suggestions and discussions. He would also like to acknowledge a Fulbright award during part of his stay at the Research Institute for Theoretical Physics, Hensinki, Finland, where the present ideas originated.

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SIGN OF THE K_1^0–K_2^0 MASS DIFFERENCE*

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Evidence is presented that the long-lived neutral K is heavier than the short-lived.

We have performed an experiment to measure the sign of m_1-m_2 using the method suggested by Camerini, Fry, and Gaidos.[1] We find K_2^0 to be heavier than K_1^0. Our statistical confidence level depends on the unresolved Fermi-Yang-type (F-Y) ambiguity that exists at present in the KN (strangeness $S=+1$) phase shifts in isospin state $I=0$. If the F solution (large positive $p_{3/2}$ phase shift) is the correct solution, we obtain Monte Carlo betting odds of 45 to 1 for $m_2>m_1$, assuming $|m_1-m_2| = 0.57\tau_1^{-1}$. If instead the Y solution (large positive $p_{1/2}$ phase shift) is correct, our betting odds for $m_2>m_1$ are 5 to 1.[2] We have not resolved the F-Y ambiguity.[3]

The experiment uses 6040 K^0 mesons produced in the Alvarez 72-inch hydrogen bubble chamber via the reactions

$$\pi^- + p \to \Lambda + K^0 \quad (4771 \text{ events}) \tag{1}$$

and

$$\pi^- + p \to \Sigma^0 + K^0, \Sigma^0 \to \Lambda + \gamma \quad (1269 \text{ events}), \tag{2}$$

where the Λ decays visibly via $\Lambda \to p+\pi^-$. This is the same sample of K^0 we used in a previous experiment to determine $|m_1-m_2|$ by means of secondary hyperon production,[4] except that in the present experiment we discard K^0 with momentum greater than 600 MeV/c, because of present lack of information on the $I=1$ $\bar{K}N$ ($S=-1$) scattering amplitudes above 600 MeV/c.

The predicted K^0 direction from Reaction (1) is known to within about ±0.5 deg; that from Reaction (2) is known to within about ±20 deg. In the case of Reaction (1), we scan along this predicted direction, within a cone ±5 deg wide; for Reaction (2), we scan within the entire volume downstream from the vertex. We look for elastic scatters

$$K_{\text{neutral}} + p \to K_1^0 + p, \tag{3}$$

where the final K_1^0 is detected by its visible decay $K_1^0 \to \pi^+ + \pi^-$ (double-vee events). There is no cutoff on the length of the recoil proton. We find 23 double-vee events with initial K^0 momentum $P_K < 600$ MeV/c.[5] Our demand for a visible Λ decay gives us essentially 100% detection efficiency for finding double-vee events. There are no ambiguous events and no background.

For a K^0 produced at $t=0$ with c.m. momentum $\hbar k$, the probability $P(x)dx$ that an elastic scatter of type (3) will occur at proper time t in lab distance interval dx and with c.m. scattering angle θ (of the outgoing K with respect to the incident direction) in differential solid angle $d\Omega$ is given by

$$P(x)dx = \tfrac{1}{2}\eta(t)I(t,\theta,k)ndxd\Omega. \quad (4)$$

Here n is the number of protons per unit volume, and x lies between 0 and $x_{\max}$, with $x_{\max}$ determined for each event by the fiducial volume. The factor $\eta(t)$ is an escape correction factor given by $\eta = 1-\exp(-\lambda_1 T')$, where T' is the escape time of the scattered K_1^0 and is a known function of t for each event. [For most events $\eta(t)$ is approximately 1 except near $t = t_{\max} \equiv T$.] The remaining factor is

$$I(t,\theta,k) = |f_{11}\exp(-i\omega_1 t) + f_{12}\exp(-i\omega_2 t)|^2 + |g_{11}\exp(-i\omega_1 t) + g_{12}\exp(-i\omega_2 t)|^2, \quad (5)$$

with $\omega_1 = m_1 - \tfrac{1}{2}i\lambda_1$ and $\omega_2 = m_2 - \tfrac{1}{2}i\lambda_2$, where λ_1 and λ_2 are the inverse lifetimes of K_1^0 and K_2^0. Amplitudes f_{11} and g_{11} correspond, respectively, to spin-nonflip and spin-flip scattering amplitudes for $K_1^0 + p \to K_1^0 + p$; f_{12} and g_{12} are spin-nonflip and spin-flip amplitudes for $K_2^0 + p \to K_1^0 + p$. Thus, $f_{11} = \tfrac{1}{2}(f+\bar{f})$, $g_{11} = \tfrac{1}{2}(g+\bar{g})$, $f_{12} = \tfrac{1}{2}(\bar{f} - f)$, and $g_{12} = \tfrac{1}{2}(g-\bar{g})$, where f and g are spin-nonflip and spin-flip amplitudes for $K^0 + p \to K^0 + p$, and $\bar{f}$ and $\bar{g}$ are those for $K^0 + p \to \bar{K}^0 + p$.

