MEASUREMENT OF THE DECAY OF THE LONG-LIVED NEUTRAL K MESON INTO TWO NEUTRAL PIONS

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The observation of the decay[1] $K_L^0 \to \pi^+ + \pi^-$ and of interference effects between K_S^0 and K_L^0 in the decay[2] is normally accepted as evidence of CP nonconservation, but there is considerable discussion about the origin of the nonconservation. There are theoretical papers attributing it to the weak interaction, the electromagnetic interaction, the strong interaction, and a new superweak interaction with $\Delta S = 2$.[3]

This Letter is a preliminary report of a measurement of the decay rate for $K_L^0 \to \pi^0 + \pi^0$. The measured relative transition amplitude $|\eta^{00}|$ is $(4.3_{-0.8}^{+1.1}) \times 10^{-3}$.[4] This value differs from that given by the superweak theory[5] by 3.0 standard deviations. The result indicates that the CP nonconservation is partially due to a $\Delta I \geqslant \frac{3}{2}$ amplitude.

A neutral beam taken at 17° from an internal target in the CERN proton synchrotron was passed through 7.5 cm of lead and a sweeping magnet to remove gamma rays and charged particles. The beam dimensions, defined by a collimator placed 9 m from the target, were 18 cm wide and 20 cm high at the detection equipment situated 36 m from the target. Figure 1 is a diagram of the spark chambers and scintillation counters used to detect the four gamma rays resulting from the $2\pi^0$ decay of K_L^0. The spark chambers were constructed of two-gap modules[6] 160 cm high and 100 cm wide, placed in banks of 29 modules (58 gaps) on either side of the beam and inclined at 10° to the beam. The separation at the front edge was 33 cm. The first 21 modules on each side were made with 5-mm thick aluminum plates and the last eight modules with 5-mm brass plates making a total spark-chamber thickness of 11.6 radiation lengths. The first 3.6 radiation lengths (aluminum chambers) occupied 100 cm giving an average radiation length of 28 cm; the last 8 radiation lengths (brass chambers) occupied 32 cm giving an average radiation length of 4.0 cm.

Scintillation counters for the trigger were inserted in both sides after the eighth and nineteenth aluminum modules (equivalent to 1.36 and 3.2 radiation lengths). The electronics were arranged to require a four-fold coincidence between left-upper, left-lower, right-upper, and right-lower quadrants. The signal from each quadrant was from either one, or both, of the counters at 1.36 and 3.2 radiation lengths. This arrangement was designed to favor four-gamma events in which one gamma ray converted in the aluminum section of each quadrant of the spark chamber. Scintillation counters were put in front of the spark chambers and used to veto counts from charged particles entering the detection system. Further anticoincidence counters designed to detect γ rays, and comprising multiple layers of scintillation counters and lead or steel converters, were placed between the spark chambers and

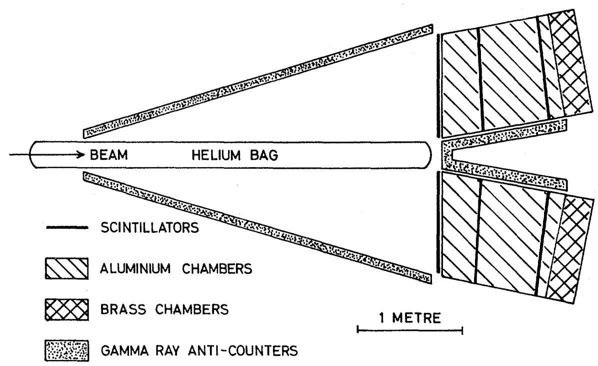

FIG. 1. Experimental apparatus.

completely around the decay region. These biased against events in which more than four gamma rays were produced and reduced the trigger rate from the decay $K_L{}^0 \to 3\pi^0$, which was the main source of background.

