First observation of direct CP violation in weak decays of neutral K mesons

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Symmetries and conservation laws have long played an important role in physics. The simplest examples of macroscopic relevance are the laws of conservation of energy and momentum, which are due to the invariance of forces under translation in time and space, respectively. Both are continuous transformations. In the domain of quantum phenomena, there are also conservation laws corresponding to discrete transformations. One of these is reflection in space (the “parity operation”) P . A second discrete transformation is particle-antiparticle conjugation C . This transforms each particle into its antiparticle, whereby all additive quantum numbers change their sign. A third transformation of this kind is time reversal T , which reverses momenta and angular momenta. It corresponds formally to an inversion of the direction of time. According to the CPT theorem of Lüders and Pauli, there is a connection between these three transformations such that, under rather weak assumptions in a local field theory all processes are invariant under the combined operation $C \cdot P \cdot T$.

Fundamental interactions in particle physics obey symmetry laws. The strong and electromagnetic interactions are both symmetric under each of all three discrete mirror operations: spatial inversion or parity operation P , particle-antiparticle inversion C and time reversal T . Consequently, there are conserved quantum numbers like parity P and charge parity C . A consequence is the prediction that the visible spectral lines from atoms and their

antiatom partners are identical and cannot be used to identify antimatter in the Universe.

However, the weak interaction governing nuclear beta decay and related slow processes like the proton-proton fusion in the Sun, shows a violation of these conservation laws. Parity conservation was found to be broken in 1957, and the combined CP parity transforming a particle into its antiparticle is violated in decays of neutral K mesons, as discovered by Christenson, Cronin, Fitch and Turlay in 1964 [1].

K mesons carry a quantum number S called strangeness, which is conserved in strong interactions but can change in weak interactions. The neutral K^0 meson produced in strong interactions carries $S = +1$, while its CP-conjugate antiparticle $\bar{K}^0 = CPK^0$ has $S = -1$. The eigenstates of CP are $K_1 = (K^0 + \bar{K}^0)/\sqrt{2}$ with eigenvalue $+1$ and $K_2 = (K^0 - \bar{K}^0)/\sqrt{2}$ with eigenvalue -1 . If the weak interaction is invariant under CP transformation, the long-lived K_2 state cannot decay to a final state of two pions which have an eigenvalue $+1$ of CP. Since CP is not conserved in the decay of the long-lived kaons to two pions, the eigenstates of the weak interaction are no longer equal to the CP eigenstates. The physical states are then the long-lived state $K_L = K_2 + \epsilon K_1$, and the short-lived state $K_S = K_1 + \epsilon K_2$, with a complex mixing parameter ϵ whose modulus is about 2×10^{-3} . CP violating effects have subsequently been observed in the decay $K_L \rightarrow 2\pi^0$ [5, 6], the charge asymmetry in K_L

▲ Fig.1: Schematic layout of the NA31 apparatus

$\rightarrow \pi^+ e^- \nu$ [3] and $K_L \rightarrow \pi^+ \mu^- \nu$ [4], the decay $K_L \rightarrow \pi^+ \pi^- \gamma$ [7], and more recently as an asymmetry between the decay planes of $\pi^+ \pi^-$ and $e^+ e^-$ in $K_L \rightarrow \pi^+ \pi^- e^+ e^-$ [8]. All these effects are successfully described by the mixing between K^0 and $\bar{K}^0$ strangeness eigenstates.

The origin of this CP violation remained unclear. Mixing can be due to the weak force or to a “super-weak” force as proposed ad hoc by Wolfenstein [2]. In the super-weak model the ratio of the decay amplitude for CP violating decays of K_L and K_S mesons to the amplitude for CP conserving decays equals the complex mixing parameter ε .

With three flavour generations CP violation can be incorporated in a natural way in the standard theory of weak interactions [9]. It is then possible that the CP odd eigenstate $K_2 = (K^0 + \bar{K}^0)/\sqrt{2}$ can decay directly via weak interactions into a pion pair. This is dubbed “direct CP violation”. A difference appears then in the CP violating decay rates of short- and long-lived neutral kaons into neutral and charged pions. The parameter ε' describing direct CP violation is proportional to the CP violating part of the decay amplitude of K mesons to the two-pion state with isospin 2. In the Kobayashi-Maskawa [9] model of CP violation ε' is in general not zero as opposed to the superweak model. The “experimentum crucis” is therefore to investigate whether ε' differs from zero.

The NA31 experiment

The NA31 experiment “Measurement of $|\eta_{00}/\eta_{+-}|^2$ ” was proposed by the CERN-Edinburgh-Mainz-Orsay-Pisa-Siegen collaboration to the SPS committee at the end of 1981 [10]. At the time of the proposal, estimates for $|\varepsilon'/\varepsilon|$ ranged from 10^{-3} [11] to 10^{-2} [12]. A difference in the CP violating decay rates of K_S and K_L to charged and neutral pions of the order of a percent or more could be expected and seemed measurable. The detector (Fig.1) employed wire chambers combined with calorimetry to determine the basic K^0 parameters such as energy and decay vertex with the precision required. A special feature was a K_S beam mounted on a train which was moved along the beam direction covering a 50 m K_L decay region with K_S decays (Fig. 2). Previous experiments had achieved an accuracy of about ten percent [13]. Experiments designed to reach the one percent level were in progress at BNL and FNAL [14].

