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STUDY OF CP VIOLATION IN A TAGGED NEUTRAL KAON BEAM

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Presented by L. Tauscher

ABSTRACT

A novel method to study symmetry violation in the decay of neutral kaons is presented. The method makes use of initially pure K^0 and $\bar{K}^0$ beams, produced in pp annihilations at LEAR. The detector and the tagging are described, and the envisaged physics is discussed.

1. INTRODUCTION

The non-existence of right-handed neutrinos and left-handed anti-neutrinos is a well-established manifestation of maximal P and C violation in weak interactions. In general, however, the combined CP symmetry is conserved in weak interactions. The only exception observed so far occurs in the decay of the long-lived neutral kaon. Since it is unlikely that in the near future CP violation will become observable in

other systems, we will try in the following to outline schematically the properties of the neutral kaon system, to put forward reasons why there is revived interest in its investigation, and to discuss a novel experimental method.

Generally, the neutral kaon, henceforth denoted by K_0 , is produced in a strong process, which conserves all relevant symmetries. Since neither the K^0 ($\bar{s}d$) nor the $\bar{K}^0$ ($s\bar{d}$) are eigenstates of CP, but their weak decay is expected to conserve CP symmetry, the expected physical particles are superpositions of K^0 and $\bar{K}^0$, yielding the CP eigenstates $K_1 = (K^0 + \bar{K}^0)/\sqrt{2}$ and $K_2 = (K^0 - \bar{K}^0)/\sqrt{2}$. This mixing is due to weak CP-conserving $\Delta S = 2$ processes, which transform an original K_0 into its antiparticle. However, the observed CP violation requires additional CP-violating $\Delta S = 2$ currents, such that the finally observed physical mixtures contain CP impurities, characterized by the complex number ϵ : $K_S = K_1 + \epsilon K_2$, $K_L = K_2 + \epsilon K_1$ (to first order in ϵ).

The standard model attributes these CP-violating $\Delta S = 2$ currents to the so-called "box" diagrams, where the CP violation is introduced through the complexity of the Kobayashi Maskawa mixing scheme for the heavy quarks (Fig. 1a). In addition, the standard model also predicts CP-violating $\Delta S = 1$ currents through the so-called "penguin" diagrams (Fig. 1b), which lead to CP violation in the decay of the CP-pure component K_2 of the K_L . The strength of this type of CP violation is related to the parameter ϵ' (defined later)¹⁾. So far $\Delta S = 1$ CP-violating effects have not been observed.

Fig. 1

2. THE MEASURED QUANTITIES²⁾

CP violation has been observed in the decay of the K_L into two pions. The measured parameter is the ratio of the forbidden to the allowed amplitude:

$$\eta = \frac{\langle \pi\pi | H | K_L \rangle}{\langle \pi\pi | H | K_S \rangle} = |\eta| e^{i\phi} \quad (1)$$

with

$$\begin{aligned} |\eta_{+-}| &= (2.274 \pm 0.022) \times 10^{-3}, & \phi_{+-} &= (44.6 \pm 1.2)^\circ \\ |\eta_{00}| &= (2.325 \pm 0.082) \times 10^{-3}, & \phi_{00} &= (54.5 \pm 5.3)^\circ \end{aligned} \quad (2)$$

The ratio η is related to ϵ and ϵ' via¹⁾

$$\eta_{+-} = \epsilon + \epsilon', \quad \eta_{00} = \epsilon - 2\epsilon'. \quad (3)$$

With the above values of η , we obtain

$$|\epsilon| = (2.28 \pm 0.06) \times 10^{-3} \text{ and } |\epsilon'/\epsilon| = 0.004 \pm 0.012. \quad (4)$$

The phase of ϵ is given from unitarity³⁾

$$\phi_\epsilon = \text{artg} (2\Delta m/\gamma_S) = (43.72 \pm 0.14)^\circ \quad (5)$$

where Δm is the $K_L - K_S$ mass difference, and γ_S is the width of K_S .

The charge asymmetry δ in the semileptonic K_L decay depends on ϵ and hence is sensitive to CP violation too:

$$\delta = \frac{R(K_L \rightarrow \pi^- \ell^+ \nu) - R(K_L \rightarrow \pi^+ \ell^- \nu)}{R(K_L \rightarrow \pi^- \ell^+ \nu) + R(K_L \rightarrow \pi^+ \ell^- \nu)} = 2 \text{ Re } \epsilon. \quad (6)$$

It has been measured to be $\delta = (3.30 \pm 0.12) \times 10^{-3}$, hence, with Eq. (5) $|\epsilon| = (2.24 \pm 0.08) \times 10^{-3}$.

