Annihilations of Antiprotons at Rest in Hydrogen. VI. Kaonic Final States*

N. BARASH,† L. KIRSCH,‡ D. MILLER,§ AND T. H. TAN‖
Nevis Laboratories and Physics Department, Columbia University, New York, New York

(Received 30 September 1966)

We present here experimental results on the annihilation of stopped antiprotons into $K\bar{K}+3\pi$, $K\bar{K}\eta$, and $K\bar{K}\omega$. We find the branching ratios for $\bar{p}+p\rightarrow K_1K_1\eta$ and $\bar{p}+p\rightarrow K_1K_1\omega$ to be $(0.25\pm0.04)\times10^{-3}$ and $(1.08\pm0.16)\times10^{-3}$, respectively. From events of the latter reaction we find the width of the ω meson to be 12.3 ± 2.0 MeV. The E^0 meson is observed and evidence is seen for the assignment of even charge conjugation and even G parity to this resonance. In addition, we have used events from the reaction $\bar{p}+p\rightarrow K_1K^{\pm}\pi^{\pm}$ to measure the mass difference between the charged and neutral K^*. We find $M_{K^{*0},\bar{K}^{*0}}-M_{K^{*\pm}}=6.3\pm4.1$ MeV.

I. INTRODUCTION

In this final paper in our study of antiproton annihilations at rest in hydrogen, we present results on the reactions

(1) $\bar{p}+p\rightarrow K_1K^{\pm}\pi^{\pm}\pi^{\mp}\pi^{\mp}$,

(2) $\bar{p}+p\rightarrow K_1K_1\pi^+\pi^-\pi^0$,

(3) $\bar{p}+p\rightarrow K_1K_1\eta$,

(4) $\bar{p}+p\rightarrow K_1K_1\omega$.

In addition, we have used events from the reaction $\bar{p}+p\rightarrow K_1K^{\pm}\pi^{\mp}$ to determine the mass difference between the charged and neutral K^* mesons.

This study is based on an exposure of the 30-in. Columbia-BNL bubble chamber to a low-energy separated antiproton beam at the Brookhaven AGS. The exposure consisted of 630 000 pictures, yielding a total flux of 7.35×10^5 antiprotons. The results of other reactions on antiproton annihilation are presented in Refs. 1–5.

II. EXPERIMENTAL PROCEDURE

The film was scanned for the following topologies:

(a) two "V" 's and no charged prongs,
(b) two "V" 's and two charged prongs,
(c) one "V" and four charged prongs.

The number of events measured of topologies (a), (b), and (c) were 427, 1154, and 939, respectively. For events of topology (c), each track was assigned an ionization code, in order to facilitate the identification of the charged kaon.

Each measured event was reconstructed in space using the Nevis program NP54.[6] At this point, 11% of all events of topology (a), and 14% of the events of each of topologies (b) and (c) were lost because of failure to be successfully reconstructed. These events were not remeasured, but were accounted for in determining branching ratios. The GRIND[7] kinematics program was used to fit the "V" 's to the three-constraint hypothesis $K_1^0\rightarrow\pi^+\pi^-$. For those events which had a successful K_1^0 decay fit, the K^0 momentum calculated in the 3-C fit, together with its errors, was used in fitting the following production hypotheses (given in Table I), at the $\bar{p}$ vertex. In order for an event to be listed as fitting it must have a $\chi^2<5\times$ constraint class, and for topology (c) all charged tracks must have an apparent ionization consistent with momentum and mass. Approximately 50% of the events of topology (c) were lost because of failure of the "V" to fit as a K_1^0 in the 3-C fit. This is consistent with the fact that of the multipion annihilations, the most common topology was four charged prongs. Thus, an unrelated "V" in a picture, such as a pion which enters the chamber and decays in flight, or a K_1^0 coming from another annihilation vertex is more likely to be associated by the scanner with such a topology than with any other. About half of the remaining events were those in which two of the prongs at the

TABLE I. Production fits with K_1^0's.

Topology	Hypothesis	No. of constraints	No. of events fitting
(a)	K_1K_1+(missing mass)	0	291
(b)	$K_1K_1\pi^+\pi^-$	4	491
	$K_1K_1\pi^+\pi^-\pi^0$	1	241
(c)	$K_1K^{\pm}\pi^{\pm}\pi^{\mp}\pi^{\mp}$	4	167
	$K_1(K^0)\pi^+\pi^+\pi^-\pi^-$	1	0

* Research supported in part by the U. S. Atomic Energy Commission under Contract No. AT(30-1)-1932.
† Present address: Department of Physics and Astronomy, University of Maryland, College Park, Maryland.
‡ Present address: Physics Department, Brandeis University, Waltham, Massachusetts.
§ Present address: Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts.
‖ Present address: Physics Department, Stanford University, Stanford, California.

[1] N. Barash, P. Franzini, L. Kirsch, D. Miller, J. Steinberger, T. H. Tan, R. Plano, and P. Yeager, Phys. Rev. **139**, B1659 (1965).
[2] C. Baltay, P. Franzini, N. Gelfand, G. Lütjens, J. C. Severiens, J. Steinberger, D. Tycko, and D. Zanello, Phys. Rev. **140**, B1039 (1965).
[3] C. Baltay, P. Franzini, G. Lütjens, J. C. Severiens, J. Steinberger, D. Tycko, and D. Zanello, Phys. Rev. **140**, B1042 (1965).
[4] N. Barash, L. Kirsch, D. Miller, and T. H. Tan, Phys. Rev. **145**, 1095 (1966).
[5] C. Baltay, P. Franzini, G. Lütjens, J. C. Severiens, D. Tycko, and D. Zanello, Phys. Rev. **145**, 1103 (1966).
[6] R. J. Plano and D. H. Tycko, Nucl. Instr. Methods **20**, 458 (1963).
[7] R. Bock, CERN Report No. 61–29, 1961 (unpublished).

