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INTERACTIONS OF NEUTRAL K MESONS IN HYDROGEN*

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ABSTRACT

The reaction $\pi^- + p \rightarrow \Lambda + K^0$ in the 72-inch hydrogen chamber was used to produce 7220 K^0 mesons associated with a visible decay $\Lambda \rightarrow p + \pi^-$. The time dependence and absolute yield of the subsequent strong interactions of K^0 and $\overline{K}^0$ in hydrogen were used to determine all the parameters of the neutral K system, without the assumption of CPT invariance or other assumptions about the weak interactions of neutral K's. From the time distribution of 59 events of the type $\overline{K}^0 + p \rightarrow$ hyperon we find the magnitude of the $K_S^0 - K_L^0$ mass difference. We then determine the mixing parameters p, q, p', q' of the neutral K system by means of the time dependence and absolute yield of 11 charge-exchange events, $K^0 + p \rightarrow K^+ + n$, and the absolute yield of 49 two-body interactions, $\overline{K}^0 + p \rightarrow$ hyperon + pion. The results are consistent with CPT invariance and with values of the mixing parameters determined by means of weak interactions.

We find the Biswas ratio $R \equiv \sigma[K_L p \to K_S p]/\sigma[K_L p \to \text{hyperon}]$ to be $R = 0.41 \pm 0.13$ averaged over K_L momenta from about 200 to 600 MeV/c. This agrees with Solution I of Kim and with the results of Kadyk et al. Our absolute yields for $\bar{K}^0 + p \to$ hyperon + pion are in good agreement with the predictions of charge independence and the measured rates for $K^- + p \to$ hyperon + pion. For the front-back asymmetry of the Λ in $\bar{K}^0 + p \to \Lambda + \pi^+$ we find $(F-B)/(F+B) = -0.48 \pm 0.18$, indicating that P wave cannot be neglected relative to S wave in our momentum range. On the basis of one event satisfying the hypothesis $\bar{K}^0 + p \to \Lambda + \pi^+ + \gamma$, we obtain a branching ratio

$$\Gamma[Y_1^{*0}(1385) \to \Lambda\gamma]/\Gamma[Y_1^{*0}(1385) \to \text{all}] = 0.17.$$

I. INTRODUCTION

We have previously used the time dependence of $\overline{K}^0 + p \rightarrow$ hyperon to obtain the magnitude of the $K_S - K_L$ mass difference,[1] and used the time dependence of $K_{neutral} + p \rightarrow K_S^0 + p$ to find the sign of the mass difference.[2] In this article we analyze the absolute yields of $\overline{K}^0 + p \rightarrow$ hyperon and of $K^0 + p \rightarrow K^+ + n$, and the time dependence of $K^0 + p \rightarrow K^+ + n$, in the momentum range 0 to 900 MeV/c. In the following sections we discuss the experimental arrangement, scanning procedures, and data analysis; a determination of the mixing parameters p, p', q, and q' of the neutral K system; and a determination, based on one event, of the branching ratio of the radiative decay of the Y_1^{*0} (1385).

II. EXPERIMENTAL PROCEDURE

A. Beam

The Alvarez 72-inch hydrogen bubble chamber was exposed to a π^- beam of 1030 and 1170 MeV/c. The beam-transport system has been described previously,[3] and has as its most important characteristic a good resolution. The full width at half maximum of the beam momentum distribution is about 10 MeV/c.

At 1170 MeV/c about 9×10^4 triads of pictures were taken, and at 1030 MeV/c about 3×10^5. Approximately 17 tracks per picture entered within a chosen fiducial area. The bubble chamber magnetic field strength was 17.91 kG for the 1170-MeV/c beam and

15.70 kG for the 1030-MeV/c beam.

B. Scanning

The film was scanned for associated production events involving a visible Λ decay:

$$\pi^- + p \rightarrow \Lambda + K^0, \qquad \Lambda \rightarrow p + \pi^- \qquad \text{(5860 events)}, \quad (1a)$$

$$\pi^- + p \rightarrow \Sigma^0 + K^0, \qquad \Sigma^0 \rightarrow \Lambda + \gamma, \ \Lambda \rightarrow p + \pi^- \qquad \text{(1360 events)}. \quad (1b)$$

These events were measured with "Franckenstein" film-plane projectors, and sent through PANG and KICK.[4] When reactions (1) were thoroughly processed, a special scan along the direction of the missing K^0 was performed. Scanners searched along the calculated direction of the missing neutral for interactions or decays that may have been missed in the initial scan. We required no minimum length of the neutral K, since the topology for associated production with visible Λ decay, plus a zero-length K^0 interaction or decay, is so striking that such an event would not be missed on the rescan.

We consider ΛK^0 and $\Sigma^0 K^0$ production separately.

1. ΛK^0 Production

The missing K^0 direction is known typically to within ±0.4 deg in dip and azimuth, and the missing K^0 momentum to ±1.5%. We scanned along the missing K^0 direction, using a protractor, and provisionally accepted all interaction candidates within ±5 deg in azimuth of the predicted direction. We believe our scanning efficiency is essentially 100%.

2. $\Sigma^0 K^0$ Production

The missing K^0 direction is poorly known (because of the undetected γ from $\Sigma^0 \rightarrow \Lambda + \gamma$). We rescanned these pictures only for neutral K interactions followed by a $p\pi^-$ decay. The pictures are clean (about 17 beam π^- per picture), and we believe the second-scan efficiency is 100% for these secondary events. The background is negligible, and there are no spurious or ambiguous events.

We do not use any events for which the Λ produced in association with the K^0 in reaction (1) does not decay visibly. If we did, we could guarantee 100% scanning efficiency for K interactions, independent of K^0 proper time, only by scanning the entire film many times. No bias is introduced if we find all K interactions associated with our sample of visible Λ's in reaction (1). By demanding visible Λ's in reaction (1) we thereby eliminate the possibility of an ambiguity between two possible production vertices; the information from the Λ decay also eliminates some kinematical ambiguities that might otherwise remain.

C. Data Processing

All neutral K interactions of the following types were analyzed:

$\overline{K}^0 + p \rightarrow \Lambda + \pi^+$ (22 events), (2a)

$\Sigma^0 + \pi^+$ (18 events), (2b)

$\Sigma^+ + \pi^0$ (9 events), (2c)

$$\Lambda + \pi^+ + \pi^0 \qquad (5 \text{ events}), \qquad (2d)$$

$$\Sigma^+ + \pi^- + \pi^+ \qquad (1 \text{ event}), \qquad (2e)$$

$$\Lambda + \pi^+ + \gamma \qquad (1 \text{ event}), \qquad (2f)$$

$$K^0 + p \rightarrow K^+ + n \qquad (11 \text{ events}), \qquad (2g)$$

$$\left.\begin{array}{l} K_{neutral} + p \rightarrow K_{neutral} + p, \\ \qquad\qquad K_{neutral} \rightarrow \pi^+ + \pi^- \end{array}\right\} \qquad (23 \text{ events}). \qquad (2h)$$

There are slight differences between the numbers of events here and in Ref. 1 due to the different fiducial volumes used in the two experiments. Measurements and kinematical analysis of reactions (2) were done in a manner similar to that used in the analysis of reactions (1). For those events which proved to be especially troublesome, the Alvarez Group QUEST system[5] was used. We use χ^2 cutoffs, at the 0.3% probability level, of 8.6, 11.6, 14.0, and 16.0, for one-, two-, three-, and four-constraint fits, respectively.

In those cases in which the strange particle produced in reactions (2) does not decay, random recoil protons give a background; this is because the positive track in reactions (2) is sometimes indistinguishable on the scanning table from a recoil proton arising from an n-p scattering due to random neutron background. There are about 900 such candidates (i.e., about 15% of the missing K^0's have a random recoil proton lying within ±5 deg). We measure the neutral "track" from the production point to the recoil and reduce the amount of background by rejecting recoils that have a

neutral differing by more than five standard deviations from the predicted K^0 direction.[6] The remaining 300 events are fitted (one constraint) to reactions (2).

III. MIXING PARAMETERS OF THE NEUTRAL K SYSTEM

A. Introduction

The mixing parameters p, p', q, and q' of the neutral K system are defined by the following relationships among $|K_S\rangle$, $|K_L\rangle$, $|K^0\rangle$, and $|\bar{K}^0\rangle$:

$$\begin{aligned} |K_S\rangle &= p\,|K^0\rangle + q\,|\bar{K}^0\rangle, \\ |K_L\rangle &= p'|K^0\rangle - q'|\bar{K}^0\rangle, \end{aligned} \tag{3}$$

CP invariance demands $p = p' = q = q'$, whereas CPT invariance demands $p = p'$ and $q = q'$, but does not restrict $|p/q|$ or $|p'/q'|$ to be 1. Normalization conditions $|p|^2 + |q|^2 = |p'|^2 + |q'|^2 = 1$, absolute phase convention of $|K_S\rangle$ and $|K_L\rangle$, and relative phase convention between $|K^0\rangle$ and $|\bar{K}^0\rangle$ reduce the number of real independent parameters from eight to three, which we can take to be the complex number $(p/q)/(p'/q) \equiv |z|\,e^{i\phi} \equiv x + iy$ and either $|p/q|$ or $|p'/q'|$. Alternatively, we can take them to be $|p/q|$, $|p'/q'|$, and ϕ.

