Direct Evidence for the S^* Meson Near the $K\bar{K}$ Threshold

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We report observation of the S^* meson in the reaction $\pi^- + p \to S^* + n$. The S^* decays into $\pi\pi$ and KK and is seen most clearly in the $2\pi^0$ channel. A fit to the data gives a sheet-II pole at $987 \pm 7 - i(24 \pm 7)$ MeV and a relative coupling $g_{S\to KK}/g_{S\to\pi\pi}$ of 3.8 ± 1.0.

In an investigation of the reaction $\pi^- + p \to$ missing mass $+ n$ using our threshold mass spectrometer at the Rutherford Laboratory, we found a sharp drop in the $\pi^+\pi^-$ mass spectrum close to the K^+K^- threshold.[1] This, we suggested, could be a manifestation of the production and decay of the S^* previously seen in $\pi\pi$ scattering.[2] In this paper we report on the $2\pi^0$ channel in the same experiment, and also on the results of a second experiment with higher resolution to check whether K^+K^- pairs were indeed produced. The results give direct evidence for the S^* and strikingly confirm the general conclusions of Flatté *et al.*[2] A full description of the approach and the techniques used can be found in Ref. 1.

The mass spectrum is obtained by scanning the incident momentum through the reaction threshold. Events were required to lie in the range $0.33 < -t < 0.83$ $(\mathrm{GeV}/c)^2$ where the threshold value of t, the square of the four-momentum transfer, is about -0.45 $(\mathrm{GeV}/c)^2$. The resolution function in the missing mass had a full width at half-maximum (FWHM) of about 8 MeV.

The selection of the $\pi^+\pi^-$ channel used the near-coplanarity of the two π's and the beam. The K^+K^- channel was eliminated by demanding that at least one of the particles be in the decay counter cylinder.[1] The four γ's made the $2\pi^0$ channel more complicated, but the opening angles for each π^0 decay were small ($\sim 30°$), helping in their recognition and enabling the coplanarity requirement for the $2\pi^0$'s to be used in the selection. Table I shows the efficiencies predicted for the wanted and certain unwanted channels. All but the most forward 2π decays were accepted by the decay counters.[1] There is no detailed information on angular distributions.

In Fig. 1 we show the spectra observed (a) in missing mass with no decay selection, (b) in the $\pi^+\pi^-$, and (c) in the $2\pi^0$ selections. The X^0 and φ can be clearly seen in Fig. 1(a) together with a sudden drop close to the K^+K^- threshold. The blackened areas in (b) and (c) are the estimated feedthrough from the X^0 and φ; these events have been omitted in the subsequent analysis. The most prominent feature of the $\pi^+\pi^-$ spectrum is the break in the spectrum at the K^+K^- threshold, and there is also a fairly plausible enhancement centered just below this threshold. The $2\pi^0$ spectrum shows this enhancement very clearly and we suggest that it is due to the S^* meson. Again there appears to be a rapid fall in the spectrum close to the K^+K^- threshold.

The kinematic region investigated in this experiment differs markedly from that in which the S^* has been investigated hitherto.[2,3] In particular, s-channel effects may have an important role in determining meson production cross sections near threshold. For example, we find that in this region φ production, which cannot proceed through a π-exchange mechanism, is large compared to the K^+K^- background,[1] whereas in Ref. 2 it seems to be unimportant. Also ρ production appears to be relatively small in our experiment, which

TABLE I. Predicted decay selection efficiencies.

Selection	Channel	Efficiency (%)
$\pi^+\pi^-$	$\pi^+\pi^-$	78
	$\pi^+\pi^-\pi^0$	4
	All φ	6
	All X^0	4
$\pi^0\pi^0$	$\pi^0\pi^0$	60
	$\pi^0\pi^0\pi^0$	14
	All φ	3
	All X^0	2.5