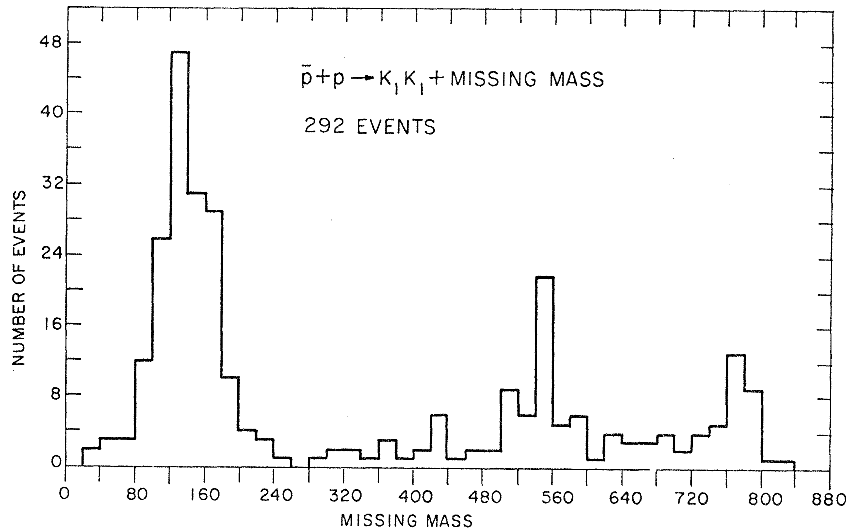

FIG. 1. Missing mass from the reaction $\bar{p}+p \rightarrow K_1K_1+$missing mass.

annihilation vertex were either electrons from a Dalitz pair or pions from the decay of a $K_1{}^0$ close to the vertex. This was checked by assuming the tracks at the vertex to be electrons, provided that their ionization was consistent with this mass assignment. The effective mass of all such neutral pairs of prongs was then plotted, and a prominent peak was noted near zero in the mass spectrum. A similar plot was made, assuming the tracks to be pions, and a peak was observed near the K^0 mass.

III. EXPERIMENTAL RESULTS

A. Branching Ratios

In determining the branching ratio into final states (1) through (4), we make use of the following efficiencies:

(a) Probability of a $K_1{}^0$ to decay into $\pi^+\pi^-$ is 0.70 ± 0.05.[8]

(b) Scanning efficiency after two scans is 0.95 ± 0.05.

(c) Probability of a $K_1{}^0$ to decay between 0.2 and 12.0 cm from the vertex, assuming the average K^0 momentum of 200 MeV/c, is 0.81 ± 0.03.

(d) The efficiency for an event to survive the geometric reconstruction program is 0.89 ± 0.06 for topology (a), and 0.86 ± 0.04 for each of topologies (b) and (c).

(e) The total flux of antiprotons entering the bubble chamber was found to be $(7.35\pm0.74)\times10^5$, based on a count of heavily ionizing tracks which end in the chamber. After correcting for annihilations in flight, this corresponds to $(6.32\pm0.74)\times10^5$ antiprotons which annihilate at rest.

Using the above efficiencies, we list the values for the branching ratios of the reaction $\bar{p}+p \rightarrow K\bar{K}\pi\pi$ in Table II.

B. ω and η Production

The missing mass from the reaction $\bar{p}+p \rightarrow K_1K_1+$ missing mass is plotted in Fig. 1, and the $\pi^+\pi^-\pi^0$ combined mass from the reaction $\bar{p}+p \rightarrow K_1K_1\pi^+\pi^-\pi^0$ is shown in Fig. 2. In both distributions there appear peaks at 550 and at 780 MeV, which can be identified with the η^0 and ω^0 mesons. From the 33 ± 6 events in the η^0 peak of Fig. 1 and the 12 ± 4 events in that of Fig. 2, we estimate the ratio

$$\frac{\eta \rightarrow \text{neutrals}}{\eta \rightarrow \pi^+\pi^-\pi^0} = 2.55\pm0.90.$$

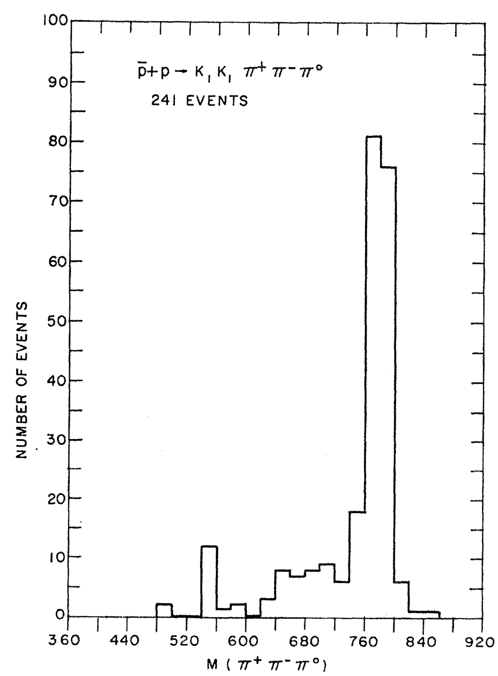

FIG. 2. Combined mass of $(\pi^+\pi^-\pi^0)$ from the reaction $\bar{p}+p \rightarrow K_1K_1\pi^+\pi^-\pi^0$.

