Discovery of CP Violation

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Abstract

This paper gives an historical review of the first CP violation effect discovered by Cronin, Fitch, et al. in 1963 with the decay of K_L in two pions [1]. Relevant theory is briefly presented, and the main experiment is described in some details. The emphasis is put on the experimental aspect of the discovery. Consequences and further related developments are discussed.

1 Introduction

Nature is beautiful. But Nature is also immensely complex. When trying to understand the Great Scheme of Things, the physicist has to follow some guiding principles which can help him to build his physical intuition. One fundamental one is the concept of *symmetry*, formalized in mathematics with group theory, and expressed in a general way in classical physics with Noether's theorem. [The spherical symmetry of the gravitational force, for example, permits us to solve exactly the 2-body problem.]

In particle physics, some important symmetries are parity transformation (P), charge conjugation (C) and time reversal (T). The traditional classical physics intuition made the physicists to firmly believe that Nature ought to be symmetric over each of those operations. The first shattering of this belief arose after C. S. Wu conducted an experiment in 1956 with the beta decay of the Cobalt 60 which demonstrated the violation of parity during some weak interactions process [4, p.123]. But it appeared that the violation of parity became an essential part of the weak interaction theory, so it wasn't too dramatic. The CP symmetry (the combination of charge conjugation and parity) was then considered as a weaker symmetry which should be respected in all interactions. Again, this firm belief was shattered by an experiment conducted by Cronin, Filtch, et al. in 1963, which showed that CP could be (weakly) violated during K^0 decays [1].

This paper will give an overview of the history of the discovery of CP violation. The main experiment will be outlined, and some of its consequences will be discussed. It will be assumed that the reader is familiar with particle physics. As to give an interesting example of the experimental methods employed in particle physics (in those days), the experiment will be described in some details.

2 Precursors and Theory

We take as starting point a beautiful paper by Gell-Mann and Pais published in 1955 [5]. In this paper, they noted that the K^0, with strangeness of $+1$, can turn into its antiparticle $\bar{K}^0$, strangeness -1, through a second-order weak interaction.

$$K^0 \leftrightarrows \bar{K}^0 \tag{1}$$

This meant that the particles one would observe in the laboratory were not K^0 or $\bar{K}^0$, but rather some linear combinations of the two. In particular, one could form eigenstates of CP as follows. Because the K^0's are pseudoscalars, we have

$$P\,|K^0\rangle = -\,|K^0\rangle\,, \qquad P\,|\bar{K}^0\rangle = -\,|\bar{K}^0\rangle \tag{2}$$

Also, by mere definition of charge conjugation, we have

$$C\,|K^0\rangle = |\bar{K}^0\rangle\,, \qquad C\,|\bar{K}^0\rangle = |K^0\rangle \tag{3}$$

Thus, if we define

$$|K_S\rangle \equiv (1/\sqrt{2})(|K^0\rangle - |\bar{K}^0\rangle), \qquad |K_L\rangle \equiv (1/\sqrt{2})(|K^0\rangle + |\bar{K}^0\rangle) \tag{4}$$

then K_S and K_L form (normalized) eigenstates of CP:

$$CP\,|K_S\rangle = |K_S\rangle\,, \qquad CP\,|K_L\rangle = -\,|K_L\rangle \tag{5}$$

This meant that *if CP was conserved in weak interactions*, then K_S could only decay into a state with $CP = +1$, whereas K_L must go to a state with $CP = -1$. It was known that neutral kaons decay into two or three pions, and that the two-pion configuration carries $CP = +1$ whereas the three-pion one carries $CP = -1$ [2]. So they concluded that, assuming CP conservation, K_S would only decay into two pions (never three) and the contrary for K_L:

$$|K_S\rangle \rightarrow \pi^+ + \pi^-, \qquad |K_L\rangle \rightarrow \pi^+ + \pi^- + \pi^0 \tag{6}$$

Finally, because the 3π decay has more excess energy available than the 2π decay, it is slower. As a consequence, Gell-Mann and Pais predicted the existence of a long-lived neutral K meson (K_L), in comparison with the short-lived meson K_S which was the neutral meson observed in laboratories at that time. The K_L meson was indeed discovered in 1956 by Lederman and his collaborators at the Brookhaven Cosmotron[1]. The importance of the paper of Gell-Mann and Pais was that they gave a theoretical setup for a test of CP conservation: if we observe a 2π decay of K_L, then CP has been violated. The experiment implementing this test will be described in section 3.

