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Kaonic Annihilations of Antiprotons in Hydrogen at 7 BeV/c*

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Results are reported from an analysis of 80 000 pictures of 6.935-BeV/c antiprotons in hydrogen leading to final states of the form $K_1^0+K_1^0+m\pi$, $m=0,1,2\cdots$. Assuming equal probability for the various $K\bar{K}$ charged states, we find the cross section for the reaction $\bar{p}+p\to K+\bar{K}+m\pi$ to be 2.5±0.5 mb. A compilation of annihilation cross sections indicates that the kaonic-annihilation final states constitute approximately 10% of all annihilations from ~1.6–7 BeV/c. The production of $K^*(1400)$ has been observed, although the formation of other resonances such as $K^*(890)$, ω, and ρ is less copious at 7 BeV/c than at 3.7 BeV/c. A $K_1^0K_1^0$ enhancement near threshold is observed similar to that observed at lower-energy annihilation reactions.

I. INTRODUCTION

THIS paper reports the results obtained from a study of 6.935-BeV/c antiprotons annihilating in hydrogen leading to K and π mesons in the final state.[1] The data were obtained from 80 000 pictures taken with the 80-in. hydrogen bubble chamber exposed to a separated beam of antiprotons at the Brookhaven Alternating Gradient Synchrotron (AGS). Studies of the pion,[2] hyperon and antihyperon production[3] from the same sample of film have been reported in the literature.

In this experiment, only events with at least one visible kaon decay of the type $K_1^0\to\pi^+\pi^-$ were accepted for measurement. Because of the ambiguity of identifying charged kaons from pions for the single-vee events, only events with two visible K_1^0 decays were used in the analysis reported here.

II. EXPERIMENTAL METHOD

This experiment was performed at the AGS using the high-energy electrostatically separated beam (Beam 3)[4] in conjunction with the Brookhaven National Laboratory 80-in. liquid-hydrogen bubble chamber.[5] Details of the experimental procedure have been described elsewhere[6]; we sketch the essential features here.

Figure 1 shows the schematic layout of the experiment. Three 70-mm cameras were used to photograph particle interactions in the bubble chamber. During the experimental run, some of the light reflectors (retrodirective "coat-hangers") in the bubble chamber were dislocated and this reduced the effective chamber length to approximately 60 in. The magnetic field across the chamber was kept constant throughout the course of the experiment: the field at the chamber center was 20.2 kG, with ~10% variation over the chamber volume.[7]

The purity of the beam,[8] determined from a study of the δ-ray momentum spectrum produced by beam-like particles was (95±1)%. Using elastic scattering events,[8] the beam momentum at the beam entrance window was found to be 6.935 BeV/c, with a spread $\Delta p/p$ of about ±1%.

Half the sample of pictures was scanned and measured at Brookhaven National Laboratory, and the other half was processed at Yale University, using essentially the same techniques although the methods employed at the two institutions differed somewhat in detail. The measuring at Yale University, for instance, was accomplished by using two digitized measuring machines linked with a small computer, Digital Equipment Corporation's PDP-1. It served as an on-line monitoring device[9] which not only checked measuring errors but also performed a three-dimensional recon-

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[1] For the sake of brevity, we will refer to the beam momentum as 7 BeV/c in the rest of this paper.

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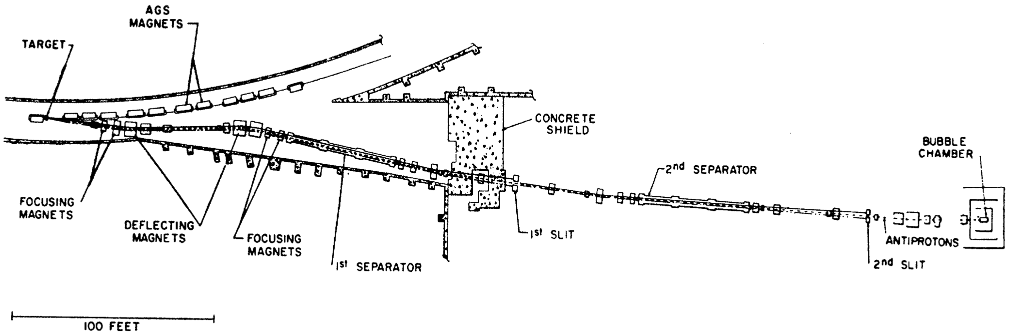

