The Past and Future of CP Violation

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What is CP Symmetry?

C is charge conjugation. It transforms a particle into its antiparticle.

P is parity. It transforms the spatial coordinates of a particle into their opposites. For example: \((x, y, z) \rightarrow (-x, -y, -z)\).

Thus, if we had a "CP mirror," CP symmetry would require the image to behave like the pre-image.
Cronin/Fitch used $K^0_S$ and $K^0_L$, which are superpositions of neutral kaons $K_0$ and $\bar{K}_0$ with identical mass but different half-lifes and decay modes.

$K^0_S$ decays into two pions with half-life $\sim 10^{-10}$s, whereas $K^0_L$ decays into three pions with half-life $\sim 10^{-8}$s.

They sent a beam of these kaons down a 17.4 meter tube so that any trace of $K^0_S$ would effectively be gone, leaving only $K^0_L$ decay products.

However, they found that 1/500 decay products were characteristic of $K^0_S$, implying that some $K^0_L$ had oscillated into $K^0_S$ and thereby broke CP symmetry!
\[ CP(K^0) = -\bar{K}^0 \]

\[ K_S = \frac{1}{\sqrt{2}}(K^0 - \bar{K}^0) \rightarrow CP(K_S) = \frac{1}{\sqrt{2}}(-\bar{K}^0 + K^0) = K_S \rightarrow \text{eigen is } +1 \]

\[ K_L = \frac{1}{\sqrt{2}}(K^0 + \bar{K}^0) \rightarrow CP(K_L) = \frac{1}{\sqrt{2}}(-\bar{K}^0 - K^0) = -K_L \rightarrow \text{eigen is } -1 \]

Therefore, \( K_{S/L} \) and its decay products must have the same CP eigenvalue.

However, the \( K_L \) were decaying into two pions (CP eigenvalue \(-1\)) and consequently violated CP symmetry!
Cronin and Fitch: Experimental Setup

In 1973, Kobayashi and Maskawa proposed a third family of quarks to explain CP violation, developing also the CKM matrix which is used to form the constraints of the unitarity triangle.

Cronin/Fitch demonstrated that CP symmetry was violated in the meson sector. However, "kaons are very difficult objects to model in theory...B mesons provide the ideal environment for measurements of CP violation." [Sciolla]

In 1999, after nearly 4 decades of performing (and perfecting) the CP violation experiment with kaons, the Stanford Linear Accelerator Center (SLAC) and the KEK laboratory built asymmetric colliders to study CP violation in B mesons.
[Figure taken from: http://www.symmetrymagazine.org/sites/default/files/legacy/pdfs/200512/deconstruction_unitarity_triangle.pdf]
Although B mesons pose less of a theoretical challenge than kaons, a lot more is required of the experiment.

The B factories must produce hundreds of millions of B mesons with asymmetric momenta in an incredibly clean environment to extract meaningful data about CP violation.

By 2006, each lab was able to collect over $10^6$ B mesons per day! [Sciolla]
The experiments at SLAC/KEK were a huge success:

1. They verified CP violation in B mesons and showed strong agreement with the Kobayashi/Maskawa theory.

2. They measured various lengths/angles of the unitarity triangle ($\beta$ within $1.2^\circ$ uncertainty)

3. They measured $\beta$ in so-called ”penguin modes” and found that it differs by 2.7 standard deviations.
The Future of CP Violation

Although current research affirms the Kobayashi/Maskawa theory, each angle and side-length of the unitarity matrix can be measured more accurately (and with different methodology).

CP violation in the quark sector has now been well documented, but it does not account for the matter/antimatter imbalance we see in the universe. Researchers are not looking to the lepton sector (particularly at neutrinos) for additional sources of CP violation. (T2K) Tokai to Tamioka
References (1)


References (2)


2. Cronin and Fitch Experiment with Kaons: http://hyperphysics.phy-astr.gsu.edu/hbase/particles/cronin.html


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