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Interactions of Neutral K Mesons in Hydrogen *

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The reaction $\pi^- + p \to \Lambda + K^0$ in the 72-in. hydrogen chamber was used to produce 7220 K^0 mesons associated with a visible decay $\Lambda \to p + \pi^-$. The time dependence and absolute yield of the subsequent strong interactions of K^0 and $\bar{K}^0$ 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 $\bar{K}^0 + p \to$ 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, $K^0 + p \to K^+ + n$, and the absolute yield of 49 two-body interactions, $\bar{K}^0 + p \to$ 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 the P wave cannot be neglected relative to the S wave in our momentum range.

I. INTRODUCTION

We have previously used the time dependence of $\bar{K}^0 + p \to$ hyperon to obtain the magnitude of the K_S-K_L mass difference,[1] and used the time dependence of $K_{\text{neutral}} + p \to K_S^0 + p$ to find the sign of the mass difference.[2] In this paper we analyze the absolute yields of $\bar{K}^0 + p \to$ hyperon and of $K^0 + p \to K^+ + n$, and the time dependence of $K^0 + p \to K^+ + n$, in the momentum range 0 to 900 MeV/c. In the following sections we discuss the experimental arrangement, scanning procedures, data analysis, and a determination of the mixing parameters p, p', q, and q' of the neutral K system.

II. EXPERIMENTAL PROCEDURE

A. Beam

The Alvarez 72-in. 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:

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

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

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 $\Sigma^0 \to \Lambda + \gamma$). 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:

$$\bar{K}^0 + p \to \Lambda + \pi^+ \quad (22 \text{ events}) \tag{2a}$$

$$\to \Sigma^0 + \pi^+ \quad (18 \text{ events}) \tag{2b}$$

$$\to \Sigma^+ + \pi^0 \quad (9 \text{ events}) \tag{2c}$$

$$\to \Lambda + \pi^+ + \pi^0 \quad (5 \text{ events}) \tag{2d}$$

$$\to \Sigma^+ + \pi^- + \pi^+ \quad (1 \text{ event}) \tag{2e}$$

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

$$K^0 + p \to K^+ + n \quad (11 \text{ events}), \tag{2g}$$

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

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 5 standard deviations from the predicted K^0 direction.[6] The remaining 300 events are fitted (one constraint) to reactions (2). Of the 34 events of type (1a) and (2a) or (2b), 23 had a visible $p\pi^-$ decay mode following the $\bar{K}^0$ interaction. The remaining 11 events had no visible $p\pi^-$ decay, in good agreement with the prediction from the known Λ branching ratio.

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 $|\overline{K}^0\rangle$:

$$|K_S\rangle = p|K^0\rangle + q|\overline{K}^0\rangle, \quad |K_L\rangle = p'|K^0\rangle - q'|\overline{K}^0\rangle. \tag{3}$$

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 $|\overline{K}^0\rangle$ 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]

$$|q'/p'| = 1.00 \pm 0.016, \quad (\approx 0.97) \leq |q/p| \leq (\approx 1.03), \quad (\approx -0.03) \leq \phi \leq (\approx +0.03).$$

We shall now determine these parameters using only strong interactions. The results must of course agree with those determined, using weak decays alone, for a consistent two-component theory of neutral K mesons. The determination of the mixing parameters from weak decays and strong interactions is in both instances based upon a formalism which uses Eq. (3) as its base. The essential difference is that whereas the former method projects out K_S^0 and K_L^0 from the neutral K-wave function, the latter method projects out the K^0 and $\overline{K}^0$ components.

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

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

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

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

where k is a constant $[= 1/(28.6\times 10^3 \text{ mb cm})$ 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

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

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

$$g = \frac{1}{T}\int_0^T |\langle K^0, \psi_K\rangle|^2\epsilon(t)dt = \frac{1}{T}\frac{1}{(1+x)^2+y^2}\int_0^T [(x^2+y^2)e^{-\lambda_S t} + e^{-\lambda_L t} + 2e^{-(\lambda_S+\lambda_L)t/2}(x\cos mt + y\sin mt)]\epsilon(t)dt. \tag{6}$$

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

$$N(t) = (x^2+y^2)e^{-\lambda_S t} + e^{-\lambda_L t} + 2e^{-(\lambda_S+\lambda_L)t/2}(x\cos mt + y\sin mt). \tag{7}$$

