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K_1^0-K_2^0 Mass Difference*

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The K_1^0-K_2^0 mass difference has been measured by the "gap method" to high precision. This method is especially insensitive to possible systematic biases. The measurement yields $|\Delta M| = (0.534 \pm 0.007)\times 10^{10}\ \text{sec}^{-1}$. Expressed in units of the inverse K_1^0 lifetime, $\tau_1 = 0.862 \times 10^{-10}$ sec, $|\delta| = 0.460 \pm 0.006$, or equivalently, $26.4° \pm 0.3°$ per K_1^0 mean decay length.

INTRODUCTION

This paper describes a 1% determination of the magnitude of the mass difference ΔM between the K_1^0 and K_2^0 mesons.

Since the original suggestion[1] that the K_1^0 and the K_2^0 mesons would be expected to have somewhat different masses, a large number of measurements of this quantity have been made.[2] This area of investigation has a general interest in that it is the only place in nature where a self-energy due to the weak interactions is susceptible to measurement. More specific impetus for measurement was originally provided by Okun and Pontecorvo,[3] who observed that if direct $\Delta S = 2$ transitions were permitted in the weak interactions, the mass difference might be expected to be of the order of $10^7\hbar/\tau_1$, where τ_1 is the K_1^0 mean life; whereas, if the mass difference were a second-order effect involving the known $\Delta S = 1$ transitions, values in the region of $\hbar/\tau_1$ could be expected. The experimental data indeed have fallen in the latter region. As a consequence, the mass difference has been useful in studying, for example, the convergence behavior of an intermediate-boson field theory, as parametrized by the momentum cutoff Λ.[4]

More recently, a relatively precise measure has been of interest to assist in determining the phase of the CP-noninvariance parameter

$$\eta_{+-} = \text{amplitude}(K_2^0 \to \pi^+\pi^-)/\text{amplitude}(K_1^0 \to \pi^+\pi^-).$$

One method used to determine this relative phase is to measure the interference between the $K_1^0 \to \pi^+\pi^-$ and $K_2^0 \to \pi^+\pi^-$ amplitudes after the production of, for example, a K^0. The maximum sensitivity occurs after about 12 K_1^0 decay lengths.[5,6] A phase $\Phi = \delta\tau + \phi_{+-}$ is measured, where ϕ_{+-} is the phase of η_{+-}, δ is the mass difference, $m_1 - m_2$, in reciprocal units of τ_1, and τ is the elapsed time from production. A 1% error in δ produces a 0.05-rad contribution to the error in ϕ_{+-}. In fact, the error in δ has been the limiting factor recently in the determination of $\arg(\eta_{+-})$ using this method.[5,6]

The present measurement of the mass difference uses the so-called "varying gap method," utilized first by Christenson *et al.*,[7] and then by Carnegie[8] and Aronson *et al.*[9] It is a method suitable for a precise measurement, since it is especially immune to possible systematic errors. Specifically, one measures the integrated coherent $K_{\pi 2}$ decay rate over a fixed decay volume, downstream of two regenerators, solely as a function of the gap between the regenerators. This minimizes the sensitivity to the geometric detection efficiency. The amount of material in the beam is always the same. Since a quantitative description of the general method is contained in Ref. 7, we will only briefly describe it here. In traveling the distance G from the upstream to the downstream slab (see Fig. 2 below), the amplitude of the K_1^0 wave regenerated by the upstream slab accumulates a change of phase $\Delta\Phi = \delta G/\Lambda_1$ relative to the K_2^0 wave, where

