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New Measurement of the $K_L^0 \to \pi^+\pi^-$ Branching Ratio*

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We have measured the ratio $\Gamma(K_L^0 \to \pi^+\pi^-)/\Gamma(K_L^0 \to \text{all charged})$ to be $(2.64 \pm 0.09)\times 10^{-3}$, a value significantly higher than the current accepted world average of $(2.00 \pm 0.07)\times 10^{-3}$. This ratio, together with currently accepted values for the $K_S^0 \to 2\pi$ branching ratio and $K_{L,S}^0$ lifetimes, yields a value of $|\eta_{+-}| = (2.23 \pm 0.05)\times 10^{-3}$.

Recent reports from Geweniger *et al.* at CERN[1] have indicated that the magnitude of η_{+-} is substantially higher than the heretofore published and accepted value of $(1.96 \pm 0.03)\times 10^{-3}$. We report herewith the result of an experiment carried out at the Stanford Linear Accelerator Center (SLAC) which supports the CERN observation.

The quantity

$$|\eta_{+-}| = \left[\frac{K_L^0 \to \pi^+\pi^- \text{ rate}}{K_S^0 \to \pi^+\pi^- \text{ rate}}\right]^{1/2}$$

is a fundamental parameter in the phenomenological description of *CP* noninvariance. Measurement of $|\eta_{+-}|$ entails a measurement of the $K_L^0 \to \pi^+\pi^-$ and $K_S^0 \to \pi^+\pi^-$ branching ratios and the ratio of K_L^0 and K_S^0 lifetimes.

This experiment, which measured the $K_L^0 \to \pi^+\pi^-$ branching ratio, was conducted at the SLAC K_L^0 spectrometer facility. Briefly, the spectrometer consists of a large-aperture (2.5 m×1.0 m) magnet, with 12.5 kG-m field integral, twenty wire chamber planes, and a large array of scintillation counters for triggering and time-of-flight measurement. The apparatus has been described in detail elsewhere.[2] The detection efficiency for all K_L^0 charged decay modes averaged over the K_L^0 momentum spectrum is 22%. The K_L^0 time of flight was measured over a 62.5-m flight path with a resolution of ±0.33 nsec, which allows useful momentum determination up to 7.5 GeV/*c*.

The trigger required that at least two charged tracks traverse the apparatus. Subsequent analysis programs retained only those events which gave a satisfactory vertex in the decay volume. The majority of $K_{\mu 3}^0$ events were then eliminated by the requirement that there be no signal in the counters behind the muon filter. Finally, an enriched $K_L^0 \to 2\pi$ sample was obtained by the requirement $\theta^2 < 4\times 10^{-6}$ rad^2, where $\cos\theta = \hat{P}_K \cdot (\vec{P}_+ + \vec{P}_-)/|(\vec{P}_+ + \vec{P}_-)|$. The mass spectrum for the events which pass this cut, with π masses assigned to each charged track, is shown in Figs. 1(a)–1(c), where the data have been divided into approximately equal subsets according to the reconstructed momentum of the K_L^0. The $K_L^0 \to 2\pi$ signal is clearly seen above a small background consisting mainly of K_{e3}^0 events.

The detection efficiency for all charged decay modes of the K_L^0 was calculated using Monte Carlo techniques. The Monte Carlo program generated data tapes identical in format to the actual data, which were then processed by the data reconstruction programs. Experimental uncertainties in the data, such as those due to discrete wire spacing, spark jitter, and time-of-flight resolution, were measured by studying a sample of regenerated K_S^0 decays; these effects were includ-