The NA31 experiment aimed at an accuracy of a few parts in a thousand. The experiment was approved in autumn 1982, and took data in the years 1986–89 (Fig. 3).

The measured double ratio R of the four decay rates of K_S and K_L mesons to $2\pi^0$ and $\pi^+ \pi^-$ final states was published in 1988 [15]. From the experimental result $R = 0.980 \pm 0.004 \pm 0.005$ the real part $\text{Re}\varepsilon'/\varepsilon = (3.3 \pm 1.1) \times 10^{-3}$ was derived.

	Year	$\text{Re}\varepsilon'/\varepsilon$	χ^2	
E731	1988	$(3.2 \pm 3.0) \times 10^{-3}$	0.32	[16]
NA31	1988	$(3.3 \pm 1.1) \times 10^{-3}$	(1.48)	[15]
E731	1993	$(0.74 \pm 0.6) \times 10^{-3}$	1.58	[17]
NA31	1993	$(2.0 \pm 0.7) \times 10^{-3}$	1.56	[18]
	Average	$(1.49 \pm 0.44) \times 10^{-3}$	4.94	

▲ **Table 1:** The 1993 average of $\text{Re}\varepsilon'/\varepsilon$ for the NA31 and E731 experiments

► **Fig. 2:** The “train” carrying the beam elements guiding the 450 GeV proton beam onto the target producing K_S mesons

The data accumulated during three years of data taking included a sample of $4 \times 10^5 K_L \rightarrow 2\pi^0$ events, two orders-of-magnitude more than in previous experiments. The statistical uncertainty on this event number is the largest error and determines the uncertainty of the result. The final results on $\text{Re}\varepsilon'/\varepsilon$ of the NA31 experiment at CERN and the concurrent E731 experiment at Fermilab were published in 1993 [18, 17] and are displayed in Table 1.

The average is 3.4 standard deviations above zero with a confidence level of 18% for the consistency of the different measurements. This is a low but acceptable χ^2 probability. These measurements confirm that $\text{Re}\varepsilon'/\varepsilon$ is nonzero and, therefore, that direct CP violation occurs in $K_0 \rightarrow 2\pi$ decays.

This view of the experimental situation was not shared unanimously, and it remained controversial for several years. Theoretical prejudice favoured the second E731 result which was in the range of the latest predictions from the Standard Model. Gluon penguin diagrams were originally assumed to dominate direct CP violation. The large mass of the top quark implied that electroweak penguin diagrams cancel the gluon contribution to a certain extent. This led to a significant reduction the theoretical estimates combined with considerable uncertainties [19].

Subsequent experiments

In order to check the observation of the NA31 experiment, a new round of experiments was initiated in 1990 by the NA48 proposal for “A precision measurement of ε'/ε in CP violating $K_0 \rightarrow 2\pi$ decays”, and by a proposal at Fermilab named KTeV. The measurement principle of NA48 was to a large extent exploiting cancellations in the double ratio. All four decay modes were collected concurrently in order to minimize differences in accidental activity and detection efficiencies.

The experiment was approved in 1991 and took data in the years 1997–2001. The higher beam intensity and the faster performance of the detector allowed a tenfold increase in the recorded event numbers compared to NA31. The leading statistical uncertainty comes from the number of 4.8 million registered $K_L \rightarrow \pi^0 \pi^0$ decays.

The KTeV experiment at the 800 GeV/c Tevatron was the successor to the E731 experiment. K_S mesons were created from a slab of material inserted in a K_L beam by coherent regeneration, in one half of the beam cross-section. In the other half, the K_L beam

▲ Fig. 3: Photograph of the NA31 detector

continued its way. This K_L “double beam” entered the decay volume upstream of the detector. All four decay modes were registered in the same exposure, and the number of recorded K_L decays to $\pi^0\pi^0$ was 3.3 million.

Conclusions about direct CP violation

After twelve years of experimentation and analysis, both experiments NA48[20] and KTeV [21] confirm a non-zero amplitude ϵ'/ϵ . NA48 finds $\text{Re}(\epsilon'/\epsilon) = (1.5 \pm 0.2) \times 10^{-3}$, and KTeV $(2.1 \pm 0.3) \times 10^{-3}$. Both experiments have definitively confirmed the original observation of the NA31 team that direct CP violation exists. The results of all published experiments on ϵ'/ϵ are shown in Fig. 4. The observed magnitude and sign of direct CP violation is at the level of theoretical predictions based on weak quark mixing. The experimental result for ϵ'/ϵ is rather precise already. However, the theoretical calculations of ϵ'/ϵ within the Standard Model, are still limited in their accuracy [22]. The main conclusion of the experiments is that ϵ' differs from zero and is positive, i.e. direct CP violation exists.