Λ_1 is the K_1^0 mean decay length. On the other hand, the K_1^0 wave regenerated from the unscattered K_2^0 beam by the downstream regenerator has a phase relative to the K_2^0 wave that is independent of the position of the upstream regenerator. Consequently, the sum ρ of the two K_1^0 amplitudes behind the split regenerator, when squared to give the intensity of the K_1^0's observed, exhibits changing interference effects characterized by δ, as the gap G is varied:

$$\begin{aligned}\rho &= \rho_1 e^{-(i\delta+1/2)(G+L_2)/\Lambda_1} + \rho_2,\\ |\rho|^2 &= |\rho_1|^2 e^{-(G+L_2)/\Lambda_1} + |\rho_2|^2\\ &\quad + 2|\rho_1||\rho_2| e^{-(G+L_2)/2\Lambda_1}\\ &\quad \times \cos[\psi_1 - \psi_2 - \delta(G+L_2)/\Lambda_1],\end{aligned} \tag{1}$$

where

$$\begin{aligned}\rho_{1(2)} &= \frac{2\pi i N \Lambda_1}{k} \frac{f(0) - \bar{f}(0)}{2}\\ &\quad \times \frac{1 - e^{-(i\delta+1/2)L_{1(2)}/\Lambda_1}}{i\delta + 1/2}\\ &= |\rho_{1(2)}| e^{i\psi_{1(2)}}\end{aligned}$$

is the regeneration amplitude from the upstream (downstream) regenerator of thickness $L_{1(2)}$, where N is the density of the scattering centers each contributing a forward amplitude $f(0)$ ($\bar{f}(0)$) for K^0 ($\bar{K}^0$), and where k is the wave number.

APPARATUS

The experiment was performed at the Alternating Gradient Synchrotron (AGS) at Brookhaven National Laboratory as part of a program to measure precisely the CP-noninvariant parameters involved in $K_2^0 \to \pi^+\pi^-$ decay. A plan view of the experimental arrangement is shown in Fig. 1. Three tapered collimators defined the beam to be 4.5 in. wide and 11 in. high at the regenerator. Between collimators 1 and 2 a sweeping magnet of 400 kG in. removed charged particles from the beam. Immediately upstream of collimator 3, a scintillation counter telescope of three elements monitored the neutron intensity in the center of the beam. The details of the magnetic spectrometer arrangement for measuring the $\pi^+\pi^-$ decay products are shown in Fig. 2.

The two copper regenerators, 8.00 in. and 1.125 in. thick, were positioned about 900 in. (~200 K_1^0 decay lengths at the mean momentum of 2 GeV/c) from the internal target of the AGS. During the running of this experiment, the gap between the regenerators was continuously varied from 0 in. to 30 in. by placing the upstream regenerator on a motor-driven cart that completed a round trip in 30 min. The instantaneous cart position was recorded for each event.

The spectrometer consisted of a magnet preceded and followed by wire-plane neon-filled spark chambers for track delineation. The magnet in the spectrometer was 72 in. wide and had a vertical gap of 18 in.; the pole tips extended 18 in. along the beam line. The magnet was powered to produce a field integral of 207 kG in., corresponding to a transverse momentum of 158 MeV/c. The scintillation-counter arrays before and after the magnet defined the decay volume and selected two charged particles traversing the spectrometer, one on each side of the beam line. Veto counters A, H, and K were used to minimize spurious triggers. An over-all coincidence-anticoincidence $\bar{A}\cdot E\cdot\bar{H}\cdot F_L\cdot F_R\cdot B_L\cdot B_R\cdot\bar{K}$ (where the bar denotes an anticoincidence) was required to trigger the spark chambers. The nine spark chambers used in the experiment each consisted of two orthogonal wire planes with a magnetostrictive readout.[10] Each plane was made of 0.005-in. Cu wire spaced at 0.020 in. During this experiment, the average number of sparks in each spark chamber was, representatively, 2.3 in chamber 1 and 1.1 in chambers 3 and 5. These numbers reflect the fact that chamber 1 was the

