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Measurement of the $\pi^+\pi^- \to K_s^0K_s^0$ Scattering Cross Section

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Data from the reaction $\pi^-p \to nK_s^0K_s^0$ have been used to determine the cross section for the reaction $\pi^+\pi^- \to K_s^0K_s^0$ by extrapolation to the pion pole. The reaction $\pi^+\pi^- \to K_s^0K_s^0$ is dominated by S^* and f^0 production. The $\pi^+\pi^- \to K_s^0K_s^0$ cross section is well below the S-wave unitarity limit in the S^* (threshold) region. We discuss implications for the SU(3) scalar meson nonet and for $\pi\pi$ phase-shift analyses.

The purpose of this paper is to present the cross section for the reaction

$$\pi^+\pi^- \to K_s^0K_s^0 \tag{1}$$

deduced from an extrapolation of data from the reaction $\pi^-p \to nK_s^0K_s^0$. We find that the cross section for this reaction is dominated by resonance production and is consistent with pure S^*+f^0 production. Assuming S^* and f^0 production are indeed the dominant processes present, we deduce (1) η_0^0, the $I=0$, S-wave absorption parameter in $\pi^+\pi^-$ scattering near $K\bar{K}$ threshold (the S^* region), and (2) $R_1 = (f^0 \to K\bar{K})/(f^0 \to \text{all})$, the f^0 branching ratio to $K\bar{K}$.

Since R_1 has been measured by more direct means,[1] we consider its measurement in our analysis to be a consistency check of our extrapolation procedure and our assumption of S^*+f^0 dominance. The value of η_0^0 that we deduce is considerably larger than that obtained in elastic $\pi\pi$ phase-shift analyses.[2,3] This implies that $g_{S^*}^{\pi\pi}$, the $\pi\pi S^*$ coupling constant, is comparable to $g_{S^*}^{K\bar{K}}$ rather than much less than $g_{S^*}^{K\bar{K}}$. This observation has significant implications for the SU(3) scalar meson nonet. In particular, we show that the $(S^*, \delta, \kappa, S^{*\prime})$ mesons can comprise the scalar meson nonet with a "normal" mixing angle of approximately 40°. (Here we denote by $S^{*\prime}$ the new scalar meson under the f^0 previously observed[4] in this experiment and later confirmed[5] by Pawlicki *et al.* who have shown its isospin to be zero.[6])

The data we analyze here come from an experiment to study the reaction $\pi^-p \to nK_s^0K_s^0$ at 6.0 and 7.0 GeV/c carried out at the streamer-chamber facility at Argonne National Laboratory. Some experimental details and results have been published previously[4,7] and complete details will be published elsewhere. The data consist of a very clean sample of 5096 events. The acceptance of the experiment varies slowly with t (the four-momentum transfer from the proton to the neutron) as well as $\cos\theta$ and φ (the Jackson and Treiman-Yang angles), and does not depend strongly on M, the $K_s^0K_s^0$ effective mass. In particular, there are no zeros of the acceptance in any of the above kinematic variables.

In order to determine $\sigma(\pi^+\pi^- \to K_s^0K_s^0)$, we have divided the data into bins of M and t and performed a Chew-Low[8] extrapolation to the pion pole using the 7-GeV/c data. The slope of the t distribution decreases slowly with increasing M

as shown in Figs. 1(a) and 1(b) for $M < 1.1$ GeV and $1.25 < M < 1.35$ GeV. The slope of the t distribution as determined from a least-squares fit to the data of the form Ae^{Bt} for $0.02 \leq |t| \leq 0.30$ GeV^2 yielded values of $B = 9.1 \pm 0.6$ GeV^{-2} for Fig. 1(a) and $B = 6.8 \pm 0.3$ GeV^{-2} for Fig. 1(b). This decrease of B indicates that one-pion exchange (OPE) becomes less dominant as M increases. (In fact we have shown[4] that the $S^{*\prime}$ at 1300 MeV is produced dominantly by non-OPE processes.) Thus, although the extrapolation procedure in principle yields the true OPE contribution, one must be more wary of the results as M increases. However, near threshold the data are consistent with quite pure OPE and the results of the extrapolation should be very reliable.

