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$K\bar{K}\pi$ RESONANCE AT 1280 MeV*

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The $K\bar{K}(n\pi)$ final states produced by annihilation of stopped antiprotons have been analyzed systematically by Armenteros et al.[1] They observed a strong enhancement at $M \simeq 1410$ MeV with $\Gamma \simeq 60$ MeV in the effective-mass distribution for the neutral $K\bar{K}\pi$ combinations from the reactions

$$\bar{p}+p \to K_1^0 + K^\pm + \pi^\mp + \pi^{+,0} + \pi^{-,0}$$

and

$$\to K_1 + K_{1,2} + \pi^0 + \pi^+ + \pi^-.$$

Since no analogous effect was apparent in either the singly or doubly charged combinations also accessible, they concluded that the enhancement at 1410 MeV most likely resulted from the production and subsequent decay of an unstable state (E meson) with isotopic spin $I=0$; no determination of J^P was possible.[1] In this Letter we report the observation of a similar enhancement in the $K\bar{K}\pi$ systems produced in π^-p interactions. The same final states show an additional peak in the neutral $K\bar{K}\pi$ combinations at $M = 1280 \pm 10$ MeV. We interpret this peak as evidence for a new $I=0$ state (D meson) and discuss possible I^GJ^P assignments.

In a continuing study of resonant states produced in π^-p interactions over the momentum interval 1.7 to 4.2 BeV/c, we have obtained 1062 events whose best fits are to the hypotheses

$$\pi^- + p \to K^+ + \bar{K}^0 + \pi^- + n, \tag{1a}$$

$$\to K^0 + K^- + \pi^+ + n, \tag{1b}$$

$$\to K^0 + \bar{K}^0 + \pi^- + p, \tag{1c}$$

$$\to K^0 + K^- + \pi^0 + p, \tag{1d}$$

$$\to K^+ + K^- + \pi^- + p. \tag{1e}$$

These final states are of particular interest since they may represent important decay modes for unstable mesons whose decay into two or three pions is forbidden. The data are summarized in Table I. In all cases track ionization on the film was checked for consistency with the calculated fits.

Table I. Momentum distribution for final states used in this analysis.

Final state	Momentum interval (BeV/c) 1.8 to 2.7	2.7 to 3.3	3.8 to 4.3	1.8 to 4.3
$K^+\bar{K}^0\pi^-n$	31	137	77	245
$K^0K^-\pi^+n$	8	116	92	216
$K^0\bar{K}^0\pi^-p$	20	159	103	282
$K^0K^-\pi^0p$	15	129	60	204
$K^+K^-\pi^0p$	9	76	30	115

The $M(K\bar{K}\pi)$ distribution for the charged com-

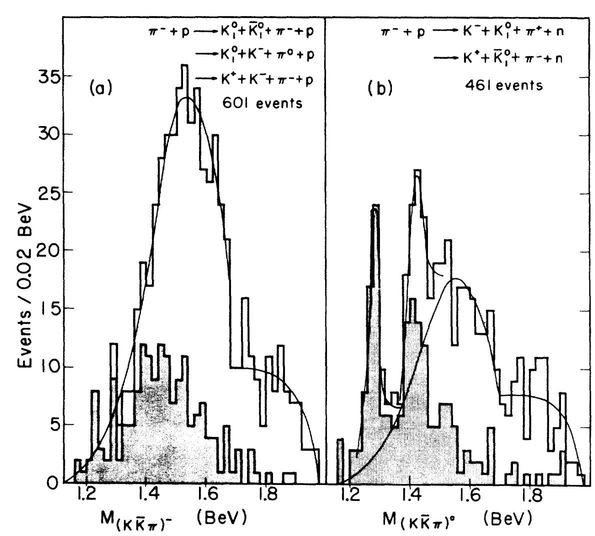

FIG. 1. Effective mass distributions for the charged and neutral $K\bar{K}$ combinations. To illustrate the difference in structure, events with $M(K\bar{K}) \leq 1.1$ BeV are shown separately in the shaded areas.

binations is shown in Fig. 1(a). No significant evidence for structure is apparent. For later use a smooth curve has been drawn arbitrarily through the experimental points; the curve differs little from a phase-space distribution averaged over the momentum interval studied.

