# Evidence for $\iota(1460)$ Production in $\pi^- p$ Interactions at 21.4 GeV/$c$

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The $K_S^0 K_S^0 \pi^0$ system has been studied in the exclusive reaction $\pi^- p \to K_S^0 K_S^0 \pi^0 n$ at 21.4 GeV/$c$. Evidence for the production of the $f_1(1285)$ and the $\eta(1460)$ is presented. The $\eta(1460)$ is produced away from minimum momentum transfer in the presence of nonresonant $K^*K$ ($S$-wave) production and phase-space background. The observed mass, width, and decay properties of the $\eta(1460)$ are consistent with those attributed to the $\iota(1460)$ observed in radiative $J/\psi$ decay.

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Spectroscopy of meson systems with $J^P = 0^-$ and $1^+$ in the mass range between 1250 and 1550 MeV/$c^2$ has progressed significantly; several recent experiments have studied the $K\bar{K}\pi$ system (as well as the $\eta\pi\pi$ system) produced under a variety of experimental conditions. The experiments have included both peripheral[1-3] and central[4] hadroproduction; $p\bar{p}$ annihilation[5,6]; production in $\gamma\gamma$ interactions[7,8]; and radiative and hadronic decay of the $J/\psi$.[9,10] It is now known that $1^+$ states coupling to $K\bar{K}\pi$ and $\eta\pi\pi$ (Refs. 3 and 8) exist at 1285,[2,4] at 1380,[1] at 1420,[4,7,8,10] and at 1530 MeV/$c^2$.[1,11] Furthermore, $0^-$ states coupling to $\eta\pi\pi$ at 1275 MeV/$c^2$,[3,12] and to both $\eta\pi\pi$ and $K\bar{K}\pi$ at 1420 and at 1460 MeV/$c^2$ have been reliably observed.[2,3,5,6,9]

In both the $0^-$ and $1^+$ cases there remain puzzles. More states have been observed in each than can be accommodated in simple $q\bar{q}$ nonets and, in the case of the $0^-$ states, even though a surplus of states exists, no good candidate for the $s\bar{s}$ member of the nonet exists. In the $1^+$ system, the $f_1(1285)$ [formerly the $D(1285)$ meson] and the $f_1'(1530)$ appear to be the most likely candidates for the $I=0$ nonstrange and strange members of the axial-vector nonet, respectively, while the $f_1(1420)$ is a candidate for a four-quark or a hybrid meson. In the $0^-$ system, the $\eta(1275)$ could be the nonstrange $I=0$ member of the radially excited pseudoscalar nonet. The $\iota(1460)$ remains a glueball candidate and the $\eta(1420)$ may be a four-quark state or a hybrid meson.[2]

In this experiment, the $K_S^0 K_S^0 \pi^0$ final state produced exclusively with a neutron in $\pi^- p$ interactions at 21.4 GeV/$c$ is studied. The experiment has the potential of adding qualitatively new information to the study of this system for two reasons. First, the energy of the beam is significantly higher than previous peripheral hadroproduction experiments where exclusive final states have been studied. Second, the $K_S^0 K_S^0 \pi^0$ final state offers the significant advantage that it couples only to states with $C=+1$, eliminating analysis complications introduced by the potential presence of $C=-1$ states in the data.

The experiment was performed at the Brookhaven Alternating Gradient Synchrotron (AGS) using the High Energy Unseparated Beam (~98% 21.4 GeV/$c$ $\pi^-$) incident on a 30-cm liquid-hydrogen target. Final-state detection was done with the Brookhaven Multiparticle Spectrometer (MPS II)[13] supplemented with a lead-glass hodoscope. The layout of the experiment is the same as that shown in Ref. 13 with the exception of the location of the seven drift chambers and three proportional wire chambers and with the addition of a lead-glass hodoscope directly downstream of the MPS. Design and construction of the hodoscope was very similar to that described in Ref. 14. Experimental details regarding the equipment, trigger, and event reconstruction will be published elsewhere.