From weak decays alone, and with no assumption of CPT invariance, we have the relationships[7]

$$|q'/p'| = 1.00 \pm 0.016, \quad (\approx 0.97) \leq |q/p| \leq (\approx 1.03),$$

$$(\approx -0.03) \leq \phi \leq (\approx +0.03).$$

We shall now determine these parameters using only strong inter-

actions. The results must of course agree with those determined, using weak decays alone, for a consistent two-component theory of neutral K mesons.

B. $K^0 + p$ Charge Exchange

If at $t = 0$ the neutral kaon system is pure K^0, then at a later time t, the probability amplitude ψ_K of the system is given by

$$\psi_K = \left(\frac{1}{pq' + p'q}\right)\Big\{|K^0\rangle[(q'p)\exp(-\tfrac{1}{2}\lambda_S t - im_S t) + (qp')\exp(-\tfrac{1}{2}\lambda_L t - im_L t)] + |\overline{K}^0\rangle(q'q)[\exp(-\tfrac{1}{2}\lambda_S t - im_S t) - \exp(-\tfrac{1}{2}\lambda_L t - im_L t)]\Big\}. \tag{4}$$

Here λ_S and λ_L are the decay constants and m_S and m_L are the masses of K_S and K_L, respectively.[8] When the $|K^0\rangle$ component from (4) is projected out, the probability dp of $K^0 + p$ charge exchange at proper time t within an interval dt is given by

$$dp\,(x, y, t) = k\sigma|(K^0, \psi_K)|^2\ P_K/m_K\ c\epsilon(t)dt,$$

where k is a constant [$= 1/(28.6\times 10^3$ mb cm) in hydrogen], σ is the cross section in mb for reaction (2g) at a K^0 momentum P_K, $m_K = 498.0$ MeV/c^2, $c = 3\times 10^{10}$ cm/sec, and $\epsilon(t)$ is the geometrical detection efficiency for reactions (2).

If we integrate over dt from 0 to the potential proper time T, and sum over reactions (1a), the expected number of charge-exchange events n is given by

$$n = k\sum_{i=1}^{N^\Lambda} \sigma_i \ell_i g_i, \tag{5}$$

where ℓ is the potential path length of the kaon, and where g, the probability for the neutral kaon to be a K^0 along its potential path, is given by

$$g = \frac{1}{T} \int_0^T \left| (K^0, \psi_K) \right|^2 \epsilon(t) dt, \tag{6}$$

$$g = \frac{1}{T} \frac{1}{(1+x)^2 + y^2} \int_0^T \left\{ (x^2 + y^2) \exp - \lambda_S t + \exp - \lambda_L t \right.$$

$$\left. + 2 \exp[-\tfrac{1}{2}(\lambda_S + \lambda_L)t][x \cos mt - y \sin mt] \right\} \epsilon(t)\, dt.$$

Of the 11 observed $K^0 + p$ charge-exchange interactions, five were unambiguously identified as having a K^+n final state by kinematical fits. (Two of the five were tagged by K^+ decays.) Examination of relative ionization on the scanning table identified five more K^+, and the remaining event was resolved by gap counting. A list of these 11 events is given in Table I. The expected time distribution of these events is given by $N(t)\, \epsilon(t)$, where

$$N(t) = (x^2 + y^2) \exp(-\lambda_S t) + \exp(-\lambda_L t)$$

$$+ 2 \exp[-\tfrac{1}{2}(\lambda_S + \lambda_L)t](x \cos mt - y \sin mt). \tag{7}$$

The time distribution of our 11 events is shown in Fig. 1. The smooth curves are expected distributions.

We use the method of maximum likelihood to find our most probable values of x and y. For a given x and y, the likelihood

L (x, y) for our experiment is

$$L(x, y) = \prod_i \frac{N(t_i)}{\int_0^{T_i} N(t)\, dt},$$

where t_i is the proper time of interaction, and where T is the potential proper time of K^0. Results are shown in Fig. 2 (a), where the solid circle gives the value of x and y which maximizes L(x, y) : x = -3, y = +4.2. The closed curves correspond to values of equal likelihood given by $L = \exp(-n^2/2)\, L_{max}$, where n = 1 and 2. There are two n = 2 contours. The smaller n = 2 contour surrounds a "hole" and passes very close to the values x = 1, y = 0 predicted by CPT invariance.

For a given value of x and y, we calculate the expected number of K^0 + p charge-exchange events from Eqs. (5) and (6). The path length as a function of momentum over which the neutral kaon is a K^0 is shown in Fig. 3, using the assumption p = p' = q = q' = 1. The average momentum of K^0's from reaction (1a), weighted by their potential path length, is 527 MeV/c. We assume charge symmetry and use the measured cross section[9] at 530 MeV/c for $K^+ + n \rightarrow K^0 + p$ of 6.60 ± 0.56 mb. We plot the results in Fig. 2b as contours of equal expected counts, as a function of x and y. Besides the 11 unambiguous K^+n events, we have an additional 1.3 events, prorated from six ambiguous events on the basis of kinematic and ionization information. The result is a total of 12.3 interactions of type (2g). Using Eqs. (5) and (6), the above cross

section, and the values of x and y corresponding to CPT invariance ($x = 1$, $y = 0$), we predict 16.1 $K^0 + p$ charge exchanges, which is in reasonable agreement with the corrected experimental number of 12.3.

Using Eq. (7), we form a likelihood function as described above to determine $|m|$ with our 11 events, assuming CPT invariance. We show $L(x=1,\ y=0,\ |m|)$ in Fig. 4 for the 11 events. L is maximized at $|m| = 1.3\lambda_S$. The limits indicated by the horizontal bar correspond to $L = \exp(-\frac{1}{2})L_{max}$. Our data are not inconsistent with the world average of $|m| = 0.46\ \lambda_S$.

C. Inelastic $\overline{K}^0 + p$ Reactions

The probability $d\overline{p}$ that a neutral kaon will scatter inelastically to produce a hyperon is given by

$$d\overline{p}(x, y, t) = k\overline{\sigma}\,|(\overline{K}^0, \psi_K)|^2 \left(\frac{P_k}{m_k}\right) c\,\epsilon(t)\,dt,$$

where $\overline{\sigma}$ is the appropriate cross section, and where ψ_K is given by Eq. (4). When $d\overline{p}$ is integrated as before, the total number of expected counts $\overline{n}$ is given by

$$\overline{n} = k\left[\sum_{i=1}^{N^\Lambda} \ell_i \overline{g}_i \overline{\sigma}_\Lambda + 0.663 \sum_{i=1}^{N^\Sigma} \ell_i \overline{g}_i \overline{\sigma}_i\right], \tag{8}$$

where N^Σ indicates that the second summation is over reaction (1b), where the factor 0.663 is the branching ratio $\Gamma(\Lambda \to p\pi^-)/\Gamma(\Lambda \to \text{all})$ and is there because for $\Sigma^0 K^0$ production we demand a visible Λ decay,

and where $\bar{g}$, the probability for the neutral kaon to be a $\bar{K}^0$ along the potential path, is given by

$$\bar{g} = \frac{1}{T} \int_0^T |(\bar{K}^0, \psi_K)|^2 \, \epsilon(t)\, dt,$$

$$\bar{g} = \frac{1}{T} \frac{|q'/p'|^2}{(1+x)^2 + y^2} \int_0^T \Big\{ \exp^{-\lambda_S t} + \exp^{-\lambda_L t} \tag{9}$$

$$-2 \exp[-\tfrac{1}{2}(\lambda_S + \lambda_L)t] \cos mt \Big\} \, \epsilon(t)\, dt.$$

Since the integrand to Eq. (9) is independent of x, y, $|p/q|$, and $|p/q'|$, we can use events of type (2a-2f) to determine the magnitude of the mass difference, without assuming CPT invariance. Our result[1] of $0.65 \pm 0.30\, \lambda_S$, in agreement with the world average of $0.46\, \lambda_S$, indicates that our scanning and data-analysis procedures are free from biases.

Denoting the cross sections for reactions (2a) (2b), and (2c) by σ_a, σ_b, and σ_c, and those for the processes $K^- + p \to \Lambda + \pi^0$, $K^- + p \to \Sigma^- + \pi^+$, $K^- + p \to \Sigma^+ + \pi^-$, and $K^- + p \to \Sigma^0 + \pi^0$ by σ_1, σ_2, σ_3, and σ_4, we can use charge independence to get the relation

$$\sigma_a + \sigma_b + \sigma_c = 2[\sigma_1 + \sigma_2 + \sigma_3 - 2\sigma_4]. \tag{10}$$

When the K^0 momentum from reactions (1a) and (1b) is weighted by its potential path, the average $\bar{K}^0$ momentum is 527 and 345 MeV/c, respectively. In Fig. 5 we show the measured values for the right-hand side of Eq. (10), using data from Watson et al.,[10] Bastien and Berge,[11] and Wojcicki.[12] From the smooth curve through the

points, we read off cross sections at 345 and 527 MeV/c of $\approx 25.0 \pm 5.0$ mb and 15.0 ± 3.0 mb, respectively. Including corrections for ambiguous events (an additional 3.5 counts) and corrections to reaction (2c) via ΣK production (2.16 ± 0.74 events), there is a total of 55.88 ± 7.52 events of types (2a), (2b), and (2c). Using this information, the cross sections mentioned above, and Eqs. (8) and (9), we can solve for $|q'/p'|$ for given values of x and y. If CPT invariance holds ($x = 1$, $y = 0$, or $q/p = q'/p'$), we find $|q'/p'| = 1.16 \pm 0.12$, in good agreement with $|q'/p'| = 1.00 \pm 0.016$, obtained from weak interactions without assuming CPT invariance. Our value is also in agreement with the value expected if CP invariance holds ($|q'/p'| = 1.0$). If we use the values of x and y which maximize the likelihood function ($x = 3.0$, $y = +4.3$), we get $|q'/p'| = 2.75 \pm 0.29$, in considerable disagreement with the weak-interaction value. Because of the large statistical uncertainties in our values of x and y, this disagreement is not significant.

