CP violation’s early days

A brief look back at a discovery that surprised the world of particle physics 50 years ago.

In the summer of 1964, at the International Conference on High-Energy Physics (ICHEP) in Dubna, Jim Cronin presented the results of an experiment studying neutral kaons at Brookhaven National Laboratory. In particular, it had shown that the long-lived neutral kaon can decay into two pions, which implied the violation of CP symmetry—a discovery that took the physics community by surprise. The news was greeted with some skepticism and met a barrage of questions. Everyone wanted to be satisfied that nothing had been overlooked, and that all other possibilities had been considered carefully and ruled out. People need not have worried. Cronin, together with Val Fitch, visiting French physicist René Turlay and graduate student Jim Christenson, had spent months asking themselves the same questions, testing and cross-checking their results thoroughly. There was, in the end, only one conclusion that they could draw from their observations: CP symmetry was not a perfect symmetry of nature. Only when the researchers were completely satisfied did they make their findings known to the physics community. It is testament to their patience and the quality of their work that the result was so robust to scrutiny. It was 15 years later that Cronin and Fitch received the 1980 Nobel Prize in Physics for the discovery.

The announcement of a broken symmetry was not new to the physics community, having first occurred only a few years previously, when the maximal non-conservation of parity (P) in the weak interaction was discovered by Chien-Shiung Wu and her colleagues in 1957, following the proposal by Tsung-Dao Lee and Chen-Ning Yang that parity violation might explain puzzles in the decays of charged kaons. The disturbing conclusion that the laws of physics depend on the frame of reference was evaded, however, because experiments soon showed that symmetry under charge-conjugation (C) was also maximally violated. Therefore, as long as the combined operation, CP, was a good symmetry, the possibility of an absolute distinction between left-handed and right-handed co-ordinate systems would be prevented, being compensated exactly by the asymmetry between particles and antiparticles. CP invariance had already been suggested as the means to restore symmetry conservation by Abraham Pais to propose, in 1955, that the states of definite mass and lifetime, labelled K+ and K−, were instead admixtures of the two particles, and were even and odd, respectively, under the CP transformation. Under the assumption of CP invariance, the K+ was forbidden to decay to two pions. This gave it a much longer lifetime than the K−, as observed.

The primary motivation for the experiment at Brookhaven was to study a phenomenon peculiar to the kaon system called regeneration (see box, p22). Fitch, an expert on kaons, had approached Cronin, who with Christenson and Turlay had built a state-of-the-art spectrometer based on spark chambers, which could be operated with an electronic trigger to select rare events. It was just what was needed for further tests of regeneration. Finding a “new upper limit” for K+ decaying to 2π was a secondary consideration.

The experiment that discovered CP violation at Brookhaven was set up in a neutral beamline, directed inside the ring of the Alternating Gradient Synchrotron. Visible here are the two spectrometer magnets positioned at 2π to the beam. Spark chambers tracked particles before and after the magnets. (Image credit: Brookhaven National Laboratory.)
Neutral kaon mixing, oscillations and regeneration

Because the weak interaction does not conserve strangeness, second-order weak interactions mediate transitions between the strange eigenstates $K^+$ and $\bar{K}^0$. Therefore, the physical particles (masses and lifetimes) are linear combinations of $K^+$ and $\bar{K}^0$, and states become the other “oscillable” between these two eigenstates before decaying. The two physical eigenstates are called $K_s$ and $K_L$, and $K_s$ is the “regenerated” in the beam. Regeneration is not an effect of CP violation, but it is used extensively in “regenerators” in kaon experiments.

The NA48 experiment at CERN’s Super Proton Synchrotron, which followed NA31 in the 1990s. From right to left: the target for the production of the $K_s$ beam (in the blue frame) followed by the multicoloured final collimator; the almost 120-m-long evacuated decay tube; the liquid krypton calorimeter – new for NA48 and key to detecting the decays to neutral pions. (Image credits, right to left: CERN-EX-9610003-07, CERN-EX-9610003-05, CERN-EX-9610003-04.)

Over two decades, two experiments at CERN proved the existence of a subtle difference between particles and antiparticles.

In 1973 – almost 10 years after the surprising discovery of CP violation – Makoto Kobayashi and Toshihide Maskawa produced the first theory of the phenomenon in the context of the Standard Model. They proposed a bold generalization of electroweak interactions, proposed by Sheldon Glashow, John Iliopoulos and Luciano Maiani had put forward in 1970. The “GIM mechanism” suppressed strangeness-changing weak neutral currents through the introduction of a fourth quark – charm – and, in turn, an extension of ideas that began with Nicola Cabibbo (CERN Courier September 2013 p35). Kobayashi and Maskawa introduced a third generation of quarks (b and t), and a full 3 x 3 unitary matrix parameterizing complex couplings between the quark-mass eigenstates and the charged weak gauge bosons ($W^\pm$).

In this model, a single complex phase in the matrix accounted for all observed CP-violating effects in the kaon system and provided for CP violation in matrix elements, both for mixing and for decays – that is, for both indirect and direct CP violation. The discovery of the $b$ quark in 1977 brought the theory of Kobayashi and Maskawa well and truly into the spotlight, and the hunt began to search for the predicted CP violation in the $b$-quark system (p26). In kaon physics, the crucial experimental question now was to disprove the superweak model for CP violation (p22), which had no need for direct CP violation. In contrast, in the Kobayashi-Maskawa model, the parameter describing direct CP violation, $\epsilon'$, was nonzero. However, considerable theoretical uncertainty remained concerning its value, which was potentially too small to be measured by the existing experimental techniques. This provided fresh impetus to the search for direct CP violation, and prompted renewed efforts at CERN and at Fermilab to meet the experimental challenges involved.

At CERN, the NA31 experiment was proposed in 1982 with the explicit goal of establishing whether the ratio $\epsilon'/\epsilon$ was nonzero. This required measuring all four decay rates of $K_s$ and $K_L$ to the charged pion (see box p24). The concept behind NA31 was to measure $K_s$ and $K_L$ decays at the same locations (binned in momentum) to provide essentially the same acceptance for each set of events, and so reduce the dependence on Monte Carlo simulation. The experiment employed a mobile $K_s$ target, able to move along a 50-m track, with data-taking stations every 1.2 m. Additionally, beam and detector fluctuations were limited by rapidly alternating the data-taking between $K_s$ and $K_L$. The experimental limitations were determined by statistics and background suppression. In both cases, a liquid argon calorimeter was used to achieve the stable, high-quality energy and position resolution that was crucial for reconstructing the $\pi^0$ decays. The calorimeter was greatly simplified by exploiting the expertise acquired by the group of Bill Willis at CERN with the first liquid-argon calorimeter at the Intersecting Storage Rings.

In 1988, NA31 found the first evidence for direct CP violation, with a result that was about three standard deviations from zero. However, shortly after this the E731 experiment at Fermilab reported a measurement that was consistent with zero. These conflicting results increased the importance of answering the question on the existence of direct CP violation, and prompted the design of a new generation of detectors, both at CERN (NA48) and at Fermilab (KTeV).