Another concept arising from the K_S-K_L duality is the phenomenon of *regeneration*, which was described in a paper by Pais and Piccioni [7]. In passing through matter, neutral K mesons displayed a behaviour very similar to light passing through a birefringent material. It appeared that when K_L passed through matter, the positive and negative strangeness components were attenuated by different amounts. So when the particle emerged from matter, the balance between the positive and negative components were altered so that a superposition of K_L and short-lived K_S mesons was obtained. This meant that even though a beam of K_L could be obtained by having a very long K^0 beam (so that most of K_S would have decayed already, leaving only their long-lived counterparts), as soon as the beam passed through matter, the K_S were "regenerated".

This phenomenon was studied by Adair, Chinowsky and collaborators by placing a hydrogen bubble chamber in a neutral beam at the Brookhaven Cosmotron [6]. They found that the regeneration rate was too large by a factor of 10 to 20. This anomaly had intrigued Val Fitch, who was a specialist of K Mesons at the time. This bring us to the famous experiment of Cronin and Fitch.

3 Experiment

3.1 Purpose of Experiment and Innovations

Fitch and Cronin were working at the time on separate experiments at Brookhaven. When Adair experiment appeared in preprint form, Cronin was just finishing an experiment on the production of ρ mesons at the Cosmotron, using a spark-chamber spectrometer. At that time, optical spark chambers were a new tool in which one could, by selective electronic trigger, record the trajectories of the desired events out of a very high-rate background. This is what one could consider as the main experimental innovation which gave rise to the CP violation discovery. Fitch came to Cronin and suggested to look for Adair's anomalous regeneration with Cronin's spectrometer. In addition to checking the Adair effect, this experiment would give them the opportunity to make other measurements on K_L with greater precision. Amongst them, they wanted to improve the upper limit on the amount of $\pi^+\pi^-$ decays from a K_L beam: others had already looked for these and found that no more than 1 in 300 of the decays was of the

[1] The experimental lifetimes are $\tau_S = 0.89 \times 10^{-10}s$, $\tau_L = 5.2 \times 10^{-8}$ s; so the K_S's are mostly gone after a few centimeters, whereas the K_L's can travel many meters [4, p.132].

CP violating type (using mostly bubble chambers). Cronin and Fitch estimated that with their new spark chamber, they could easily push that limit down to 1 in 10 000[2].

3.2 Description

The main principle of the CP violation part of the experiment was to detect 2π decays very far away from a K^0 target, so that only K_L mesons could survive until there. Figure 1 shows a schematic view of the whole experimental setup. The experiment was done in the Alternating Gradient Synchrotron (AGS), a 30-GeV proton accelerator. As we can see on the figure, the proton beam intercepted a K_0 target, and a neutral beam was obtained at 30^o using a sweeping magnet and lead collimators. A $1\frac{1}{2}$-in thickness of Pb was placed in front of the first collimator to attenuate the gamma rays in the beam.

Figure 2 shows a detailed view of the spectrometer. The region of observed decays was done in an He bag in order to minimize interactions (and regeneration, in particular). This region was pretty far from the K_0 target (57 ft), so the beam was now only consisting of K_L mesons. The arms of the spectrometer consisted of two magnets, with an angle adjustable. Spark chambers before and after the magnet permitted to obtain the trace of the charged pions. The first chamber trace gave the direction of the pion momentum. From the second chamber trace, one could compute the magnitude of the momentum by looking how much the particle had been deflected by the magnetic field.

The neutral pion doesn't leave a trace in the spark chamber, so you need to use the conservation of energy-momentum in the decay to distinguish a 2π decay from a 3π decay. The neutral pion can be inferred when the two momenta of the charged pions don't add up vectorially in the direction of the beam. So the 2π decays correspond to events where the momenta add up in the direction of the beam.

An important calibration of the apparatus and data reduction system was afforded by observing the decays of the K_S mesons produced by coherent regeneration in tungsten. These decays could simulate the direct decay of the K_L in two pions. By placing the regenerator at different positions along the decay region, they could obtain an approximation of the spatial distribution of the CP-violating events.

4 Results

The data was acquired during May and June 1963. Data were taken on many aspects of K_L's, including a measurement of the K_S-K_L mass difference (around 10^{-12} MeV) and the density dependence of the coherent regeneration in copper. No analysis was done before they had ended all the data acquisition, so there was no historical enthusiasm during their experiment...

