29. *CP* VIOLATION

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The symmetries C (particle-antiparticle interchange) and P (space inversion) hold for strong and electromagnetic interactions. After the discovery of large C and P violation in the weak interactions, it appeared that the product CP was a good symmetry. Then CP violation was observed in K^0 decays at a level given by the parameter $\epsilon = 2.3 \times 10^{-3}$. Larger CP-violation effects are anticipated in B^0 decays.

The eigenstates of the K^0–$\overline{K}^0$ system can be written

$$|K_S\rangle = p|K^0\rangle + q|\overline{K}^0\rangle \; , \qquad |K_L\rangle = p|K^0\rangle - q|\overline{K}^0\rangle \; . \tag{29.1}$$

If CP invariance held, we would have $q = p$ so that K_S would be CP even and K_L CP odd. (We define $|\overline{K}^0\rangle$ as $CP\ |K^0\rangle$). CP violation in K^0–$\overline{K}^0$ mixing gives

$$\frac{p}{q} = \frac{(1+\widetilde{\epsilon})}{(1-\widetilde{\epsilon})} \; . \tag{29.2}$$

CP violation can also occur in the decay amplitudes

$$A\big(K^0 \to \pi\pi(I)\big) = A_I e^{i\delta_I} \; , \qquad A\big(\overline{K}^0 \to \pi\pi(I)\big) = A_I^* e^{i\delta_I} \; , \tag{29.3}$$

where I is the isospin of $\pi\pi$, δ_I is the final-state phase shift, and A_I would be real if CP invariance held. The ratios of CP-violating to CP-conserving amplitudes $\eta_{+-} = A(K_L^0 \to \pi^+\pi^-)/A(K_S^0 \to \pi^+\pi^-)$ and $\eta_{00} = A(K_L^0 \to \pi^0\pi^0)/A(K_S^0 \to \pi^0\pi^0)$ can be written as

$$\eta_{+-} = \epsilon + \epsilon' \; , \qquad \eta_{00} = \epsilon - 2\epsilon' \; , \tag{29.4a}$$

$$\epsilon = \widetilde{\epsilon} + i \; \big(\mathrm{Im}\ A_0/\mathrm{Re}\ A_0\big) \; , \tag{29.4b}$$

$$|\sqrt{2}\epsilon'| = (\mathrm{Re}\ A_2/\mathrm{Re}\ A_0) \; \big(\mathrm{Im}\ A_2/\mathrm{Re}\ A_2 - \mathrm{Im}\ A_0/\mathrm{Re}\ A_0\big) \; . \tag{29.4c}$$

If CP violation is confined to the mass matrix, as in a superweak theory, ϵ' is zero and $\eta_{+-} = \eta_{00} = \epsilon = \widetilde{\epsilon}$. The measurement of ϵ'/ϵ has as its goal finding an effect that requires CP violation in the decay amplitude; this corresponds to a relative phase between A_2 and A_0 as seen in Eq. (29.4c).

In the Standard Model CP violation arises as a result of a single phase entering the CKM matrix (q.v.). As a result in what is now the standard phase convention, two elements have large phases, $V_{ub} \sim e^{-i\gamma}$, $V_{td} \sim e^{-i\beta}$. Because these elements have small magnitudes and involve the third generation, CP violation in the K^0 system is small. A definite nonzero value for ϵ'/ϵ is expected but hadronic uncertainties allow theoretical values between 10^{-4} and 3×10^{-3}. On the other hand, large effects are expected in the B^0 system, which is a major motivation for B factories.