

**$K_L^0 p$  charge-exchange scattering from 550 to 1000 MeV/c\***R. M. Edelman, H. E. Fisk,<sup>†</sup> P. Joseph,<sup>‡</sup> E. L. Miller,<sup>§</sup> J. S. Russ, M. O. Schick,<sup>||</sup> and R. C. Thatcher<sup>¶</sup>  
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Employing a neutral kaon beam at the Argonne Zero Gradient Synchrotron, a high-resolution magnetic spectrometer, and a neutron detector, differential cross sections have been obtained in the forward direction [ $0.045 < |t| < 0.18$  (GeV/c)<sup>2</sup>] for the reaction  $K_L^0 p \rightarrow K^+ n$ . Previous studies of the time-reversed process in deuterium,  $K^+ d \rightarrow K^0 p(p)$ , have not yielded direct cross-section measurements in the forward direction because there is an inhibition of the non-spin-flip process in deuterium due to the Pauli exclusion principle. Nevertheless, our data are in agreement with the extracted free-neutron cross sections of deuterium studies as determined from the impulse and closure approximations.

## I. INTRODUCTION

Interest in  $K$ -nucleon reactions has been stimulated by high-precision total-cross-section measurements of  $K^+$  on hydrogen and deuterium.<sup>1,2</sup> Although an extraction of the  $I=0$  (isospin) total cross section is complicated by the unfolding of deuterium effects, there is some evidence for the existence of a resonance ( $Z_0^*$ ) in the 0.7–0.9 GeV/c  $K^+$  momentum range. Such a resonance, with quantum numbers  $S=+1$  and  $Y=+2$ , is not predicted by the simple three-quark model of SU(3). One experimental group<sup>3</sup> has fitted their extracted  $I=0$  total cross section with a modified Breit-Wigner distribution, and their suggested interpretation is a broad, nearly elastic  $P_{1/2}$  resonance with a mass of  $\sim 1750$  MeV and a width of 600 MeV. Efforts to measure  $K$ - $N$  differential cross sections have concentrated on  $K^+ p$  and  $K^+ n$  elastic scattering and  $K^0 p$  and  $K^+ n$  charge exchange. Differential cross sections, in terms of the isoscalar and isovector scattering amplitudes  $f_0$  and  $f_1$  and the Coulomb amplitude  $f_c$ , are

$$\text{elastic: } d\sigma/dt(K^+ p) = |f_1 + f_c|^2,$$

$$d\sigma/dt(K^+ n) = \frac{1}{4} |f_1 + f_0|^2;$$

$$\text{charge-exchange: } d\sigma/dt(K^0 p \rightarrow K^+ n) = \frac{1}{4} |f_1 - f_0|^2,$$

$$d\sigma/dt(K^+ n \rightarrow K^0 p) = \frac{1}{4} |f_1 - f_0|^2.$$

Phase-shift analyses based on  $K^+ p$  elastic scattering data<sup>4,5</sup> indicate that the isovector amplitude  $f_1$  is dominated by a negative  $S_{1/2}$ , repulsive wave.<sup>6,7</sup> Experiments to measure  $K^+ n$  elastic<sup>8</sup> and  $K^+ n$  charge-exchange<sup>9,10,11</sup> differential cross sections have been performed using deuterium targets. The

difficulty in these experiments lies in extracting the free-neutron cross sections. In the charge-exchange experiment, for example, one measures the differential cross section for  $K^+ n(p) \rightarrow K^0 p(p)$ , and assumptions must be made about the influence of the "spectator" proton. Procedures to extract the charge-exchange cross section are invalid for small scattering angles of the  $K^0$  from the incident  $K^+$  direction due to the inhibiting effect of the Pauli principle. There is no unique way to correct for the bound neutron in deuterium studies, and, in addition, one must cope with energy smearing due to the Fermi motion of the neutron.