The experimental $M(K\bar{K}\pi)$ distribution for the neutral combinations is plotted in Fig. 1(b). To provide some estimate for background, the smooth curve drawn through the charged distribution was renormalized to the number of neutral events with $M(K\bar{K}\pi)$ greater than 1500 MeV. However, the exact normalization is not important for the following discussion; we need only establish the approximate slope of the background below 1500 MeV. Two well-defined peaks are then apparent. To emphasize the difference in structure between the charged and neutral combinations, events with $M(K\bar{K}) \leq 1.1$ BeV are shown separately in Figs. 1(a) and 1(b). Using a Breit-Wigner resonance curve to fit the upper peak, we obtain $M = 1420 \pm 10$ MeV and $\Gamma = 60 \pm 10$ MeV, in adequate agreement with the values reported by Armenteros et al. for the E meson.[1] If the E meson represents a state with definite I^GJ^P, the lack of any enhancement in the charged $K\bar{K}\pi$ distribution supports the $I=0$ assignment.

In addition to the E meson, 59 events are observed in the interval 1280 ± 40 MeV, where ~9 were expected; the probability that this represents a statistical fluctuation is negligible. We have investigated two sources of background that might contribute to this peak. Approximately one-third of the events provide an acceptable fit ($\chi^2 \leq 6.0$; one constraint) to the $\Lambda\pi^+\pi^-K^0$ or $\Sigma^0\pi^+\pi^-K^0$ hypothesis with an unobserved Λ or Σ^0; although an examination of ionization indicates that these fits are unlikely, they cannot always be unambiguously excluded. To determine the effect of contamination due to misidentified Λ(or Σ^0)$\pi^+\pi^-K_1^0$ events, 340 cases in which both the Λ and K^0 decayed via the charged modes were refitted to hypotheses (1a) to (1d) after deletion of the Λ-decay tracks. For selection criteria identical to those in the original sample, 44 events fit the $K_1K^\pm\pi^\mp$ hypotheses; the $M(K\bar{K}\pi)$ distribution for these events shows no peak at either 1280 or 1420 MeV. The second possibility for contamination arises from $\Sigma^\pm\pi^\mp(\pi^0)K_1^0$ events in which the $\Sigma^\pm$ decay occurs too close to the production vertex for identification. The effect of such events was checked by taking 456 events in which the $\Sigma^\pm$ was clearly visible and fitting the $\Sigma^\pm$-decay pion with the associated $\pi^\mp K_1^0$ to the $nK_1K^\pm\pi^\mp$ hypotheses. The selection criteria yielded 35 events with adequate fits; the $M(K\bar{K}\pi)$ distribution for these events again shows no enhancements. We conclude that the low-mass peak represents a valid effect in the $K\bar{K}\pi$ system.

With the assumption that the peak results from production and decay of a state with definite I^GJ^P, the absence of any effect in the charged combinations strongly suggests $I=0$. A Breit-Wigner curve fitted to the data gives $M = 1280 \pm 10$ MeV and $\Gamma = 40 \pm 10$ MeV. The resolution function for events in the peak indicates that measurement errors are less than 10 MeV; consequently, the observed width probably approximates the true width, and decay occurs through the strong interactions.[2] In this case there is no change in G parity during decay.