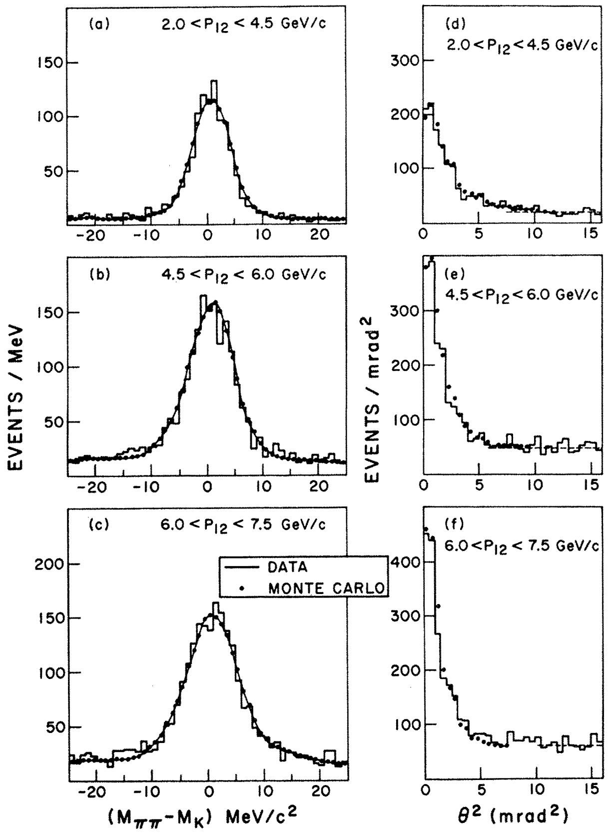

FIG. 1. (a)–(c) Number of events with $\theta^2 < 4\times10^{-6}$ rad^2 plotted as a function of $M_{\pi\pi} - M_K$ for three ranges of incident K_L^0 momenta. Dots, fits obtained using a linear combination of a Monte Carlo–predicted $K_{\pi 2}^0$ signal and K_{l3}^0 background. All fits had a χ^2 per degree of freedom ≈ 1.0. (d)–(f) Number of events with $|M_{\pi\pi} - M_K| \leq 10$ MeV/c, plotted as a function of θ^2 for three ranges of incident K_L^0 momenta. Dots, Monte Carlo predictions.

ed in the Monte Carlo program. The K_L^0-decay momentum spectrum was determined from a study of $K_{\pi 3}^0$ decays. Our understanding of the spectrum, as well as of the geometrical acceptance of the apparatus, is illustrated in Figs. 1(d)–1(f), 2(a), and 2(b), which display the θ^2 distributions for the K_L^0 momentum regions indicated, the reconstructed K_L^0 momentum spectrum, and the K_L^0-decay vertex distribution for events in the $K_{\pi 2}^0$ peak (498 ± 5 MeV) for both the data and Monte Carlo results.

We next consider the extraction of the $K_L^0 \to 2\pi$ signal from the background of K_{l3}^0 events. To obtain the actual number of $K_L^0 \to 2\pi$ events, we have fitted the observed π-π mass spectrum by the form

$$R(M_{\pi\pi}) = N[\alpha S_{K_{\pi 2}}(M_{\pi\pi}) + (1-\alpha) B_{K_{l3}}(M_{\pi\pi})],$$

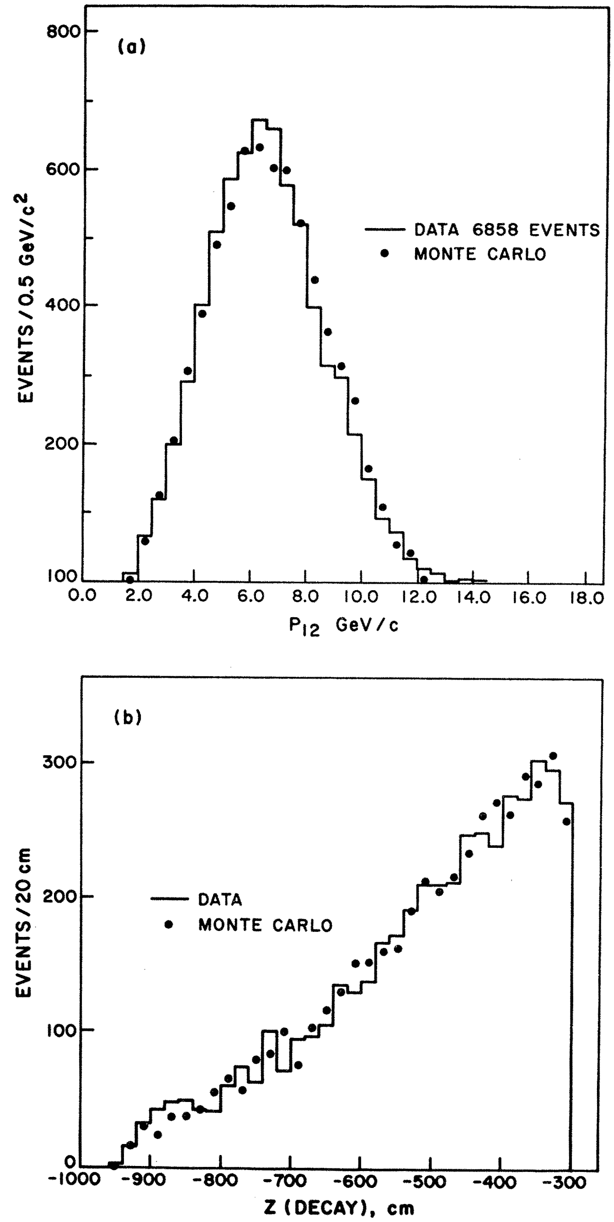

FIG. 2. (a) Reconstructed K_L^0 beam momentum and Monte Carlo predictions (dots) for events with $|M_{\pi\pi} - M_K| \leq 10$ MeV/c^2 and $\theta^2 < 4\times10^{-6}$ rad^2. χ^2 per degree of freedom ≈ 1.1. (b) Z distributions (along beam direction) of decay vertices for data and Monte Carlo results (dots) for events passing cuts described in (a). χ^2 per degree of freedom ≈ 1.4.