FIG. 1. Schematic of Beam 3.

struction of tracks to determine the vertex of origin and the nature of each vee.

Thus, the measurer completed the measurement of a frame only after the nature and the associated vertex of each vee had been determined. After an event had passed the reconstruction checks and measuring precision tests, the measurement was recorded on a magnetic tape. These features greatly simplified our bookkeeping and event analysis efforts.

The measurements from both laboratories were processed through the Yale reconstruction and kinematic fitting program YACK. These events were fitted to various final-state hypotheses, up to a maximum of 6 kaons in the final state.[10] In order to eliminate contamination from hyperon or antihyperon events, vees were also fitted to Λ and $\bar{\Lambda}$ decays. Events were identified by applying a set of χ^2 and missing-mass criteria in association with a bubble-density determination of the charged tracks. In view of the relatively high laboratory momenta of the particles, track ionization information was not always capable of resolving the several final state interpretations which were consistent for a given event. This was particularly true of the events with one vee. For this sample the charged tracks were unambiguously identified in only 31% of the events. All the charged tracks in approximately 60% of the two-vee events were unambiguous, with a majority of these having no more than one missing neutral particle and hence were kinematically fittable. In the analysis that follows, except where specifically stated, data were taken from the two-vee events only.

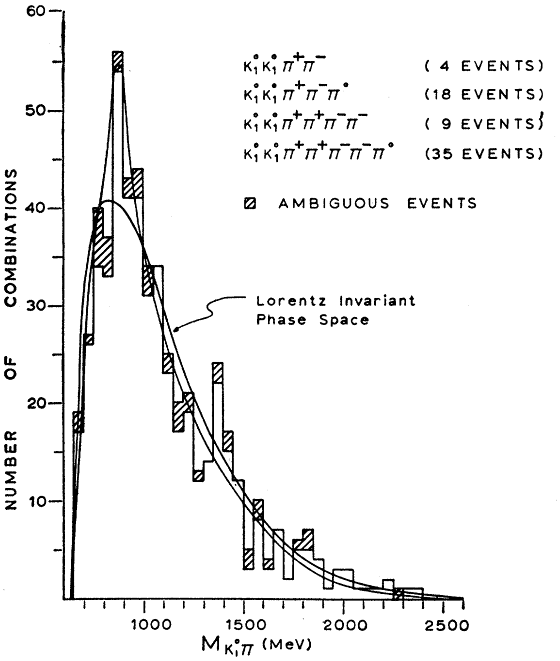

FIG. 2. The combined $K_1^0\pi$ effective mass spectrum from four final states. The unmarked curve represents the Lorentz invariant phase space modified by 10% $K^*(890)$ production in the seven-body final state.

III. RESULTS

A. Resonances and Other Effects

There is considerable current interest in mesonic resonant states involving kaons. Data from our study of kaonic annihilations have been studied with respect to the production of several reported resonances. The following reactions comprised a majority of the fittable events from our two-vee topologies:

$$\bar{p}+p\rightarrow K_1^0+K_1^0+\pi^++\pi^-, \quad (1)$$

$$\bar{p}+p\rightarrow K_1^0+K_1^0+\pi^++\pi^-+\pi^0, \quad (2)$$

$$\bar{p}+p\rightarrow K_1^0+K_1^0+\pi^++\pi^++\pi^-+\pi^-, \quad (3)$$

$$\bar{p}+p\rightarrow K_1^0+K_1^0+\pi^++\pi^++\pi^-+\pi^-+\pi^0. \quad (4)$$

A small fraction of these events were ambiguous with four-kaon production, but they have been included among the two-kaon final states since the level of four-kaon contamination is less than 10%.