In the equality $\delta = 2 \text{ Re } \epsilon$ the strict validity of the $\Delta S = \Delta Q$ rule was assumed. The ratio of the forbidden to the allowed amplitude, x , is a measure of the validity of this rule:

$$x = \frac{\langle \pi^- \ell^+ \nu | H | \bar{K}^0 \rangle}{\langle \pi^- \ell^+ \nu | H | K^0 \rangle}. \quad (7)$$

The measured value is $\text{Re } x = 0.009 \pm 0.020$, $\text{Im } x = -0.004 \pm 0.026$. The standard model requires x to be strictly zero.

The existence of $\Delta S = 1$ CP-violating currents has been checked recently by a precise determination of

$$|\varepsilon'/\varepsilon| = (1 - |\eta_{00}/\eta_{+-}|^2)/6 . \quad (8)$$

The values are

$$|\varepsilon'/\varepsilon| = +0.0017 \pm 0.0072 \text{ (statistical)} \pm 0.0043 \text{ (systematic)}^{4)}$$

$$|\varepsilon'/\varepsilon| = -0.0046 \pm 0.0053 \text{ (statistical)} \pm 0.0024 \text{ (systematic)}^{5)}$$

The questions to be asked are: What has not been measured, and where are improvements necessary? Not measured at all is the expected CP violation in the K_S decay, i.e. η_{+-0} and η_{000} . Improvements are required on all parameters, mentioned above, in particular on $\phi_{00}^{3)}$, and on ε'/ε that has to be measured to an accuracy of $(1-2) \times 10^{-3}$ in order to become relevant. All these improvements are necessary for a better understanding of CP violation, which, with present accuracies can be thoroughly explained by the superweak model (see Ref. 1), and the parameter ε alone.

3. THE DECAY OF THE NEUTRAL KAON

The initial state of a K_0 in an experiment is usually given by a mixture of K_S and K_L :

$$b|K_0\rangle = b_S|K_S\rangle + b_L|K_L\rangle . \quad (9)$$

This mixture then decays within the experimental apparatus into a final state $\langle f|$ with the characteristic decay times and according to the corresponding amplitudes:

$$b(t) \langle f|H|K_0\rangle = b_S a_S e^{-M_S t} + b_L a_L e^{-M_L t} , \quad (10)$$

with $M = im + \gamma/2$ and $a = \langle f|H|K \rangle$, m and γ being the mass and the width of the K_S or K_L , respectively. The observable decay rate is

$$R_{K_0 \rightarrow f} = b_S^2 |a_S|^2 e^{-\gamma_S t} + b_L^2 |a_L|^2 e^{-\gamma_L t} + b_S b_L |a_S| |a_L| \exp[-(\gamma_S + \gamma_L)t/2] \cos(\Delta m t - \phi) \quad (11)$$

The eminently important feature of the K_0 system is the approximate equality of Δm and $\gamma_S/2$, which renders the interference term observable before the K_S component has died out.

4. EXPERIMENTAL METHODS

4.1 K_S/K_L Beams

The usual method of studying the decay of the K_0 is to use a K_0 beam produced in a high-energy p-nucleus collision. If the production target is sufficiently far away from the experiment, the beam is a pure K_L beam, hence $b_S = 0$ in Eq. (9). For investigation of interference phenomena and for normalization purposes, the K_S component is regenerated, which leads to $b_S \neq 0$ in Eq. (9). This method faces a number of problems, leading to systematic uncertainties: incoherence of regeneration, regeneration phase, Monte Carlo based acceptance calculations for normalization, etc. Currently running experiments on $|\epsilon'/\epsilon|^{6)}$ have invested extraordinary efforts in order to reduce these sources of errors.

4.2 Pure K^0 or $\bar{K}^0$ Beams

Based on an idea of Gabathuler and Pavlopoulos⁷⁾ our Collaboration has proposed an experiment to investigate the K_0 system with pure K^0 or $\bar{K}^0$ beams⁸⁾. The advent of LEAR as a source of slow $\bar{p}$'s has opened up the possibility of producing initially pure K^0 or $\bar{K}^0$ beams through the reactions $p\bar{p}$ (at rest) $\rightarrow \bar{K}^0 K^+ \pi^-$ or $K^0 K^- \pi^+$, which have a branching ratio of 0.2% each. The sign of the charge of the $K^\pm$ defines uniquely the strangeness of the K_0 . The momenta of the K_0 's are such that the average decay length of the K_S is ~ 3 cm.