Phase-shift analyses of deuterium studies offer conflicting evidence on the existence of the  $Z_0^*$  resonance. One group<sup>12</sup> has fitted  $K^+ d$  charge-exchange data from the Bologna-Genoa-Rome-Trieste (BGRT) collaboration.<sup>13</sup> They find in the  $I=0$   $KN$  channel a  $D_{3/2}$  resonance and also either a  $P_{1/2}$  or  $S_{1/2}$  resonance, depending on which of their solutions they accept. The BGRT collaboration has fitted their own  $K^+ n$  elastic scattering data<sup>13</sup> (extracted from  $K^+ d$ ), and they state that they can neither find a unique solution nor establish the existence of the  $Z_0^*$ . Their strongest candidate for a resonance is the  $P_{1/2}$  wave in their "D" solution. Fitted parameters to the "D" solution yield a mass of 1740 MeV and a width of 300 MeV. Hirata *et al.*<sup>10</sup> have fitted their  $K^+ n$  charge-exchange data at 865 and 970 MeV/c with  $I=1$  phase shifts taken from Hall *et al.*<sup>7</sup> and an  $I=0$   $P_{1/2}$  phase shift as determined from the resonance energy, 1780 MeV, and width 560 MeV.<sup>14</sup> Their free-neutron cross sections were extracted from  $K^+ d$  charge-exchange data using the impulse and closure approximations. They can find no fit to

their data with a repulsive  $S_{1/2}$   $I=1$  partial wave and a resonant  $P_{1/2}$   $I=0$  wave. They point out that such a combination leads to backward peaking in  $K^+n$  charge exchange, which is not observed.

Our study of  $K^0p$  charge-exchange scattering is free of deuterium effects, and we have concentrated on the low- $|t|$  range [around  $0.1 \text{ (GeV/c)}^2$ ] where corrections in deuterium studies are largest. We compare our data with the extracted free-neutron cross sections of Hirata *et al.* and find the two to be in agreement. Thus, our data provide an experimental verification of the extraction procedures employing the impulse and closure approximations which are applied to the deuterium data.

## II. EXPERIMENTAL PROCEDURE

The experimental layout is shown in Fig. 1. 12.8-GeV/c protons from the Argonne Zero Gradient Synchrotron (ZGS) struck a 7.6-cm copper production target. The neutral beam line was defined by two brass collimators subtending  $0.05 \text{ msr}$  at  $17.5^\circ$  with respect to the external proton beam. The collimators were tapered to produce a  $10 \text{ cm} \times 10 \text{ cm}$  beam spot at the liquid hydrogen target, a cylindrical flask 30.5 cm long and 15 cm in diameter. Charged particles were eliminated from the neutral beam with 2 sweeping magnets, and  $\gamma$  rays were attenuated with a 5-cm lead brick

( $\sim 9$  radiation lengths) placed downstream of the first collimator. The preponderance of neutrons in the beam (the estimated  $n/K_L^0$  flux ratio was 400) provided a major difficulty in the experiment. The kinematics for  $np$  charge exchange are quite similar to those for  $K^0p$  charge exchange so that the detection apparatus was sensitive to both reactions. A threshold Čerenkov counter selected against low-momentum  $np$  charge-exchange triggers. The counter (isopropyl alcohol) had a threshold of  $\beta=0.726$ , which corresponded to a proton momentum of  $\sim 1 \text{ GeV/c}$ , and it set the maximum momentum for which  $K^0p$  events could be cleanly separated from  $np$  events in the time-of-flight analysis. Most (85%) of the recorded data showed charged-particle momenta above  $1 \text{ GeV/c}$  and was not used.

The neutron component of the beam was useful in monitoring the  $K_L^0$  flux. The monitor  $M$  was a four-counter telescope ( $M = \bar{M}_1 \cdot M_2 \cdot M_3 \cdot M_4$ ) with a 1.25-cm-thick polyethylene converter after  $M_1$  to convert neutrons to charged particles. Total counts were recorded for  $M\bar{A}$ , where  $A$  was the mixed output of anticoincidence counters surrounding the hydrogen target. A previous experiment<sup>15</sup> with the same neutral beam line had determined the absolute  $K_L^0$  momentum spectrum to an accuracy of 6% by measuring the  $2\pi$  decays of the  $K_L^0$ . The  $K_L^0$  flux over the momentum range 550–1000 MeV/c was approximately 3000/ZGS pulse.

