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PHYSICAL REVIEW D VOLUME 7, NUMBER 7 1 APRIL 1973

Properties of $K\bar{K}$ and $K\bar{K}\pi$ Systems and Diffraction Dissociation*

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We present data on the $K\bar{K}$ system which is produced in the interaction of 7-GeV/c pions with nucleons. The neutral $K\bar{K}$ system is produced with a relatively large cross section, and the characteristics of the reaction seem consistent with one-pion exchange. The charged $K\bar{K}$ system is produced with a smaller cross section and is not dominated by one-pion exchange. The neutral $K\bar{K}$ system is dominated by an S-wave $K\bar{K}$ interaction up to a dikaon mass of about 1.3 GeV/c^2. If one examines the neutral $K\bar{K}$ system produced in conjunction with a π meson, the characteristics of the interaction seem to indicate diffraction dissociation as the production mechanism. The cross section for production of $\pi+(K\bar{K})^0$ is of the order of 150 μb. The system consisting of $\pi+(K\bar{K})^\pm$ is dominated by a K^+K^{*-} amplitude. The cross section for the production of the $\pi(K\bar{K})^\pm$ system is four or five times smaller than for the $\pi(K\bar{K})^0$ system. Both the $\pi(K\bar{K})^0$ and the $\pi(K\bar{K})^\pm$ systems seem to be diffractively produced.

This paper contains discussion of the $K\bar{K}$ and $\pi K\bar{K}$ systems formed in π-nucleon collisions at 7 GeV/c. We discuss these two systems together since they are intimately related. The $K\bar{K}$ system can have isospin 0 or 1 and can be in natural-parity states of 0^+, 1^-, 2^+, 3^-, etc. We are concerned primarily with states that can be reached by one-pion exchange since these states will be made with relatively large cross sections in π-nucleon collisions. We are particularly concerned with the $I=0$, $J^P=0^+$ system.

I. EXPERIMENTAL PROCEDURE

These events were collected in the course of several experiments on π^--p and π^+-d experiments at or close to 7 GeV/c. All but the Ohio University part were done in the MURA-ANL 30-in. bubble chamber. The list of reactions is given in Table I.

V's were done in the standard bubble-chamber fashion. The V's were measured and the identification was done as a result of hypothesis test. Reactions involving only charged K's were found by hypothesis test without requirement of any signature of a strange particle. In the case of reactions (3), (5), (7), (8), and (9) ionization measurements were made with a vidicon device if the possibility of checking the particle identity existed. The separation of these events seems to be quite good (background <10%).

II. $K\bar{K}$ SYSTEM

In Figs. 1–3 we show the $K\bar{K}$ spectra for cases without and with an additional π. In Fig. 1 we show a summary of $(K^0\bar{K}^0)$ mass spectra obtained from the publication of Fischer and Beusch *et al.*,[1] from the present work,[2] and published work by Crennell *et al.*[3] Figure 2 shows $(K\bar{K})^0$ spectra obtained from the reactions reported here. Figure 3 shows the K_1^0-K_1^0 mass spectrum for the inclusive class of reactions $\pi^- p \to K_1^0 K_1^0 + ?$. The mass spectra close to the $K\bar{K}$ threshold seems to show a prominent S^* (mass ~1070 MeV/c^2). A description

TABLE I. $K\bar{K}$ cross sections.

	Reaction	No. of events	σ in μb
(1)	$\pi^- p \to K_1^0 K_1^0 n$	61	14^{+10}_{-3}
(2)	$\to K^- K_1^0 p$	104	34 ± 5
(3)	$\to K^- K_1^0 \pi^0 p$	110	34 ± 5
(4)	$\to \pi^- K_1^0 K_1^0 p$	61	78 ± 15 (4)–(5)
(5)	$\to \pi^- K_1^0 (K_u^0) p$	191	
(6)	$\to \pi^- K^+ K^- p$	187	55^{+20}_{-5}
(7)	$\pi^+ d \to K^+ + K^- + p + p$	456	75 ± 6
(8)	$\to K^+ + K^- + \pi^0 + p + p_s$	151	63 ± 7
(9)	$\to K^+ + K^- + \pi^+ + n + p$	170	100 ± 20
(10)	$\to K^+ + K^0 + p + n$	78	34 ± 5
(11)	$\to K_1^0 + K^0 + p + p_s$	128	56 ± 10
(12)	$\to K^+ + K_1^0 + \pi^- + p + p_s$	71	34 ± 5
(13)	$\to K^0 + K^- + \pi^+ + p + p_s$	68	34 ± 5
(14)	$\to K_1^0 + K_1^0 + \pi^0 + p + p_s$	11	14 ± 5
(15)	$\to K_1^0 + K_1^0 + \pi^+ + p + n_s$	71	100 ± 20