[8] M. Chretien, V. K. Fischer, H. R. Crouch, Jr., R. E. Lanou, Jr., J. T. Massimo, A. M. Shapiro, J. P. Averell, A. E. Brenner, D. R. Firth, L. G. Hyman, M. E. Law, R. H. Milburn, E. E. Ronat, K. Strauch, J. C. Street, J. J. Szymanski, L. Guerriero, I. A. Pless, L. Rosenson, and G. A. Salandin, Phys. Rev. **131**, 2208 (1963).

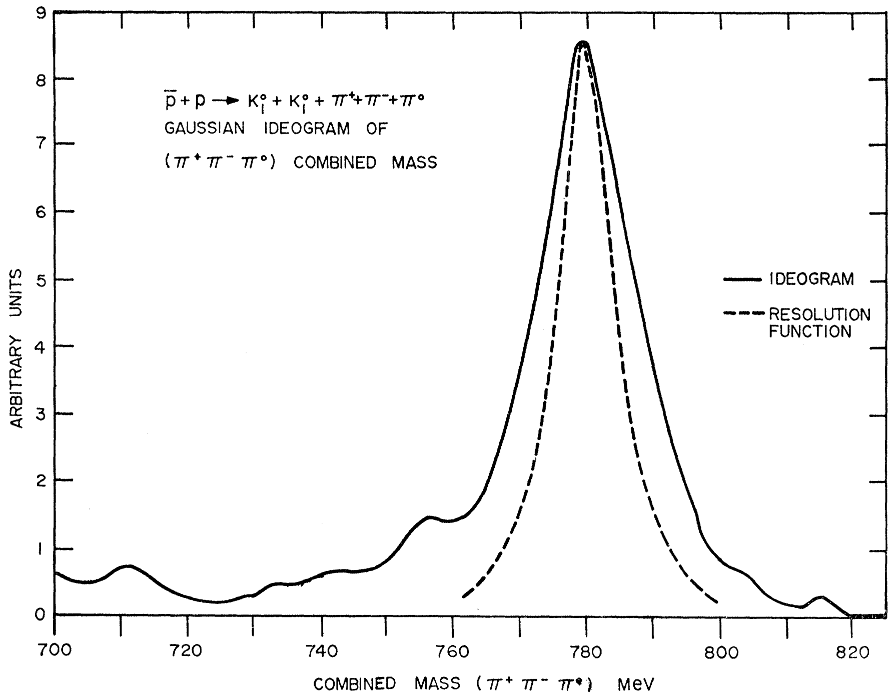

FIG. 3. Gaussian ideogram and resolution function for events of reaction $\bar{p}+p \rightarrow K_1K_1\pi^+\pi^-\pi^0$, where the combined mass of $(\pi^+\pi^-\pi^0)$ is in the region of the ω^0.

The 171±13 ω events in Fig. 2, together with the 19±5 ω events in Fig. 1, give a value for the ratio

$$\frac{\omega \rightarrow \text{neutrals}}{\omega \rightarrow \pi^+\pi^-\pi^0}=0.10\pm0.03.$$

Both of these numbers are in good agreement with the averages of previous experimental measurements, which are quoted by Rosenfeld as 2.76±0.2 and 0.106±0.01, respectively.[9] Using the branching ratios[9] $(\eta \rightarrow \text{neutrals})/(\eta \rightarrow \text{all modes})=0.694\pm0.035$, and $(\eta \rightarrow \pi^+\pi^-\pi^0)/(\eta \rightarrow \text{all modes})=0.250\pm0.016$, combined with the number of η^0 decays observed in Figs. 1 and 2, we find the branching ratio of $\bar{p}+p \rightarrow K_1K_1\eta$ to be $(0.25\pm0.04)\times10^{-3}$. Similarly, using the values for $(\omega \rightarrow \text{neutrals})/(\omega \rightarrow \text{all modes})=0.106\pm0.010$ and $(\omega \rightarrow \pi^+\pi^-\pi^0)/(\omega \rightarrow \text{all modes})=0.88$,[9] we find the branching ratio for $\bar{p}+p \rightarrow K_1K_1\omega$ to be $(1.08\pm0.16)\times10^{-3}$. We expect the branching ratios into $K_2K_2\eta$ and $K_2K_2\omega$ to be the same as into $K_1K_1\eta$ and $K_1K_1\omega$.

C. The Width of the ω

We have previously reported a value for the width of the ω meson from a study of the reaction $\bar{p}+p \rightarrow K^+K^-\omega^0$, $\omega^0 \rightarrow \pi^+\pi^-\pi^0$.[10] We report here a value for the ω width using the reaction $\bar{p}+p \rightarrow K_1K_1\omega$, $\omega \rightarrow \pi^+\pi^-\pi^0$. It is apparent from the histogram of Fig. 2 that the reaction is dominated by ω production with almost no background. Figure 3 is a Gaussian ideogram of the three-pion combined mass for these events. The individual errors were calculated using the vector momenta of the two K_1^0's. The errors obtained for each event are of the order of 5–10 MeV. The resolution function constructed from these errors is also shown in Fig. 3, with a width of 11±1 MeV.