Figure 2 shows the $K_1^0\pi$ effective mass distribution. Two curves have been superimposed on the histogram: one representing the Lorentz-invariant phase space normalized to the total number of events, the other being phase space modified by the production of the $K^*(890)$. A discernible signal of $K^*(1400)$ is ob-

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[10] For details, see Ref. 6.

served.[11–14] We note that the $K^*(890)$ signal comes mostly from reaction (4), whereas the contribution to the $K^*(1400)$ signal consists almost entirely of events from reactions (2) and (3).

There is no significant evidence for the production of the ρ and ω mesons among reactions (1)–(4). The 2π and 3π mass spectra are consistent with phase-space distributions.

A $K\bar{K}$ enhancement at low mass (near threshold) was reported for kaonic annihilations in $\bar{p}$-p interactions at 3.7 BeV/c.[15] From our present study of the two-vee events, we observe a similar enhancement in the effective mass distribution of $K_1^0K_1^0$. Figure 3 shows such a distribution for reactions (1)–(4), together with the phase space predictions. It should be noted that the ambiguous events included in Fig. 3 are ambiguous with respect to the identity of charged particles emanating from the production vertex and not with regard to the identity of the two vees.

The unfittable two-vee events show a similar effect near the $K_1^0K_1^0$ threshold, but the significance is somewhat difficult to evaluate since the comparison phase space is not known. A sample of 50 events which uniquely fitted the final states, $K_1^0K^+\pi^\mp\pi^+\pi^-$ and $K_1^0K^\pm\pi^\mp\pi^+\pi^-\pi^0$, also shows an excess of events near the threshold of the $K\bar{K}$ spectrum. But since the identification of the charged kaons by track ionization is highly dependent on the laboratory momentum of the charged particles, this sample of unambiguous events is biased in favor of low laboratory momentum charged kaons.

It is interesting to note that in Fig. 3, there is an enhancement at ~1140 MeV in the $K_1^0K_1^0$ effective mass. A similar effect can be found in antiproton annihilations at 3.7 BeV/c, and in particular, in the final state $K_1^0K_1^0\pi^+\pi^-\pi^0$.[15] This enhancement appears to be at a mass of about 100 MeV above the previously observed $K_1^0K_1^0$ effect at 1068 MeV.[16]

A search for resonances in the $K\pi\pi$ and $K\bar{K}\pi$ states[17–24] has yielded negative results at the present level of statistics. Shown in Figs. 4 and 5 are the effective mass distributions of the two charged states of the $K\pi\pi$ system from the two-vee events. Figure 6 shows the $K\bar{K}\pi$ mass spectra from the same data.

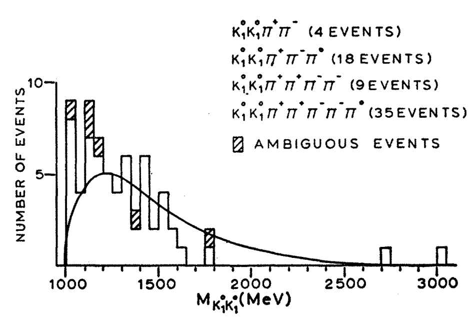

FIG. 3. Effective mass distribution of the $K_1^0K_1^0$ system.

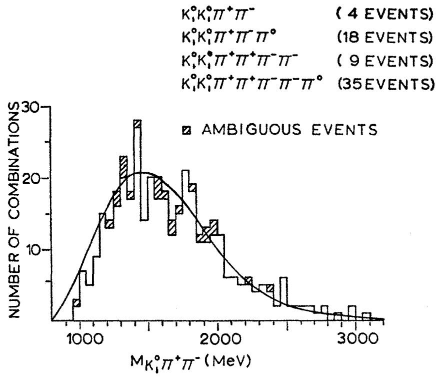

FIG. 4. Effective mass distribution of the neutral ($K\pi\pi$) system.