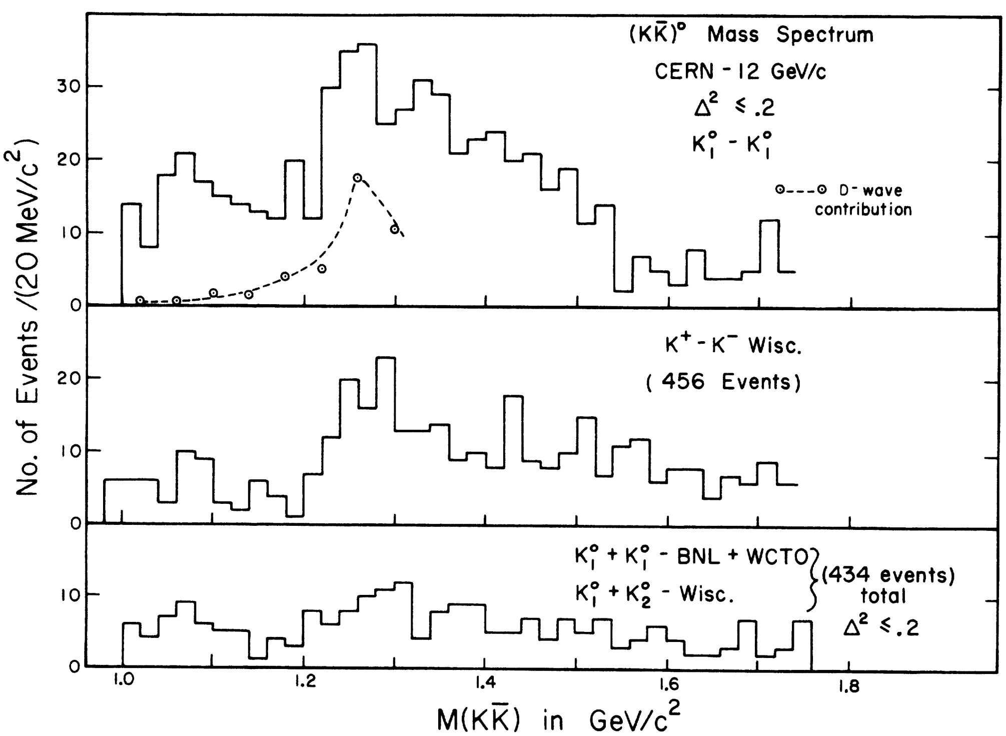

FIG. 1. Spectra of $(K\bar{K})^0$ taken from reactions $\pi^- + p \to K_1^0 + K_1^0 + n$, $\pi^+ + d \to K^+ + K^- + p + p_s$, and $\pi^+ + d \to K_1^0 + K^0 + p + p_s$.