The aluminum chambers were photographed with 90° stereo and the brass chambers in side view. Adox track-chamber 70-mm film was used. 190 000 pictures were taken at an average rate of 0.15 per machine burst. 77% of the data was obtained with the decay region filled with a helium bag. In addition, 50 000 pictures were taken with a carbon regenerator placed in the $K_L{}^0$ beam. 10- and 20-cm thicknesses of regenerator of density 1.55-1.68 g/cm^3 were used at distances of 150-250 cm from the spark chambers. The branching ratio of $K_L{}^0 \to 2\pi^0$ was obtained by comparing the rate observed for $2\pi^0$ decay from regenerated $K_S{}^0$ with that from $K_L{}^0$ free decay. The regeneration of $K_S{}^0$ in helium gas is negligible.

The pictures were first scanned for events with four gamma rays converted in the first 19 modules (38 gaps) of the aluminum section of the spark chambers. All events with a clear fifth or sixth gamma ray in the aluminum or brass sections of the chamber were rejected. Events with a dubious fifth gamma ray were included and analyzed ignoring the dubious gamma ray. (These represent only 3% of the events in the final mass plot.) All selected events were measured using hand-operated image-plane digitizers, and the following quantities were measured for each gamma ray:

(a) Conversion point (estimated accuracy ±1 mm in real space).

(b) γ-ray direction determined from the early development of the shower in the aluminum section of the chamber. The accuracy is mainly limited by multiple scattering and thus dependent upon the energy of the gamma rays. A typical error is 30 mrad.

(c) The number of sparks within the shower in the aluminum section N_A and the brass section N_B. The counting was carried out in the side view. Care was taken to cross-check the results from different scanners and measurers to ensure a uniform treatment of the data.

All measured events were analysed using an Atlas (ICT) or CDC 6600 computer. A least-squares fit was made to determine the decay point using the measured gamma-ray directions. Events in which the line joining the decay point to the conversion points differed from the measured gamma-ray directions by greater than 100 mrad were reanalyzed using the three best fitting gamma rays and if the fit was still bad, the event was rejected (the loss was 3%). The energies of the gamma rays were determined from the spark count using the empirical relation $E_\gamma(\text{MeV}) = 8N_A + 24N_B$ derived from previous data.[7] This relation was checked using regenerated $K_S{}^0$ events. The standard deviation error for energy determination by spark counting was found to be 25%. Small corrections were made to the actual number of sparks counted to make the average number of sparks per event constant for each film (~2000 pictures, giving ~700 measured events). These corrections were typically ~10% and were necessary because of small changes in the multitrack efficiency of the spark chambers, probably resulting from small changes in gas conditions.

There are three possible ways to combine four gamma rays from two neutral pions, but the Monte Carlo calculation described below indicated that the only important configuration was that with the gamma rays from one π^0 converting in the chambers on the left and those from the other π^0 in the chambers on the right. The computed contribution from the other pairings was about 2%. This was confirmed by the regeneration data. The results presented below were computed using the preferred pairing. The energy of each π^0 was calculated using the opening angle φ between the two gamma rays (determined by joining the decay point to the conversion points) and the ratio of the gamma-ray energies D:

$$E_\varphi = m_0(1+D)[2D(1-\cos\varphi)]^{-1/2};$$

m_0 is the rest mass of the π^0. The energy E_φ was compared with the energy E_γ obtained directly from spark counting, resulting in one constraint for each π^0. Among the other quantities calculated for each event were the mass M, momentum p_k, and direction θ of the incoming particle assumed to decay into $2\pi^0$. Genuine $2\pi^0$ events should then have values of M centered on the K^0 mass and values of θ close to zero. Selection of $2\pi^0$ events can therefore be based upon four constraints. It was found that the application of an energy constraint to each π^0 resulted in the number of background events being highly sensitive to the exact energy calibration assumed for the spark chamber. Therefore a single-constraint test of the

$2\pi^0$ hypothesis was made, namely

$$\left[\left(\frac{E_\gamma - E_\varphi}{0.25E_\gamma}\right)_{\pi 1} - \left(\frac{E_\gamma - E_\varphi}{0.25E_\gamma}\right)_{\pi 2}\right]^2 < 2.$$

This quantity is insensitive both to the energy calibration and to errors in computing the decay point. Three further criteria were applied: $\theta < 40$ mrad, $p_k > 1.5$ GeV/c, and decay point within 350 cm of the chamber. The last condition was included to limit the decay to the region inside the large gamma-ray anticoincidence shield.