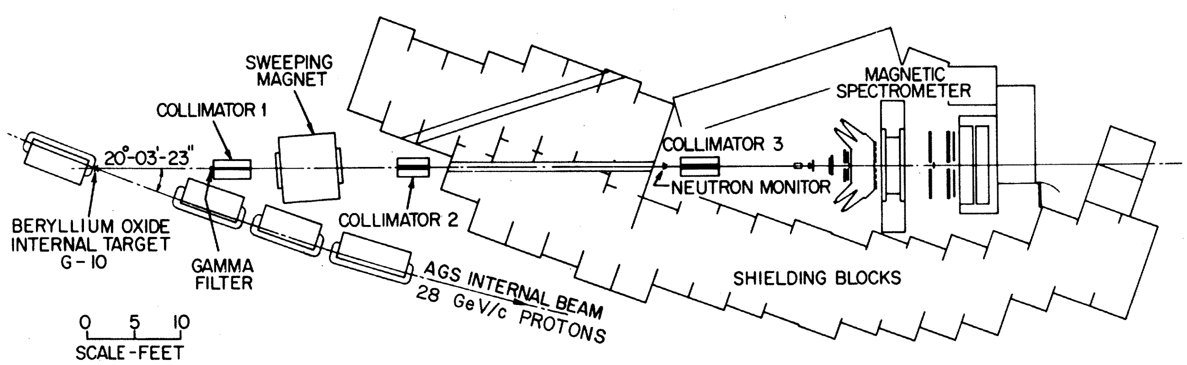

FIG. 1. Plan view of beam line and spectrometer.

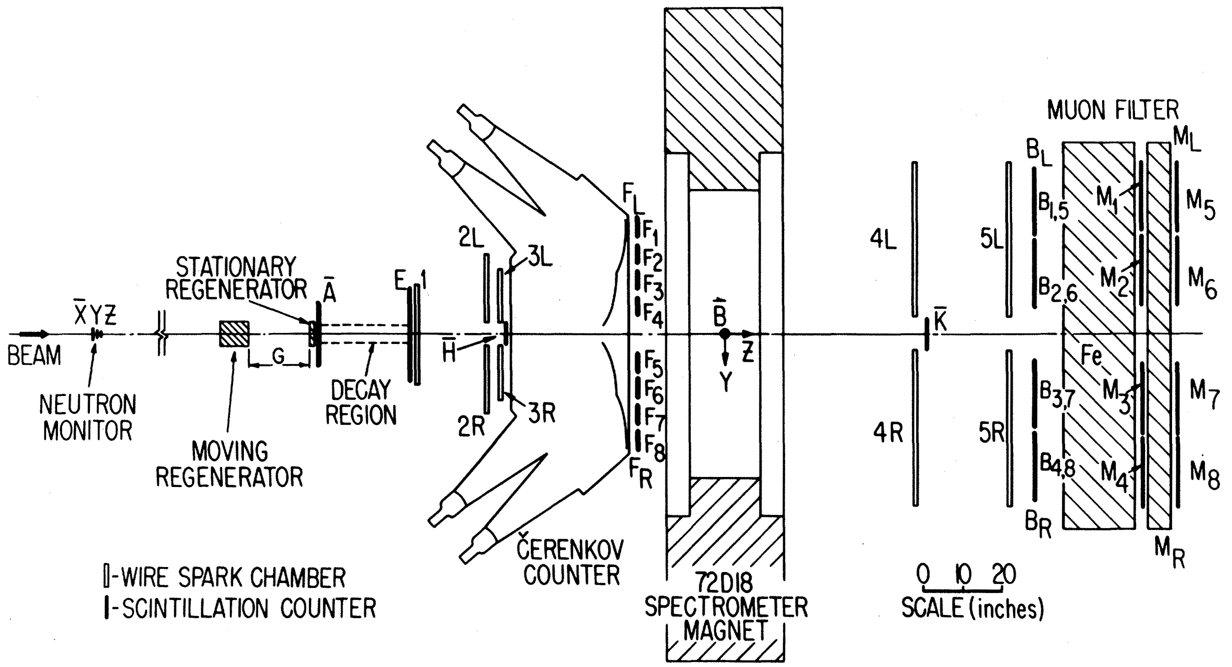

FIG. 2. Expanded view of spectrometer, showing magnet, wire spark chambers, and trigger counters.

only one which registered both decay products. The combined signals from the counters A, H, and K were also used to veto the neutron intensity monitor in order to measure the true amount of beam exposure.