The advantage of initially pure K^0 or $\bar{K}^0$ beams is obvious, since they contain exactly equal amounts of K_S and K_L :

$$|K^0\rangle = (1 - \epsilon) (|K_S\rangle + |K_L\rangle)/\sqrt{2}, \quad |\bar{K}^0\rangle = (1 + \epsilon) (|K_S\rangle - |K_L\rangle)/\sqrt{2}. \quad (12)$$

The corresponding decay rates are then [see Eq. (11)]

$$R_{K^0/\bar{K}^0 \rightarrow f} = (0.5 \mp \text{Re } \epsilon) \left[|a_S|^2 e^{-\gamma_S t} + |a_L|^2 e^{-\gamma_L t} \pm |a_S||a_L| \exp[-(\gamma_S + \gamma_L)t/2] \cos(\Delta m t - \phi) \right]. \quad (13)$$

A further advantage of the method is that, by measuring differences and ratios of these rates, errors introduced through the apparatus are largely reduced, because solid angle, detection efficiencies, etc., are independent of whether the initial state was a K^0 or a $\bar{K}^0$. Such rates are, to first order in ϵ :

$$A_f(t) = \frac{R(\bar{K}^0 \rightarrow f) - R(K^0 \rightarrow f)}{R(\bar{K}^0 \rightarrow f) + R(K^0 \rightarrow f)} = 2 \left[\frac{|\eta_f| \exp(\gamma_S t/2) \cos(\Delta m t - \phi)}{1 + |\eta_f|^2 e^{+\gamma_S t}} - \text{Re } \epsilon \right] \quad (14)$$

and

$$U_f(t) = 1 - \frac{R(K^0 \rightarrow f)}{R(\bar{K}^0 \rightarrow f)} = -4 \left[\frac{|\eta_f| \exp[-(\gamma_S + \gamma_L)t/2] \cos(\Delta m t - \phi)}{e^{-\gamma_L t} - 2|\eta_f| \exp[-(\gamma_S + \gamma_L)t/2] \cos(\Delta m t - \phi)} - \text{Re } \epsilon \right] \quad (15)$$

Both A_f and U_f depend only on the interference term. If time dependence is not needed, it is sufficient to measure the integral rate asymmetry:

$$I_f = \frac{\int_0^{t_0} R(\bar{K}^0 \rightarrow f) dt - \int_0^{t_0} R(K^0 \rightarrow f) dt}{\int_0^{t_0} R(\bar{K}^0 \rightarrow f) dt + \int_0^{t_0} R(K^0 \rightarrow f) dt} =$$

$$= \begin{cases} 4 \operatorname{Re} \eta_f - 2 \operatorname{Re} \epsilon & (\text{for } K_0 \rightarrow \pi\pi) \\ \frac{4}{\gamma_{S^0}^2} \operatorname{Re} \eta_f - 2 \operatorname{Re} \epsilon & (\text{for } K_0 \rightarrow \pi\pi\pi) \end{cases} \quad (16)$$

5. THE DETECTOR

The detector has to fulfil the tasks of detecting as many of the produced K_0 's as possible, of tagging the strangeness of the K_0 , of identifying the decay channels of the K_0 , and of measuring the time of decay.

The first task requires a large solid-angle detector, since the emission of K_0 's after a $p\bar{p}$ annihilation at rest is isotropic.

The second task requires the identification of a $K^\pm$ and its charge. The $K^\pm$ identification needs a threshold Cherenkov detector, the identification of the charge needs a magnetic field and tracking chambers.

The third task requires a set of scintillation counters for the charged decay products ($\pi^+\pi^-$, $\pi^\pm\pi^\pm$) and a segmented electromagnetic shower calorimeter with good detection efficiency for the identification of the neutral channels ($\pi^0\pi^0$, $3\pi^0$).