We have checked for systematic errors in the determination of the K_1^0 momentum from the decay $K_1^0 \rightarrow \pi^+\pi^-$. This was done using a monoenergetic source of K_1^0 mesons produced in the reaction $\bar{p}+p \rightarrow K_1^0 +(K_1^0)$ where the annihilation takes place at rest. The momentum of the K_1^0 is then 795 MeV/c. We have calulated two Gaussian idoeograms for these events. The first is for the fitted momenta and the fitted errors of the individual events. The second is the resolution function constructed by ideogramming the individual fitted errors multiplied by $\sqrt{2}$ about a common value. The two ideograms are displayed in Fig. 4. The agreement between the two curves suggests that there are no systematic errors in the determination of the momentum of a K_1^0 from the fitting of the decay hypothesis.

The width of the three-pion mass distribution above a small background is 16.5±1.7 MeV, the error being

TABLE II. Branching ratios for the reaction $\bar{p}+p \rightarrow K\bar{K}\pi\pi\pi$.

Reaction	Events observed	Detection efficiency	Branching ratio
$\bar{p}+p \rightarrow K_1K_1\pi^+\pi^-\pi^0$	241±15	0.256±0.023	$(1.49\pm0.22)\times10^{-3}$
$\bar{p}+p \rightarrow K_1K^\pm\pi^\pm\pi^\mp\pi^\mp$	167±13	0.452±0.055	$(0.59\pm0.08)\times10^{-3}$

[9] A. Rosenfeld, A. Barbaro-Galtieri, W. Barkas, P. Bastien, J. Kirz, and M. Roos, Rev. Mod. Phys. **37**, 633 (1965).

[10] N. Gelfand, D. Miller, M. Nussbaum, J. Ratau, J. Schultz, J. Steinberger, T. H. Tan, L. Kirsch, and R. Plano, Phys. Rev. Letters **11**, 436 (1963); D. Miller, Ph.D. thesis, Columbia University (unpublished).

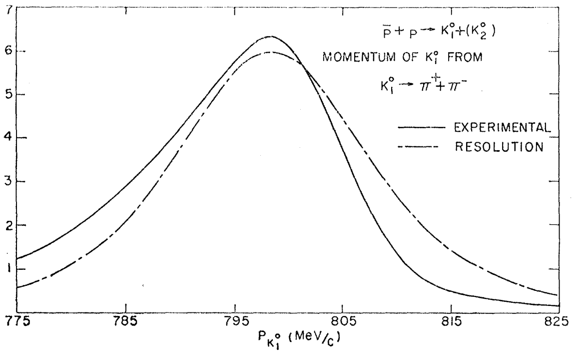

FIG. 4. Gaussian ideogram and resolution function of the K_1^0 momentum from the reaction $\bar{p}+p \to K_1^0(K^0)$ where the second K^0 is not seen. The momentum and its errors are determined from the 3-C fit $K_1^0 \to \pi^+\pi^-$.

due largely to an estimate of the amount of background in the reaction. After unfolding the resolution function from the experimental distribution, we obtain for the mass and natural width of the ω,

$$M_\omega = 779.5 \pm 1.5 \text{ MeV},$$
$$\Gamma_\omega = 12.3 \pm 2.0 \text{ MeV}.$$

This experiment differs from our previous one in two respects. First, the momentum of the K_1^0's is not as well determined from the fitting of the decay as was the momentum from range of the stopping charged K's. This results in a wider resolution function. However, the background in the reaction $\bar{p}+p \to K_1K_1\omega$ is negligible. The background in the earlier reaction was of the order of 33%, and the determination of the width was limited by lack of knowledge of its exact size and shape. The values for the width measured using the two reactions agree within one standard deviation.

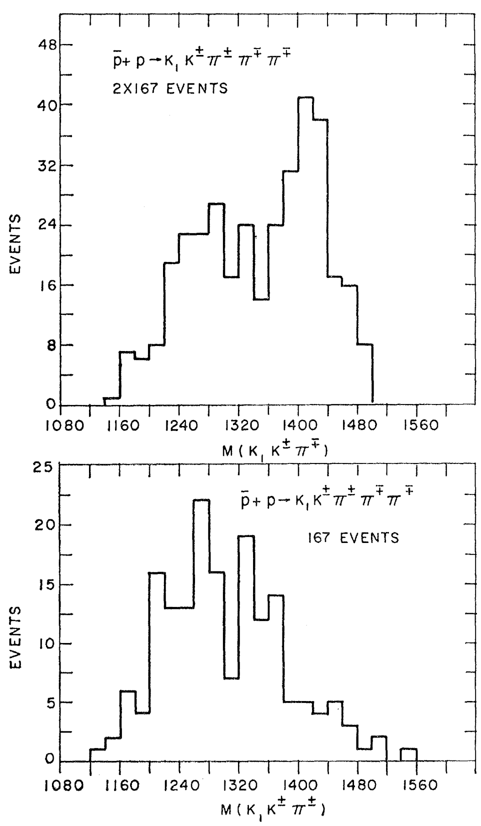

FIG. 5. Combined mass of $K_1^0K^\pm\pi^\mp$ and $K_1^0K^\pm\pi^\pm$ from the reaction $\bar{p}p \to K_1^0K^\pm\pi^\pm\pi^\mp\pi^\mp$.