To obtain the $S = +1$ phase shifts we use the *SPD* solutions of Stenger et al.[6] The $I = 1$ phase shifts are well determined, but the $I = 0$ phase shifts contain the F-Y ambiguity.

For $S = -1$ amplitudes we draw on several published K^--p interaction experiments,[7-10] on recent K_2^0-p interaction results,[11] and on parts of our own data. We describe here three sets of solutions which we label T (Tripp), KT (Kim-Tripp), and KT′. Solution T is Solution I of Watson, Ferro-Luzzi, and Tripp.[8] Solution KT consists of Solution I of Kim[10] for $L = 0, I = 1$, and Solution I of Watson, Ferro-Luzzi, and Tripp,[8] for $L = 1$ and $2, I = 1$. Our preference for Kim's S-wave scattering length is based partly on recent results of Kadyk et al.[11] for the ratio $R \equiv \sigma(K_2^0 + p \to K_1^0 + p)/[\sigma(K_2^0 + p \to \Lambda + \pi^+) + 2\sigma(K_2^0 + p \to \Sigma^0 + \pi^+)]$ and partly on our own data.

We test a set of solutions by comparing the predicted with the observed number of events produced by our sample of neutral kaons for each of the following six categories: charge-exchange production of K^+, inelastic scattering of $\bar{K}^0$ (hyperon production), and forward-scattered and backward-scattered neutral kaons in double-vee and single-vee events. The fact that the potential path is usually large compared with the mean K_1^0 decay path length (the median potential proper time is about 15×10^{-10} sec) leads to predictions that are insensitive to the magnitude and sign of $m_1 - m_2$. We can, therefore, test the scattering amplitudes before using them to determine $m_1 - m_2$. For the solutions T + F and T + Y we obtain $\chi^2 = 46.7$ and 20.0, respectively, with $\langle\chi^2\rangle = 6$. For KT + F and KT + Y we find $\chi^2 = 28.8$ and 15.0, which, although an improvement, is still a poor fit for both solutions.

We have searched for solutions that give better predictions for our six mass-independent data. We arbitrarily leave the $S = +1$ solutions untouched and vary the $S = -1$ amplitudes. Our present best solution of this kind we call KT′, which is solution KT modified by changing the real part of the $p_{3/2}$ scattering length from +0.0409 to −0.0409, and by changing the $p_{1/2}$ scattering length from $-0.042 + i0.0092$ to $-0.1 - i0.015$. We then obtain $\chi^2 = 10.4$ for solution KT′ + F and 7.0 for KT′ + Y.

We find that it makes very little difference to our subsequent time-dependence analysis (to find $m_1 - m_2$) whether we use solutions T, KT, or KT′. We proceed as follows: For a given event i we form a normalized probability distribution function $p_i(t) = I_i(t)\eta_i(t)/\int I_i(t) \times \eta_i(t)dt$, where the integral is from $t = 0$ to T_i and where $I_i(t) = I(t, \theta_i, k_i)$ from Eq. (5), with a given set of phase shifts and with a choice for $m_1 - m_2$. To compare graphically the predicted and observed time distributions, we sum $p_i(t)$ over the 23 events and plot the result in Fig. 1 for the four cases corresponding to KT

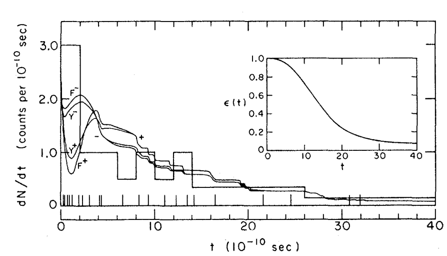

FIG. 1. Time distribution of 23 events. (One event with $t > 40 \times 10^{-10}$ sec is not shown.) Labels F and Y on the curves refer to phase-shift solutions KT + F and KT + Y, with superscripts + and − referring to $m_1 - m_2 = +0.57$ and −0.57. The curves are constructed by summing $p_i(t)$ over the 23 events; therefore, a discontinuity occurs at each time $t = T_i$ (potential proper time for ith event). The individual events are shown as vertical bars. The histogram gives counts per 10^{-10} sec in the indicated interval. The detection efficiency $\epsilon(t)$ is the fraction of the 6040 K^0 mesons having potential time $T > t$.

+ F and to KT + Y, each with $m_1 - m_2 = +0.57$ and -0.57 (in units of τ_1^{-1}, assuming $\tau_1 = 0.88 \times 10^{-10}$ sec).[12] The observed time distribution exhibits an enhancement in the first 2×10^{-10} sec and favors negative $m_1 - m_2$.

To use all of the information, we form a likelihood function $\mathcal{L}(m_1 - m_2)$ by setting $t = t_i$ in $p_i(t)$ and taking the product over the 23 events, $\mathcal{L} = \prod_i 50 p_i(t_i)$, for a given set of scattering amplitudes. (The factor 50 is a convenient normalization factor.) The results for solutions KT + F and KT + Y are shown in Fig. 2. (Those using KT′ are very similar and are not shown.) The fact that $\mathcal{L}(m_1 - m_2)$ does not have its maximum value near the known magnitude $|m_1 - m_2| \approx 0.57$ has given us concern. We find that varying the phase shifts or scattering lengths within reasonable limits has little effect on the shape of $\mathcal{L}(m_1 - m_2)$. Monte Carlo studies have convinced us that, with only 23 events, we have suffered a reasonable statistical fluctuation; for a "true" value of $m_1 - m_2 = -0.57$ we find that the probability that $\mathcal{L}$ will have a maximum somewhere between $m_1 - m_2 = -1$ and $+1$ is only about 33%.