The fourth task needs first a precise determination of the K_0 four momentum (necessary to determine the K_0 eigentime), hence precise measurements of the primary $K^\pm\pi^\pm$ momenta. Secondly, it requires precise reconstruction of the K_0 decay vertex, in order to determine the time of decay. This is possible either by tracking the charged decay products in a set of wire chambers, or by measuring the impact positions and the energy of the decay γ 's in the calorimeter.

The magnet to be used is the DM2 magnet of Orsay⁹⁾, which provides a uniform magnetic field of 0.5 T in a volume of 3 m length and 2 m diameter. Figure 2 shows the proposed layout: the gaseous H_2 target in the centre, a set of two MWPCs at small radii (K_S decays will typically occur inside these chambers), and a set of chambers with larger radii, used essentially for tracking the decay products. A double layer of streamer tubes provides the z positions of the charged particles. A system of plastic scintillators, Cherenkov detectors and, again, plastic

Fig. 2

scintillators serves the purpose of K/π separation by Cherenkov discrimination and by time of flight (TOF), and of multiplicity counting. The cylindrical coil has a thickness of 0.8 radiation length. The calorimeter is placed outside the coil. A modular system of lead-glass detectors is proposed.

We intend to use a $\bar{p}$ beam of 100 MeV/c, which allows for a sufficiently restricted annihilation volume in the H_2 gas (STP).

6. THE TRIGGER

In view of the low branching ratio for the tagging channel, we have to be able to reject an ordinary multipionic annihilation event rapidly. This requires a fast trigger. Successive steps are foreseen. A fast scan of the scintillators and the Cherenkovs requires a multiplicity of $N = 2$ or 4 from the scintillators and of $N' \leq N - 1$ from the Cherenkovs. This may be achieved within 40 ns.

A fast tracking through the wire chambers identifies the primary $K^\pm \pi^\pm$, defines the charge of the $K^\pm$, and imposes a cut on the transverse momenta ($p_T \geq 200$ MeV/c), thus improving the Cherenkov efficiency. This step takes 250 ns.

A hardwired processor then implements the z information of the streamer tubes, determines the momenta of the $K^\pm$ and $\pi^\pm$, and obtains the invariant mass of the K_0 and its momentum. We expect a resolution of

$\sigma_{K_0} \approx 70 \text{ MeV}/c^2$ and of $\sigma(p_{K_0}) \approx 0.05 p_{K_0}$. This evaluation should take not more than $1 \mu\text{s}$.

A more sophisticated analysis is done in a second hardwired processor. The evaluation of the TOF measurement improves the $K^\pm$ identification. The evaluation of the calorimeter information provides the γ multiplicities. This step takes about $2 \mu\text{s}$.

Hence, after about $3.5 \mu\text{s}$ a master trigger is ready. Assuming a $\bar{p}$ rate of $2 \times 10^6 \text{ s}^{-1}$, we never exceed a dead time of 10%.

7. EXAMPLES OF PHYSICS

We first discuss the measurement of CP violation in the $K_0 \rightarrow \pi\pi$ decay. The determination of $|\eta|$ and ϕ requires the measurement of the time-dependent asymmetry A_f [see Eq. (14)]. The expected asymmetry is shown in Fig. 3. The relevant times are $t > 5\tau_S$.

Fig. 3

Fig. 4

7.1 $K_0 \rightarrow \pi^+ \pi^-$

The trigger requires two hits in the inner chambers, and four hits in the outer chambers. This eliminates times $t < 5\tau_S$. We expect a time resolution of $\sigma(t) = 0.07\tau_S$ (~ 2 mm). Figure 4 shows the expected rate [Eq. (13)] as a function of time and the contribution from the only background, namely the $K_L \rightarrow \pi \ell \nu$. Since this varies slowly in time, it is easy to correct for it.

7.2 $K_0 \rightarrow \pi^0 \pi^0$

The trigger requires two hits in all chambers, and four hits in the calorimeter. A fast on-line vertex reconstruction excludes times $t \lesssim 5\tau_S$. We expect a time resolution of $\sigma(t) \approx 1\tau_S$ (~ 3 cm). This channel has no relevant background. The only contributions could be due to $K_L \rightarrow 3\pi^0$, which is very rare and nearly constant, and from falsely identified $K^\pm$, hence from the reaction $p\bar{p} \rightarrow \pi^+ \pi^- \pi^0 \pi^0$, which comes from the target region only ($t = 0$).