A total of 9504 events with two reconstructed separated showers were found to be consistent with the reaction

$$\pi^- p \to n K_S^0 K_S^0 \pi^0. \quad (1)$$

For the final event sample, a missing-mass-squared cut between $-3.0$ and $+1.8$ (GeV/$c^2$)$^2$ containing 6265 events was made. This sample includes 1624 single-cluster events in which the photons are assumed to be unseparated at the lead glass. In order to estimate the background from events with extra missing $\pi^0$('s), a fit to the missing-mass distribution (not shown) was performed. Using this fit, we estimate that the neutron-to-background ratio is 3.79. This "background" consists primarily of $K_S^0K_S^0\pi^0X$ events with $X$ not being a neutron alone, but a neutron in the presence of one or more $\pi^0$'s.

Distributions of the $(K_S^0K_S^0)$ and $(K_S^0\pi^0)$ effective masses are shown in Figs. 1(a) and 1(b). Structure in both the $f/A_2$ region and at threshold (the $\delta$ region) is present in the former and the $K^*$ peak is prominent in the latter. It is clear that many of the $K_S^0K_S^0\pi^0$ events involve $K_S^0K_S^0$ or $K_S^0\pi^0$ resonances.

The production mechanism for reaction (1) varies strongly with $K_S^0K_S^0\pi^0$ effective mass as evidenced by the strong variation in the distribution of the momentum transfer $t' = -(t - t_{\min})$ with $K_S^0K_S^0\pi^0$ effective mass. If we fit the momentum-transfer distribution for various $K_S^0K_S^0\pi^0$ mass intervals with a function of the form $e^{-bt'}$, the parameter $b$ has a value of about 2.5 $(\mathrm{GeV}/c^2)^{-2}$ up to a mass of about 1500 MeV/$c^2$ where it rises sharply to a value of between 4 and 5 $(\mathrm{GeV}/c^2)^{-2}$ [Fig. 1(d)]. The $K_S^0K_S^0\pi^0$ effective-mass distribution with $t' > 0.2$ GeV$^2$ [Fig. 1(c)] shows a broad enhancement around 1460 MeV/$c^2$ with significantly less background than without the $t$ cut (not shown), indicating that resonance production occurs via a less peripheral mechanism than the nonresonant background production in this region. The overall acceptance, including reconstruction efficiency, is a maximum at about 1.80 GeV/$c^2$. This acceptance is slowly varying, decreasing to 93% of the maximum at 1.50 GeV/$c^2$ and to 75% of the maximum at 1.28 GeV/$c^2$.

At this point, it is interesting to note that the $K_S^0K_S^0\pi^0$ effective-mass distribution for the data from this experiment is significantly different from that observed in lower-energy hadroproduction experiments[2] studying the

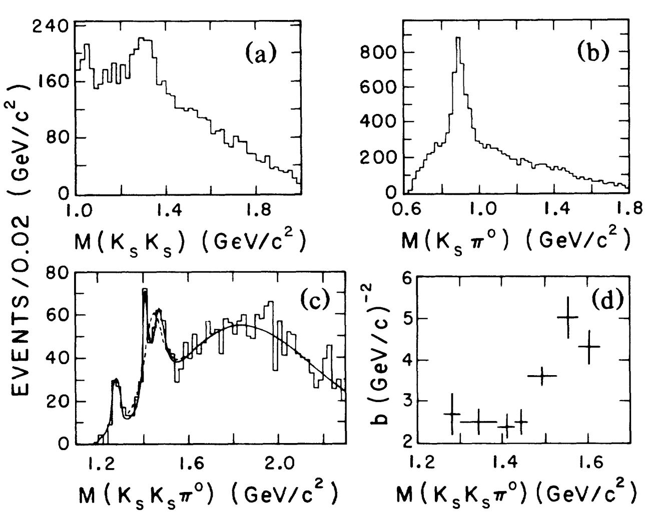


FIG. 1. (a) The $K_S^0K_S^0$ effective-mass distribution. (b) The $K_S^0\pi^0$ effective-mass distribution. (c) The $K_SK_S\pi^0$ effective-mass distribution where $-t' > 0.2$ GeV$^2$ (2953 events). The fits are described in the text. (d) The fitted parameter $b$ as a function of $K_S^0K_S^0\pi^0$ effective mass, where $d\sigma/dt' - e^{-(bt')}$.