Possible spin and parity assignments may be inferred from the experimental decay correlations. In general, we have $G = (-1)^{l+I}$ for a $K\bar{K}$ system with relative angular momentum l. Consequently, G is +1 (or −1) for the $K_1K^\pm\pi^\mp$ system if the state contains only even (odd) relative $K\bar{K}$ angular momenta. Phenomenological matrix elements may be expressed in terms of the $K\bar{K}\pi$ center-of-mass momenta, $\vec{p}_K$, $\vec{p}_{\bar{K}}$, and $\vec{p}_\pi$, with $\vec{p} = \vec{p}_K - \vec{p}_{\bar{K}}$. The lowest-order terms for $J \leq 2$ are summarized in Table II.[3] The features of the matrix elements (in particular, the zeros) are determined from the symmetries implied by I^GJ^P; strong interactions among particles in the final states can result only in multiplicative functions symmetric in p_K^2 and $p_{\bar{K}}^2$. Angular distributions in $\cos\theta = \vec{p}\cdot\vec{p}_\pi$ are evaluated in the $K\bar{K}$ center of mass. For comparison with the experimental distributions, the matrix elements have been integrated over

Table II. Lowest-order decay matrix elements squared for the $K\bar{K}\pi$ system, neglecting effects other than centrifugal barriers; $\vec{p}$ is the relative $K\bar{K}$ momentum and $\vec{p}_\pi$ the pion momentum. Angular correlations are calculated in the $K\bar{K}$ center of mass, where $\cos\theta = \vec{p}\cdot\vec{p}_\pi$.

J^P	$G=+1$	$G=-1$
0^-	1	$p^2p_\pi^2\cos^2\theta$
1^+	p_π^2	p^2
1^-	$p^4p_\pi^4\sin^2\theta\cos^2\theta$	$p^2p_\pi^2\sin^2\theta$
2^+	$p^4p_\pi^2\sin^2\theta$	$p^2p_\pi^4\sin^2\theta$
2^-	$\lvert a\rvert^2p^4 + \lvert b\rvert^2p_\pi^4 + \mathrm{Re}\,a^*bp^2p_\pi^2(3\cos^2\theta-1)$	$p^2p_\pi^2(1+\frac{1}{3}\cos^2\theta)$

the mass and width of the resonance, keeping the appropriate variable fixed.

The observed distribution in $\cos\theta$ is plotted in Fig. 2(a). To reduce possible background, we have used only the 44 events produced at incident momenta above 2.7 BeV/c with 1260 $\leq M(K\bar{K}\pi) \leq 1310$ MeV.[4] The distribution suggests no tendency towards a zero at either $\cos\theta = 0$ or ±1, consistent with $I^GJ^P = 0^+0^-, 0^+1^+$, 0^+2^- or $0^-1^+, 0^-2^-$. The $M(K\bar{K})$ distribution for the same events is given in Fig. 2(b). The strong accumulation of events at low $M(K\bar{K})$ appears incompatible with either the phase-space distribution expected for $J^P = 0^-$ or the $K\bar{K}$ centrifugal barrier required for any of the $G = -1$ matrix elements. Consequently, when fitted to the matrix elements in Table II, the most likely assignments are $I^GJ^P = 0^+1^+$ or 0^+2^- (with $a \equiv 0$).

To obtain a better fit to the data we have examined possible modifications of the matrix elements. Although the maximum effective mass for the $K\pi$ system is only 785 MeV, all matrix elements were recalculated taking into account the strong P-wave $K\pi$ (K^*) interaction. In general, this resulted in a slight enhancement of the low $K\bar{K}$ region; calculated curves including this effect are shown in Fig. 2 for $I^GJ^P = 0^+1^+$ and 0^-1^+.

The matrix elements may be more drastically modified by inclusion of a strong $I = 1$ S-wave $K\bar{K}$ interaction. The existence of a strong threshold K_1K_1 enhancement is well known from studies of the reaction $\pi^- + p \to K_1 + K_1 + n$.[5,6] Although no analogous enhancement has been observed in the associated $K^-K_1^0p$ events, it is important to note that the $K\bar{K}$ systems appear to be produced in peripheral collisions involving pion exchange; consequently, only the sequence $I^GJ^P = 0^+0^+, 1^+1^-, 0^+2^+, \cdots$ is copiously produced. Alternatively, the $K^{\pm}K_1\pi^+$ systems produced in annihilation of stopped antiprotons have been studied by Armenteros et al.[7]; in this case a strong peak is observed in the region $M(K^{\pm}K_1) \simeq 1020$ MeV.[1] These results suggest that both the $I^GJ^P = 0^+0^+$ and $1^-0^+K\bar{K}$ systems interact strongly near threshold.[8] When such an effect is included in the matrix elements for the $I^GJ^P = 0^+0^-$, 0^+1^+, or 0^+2^- states, the calculated curves may be brought into good agreement with the experimental distributions.