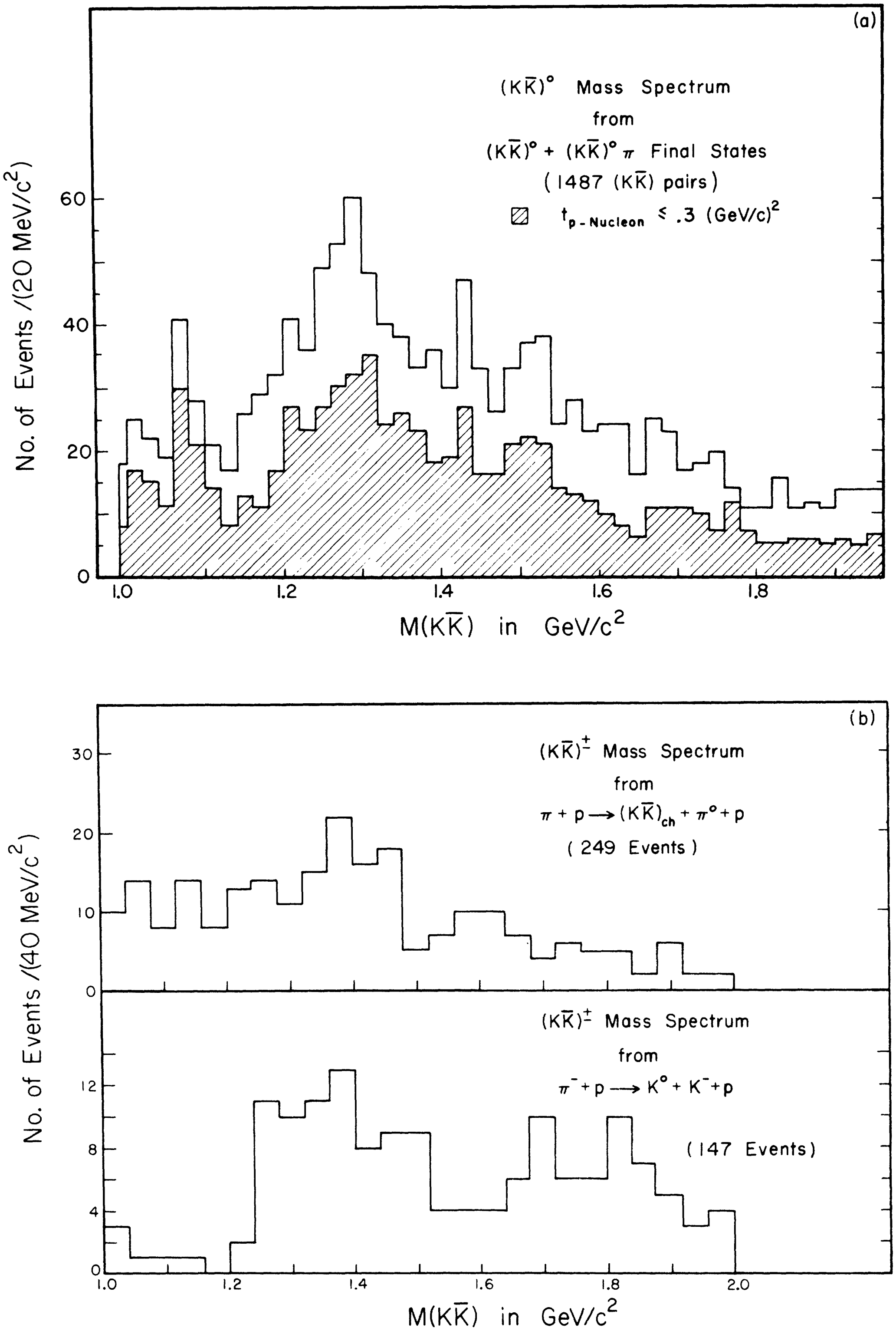

FIG. 2. (a) $(K\bar{K})^0$ spectrum taken from reactions $\pi^- + p \to (K\bar{K})^0 + n$, $\pi^- + p \to (K\bar{K})^0 + \pi^- + p$, $\pi^+ + d \to K^+K^- + p + p_s$, $\pi^+ + d \to (K\bar{K})^0 + \pi^0 + p + p_s$, and $\pi^+ + d \to (K\bar{K})^0 + \pi^+ + p + n_s$. (b) $(K\bar{K})_{ch}$ mass spectrum taken from reactions $\pi^- + p \to K^- + K^0 + \pi^0 + p$, $\pi^+ + d \to K^{\pm}K^0 + \pi^{\mp} + p + p_s$, $\pi^- + p \to K^- + K^0 + p$, and $\pi^+ + d \to K^+K^0 + p + n_s$.

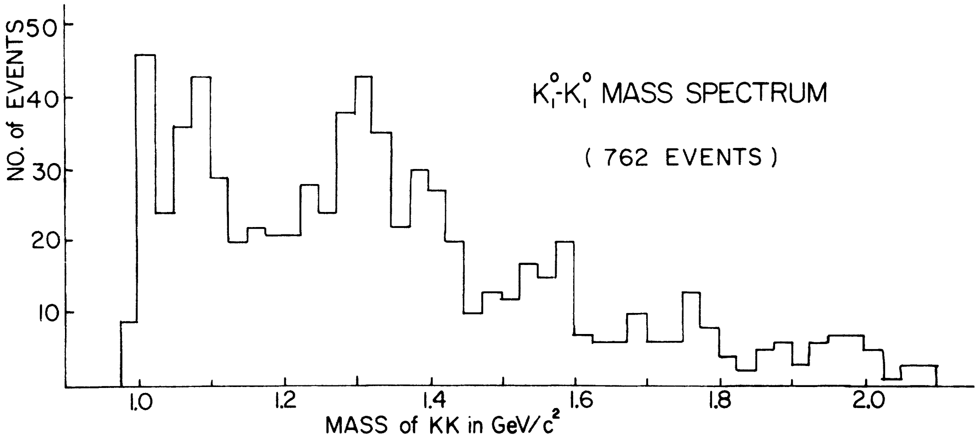

FIG. 3. $K_1^0 K_1^0$ mass spectrum taken from reactions π + nucleon→$K_1^0+K_1^0$+anything.

of this mass region solely in terms of a scattering length or a resonance at 960 does not fit the data well, as can be seen in the paper of Protopopescu *et al.*[4] We believe it is probable that there is an additional resonance at 1070 MeV/c^2. What is meant by "resonance" must be discussed in terms of the Argand diagram for the $I=0$, S-wave, π-π amplitude.[4,5] In fact, the whole $(K\overline{K})^0$ mass spectra up to a mass of about 1.3 GeV/c^2 is dominated by the S wave. This is apparent from looking at the angular distributions shown by Beusch, and also shown in Fig. 4 from our neutral $K\overline{K}$ state. By using the angular distribution given by Beusch, we have estimated the D-wave contribution as shown in Fig. 1. We find no appreciable asymmetry in the K^+K^- in the 1.0–1.4-GeV/c^2 mass range which shows the lack of very much P wave in the $K\overline{K}$ system (or at least P-wave dikaon produced with 0 helicity). We estimate a branching ratio of $f^0\to\overline{K}K$ of $(3.5\pm0.7)\%$ on the basis of the observed angular distributions. So far as our discussion of the $\pi K\overline{K}$ system is concerned, we note this dominance of the $I=0$, S wave in the $K\overline{K}$ system in the 1.0–1.3-GeV/c^2 mass range. The cross section for the production of $K^+K^-+K^0\overline{K}^0$ is 130 ± 20 μb as compared to 34 ± 5 μb for the production of K^-K^0, which clearly shows the dominance of the $I=0$, $K\overline{K}$ system.

III. $\pi K\overline{K}$ SYSTEM

In Table I we have listed the reactions that we tabulated in these experiments which involve a $K\overline{K}$ plus a pion. An important fact that we note is that for the π^--p interactions that the reactions of the type

