K_S REGENERATION AND $K_L \to \pi^+ + \pi^-$ DECAY IN THE 80-INCH HYDROGEN BUBBLE CHAMBER*

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Since the discovery by Christenson et al.[1] that the long-lived neutral K meson (K_L) decays into two charged pions, a number of related experiments have been reported. These have confirmed the result,[2] have shown that the branching fraction into two charged pions is independent of the laboratory energy of the K_L meson,[3,4] and have given evidence for the interference between $K_L \to \pi^+ + \pi^-$ decays and and $K_S \to \pi^+ + \pi^-$ decays, where the short-lived K_S mesons are regenerated by matter in the K_S beam.[5-7] All of these experiments have used the counter, spark-chamber technique.

We report here the results of a hydrogen bubble-chamber investigation of K_S regeneration and $K_L \to \pi^+ + \pi^-$ decay. In general our results on the $K_L \to \pi^+ + \pi^-$ decay confirm those of previous experiments. We have measured the relative phase of the $K_L \to \pi^+ + \pi^-$ and $K_S \to \pi^+ + \pi^-$ amplitudes by using interference with hydrogen-regenerated K_S mesons. The results of this analysis are summarized in Table I.

We have exposed the 80-inch hydrogen bubble chamber at the Brookhaven National Laboratory AGS to a beam of K_L mesons produced from a 7-BeV/c π^- beam striking an aluminum target. The distance from the target to the center of the bubble chamber was 31 feet. The experimental arrangement is shown in Fig. 1. Approximately 5 K_L mesons were incident in the chamber per pulse, and about 190 000 pictures were taken of which about $\frac{2}{3}$ have been analyzed.

The incoming momentum spectrum of the neutral beam was determined from a study of a sample of the decay, $K_L \to \pi^+ + \pi^- + \pi^0$, in which both γ rays from the decay of the π^0 produce electron showers in a tantalum plate located near the downstream end of the bubble chamber. The incoming K_L momentum spectrum ranges from 1 to 7 BeV/c, and is peaked at about 5 BeV/c. For this report we consider only events with momenta greater than 2 BeV/c, since the analysis of K_S regeneration is simpler above the $\bar{K}$-N resonance region.

The total incoming K_L flux was determined from the number of leptonic and 3π decays with visible momenta greater than 2 BeV/c. The total flux in about 120 000 pictures was about 600 000 K_L mesons with about 510 000 above 2 BeV/c.

The regeneration in the hydrogen was determined by measuring decay events associated with one-pronged interactions identifiable by ionization as protons. Figure 2 shows the differential cross section for this reaction as a function of Δ^2, the four-momentum transfer to the proton, for those events with incoming momenta greater than 2 BeV/c. The comparison with the forward scattering amplitude expected from calculations involving K^+N and K^-N total cross sections[8] is as follows: From this experiment, we obtain

$$\left(\frac{d\sigma}{d\Delta^2}\bigg|_{\Delta^2=0}\right)^{1/2} = \{[\mathrm{Im}f(0)]^2 + [\mathrm{Re}f(0)]^2\}^{1/2}$$

$$= (0.088 \pm 0.015) \times 10^{-13}\ \mathrm{cm/BeV}/c,$$

while the result from the optical theorem and cross sections is

$$\mathrm{Im}f(0) = (0.138 \pm 0.017) \times 10^{-13}\ \mathrm{cm/BeV}/c.$$

We remark that because of the spread in incident beam momentum, it is convenient to define the scattering amplitude f such that $|f|^2 = d\sigma/d\Delta^2$ (rather than $|f|^2 = d\sigma/d\Omega$). This com-

Table I. Phase angle of η_{+-} = (amplitude for $K_L \to \pi^+ + \pi^-$)/(amplitude for $K_S \to \pi^+ + \pi^-$).