The extrapolations are based on the assumption that the differential cross section for $\pi^- p \to n K_s^0 K_s^0$ is given by the Chew-Low formula[8] modified by the Dürr-Pilkuhn form factor,[9]

$$F(t) = \frac{1 + R^2 Q^2(M_p, \mu^2, M_n)}{1 + R^2 Q^2(M_p, t, M_n)}.$$

Here

$$Q^2(M_1, t, M_3) = [(M_3 - M_1)^2 - t][(M_3 + M_1)^2 - t]/4M_3^2$$

and R was taken to be 2.66 GeV^{-1}. The quantities M_p, μ, and M_n are the proton, pion, and neutron masses, respectively.

Shown in Fig. 2 for four typical M intervals are plots of $(d^2\sigma/dM\,dt)(\mu^2 - t)^2/F(t)$, which, according to the Chew-Low[8] hypothesis, is proportional to $\sigma(\pi^+\pi^- \to K_s^0 K_s^0)$ at $t = \mu^2$. Extrapolations to the pion pole were carried out for $M < 1.45$ GeV in 25-MeV intervals and for $|t| < 0.1$ GeV^2. The curves in Fig. 2 correspond to least-squares extrapolations assuming a linear dependence on t and requiring the extrapolation to go through the origin. Data in all mass regions are consistent with this linear, nonevasive hypothesis. Also carried out were extrapolations quadratic in t, evasive extrapolations, and extrapolations with no form factors. We find that the evasive extrapolations are generally consistent with the nonevasive results but with larger errors in the extrapolated cross section. The extrapolations without form factors generally lead to results for $\sigma(\pi^+\pi^- \to K_s^0 K_s^0)$ some 35% lower than those using form factors.

The quadratic extrapolations yield cross sections consistent with linear extrapolations below $M \simeq 1.2$ GeV and cross sections ~ (20–40)% lower than the linear extrapolations above $M \simeq 1.2$ GeV. The uncertainties in the extrapolated points are again much larger than those obtained in the linear fits. For the remainder of this paper we will discuss the results based on the linear, nonevasive extrapolation using the Dürr-Pilkuhn form factors. Our conclusions do not depend strongly on this hypothesis, and dependence of our conclusions on the extrapolation procedure will be discussed when appropriate.

The results are shown in Fig. 3 where $\sigma(\pi^+\pi^- \to K_s^0 K_s^0)$ is shown as a function of M. We note

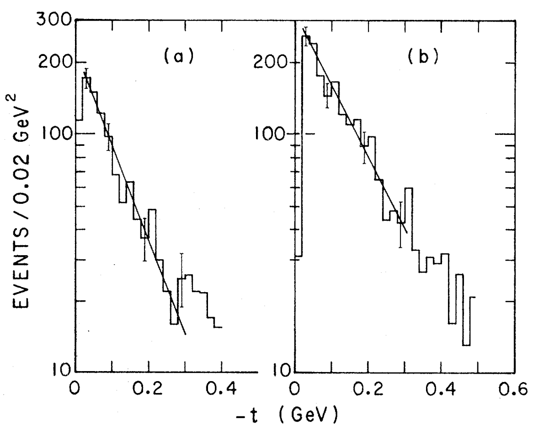

FIG. 1. Four-momentum transfer from the target proton to the outgoing neutron for events with $K_s^0 K_s^0$ effective mass from (a) less than 1.1 GeV and (b) 1.25 to 1.35 GeV. The curves shown are fits to the data described in the text.

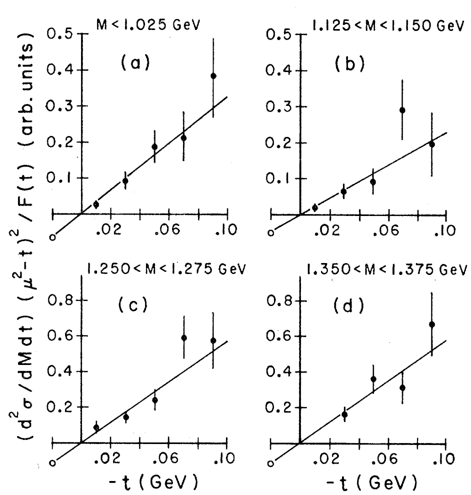

FIG. 2. Plots of $(d^2\sigma/dM\,dt)(\mu^2 - t)^2/F(t)$ for four typical $K_s^0 K_s^0$ mass ranges. The extrapolation curves shown are linear and required to pass through the origin.