$K^{\pm}K_S^0\pi^{\mp}$ system. In particular, those experiments observe a narrower peak structure at lower mass (about 1420 MeV/$c^2$). The broader, higher-mass line shape observed here more closely resembles that of the $\iota$ seen in $J/\psi$ radiative decay.[9] The $t$-cut $K_S^0K_S^0\pi^0$ distribution has been fitted by relativistic Breit-Wigner functions in the $D$ region (1285 MeV) and the $E$ region (1400-1500 MeV), both with fixed widths and with the phase-space factor modifying the resonance width. The $K_S^0K_S^0\pi^0$ mass has a resolution with $\sigma \sim 1.5\%/[M\ (\mathrm{GeV})]$, or 19 MeV in the $D$ and 21.8 MeV in the $E$ region. All widths quoted from the fits have this resolution unfolded.

The best fit to the $D$ region yielded mass $1280 \pm 2$ MeV/$c^2$ and width $18 \pm 11$ MeV/$c^2$, consistent with Particle Data Group[15] values for the $D(1285)$.

The best fit to the $E$ region with a single $\delta\pi$ ($S$ wave) Breit-Wigner form had mass $1453 \pm 7$ MeV/$c^2$ and width $100 \pm 11$ MeV/$c^2$. It is interesting to note that the mass and width are consistent with those from other experiments—specifically the $\iota(1460)$ parameters.[9] The dashed curve shown on the $K_S^0K_S^0\pi^0$ mass distribution in Fig. 1(c) corresponds to this fit which has a $\chi^2$ probability of 2.7%.

Since it has been suggested that there may be more than one resonance in this region,[16] we have also fitted the data with two Breit-Wigner functions despite the fact that the statistics are insufficient to prove the existence of two separate peaks. Such a fit yields masses of $1412 \pm 4$ and $1488 \pm 5$ MeV/$c^2$ and widths of $25 \pm 5$ and $82 \pm 8$ MeV/$c^2$ with a $\chi^2$ probability of 28.8%. This improvement in $\chi^2$ is a result of fitting the bin between 1400 and 1420 MeV/$c^2$ with a narrow peak, as is seen in the (solid) curve in Fig. 1(c). The parameters of this lower peak are, in fact, consistent with the single peak observed at lower energy.[2]

The data were divided into $K_S^0K_S^0\pi^0$ mass bins and the Dalitz plots were fitted by the Zemach[17] tensor method in the context of the isobar formalism. The three Dalitz plots in the region of $K_S^0K_S^0\pi^0$ mass between 1390 and 1530 MeV/$c^2$ (the $E$ region) are shown in Fig. 2. Spin-parities of $0^-$ and $1^+$ were allowed and the isobars assumed were $\delta\pi$ ($S$ and $P$ wave) and $K^*K$ ($S$ and $P$ wave). A uniform background was also assumed.

The logarithm of the likelihood ($\ln\mathcal{L}$) is given by the function

$$\ln\mathcal{L} = \sum_{n=1}^{N} \ln \frac{\sum_{J^P} |A_{J^P}|^2}{\sum_{ij} |\alpha_i \alpha_j|}.$$

The sum over $n$ is for all data points, $J^P$ are the spin-parities, and $i,j$ are the decay channels, so that $|A_{J^P}|^2 = |\sum_i \alpha_i A_{J^P}^i|^2$. Each $|A_{J^P}^i|^2$ is normalized and corrected for acceptance which is quite uniform across the Dalitz plot. The functional forms of the $A_{J^P}^i$ are given explicitly in Ref. 18.