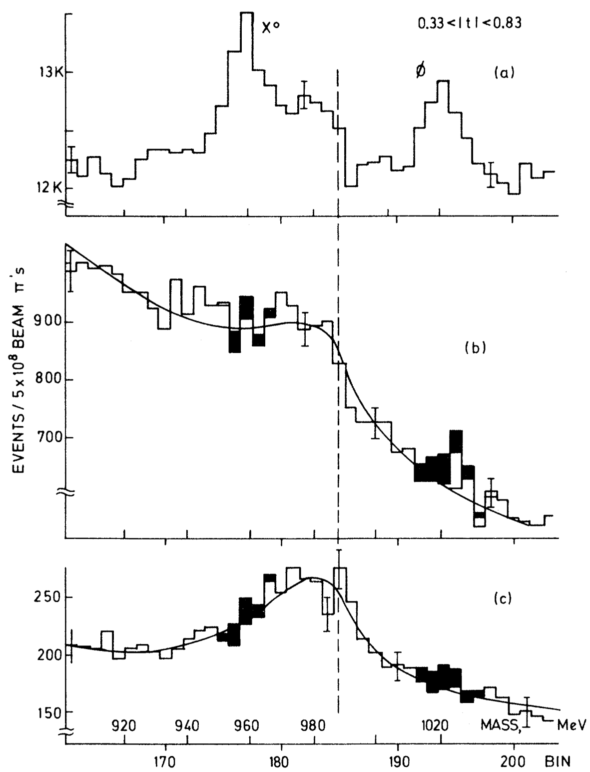

FIG. 1. Missing-mass spectra in the t range indicated (mass bins about 3.6 MeV, about 5×10^8 incident π's per bin). (a) With no decay selection; an abrupt but small drop is seen between the X^0 and the φ. (b), (c) $\pi^+\pi^-$ and $2\pi^0$ selections, respectively. The shaded events are the predicted contributions to the spectra from the X^0 and φ. Some events from other final states may also be present (see Table I). The dashed line indicates the K^+K^- threshold. The curves are fits to the S^* together with a quadratic background over a range from 840 to 1070 MeV. Note the suppressed origins.

again contrasts with Refs. 2 and 3.

The shape of the spectra, in particular the rise below the K^+K^- threshold and the sharp fall just above, can be understood most simply by a model in which the S^* is produced, as an isolated meson, and then decays into $\pi\pi$ and KK. To quantify this we assume the S^* to be a $J^P=0^+$ meson of isospin zero and use a parametrization of the form

$$\sigma_{\pi,K} \propto \left|\frac{\Gamma_{\pi,K}^{1/2}}{M_0 - M - i(\Gamma_\pi + \Gamma_K)/2}\right|^2,$$

where $\sigma_{\pi,K}$ are the cross sections in the $\pi\pi$ and KK channels, respectively. M_0 is a fixed mass, $\Gamma_\pi = g_\pi P_\pi$, and $\Gamma_K = g_K P_K{}^+ + g_K P_K{}^0$, where P_π, $P_K{}^+$, and $P_K{}^0$ are the final-state c.m. momenta of the π, K^+, and K^0, respectively. g_π and g_K

TABLE II. Fits to the 2π data of Fig. 1 (49 degrees of freedom).

Best fits	M_0 (MeV)	Γ_π (MeV)	α	χ^2	Pole position (sheet II) (MeV)
$\pi^+\pi^-$	958	70	2.4	49.0	$977-i25$
$2\pi^0$	948	110	3.8	25.5	$987-i24.5$
$2\pi_{\text{tot}}$	956	75	3.0	46.0	$980-i23.5$
Other	940	140	4.0	25.6	$991-i25.5$
$2\pi^0$	960	80	3.0	25.8	$984-i24$
fits	940	160	4.0	26.0	$994-i25.5$
	920	160	5.0	26.0	$990-i22$
	940	120	4.0	26.1	$987-i25$
	940	100	5.0	26.1	$985-i19.5$

are the couplings of the S^* to $\pi\pi$ and KK. Below each KK threshold, we have $P_K = +i(M_K{}^2 - M^2/4)^{1/2}$.

Distributions were generated for a series of values of the three parameters M_0, $\Gamma_\pi(M_0)$, and $\alpha = g_K/g_\pi$ and folded in with the resolution function. Fits were made to the $\pi^+\pi^-$ and $\pi^0\pi^0$ channels separately and to the sum of the two. A quadratic background term was included. The best values of the parameters are shown in Table II. All the fits are satisfactory. Fig. 1 shows the resultant distributions assuming the best values, $M_0=948$, $\Gamma_\pi=110$, $\alpha=3.8$, obtained from the fit to the $2\pi^0$ spectrum.