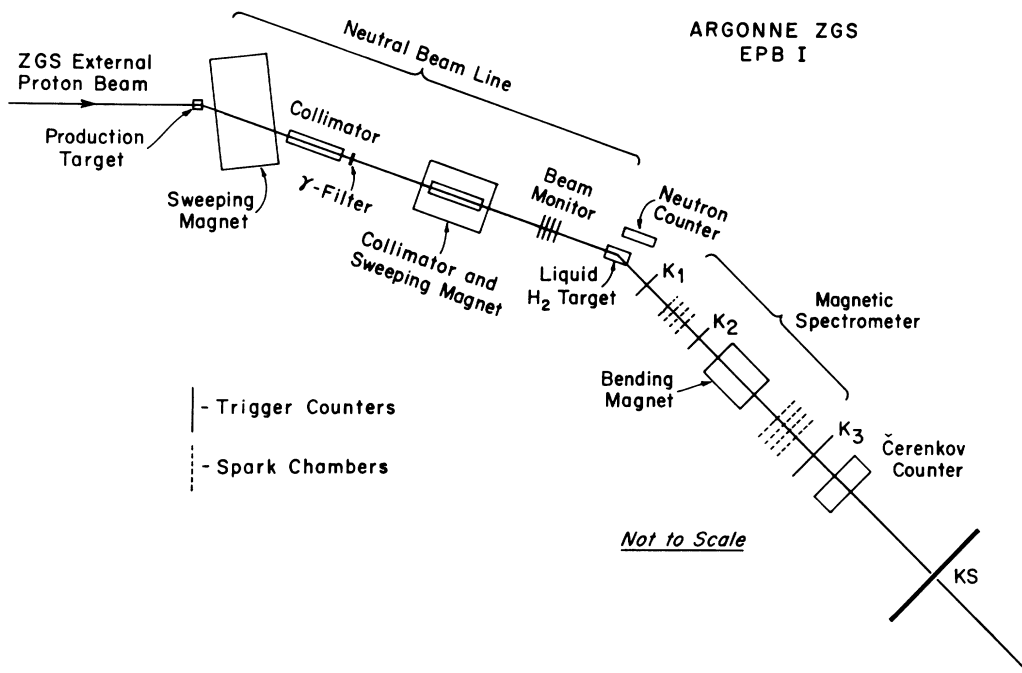


FIG. 1. Layout of the experimental apparatus.

The recoil neutron was detected in a bank of 6 Ne-110 scintillation counters (15 cm × 15 cm × 76 cm) with photomultipliers mounted at each end. Anticoincidence counters between the hydrogen target and the neutron counter ensured that only neutrals activated the neutron counter. Singles rates in the neutron counters were typically  $2 \times 10^5$ /ZGS pulse, and the overall accidental triggering rate was typically 15%. The accidental events did not reconstruct kinematically, so that the only correction for accidentals was a 4% increase in normalization due to a loss of events when an accidental neutron count preceded the valid recoiling neutron. The neutron azimuthal angle  $\phi$  could be measured to  $\pm 3^\circ$ , and the neutron interaction point in the 76.2 cm counters measured to  $\pm 10$  cm. The neutron time of flight (NTOF) was measured to an accuracy of 1.4 nsec for a typical flight time of 6 nsec. The neutron-counter detection efficiency had been measured in a previous experiment<sup>16</sup> for various threshold biases as a function of neutron kinetic energy. In this experiment the neutron detection efficiency was  $\sim 30\%$  over neutron kinetic energies 15–110 MeV.