[2]Note that they were always talking about lowering a limit; nobody was expecting to find any evidence of CP violation.

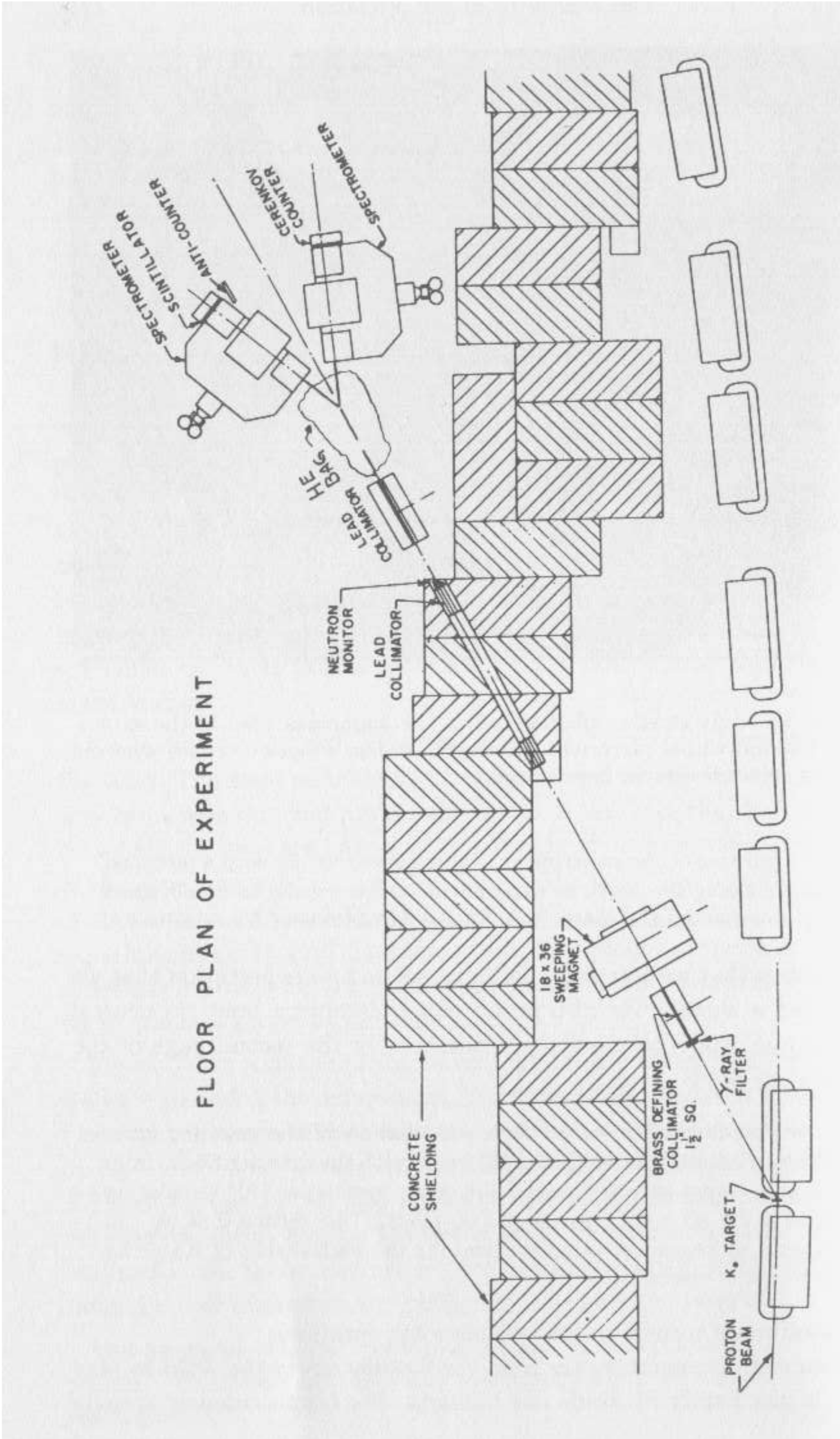

Figure 1: **Schematic view of the experimental arrangement for the CP invariance test.** Taken from [3, p.122].