D. The E Meson

Armenteros *et al.*,[11] in studying the reaction $\bar{p}+p \to K_1K^\pm\pi^\pm\pi^\mp\pi^\mp$, have noted a striking enhancement in the $K_1K^\pm\pi^\mp$ combined mass spectrum at 1410 MeV. This was attributed to a possible resonance, the E meson, and evidence was seen for the decay of this meson into the state K^*K. A similar enhancement in the neutral $K\bar{K}\pi$ spectrum was seen in the reaction $\pi^-p \to K^+\bar{K}^0\pi^-n$.[12] Our data also show a neutral $K\bar{K}\pi$ enhancement in the final state $K_1K^\pm\pi^\pm\pi^\mp\pi^\mp$, as can be seen in Fig. 5. Figure 6 is a Dalitz plot for all events with $K_1K^\pm\pi^\mp$ mass in the region 1360–1440 MeV. The outline drawn corresponds to a $K\bar{K}\pi$ mass of 1410 MeV. There is a clustering of points in the upper right-hand

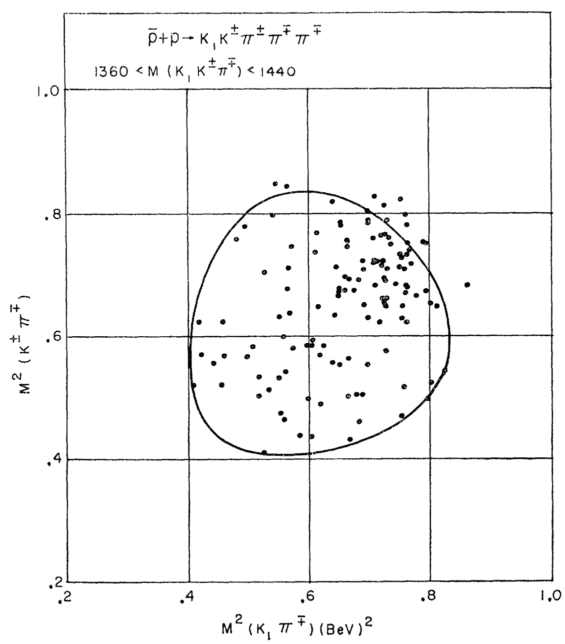

FIG. 6. Dalitz plot for events whose $(K_1K^\pm\pi^\mp)$ combined mass is between 1360 and 1440 MeV. The outline drawn corresponds to a $K\bar{K}\pi$ mass of 1410 MeV.

[11] R. Armenteros, D. N. Edwards, T. Jacobsen, L. Montanet, J. Vandermeulen, C. d'Andlau, A. Astier, P. Baillon, J. Cohen-Ganouna, C. Defoix, J. Siaud, and P. Rivet, in *Proceedings of the International Conference on High-Energy Physics, Dubna, 1964* (Atomizdat, Moscow, 1965).

[12] D. H. Miller, S. U. Chung, O. I. Dahl, R. I. Hess, L. M. Hardy, J. Kirz, and W. Koellner, Phys. Rev. Letters **14**, 1074 (1965).

corner of the plot, which may be interpreted either as an enhancement at low $K\bar{K}$ combined mass, or as large positive interference of two K^* bands.

For those events in the final state $K_1K_1\pi^+\pi^-\pi^0$ not containing an ω or an η [i.e., $M(\pi^+\pi^-\pi^0)$ between 620 and 740 MeV], the $K_1K_1\pi^0$ combined mass has been plotted in Fig. 7 (the shaded region). Although statistics are poor, there is some evidence of an enhancement here too at about 1410 MeV, while the $(K_1K_1\pi^\pm)$ combined mass is consistent with having a flat distribution.

Assuming that the E meson does exist, and can decay via the channel $K\bar{K}\pi$, the relative numbers decaying into $K_1K^\pm\pi^\mp$ and $K_1K_1\pi^0$ can be used to determine the charge conjugation C and G-parity quantum numbers of this meson. The $K\bar{K}$ system in a state of isotopic spin 1 (it appears as K^0K^- or $\bar{K}^0K^+$, both with $|I_z|=1$)

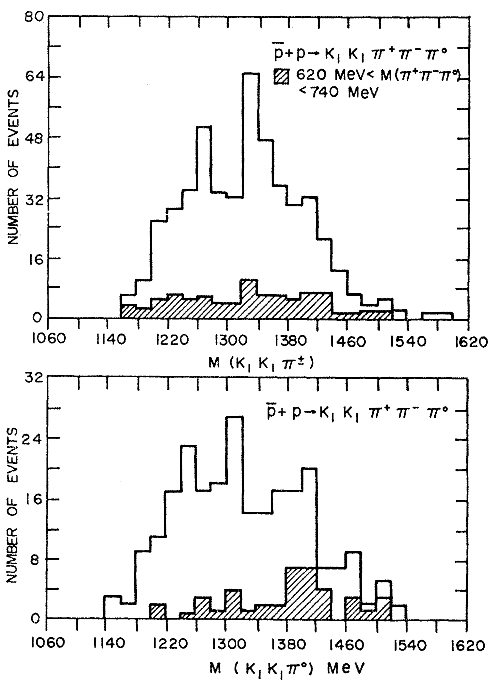

FIG. 7. Combined mass of $(K_1K_1\pi^0)$ and $(K_1K_1\pi^\pm)$ from the reaction $\bar{p}+p\rightarrow K_1K_1\pi^+\pi^-\pi^0$. The shaded region indicates events where the $(\pi^+\pi^-\pi^0)$ combined mass is between 620 and 740 MeV.

