Contraria sunt complementa,* contraries are complementary. This principle of complementarity, that contrary modes of being somehow unite in a single entity, became a cornerstone of the Copenhagen edifice.

There are more or less *unphysical* ways of looking at quantum mechanical waves. From the beginning many physicists saw them as probability equations only, simply a way of saying that a given particle was likely to be found in a given region of space, nothing physical to them at all. Most recently David Bohm and B. J. Hiley of Birkbeck College of the University of London, England, propose that the waves refer to a kind of information that determines which path a particle will take. In their formulation, briefly described in the Dec. 2, 1985, PHYSICAL REVIEW LETTERS, they opt for no difference in the nature of reality between microscopic and macroscopic worlds.

Particles are real in both domains, say Bohm and Hiley, and the difference between the two realms is not one of size, as Bohr's correspondence principle would have it. Bohm and Hiley are responding particularly to recent experimental findings that quantum mechanical laws govern certain macroscopic phenomena — for example, the quantized Hall effect, for which the 1985 Nobel Prize was given. On any size level, they say, the behavior of a particle is governed by an equation that contains a term called a "quantum potential." If this quantum potential is large, the behavior goes according to quantum mechanics; if the quantum potential is small or zero, the process goes like a classical one, no matter what sizes are involved. If this demarche goes anywhere, it could transpose the Bohr-Einstein debate to a new key.

Bohr tried to apply complementarity to many things outside physics, even to ethics and morality. He used it, for example, in discussing the paradox that human beings feel interiorly that they possess a free will, and yet many things in the world go according to laws that are deterministic and leave no room for free choices. Gunther Stent of the University of California at Berkeley uses it to criticize the sociobiologists, saying that their attitude that behavior can be explained by physiology is "ill conceived." "Moral behavior," says Stent, "must be taken as a primitive fact, which cannot be explained but must be taken as a starting point."

Bohr had attempted to use the complementarity principle to explain life on the basis of a similar idea, as Stent puts it, that "life cannot be explained, but must be taken as the starting point of biology." Particularly, in genetics, known physics and chemistry might be an insufficient explanation of how the traits of living beings arise from otherwise dead matter, in analogy to the way classical physics cannot explain atomic behavior.

Bohr's pupil Max Delbrück was most taken with this possibility, says Stent. Ironically, molecular biological work that Delbrück inspired, particularly the unraveling of DNA, showed that no new physics or chemistry was necessary, and in 1962, just before his death, Bohr recanted that effort. Not all such attempted applications work. Nevertheless, says Stent, "In Delbrück Bohr found his most influential disciple outside physics. Delbrück transferred the Copenhagen spirit to Pasadena," where he established an institute for microbiology.

The Copenhagen spirit, the famous *Kopenhagener Geist,* attracted some scientists, repelled others. It consisted of a tremendous openness to new ideas, a willingness to junk almost anything from the past. At one point Bohr played with the idea of throwing out the sacred laws of conservation of matter and energy. This is like a rabbi throwing out the Torah. It didn't come to that, but it did come to other radical breaks.

The Copenhageners were also famous for a joy in the contemplation of nature that could lead at times to flippancy. This annoyed the sort of people who believe that science has to be solemn to get any respect. A visitor said to Bohr: "In your institute nobody takes anything seriously." Bohr replied: "That's quite true and even applies to what you just said." Or, as John S. Bell of the CERN laboratory in Geneva quotes him, "No paradox, no progress." □