A threshold Čerenkov counter contained CO_2 at atmospheric pressure and, in the momentum range of the particles detected in this experiment, was sensitive only to electrons. This counter was used to identify the K_{e3} decay mode, which was used as a completely independent beam-exposure monitor.

With each event, the output of each of the counters, the instantaneous value of the regenerator gap, and the spark locations in each of the chambers were stored in a buffer memory which could record up to 40 events. At the end of each beam-acceleration cycle the buffer memory contents were written onto magnetic tape for later analysis. In parallel, the data were channeled to a small computer for online monitoring of the apparatus.

DATA ANALYSIS

The chief analysis tasks were the separation of the $\pi^+\pi^-$ decays of the coherently produced K_1^0's from the incoherent $K_{\pi 2}$ decays, $K_{\mu 3}$ decays, and other backgrounds, and the normalization of the $K_{\pi 2}$ rate to the effective beam exposure at each gap interval.

The forward $K_{\pi 2}$ decays were separated from background by the requirement that there be no Čerenkov signal, and by cuts on the invariant mass m^* of the two pions and on the square of the momentum transfer to the regenerator, $-t$. Figure 3 exhibits the $-t$ distribution of data taken with no gap between the regenerators. Figure 4 shows the same distribution for data in the most unfavorable gap interval, i.e., from the region that gave the smallest coherent $K_{\pi 2}$ rate. Figure 5 shows the m^* distribution of data in the same gap interval, with a loose cut on t. Figure 6 magnifies the background region under the 2π peak, and shows the mass distribution of the $K_{\mu 3}$ background. The precise subtraction of the $K_{\mu 3}$ background requires special attention because its t distribution is not smooth and, furthermore, changes with mass cuts. Rather than relying on Monte Carlo calculations, we have corrected for this background using the data themselves. Data taken without the regenerator present were normalized to the split-regenerator events in the region $404 < m^* < 448$ MeV/c^2 (Fig. 6). A fraction of the free-decay events corresponding to the unscattered $K_{\mu 3}$ component was subtracted from the split-regenerator data as a function of t, G, and p, the momentum of the K_2^0. The remaining background, primarily incoherently regenerated K_1^0's, is smooth and was simply subtracted using an exponential fit to the t distribution in the region $0.0008 < -t < 0.004$ (GeV/c)^2. The results of the analysis were the same for a $\pm 2\sigma$ or $\pm 3\sigma$ cut on m^*, where $\sigma(m^*) = 6$ MeV/c^2.

For the beam-exposure normalization it was

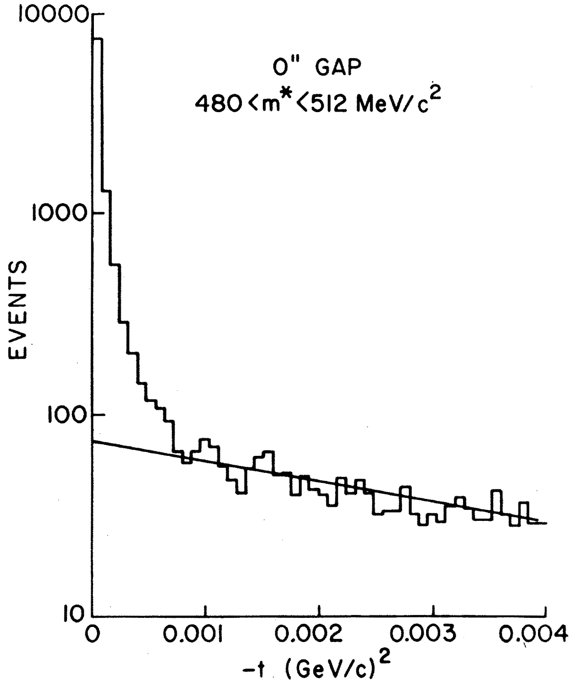

FIG. 3. Distribution in $-t$ for data taken with 0-in. gap between regenerators. The $\pi\pi$ invariant mass has been restricted to $480 < m^* < 512$ MeV/c^2.

