Fifty Years of Antimatter

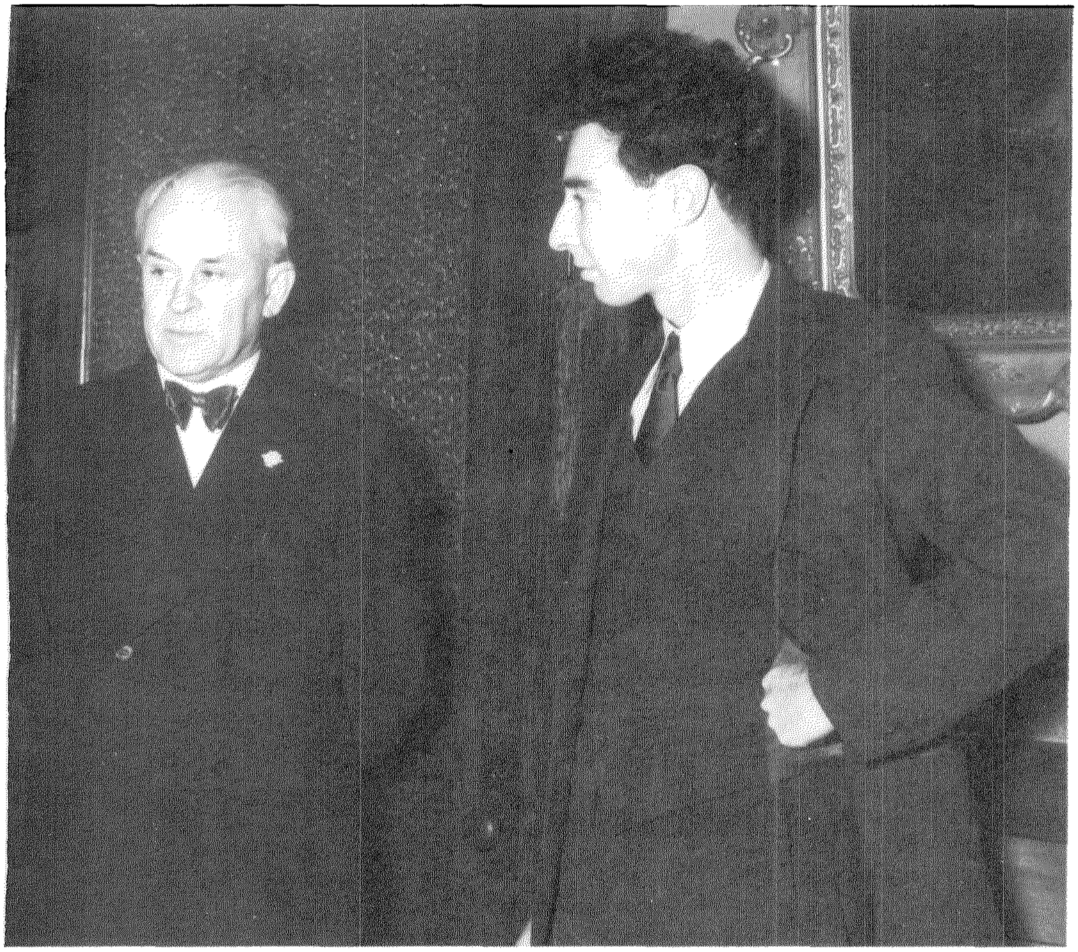
by John H. Schwarz

THE CONCEPT of antimatter arose with P. A. M. Dirac's pioneering work of 1928 — four years before Carl Anderson's discovery of the positron confirmed it. Dirac formulated an equation for the electron incorporating the requirements of quantum mechanics, electrodynamics, and special relativity. This equation not only successfully accounted for small relativistic effects in the energy levels of the hydrogen atom, but led to additional predictions that were completely new and unexpected.