$$\pi^- + p \to \pi^- + (K\overline{K})^0 + p \quad (153\pm20\ \mu\text{b})$$

have a cross section about four times as large as the reaction

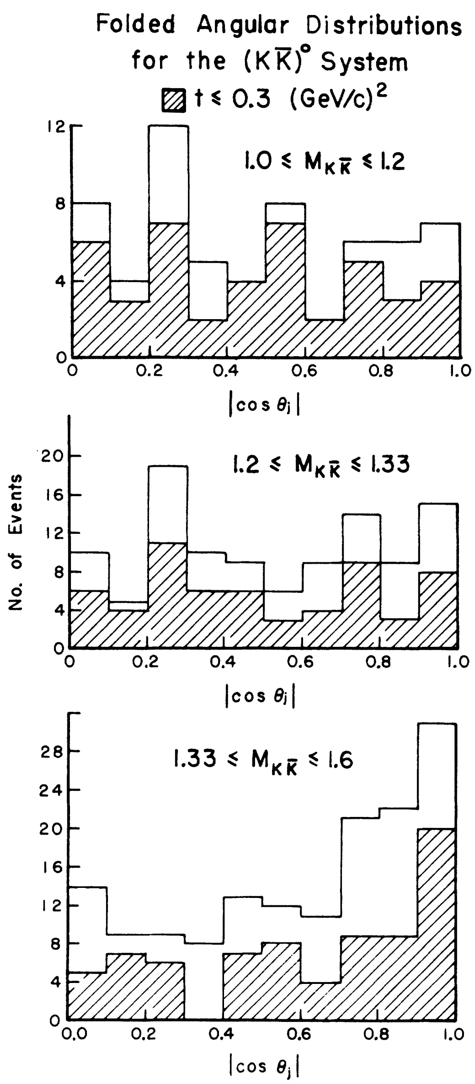

FIG. 4. Folded Jackson angular distributions of K^+K^- and K^0K^0.

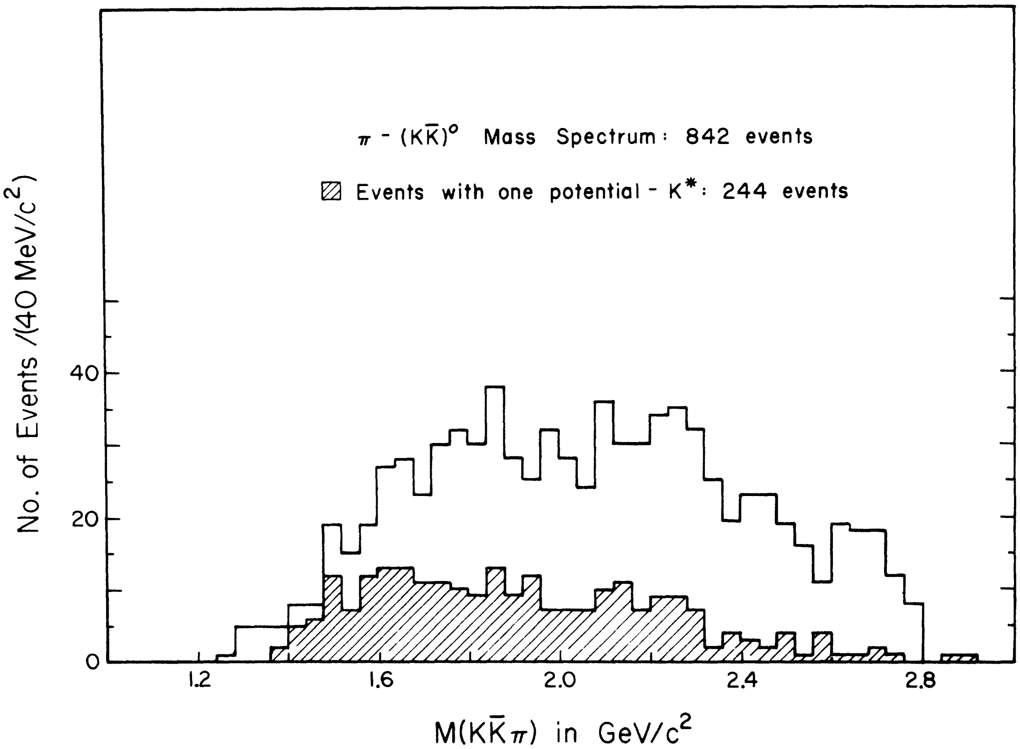

FIG. 5. $\pi_{ch}\,(K\bar{K})^0$ mass distribution. The cross-hatched events show the mass spectrum of events showing a K^* or $\bar{K}^*$.