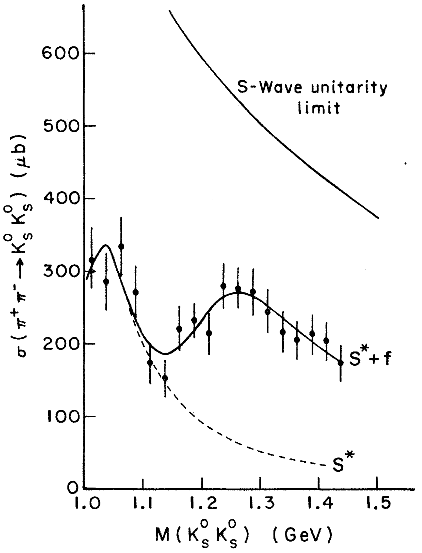

FIG. 3. The cross section $\sigma(\pi^+\pi^-\rightarrow K_s^0K_s^0)$ determined from the extrapolation as a function of $K_s^0K_s^0$ mass. The smooth curve is a two–Breit-Wigner fit to the data described in the text.

the presence of a peak at threshold (the S^*) and following a dip, a second peak in the region of the f^0. We have fitted the data with an incoherent sum of S-wave and D-wave Breit-Wigner amplitudes.[10] We find the data consistent with this hypothesis as shown by the curve in Fig. 3.

In order to see whether the "f^0" peak is consistent with true f^0 production, we have determined the $f^0\rightarrow K\bar{K}$ branching ratio assuming that the cross section for $\pi^+\pi^-\rightarrow f^0\rightarrow K_s^0K_s^0$ at 1270 MeV is 210 ± 40 μb as determined from the fit shown in Fig. 3. Using an f^0 absorption parameter $\eta_2^0=0.67$ from the literature,[11] we find

$$\sigma(\pi^+\pi^-\rightarrow f^0\rightarrow\pi\pi)$$
$$=\tfrac{8}{3}\pi\lambda^2(2l+1)[\tfrac{1}{2}(1+\eta_2^0/2)]^2=29.5\text{ mb}.$$

Thus we find $R_2=(f^2\rightarrow K\bar{K})/(f^0\rightarrow\pi\pi)=4(0.210)/29.5=0.028\pm0.005$. Using the value[11] of $R_3=(f^0\rightarrow\pi\pi)/(f^0\rightarrow\text{all})=0.84$ we find $R_1=(f^0\rightarrow K\bar{K})/(f^0\rightarrow\text{all})=0.024\pm0.004$. This is consistent with our direct measurement using the Y_4^0 moment of $R_1=0.023\pm0.008$ and that of Wetzel *et al.*,[12] $R_1=0.024\pm0.005$, but is below another direct measurement of Pawlicki *et al.*[1] who obtain $R_1=0.038\pm0.004$. We conclude that our extrapolation procedure and interpretation of the data seem reasonable.

The cross section at threshold is approximately 300 μb, considerably below the S-wave unitarity limit of $(1/6)\pi\lambda^2=\sigma_u=880$ μb at 1 GeV. We have calculated the $\pi^+\pi^-\rightarrow\pi^+\pi^-$ $I=0$, S-wave absorption η_0^0 in the S^* region assuming that the S^* is a standard two-channel resonance with only $\pi\pi$ and $K\bar{K}$ decay modes. In this case

$$(\eta_0^0)^2=1-\sigma(\pi^+\pi^-\rightarrow S^*\rightarrow K_s^0K_s^0)/\sigma_u=1-|S|^2$$

yielding $\eta_0^0=0.81^{+0.09}_{-0.04}$ and $|S|^2=0.34^{+0.07}_{-0.15}$. (The errors here include the systematic uncertainty introduced by the extrapolation procedure. Systematic uncertainties combined with statistical errors could yield a cross section as high as 360 μb at threshold. Even if the cross section were as large as 450 μb, η_0^0 would only be as low as 0.7.) These values are consistent[13] with Wetzel *et al.*[12] who obtain $|S|^2\approx0.39\pm0.05$ corresponding to $\eta_0^0=0.78\pm0.03$.