B. Cross Sections

The topological distribution of events is summarized in Table I. For purposes of determining the total cross section for two-kaon production, we have used only the

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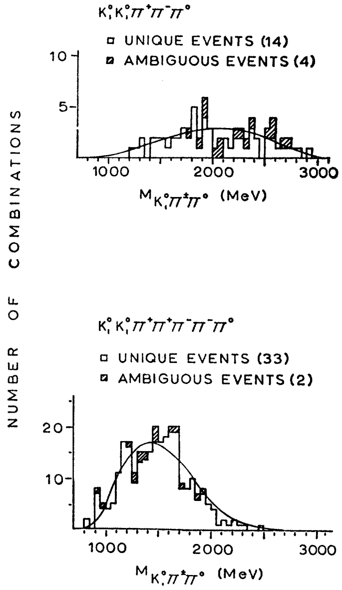

FIG. 5. Effective mass distributions of the singly charged ($K\pi\pi$) system.

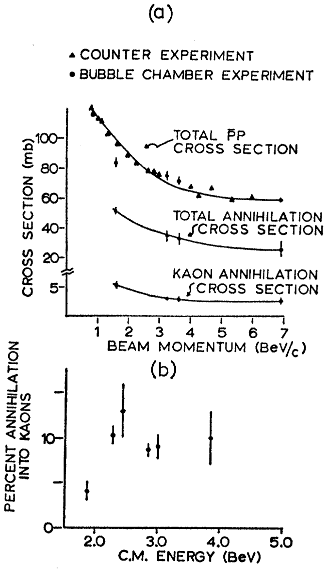

FIG. 7. (a) Variations of the $\bar{p}$-p total, annihilation, and kaonic annihilation cross sections with incident antiproton momentum. (b) Percentage of annihilations yielding kaons as a function of barycentric energy.

two-vee events. Corrections were made for the following detection losses: (a) scanning inefficiency, (b) decay of the K_1^0 too near the production vertex, or outside our fiducial volume, (c) decay of the K_1^0 into two neutral pions, and (d) decay of the neutral K meson as a K_2^0.

To correct for the scanning losses, the film was scanned at least twice to determine the scanning efficiency. A MONTE CARLO computer program[25] was used to calculate the detection losses due to the other circumstances. Assuming that the neutral kaon decays with equal probability as a K_1^0 and a K_2^0, the cross section for $\bar{p}+p \rightarrow K^0+\bar{K}^0+m\pi$ ($m=0, 1\cdots$) is 0.6 ± 0.1 mb. With the assumption that $K^0\bar{K}^0$, K^+K^-, $K^+\bar{K}^0$, and K^-K^0 are produced with equal probability, we find $\sigma(\bar{p}+p \rightarrow K+\bar{K}+m\pi)$ to be 2.5+0.5 mb.

There were no events which were consistent with the final states $K^0+\bar{K}^0$ or $K^0+\bar{K}^0+\pi^0$. There were likewise no events consistent with $K+K^*$ production without additional pions. We did observe four-kaon events with and without pions, and these gave a cross section of $0.10_{-0.02}^{+0.20}$ mb for four-K-meson production. These cross sections are summarized in Table II.

In Fig. 7 are shown the available data on annihilation cross section.[26] For comparison, the total $\bar{p}$-p interaction cross section is also indicated.[27] There appears to be an

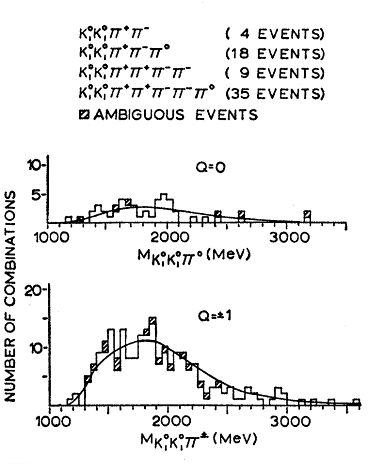

FIG. 6. Effective mass distributions of the ($\bar{K}K\pi$) system.