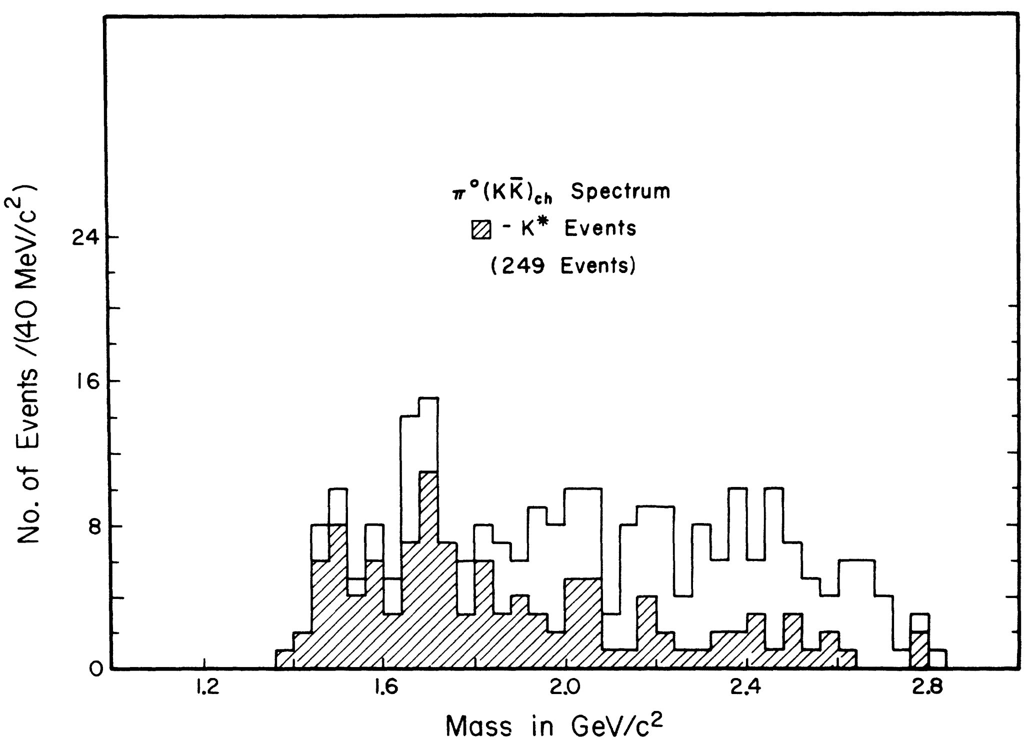

FIG. 6. $\pi^0(K\bar{K})_{ch}$ mass distribution. The cross-hatched events show the mass spectrum of events showing a K^* or $\bar{K}^*$.

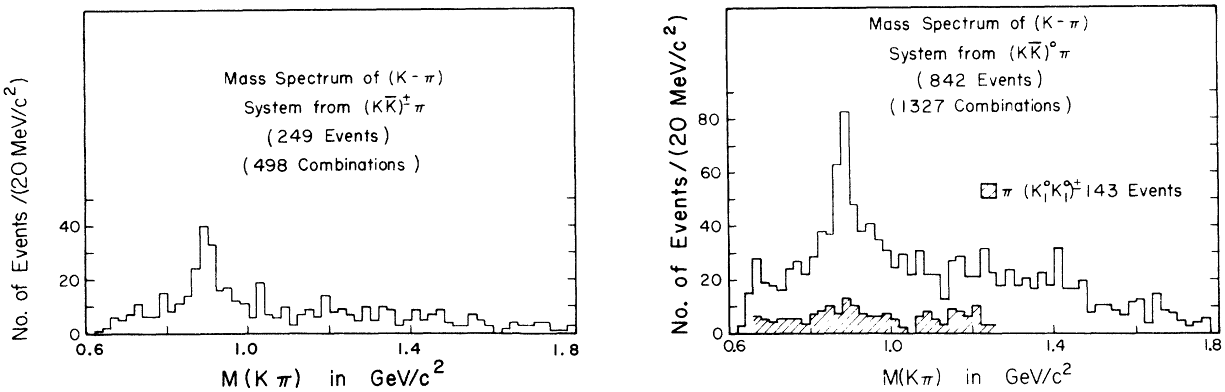

FIG. 7. K-π mass spectrum for combinations that have $I_z = \pm\frac{1}{2}$.