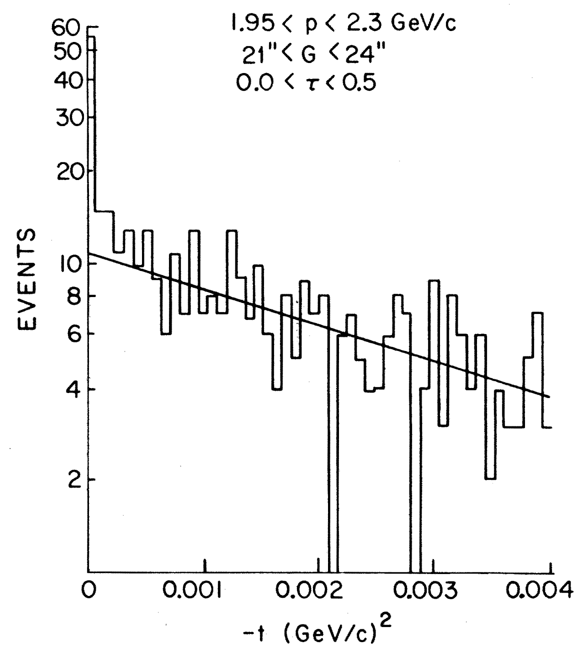

FIG. 4. Distribution in $-t$ for data taken with regenerator gap between 21 in. and 24 in. This region had fewest $K_{\pi 2}$ decays from coherent processes and the poorest signal-to-background ratio.

crucial to take into account any systematic variation of detection efficiency with regenerator gap. Such a variation could occur because the $K_{\pi 2}$ rate in the decay volume was much higher for small regenerator gaps. This led to more multiple track events for small gaps, with a possible decrease in detection efficiency. For this reason we chose to normalize to the number of K_{e3} decays observed behind the regenerator, to compensate for any change in detection efficiency with gap. This procedure is subject to one correction that, however, can be made with confidence. Namely, as the gap is increased those K_2^0's that have been diffractively scattered will occupy a somewhat larger region of space transverse to the beam, and will correspondingly be detected with a smaller efficiency. The magnitude of the effect is 8% over the 30-in. excursion of the gap in the regenerator. As a final precaution, that gap region where the 2π rate was changing most rapidly with gap (0 in. to 6 in.) was excluded from the final fit.

The final result for δ is sensitive to the measured momenta, a 1% change in measured momenta producing a 3% change in mass difference. For this reason the momentum reconstruction was carefully calibrated using the known K^0 mass and a precise determination of the opening angles between the two pions. The angle calibration was effected by reconstructing the regenerator position from the data. The spatial separation of the two pions in chamber 1, coupled with the reconstructed regenerator position, determined an average opening angle. A comparison of the reconstructed regenerator position with the true position calibrated the opening-angle measurement. With the opening angle calibrated, it was possible to use the invariant K^0 mass to calibrate the measured momenta. This procedure divorced the momentum calibration from complicated magnetic-field mapping and point-by-point field integration along the particle paths. The correction to the raw momentum measurement ranged from 0.3% to 0.8% over the accepted band.