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

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	-0.73

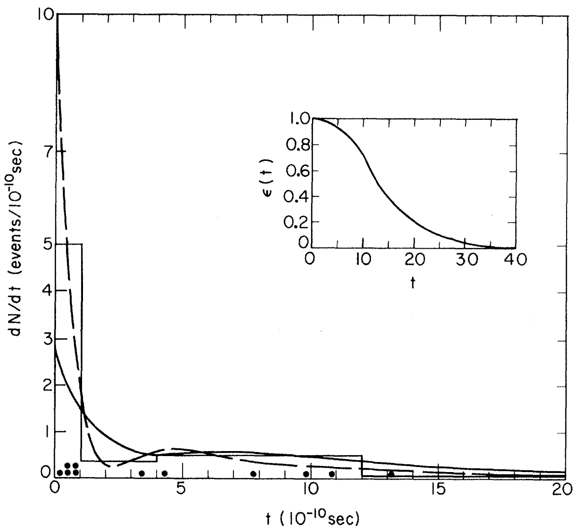

FIG. 1. Time distribution of 11 K^0+p charge-exchange events. Solid curve: the expected distribution for values of x and y demanded by *CPT* invariance ($x=1$, $y=0$). Dashed curve: distribution that best fits the data ($x=-3.0$, $y=+4.2$). Individual events are shown as solid circles; $\epsilon(t)$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

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 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 $L=e^{-n^2/2}L_{\max}$, 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 $K^++n\to K^0+p$ of 6.60 ± 0.56 mb. We plot the results in Fig. 2(b) 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

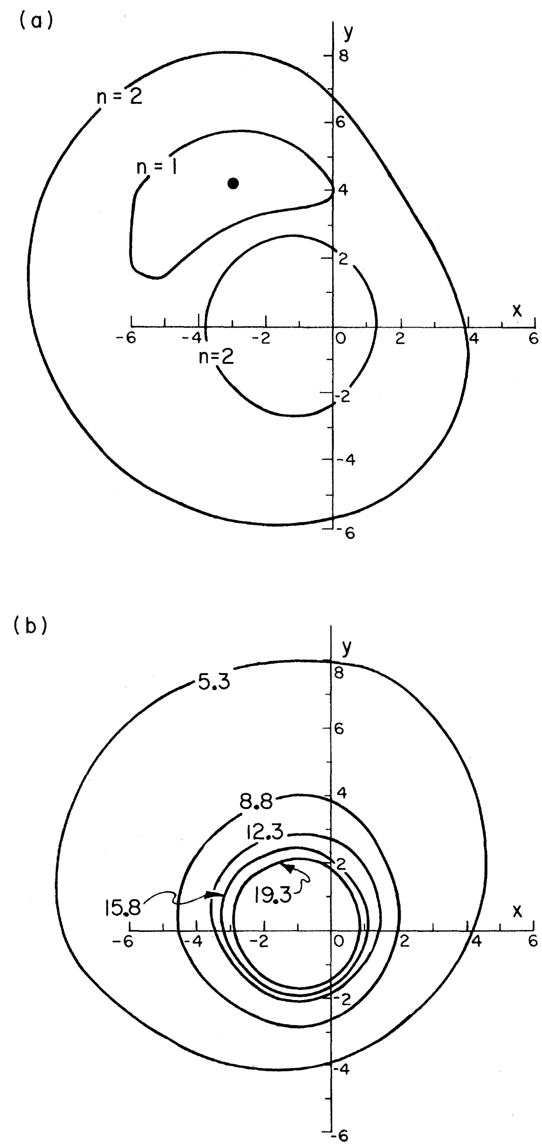

FIG. 2. (a) Contours of equal likelihood based on the time distribution of 11 K^0+p charge-exchange events. Our most probable value is given by the solid circle; contours mark equal likelihood given by $L_{\max}\,e^{-n^2/2}$, where $n=1$ and $n=2$. (b) Contours of equal expected number of K^0+p charge-exchange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

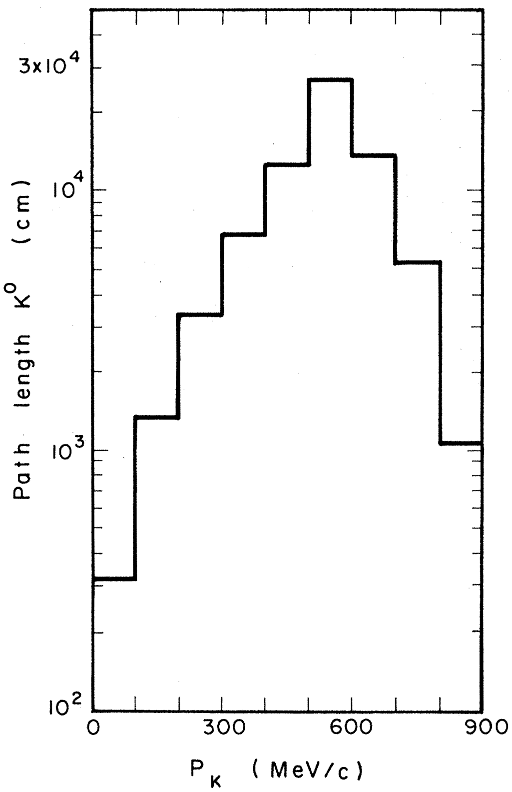

FIG. 3. Path length available for K^0+p charge exchange from reaction (1a).