Given the magnitude $\delta \equiv |m_1 - m_2|$, we summarize our data by giving the likelihood ratio $\mathcal{L}(-\delta)/\mathcal{L}(+\delta) \equiv R(\delta)$, which is expected to be greater (less) than 1.0 for K_2^0 heavier (lighter) than K_1^0. For solutions KT + F and KT + Y we obtain $R(0.57) = 95.1$ and 7.4, respectively. These likelihood ratios cannot be immediately interpreted as statistical "betting odds." To understand their statistical significance we use a Monte Carlo (MC) method in which we simulate many "experiments" of 23 events each. This method gives betting odds of 5 to 1 for K_2^0 heavier than K_1^0, assuming KT + Y. The corresponding betting odds using KT + F are 45 to 1 for K_2 heavier than K_1.

We also use the MC experiments to estimate the "goodness of fit" in a manner entirely analogous to the χ^2 tests that one can use with a larger sample of events. The fit of the data to the hypothesis $m_1 - m_2 = -0.57$ is good for both solutions KT + F and KT + Y. The MC result for the hypothesis $m_1 - m_2 = +0.57$ is that the probability of getting $\log \mathcal{L}(+0.57)$ as low or lower than our observed value is only 0.027 for solution KT + Y and 0.001 for KT + F. Thus the fit is poor for the hypothesis $m_1 - m_2 = +0.57$.

Two other experiments, both based on coherent regeneration, have also reported evidence for K_2^0 heavier than K_1^0.[13,14]

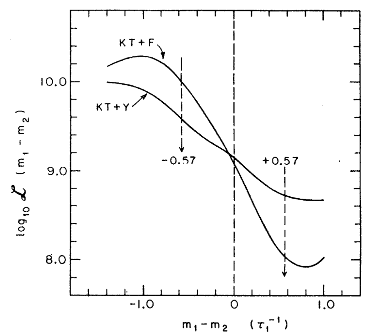

FIG. 2. Likelihood function $\mathcal{L}(m_1 - m_2)$ for 23 events.

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NEW Σ DECAY PARAMETERS AND TEST OF $\Delta I=\frac{1}{2}$ RULE*

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New values for the three decay asymmetry parameters in the nonleptonic decays of Σ hyperons are presented. The selection rule $\Delta I=\frac{1}{2}$ is found to be well satisfied.

Evidence for a mild disagreement with the selection rule $\Delta I=\frac{1}{2}$ in the nonleptonic decay of Σ hyperons has existed since 1962.[1] The principal source of this disagreement was the nonmaximal value reported[2] for the asymmetry parameter α_0 in the decay $\Sigma_0^+\to p+\pi^0$. In this Letter we present results for the three asymmetry parameters α_+, α_0, and α_- obtained from a partial analysis of a large number of well-polarized $\Sigma^\pm$. These parameters are defined as in Ref. 1; by this convention the helicity of the decay nucleon has the same sign as α. The new values listed in Table I are consistent with the $\Delta I=\frac{1}{2}$ rule.

In the experiment the Lawrence Radiation Laboratory's 25-inch hydrogen bubble chamber was exposed to a beam of K^- mesons. About 15 000 examples of the reactions $K^-+p\to\Sigma^\pm+\pi^\mp$ have been analyzed to date. The K^- momenta, ranging from 365 to 415 MeV/c, were chosen to excite Y_0^* (1520) in such a manner that the resonant $D_{3/2}$ amplitude had the

Table I. Asymmetry parameters, lifetimes, and branching fractions Σ decays.

	This experiment	Other experiments	Combined	Least-squares $\Delta I=\frac{1}{2}$ fit
α_-	-0.010 ± 0.043	-0.16 ± 0.21^a	-0.017 ± 0.042	-0.037
α_+	$+0.014\pm0.052$	-0.03 ± 0.08^b -0.20 ± 0.24^a	-0.006 ± 0.043	-0.026
α_0	-0.986 ± 0.072	-0.80 ± 0.18^c	-0.960 ± 0.067	-0.9996
$\tau_-(\times10^{10})$		1.58 ± 0.05^d 1.666 ± 0.026^e	1.648 ± 0.023	1.644
$\tau_+(\times10^{10})$		0.794 ± 0.026^d 0.830 ± 0.018^e	0.818 ± 0.015	0.821
$\dfrac{\Sigma_+^+}{\Sigma_+^++\Sigma_0^+}$		0.490 ± 0.024^d 0.460 ± 0.020^e	0.473 ± 0.015	0.489

[a]See Ref. 1. [b]See Ref. 5. [c]See Ref. 2. [d]See Ref. 6. [e]See Ref. 7