In summary, we use Eq. (9) and the time distribution of inelastic $\bar{K}^0 + p$ reactions to give us a value of $|m_S - m_L|$, and the time distribution of $K^0 + p$ charge exchange to obtain values of x and y through Eq. (7). We use absolute cross sections for additional information on x and y as well as a determination of $|p'/q'|$, by means of Eqs. (5), (6), (8), and (9). Our data give values of the kaon mixing parameters in agreement with CPT and with values determined from weak interactions.

IV. PARTIAL CROSS SECTIONS

In this section we assume that CP invariance holds ($x = 1$, $y = 0$; or $q/p = q'/p' = 1$).

A. K_L-p Interactions

Biswas[13] first pointed out the importance of the ratio $R \equiv \sigma(K_L\, p \to K_S\, p)/[\sigma(K_L\, p \to \text{hyperon})]$ in resolving the twofold ambiguity in complex S-wave scattering lengths obtained from low-energy $K^- + p$ elastic and charge-exchange scattering. The sensitivity of R to the various solutions is due to the interference terms between amplitudes corresponding to elastic scattering of different strangeness states.

Taking a time cutoff of three K_S^0 lifetimes, we can calculate the partial cross sections for $K_L + p$ scattering into the $\Lambda + \pi$, $\Sigma + \pi$, and $K_S + p$ channels from our data for reactions (2). We restrict ourselves to K^0 momentum less than 600 MeV/c to avoid the presence of large P waves. From Table I of Ref. 1 there are 17 interactions of the type (2a) satisfying these criteria. Two corrections are necessary for reactions (2a) where the Λ does not decay visibly. The first is from ambiguous events, which contribute 3.5 events. Since we scanned for reactions (1b) and (2) only where the Λ decays visibly, we have an additional correction of 3.2 events, resulting in a total number n_Λ of reactions (1) in which the K_L interacts to produce $\Lambda + \pi^+$, giving $n_\Lambda = 23.7 \pm 5.3$ events. Similar considerations for the number n_{Σ^0} of reactions (1) in which the K_L interacts to

produce $\Sigma^0 + \pi^+$ result in $n_{\Sigma}{}^0 = 15.3 \pm 4.1$. Also, the number n_{Σ^+} of reactions (1) followed by the reaction $K_L + p \rightarrow \Sigma^+ + \pi^0$ becomes $n_{\Sigma^+} = 8.5 \pm 3.5$. Including reactions (2d), (2e), and (2f), which satisfy our criteria, and correcting for neutral hyperon decays, we have a total of 53.4 ± 8.2 events of type (1) followed by $K_L + p \rightarrow$ hyperon.

Using the data from Ref. 2,[14] we find a total of 22.0 ± 5.7 events of type (1) followed by the reaction $K_L + p \rightarrow K_S + p$. Combining this data with the above, we obtain

$$R = 0.41 \pm 0.13,$$

at an average momentum of 500 MeV/c. This value of R agrees with the experimental values of Kadyk et al.,[15] and with the prediction of Solution I of Kim.[16]

The partial cross sections for $K_L + p$ into the $\Lambda + \pi^+$, $\Sigma^0 + \pi^+$, $\Sigma^+ + \pi^0$, $K^+ + n$, and $K_S + p$ channels, as well as the total inelastic hyperon cross section [reactions (2a) through (2e)], are given in Table II for the momentum range 0-600 MeV/c. In Fig. 6 we show some of these values as well as those from Luers et al.[17]

B. Charge Independence

1. $\bar{K}N$ Channel

Using Ref. 1, and including corrections mentioned in Sec. IV.A, we find that the total number n_0 of reactions (1) followed by reaction (2b) is 20.1 ± 4.8. Similarly, the number n_+ of reactions

(1) followed by reaction (2c) is 12.8 ± 4.3. The ratio $n_0/n_+ = 1.57 \pm 0.65$ is in reasonable agreement with the value 1.0 expected if charge-independence invariance holds.

The left side of Eq. (10), based on 55.88 ± 7.52 events and at an average $\bar{K}^0$ momentum of 483 MeV/c, is equal to 22.50 ± 3.03 mb. The right side, from Fig. 5, is equal to 17.0 ± 4.5 mb. The ratio of these two numbers, 1.32 ± 0.39, is in good agreement with the charge-independent value of 1.0.

2. KN Channel

If CPT invariance is assumed, our data give a charge-exchange cross section, at the weighted average K^0 momentum of 527 MeV/c, of 4.50 ± 1.36 mb, in good agreement with the measured[9] charge-symmetric cross section of 6.60 ± 0.56 mb at the same energy.

C. $\Lambda\pi$ Front-back Asymmetry

In Fig. 7 we show a scatter plot of P_K vs $\cos\theta^*_{\Lambda K}$, for the 22 events of type (2a). $\theta^*_{\Lambda K}$ is the c.m. scattering angle between the outgoing Λ and the incident $\bar{K}^0$. The front-back asymmetry is given by

$$\frac{F-B}{F+B} = -0.45 \pm 0.27,$$

where F is the number of Λ's with $\cos\theta^*_{\Lambda K}$ greater than zero in reaction (2a), and B is the number with $\theta^*_{\Lambda K}$ less than zero. This anisotropy, although based on limited statistics, is in

qualitative agreement with that seen by Kadyk et al.,[15] and indicates, as does the front-back asymmetry for reactions (2h) (see Ref. 14), the need for substantial P wave in the $\bar{K}N$ system at low energy.

D. $Y_1^*(1385)$

1. Production Cross Section

Included in the 59 events listed in Ref. 1 are seven three-body final states: $\Lambda\pi^+\pi^0$ (5 events), $\Sigma^+\pi^+\pi^-$ (1 event), and $\Lambda\pi^+\gamma$ (1 event). The events with Λ production are partially summarized in Table III. Both measured and fitted quantities are used as input.

In Fig. 8 we show the path length available from reactions (1) for inelastic $\bar{K}^0 + p$ interactions as a function of momentum in bins of 100 MeV/c. We also show the momentum of the six $\Lambda\pi^+\pi^0$, $\Lambda\pi^+\gamma$ events. Note that the $\bar{K}^0$ momentum threshold for $Y^*\pi$ production is $\approx$ 405 MeV/c, whereas $\Lambda\pi^+\pi^0$ production can occur at rest. In Fig. 9 we show the Dalitz plots for these six events. Two events are shown on the same plot if the beam momenta of the pair are sufficiently close.

Three-body production at low $\bar{K}^0$ momentum is inhibited because of phase-space and symmetry considerations, which dictate that the two pions be in a relative P-wave final state. We take the fact that the lowest beam momentum of these three-body final states is 100 MeV/c above the $Y_1^*(1385)$-π threshold and the proximity of these events to the $Y_1^*(1385)$ bands on the Dalitz

plots as evidence for $Y_1^* \pi$ production. On the basis of 6 Y^{*0} and 4 Y^{*+} candidates,[18] we report cross sections for the reactions $\bar{K}^0 p \rightarrow Y^{*0} \pi^+$ and $K^0 p \rightarrow Y^{*+} \pi^0$, averaged over the momentum range $400 \leq P_K \leq 900$ MeV/c, of 4.9 ± 2.0 mb and 3.3 ± 1.6 mb, respectively.

2. Evidence for Radiative Decay of $Y_1^*(1385)$

We have used TVGP and SQUAW[19] to kinematically analyze the $\Lambda \pi^+ \gamma$ candidate. All three views are used in the reconstruction of the event, and the entire event may be fitted at once. For example, we may fit the entire reaction $\pi^- + p \rightarrow \Lambda + K$, $\Lambda \rightarrow p + \pi^-$, $\bar{K}^0 + p \rightarrow \Sigma^0 + \pi^+$, $\Sigma^0 \rightarrow \Lambda + \gamma$, $\Lambda \rightarrow p + \pi^-$ at once with 11 constraints. Similarly, we may check for Coulomb scattering on the recoil π^+ with 10 constraints if $\Lambda + \pi^+$ are produced at the secondary vertex or four constraints if $\Sigma^0 + \pi^+$ are produced. Fits to all these hypotheses resulted in very high χ^2's. We are also able to definitely rule out $\Sigma^0 + K^0$ production. The kinematic fit as well as the ionization of all the tracks in the event is consistent with the hypothesis $\pi^- + p \rightarrow \Lambda + K^0$, $\Lambda \rightarrow p + \pi^-$, $\bar{K}^0 + p \rightarrow \Lambda + \pi^+ + \gamma$, $\Lambda \rightarrow p + \pi^-$; the event is further constrained by the stopping of both decay products of the secondary Λ. The above hypothesis is the only one giving a χ^2 for the entire event of less than 40; the 10-constraint fit to the $\Lambda \pi^+ \gamma$ hypothesis gives an overall $\chi^2 = 6.4$. Fits for each separate vertex are also consistent with our hypothesis.