A mass plot, obtained from an analysis of 30 000 pictures, for free decay events satisfying the above criteria is shown in Fig. 2(b). The corresponding plot for regenerated events is given by the solid histogram in Fig. 2(a). In both cases a peak can be clearly seen at the mass of the K^0. All events in these plots have been rescanned and remeasured. The events

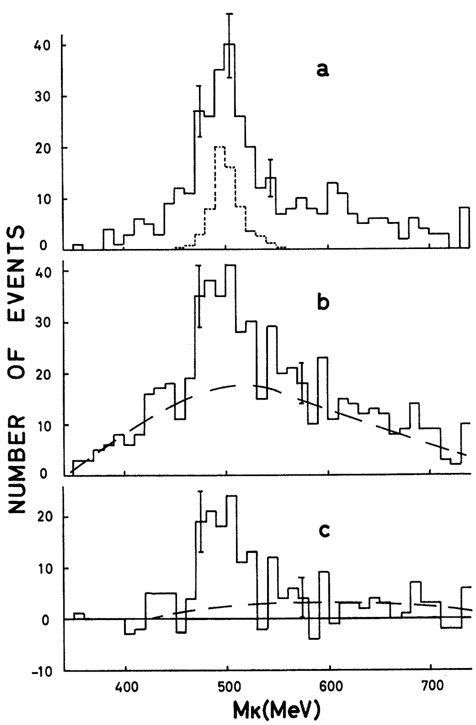

FIG. 2. (a) Experimental mass distribution for regenerated events. The dashed histogram is the 2π spectrum shape calculated with the Monte Carlo program. (b) Experimental mass plot for free decay events. The dashed line is the background spectrum shape calculated with the Monte Carlo program for $3\pi^0$ decays. (c) Experimental mass plot for free decay events with the Monte Carlo spectrum subtracted. The dashed line is a fit by eye to the residual background.

were shown to have measurement errors of ±3 MeV for the mass, ±15 mrad for θ, and ±6% for the distance between decay point and chamber.

Before these spectra can be taken as evidence for the decay $K^0 \to 2\pi^0$, it is necessary to verify that $3\pi^0$ events cannot produce a similar peak at the mass of the K^0. To check this a Monte Carlo program was written to simulate both $2\pi^0$ and $3\pi^0$ events, including the effect of the veto counters and the trigger requirements. The true directions of the gamma rays were smeared by adding Gaussian distributed errors with standard deviations given by $\sigma(\theta) = 4.3 + 8900/E$ mrad, where E is the energy of the gamma ray in million electron volts. The gamma-ray energies were treated similarly using standard deviations $\sigma(E) = 0.25\,E$. Both of these error estimates were chosen to match the accuracy expected in the experiment. The $K_L{}^0$ momentum spectrum used in the Monte Carlo calculation was that measured in the same beam by Böhm et al.[8] (These measurements were made for momenta above 1.5 GeV/c and hence the data were limited to exclude events below this momentum.) The simulated 4γ events were computed in the same way as the data and subjected to the same selection criteria. The dashed lines in Figs. 2(a) and 2(b) are the resulting spectral shapes for $2\pi^0$ and $3\pi^0$ decays, respectively. The calculated distribution of the $3\pi^0$ events along the beam is highly sensitive to the efficiency assumed for the veto counters and does not agree well with the distribution observed. Since it is impossible to make a reliable calculation of the absolute anticoincidence efficiencies, the spectral shape alone is used. The free decay spectrum shows an excess of events, compared with the Monte Carlo spectrum, at high mass values, probably due to interaction of neutrons in the helium filling the decay region. The $3\pi^0$ Monte Carlo spectrum shows no indication of a peak at the mass of the K^0, and the peak observed from the data, both for regenerator and free decay, has the width predicted by the Monte Carlo calculation for $2\pi^0$ events. Figure 2(c) is the difference between the free decay data and the Monte Carlo $3\pi^0$ spectrum. Figure 3 shows θ^2 plots for free decay events in three different mass intervals. The dashed line in Fig. 3(b) for the mass interval including the K^0 mass is obtained by averaging the values for the mass intervals above and below the K^0