	$\delta = M_{K_S} - M_{K_L}$ -0.5	+0.5
Arg[η_{+-}]	$(-150 \pm 45)°$	$(-230 \pm 45)°$
Arg[$\eta_{+-}(i\delta + \frac{1}{2})$]	$(-195 \pm 45)°$	$(-185 \pm 45)°$

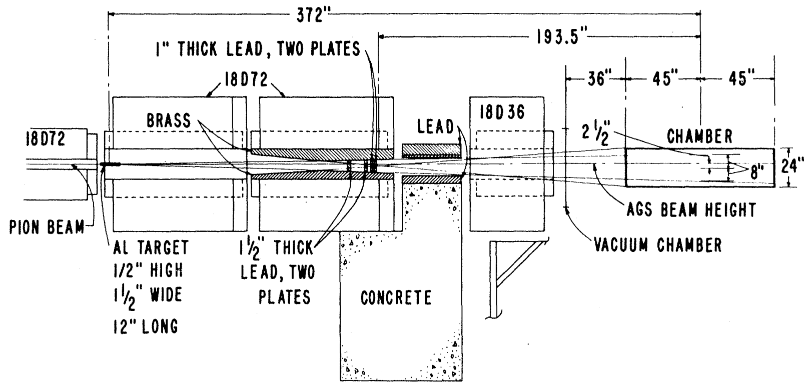

FIG. 1. The experimental arrangement at the 80-inch bubble chamber.

parison indicates the absence of any substantial real parts in the scattering amplitude for $K_L + P \rightarrow K_S + P$ in hydrogen. The observed cross section for this reaction for events with K_L momenta above 2 BeV/c is 46.0 ± 10.4 μb.

Several factors contributed to the effective angular resolution of the beam direction: the intrinsic measurement errors, about 1 mrad; the finite size of the target, also about 1 mrad; and a broadening due to scattering in the lead γ-ray filter located approximately half-way between the target and bubble chamber. Through a careful study of the angular distribution of the incoming K_L meson as determined from the hydrogen regeneration, we measured the fraction of the beam scattered in the lead and the spread in resolution caused by this scattering. The resulting over-all angular resolution is better than 10 mrad.

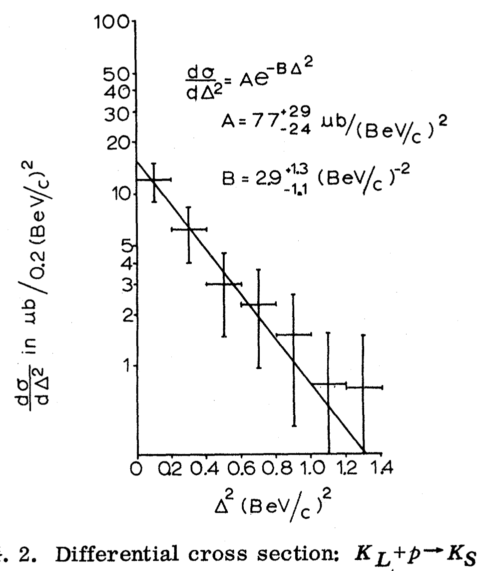

FIG. 2. Differential cross section: $K_L + p \rightarrow K_S + p$ in hydrogen for events with $P_{inc} \geq 2$ BeV/c.

A potentially complicating feature of this experiment is the regeneration of K_S mesons in the $\frac{1}{4}$-inch stainless-steel window of the bubble chamber. We cannot measure the window regeneration amplitude adequately because of leptonic background and statistics, but a series of optical-model calculations, using a Woods-Saxon nuclear density distribution, measured cross sections with their errors,[8] and real parts of up to 40% added to the strangeness +1 scattering amplitude, indicate that the forward-regeneration intensity in the window, $(dN/d\Delta^2)|_{\Delta^2=0}$, is not in excess of 2×10^4 $(\mathrm{BeV}/c)^{-2}$. We have therefore reduced the fiducial volume to a region of the chamber (beginning at 50 cm from the window and extending for 102 cm) in which our results are insensitive to changes in the window intensity up to $(dN/d\Delta^2)|_{\Delta^2=0} = 2\times10^4$ $(\mathrm{BeV}/c)^{-2}$.