On the basis of the kinematical fit and of Fig. 9(d), we can interpret 1405053 to be either $\bar{K}^0 + p \rightarrow Y_1^{*0} + \pi^+$, $Y_1^{*0} \rightarrow \Lambda + \gamma$ or

$K^0 + p \rightarrow Y_1^{*+} + \gamma$, $Y_1^{*+} \rightarrow \Lambda + \pi^+$. The former interpretation allows for a more plausible explanation than does the latter.

The reaction $K^- + p \rightarrow \Lambda + \pi^+ + \pi^-$ has been most often used to study properties of the $Y_1^{*\pm}(1385)$. Reactions which allow examination of the neutral Y_1^* include $\bar{p}p$ annihilation, $K^- + p \rightarrow \Lambda + \pi^+ + \pi^- + \pi^0$, $\pi^- + p \rightarrow \Lambda + K^0 + \pi^0$, and $K_2^0 + p \rightarrow \Lambda + \pi^+ + \pi^0$. Martin et al.,[20] who used the last reaction, were restricted to a zero-constraint fit because of uncertainty in the beam momentum, and hence were unable to search for γ rays.

It was not possible to separate γ rays from π^0's in most of the experiments which have been executed[21] using the reactions mentioned above. Our experiment has sufficient beam momentum resolution so that the small uncertainty in the $\bar{K}^0$ momentum ($\approx 1.5\%$) allows us to distinguish γ's from π^0's.

Assuming that all the events in Table III are $[Y_1^*(1385)]^0$ production, we find the branching ratio (based on one event).

$$R \equiv \Gamma[(Y_1^*)^0 \rightarrow \Lambda\gamma]/\Gamma[(Y_1^*)^0 \rightarrow \text{all}] = 0.17. \qquad (11)$$

The radiative decay can occur either by a magnetic dipole or by an electric quadrupole transition. The assumption of U-spin invariance leads to a prediction of the radiative branching ratio of the $(Y_1^*)^0$. Levinson et al.[22] give the following relation between the amplitudes for the electromagnetic decay of the $(Y_1^*)^0$ and of the $[N^*(1238)]^0$:

$$\text{amp}\,(N^{*0} \rightarrow n\gamma) = 2/\sqrt{3}\ \text{amp}\,(Y^{*0} \rightarrow \Lambda\gamma). \qquad (12)$$

We make the ansatz that the reduced width $\gamma(N^{*+} \to \gamma p)$ for the process $(N^*)^+ \to \gamma + p$ equals the reduced width $\gamma(N^{*0} \to \gamma n)$ for the decay $(N^*)^0 \to \gamma + n$. Using the principle of detailed balance and taking the photoproduction cross section for the reaction $\gamma + p \to n + \pi^+$ from Källen,[23] we find that, at a c.m. energy of 1238 MeV, $\sigma(n\pi^+ \to \gamma p) = 0.664$ mb. Charge independence equates $N^*(1238)$ production cross section from $\pi^+ + n$ and $\pi^- + p$ interactions, so that, taking the cross section for the reaction $\pi^- + p \to N^*(1238)$ of ≈ 200 mb[24] at resonant energy, we have the branching ratio $[\sigma(\pi^+ n \to (N^*)^+ \to \gamma p)]/\sigma[\pi^+ n \to \text{all}] = 0.0033$. Using a total width of 120 MeV, we have the experimental width $\Gamma[(N^*)^0 \to \gamma p] = 0.40$ MeV. To relate Γ to the reduced width $\gamma = c^2 |M|^2$, where c^2 is the SU(3) Clebsch-Gordan coefficient, and where M is the effective SU(3) matrix element, we use the relations[25]

$$\Gamma = \gamma D,$$

$$D = \frac{[P^2 X^2]^{\ell}}{1 + P^2/X^2} \frac{P}{M}, \tag{13}$$

where P is the momentum of the decay products in the rest frame of the Y_1^* of mass M, ℓ is the orbital angular momentum in the final state, and X is the interaction length. Using an interaction radius of $(1.5\ m_\pi)^{-1}$, we find $\gamma(N^* \to \gamma p) \equiv \gamma(N^* \to \gamma n) = 4.8$ MeV. Using relations (12) and (13), we find $\Gamma[Y_1^{*0} \to \Lambda\gamma] \approx 0.3$ MeV, so that the predicted radiative branching ratio of the Y_1^{*0} is $R \approx 0.007$. Our experimental value is 0.17 based on one event. The predicted number of events is $0.007/0.17 = 0.04$ event. The <u>a priori</u>

probability of seeing our one event is therefore 0.04, according to the above prediction. Perhaps we were lucky.

V. CONCLUSIONS

1. We have used the time distribution of 11 $K^0 + p$ charge-exchange events and the absolute cross section for these events and for 49 $\overline{K}^0 + p$ inelastic two-body interactions to determine the three independent parameters of the neutral kaon system, without assumptions of CPT invariance. Our result for the value of the complex number $(p/q)/(p'/q') \equiv z$ is consistent within the statistical uncertainties with the values predicted by CPT invariance (Re $z = 1$, Im $z = 0$). We then find the third independent parameter $|q'/p'| = 1.16 \pm 0.12$, in agreement with the value obtained from weak interactions without assuming CPT invariance (1.00 ± 0.016).

2. We find inelastic cross sections in the $K^0 + p$ and $\overline{K}^0 + p$ channels which are consistent with charge symmetry (for $K^0 + p$) and charge independence (for $\overline{K}^0 + p$).

3. Partial cross sections of $K_L + p$ give evidence that favors solution I of the ambiguity in Kim's S-wave scattering lengths.[16]

4. The front-back asymmetry which we observe in the reaction (2a) indicates the need for P wave below 600 MeV/c in the $\overline{K}^0$ p system.

5. From one event of the type $\overline{K}^0 + p \rightarrow \Lambda + \pi^+ + \gamma$, we find

$$\frac{\Gamma[Y_1^{*0}(1385) \rightarrow \Lambda\gamma]}{\Gamma[Y_1^{*0}(1385) \rightarrow \text{all}]} = 0.17.$$

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Footnotes and References

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Table I. Summary of 11 $K^0 + p$ charge-exchange events; t and T are the actual and potential interaction proper times in 10^{-10} sec, P_K is the lab momentum in MeV/c, and θ^*_{KK} is the c.m. scattering angle of the K^+.

Event	t	T	P_K	$\cos\theta^*_{KK}$
515 386	4.25	19.93	555.0	0.23
562 226	9.92	18.12	382.7	0.97
588 069	0.70	28.34	587.0	0.62
725 410	0.81	24.10	597.9	0.64
868 369	0.43	11.93	537.3	0.39
1 385 305	0.15	13.21	778.5	0.64
1 728 083	10.89	22.25	575.0	0.99
1 813 540	3.42	19.44	292.6	0.71
1 823 566	7.81	12.82	464.2	0.64
1 835 095	12.97	21.88	624.8	0.12
1 849 589	0.45	11.67	338.6	-.73

Table II. Cross sections for $K_L + p$ interactions over the momentum range $0 < P_K < 600$ MeV/c. The fourth entry is the sum of the first three entries plus an additional 1.4 mb due to reactions (2d) and (2e).

Final state	Cross section (mb)
$\Lambda\pi^+$	5.40 ± 1.21
$\Sigma^0\pi^+$	3.50 ± 0.94
$\Sigma^+\pi^0$	1.94 ± 0.80
$Y\pi(\pi)$	12.18 ± 1.87
$K_S\,p$	5.04 ± 1.30
K^+n	1.61 ± 0.72

Table III. Missing-mass information for the reactions (1) followed by $\bar{K}^0 + p \rightarrow \Lambda + \pi^+ + mm$, $\Lambda \rightarrow p + \pi^-$. Under "Type" are the final-state products.

Event	Type	P_K	$(mm)^2 \pm \delta(mm)^2$
1 352 419	$\Lambda\pi^+\pi^0$	739.9 ± 5.6	0.0210 ± 0.0115
1 405 053	$\Lambda\pi^+\gamma$	574.8 ± 4.6	0.0026 ± 0.0024
1 462 557	$\Lambda\pi^+\pi^0$	768.9 ± 7.0	0.0121 ± 0.0162
1 722 436	$\Lambda\pi^+\pi^0$	517.5 ± 8.6	0.0108 ± 0.0030
1 754 465	$\Lambda\pi^+\pi^0$	549.9 ± 11.7	0.0185 ± 0.0010
1 821 055	$\Lambda\pi^+\pi^0$	602.0 ± 5.3	0.0186 ± 0.0026

FIGURE CAPTIONS

Fig. 1. Time distribution of 11 $K^0 + p$ charge-exchange events. Solid curve: the expected distribution for values of x and y demanded by CPT invariance ($x = 1$, $y = 0$). Dotted curve: distribution that best fits the data ($x = -3.0$, $y = +4.2$). Individual events are shown as solid circles; $\epsilon(t)$ is the geometrical detection efficiency for the charge-exchange reactions.