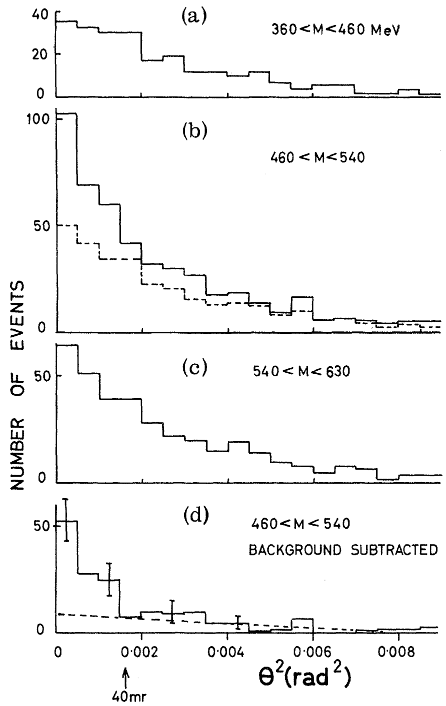

FIG. 3. (a)-(c) θ^2 plot in three mass ranges. The dashed line in (b) shows the background obtained by averaging the observed angular distributions for low- and high-mass ranges. (d) The observed distribution with background subtracted. The dashed line is a fit by eye to the residual background.

mass [Figs. 3(a) and 3(c)], and Fig. 3(d) is the difference between solid and dashed lines in Fig. 3(b). An excess of events is seen for small values of θ^2. The mass plot [Fig. 2(c)] and the angular distribution [Fig. 3(d)] are taken as definite evidence of the observation of the decay[9] $K_L{}^0 \rightarrow 2\pi^0$. The spatial distribution of the decay points for the observed events agrees well with that expected from the beam size and is within the helium bag.

The number of free decay events is estimated from Fig. 2(c) by taking the area between mass values of 460 and 540 MeV above the dashed line shown, which was drawn to fit the residual background. This number is 90 ± 22, where the error includes an estimate of that resulting from the uncertainty in the background subtraction. The corresponding number from the θ^2 plot for $\theta < 40$ mrad [Fig. 3(d)] is 84 ± 22. The average value 87 ± 22 is used below. Similar treatment for the regenerator data gives 125 ± 20, but this figure has to be corrected for free decay events. Neglecting interference effects,[10] the number of regenerated events is 89 ± 25.

To calculate the branching ratio for $K_L{}^0 \rightarrow 2\pi^0$, it is necessary to know the relative efficiency for detecting $K_L{}^0 \rightarrow 2\pi^0$ for free decay compared with that for regenerating $K_S{}^0$ and then detecting $K_S{}^0 \rightarrow 2\pi^0$. The regeneration probability has been calculated including the effect of absorption of $K_L{}^0$ and $K_S{}^0$, absorption of gamma rays from regenerated $K_S{}^0$ decaying within the carbon regenerator, coherent regeneration, and incoherent regeneration within an angular range of 40 mrad. The regeneration amplitude $f_{21}(0)$ for carbon was taken from the measurements of Böhm et al.[8] for momenta between 1.8 and 3.7 GeV/c and from the value of Bott-Bodenhausen et al.[2] at an average momentum of 4.5 GeV/c. The value of $|f_{21}(0)|^2$ used increases approximately linearly with momentum from 9.2×10^{-26} cm^2 at 1.5 GeV/c to 32.0×10^{-26} cm^2 at 4.5 GeV/c. The relative detection efficiencies were obtained from the Monte Carlo calculation. The branching ratio of $(K_S{}^0 \rightarrow 2\pi^0)/(K_S{}^0 \rightarrow \text{all decays})$ was taken as 0.309 ± 0.022.[11] (All relevant constants for the K^0 decay parameters are taken from the review of Trilling.[11])

The deduced branching ratio at an average momentum of 2.1 GeV/c is $(K_L{}^0 \rightarrow 2\pi^0)/(K_L{}^0 \rightarrow \text{all decays}) = (3.3^{+1.8}_{-1.1}) \times 10^{-3}$, giving $\Gamma(K_L{}^0 \rightarrow 2\pi^0) = (6.5^{+3.5}_{-2.2}) \times 10^4$ sec^{-1}. The errors quoted include an estimate for possible systematic effects from $f_{21}{}^2$ which are assumed to be $\pm 10\%$.