The forward 2π decays were collected in five different momentum intervals and eight gap intervals of 3 in. width. These data, normalized to the K_{e3} decays observed behind the regenerator, were fitted to the function

$$\int_{G_1}^{G_2} dG \int_{p_1}^{p_2} dp \int_0^2 d\tau\, \epsilon(p,\tau) \times [\,|\rho(G,p,\tau)+\eta_{+-}|^2 - |\eta_{+-}|^2].$$

Here G was divided into 10 intervals of 3 in. each and p into 5 bins; $\epsilon(p,\tau)$ is the detection efficiency, as determined from data taken at 0 in. gap, and ρ is as in Eq. (1). An additional amplitude η_{+-} has

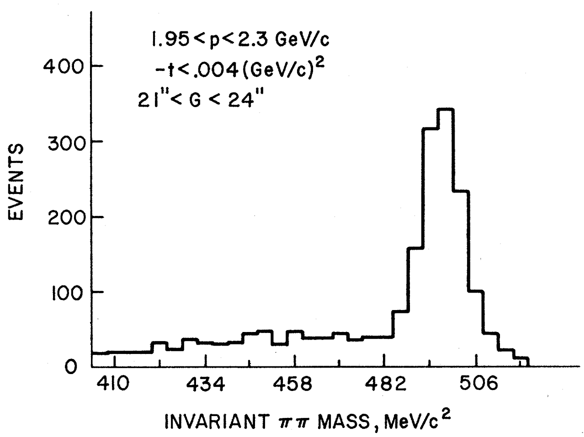

FIG. 5. Distribution in $\pi\pi$ invariant mass for data taken with regenerator gap between 21 in. and 24 in.

been added to the K_1^0 amplitude before squaring, to take into account the CP-noninvariant decay $K_2^0 \to \pi^+\pi^-$. Correspondingly, $|\eta_{+-}|^2$ was subtracted because it was removed in the background-subtraction procedure. The decay region was limited

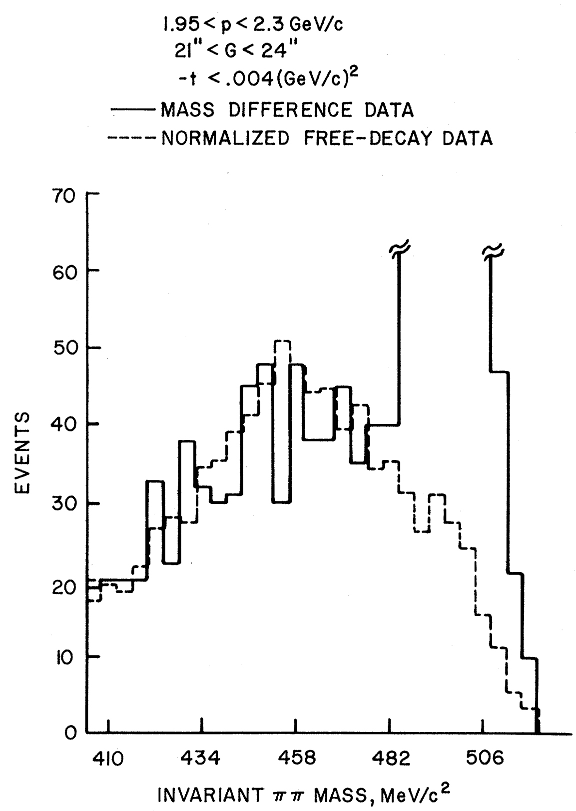

FIG. 6. A magnification of the $\pi\pi$ invariant mass distribution in Fig. 5, showing the free-decay subtraction procedure. Normalization of the free-decay events to the regenerator events occurred in the region $404 < m^* < 448$ MeV/c^2.

to two K_1^0 decay lengths downstream of the split regenerator in order to minimize sensitivity to the CP-noninvariant term.