Although negative energy has no meaning in classical physics, Dirac's equation seemed to say that an electron could have negative energy. He argued, however, that a consistent interpretation would be possible by supposing that the negative energy states are all occupied and therefore unobservable. Furthermore, by supplying suitable energy it would be possible to knock an electron out of the "infinite sea of negative-energy electrons," creating a real positive-energy electron and a "hole" in the sea. This hole would behave as a particle in its own right, with properties identical to those of the electron, except that its electric charge would be opposite (positive). At first Dirac suggested that the holes be identified as protons, but he soon rejected this interpretation, since the proton is some 2000 times heavier than an electron. Thus by 1931 Dirac was predicting the existence of an "anti-electron." Few people had any belief that an actual particle existed, and so no search was under way at the time the particle was discovered in the following year by Anderson, who called it the positron (a contraction of "positive electron"). In recent years the positron has been found experimentally to have the same mass as the electron with extremely high precision.

The positron was the first antiparticle to be discovered, but it was clear from Dirac's work that *all* elementary particles should have their own antiparticles. In particular, he predicted the existence of antiprotons. Since they are very rare in cosmic rays (and interact high in the atmosphere) and more difficult than positrons to produce with particle accelerators because of their greater mass, it was not possible to confirm the existence of antiprotons until the proton synchrotron called the "Bevatron" was completed in Berkeley in 1955. It was the first accelerator with sufficient energy to create antiprotons by converting kinetic energy into mass in accordance with the rules of relativity ($E=mc^2$). The pace of discovery has quickened since then, and by now many more species of particles and antiparticles have been observed.

In modern theoretical treatments, matter and antimatter are described in a completely symmetrical fashion without the need for reference to the Dirac sea. The existence of antimatter is understood as a consequence of a fundamental symmetry — called TCP — that is an inescapable consequence of any relativistic quantum theory. T refers to time reversal, C to particle-antiparticle conjugation, and P to spatial inversion (parity). This symmetry means that a movie of antimatter



A photography session at Caltech in May 1935 involved these three famous physicists: from left to right, Paul Dirac, Robert Millikan, and Robert Oppenheimer. Dirac first formulated the concept of antimatter, for which he received the Nobel Prize in physics in 1933 at the age of 32.

— run backwards in time and side-reversed — is described by the same equations as ordinary matter in real life.

Nowadays positrons and antiprotons are the bread-and-butter tools of high-energy experimental physics, and such particles are produced by the trillions for use in colliding beam experiments. At SLAC (the Stanford Linear Accelerator Center) there are two "storage rings," called SPEAR and PEP, in which electrons and positrons circulate in opposite directions, guided by magnetic fields and accelerated by electric fields, making head-on collisions in several intersection regions that are observed by very sophisticated detector systems. Similar experiments are done at storage rings called DORIS and PETRA at DESY (the Electron Synchrotron Laboratory in Hamburg, Germany). Proton-antiproton colliding-beam experiments have recently begun at CERN (the large European high-energy physics laboratory) and will take place in a few years at Fermilab (its American counterpart in Batavia, Illinois). These are by far the highest-energy experiments of all and therefore of great current interest.

An interesting challenge that cuts across the disciplines of particle physics and cosmology is to reconcile the observed excess of matter over antimatter in the universe with the symmetry between them in the fundamental equations. There is some evidence that our galaxy is made entirely from matter, and it is generally believed that the same is true of all galaxies throughout the universe. Observations indicate that there is roughly one proton (and no antiproton) for every billion photons (the quanta of light) in the universe. In recent years a surprising amount of progress has been made toward deducing the relative numbers of photons, protons, and antiprotons from first principles within the context of a new type of quantum field theory that unifies the description of the strong nuclear forces with that of the electromagnetic and weak nuclear forces. These theories also predict the instability of protons with a lifetime of about 10^{31} years. Numerous large experimental efforts are currently under way searching for proton decay. The chain of events that has followed the first sighting of a positron 50 years ago is remarkable indeed! Now, particle physics and cosmology appear to be entering a new era that should be just as exciting and challenging. □