It was found, as shown in the lower section of Table II, that the data could be well represented by quite a wide range of the three parameters. Following Ball *et al.*[4] we have therefore investigated the location of the pole in the complex energy plane. For each set of parameters we find a pole on sheet II (see Table II). The position of the pole is relatively insensitive to the particular combination of the parameters used to describe the data, probably because of the proximity of the threshold. There is also a sheet-III pole but this is much further from the physical boundary and is therefore ignored.

Continuing the examination of the data, we find that the relative size of the observed signals for $2\pi^0$ and $\pi^+\pi^-$ is 0.53 ± 0.08. Allowing for a 10% error in each of the estimated efficiencies for the decay selection (Table I), this gives a ratio of 0.68 ± 0.14 which is consistent with the expected value of 0.5 for an $I=0$ meson. The two channels together can account for much, but possibly not all, of the drop seen in missing mass alone [Fig. 1(a)].

The modified decay system used in the second

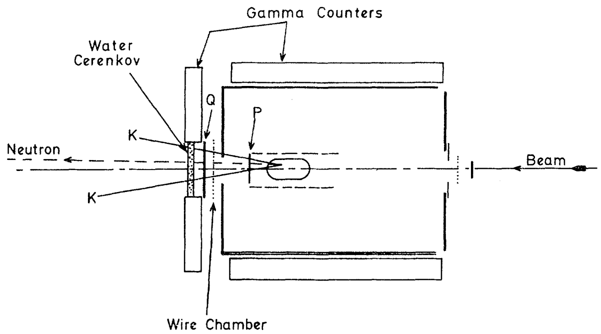

FIG. 2. Rearrangement of the decay system to detect K^+K^- pairs. For this selection two particles are required in the wire chamber with no signal from the water Cherenkov counter or γ counters. The total ionization in each of scintillation counters P and Q must be near 4× minimum.

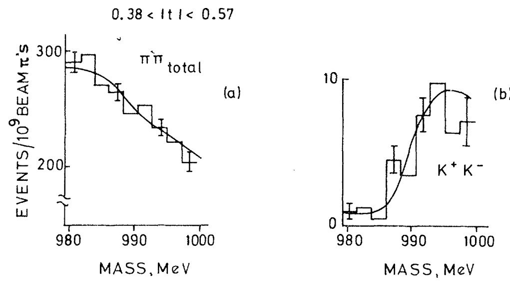

FIG. 3. Observed spectra from the later data (mass bins about 2.3 MeV). The total $\pi\pi$ spectrum has been fitted using the parameters determined from the data in Fig. 1 apart from the overall normalization and the ratio of the coupling constants $\alpha = g_K/g_\pi$. The curve shows the best fit, namely, $\alpha = 3.8$. The selection for K^+K^- has a clear rise above the threshold. Apart from a small noise level the curve is an absolute prediction of of the spectrum and shows reasonable agreement with the measurement. A normalization error of about 20% has not been included.

experiment is shown in Fig. 2. The hydrogen target length was reduced to 10 cm and the incident π momentum determined more precisely with multiwire proportional chambers. The neutron counter distance was unaltered at 6.15 m but to improve the resolution the t range was restricted to $0.38 < -t < 0.57$ $(\mathrm{GeV}/c)^2$. The FWHM of the resolution function was about 4 MeV.

The observed spectra are shown in Fig. 3. As in the earlier experiment, the mass scale is defined in terms of a floating-wire calibration. The data confirm the rapid fall in the 2π channel, typically about 25% over 15 MeV. They also show a rapid rise from a low instrumental background level in the selection for K^+K^- pairs.

The model predicts that very close to the threshold the behavior in both channels is dominated by $\alpha = g_K/g_\pi$. This was used to determine α from the high-resolution $\pi\pi$ data. M_0, Γ, and the ratio of S^* to background (within the same range of t) were taken from the earlier experiment. The results are $\alpha = 4.0 \pm 1.0$ and 3.8 ± 1.0 with $M_0, \Gamma = 956$, 75 (total $\pi\pi$) and 948, 110 ($2\pi^0$), respectively. The fitted distribution for $\alpha = 3.8$ is shown in Fig. 3(a). Both fits gave a normalization relative to the earlier data of 0.32, close to the ratio of the respective lengths of hydrogen targets of 0.34.