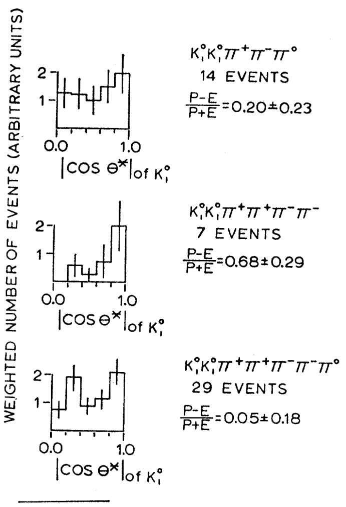

FIG. 8. Barycentric production angular distributions of K_1^0 mesons from the two-vee final states at 7 BeV/c.

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[25] This program is described in Ref. 15 and in greater detail in Ref. 6.

[26] These cross sections are compiled from N. Horwitz, D. Miller, J. Murray, and R. Tripp, Phys. Rev. **115**, 472 (1959); L. Angew, T. Elioff, W. B. Fowler, R. Lander, W. Powell, E. Segrè, H. Steiner, H. White, C. Wiegand, and T. Ypsilantis, *ibid.* **118**, 1371 (1960); S. Goldhaber, G. Goldhaber, W. Powell, and R. Silberberg, *ibid.* **121**, 1525 (1961); J. Button, G. R. Kalbfleisch, G. R. Lynch, B. C. Maglić, A. H. Rosenfeld, and M. L. Stevenson, *ibid.* **126**, 1858 (1962); and G. R. Kalbfleisch, thesis, University of California, Radiation Laboratory UCRL Report No. 9597, 1961 (unpublished). For cross sections between 3–4 BeV/c, see Ref.15 and the publications quoted there.

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TABLE I. Topological distribution of events.

Event topology[a]	0 prong +1 vee	2 prong +1 vee	4 prong +1 vee	0 prong +2 vees	2 prong +2 vees	4 prong +2 vees
Total No. of events	127	278[b]	577[b]	12	108	88
No. with uniquely identified charged tracks	127	82	100	12	45	63
No. of fittable unique events	0	11	57	0	24	46

[a] There were 110 events belonging to other topologies whose vees were identified as K_1^0 decays. Of these, 106 were 6 prong+1 vee, three were 2 prong +3 vees and one 6 prong+2 vees. Some of these might not be annihilation events, however.

[b] These topologies were studied in the Yale University half of the film only.

over-all decrease in the kaonic- and total-annihilation cross sections with increasing $\bar{p}$-p energy. A similar decrease also occurs for the $\bar{p}$-p total cross section. The rate of decrease in the three cross sections is approximately the same in the momentum range of 1.6–7 BeV/c: 96–58 mb for the total cross section, 51–25 mb for all annihilations, and 5.2–2.5 mb for kaonic annihilations. Figure 7 also shows the constancy ($\sim 10\%$) of the fraction of annihilations proceeding to kaonic final states, after an initial rise from antiproton capture at rest. A calculation of the statistical theory[28] extrapolating from low energy data predicts that the fraction of annihilations proceeding to kaonic final states continues to increase with incident energy in this energy region.

C. Angular Distributions

The production angular distributions of the K_1^0 and π mesons from the two-vee final states have been studied. They are compared with the data obtained from kaonic annihilations at 3.7 BeV/c. These distributions are weighted according to the inverse of the detection probability of the events (see Sec. III B).