is coupled with a π, of isotopic spin 1. The isospin of the E is probably 0, since only a neutral component has been seen.[12] Coupling isospin 1 with isospin 1 to give a total isospin 0, we have the following relation among the various amplitudes:

$$|00\rangle=\frac{1}{\sqrt{3}}(K^-K^0)\pi^+ -\frac{1}{\sqrt{3}}\left(\frac{K^+K^-+K^0\bar{K}^0}{\sqrt{2}}\right)\pi^0+\frac{1}{\sqrt{3}}(K^+\bar{K}^0)\pi^-.$$

Thus, the ratio

$$(E\rightarrow K^0K^\pm\pi^\mp):(E\rightarrow K^+K^-\pi^0):(E\rightarrow K^0\bar{K}^0\pi^0)=1:\tfrac{1}{4}:\tfrac{1}{4}.$$

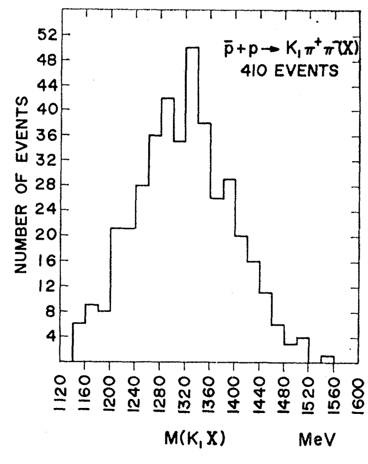

FIG. 8. Effective mass of (K_1X) from the reaction $\bar{p}+p\rightarrow K_1\pi^+\pi^-(X)$, where the mass of X is greater than 620 MeV.

If N is the number of events in the E peak in the channel $K_1K^\pm\pi^\pm\pi^\mp\pi^\mp$, then $3N$ is the total number of E mesons produced in the reaction $\bar{p}+p\rightarrow E^0\pi^+\pi^-$, which decay into $K^0K^\pm\pi^\mp$. We therefore expect $\frac{3}{4}N$ to be produced in the same way and decay into $K^0\bar{K}^0\pi^0$. The charge-conjugation quantum number of the E is the product $C(K\bar{K})\times C(\pi^0)=+C(K\bar{K})$. If $C(E)$ is $+1$, then $C(K\bar{K})=+1$, and the $K\bar{K}$ must decay as K_1K_1 or K_2K_2. Con-

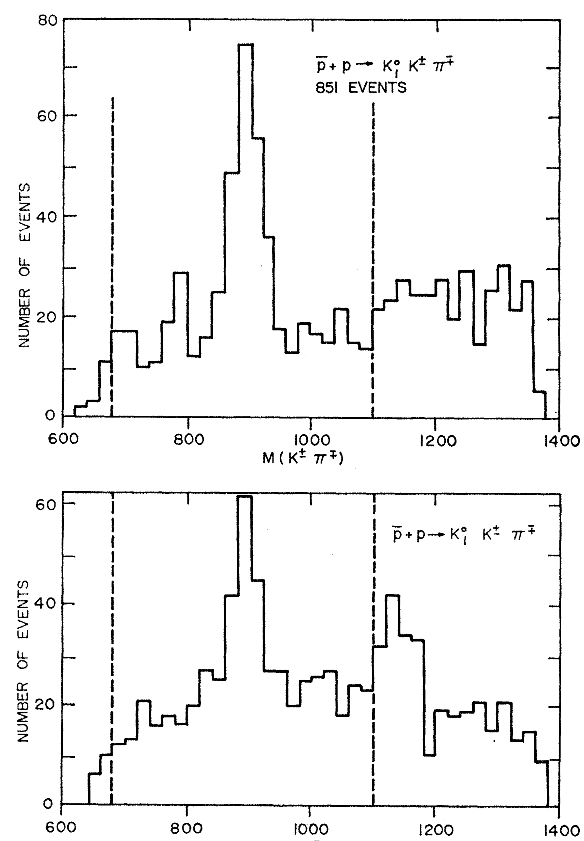

FIG. 9. Effective mass of neutral and charged $(K\pi)$ combinations from the reaction $\bar{p}+p\rightarrow K_1K^\pm\pi^\mp$. The region between the dashed lines was used in fitting for the K^* mass difference.

versely, if $C(E)=-1$, then the $K\bar{K}$ must decay as K_1K_2. In the case that $C(E)$ is $+1$, half of the events decaying as $K^0\bar{K}^0$ will appear as $K_1K_1\pi^0$, and approximately 4/9 of these will appear as double "V" events and should be seen as a bump at 1410 in the $K_1K_1\pi^0$ spectrum from the final state $K_1K_1\pi^+\pi^-\pi^0$. Since there are about 75 events above background in the peak at 1410 in Fig. 5, we would expect $\frac{3}{4}\times\frac{1}{2}\times(4/9)\times 75=12$ events above background in the $K\bar{K}\pi^0$ spectrum in the final state $K_1K_1\pi^+\pi^-\pi^0$. As can be seen from the shaded portion of Fig. 7, this prediction agrees with the experimental data. If $C(E)$ were -1, we would expect all events where the E decayed into two neutral K's to appear as $K_1K_2\pi^0$. The final state $K_1K_2\pi^+\pi^-\pi^0$ is not directly observable in this experiment. However, an estimate of the rate $E^0\to K_1K_2\pi^0$ can be obtained by considering events of the topology two prongs and one "V," where both prongs have ionization consistent with being pions. Interpreting these as $\bar{p}+p\to K_1\pi^+\pi^-(X)$, and selecting those events where the mass of X is greater than 620 MeV, we plot in Fig. 8 the combined mass of K_1X and find no peak in the region about 1410 MeV. We would expect 12 E^0 events in this plot if $C(E)$ were $+1$ and the decay of one of the $K_1{}^0$'s was not seen, and 37 events if $C(E)$ were -1 and the E^0 decays into $K_1{}^0K_2{}^0\pi^0$. Thus, it seems reasonable to assign an even charge-conjugation quantum number to the E meson. The G parity of the E is determined once C is known, since $G=C\times(-1)^I=+1$.