where the function $S_{K\pi 2}(M_{\pi\pi})$ is the anticipated experimental mass spectrum of the true $\pi^+\pi^-$ events, and the function $B_{K_{l3}}(M_{\pi\pi})$ is that spectrum which is obtained by misidentifying a K_{l3}^0 event as a $K_{\pi 2}^0$ event. N is the total number of events in the mass range 498 ± 25 MeV, and α is a best-fit parameter as determined by a least-

TABLE I. Data analysis: $K_L^0 \to \pi^+\pi^-$ normalized to the reaction $K_L^0 \to \pi^+\pi^-\pi^0$ and $K_L^0 \to \pi^+\pi^-$ normalized to the reactions $K_L^0 \to$ all charged modes, for the three ranges of K_L^0 lab momentum indicated.

			Normalization to $K_L^0 \to \pi^+\pi^-\pi^0$			
$P(K_L^0)$ GeV/c	# $K_{\pi 2}^0$ [a]	$\epsilon_{2\pi}$ (%)	# $K_{\pi 3}^0$ x10^{-3}	$\epsilon_{3\pi}$ (%)	$(K_{\pi 2}^0/K_{\pi 3}^0)$x 10^2	$(K_{\pi 2}^0/K_L^0 \to$ All Charged)x 10^3
$\theta^2 < 4 \times 10^{-6}$						
2.0-4.5	986±34	4.34±.06	313.6±.6	22.56±.17	1.63±.06	2.62±.12
4.5-6.0	1466±53	18.88±.22	288.5±.5	61.75±.50	1.66±.07	2.67±.14
6.0-7.5	1552±56	36.93±.43	193.5±.4	77.99±.76	1.69±.08	2.72±.15
$\theta^2 < 8 \times 10^{-6}$						
2.0-4.5	1169±40	5.14±.07	313.6±.6	22.56±.17	1.64±.06	2.64±.12
4.5-6.0	1517±56	20.30±.24	288.5±.5	61.75±.50	1.60±.07	2.58±.14
6.0-7.5	1633±75	38.69±.44	193.5±.4	77.99±.76	1.70±.08	2.74±.15
Weighted Average (both θ cuts)					1.64±.04	2.64±.09

			Normalization to $K_L^0 \to$ All Charged [b]		
$P(K_L^0)$ GeV/c	$\#K_{\pi 2}$ [a]	$\epsilon_{2\pi}$ (%)	$\#K_L^0$ x 10^{-3}	ϵ_{all} (%)	$(K_{\pi 2}^0/K_L^0 \to$ All charged)x 10^3
2.0-4.5	1048± 38	4.83±.07	775.1±.9	9.43±.04	2.64±.11
4.5-6.0	1396± 54	21.33±.24	798.3±.9	31.14±.14	2.55±.11
6.0-7.5	1144± 55	30.33±.39	559.1±.7	38.75±.21	2.61±.14
Weighted Average					2.60±.07

[a]See Ref. 4.

[b]See Ref. 5.

squares method. Thus the number of observed $K_L^0 \to \pi^+\pi^-$ events in a given mass range is $N\alpha$.[3] The quality of the fits is shown in Figs. 1(a)–1(c). The total number of $K_L^0 \to \pi^+\pi^-$ decays in each momentum bin was then obtained from the observed number by dividing by the appropriate Monte Carlo–calculated detection efficiency (11% averaged over the three momentum intervals). The procedure was repeated, changing the angle cut to $\theta^2 < 8\times10^{-6}$ rad^2. The results are shown in Table I, top.

The total number of K_L^0 decays was obtained in two different ways. The first method utilized readily identifiable $K_L^0 \to \pi^+\pi^-\pi^0$ decays. Using the cuts $M_{\pi\pi} < 0.365$ GeV/c^2, $P_\perp < 0.135$ GeV/c, $P_0'^2 \geq -0.004$ (GeV/c)^2, and with the requirement of no μ signature, we obtained a relatively pure sample of $K_{\pi 3}^0$ decays (8% contamination). The momentum of each event was then determined from kinematics, since the usual quadratic ambiguity could be resolved by the time-of-flight measurement. In this manner, the $(K_L^0 \to \pi^+\pi^-)/(K_L^0 \to \pi^+\pi^-\pi^0)$ branching ratio was determined for each of the three K_L^0 momentum intervals in question using the fitted K_L^0 momentum.[6] The results are presented in Table I, top. The good agreement between the results for $\theta^2 < 4\times10^{-6}$ rad^2 and $\theta^2 < 8\times10^{-6}$ rad^2 confirms our understanding of the background.