For purposes of calculating the production angular asymmetries, the barycentric angle θ^* of the kaon (anti-kaon) with respect to the initial proton (antiproton) direction is divided into four regions: polar ($|\cos\theta^*| > 0.5$), equatorial ($|\cos\theta^*| < 0.5$), forward ($\cos\theta^* > 0$), and backward ($\cos\theta^* < 0$).

Figure 8 shows the K_1^0 angular distributions from this experiment. Shown for comparison are the corresponding distributions from the 3.7-BeV/c annihilation study[6] (see Fig. 9). The charged- and neutral-pion distributions are shown in Figs. 10 and 11. For the charged pions, the π^- meson direction has been plotted with respect to the initial-antiproton direction, to which have been added the π^+ plotted with respect to the initial-proton direction. The π^0 mesons are histogrammed with respect to the antiproton direction.

It is interesting to note that the neutral pions from kaonic annihilations are consistent with isotropic emission from the $\bar{p}$-p center of mass, whereas there is some tendency for the charged pions to be emitted preferentially in the polar regions. This is to be compared with purely pionic annihilations where the pions are preferentially emitted in the polar regions in the low-multiplicity

TABLE II. Cross sections.

Reactions	σ (mb)
$\bar{p}+p \rightarrow K^0+\bar{K}^0+m\pi$ (m=0, 1, 2$\cdots$)	0.6 ± 0.1
$\bar{p}+p \rightarrow K+\bar{K}+m\pi$	2.5 ± 0.5[a]
$\bar{p}+p \rightarrow K^0+\bar{K}^0$	<0.02
$\bar{p}+p \rightarrow K+\bar{K}^*$ and $\bar{K}+K^*$	<0.03
$\bar{p}+p \rightarrow K+K+\bar{K}+\bar{K}+m\pi$	$-0.10_{-0.02}^{+0.20}$
$\sigma(\bar{p}p \rightarrow K+\bar{K}+m\pi)/\sigma(\bar{p}p \rightarrow \text{all annihilations}) = (10.2\pm3.1)\%$	

[a] Calculated with the assumption that K^+K^-, $K^+\bar{K}^0$, K^0K^-, and $K^0\bar{K}^0$ are produced with equal probability.

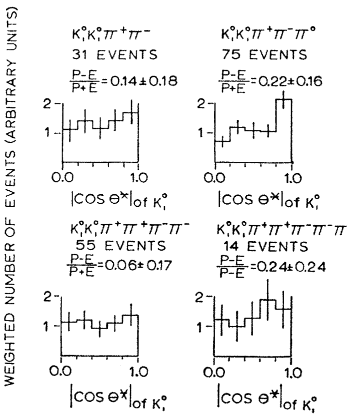

FIG. 9. Barycentric production angular distributions of K_1^0 mesons from the two-vee final states at 3.7 BeV/c.

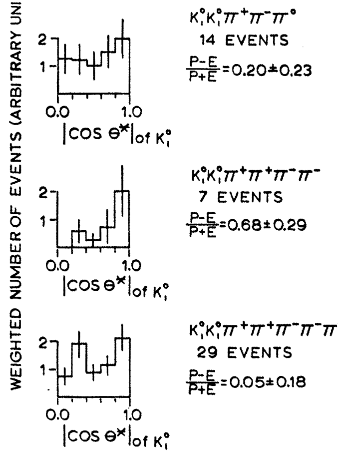

FIG. 10. Charged-pion barycentric production angular distribution at 7 BeV/c. All charged pions from each final state are included. The corresponding data at 3.7 BeV/c can be found in Ref. 15.