E. K^* Mass Difference

A number of predictions have been made as to the sign and magnitude of the mass difference between the charged and neutral components of the K^* meson.[13–16] We have attempted to measure the quantity $(M_{K^{*0},\bar{K}^{*0}}-M_{K^{*\pm}})$ using events from the reaction $\bar{p}+p\to K_1{}^0K^\pm\pi^\mp$. There are two advantages to using this reaction. First, both the charged and neutral K^*'s appear as prominent peaks above a relatively flat background, as may be seen in Fig. 9. In addition, both the charged and neutral components are seen in the same reaction. This eliminates both the possibility of an apparent shift in the position of a resonance when the incident energy in the production reaction is varied,[17] and the chance of systematic errors which may occur when the results of two independent experiments are combined. For details on selection and fitting of these events, see Ref. 1, in which the reaction $\bar{p}+p\to K_1{}^0K^\pm\pi^\mp$ is discussed more fully.

Events with neutral or charged $K\pi$ combined mass between 680 and 1100 MeV were chosen, and both classes of events were independently fitted, using the maximum-likelihood method,[18] to a function of the form

$$a_0+a_1m+a_2m^2+\frac{a_3+a_4(m-a_5)}{(m-a_5)^2+(a_6/2)^2},$$

where the first three terms describe the nonresonant background, and the last two terms describe pure resonance production and the interference between resonances and background. Because we have used a Bret-Wigner function alone, and have not multiplied it by phase space, the parameter a_5 does not correctly correspond to the mass of the K^*. However, since both neutral and charged K^*'s are produced in the same three-body reaction, the difference in this parameter between the neutral and charged spectra does give the mass difference. The value so obtained is

$$M_{K^{*0},\bar{K}^{*0}}-M_{K^{*+},K^{*-}}=6.3\pm 4.1 \text{ MeV}.$$

In order to check for systematic errors, we have used the same method to measure the quantities $(M_{K^{*-}}-M_{K^{*+}})$ and $(M_{\bar{K}^{*0}}-M_{K^{*0}})$, both of which should be zero if we assume TCP invariance. We find

$$M_{K^{*-}}-M_{K^{*+}}=3.7\pm 7.4\,,$$
$$M_{\bar{K}^{*0}}-M_{K^{*0}}=2.3\pm 4.8\,.$$

Both values are less than one standard deviation from zero. Even so, it should be noted that the direction in which each of these quantities deviates from zero is such that the K^0 momentum is lower and the K^- momentum higher than expected in the reaction $\bar{p}+p\to K^0K^-\pi^+$, while the $\bar{K}^0$ momentum is too high and the K^+ momentum too low in the reaction $\bar{p}+p\to\bar{K}^0K^+\pi^-$. Since events of the type $\bar{K}^0K^+\pi^-$ and $K^0K^-\pi^+$ are treated identically, and since no distinction is made between K^0 and $\bar{K}^0$, or between K^+ and K^-, it is therefore probable that the nonzero results for $(M_{K^{*-}}-M_{K^{*+}})$ and $(M_{\bar{K}^{*0}}-M_{K^{*0}})$ are not due to systematic errors in our experiment, but are merely statistical fluctuations.

Theoretical calculations by Duimio and Scotti[13] and by Bose[15] have both predicted the charged K^* to be heavier than the neutral K^*. Harari[14] and Rubinstein[16] have shown, however, that within the framework of $SU(6)$ and the quark model, the relation

$$M_{K^{*0},\bar{K}^{*0}}-M_{K^{*\pm}}=M_{K^0,\bar{K}^0}-M_{K^\pm}=4.2\pm 0.05$$

is expected to hold. Our result is in agreement with the latter prediction, but, because of limited statistics, a negative value for the quantity $(M_{K^{*0},\bar{K}^{*0}}-M_{K^{*\pm}})$ cannot be completely excluded.

ACKNOWLEDGMENTS

We would like to thank Dr. A. Prodell, the bubble chamber operating crews, and the AGS operations staff at Brookhaven National Laboratory for their help in

[13] F. Duimio and A. Scotti, Phys. Rev. Letters 14, 926 (1965).
[14] H. Harari, Phys. Rev. 139, B1323 (1965).
[15] S. Bose, Phys. Rev. 140, B349 (1965).
[16] H. R. Rubinstein, Phys. Rev. Letters 17, 41 (1966).
[17] J. D. Jackson, Nuovo Cimento 34, 1644 (1964).

