impossible, classically, for that ball to escape by itself. But we have specified both position ("bottom of the box") and momentum ("at rest") as if we could know such parameters with absolute certainty. For objects as large as a ball, the uncertainties are indeed so small that we would not expect ever to see a trapped ball suddenly appear outside the box, rolling away. But if the box is made of electric fields, and the ball is an electron classically trapped within those fields, then the quantum theory uncertainty becomes serious. In the language of the new physics, the electron's wave function penetrates the walls, giving a high probability of finding the electron trapped, and a low but non-zero probability of finding it outside. Thus the electron can sometimes be observed to have escaped through the classically impenetrable barrier. This phenomenon is known as "tunneling," although this word is inadequate because no tunnel under the barrier is imagined to exist. A device known as a "tunnel diode" makes practical use of this property of electrons, and is employed routinely in television sets.

Radioactivity is another example of this classically impossible quantum physics behavior. The constituents of the nuclei of atoms are trapped by electric and nuclear forces, and classically should never be able to escape. But the wave functions of sub-atomic particles (the old language must be used) cannot be perfectly contained by finite forces, so the functions interpenetrate the entire nucleus and spread beyond any "boundary" that could be classically envisioned. For "stable" atoms, like lead, the nucleus is so well bound that we would not expect, on average, to see one disintegrate in the lifetime of the universe to date. But the nuclei of other atoms, such as radium, are less tightly bound, and components of the nucleus can suddenly break free. According to quantum theory, this process is entirely random. An individual nucleus may remain stable for a billion years after its formation, or for only a fraction of a second. There is no way to determine in advance which any particular nucleus will do. The random clicks of a geiger counter near a radium watch dial are the sounds of an acausal realm.

Historian of science Arthur Miller has described this period in physics as a loss and then a partial recovery of the physicists' ability to visualize meaning. Miller sees the emergence of the "Copenhagen interpretation" by Bohr and his colleagues, including the Principle of Complementarity as a key element, as a demonstration of the central role of personal aesthetics in science:

...the path to regaining visualization is characterized by the high drama of the intense personal struggles among the dramatis personae over their choices of the themata in conflict – continuity versus discontinuity, the usefulness of mathematical models versus mechanistic-materialistic models, and whether to maintain causality. These are among the themata that have emerged from Gerald Holton's pioneering historical case studies as having been of great concern to scientists through the ages. Holton refers to them as "thema-antithema couples." His studies reveal that a scientist's criteria for the choice between a thema-antithema couple cannot be reduced either to logic or to a suggestion derived directly from experimental data. Holton's observation and terminology are applicable here because the choice is based upon the individual scientist's aesthetic. What is so fascinating about the genesis of quantum theory is that not only does the personal nature of the struggle between themata emerge from the scientific papers of the period, but the themata clash here as never before in the history of science.

Einstein himself was the first and most persistent aesthetic protester against what he saw as the abandonment of the goal of complete knowledge. "But, surely God does not throw dice in determining how electrons should go!" In a letter to Max Born, Einstein expressed the same concern: "I find the idea quite intolerable that an electron exposed to radiation should choose of its own free will, not only its moment to jump off, but also its direction. In that case I would rather be a cobbler, or even an employee in a gaming-house, than a physicist." For classicists, and in many ways Einstein was at one with them, continuity in nature had meant a rigorous causality. For them, "the evolution of any physical system could be represented by a continuous chain of events causally related." Continuity meant that the
position and momentum of an object at one instant determined its position and momentum at the next. It meant that events take place in the same determined way whether or not one is observing them. It meant that inconsistent answers result from inaccuracies or incompleteness of present knowledge, but are not "built in" to the universal system.

Einstein fought for forty years against accepting the new theory as the most complete description possible of the knowable universe. He proposed to his friend Bohr a series of "thought experiments" that might (but did not) reveal inconsistencies in the theory. He proposed critical tests, such as the Einstein-Podolsky-Rosen experiment, that could check for "hidden variables" that might be producing the apparent uncertainties revealed by quantum physics. Practical means for conducting and interpreting that experiment were achieved recently with the development of new instruments and with a mathematical tool, Bell's Theorem. Experiments are being conducted at the present time which, if successful, will resolve some of the basic dilemmas which Einstein proposed and which have remained unanswered.

Einstein also tried to develop alternative theories, including his proposed "Unified Field Theory," which would replace the quantum theory with an expanded version of General Relativity. Although Einstein stimulated much valuable new work with his efforts, none of them dislodged the quantum theory. In the sub-atomic realm, experiment after experiment has confirmed the theory. Although the effects of the "Uncertainty Principle" can only be detected for masses far smaller than a speck of dust, in the realm of the atom the theory reigns without rival. Einstein never tired, however, of repeating his belief that "God does not play dice with the Universe." Einstein's challenge, as well as the quantum theory itself, are concepts that have been spreading into 20th-century culture.

Quantum theory reaches beyond physics

Helping to popularize these quantum theory concepts in his Physics and Philosophy, Sir James Jeans reiterated the position he had consistently taken since the new physics emerged. "So much of what used to be thought to possess an objective physical existence now proves to consist only of subjective mental constructs . . . . In this progress towards the truth, let us notice that each step was from particles to waves, or from the material to the mental; the final picture consists wholly of waves and its ingredients are wholly mental constructs."

Many physicists did and still do take exception to such statements. Nowhere does Jeans make the distinction that Herman Weyl does between "the objective state of affairs" and the "subjective appearance" of that state. While Bohr proposes that quantum theory blurred the dividing line between subject and object, de Broglie insists that "physics neither abolishes, nor even diminishes, the traditional distinction between subject and object." For de Broglie, the description of reality - not reality itself - is dependent on the observer.

But for Jeans and for many others, the new physics justified dropping Cartesian dualism and accepting instead a philosophy in which all paradoxes, such as wave and particle, were simply complementary aspects of the same mental picture.

The apparent subjectivity in modern physics often came across to the lay public in two opposing impressions. On the one hand, this new physics seemed to have restored importance to the individual. Those inclined to rebel against classical insistence on objective distance gladly accepted what they believed to be this scientific justification of subjectivity. On the other hand, the new physics could be seen to argue for an awareness of man's inadequacy, a fundamental limitation on his ability to know what happens.

The well-established, secure classical system which seemed to correspond to common sense ideas of everyday reality, gave way to a more ambiguous new view of man and his world - an open system of paradoxes and uncertainties in which man dealt with fictions rather than absolute truths. Herbert Muller summarizes the revolution in physics as "the triumph of the postulate over the axiom," or the shift from scientific laws universally accepted as true to scientific statements assumed without proof to be true. He sees three periods in the history of thought: "A Greek period, metaphysical and idealistic, in which emphasis was primarily upon the observer; the scientific period, semi-empirical and materialistic, in which emphasis was primarily on the thing observed; and the period now dawning in which knowledge is a transaction between the observer and the observed."

In his "Dilemma of Determinism," 1884, William James wrote that "the world must not be regarded as a machine" and that the intellectual absolutists, in their blind fear of ambiguity, mistakenly