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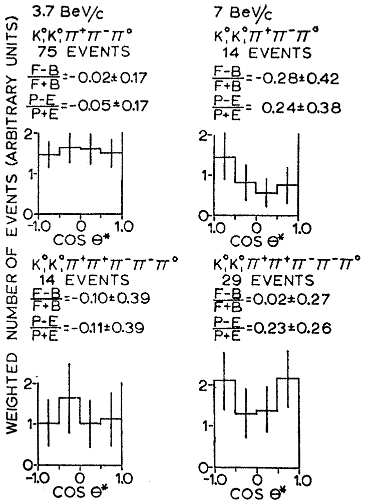

FIG. 11. Neutral-pion barycentric production angular distributions from two corresponding final states at 3.7 and 7 BeV/c.

($\leq$5 particles) states. This effect diminishes with higher multiplicity.[2,8,29]

D. Properties of the $K_1{}^0$

The lifetime distribution of the $K_1{}^0$ decays from the present study is shown in Fig. 12. To avoid possible scanning biases, only those types of events processed at both Yale University and Brookhaven National Laboratory have been included (See Table I). The theoretical expectations based on the exponential decay law, represented by the smooth curve, are shown superimposed on the data. Shown for comparison are the data from the corresponding event topologies in the 3.7-BeV/c study.

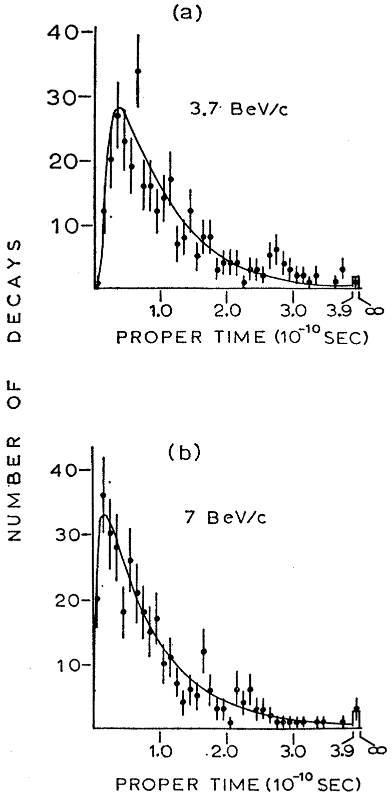

FIG. 12. Distributions of the decay lifetime for neutral kaons produced in annihilations at (a) 3.7 and (b) 7 BeV/c. The smooth curves represent theoretical expectations based on the exponential decay law.

For each event, we imposed the requirement that both the production and decay vertices should lie within our fiducial volume and that the $K_1{}^0$ decay occur no less than 0.5 cm from the production vertex. These cutoffs were translated into a minimum and a maximum proper time, $\tau_{\min}$ and $\tau_{\max}$, respectively, consistent with the observation of each vee. For each decay that met these criteria, we evaluated the normalization constant,

$$C_i=\int_{\tau_{\min i}}^{\tau_{\max i}}\exp(-t/\tau^*)dt,$$

where τ^* is the assumed mean life of the decay. For the total sample of vees, we evaluated the function

$$F(T+\Delta T)=\sum_{i=1}^{N}\frac{1}{C_i}\int_{T}^{T+\Delta T}\exp(-t/\tau^*)dt$$

for all time intervals. For the distributions shown, we used the value of $\tau^*=0.90\times10^{-10}$ sec. The errors shown on the graphs are statistical. A comparison of our data with the curves shows that they are in agreement with theoretical expectations based on exponential decay.

With the same sample of events, maximum-likelihood analysis was performed to obtain the $K_1{}^0$ mean life and the neutral kaon mass. Assuming exponential decay, we maximized the likelihood function,

$$\mathcal{L}(\tau)=\prod_{i=1}^{N}\frac{1}{\tau}\frac{\exp(-\tau_i/\tau)}{\exp(-\tau_{\min_i}/\tau)-\exp(-\tau_{\max_i}/\tau)},$$

where τ is the proper time of the observed $K_1{}^0$ decay and other quantities are as defined above. This yielded a mean life of $\tau_{K_1{}^0}=(0.96\pm0.06)\times10^{-10}$ sec where the error is statistical.