Figure 3 shows the angular distribution of decays in the reduced fiducial volume with visible momenta greater than 2 BeV/c, and with the invariant mass of the visible tracks, interpreted as pions, within ±15 MeV of the K_S mass. A peak in the forward direction remains above all incoherent background. Figure 3 also shows the same plot for those decays with invariant mass from 15 to 30 MeV above or below the K_S mass. The data in this "off-mass" plot show no forward peak and are explained on the basis of the leptonic decays of the K_L meson alone.

If there were no $\pi^+\pi^-$ decay of the K_L meson, this peak would represent a 2.7-standard-deviation effect above the coherent and incoherent backgrounds. The statistics clearly do not allow an independent determination of the

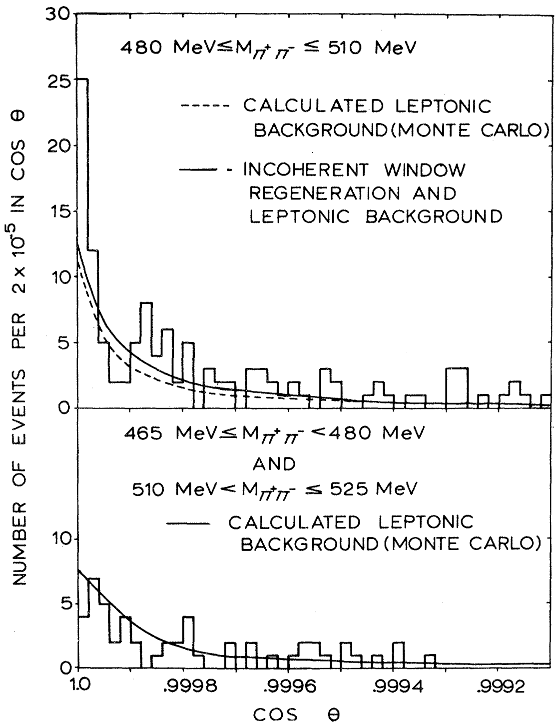

FIG. 3. Angular distribution of decays in the reduced fiducial volume with $P_{\text{vis}} \geq 2$ BeV/c. Top: The invariant mass of the visible tracks, interpreted as pions, within ±15 MeV of the K_S mass. Bottom: The invariant mass from 15 to 30 MeV above or below the K_S mass.

rate $K_L \to \pi^+ + \pi^-$ or a demonstration of the necessity of interference with regenerated $K_S \to \pi^+ + \pi^-$. However, we take the point of view that $K_L \to \pi^+ + \pi^-$ and interference with regenerated K_S mesons are established[1,5,7] and have tried to analyze our data for information on the phase angle of the amplitude ratio η_{+-}, where

$$\eta_{+-} = |\eta_{+-}| \exp(i\varphi_\eta) = \frac{\text{amplitude for } K_L \to \pi^+ + \pi^-}{\text{amplitude for } K_S \to \pi^+ + \pi^-}.$$

We have constructed a likelihood function that uses the known $K_L \to \pi^+ + \pi^-$ decay rate,[1] the forward regeneration amplitude in hydrogen $[A_{\text{H}} \exp(i\varphi_{\text{H}})]$ as determined in this experiment, and the forward window-regeneration intensity in the range (1 to 2)$\times 10^4$ (BeV/c)$^{-2}$. In this analysis we have assumed that the window and hydrogen regeneration amplitudes are functions solely of four-momentum transfer, which is consistent with our data at momenta above 2 BeV/c, above the $\bar{K}$-N resonance region. The phase-angle differences between η_{+-} and the window- and hydrogen-regenerated K_S amplitudes were allowed to vary. Figure 4 shows the results of the likelihood analysis for $(\varphi_{\text{H}}-\varphi_\eta)$, which gives the best fit to the data at $(\varphi_{\text{H}}-\varphi_\eta) = 240$ deg, independent of both the phase and magnitude of the window-regeneration amplitude. Using the value $\varphi_{\text{H}} = 90°$, we obtain the results summarized in Table I. We note that although the phase of η_{+-} is sensitive to the sign of the mass difference, the phase of $\eta_{+-}(i\delta + \frac{1}{2})$, where