The $\alpha_i$ are variables of the fit representing the spin-parity decay-channel amplitudes. Different decay channels of like spin-parity were allowed to interfere, the coherence of the interference being a variable of the fit.

The $K^*$ was parametrized as a relativistic spin-1 Breit-Wigner function. The $\delta$ was parametrized as a coupled-channel resonance with the Flatté[19] parametrization. This form, with the ratio of coupling strengths $(g_k/g_\eta)=1.5$, $m_\delta=983$ MeV/$c^2$, and $\Gamma_\delta=54$ MeV/$c^2$ is found to maximize the $1^{++}\delta\pi$ ($P$-wave) contribution to the fit in the $D$ region. The amount of $0^{-+}$ in this region is found to be about 10%, although as much as 40% could be accommodated by the data.

The fits to the uncut data (not shown) are dominated by the $1^{++}$ wave, which is found to be ~100% $K^*K$ ($S$) above 1430 MeV. This wave rises sharply at $K^*K$ threshold and remains constant at higher mass. There appears to be no peak present. On the other hand, the $0^{-+}$ wave is consistent with a peak at about 1460 MeV.

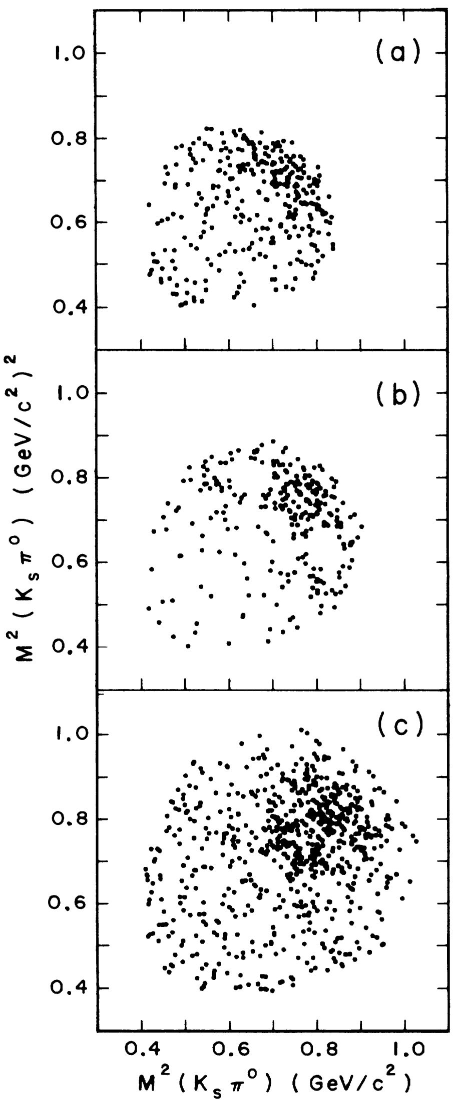


FIG. 2. Dalitz plots from the data without a $t'$ cut for (a) the lower $E$ region [1.39 GeV/$c^2 < M(K_S^0K_S^0\pi^0) <$ 1.43 GeV/$c^2$], (b) the middle $E$ region [1.43 GeV/$c^2$ $< M(K_S^0K_S^0\pi^0) <$ 1.46 GeV/$c^2$], and (c) the upper $E$ region [1.46 GeV/$c^2 < M(K_S^0K_S^0\pi^0) <$ 1.53 GeV/$c^2$]; each event is plotted twice.