The trigger was defined as  $K_1 \cdot K_2 \cdot K_3 \cdot C \cdot K_s \cdot N \cdot \bar{A}$ , where  $K_1$ ,  $K_2$ ,  $K_3$ , and  $K_s$  are scintillation counters,  $C$  represents the Čerenkov counter, and  $N$  is the neutron counter. The triggering rate was typically 25 triggers/ZGS pulse. The forward-going charged particle was detected in a magnetic spectrometer with magnetorestrictive readout spark chambers. The spark-chamber resolution was  $\pm 20$  mils, leading to an uncertainty of  $\pm 1\%$  in the momentum measurement. A square field approximation was used for the bending magnet with  $\int Bdl$  constant to within 0.2%. The time of flight (TOF) of the charged particle was measured between  $K_1$  and  $K_s$  to  $\pm 0.6$  nsec the accuracy limited by the inherent resolution of the counters. Data were collected with a SAC readout system and transferred to a PDP-7 computer to be written on magnetic tape. Approximately  $3 \times 10^6$  triggers were taken, 2000 of which were  $K^0p$  charge-exchange events.

### III. ANALYSIS

Analysis of the data involved reconstruction of the charged-particle tracks in the spectrometer, a determination of the particle momentum, path length, and time of flight, and a calculation of the neutron time of flight, interaction point in the neutron counter, and scattering angle  $\phi$ . Up to two tracks were fitted to the sparks in each of the four chamber segments, upstream and downstream, vertical and horizontal projections. The

proper track was selected by comparing the intercepts of the fitted trajectories at the center of the bending magnet. Cuts were made on the front-to-back differences of the horizontal intercepts and vertical slopes to eliminate particles scattering off the magnet pole tips or steel end guards.

Time-of-flight information was used to separate  $K^+$  mesons from protons and pions (produced inelastically) in the charged arm of the spectrometer. At 1 GeV/ $c$  the time-of-flight difference between kaons and protons is 4.5 nsec (for a path length of 5.25 m), and the difference between kaons and pions is 1.9 nsec. A considerable effort was made to reduce systematic errors in the determination of the measured time of flight. Two measurements were made with start pulses provided by photomultiplier tubes mounted on the top and bottom of the  $K_1$  scintillant and a stop pulse provided by  $K_s$ . Corrections to the timing ( $\sim 0.2$  nsec) were made for the light propagation time in  $K_1$  and  $K_s$  as a function of the particle interaction point.  $K_s$  was a  $4 \times 4$  array of 23 cm high  $\times$  38 cm wide counters. Timing corrections were made for the relative timing differences among these counters ( $\sim 0.2$  nsec) due to different response characteristics and variation in cable lengths. A latch assembly determined which of the 16 counters had been struck, and the particle trajectory as determined by the downstream chambers was required to intersect the struck counter. In addition, timing corrections were made for shifts in the ADC (analog-to-digital converter) pedestals ( $\pm 1$  count =  $\sim 0.2$  nsec) over the running of the experiment. These shifts were observed in the  $np$  charge-exchange timing and applied to the data as a function of run number. The charged particle TOF was predicted from its momentum and path length assuming the  $K^+$  mass. The predicted TOF was compared to the measured value and cuts were made on the difference at  $\pm 1.2$  nsec. The difference distribution  $D_{\text{TOF}}$  is shown in Figs. 2(a), 2(b), and 2(c) for the  $K_L^0$  beam-momentum intervals 550–700, 700–850, and 850–1000 MeV/ $c$ , respectively. The kaon signal is centered around  $D_{\text{TOF}} = 0$  while the proton peak appears at  $D_{\text{TOF}} > 0$  and the pion signal at  $D_{\text{TOF}} < 0$ . An “elastic” cut (described below) has already been made on these data. The preponderance of  $np$  charge-exchange events in these histograms is clear. Background under the kaon “bump” in the 850–1000 MeV/ $c$  interval was calculated to be  $(15 \pm 3)\%$ , and background at lower momenta was negligible.