Fig. 2. (a) Contours of equal likelihood based on the time distribution of 11 $K^0 + p$ charge-exchange events. Our most probable value is given by the solid circle; contours mark equal likelihood given by $L_{max} \exp(-n^2/2)$, where $n = 1$ and $n = 2$. (b) Contours of equal expected number of $K^0 + p$ charge-exchange events as a function of x and y.

Fig. 3. Path length available for $K^0 + p$ charge exchange from reaction (1a).

Fig. 4. Likelihood function for 11 $K^0 + p$ charge-exchange events, with $|m|$ a free parameter, assuming $x = 1$, $y = 0$.

Fig. 5. $2(\sigma_{K^- p \to \Lambda \pi^0} + \sigma_{K^- p \to \Sigma^- \pi^+} - 2\sigma_{K^- p \to \Sigma^0 \pi^0})$ as a function of P_K. Arrows indicate range of experimenters' data. Smooth curve is an "eyeball" fit to the data.

Fig. 6. Cross section for the processes $K_L + p \rightarrow$ (a) $\Sigma^0 \pi^+$, (b) $\Lambda \pi^+$, (c) $K_S p$, and (d) $Y\pi(\pi)$.

Fig. 7. Scatter plot for 22 $\bar{K}^0 + p \rightarrow \Lambda + \pi^+$ events, showing $P_{\bar{K}^0}$ and $\cos \theta^*_{\Lambda K}$ for each event, where $\theta^*_{\Lambda K}$ is the c.m. scattering angle.

Fig. 8. $\bar{K}^0$ path lengths available for inelastic interactions from reaction (1) for the case $x = 1$, $y = 0$. The momenta of the six three-body final-state events are indicated.

Fig. 9. Dalitz plots for 6 $\Lambda \pi^+ \pi^0 (\gamma)$ final-state events. Events 1 352 419 (open circle) and 1 462 557 (solid circle) are shown in (a), 1 754 465 (open circle) 1 722 436 (solid circle) in (b), 1 821 055 in (c), and 1 405 053 in (d). The bands correspond to $(m \pm \frac{1}{2} \Gamma)^2$ for $Y_1^*(1385)$.