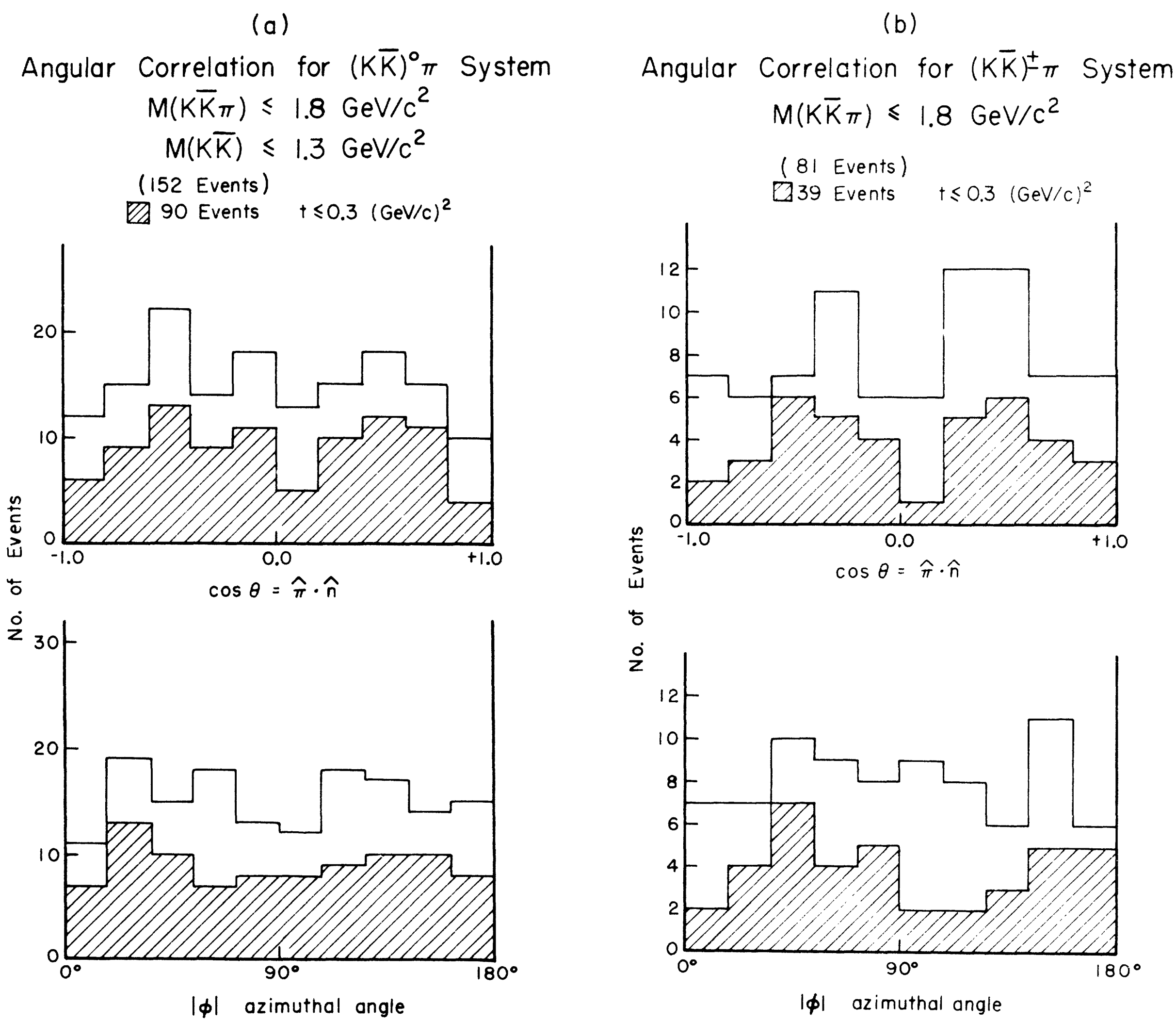

FIG. 8. Distribution of the values of $\hat{n}\cdot\hat{\pi}_i$. $\hat{n}$ is the normal to the $K\bar{K}\pi$ decay plane and $\hat{\pi}_i$ is the direction of the incoming π in the $K\bar{K}\pi$ rest frame. ϕ is the angle similar to the Treiman-Yang angle in the 2-body case. (a) $M((K\bar{K})^0) \leq 1.3$ GeV/c^2, $M(K\bar{K}\pi) \leq 1.8$ GeV/c^2. (b) $M((K\bar{K})^{\pm}\pi) \leq 1.8$ GeV/c^2.

$\pi^- + p \to \pi^0 + (K\bar{K})^- + p$ $(34 \pm 5\,\mu b)$.

The reason for this probably again has to do with the importance of the $I = 0$, $K\bar{K}$ state. In Fig. 5 we show the mass spectra for the $(K\bar{K})^0\pi^\pm$ system. The $\pi(K\bar{K})^\pm$ mass spectra is shown in Fig. 6. The spectrum for the charged $K\bar{K}$ combination shows only a hint of A_2 and nothing else. The neutral $(K\bar{K})$ spectrum shows the features noted before which, in the case of the $K\bar{K}\pi$ system, is dominated by the low-mass $K\bar{K}$ system. In Fig. 7 we show the K-π (and $\bar{K}$-π) spectra which have $I_z = \pm\frac{1}{2}$. The K^* may be seen prominently in both of these spectra. The K^* is very important in the $\pi^0(K\bar{K})^\pm$ cases [$(37 \pm 4)\%$ of the cases] and less so in the $\pi(K\bar{K})^0$ cases [$(19 \pm 4)\%$ of the cases]. The $K_1^0K_1^0\pi$ cases show only a $(13 \pm 3)\%$ branching ratio into $K^*K_1^0$. The fact that the $\pi(K\bar{K})^0$ system shows less K^* we attribute to the dominance of the $\pi + (K\bar{K})_{I=0}$ system. As pointed out in our discussion of the $K\bar{K}$ system, the S wave dominates the $(K\bar{K})^0$ up to a mass of ~1.3 GeV/c^2. If one adds an S-wave π to the $(K\bar{K})$ system, then one has an $I = 1$, $J^P = 0^-$ system (a system of negative G parity). The angular correlations observed are all consistent with such an assignment. In Fig. 8 we show the angular distribution $\hat{\pi}_i \cdot \hat{n}$ where $\hat{\pi}_i$ is the unit vector in the direction of the incoming π and $\hat{n}$ is the normal to the decay plane of the $K\bar{K}\pi$ system. The distribution is quite consistent with isotropy which indicates a $J = 0$. Likewise, one can examine the Jackson angle of the decay π relative to the incoming π. This also is consistent with isotropy and hence a 0^- assignment for the system consisting of $\pi(K\bar{K})^0$. In Fig. 8 we also show the same angular correlation for $(\bar{K}K^*)^\pm$ system. The $(\hat{\pi} \cdot \hat{n})$ distribution would be expected to show a $\sin^2\theta$ shape for a $J^P = 1^+$. The distribution is unfortunately inconclusive.

IV. DISCUSSION OF DIFFRACTION DISSOCIATION

The π is well known to have a large cross section for the production of a π-ρ system. The mass spectrum of the π-ρ system is peaked in the mass range of 1.1 GeV/c^2 and is known to have a J^P which is dominantly 1^+ and has a helicity of 0. We would expect by analogy that the π would also give rise to a $K\bar{K}^*$ system with a sizable cross section. We, indeed, see a strong K^* signal in the $K\bar{K}\pi$ system, the cross section for $\pi^- + p \to (K^*\bar{K})^- + p$ is 25 ± 5 μb. The $A_1 \to (\pi$-$\rho)$ system has a cross section for production of 2 mb. The main difference between the π-ρ and $\bar{K}$-K^* system is that the A_1 region is produced by what seems to be π exchange