The “elastic” data were separated from other reactions such as  $K^0p \rightarrow K^+\pi^0n$  by assuming the event to be elastic and applying a three-constraint fit to the neutron-counter information. A  $\chi^2$  was

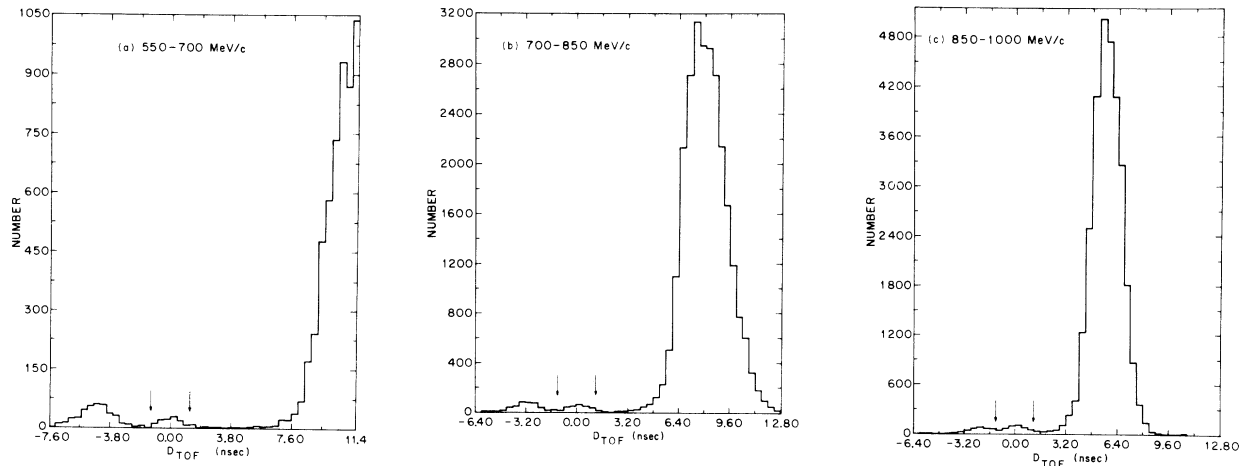


FIG. 2. Histograms of the difference between the charged particles' measured time of flight and the predicted time of flight, based on a measurement of the momentum and assuming the kaon mass. The data have been subdivided into  $K_L^0$  beam-momentum intervals as indicated. The smallness of the kaon signal (between the arrows) relative to the proton signal ( $D_{\text{TOF}} > 0$ ) is clearly evident. The "hump" at negative  $D_{\text{TOF}}$  represents pions in the spectrometer.

formed between differences of the measured and predicted values for the 3 neutron variables  $\phi$ ,  $z'$  (interaction point in the neutron detector), and NTOF, and events with confidence levels above 0.1 were accepted as "elastic." This cut eliminated approximately  $\frac{1}{2}$  of the  $K^0 p$  charge-exchange candidates. A Monte Carlo program determined the geometric acceptance of the apparatus and corrected for  $K^+$  decays (70%) in the spectrometer. Because the extrapolated kaon trajectory was required to agree with the time of flight and position information from the  $K_s$  hodoscope, very few ( $\sim 8\%$ ) kaon decay products satisfied analysis requirements. Hence, the kaon decay correction, while large, is very well known and contributes no significant error. The validity of the program was checked on the  $np$  charge-exchange data by comparing the Monte Carlo corrected results (with arbitrary normalization) with data of Shepard *et al.*<sup>17</sup> at 900–950 MeV/c. Because the  $np$  angular distribution is more sharply peaked than than for  $K^0 p \rightarrow K^+ n$ , this comparison represents a very stringent check of the Monte Carlo program. The laboratory angles at which our data diverged from the measurements of Shepard *et al.* determined the unbiased region over which we could safely apply corrections to our data. This range of laboratory angles was  $\sim 16^\circ$  to  $30^\circ$ , which roughly corresponded with the edges of apertures in our experiment.

Corrections were made to the differential cross sections for absorption of the neutrons in the  $H_2$  target (5% loss), absorption of the  $K^+$  in the spectrometer (12% loss), neutron-counter efficiency (0.30% loss), Čerenkov-counter efficiency (97%),

spark-chamber efficiency (97%), and target-empty subtraction (3% loss).