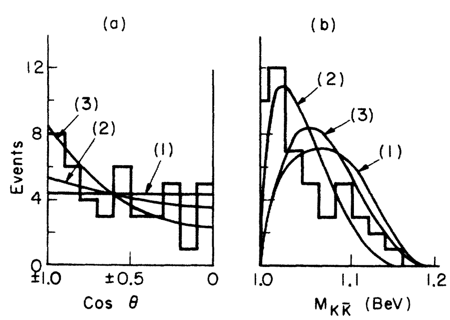

FIG. 2. (a) Angular correlation for neutral $KK\pi$ combinations in the mass interval 1260 to 1310 MeV; (b) the $K\bar{K}$ effective-mass distribution for the same events. The calculated curves represent the expected correlations for (1) phase space, (2) $I^GJ^P = 0^+1^+$, and (3) $I^GJ^P = 0^-1^+$. In (2) and (3) the effects of the strong p-wave $K\pi$ interaction have been taken into account. See text for details.

We conclude that the neutral $M(K\bar{K}\pi)$ effective-mass distributions provide unambiguous evidence for the existence of a new $I = 0$ unstable state (D meson) at $M = 1280 \pm 10$ MeV with $\Gamma = 40 \pm 10$ MeV. The data suggest $I^GJ^P = 0^+1^+$ or 0^+2^-; if a strong $I^GJ^P = 1^-0^+K\bar{K}$ interaction is introduced, the assignment $I^GJ^P = 0^+0^-$ also fits the observed $K\bar{K}\pi$ distributions.[9] The tentative assignment $I^G = 0^+$ implies the existence of the decays $D \to K_1 + K_1 + \pi^0$ and $D \to K_2 + K_2 + \pi^0$; the decay $D \to K_1 + K_2 + \pi^0$ is forbidden. In addition, decay into either 2π or 3π final states is forbidden for the preferred assignments; the decay $D \to \pi + \pi + \eta$ is allowed.

We are indebted to our scanners and measurers, in particular, T. Bonk, who made this work possible. The film was exposed in a beam designed collaboratively between the Goldhaber-Trilling and Alvarez groups. We thank especially Dr. John Kadyk, Dr. George H. Trilling, and Dr. Joseph J. Murray for their numerous contributions. It is a pleasure to acknowledge the support and encouragement of Professor Luis Alvarez throughout the course of this experiment.

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[2]This resolution is obtained because of the low Q for events in the region $M(K\bar{K}\pi) \sim 1280$ MeV; in addition,

all particles that comprise the neutral $K\bar{K}\pi$ system are observed and measured. To check for systematic mass shifts, we examined the effective-mass ideogram for each momentum interval separately; within statistics no mass shifts were observed.

[3]Phenomenological matrix elements for three-particle systems are discussed systematically by C. Zemach, Phys. Rev. 133, B1202 (1964).

[4]Events in the peak are produced over a large range of momentum transfer to the neutron. Since the relative phase space available for low-mass $K\bar{K}\pi$ systems is reduced at higher incident π^- momentum, background is reduced by rejecting events with $p_\pi < 2.7$ BeV/c.

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[7]Since no effect was observed in the corresponding $K_1K_1\pi^0$ events, Armenteros et al.[1] have suggested that the $K^\pm K_1$ peak has $I^GJ^P = 1^+1^-$. In this case, the peak represents a resonant state with allowed decay into $\pi\pi$ and, consequently, production in π^-p interactions. Although an anomalously small coupling to the $\pi\pi$ system could account for the absence of this effect in π^-p interactions, interpretation as an $I=1$ S-wave enhancement appears consistent with the $\bar{p}p$ data. Since both the $I=0$ and $I=1$ $K\bar{K}$ combinations contribute to the $K_1K_1\pi^0$ events, the expected K_1K_1 enhancement may be reduced by a partial cancellation in the two strongly interacting S waves.