Wu and Yang[12] have made a phenomenological analysis of CP invariance of K^0 decay. In their notation there are two complex parameters to determine,

$$\eta_{+-} = \frac{\text{amplitude } (K_L{}^0 \rightarrow \pi^+ + \pi^-)}{\text{amplitude } (K_S{}^0 \rightarrow \pi^+ + \pi^-)} = |\eta_{+-}| \exp(i\varphi_{+-}),$$

and

$$\eta_{00} = \frac{\text{amplitude } (K_L{}^0 \rightarrow \pi^0 + \pi^0)}{\text{amplitude } (K_S{}^0 \rightarrow \pi^0 + \pi^0)} = |\eta_{00}| \exp(i\varphi_{00}).$$

These parameters can be expressed in terms of two other parameters: ϵ, which measures the component with $CP = +1$ in $K_L{}^0$, and ϵ',[13] which depends upon the relative decay amplitudes of $K^0 \rightarrow 2\pi$ in the isospin 2 and 0 states:

$$\eta_{+-} = \tfrac{1}{2}[\epsilon + \epsilon'],$$

$$\eta_{00} = \tfrac{1}{2}[\epsilon - 2\epsilon'].$$

If the $K_L{}^0 \rightarrow 2\pi$ amplitude is pure $\Delta I = \frac{1}{2}$, $\epsilon' = 0$

and $\eta_{00}=\eta_{+-}$.

$|\eta_{+-}|$ is $(1.98\pm0.06)\times10^{-3}$,[11] and Rubbia and Steinberger[14] deduce a value of $\varphi_{+-}=(34\pm13)°$ if the mass of $K_L{}^0$ is taken as greater than mass of $K_S{}^0$.[15] The following conclusions can be drawn from the results of this experiment:

(a) The observation of 87 ± 22 examples of $K_L{}^0\to2\pi^0$ is a further proof of CP nonconservation in K^0 decay. Under CP conservation $K_L{}^0\to\pi^0+\pi^0$ would be forbidden even if pions did not obey Bose statistics.[16]

(b) If ϵ' is zero (i.e., pure $\Delta I=\frac{1}{2}$ amplitudes), the phase $\varphi_{00}=\varphi_{+-}$. The magnitude of the interference between $K_L{}^0$ decay and regenerated $K_S{}^0$ depends upon $\varphi=\varphi_{00}-\varphi_f$ where φ_f is the phase change due to regeneration. Several experiments have measured φ for copper and carbon regenerators and the results are reviewed by Rubbia and Steinberger.[14] A reasonable value for carbon regenerator at an average momentum of 2.1 GeV/c is ~80°. In this experiment the assumption $\varphi_{00}=\varphi_{+-}$ gives rise to constructive interference and results in a value of $|\eta_{00}|=(4.8^{+1.2}_{-0.9})\times10^{-3}$. A change in φ of ±10° from 80° produces a relative change in $|\eta_{00}|$ of ±1%. $|\eta_{00}|=4.8\times10^{-3}$ is three standard deviations greater than $|\eta_{+-}|$ and is contradictory to the assumption of pure $\Delta I=\frac{1}{2}$ amplitude and to the superweak theory of Wolfenstein.[5]

(c) The value of ϵ and ϵ' can be determined by drawing an amplitude triangle, following Wu and Yang[12] and Wolfenstein.[13] One possible solution has ϵ approximately zero which corresponds to a CP nonconservation from a $\Delta I\geq\frac{3}{2}$ amplitude alone.[12,17]