#### IV. RESULTS

Differential cross sections for  $K^0 p \rightarrow K^+ n$  are given in Table I and plotted in Figs. 3(a), 3(b), and 3(c) for the 3 beam-momentum intervals 550–700, 700–850, and 850–1000 MeV/c. Also plotted are differential cross sections for  $K^+ d \rightarrow K^0 p(p)$  from Slater *et al.*<sup>11</sup> at 642 and 812 MeV/c and from Hirata *et al.*<sup>10</sup> at 865 MeV/c. The solid curves are their predictions for the free-neutron cross sections as calculated from the impulse and closure approximations. The errors on our data points are statistical only and do not include the

TABLE I. Differential cross sections for  $K^0 p \rightarrow K^+ n$ . Errors are statistical only.

$t$ [(GeV/c) <sup>2</sup> ]	$d\sigma/dt$ [mb/(GeV/c) <sup>2</sup> ]
550–700 MeV/c	
0.045–0.065	19.9 ± 3.3
0.065–0.085	18.5 ± 3.8
700–850 MeV/c	
0.06–0.08	12.4 ± 1.7
0.08–0.10	14.6 ± 2.0
0.10–0.12	14.1 ± 2.2
850–1000 MeV/c	
0.08–0.10	10.4 ± 1.2
0.10–0.12	10.8 ± 1.4
0.12–0.15	10.1 ± 1.3
0.15–0.18	13.0 ± 1.7