RESULTS AND CONCLUSIONS

The data and the best fits for the five different momentum bins are displayed in Fig. 7. External parameters that have been inserted are $\tau_1 = (0.862 \pm 0.006) \times 10^{-10}$ sec, and the magnitude and phase of the ratio of η_{+-} to the regeneration amplitude. We have used

$$|f(0) - \bar{f}(0)| = (21 \pm 2) f$$

at 1.5 GeV/c,[11] a relative phase between the regeneration amplitude and η_{+-} of

$$\phi_T = \phi_{+-} - \arg\{i[f(0) - \bar{f}(0)]\} = 92° \pm 6°,$$

along with

$$|\eta_{+-}| = (1.92 \pm 0.05) \times 10^{-3}.$$

The momentum dependence of $|f(0) - \bar{f}(0)|$ and ϕ_T have also been taken from Ref. 11. The best-fit solution is most sensitive to the regeneration amplitude, where a 10% increase raises δ by 0.6%. It is of interest that when we allow both δ and ϕ_T to be fitted, we obtain $\phi_T = 83.0° \pm 8.6°$, in excellent

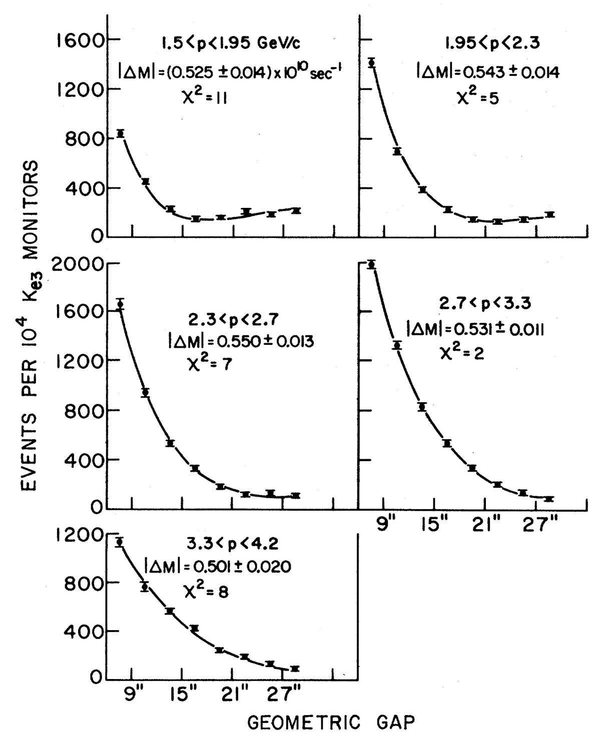

FIG. 7. Number of coherently produced $\pi^+\pi^-$ events vs regenerator gap, for five K_2^0 momentum bands. The results of the fits to the mass difference $|\Delta M|$ are shown. Each fit had 6 degrees of freedom.

agreement with the accepted value at 2 GeV/c.

The final result for the mass difference in each of the five momentum bands is given in Fig. 7. Summing the χ^2 contribution from each momentum interval and minimizing the over-all χ^2, yields $|\Delta M| = (0.534 \pm 0.005) \times 10^{10}$ sec^{-1} with $\chi^2 = 166$ for 139 degrees of freedom. Allowing for the uncertainties in the external parameters, the error becomes 0.0063. We round this upward to give the final result

$$|\Delta M| = (0.534 \pm 0.007) \times 10^{10}\ \text{sec}^{-1}.$$

This result is to be compared with two other recent experiments[12,9] of comparable accuracy, which both yielded $(0.542 \pm 0.006) \times 10^{10}$ sec^{-1}. The weighted average of the three measurements is

$$|\Delta M| = (0.539 \pm 0.0035) \times 10^{10}\ \text{sec}^{-1}, \qquad (2)$$

or in units of $\hbar/\tau_1$,

$$|\delta| = 0.464 \pm 0.003.$$

It is convenient in the design of experiments to note that this mass difference corresponds to a change in the relative phase of the K_1^0 and K_2^0, at the same energy, of $26.7° \pm 0.2°$ per K_1^0 mean decay length.

When value (2) is applied to the results of the "vacuum regeneration" experiments,[5,6] one obtains

$$\phi_{+-} = 41.2° \pm 4.9°.$$

This result for ϕ_{+-} is consistent with those theories (in particular the superweak hypothesis) that predict $\phi_{+-} \sim 43°$.

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