Intensities for fits to the data with $t' > 0.2$ GeV$^2$ are shown in Fig. 3. The quality of these fits has been checked by Monte Carlo techniques and the fitted likelihoods are all acceptable, being within 2 standard deviations of the more probable likelihood. The curve superimposed on the $0^{-+}$ intensity is the fit described previously found by fitting the $K_S^0K_S^0p^0$ mass distribution in the $E$ region with a single Breit-Wigner function [dashed curve, Fig. 1(c)]. The intensity fits indicate that the peak present in the $K_S^0K_S^0\pi^0$ mass spectrum is most likely $0^{-+}$. Although the errors are large, the $0^{-+}$ wave shows a peak, while the $1^{++}$ is more consistent with the smooth rise present in the uncut data. The $0^{-+}$ wave in the $E$ region has approximately equal contributions from $\delta\pi$ and $K^*K$, but there are large uncertainties in these branching ratios.

The "alternative solution" shown in Fig. 3 represents an ambiguity between $0^{-+}$ $\delta\pi$ ($S$-wave) and $1^{++}$ $\delta\pi$ ($P$-wave) contributions in the fit to the bin between 1390 and 1430 MeV/$c^2$. This ambiguity is found in only this bin. The alternative solution is a fit dominated by the $0^{-+}$ $\delta\pi$ ($S$ wave) with little contribution from the $1^{++}$ $\delta\pi$ ($P$ wave).

In conclusion, the $K_S^0K_S^0\pi^0$ system produced in this experiment is characterized by the production of reso-

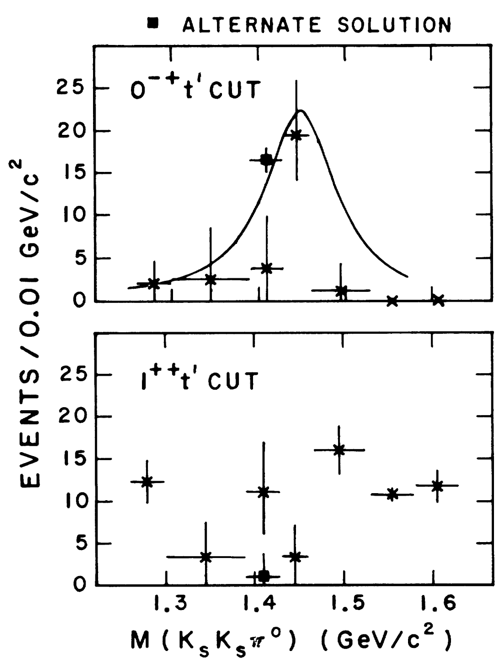


FIG. 3. Intensities of $J^{PC}=0^{-+}$ and $1^{++}$ waves for fits to the data with $t' > 0.2$ GeV$^2$. Each intensity is multiplied by the number of events per 10 MeV in the fitted bin.

nances in the $D$ region (1285 MeV) and $E$ region (1400–1500 MeV). The $D(1285)$ or $f_1(1285)$ is observed at a mass of 1280 MeV with a width of 18 MeV, consistent with earlier observations. The best fit to the spin-parity is with $J^{PC}=1^{++}$ decaying primarily to a $\delta\pi$ ($P$-wave) state. In the $E$ region, a broad resonance which has mass, width, and $J^{PC}$ consistent with the $\iota(1460)$ is observed well above the region of the $\eta(1420)$. In addition, a narrow peak which does not have strong statistical significance is observed which is nevertheless consistent with the $\eta(1420)$ observed in previous lower-energy hadroproduction.[2] The $\iota(1460)$, which is observed in hadroproduction for the first time in this experiment, couples to both $K^*K$ and $\delta\pi$, has a mass between 1450 and 1490 MeV [depending on whether one takes the $\eta(1420)$ peak as real], and has a width in the range of 80–100 MeV. In addition, a spin-parity analysis prefers $J^{PC}=0^{-+}$. These observations are quite consistent with results obtained in this mass region for the $\iota(1460)$ observed in $J/\psi$ radiative decay.

Observation of the $\iota(1460)$ in $\pi p$ peripheral production indicates that the $\iota(1460)$ is a state with a significant $q\bar{q}$ component. Although production of the $\eta(1420)$ would have been expected in this experiment, its presence is problematical—if it is present at all, its production is significantly suppressed relative to the $\iota(1460)$.

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