The second method consisted of counting all vertices observed in the decay volume. Again, the Monte Carlo program was used to calculate the detection efficiency for the charged decays —37% for $K_{\pi 3}^0$, 20% for $K_{\mu 3}^0$, and 11% for K_{e3}^0. The grouping into momentum bins was now done using the measured time of flight, both for the 2π and three-body decays. It was found that this measurement of the flux was relatively independent of K_{l3}^0 form factors. Variations in the K_{l3}^0 form factors [from $\lambda_+ = 0.05$, $\xi(0) = +1$, $\lambda_- = 0$ to

$\lambda_+ = 0.03$, $\xi(0) = -1$, $\lambda_- = 0]$ changed the overall efficiency for $K_L^0 \to$ all charged from 22.7% to 22.2%, resulting in a change in $|\eta_{+-}|$ of 1.2%.[7] The results of this method of normalization are shown in Table I, bottom.

Our final sample of $K_L^0 \to \pi^+\pi^-$ decays consists of 4200 events. This yields a branching ratio of

$$\frac{\Gamma(K_L^0 \to \pi^+\pi^-)}{\Gamma(K_L^0 \to \pi^+\pi^-\pi^0)} = (1.64 + 0.04) \times 10^{-2}.$$

Taking the current world average[8] of

$$\frac{\Gamma(K_L^0 \to \pi^+\pi^-\pi^0)}{\Gamma(K_L^0 \to \text{all charged})} = 0.161 \pm 0.004,$$

we find a ratio

$$\frac{\Gamma(K_L^0 \to \pi^+\pi^-)}{\Gamma(K_L^0 \to \text{all charged})} = (2.64 \pm 0.09) \times 10^{-3}.$$

The second method of normalization yields directly

$$\frac{\Gamma(K_L^0 \to \pi^+\pi^-)}{\Gamma(K_L^0 \to \text{all charged})} = (2.60 \pm 0.07) \times 10^{-3}.$$

Using the current world average[8] of $\tau_S = 0.862 \times 10^{-10}$ sec, our result for $|\eta_{+-}|$ is $(2.23 \pm 0.05) \times 10^{-3}$.

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[3]The number $N\alpha$ of $K_{\pi 2}^0$ events found remained essentially constant when the fitted mass range was extended to 498 ± 50 MeV, providing additional confirmation of the accuracy of our background subtraction procedure.

[4]The quoted error includes the effects of both the finiteness of the sample ($\sim N^{1/2}$), and the fitting error in the determination of α, the fraction of $K_{\pi 2}^0$ signal, added in quadrature.

[5]We have corrected the K_L^0 sample for neutron and K_L^0 interactions in the He gas, Dalitz pairs from $K_L^0 \to 3\pi^0$, accidental matching of tracks, accidental muon signatures, pion penetration of the muon filter, and pion scattering and absorption. The total correction applied amounts to $3.3 \pm 1.0\%$.

[6]The $K_{\pi 3}^0$ detection efficiency was calculated assuming the decay matrix had the form $|M|^2 = 1 + \alpha Y + \beta Y^2$, where $Y = (3T_{\pi 0} - Q)/Q$, $\alpha = 0.873 \pm 0.005$, and $\beta = 0.131 \pm 0.010$. The $K_{\pi 3}^0$ efficiency, however, is a very insensitive function of α and β because of the uniform efficiency of the spectrometer over the kinematically allowed $T_{\pi 0}$ range. See R. Messner *et al.*, in Proceedings of the Sixteenth International Conference on High Energy Physics, National Accelerator Laboratory, Batavia, Illinois, 1972 (to be published).

[7]The K_{l3}^0 detection efficiency was calculated assuming a vector interaction $\lambda_+ = 0.05$, $\lambda_- = -0.15$, and $\xi(0) = 0.63$. See G. Donaldson *et al.*, in Proceedings of the Sixteenth International Conference on High Energy Physics, National Accelerator Laboratory, Batavia, Illinois, 1972 (to be published). The variations in form factors quoted span the range of experimental uncertainty in λ_+ and $\xi(0)$, yielding the following fractional changes in the $K_{\pi 2}^0$ branching ratio: $0.32\Delta\lambda_+$ and $0.008\Delta\xi(0)$.

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