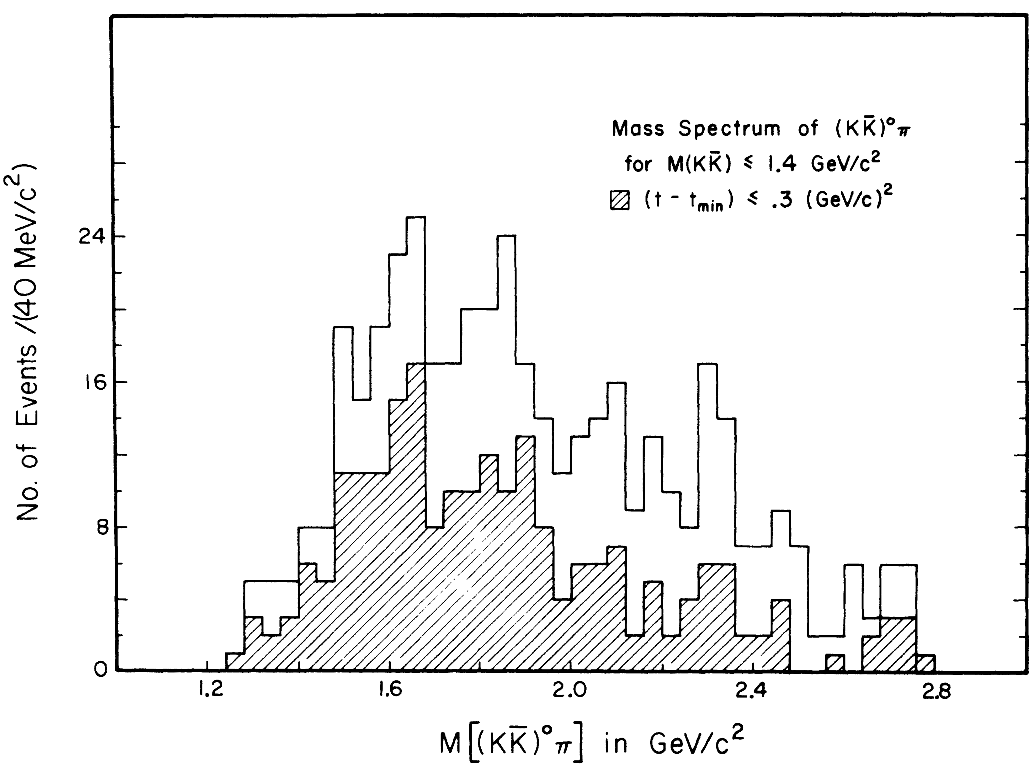

FIG. 9. $\pi(K\bar{K})^0$ mass spectrum when $M(K\bar{K}) \leq 1.4$ GeV/c^2. The mass spectrum is shown for a cut in $|t - t_{min}| \leq 0.3$.

with diffraction scattering of the π whereas the $\bar{K}$-K^* (or $\bar{K}^*$-K) system should be dominantly produced by K exchange. The expected cross section can be estimated from the width of the K^*. Taking into account the relative widths of the K^* and the ρ as well as the difference in range of interaction as a result of the π-K mass difference, we get a ratio of cross sections as follows:

$$\frac{\sigma(K\bar{K}^*+\bar{K}K^*)}{\sigma(\pi^0\rho^-+\rho^0\pi^-)}=\frac{3/4}{2}\left(\frac{m_\pi}{m_K}\right)^2$$
$$=0.03\ .$$

Thus we would expect to find a cross section in the neighborhood of 60 μb and we seem to find about $\frac{1}{2}$ of that. Differences in absorption of π-exchanged and K-exchanged processes could probably easily account for the difference.

We know of only one other process which shows diffractivelike characteristics and is likely to be dominated by one-kaon exchange. This is the process $K^+ + p \to K^+ + \phi + p$. This reaction has been observed by Bishop *et al.*[6] and more recently by a Berkeley group[7] with 13-GeV/c K^+. The cross section for this process is about 15 μb at 13 GeV/c.

The cross section for the reaction $\pi^- + p \to \pi^- + (K\bar{K})^0 + p$ is in the range 130–170 μb. If we make suitable cuts on the $\pi K\bar{K}$ system (requiring $M_{K\bar{K}} \le 1.4$ GeV/c^2, $M_{K\bar{K}\pi} \le 1.6$ GeV/c^2), we find characteristics similar to those shown by the reaction $\pi + p \to \pi + \rho + p$ and a cross section which is quite compatible with a Deck-type mechanism. The events are produced with a relatively small momentum transfer to the nucleon which is characteristic of Pomeranchukon exchange. These distributions are shown in Figs. 9 and 10. The $\pi^-(K\bar{K})^0$ system seems to be a 0^- system of $I=1^-$. It seems to be a very nice example of a $0^- \to 0^-$ transition produced in a diffractive fashion.

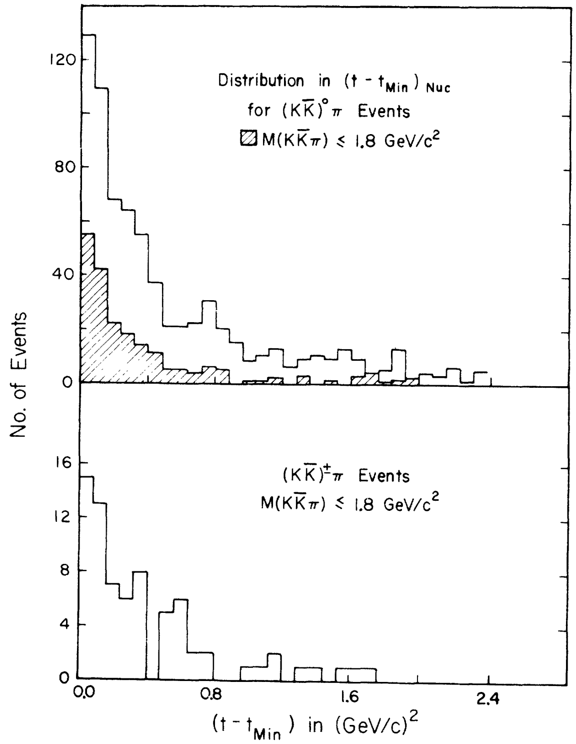

FIG. 10. $|t-t_{\min}|$ distribution for same mass cuts as in the previous figure.