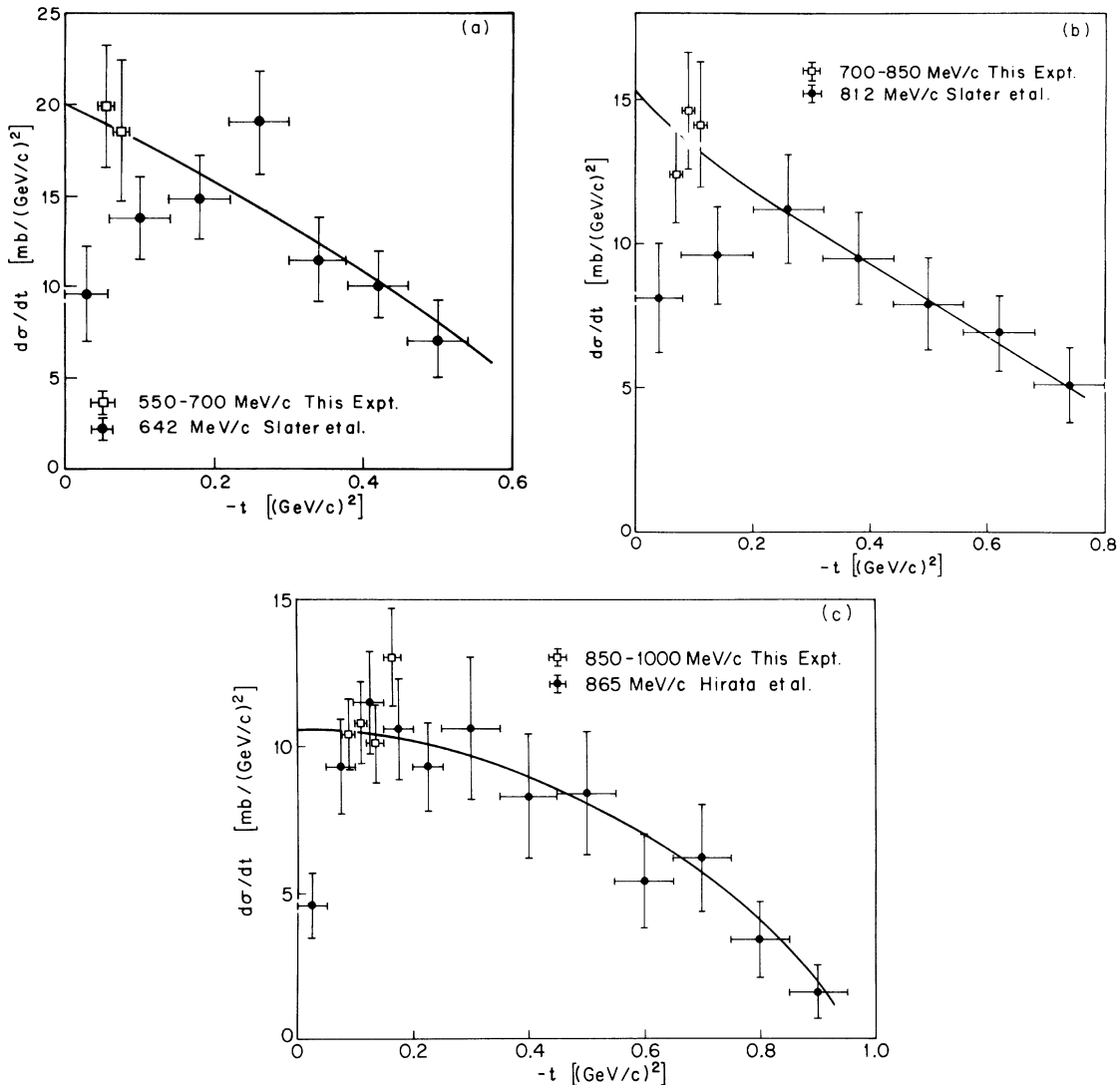


FIG. 3. A comparison of differential cross-section data from this experiment with data from the time-reversed reaction in deuterium,  $K^+d \rightarrow K^0p(p)$ . The solid curves are the extracted free-neutron cross sections from Refs. 10 and 11 as determined from the impulse and closure approximations. The falloff of the deuteron cross sections at low  $|t|$  is attributed to the effect of the Pauli exclusion principle.

6% uncertainty in normalization. Our data are in agreement with the free-neutron predictions, lending validity to the use of the impulse and closure approximations. The  $K^0p$  charge-exchange cross section appears to rise with decreasing  $|t|$  near  $t=0$ , and is significantly higher than the differential cross section for  $K^+d \rightarrow K^0p(p)$ . The difference between the two is most marked at low momenta where our data points have a  $|t| \lesssim 0.1$   $(\text{GeV}/c)^2$ . This behavior is indicative of a significant component of spin nonflip scattering for the charge-exchange process near  $t=0$ , an angular region where the deuteron charge-exchange process is inhibited by the Pauli principle. The extrapolated intercept at  $t=0$  of the free-neutron charge-exchange cross section is considerably

higher than the optical point, indicating that the charge-exchange amplitude is predominantly real.

As was mentioned, Hirata *et al.* had attempted to fit their extracted  $K^+n$  charge-exchange data with the assumption of an  $I=0$  resonant,  $P_{1/2}$  wave, but were unsuccessful because that assumption led to backward peaking. Their simplest interpretation of the  $I=0$  channel was that of a dominant  $P_{1/2}$  wave which increases in magnitude over the beam-momentum interval 0.5–1.0  $\text{GeV}/c$  but does not go through resonance. Published fits for the  $I=0$   $P_{1/2}$  phase shifts were  $65.2^\circ \pm 2.5^\circ$  at 865  $\text{MeV}/c$  and  $72.2^\circ \pm 5.0^\circ$  at 970  $\text{MeV}/c$ .<sup>10</sup> Small amounts of other partial waves were required to obtain forward peaking of the charge-exchange cross section.

To date, one other group (Armitage *et al.*)<sup>18</sup> has measured differential cross sections for  $K^0 p \rightarrow K^+ n$  at small  $|t|$  for  $K^0$  momenta between 0.5 and 1.5 GeV/c. Their preliminary results indicate a turnover in the differential cross section

for  $|t| < 0.1$  (GeV/c)<sup>2</sup> which is quite interesting in light of our results for  $|t| \gtrsim 0.1$  (GeV/c)<sup>2</sup>. If this behavior persists, a reexamination of existing phase-shift analyses of the  $I=0$  channel would be necessary.

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