Given the normalization and the mass scale and all parameters, we can predict the K^+K^- spectrum expected. This is shown in Fig. 3(b) assuming also a small background level. The data points show rather strong statistical fluctuations but the general agreement is quite good. As the statistical accuracy of the K^+K^- data is too low and as there is a 20% uncertainty in the relative detection efficiencies for K^+K^- and $\pi\pi$, we could not use the K^+K^- data to constrain further the value of α. We conclude that the higher resolution data are consistent with the results of the earlier analysis and provide an independent determination of α.

The simple model used in our analysis locates the S^* pole on the second sheet close to the $K\bar{K}$ threshold. Although the position of the pole is not very sensitive to the choice made, we prefer to take as our best value that deduced from the $2\pi^0$ channel alone, partly because the higher signal-to-background ratio makes it more reliable, and partly because the parameters deduced are in better agreement with the value of α found from the high-resolution data. Thus our preferred value of α is 3.8 ± 1.0.

The error of the pole parameters was estimated from the range of pole positions given by all fits to the $2\pi^0$ data with χ^2 within 1 of the minimum value. This procedure locates the pole at $987 \pm 7 - i(24 \pm 7)$ MeV.

The result on the pole location can be compared with that of Protopopescu *et al.*[5] of $997 \pm 6 - i(27 \pm 8)$ based on a study of $\pi^+p \to \pi^+\pi^-\Delta^{++}$; of Ochs *et al.*[6] of $1007 \pm 10 - i(15 \pm 5)$ or alternatively $989 \pm 5 - i(18 \pm 4)$; and of Estabrooks *et al.*[7] of $997 - i5$, based on the reaction $\pi^-p \to \pi^+\pi^-n$. No errors are quoted by Estabrooks *et al.*, but the authors comment that in view of the large mass bin used the narrow width found may not be reliable.

Our results are therefore in surprisingly good agreement with the other determinations, given the simplicity of the model assumed and particularly the neglect of all interference effects. In support of this our $\pi\pi$ data show peaks near 980 MeV, in contrast with the near minima in the $\pi\pi$ scattering data.[2,3] Also the S^* cross section is large, with an approximate value for $d\sigma/dt$, extracted as described,[1] of 0.3 mb/(GeV/c)^2 which is about 3 times that of the X^0 or φ.

We acknowledge discussions with D. Morgan.

[1]D. M. Binnie *et al.*, Phys. Rev. D 8, 2789 (1973).

[2]M. Alston-Garnjost *et al.*, Phys. Lett. 36B, 152 (1971); S. M. Flatté *et al.*, Phys. Lett. 38B, 232 (1972).

[3]G. Grayer *et al.*, in *Experimental Meson Spectroscopy*, AIP Conference Proceedings No. 8, edited by K. W. Lai and A. H. Rosenfeld (American Institute of Physics, New York, 1972), p. 5.

[4]J. S. Ball *et al.*, Phys. Rev. Lett. 28, 1143 (1972).

[5]S. D. Protopopescu *et al.*, Phys. Rev. D 7, 1279 (1973).

[6]Reported by W. Ochs, in *$\pi\pi$ Scattering and Associated Topics*, AIP Conference Proceedings No. 13, edited by P. K. Williams and V. Hagopian (American Institute of Physics, New York, 1973).

[7]Reported by A. D. Martin, in *$\pi\pi$ Scattering and Associated Topics*, AIP Conference Proceedings No. 13, edited by P. K. Williams and V. Hagopian (American Institute of Physics, New York, 1973).

ERRATUM

SCALING FUNCTION FOR CRITICAL SCATTERING. Michael E. Fisher and Amnon Aharony [Phys. Rev. Lett. 31, 1238 (1973)].

On page 1240, the nineteenth line should read: "... continuous spin, us^4 Hamiltonian ... ."

On page 1241, Ref. 22, the first sentence should end with "... explicitly confirmed through the coefficient $\frac{1}{8}$ of $\ln(r/\Lambda^2)$ in the expression for $K(0, r)$."