7.3 $|\epsilon'/\epsilon|$

The time-dependent asymmetry method is not precise enough to determine $|\eta_{00}/\eta_{+-}|^2$ with sufficient accuracy [see Eq. (8)]. Here we intend to use the integral asymmetry [Eq. (16)].

7.4 $K_0 \rightarrow \pi^+ \pi^- \pi^0$

CP violation in the decay of K_S becomes measurable through the interference in the 3π decay. Figure 5 shows the expected asymmetry U_{+-0} , assuming $\eta_{+-0} \approx \eta_{+-}$. The relevant times are short. The trigger requires four hits in all chambers and two hits in the calorimeter. The background is only due to falsely identified $K^\pm$ ($p\bar{p} \rightarrow \pi^+ \pi^- \pi^+ \pi^- \pi^0$). This background, however, is relevant only at $t < 0.5 \tau_S$, but with a time resolution of $0.07 \tau_S$ it can be eliminated.

Fig. 5

7.5 $K_0 \rightarrow 3\pi^0$

The trigger requires two hits in all chambers and at least five γ 's in the calorimeter. Background is due to the reaction $p\bar{p} \rightarrow \pi^+\pi^-3\pi^0$. It amounts at most to 25% (at $t = 0$) of the K_0 decay rate.

7.6 $K_0 \rightarrow \pi e \nu$

The measurement of the *semileptonic decays of K_0* allows for studying violation of CP, T, CPT and of the $\Delta S = \Delta Q$ rule. We focus our efforts on the investigation of the decay into $\pi^+e^+\nu$. All times accessible with the detector are relevant. The main background is due to

Fig. 6

the decays $K_0 \rightarrow \pi^+ \pi^-$ and $\pi^+ \pi^- \pi^0$. The former is eliminated by requiring the angle between the two charged particles to be smaller than the Jacobian angle for the $K_0 \rightarrow \pi^+ \pi^-$ decay. This reduces the number of accepted semileptonic decays to 20%. The background due to the decay $K_0 \rightarrow \pi^+ \pi^- \pi^0$ is low anyway and further reduced by the calorimeter information, such that its final contribution to the remaining semileptonic decay is expected to be less than 7% (see Fig. 6).

8. PROPOSED PHYSICS

The Collaboration intends to study thoroughly the symmetry violations in the decays of the K_0 . In particular, we want to study:

- i) CP violation, by measuring the 2π and 3π decays of the K_0 ;
- ii) T violation, by measuring the ratio

$$A_T = \frac{\bar{N}^+ - N^-}{\bar{N}^+ + N^-}$$

with $N^\pm = R(K^0 \rightarrow \pi^\mp e^\pm \nu)$ and $\bar{N}^\pm = R(\bar{K}^0 \rightarrow \pi^\mp e^\pm \nu)$;

- iii) the validity of the $\Delta S = \Delta Q$ rule by measuring the rate $N^+ + N^- + \bar{N}^+ + \bar{N}^-$, which only depends on $\text{Re } x$ [see Eq. (7)];
- iv) $\text{Im } x$, by measuring the rate

$$\frac{(\bar{N}^+ + \bar{N}^-) - (N^+ + N^-)}{(\bar{N}^+ + \bar{N}^-) + (N^+ + N^-)} ;$$

- v) Δm by measuring $N^+ - N^-$.

The expected accuracies, including systematic effects, together with the present ones are listed in the table below for a total of 10^{13} stopped $\bar{p}$'s.

Parameter	Present	This proposal
$ \phi_{+-} - \phi_{00} $	5°	2°
$ \epsilon'/\epsilon $	7×10^{-3}	2×10^{-3}
$\sigma(\Delta m)/\Delta m$	4.1×10^{-3}	1.2×10^{-3}
$ \eta_{+-0} $	$< 1.2 \times 10^{-1}$	6×10^{-4}
$ \eta_{000} $	$< 10^{-1}$	8×10^{-4}
$\text{Re } x$	$< 2 \times 10^{-2}$	6×10^{-4}
$\text{Im } x$	$< 2.6 \times 10^{-2}$	7×10^{-4}
$\sigma(A_T)/A_T$	-	6.4×10^{-2}

CONCLUSIONS

With the approval of the proposed experiment a new era of high-precision measurements of the K_0 decays has been opened. Of the many merits of the method the following are the most important: The K_S-K_L interference becomes accessible also for very short distances or times, the accuracies for the different parameters may be improved significantly, and systematic errors are small and of an entirely different nature than those with conventional methods.

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