Taking into account the four relevant experiments NA31, E731, NA48 and KTeV, the weighted average comes out to be

$$\text{Re}\left(\frac{\epsilon'}{\epsilon}\right) = (1.7 \pm 0.2) \times 10^{-3}.$$

If we call the amplitudes for the decays of the K^0 particle and its antiparticle $\bar{K}^0$ to a final state of two charged pions a and $\bar{a}$, then the asymmetry of the decay rates of particle and antiparticle, $(|a|^2 - |\bar{a}|^2)/(|a|^2 + |\bar{a}|^2)$ can be derived to be $2\text{Re}\epsilon' = (5.6 \pm 0.6) \times 10^{-6}$.

We conclude that this observation of direct CP violation definitively rules out the model invoking a new superweak force. On the other hand, this result is completely consistent with a mechanism for generating CP violation in the weak interaction via a complex phase in the Kobayashi-Maskawa quark mixing matrix. This view has been reinforced recently by the observation of a similar CP violating effect in the neutral B meson system.

However CP violation in the quark sector cannot explain the large matter-antimatter asymmetry in the Universe. In cosmology, a stronger CP violation, together with a large departure from thermal equilibrium and a baryon number violation could in principle lead to the observed baryon asymmetry. It remains an open question whether CP violation in the neutrino mixing matrix exists and could explain this enigma [23]. ■

► Fig. 4: Time sequence of published measurements of the parameter $\text{Re}\epsilon'/\epsilon$ of direct CP violation. The experiments at CERN are marked by filled circles and the experiments at Fermilab by open squares. The KTeV result from 2003 is a reanalysis of the data from the KTeV 1999 result.

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Konrad Kleinknecht studied physics at München and Heidelberg, 1966 Ph.D. on CP violating kaon decays; 1972-1984 Professor (Universität Dortmund); 1976 CalTech; 1984 Professor (Universität Mainz); 1988 Morris Loeb lecturer, Harvard University; Awards: 1990 G.W. Leibniz award of Deutsche Forschungsgemeinschaft, Bonn; 2001 Gentner-Kastler award and medal of SFP and DPG; Research: Weak interactions, CP violation, high energy neutrino scattering, electroweak interactions.

Heinrich Wahl obtained his PhD in nuclear physics at the University of Hamburg. Then he was working on meson photoproduction and $e+e-$ interactions at DESY. Research at CERN focused on neutral kaon and hyperon decays, and high energy neutrino interactions. At present he is professor of physics at the University of Ferrara.

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Physics in daily life: Cycling in the wind

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When riding our bicycle, wind is bad news, usually. For one thing, it spoils our average when making a round trip. The reason is obvious: we spend more time cycling with headwind than with tailwind.

And what about a pure crosswind, blowing precisely at a right angle from where we are heading? That cannot possibly hurt the cyclist, one might think. Wrong. A crosswind gives rise to a much higher drag. Why is that? Don't we need a force in the direction of motion to do that?

So let us have a look at the relevant forces. The key is that air drag for cyclists is proportional to the relative air speed *squared* (just like for cars, cf. EPN 35/4, p. 130). This v^2 dependence spoils our intuitive feeling, as is easily seen from a vector diagram: See the figure, which illustrates the situation of a cyclist 'heading north'.

The figure says it all: In the wind-free case (left) the cyclist feels an air speed equal to his own speed, and experiences a certain drag which we may call D . With a crosswind blowing from the East, the resulting relative air speed is much larger, and so is the drag. In our example, the relative air speed is taken twice the cyclist's speed (it comes at a 60° angle from the right). Consequently, the resulting drag is $4D$. So its component in the direction of motion is $2D$, or twice what it was in the wind-free case.

In order to profit from the wind, it has to blow slightly from behind. Of course, the angle for which the break-even point is reached, depends on the wind speed relative to that of the cyclist. In our example, where their ratio is $\sqrt{3}$, the break-even angle is 104.5 degrees, as calculated by Fokke Tuinstra from Delft. But a pure 90 -degree crosswind always hurts the cyclist.

NO WIND

CROSSWIND FROM THE RIGHT

In fact it's even worse. Also the relevant frontal area, which determines the drag, is increased dramatically. It is no longer that of a streamlined cyclist as seen from the front, but a $\sin \alpha$ projection of the cyclist plus his bike. And with α being 60° in the example, this is practically the full side view of the bicycle and his rider. Even the crouched position does not help much in this case.

Clearly, riding our bike in the storm is really brave. It makes good exercise. And it yields some funny physics, too. ■

About the author

L.J.F. (Jo) Hermans recently retired as professor of Physics at Leiden University, The Netherlands. Main research topics: Internal-state-dependence of intermolecular and molecule-surface interactions, and nuclear spin conversion in polyatomic molecules. In the 1990s he served as a member of the EPS council.

About the illustrator

Wiebke Drenckhan (28) is a postdoctoral fellow at Trinity College Dublin, Ireland, where she is trying to unravel some of the mysteries of the physics of foams and other complex systems. Much of her spare time is invested into sharing her views on science from a slightly different perspective, namely that of a cartoonist.