$L(x=1,\ y=0,\ |m|)$ 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 $L=e^{-1/2}L_{\max}$. Our data are not inconsistent with the world average of $|m|=0.46\lambda_S$.

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

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

$$d\bar{p}(x,y,t,)=k\bar{\sigma}\,|\langle\bar{K}^0,\psi_K\rangle|^2(P_k/m_k)c\epsilon(t)dt,$$

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

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

where N_Σ indicates that the second summation is over reaction (1b), where the factor 0.663 is the branching ratio $\Gamma(\Lambda\rightarrow p\pi^-)/\Gamma(\Lambda\rightarrow\text{all})$ and is there because for Σ^0K^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

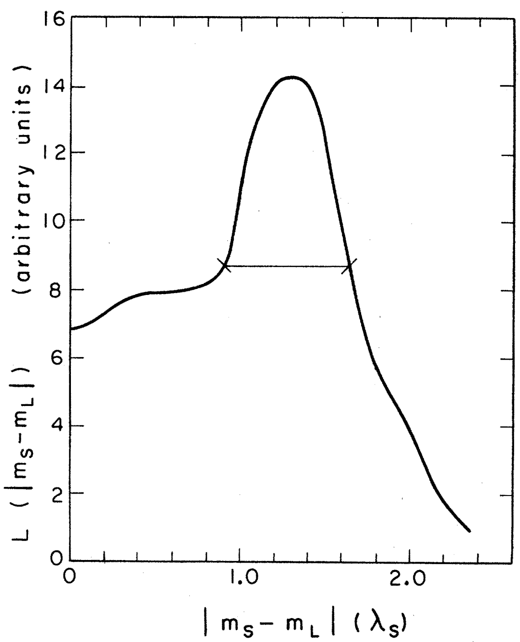

FIG. 4. Likelihood function for 11 K^0+p charge-exchange events with $|m|$ a free parameter, assuming $x=1,\ y=0$.

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

$$\bar{g}=\frac{1}{T}\frac{|q'/p'|^2}{(1+x)^2+y^2}\int_0^T(e^{-\lambda_S t}+e^{-\lambda_L t}-2e^{-(\lambda_S+\lambda_L)t/2}\cos mt)\epsilon(t)dt. \tag{9}$$

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 $(0.65\pm0.30)\lambda_S$, 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 $K^-+p\rightarrow\Lambda+\pi^0$, $K^-+p\rightarrow\Sigma^-+\pi^+$, $K^-+p\rightarrow\Sigma^++\pi^-$, and $K^-+p\rightarrow\Sigma^0+\pi^0$ 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 $\approx25.0\pm5.0$ mb and 15.0 ± 3.0 mb, respectively. In-

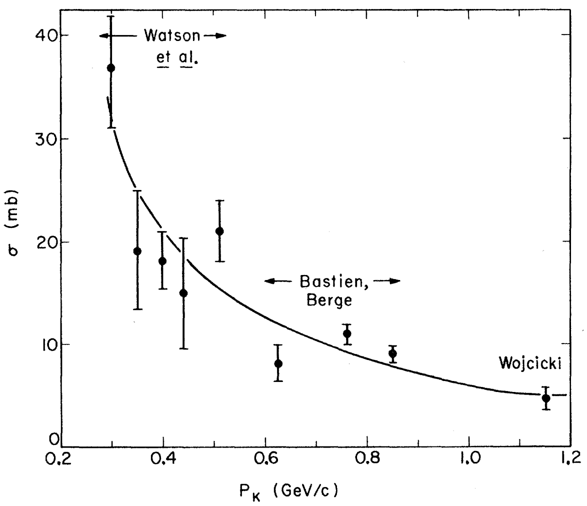

FIG. 5. $2(\sigma_{K^-p\to\Lambda\pi^0}+\sigma_{K^-p\to\Sigma^-\pi^+}-2\sigma_{K^-p\to\Sigma^0\pi^0})$ as a function of P_K. The arrows indicate the range of the experimenters' data. The smooth curve is a visual fit to the data.