The deduced values of all relevant parameters are given in Table I for both possible solutions. Solution 1 is somewhat favored by the value $\delta_2-\delta_0$ of −30° deduced by Wolf.[18] Solution 2 is supported by the value $\delta_2-\delta_0=-(66\pm13)°$ deduced by Lee and Wu.[19]

Table I. Deduced values of ϵ and ϵ' for the two possible solutions. The input information used to obtain the solutions are $|\eta_{+-}|=1.98\times10^{-3}$, the phase for $\epsilon=44°$, and a value of $|\eta_{00}|$ from this experiment which is dependent upon the interference correction, that is, upon φ_{00}. Each solution has been iterated to obtain the final corrected value of $|\eta_{00}|$. The experimental errors still remain. No attempt has been made to indicate the variation in the quantities derived resulting from experimental uncertainties in the input data.

	Solution 1	Solution 2
$\|\eta_{00}\|$	4.7×10^{-3}	3.8×10^{-3}
$\|\epsilon\|$	5.7×10^{-3}	0.1×10^{-3}
$\|\epsilon'\|$	1.9×10^{-3}	3.9×10^{-3}
φ_{00}	52°	214°
$\delta_2-\delta_0$	−25°	−56°

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MEASUREMENT OF THE DECAY RATE OF $K_2^0 \to \pi^0 + \pi^0$ †*

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An experiment to measure the decay rates $R(K_2^0 \to \pi^0 + \pi^0)$ and $R(K_2^0 \to \gamma + \gamma)$ is in progress at the Princeton-Pennsylvania Accelerator (PPA). With a small fraction of the expected data analyzed, we find that we can draw a significant conclusion from the value we obtain for the decay rate $R(K_2^0 \to \pi^0 + \pi^0)$.

It has been pointed out by many authors[1] that a comparison of the decay rate $R(K_2^0 \to \pi^0 + \pi^0)$ with the well established CP-nonconserving decay rate[2] $R(K_2^0 \to \pi^+ + \pi^-)$ can lead to definite conclusions about the source of the CP violation in the decay of the K_2^0 into two pions. In particular a difference in the amplitude ratio

$$|\eta_{00}| = [R(K_2 \to \pi^0 + \pi^0)/R(K_1 \to \pi^0 + \pi^0)]^{1/2}$$

from

$$|\eta_{+-}| = [R(K_2^0 \to \pi^+ + \pi^-)/R(K_1^0 \to \pi^+ + \pi^-)]^{1/2}$$

is direct evidence that there is a CP-nonconserving $|\Delta I| \geq \frac{3}{2}$ amplitude in the decay $K_2^0 \to \pi + \pi$.

Our technique of measurement uses the fact that the energy spectrum of the γ rays from $K_2^0 \to \pi^0 + \pi^0$ extends to significantly higher energies than the major background $K_2^0 \to 3\pi^0$ in the K_2^0 center-of-mass system. In this system the energy distribution of single γ rays from $K_2^0 \to 2\pi^0$ extends from 19 to 229 MeV in a uniform spectrum. The spectrum of γ rays from $K_2^0 \to 3\pi^0$ approaches an upper limit of 165 MeV with zero slope. The observation of a small shelf beyond this upper limit is evidence of $K_2^0 \to 2\pi^0$, and the comparison of the height of this shelf with the number of γ rays from $K_2^0 \to 3\pi^0$ gives a direct measure of the ratio $R(K_2^0 \to 2\pi^0)/R(K_2^0 \to 3\pi^0)$.

Figure 1 shows a plan view of the apparatus. A beam of K_2^0 was produced by bombarding with 3-BeV protons an internal Pt target 1.5 in. long. The K_2^0 beam was defined by a tapered collimator placed at 90° to the incident proton beam. The 6-in.×6-in. aperture at 10 ft from the target gave a nominal beam size of 12 in. ×12 in. at the detector, 20 ft from the target. Typical intensities were 5×10^4 K_2^0's/sec at a mean momentum of 250 MeV/c and 5×10^7 neutrons/sec with mean momentum of 400 MeV/