$$\delta = M_{K_S} - M_{K_L}$$

in units of the decay rate of K_S, is essentially independent of the sign of the mass difference. These results are in good agreement with those of Fitch et al.,[7] who measured the phase of η_{+-} for regeneration of K_S mesons in beryllium, using optical-model calculations to demonstrate the absence of real parts in the forward K_S regeneration amplitude in beryllium. As previously pointed out,[7,9,10] the quantity $\eta_{+-}(i\delta + \frac{1}{2})$ is expected to be real if the $\Delta I = \frac{1}{2}$ rule and the TCP theorem are valid in the $\pi^+\pi^-$ decay of the neutral K meson.

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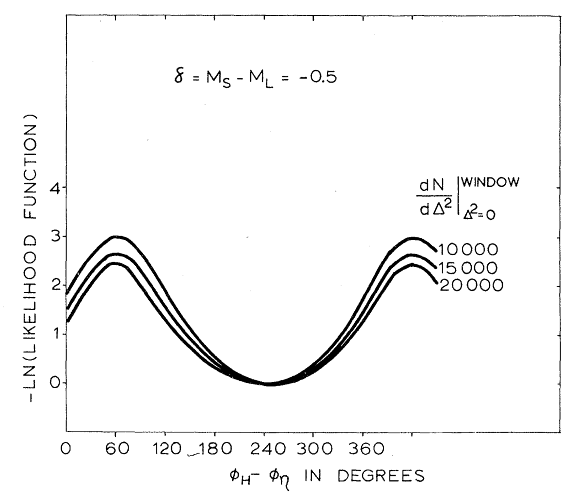

FIG. 4. Likelihood function for the phase-angle difference $(\varphi_{\text{H}}-\varphi_\eta)$.

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SIGN OF THE n-p MASS DIFFERENCE*

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The problem of the n-p mass difference has recently received new attention in the papers of Dashen and Frautschi.[1] Their calculation is unique in that it contains no obvious connection with previous field-theoretic estimates,[2] and also in that it gives essentially the right answer. We would like to point out that the lack of success of the older calculations may be due to an oversimplified treatment of the strong interactions, which should not only provide realistic nucleon charge and moment distributions, but also a background against which all weaker, electromagnetic mass shifts must be measured.[3] This is because the masses associated with strongly interacting fields are determined by a nonlinear set of equations, and any small input shift must be cycled through this, or a related, set of nonlinear equations; in principle, the output need have no obvious relationship to the input. In the absence of electromagnetic interaction, the neutron and proton masses are degenerate. When the electromagnetic interaction is turned on, these masses will be different, due to, e.g., the e^2 contribution of the self-energy graph with intermediate state consisting of a photon and nucleon. In addition to and because of this electromagnetic effect, the masses of the intermediate nucleon and pions, which enter into the strong-interaction contribution to the nucleon self-energy, are also shifted, and should be taken into account when computing the n-p mass difference.

It is convenient to make use of the Gell-Mann and Low representation,[4] as used by Ida[5] in the limit of isotopic symmetry,

$$S_c(\omega) = \frac{1}{m-\omega} + \frac{1}{\pi}\int_{m+\mu}^{\infty} d\omega' \left[\frac{\sigma_+(\omega')}{\omega'-\omega} - \frac{\sigma_-(\omega')}{\omega'+\omega}\right], \qquad (1)$$

where the replacement $\omega = i\gamma\cdot p$ yields the renormalized nucleon propagator in terms of a positive, renormalized spectral function. Barring Castillejo-Dalitz-Dyson zeroes, an