To determine the K^0 mass, we maximized the likelihood function

$$\mathcal{L}(m)=\prod_{i=1}^{N}[1/(\Delta m_i)]\exp\{-(m_i-m)^2/[2(\Delta m_i)^2]\},$$

where m_i is the mass of the kaon as determined from the measured momenta of the decay products and Δm_i is the average error of the mass determination. The neutral kaon mass, according to this analysis, was $m_{K^0}=(497.9\pm0.6)$ MeV, where the error includes an estimated systematic error of 0.4 MeV.

IV. CONCLUSIONS

The production of several well-known resonances such as the $K^*(890)$, ω and ρ, which have been ob-

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served in $\bar{p}$-p kaonic annihilations at 3.7 BeV/c, has decreased with the increased initial-state energy. The production of $K^*(890)$ has dropped from the 50% level at 3.7 BeV/c to ~10% at 7 BeV/c among the final states examined. Neither ρ nor ω has been observed among the two-vee events at 7 BeV/c, although there is some evidence for the formation of $K^*(1400)$.

A study of the energy dependence of the fraction of annihilation events leading to kaons and pions in the final state indicates that after an initial rise (from ~4%) for antiproton capture at rest, the kaonic annihilations reach ~10% of the total annihilation cross section and remain fairly constant up to 7 BeV/c, where the fraction is $(10.2\pm3.1)\%$. This is inconsistent with the predictions of the statistical theory.

Our data at 7 BeV/c show a $K_1{}^0K_1{}^0$ enhancement near threshold similar to the effect observed at 3.7 BeV/c. There is also a $K_1{}^0K_1{}^0$ enhancement at 1140 MeV, but no conclusive statement can be made concerning the significance of this effect because of the limited statistics. It is interesting, however, that a similar effect exists in the 3.7-BeV/c data.

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Reaction $K^+p \rightarrow K^+p\pi^+\pi^-$ at 2.26 BeV/c*

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The reaction $K^+p \rightarrow K^+p\pi^+\pi^-$ at 2.26 BeV/c is investigated. It is found to be dominated by the simultaneous production of the K^* (895 MeV) and N^* (1238 MeV) resonances. The production and decay angular distributions of these resonances in the double-resonance channel are analyzed and the results compared with the predictions of a single-particle-exchange model. These distributions are consistent with the assumption that the primary production mechanism responsible for the reaction $K^+p \rightarrow K^{*0}N^{*++} \rightarrow K^+\pi^-\pi^+p$ at 2.26 BeV/c is the exchange of a single π meson. A search is conducted in this channel for other possible resonant states. A Monte Carlo analysis is utilized for this purpose. The data are not found to be consistent with the production of any other resonances except the aforementioned K^* (895 MeV)and N^* (1238 MeV).

1. INTRODUCTION

WE have investigated the reaction $K^+p \rightarrow K^+p\pi^+\pi^-$ in the 20-in. hydrogen bubble chamber at Brookhaven National Laboratory. In our exposure, the K^+ beam had a laboratory momentum at the chamber entrance window of 2.260 BeV/c with a full width at half-maximum of 0.045 BeV/c.

We find this reaction to be highly resonant and dominated by the simultaneous production of the K^* (895 MeV) and N^*(1238 MeV). In addition, there is evidence for the production of these resonances singly via the channels $K^+p \rightarrow K^{*0}p\pi^+$ and $K^+p \rightarrow N^{*++}K^+\pi^-$.[1]

We have analyzed the production and decay angular distributions of the K^* and N^* in the double-resonance channel and compared our results with theoretical predictions of a single-particle-exchange model.[2–6] These experimental distributions are consistent with the assumption that the primary production mechanism responsible for the reaction $K^+p \rightarrow K^{*0}N^{*++} \rightarrow K^+\pi^-\pi^+p$ is the exchange of a single π meson between the incoming particles.

We have also conducted an extensive search for other possible resonant states which could be observed in the

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