CP SYMMETRY VIOLATION [1]

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The symmetry known as CP is a fundamental relation between matter and antimatter. The discovery of its violation by Christenson, Cronin, Fitch, and Turlay (1964) has given us important insights into the structure of particle interactions and into why the Universe appears to contain more matter than antimatter.

In 1928, Paul Dirac predicted that every particle has a corresponding *antiparticle*. If the particle has *quantum numbers* (intrinsic properties), such as electric charge, the antiparticle will have opposite quantum numbers. Thus, an electron, with charge $-|e|$, has as its antiparticle a *positron*, with charge $+|e|$ and the same mass and spin. Some neutral particles, such as the *photon*, the quantum of radiation, are their own antiparticles. Others, like the neutron, have distinct antiparticles; the neutron carries a quantum number known as *baryon number* B = 1, and the antineutron has B = –1. (The prefix *bary-* is Greek for *heavy*.) The operation of *charge reversal*, or C, carries a particle into its antiparticle.

Many laws of physics are *invariant* under the C operation; that is, they do not change their form, and, consequently, one cannot tell whether one lives in a world made of matter or one made of antimatter. Many equations are also invariant under two other important symmetries: space reflection, or *parity*, denoted by P, which reverses the direction of all spatial coordinates, and *time reversal*, denoted by T, which reverses the arrow of time. By observing systems governed by these equations, we cannot tell whether our world is reflected in a mirror or in which direction its clock is running. Maxwell's equations of electromagnetism and the equations of classical mechanics, for example, are

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invariant separately under P and T.

Originally it was thought that *all* elementary particle interactions were unchanged by C, P, and T individually. In 1957, however, it was discovered that a certain class known as the *weak interactions* (for example, those governing the decay of the neutron) were not invariant under P or C. However, they appeared to be invariant under the product CP and also under T. (Invariance under the product CPT is a very general feature of elementary particle theories.) Thus, it was thought that one could not distinguish between our world and a mirror-reflected world made of antimatter, or our world and one in which clocks ran backward.

Murray Gell-Mann and Abraham Pais (1955) used an argument based on C invariance (recast in 1957 in terms of CP invariance) to discuss the production and decay of a particle known as the *neutral K meson*, or K^0. This particle, according to a theory by Gell-Mann and Kazuo Nishijima, carried a quantum number called *strangeness*, with $S(K^0) = +1$, and so there should exist a neutral anti-K meson, called $\overline{K}^0$, with $S(\overline{K}^0) = -1$. The theory demanded that strangeness be conserved in K-meson production but violated in its decay. Both the K^0 and the $\overline{K}^0$ should be able to decay to a pair of π mesons (e.g., $\pi^+\pi^-$). How, then, would one tell them apart?

Gell-Mann and Pais solved this problem by applying a basic idea of quantum mechanics: The particle decaying to $\pi^+\pi^-$ would have to have the same behavior under C (in 1957, under CP) as the final $\pi^+\pi^-$ combination, which has CP $= +1$. (That is, its quantum-mechanical state is taken into itself under the CP operation.) A quantum-mechanical combination of K^0 and $\overline{K}^0$ with this property was called K_1^0. There should then exist another combination of K^0 and $\overline{K}^0$ with CP $= -1$ (i.e., its quantum-mechanical state is changed in sign under the CP operation). This particle was called K_2^0. (The subscripts 1 and 2 were used simply to distinguish the two particles from one another.) The

K_2^0 would be forbidden by CP invariance from decaying to $\pi\pi$ and thus, being required to decay to three-body final states, would be much longer-lived. This predicted particle was discovered in 1956.

Christenson, Cronin, Fitch, and Turlay performed their historic experiment in the early 1960s at Brookhaven National Laboratory to see if the long-lived neutral K meson could occasionally decay to $\pi^+\pi^-$. They found that indeed it did, but only once every 500 decays. For this discovery Cronin and Fitch were awarded the 1980 Nobel Prize in Physics.

The short-lived neutral K meson was renamed K_S and the long-lived one K_L. The K_L lives nearly 600 times as long as the K_S. The discovery of its decay to $\pi^+\pi^-$ was the first evidence for violation of CP symmetry. The K_S is mainly CP-even, while the K_L is mainly CP-odd. Within any of the current interaction theories, which conserve the product CPT, the violation of CP invariance then also implies T-invariance violation.

Shortly after CP violation was detected, Andrei Sakharov (1967) proposed that it was a key ingredient in understanding why the Universe is composed of more matter than antimatter. Another ingredient in his theory was the need for baryon number (the quantum number possessed by neutrons and protons) to be violated, implying that the proton should not live forever. The search for proton decay is an ongoing topic of current experiments.

CP violation can also occur in *quantum chromodynamics* (QCD), the theory of the strong interactions, through solutions which violate both P and T. However, this form of CP violation appears to be extremely feeble, less than a part in ten billion; otherwise it would have contributed to detectable effects such as *electric dipole moments* of neutrons. It is not known why this form of CP violation is so weak; proposed solutions to the puzzle include the existence of a light neutral particle known as the *axion*.

The leading theory of CP violation was posed by Makoto Kobayashi and

Toshihide Maskawa (1973). Weak coupling constants of *quarks* (the subunits of matter first postulated in 1964 by Gell-Mann and George Zweig) can have both real and imaginary parts. These complex phases lead not only to the observed magnitude of CP violation discovered by Christenson *et al.*, but also to small differences in the ratios of K_S and K_L decays to pairs of charged and neutral π mesons (confirmed by experiments at CERN and Fermilab), and to differences in decays of neutral B mesons and their antiparticles. Experiments at the Stanford Linear Accelerator Center (SLAC) using the BaBar detector (named after the character in the children's book) and at the National Laboratory for High Energy Physics in Japan (KEK) using the Belle detector have recently reported convincing evidence for this last effect (Aubert *et al.*, 2001; Abe *et al.*). At a deeper level, however, both the origin of the matter-antimatter asymmetry of the Universe discussed by Sakharov and the source of the complex phases of Kobayashi and Maskawa remain a mystery, perhaps stemming from some common source.

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