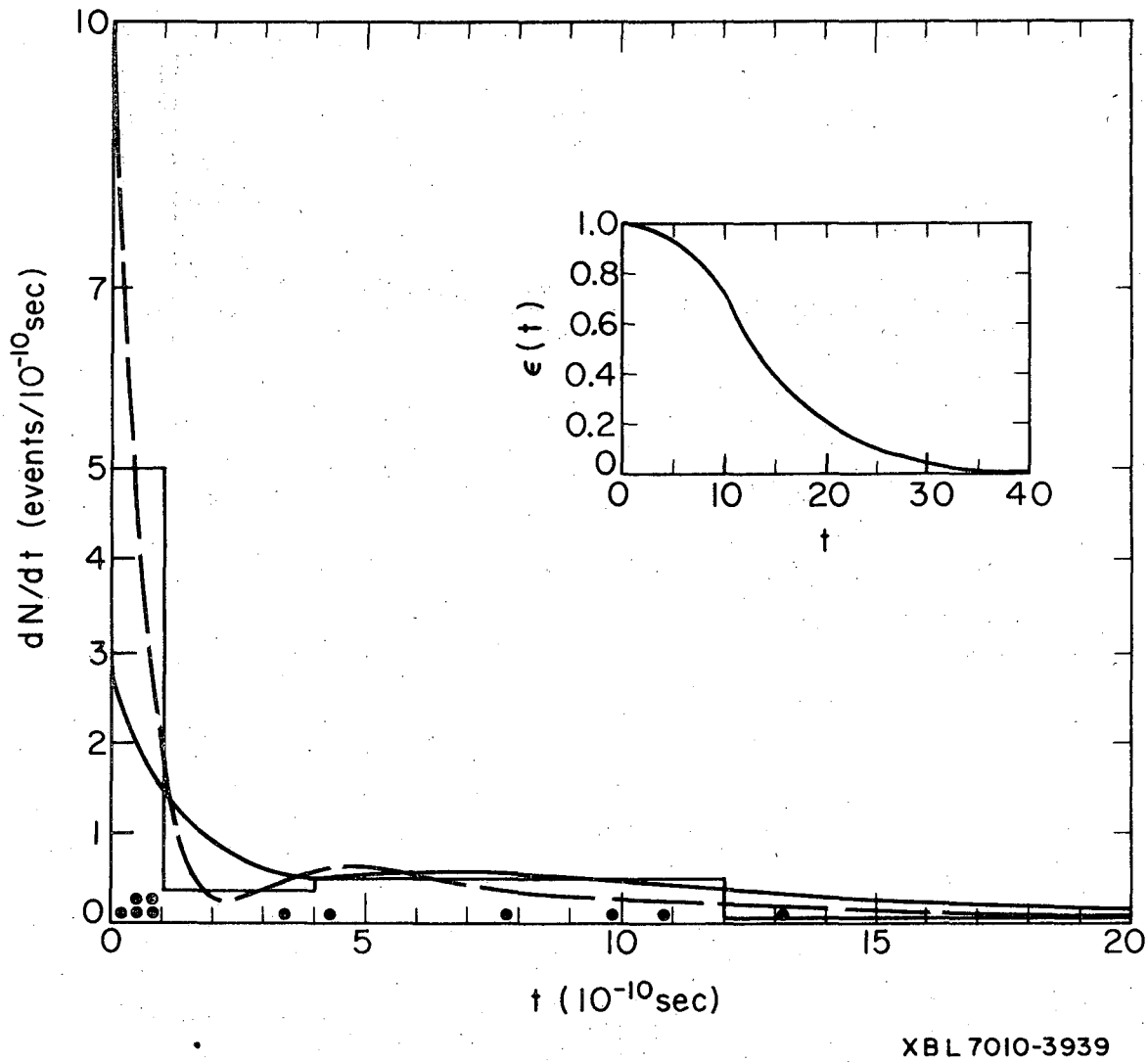

Fig. 1

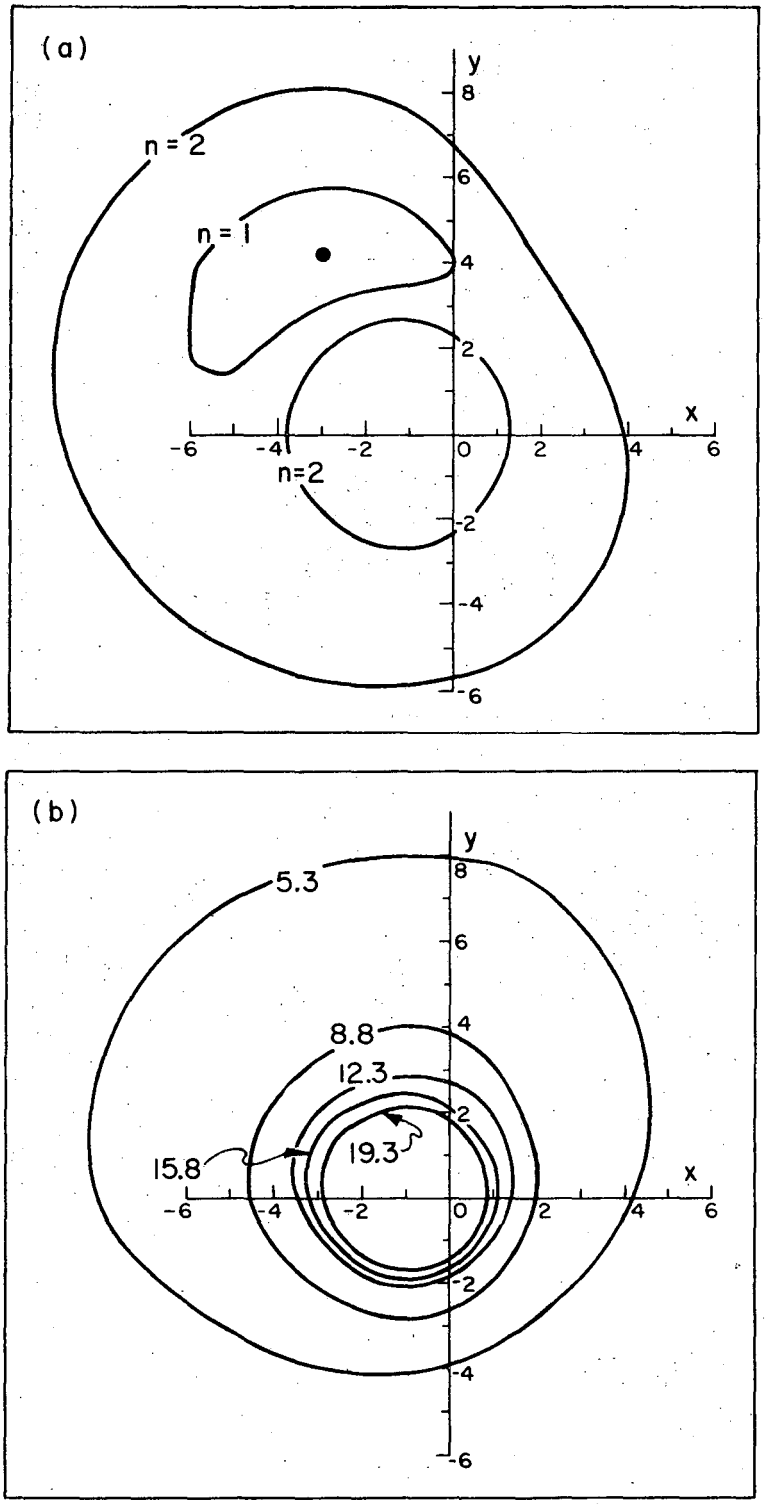

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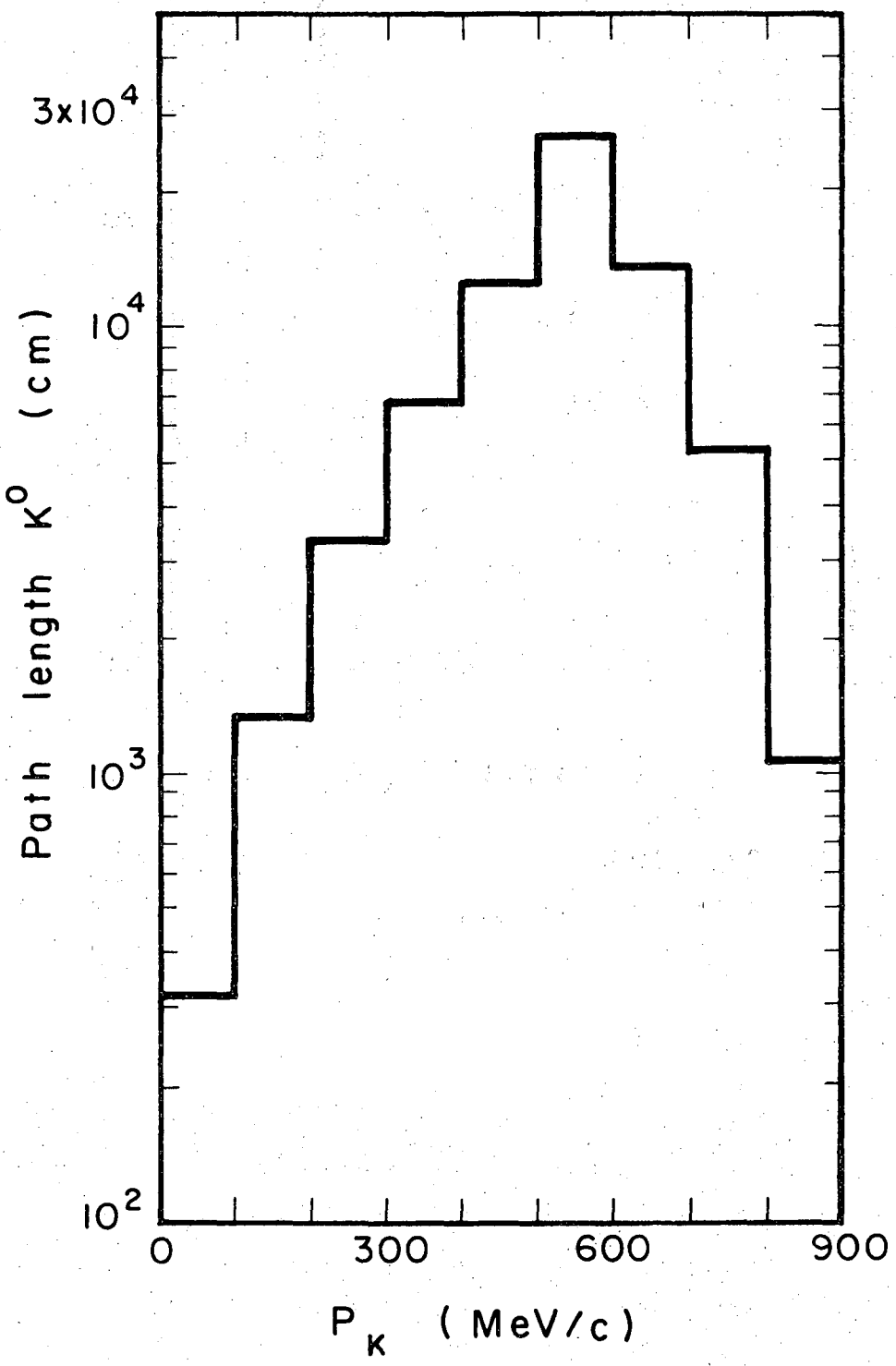
Fig. 2.



XBL7010-3934

Fig. 3.