Given our value for η_0^0, we find the cross section for $\pi^+\pi^-\rightarrow S^*\rightarrow\pi\pi$,

$$\sigma=\tfrac{8}{3}\pi\lambda^2[\tfrac{1}{2}(1+\eta_0^0)]^2$$

to be 11.5 mb. It is now possible to determine directly the ratio

$$\left(\frac{g_{S^*}{}^{\pi\pi}}{g_{S^*}{}^{K\bar{K}}}\right)^2=\frac{\sigma(\pi^+\pi^-\rightarrow S^*\rightarrow\pi\pi)}{\sigma(\pi^+\pi^-\rightarrow S^*\rightarrow K\bar{K})}\,\frac{q_K}{q_\pi}.$$

We obtain a value of $1.5^{+1.1}_{-0.3}$ for this ratio; thus we see that the $S^*\rightarrow\pi\pi$ coupling is comparable to the $S^*\rightarrow K\bar{K}$ coupling.

We now address the question of whether this coupling-constant ratio can be consistent with SU(3). We assume that the members of the scalar meson nonet are the S^*, δ, κ, and $S^{*\prime}$. In our previous work[4] we showed that the $S^{*\prime}$ is probably not produced predominantly by pion exchange because its t distribution is broad and because its production amplitude is 90° out of phase with f^0 production. Since then, it has been shown[5] that the state has $I=0$; so we expect that a correct picture of this nonet will have the $S^{*\prime}$ couple to the $\pi\pi$ channel but that the coupling will be rather weak.

The mixing angle θ can be found if the masses of the states are known. If we assume masses of 990, 970, 1100, and 1310 MeV for the S^*, δ, κ, and $S^{*\prime}$, respectively, then $\theta=41°$. (The mass of the κ is not well determined, and if $M_\kappa=1200$ MeV, $\theta=67°$ as used by Morgan.[14]) Then using the relations[14]

$$g_{S^*}{}^{\pi\pi} = (\sqrt{3}/\sqrt{5})\cos\theta g_8 + (\sqrt{3}/\sqrt{8})\sin\theta g_1, \quad (2)$$

$$g_{S^*}{}^{K\bar{K}} = (1/\sqrt{5})\cos\theta g_8 + \tfrac{1}{2}\sqrt{2}\sin\theta g_1, \quad (3)$$

$$g_{S^{*\prime}}{}^{\pi\pi} = (\sqrt{3}/\sqrt{5})\sin\theta g_8 + (\sqrt{3}/\sqrt{8})\cos\theta g_1, \quad (4)$$

and

$$g_{S^{*\prime}}{}^{K\bar{K}} = -(1/\sqrt{5})\sin\theta g_8 + \tfrac{1}{2}\sqrt{2}\cos\theta g_1, \quad (5)$$

we find, from (2) and (3) that $g_1/g_8 = -6.4$ (assuming that $g_{S^*}{}^{\pi\pi}$ and $g_{S^*}{}^{K\bar{K}}$ have the same sign[14]). If we then use (4) and (5), we get $(g_{S^{*\prime}}{}^{\pi\pi}/g_{S^{*\prime}}{}^{K\bar{K}})^2 = 0.44^{+0.08}_{-0.19}$. That is, as expected, the $S^{*\prime}$ couples to the $\pi\pi$ system relatively weakly.

In summary, we have measured the cross section for the reaction $\pi^+\pi^- \to K_s^0 K_s^0$. Despite significant systematic uncertainties, it is clear that the S^* does not couple as strongly to the $K\bar{K}$ system as one might assume from recent $\pi\pi$ phase-shift analyses[2,3] which find the absorption parameter η_0^0 to be about 0.24 in the S^* region. In fact our data are clearly inconsistent with values of η_0^0 less than about 0.7. An additional factor leading credibility to our result is the fact that, with the S^* coupling rather strongly to the $\pi\pi$ final state, the $S^{*\prime}$ is predicted by SU(3) to couple strongly to $K\bar{K}$ and weakly to $\pi\pi$, as observed.

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