It is not possible to determine whether these S-wave interactions are strong enough to produce either an $I=0$ or $I=1$ bound state of the type discussed by R. Dalitz, Phys. Rev. Letters 6, 239 (1961).

[8]It is interesting to note that should the possible $I^GJ^P = 0^+1^+$ assignment be verified in subsequent experiments, a strong $I=1$ S-wave $K\bar{K}$ interaction together with the P-wave $K\pi$ interaction provides a possible dynamical basis for such a state. An $I=0$ $K\bar{K}\pi$ system requires $I=1$ for all $K\bar{K}$ pairs; the $J^P=1^+$ configuration permits the maximum interaction in the $K\pi$, $\bar{K}\pi$, and $K\bar{K}$ pairs simultaneously. If the strong $K\bar{K}$ interaction were in the 1^+1^- state (reference 7), this model would lead to a 0^+1^- $K\bar{K}\pi$ state in complete analogy with the ω meson. The observed decay correlations are in strong disagreement with this assumption.

[9]The possibility that the D meson is part of an SU(3) octet may be considered. The $A_1(1080)$ remains the only $I^G=1^-$ enhancement reported in this mass region. Although there is little direct evidence that this enhancement represents a meson state with definite J^P, use of the Gell-Mann–Okubo mass formula leads to the expectation of an $S=\pm1$ state at ~1230 MeV. Whether the $K\pi\pi$ enhancement in this mass region reported by Armenteros et al.[1] is to be identified with such a state remains to be determined.

INDICATION OF A 0^+, $T=0$ 2π RESONANCE AT 720 MeV*

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Recent theoretical work has resulted in important methods of grouping strongly interacting particle states according to various symmetry groups. It is a further problem to relate groups with different spin and parity numbers. In this connection, it is of considerable interest to identify meson states or multiplets with low values of spin, J. Although nine pseudoscalar mesons are known at present, no scalar mesons have yet been clearly identified.

A 0^+ meson state, if of zero strangeness and even G parity, should show itself as a resonance in $\pi\pi$ scattering. The single-pion-production process, using pions incident on nucleons, has been extensively studied as a means of obtaining information on $\pi\pi$ scattering and resonances.[1-5] In the study of the $\pi^-\pi^+$ system, through this reaction, a strong forward-backward (F-B) asymmetry has been found in the "$\pi\pi$ scattering angle" distribution, in the ρ mass region ($M_{\pi\pi}$ ~ 650 to 850 MeV).[6-9] At sufficiently high beam energies, this asymmetry is clearly not due

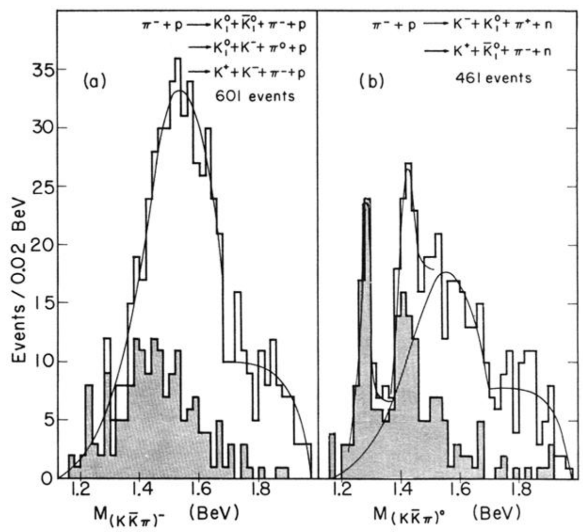

FIG. 1. Effective mass distributions for the charged and neutral $K\bar{K}$ combinations. To illustrate the difference in structure, events with $M(K\bar{K}) \leq 1.1$ BeV are shown separately in the shaded areas.