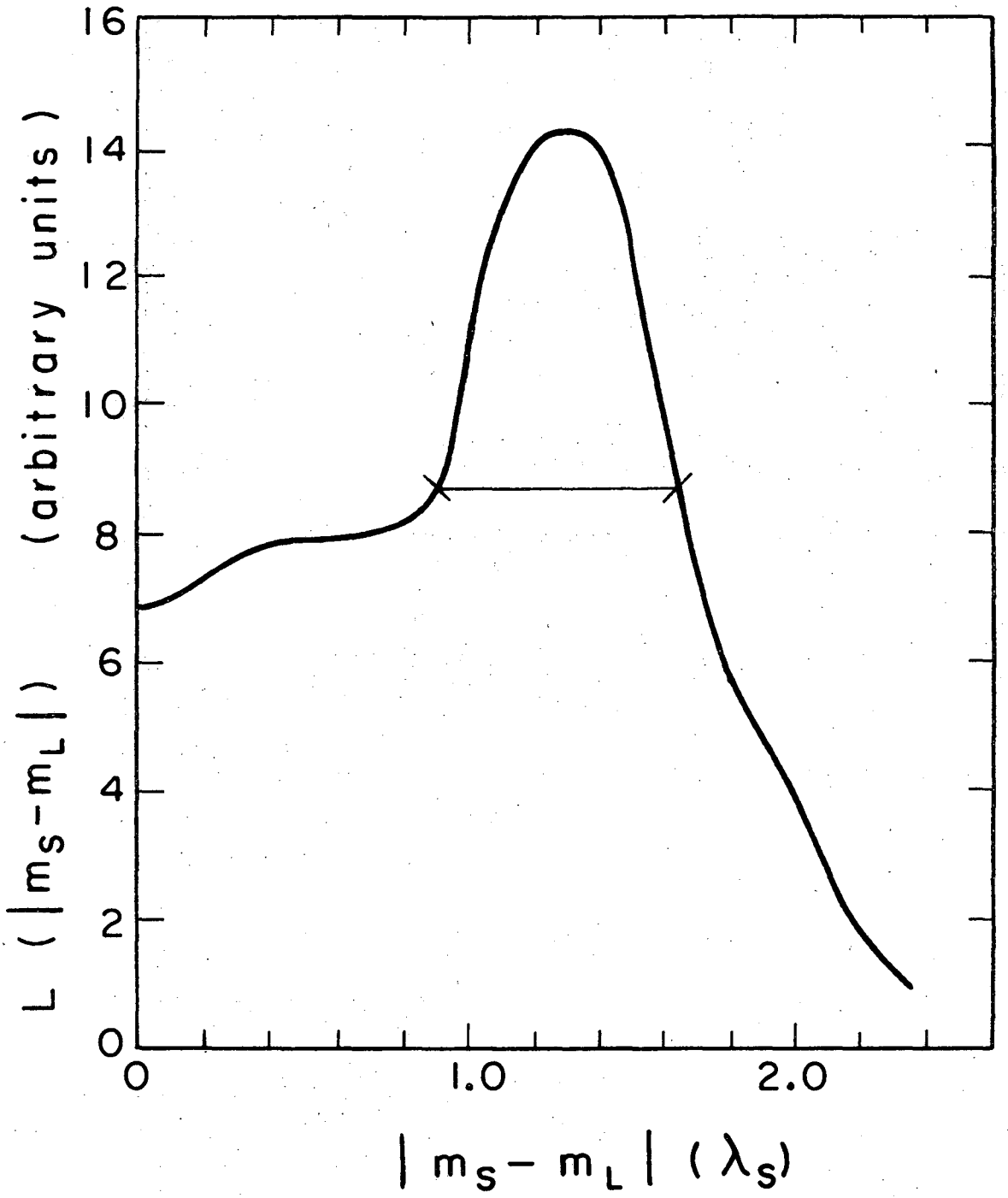


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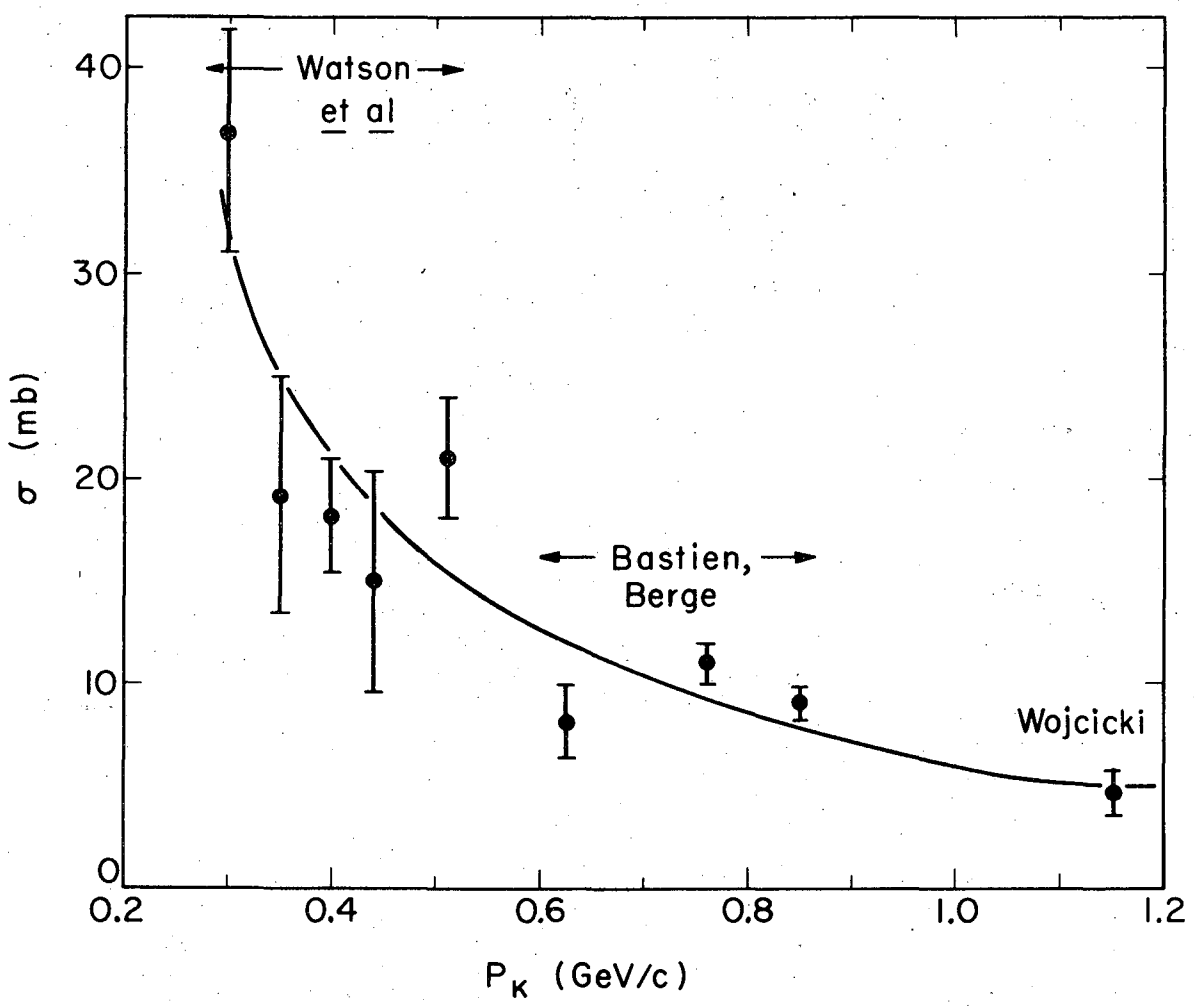
Fig. 4.



XBL 7010-3938

Fig. 5

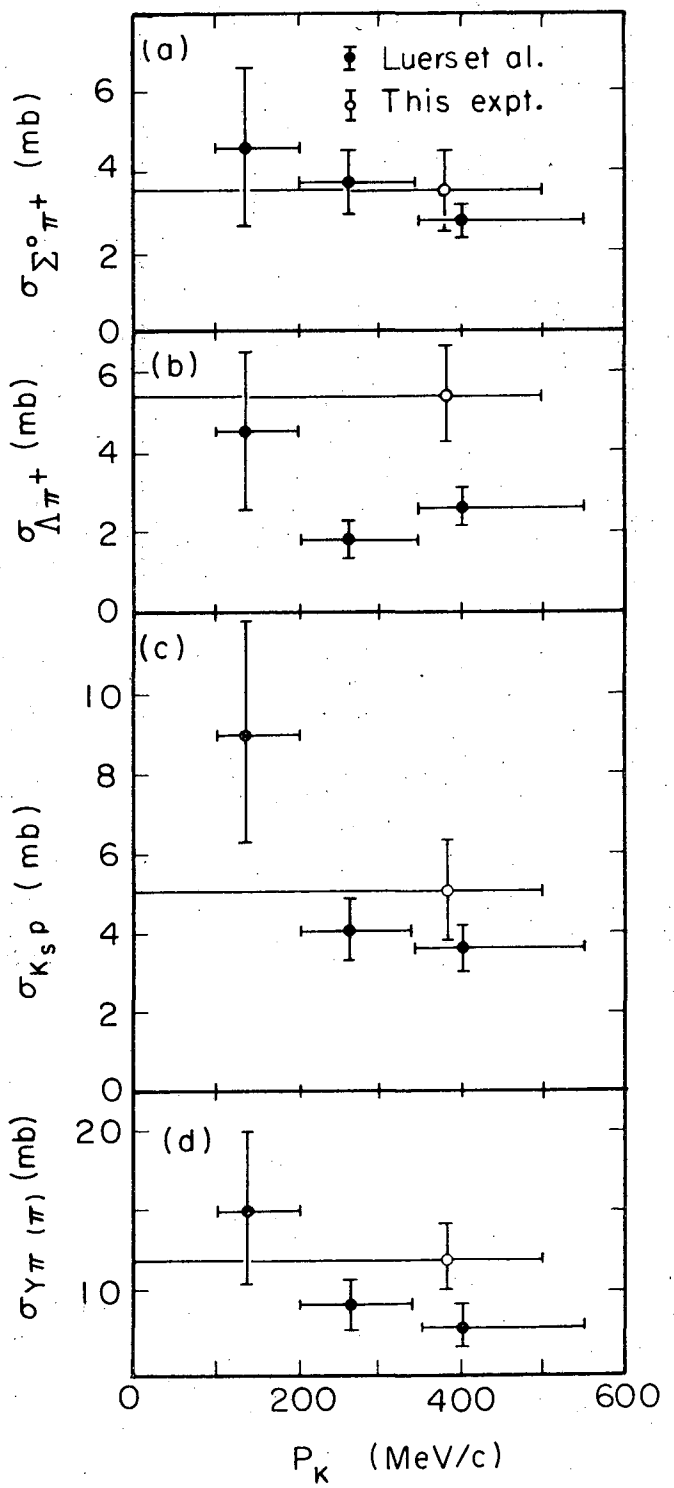


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Fig. 6

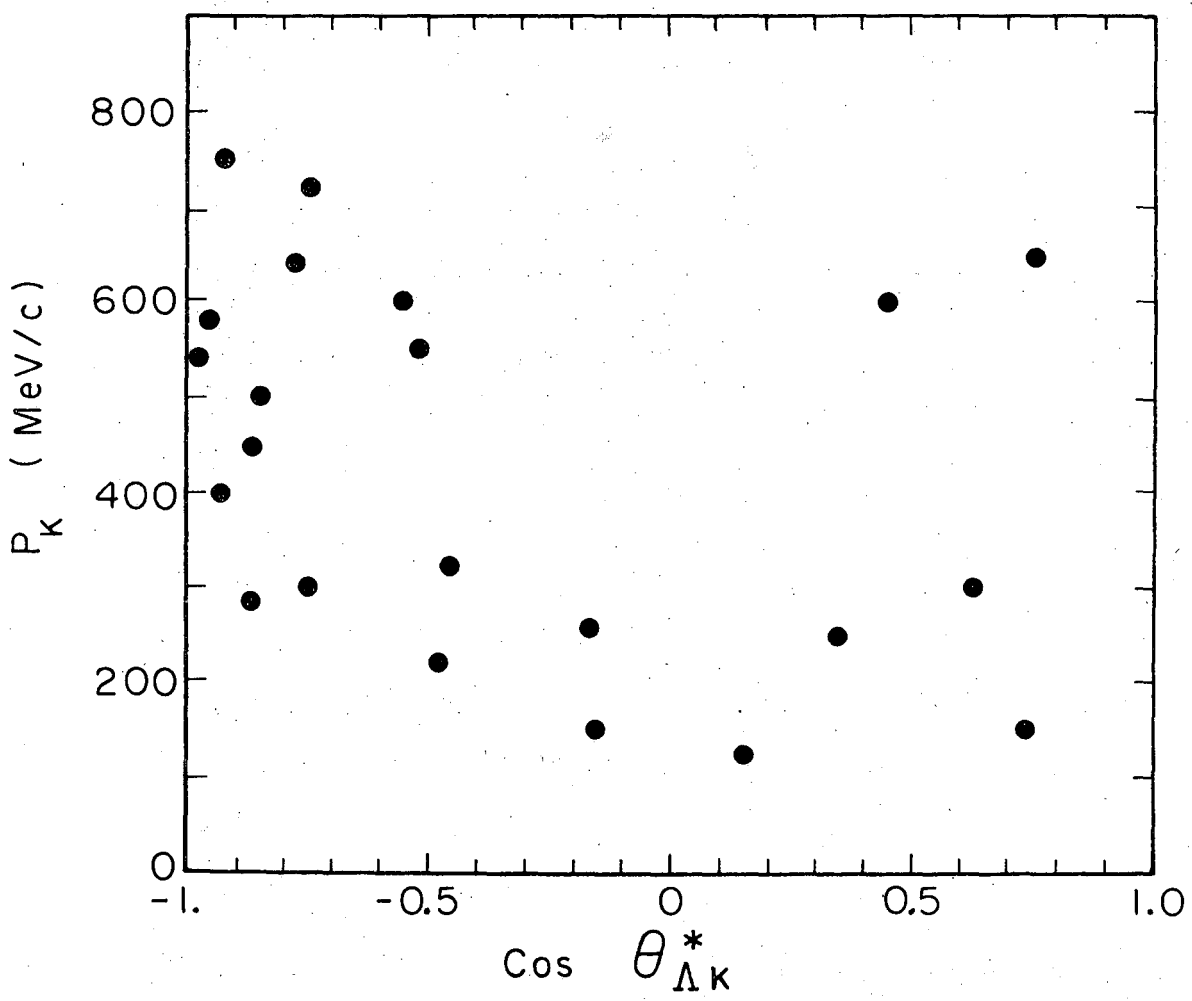

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Fig. 7.