V. CONCLUSIONS

The $(K\bar{K})^0$ system is dominated by an S wave up to a mass of about 1.3 GeV/c^2. Our $K\bar{K}$ and π-$K\bar{K}$ data are consistent with this result. The mass spectrum of $(K\bar{K})^0$ from $\pi + p \to K + \bar{K} + n$ and $\pi + p \to (K+\bar{K})^0 + \pi + p$ both show structure in the low-mass range which is not consistent with a scattering length as has been commented on previously. The S-wave $K\bar{K}$ interaction is important up to a mass value 1300 MeV/c^2 at least.

We seem to have observed the process $\pi \to K^*\bar{K}$ which is closely analogous to $\pi \to \pi + \rho$ (A_1 phenomena), but the former occurs with a much smaller cross section than the latter. The $(K\bar{K})^0\pi$ system shows features similar to the A_1 in that it is a system of negative-G parity and is produced with small momentum transfer. If anything, it is broader than the A_1 as would be expected since our $K\bar{K}$ system was selected to have a width of 300 MeV. The $\pi(K\bar{K})^0$ system seems to have the same quantum numbers as the π, and hence should be a very good example of diffraction dissociation of the π ($J^P = 0^- \to 0^-$).

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PHYSICAL REVIEW D VOLUME 7, NUMBER 7 1 APRIL 1973

Observation of Interference Effects in the Reaction $\pi^+ p \to \pi^+ p \pi^0$ *

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In the reaction $\pi^+ p \to \pi^+ p \pi^0$ at 2.67 GeV/c, the central value of the ρ mass peak and its width are found to vary as a function of position in the Dalitz plot. The major variations are associated with the crossover regions of ρp with diffractively produced $\pi^+(p\pi^0)$ and $\pi^+ N^*$ final states, and so have a natural interpretation in terms of interferences among these final states.

In a study of ρ^+ production in the reaction

$$\pi^+ p \to \pi^+ p \pi^0 \qquad (1)$$

at 2.67 GeV/c, the central value of the ρ mass peak and its width are found to vary as a function of position in the Dalitz plot.[1] These variations are associated with the crossover regions of the ρp final state with $\Delta\pi$, $N^*\pi$, and diffractively produced $\pi^+(p\pi^0)$ states, and so have a possible interpretation in terms of interferences among these final states. Such an interference of ρp with diffractive dissocation of the proton has been suggested by MacNaughton *et al.*,[2] as a means of accounting for a mass-dependent asymmetry in the dipion t-channel helicity (or Gottfried-Jackson) angular distribution, or, alternatively, a shift in the ρ mass as a function of this angle. Such effects have long been studied in terms of $\pi\pi$-scattering phase shifts, where this behavior is attributed to interference of an S-wave, $I=2$ amplitude with the resonant P-wave, $I=1$ state.[3,4] However, since the known exchanges in ρ production include, in addition to the pion quantum numbers, both isoscalar and isovector, natural- and unnatural-parity, nonzero-spin states,[1,3] and since the changes in apparent mass and width reported here are associated with the crossover in the Dalitz plot of ρp and πN^* states, it appears desirable to consider an interpretation in the context of the overall $\pi^+ p \pi^0$ production reaction. The analysis of Ref. 2 falls in this category. Those authors emphasize that their interpretation may well be equivalent to the one-pion-exchange (OPE) approach at the pion pole, and hence does not necessarily invalidate the determination of $\pi\pi$ phase shifts, provided the extrapolations involved are from a region of small enough momentum transfer. On the other hand, their model (to be discussed in more detail below) accounts in a natural way for some of the more striking features of the data to be reported here, features which are not adequately described by the known $\pi\pi$-scattering phase shifts.[2-4]

The present analysis is based on some 8400 events of reaction (1), obtained from a 300 000-picture exposure of the 25-in. hydrogen bubble chamber to a π^+ beam of 2.67-GeV/c momentum.[1] The Dalitz plot of these events, given in Fig. 1, shows that the dominant processes are the quasi-two-body production of ρp and $\Delta^{++}(1236)\pi^0$. Also apparent in the $\pi^0 p$ Chew-Low plot and mass-squared projection, Fig. 2, are small amounts of higher-mass N^*'s, and a broad distribution in mass from threshold to about 1700 MeV, produced at small momentum transfer. This latter distribution is identified as diffractive dissociation of the proton.[2,5]

Inspection of Fig. 1 gives a qualitative indication of the variation of the apparent mass and width of the ρ as a function of the ordinate of the plot. To quantify this observation, the plot has been divided into six segments (indicated by the horizontal lines in Fig. 1), and a maximum-likelihood fit of the apparent resonance parameters of the ρ has been made for each segment.[6] A description of the fitting procedure is given in Appendix I(a). The results of these fits are given in Table I(a), along with a list of the major crossing baryon states in