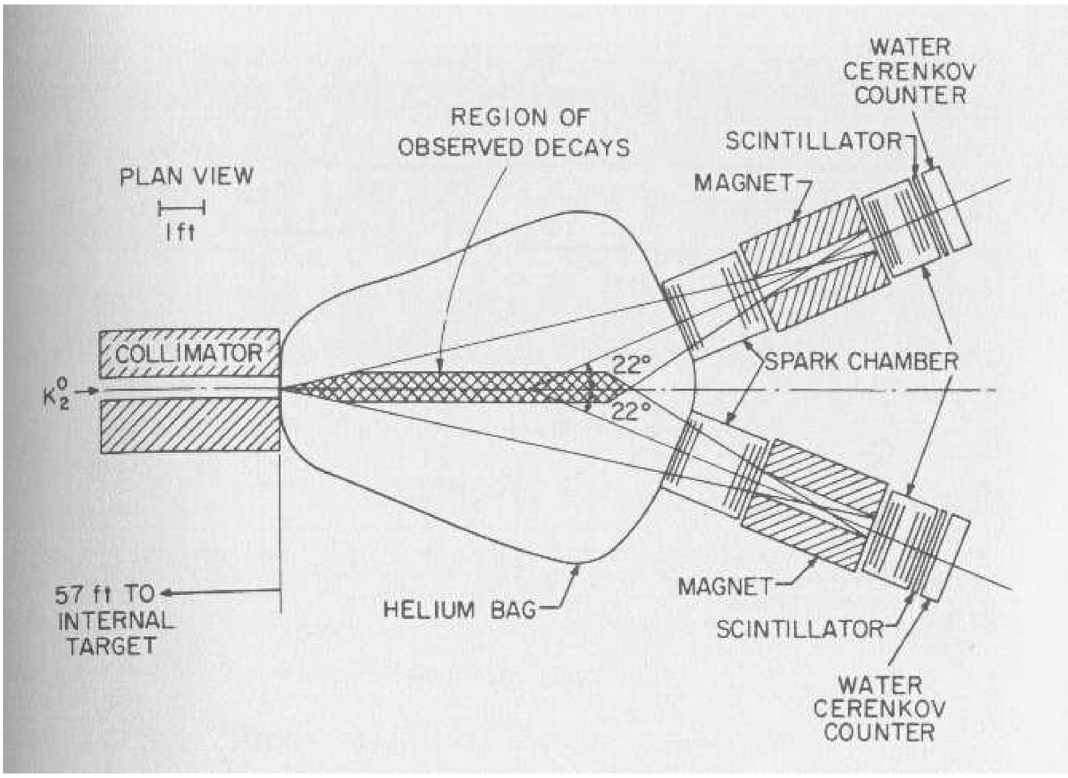

Figure 2: **Details of the spectrometer.** Taken from [3, p.123].

For the CP invariance part, 5211 events were measured and successfully reconstructed. To analyze the data, they computed the number of events which had a summed momentum at an angle θ, and which yielded a parent mass (using conservation of energy) around 498 MeV, *assuming* the two charged particles were pions. Of course, background decays could be included. But by doing a Monte Carlo calculation which took into account the nature of the interactions and the form factors involved in the decay, they could estimate the background and try extract only the important information. The key results (which were presented in the original paper) are presented in figure 3. It gives the number of events in function of the total momentum of decay products, corresponding to three parent mass ranges. We can see that something significant only happens in the parent mass range of 494 MeV to 504 MeV, which corresponds to the mass of the K_L (and K_S, but they had died out, so this corresponded without doubts to K_L events). A marked peak of about 42 events was detected for the forward direction momentum, which, as explained before, would represent a 2π decay. The number of decays obtained was a lot higher than the 1 in 10000 upper limit they were seeking. Also, they found the mass, angular resolution and spatial