cluding 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)–(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 $|q'/p'|=1.16\pm0.12$, in good agreement with $|q'/p'|=1.00\pm0.016$, 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 ($x=-3.0$, $y=+4.2$), we get $|q'/p'|=2.75\pm0.29$, in apparent disagreement with the weak-interaction value. However, since the likelihood function shows that our data are consistent with the values $x=1$, $y=0$ demanded by CPT invariance, 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 $R\equiv\sigma(K_Lp\to K_Sp)/[\sigma(K_Lp\to\text{hyperon})]$ 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 $n_\Lambda=23.7\pm5.3$ 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 $n_{\Sigma^0}=15.3\pm4.1$. Also, the number n_{Σ^+} of reactions (1) followed by the reaction $K_L+p\to\Sigma^++\pi^0$ becomes $n_{\Sigma^+}=8.5\pm3.5$. Including reactions (2d) (2d)–(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 $K_L+p\to$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 $K_L+p\to K_S+p$. Combining these data with the above, we obtain

$$R=0.41\pm0.13,$$

at an average momentum of 500 MeV/c. This value of R agrees with the experimental values of

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_Sp	5.04 ± 1.30
K^+n	1.61 ± 0.72

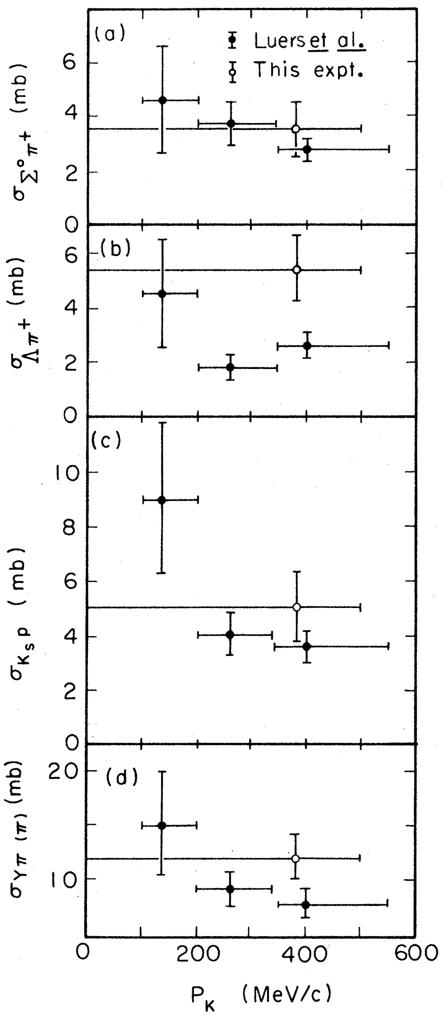

FIG. 6. Cross section for the processes $K_L + p \rightarrow$ (a) $\Sigma^0\pi^+$, (b) $\Lambda\pi^+$, (c) $K_S p$, and (d) $Y\pi(\pi)$.

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)–(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-hand side of Eq. (10), based on 55.9 $\pm$ 7.5 events and at an average $\bar{K}^0$ momentum of 483 MeV/c, is equal to 22.5 ± 3.0 mb. The right-hand 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 4.5 $\pm$ 1.4 mb, in good agreement with the measured charge-symmetric cross section of 6.6 ± 0.6 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.

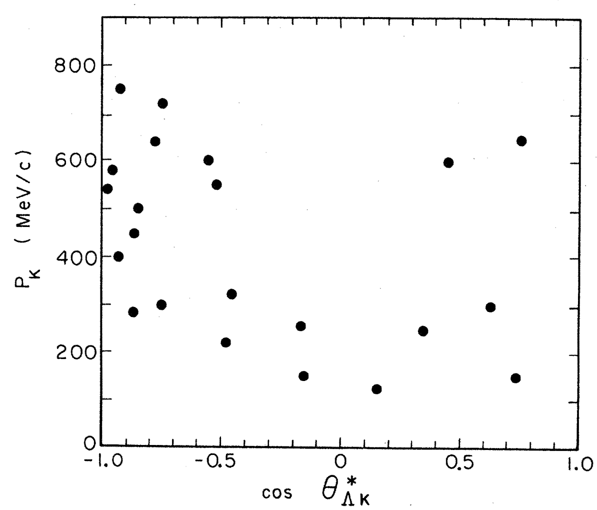

FIG. 7. Scatter plot for 22 $\bar{K}^0 + p \rightarrow \Lambda + \pi^+$ events, showing $P_{\bar{K}^0}$ and $\cos\theta^*_{\Lambda K}$ for each event, where $\theta^*_{\Lambda K}$ is the c.m. scattering angle.

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 $\bar{K}^0+p$ 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 ($\mathrm{Re}z=1$, $\mathrm{Im}z=0$). We then find the third independent parameter $|q'/p'|=1.16\pm0.12$, 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 $\bar{K}^0+p$ channels which are consistent with charge symmetry (for K^0+p) and charge independence (for $\bar{K}^0+p$).

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 reaction (2a) indicates the need for P wave below 600 MeV/c in the $\bar{K}^0p$ system.

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