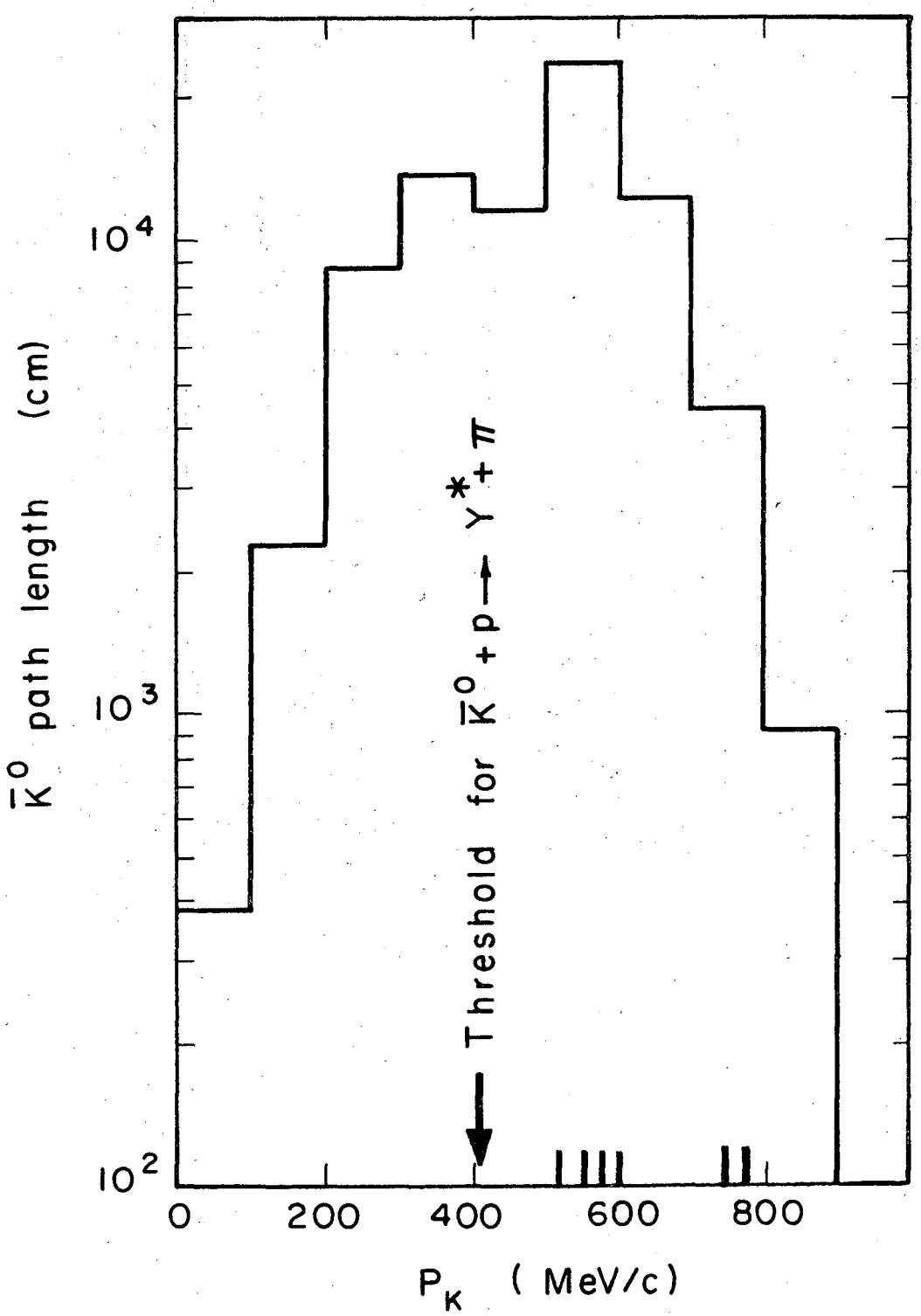

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Fig. 8

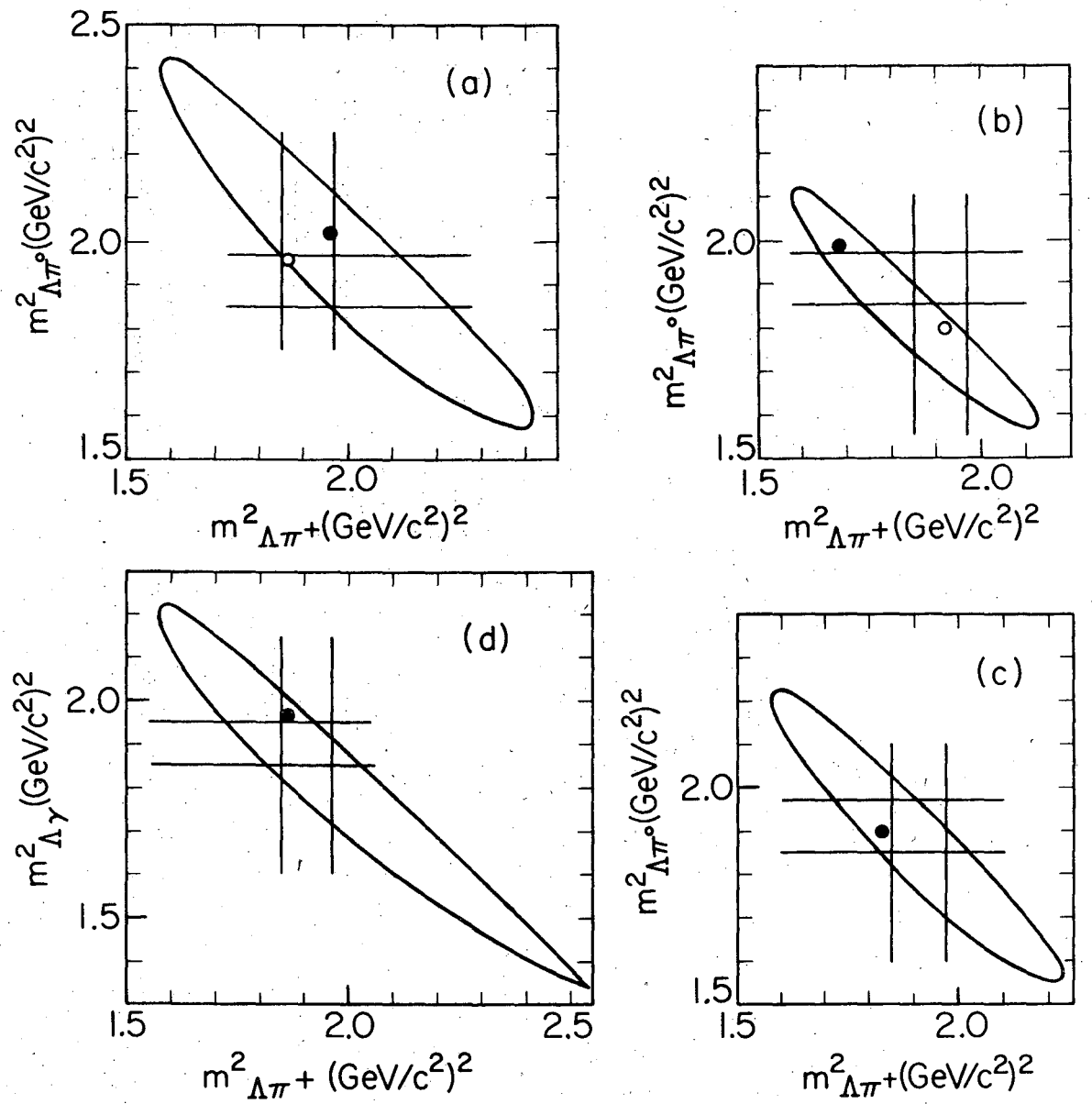
(a)
(b)
(c)
(d)
2.5
2.0
1.5
$m^2_{\Lambda\pi^0}(GeV/c^2)^2$
$m^2_{\Lambda\gamma}(GeV/c^2)^2$
$m^2_{\Lambda\pi^+}(GeV/c^2)^2$
XBL7010-3936

Fig. 9

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