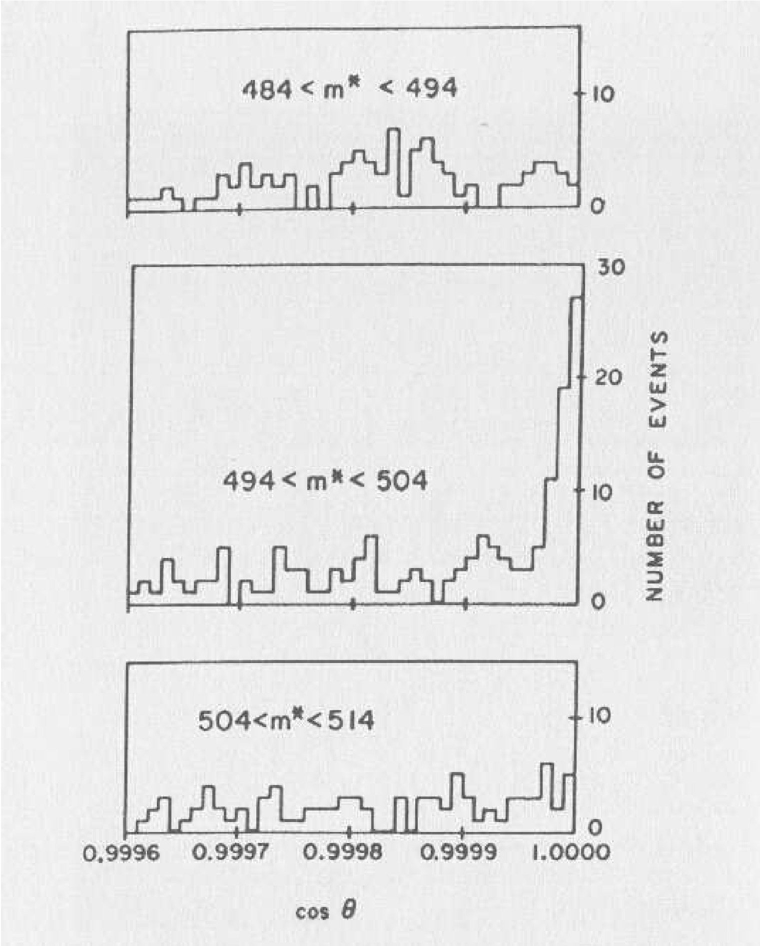

Figure 3: **Key evidence for CP violation.** This figure was taken from [3, p.130]. It was also included in the original paper [1]. It shows angular distribution in three mass ranges for events with $cos\,\theta > 0.9995$. Note the sharp peak at $\theta = 0^o$ for the mass range corresponding to the mass of the K_L (498 MeV).

distribution of the events observed with the helium bag to be identical with the regenerated K_S events done during the calibration phase. But from their own measurements of regeneration amplitudes, the regeneration in the Helium was many orders of magnitude too small to explain the effect. So they really had a strong evidence of CP violation effects (the K_L decay in 2 pions).

5 Consequences and Further Developments

The CP violation discovery was a huge surprise for the scientific community and destroyed the last hope for any form of exact mirror symmetry in Nature. It is now generally accepted that CPT ought to be the fundamental symmetry. This was derived using pretty general assumptions in Quantum Field theory. Thus CP violation meant that we could find T violation in Nature (so that the combination of CP and T would be invariant). But physicists thought that all the fundamental interactions should be symmetric with respect to time inversion, so this was also shocking.

Since the discovery of CP violation, there has been an enormous amount of work on the neutral K meson system and on searches for time reversal violation. A more dramatic evidence for CP violation was revealed by some of the semileptonic decays of K_L:

$$\text{(a)} \quad K_L \to \pi^+ + e^- + \bar{\nu}_e$$

$$\text{(b)} \quad K_L \to \pi^- + e^+ + \nu_e$$

CP takes (a) into (b), so if CP were conserved, and K_L were a pure eigenstate, (a) and (b) would be equally probable. But it was found experimentally that K_S decayed more often into a positron than into an electron, by a fractional amount of 3.3×10^{-3} [4, p.133]. So this physical process gave an absolute distinction between matter and antimatter, showing that CP violation permits one to do experiments that can distinguish between a universe of matter and one of antimatter, which was an important question of cosmological particle physics.

Another issue is the fact that all the CP violation effects that have been measured until now were very small. This can be compared with the *total* violation of parity observed with the helicity of neutrinos, for example (see [4, p.133]). In the mind of a physicist who seeks order, this is hard to swallow. But it happens that a phase factor in the so-called CKM matrix that generates relative imaginary amplitudes for the weak decays could be compatible with CP violation as seen in the neutral K system [3]. And the weak theory is such now that the constraints on the parameters of the CKM matrix from the K system predicts large CP-violating effects in some of the rare decay modes in the neutral B meson system. Soon there will be B factories with sufficient luminosity to observe these effects, so it will be interesting to see if the theory succeeds well in this case.

6 Conclusion

The discovery of CP violation was truly a milestone in particle physics. It showed that our intuition for order and symmetry doesn't necessarily reflect how Nature works. On the other hand, it permits some interesting consequences, as an avenue to "explain" the asymmetry between matter and antimatter in our universe. And the story is not finished for CP: the B meson systems will be soon under study for strong effects of CP violation.

References

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