[18] The general minimizing program MINFUN written by W. E. Humphrey was used.

the exposure. It is a pleasure to thank Dr. R. Plano and his associates at Rutgers University for their collaboration in the early stages of this experiment. We would also like to express our appreciation to Professor J. Steinberger, Professor P. Franzini, and Professor C. Baltay for many illiminating discussions. We also would like to acknowledge the efforts of the Nevis and Rutgers scanning and measuring staffs, and the aid of Mrs. A. McDowell and Miss Sharon Liebeskind for the figure drawings. Finally, we would like to thank Miss Ann Therrien and Mrs. Edna Thornton for secretarial assistance.

PHYSICAL REVIEW VOLUME 156, NUMBER 5 25 APRIL 1967

Radiative Decay of the Muon[*]

E. Bogart,[†] E. DiCapua,[‡] P. Némethy, and A. Strelzoff[§]
Columbia University, New York, New York

(Received 17 November 1966)

The radiative decay of the muon, $\mu^+ \to e^+ + \gamma + \nu_e + \bar{\nu}_\mu$, has been measured using muons from the Columbia University Nevis synchrocyclotron. The decay products e^+ and γ were observed at relative angles near 180°, using scintillation counters and two 9-in.×10-in. NaI crystals, which enabled simultaneous measurement of the positron and γ energies. The pulses from the crystals were displayed on oscilloscopes and photographed, and the measured amplitudes of these pulses were calibrated using the positron spectrum of the nonradiative decay. The two-dimensional energy spectrum for positrons and γ's was obtained for about 900 events, after subtraction of background. This spectrum and the measured rate, obtained by normalizing to the nonradiative decay, were compared with theoretical predictions for the radiative decay. The results were in good agreement with the theory, within statistics, for the case of pure V-A coupling.

I. INTRODUCTION

The radiative decay of the muon, $\mu^+ \to e^+ + \gamma + \nu_e + \bar{\nu}_{\mu'}$, has been observed by several groups.[1–4] Kim, Kernan, and York[3] measured the γ spectrum at forward electron-γ angles, and Rey[4] measured the angular correlation and electron range distribution for backward electron-γ correlations. Both of these experiments obtained good agreement with theoretical predictions for the radiative mode.

Theoretical calculations for radiative muon decay were developed by many authors.[5–9] Behrends, Finkelstein, and Sirlin[6] calculated the probability of inner bremsstrahlung as part of the complete radiative corrections for muon decay; and, in fact, the agreement of the radiative decay experiments with theory has served to substantiate these radiative corrections. Fronsdal and Überall[9] worked out the most general dependence of the radiative decay process on the weak-interaction coupling constants, including parity-nonconserving combinations. They noted that the radiative decay spectrum depends on the same parameters (e.g., ρ) as the nonradiative decay, but that the spectrum is also slightly sensitive to two new parameters which, like the others, are simple functions of the coupling constants.

The present experiment was undertaken in order to measure the first of the parameters introduced by Fronsdal and Überall. This parameter, denoted by η,[10] occurs only in the radiative mode, and measures directly the fraction of scalar and pseudoscalar coupling entering into muon decay. A measurement of η is in fact most comparable to a determination of the electron polarization; and it is a well-known fact that measurements of the nonradiative decay spectrum alone, without the polarization, cannot determine the nature of the weak-interaction coupling in muon decay.

---

* Work supported in part by the U. S. Office of Naval Research under Contract No. Nonr-266(72).

† Present address: Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania.

‡ Present address: Instituto di Fisica dell'Università di Roma, Rome, Italy.

§ Present address: Department of Physics, University of Rochester, Rochester, New York.

[1] J. Ashkin, T. Fazzini, G. Fidecaro, N. H. Lipman, A. W. Merrison, and H. Paul, Nuovo Cimento **14**, 1266 (1959); R. R. Crittenden, W. D. Walker, and J. Ballam, Phys. Rev. **121**, 1823 (1961).

[2] D. Bartlett, S. Devons, and A. M. Sachs, Phys. Rev. Letters **8**, 120 (1962); S. Frankel, J. Halpern, L. Holloway, W. Wales, M. Yearian, O. Chamberlain, A. Lemonick, and F. M. Pipkin, *ibid.* **8**, 123 (1962); S. Frankel, W. Frati, J. Halpern, L. Holloway, W. Wales, and O. Chamberlain, Nuovo Cimento **27**, 894 (1963); S. Parker, H. L. Anderson, and C. Rey, Phys. Rev. **133**, B768 (1964).

[3] C. Kim, W. Kernan, and C. York, Phys. Rev. **120**, 983 (1960).

[4] C. Rey, Phys. Rev. **135**, B1215 (1964).

[5] A. Lenard, Phys. Rev. **90**, 968 (1953); T. Kinoshita and A. Sirlin, *ibid.* **107**, 593 (1957); S. G. Eckstein and R. H. Pratt, Ann. Phys. (N. Y.) **8**, 297 (1959).

[6] R. Behrends, R. Finkelstein, and A. Sirlin, Phys. Rev. **101**, 866 (1956).

[7] N. Tzoar and A. Klein, Nuovo Cimento **8**, 482 (1958).

[8] R. H. Pratt, Phys. Rev. **111**, 649 (1958).

[9] C. Fronsdal and H. Überall, Phys. Rev. **113**, 654 (1959).

[10] We have preserved the notation of Fronsdal and Überall in denoting this parameter by η. It should be emphasized that this parameter is not the same as the low-energy shape parameter for muon decay, which has also come to be denoted by η.