Neutron-Proton Charge-Exchange Scattering from 8 to 29 GeV/c*

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We present differential cross sections for neutron-proton charge-exchange scattering from 8 to 29 GeV/c. The data, based on ~23 000 events, extend to four-momentum transfers $|u|$ as large as 1.0 (GeV/c)^2. The shape of the differential cross sections and the momentum dependence are examined in detail.

In this Letter we present the results of a high-statistics spark-chamber measurement of the differential cross section for the charge-exchange reaction

$$n+p\rightarrow p+n, \qquad (1)$$

covering incident neutron momenta from 8 to 29 GeV/c and four-momentum transfers squared $|u|$ from 0.002 to 1.0 (GeV/c)^2. We used a well-collimated beam containing neutrons with momenta from 6 to 29 GeV/c, and measured simultaneously the differential cross sections over the entire range of $|u|$ and incident momenta. We measured the momentum vectors of both the proton and the neutron in the final state. The resulting three-constraint fit for elastic events allowed a clean separation from background and determined the momentum of the incident neutron.

A schematic drawing of the experimental apparatus is shown in Fig. 1. The neutron beam was taken off at 0° from a Be target in the slow extracted proton beam (kinetic energy 28.5 GeV) at the Brookhaven alternating gradient synchrotron. At the liquid-hydrogen target, the neutron beam was approximately 2.5 cm in diameter with typically 5×10^5 neutrons per pluse. The target was a 7.5-cm-diam Mylar cylinder with its axis vertical. An anti-counter array (A_0, A_1, A_2, and A_3), sensitive to both charged particles and γ rays, reduced the trigger rate from inelastic events. The high-energy forward-going protons from Reaction (1) were detected by the counters P_1, P_2, and P_3. The proton momentum and angles were measured in a wire-spark-chamber spectrometer, consisting of eight wire planes on each side of a 30-in.-wide by 72-in.-long analyzing magnet.

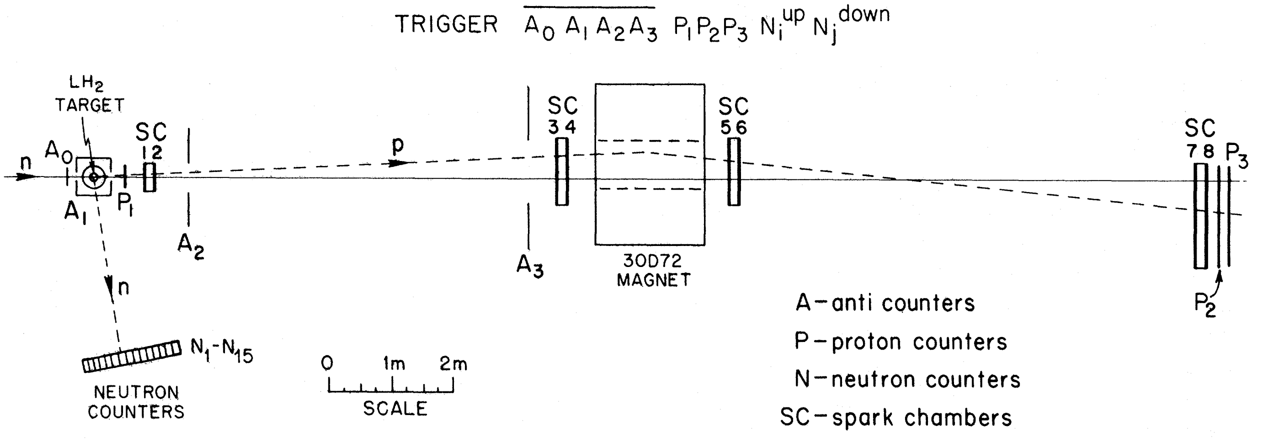

FIG. 1. Plan view of the experimental apparatus.

Typical uncertainties in the proton measurements were ±0.2 mrad in angle and ±1.0% in momentum.

Recoil neutrons with kinetic energies of 1 MeV or higher were detected in a bank of fifteen liquid scintillation counters, N_1-N_{15}, which subtended the angular region from 60° to 90° with respect to the incident beam. Each neutron counter was 5 cm wide, 10 cm thick, and 120 cm high and was viewed by two RCA-8575 photomultiplier tubes, one at each end. Relative timing between the two photomultipliers determined the position of the neutron interaction in the counter. The time difference between P_1 and the neutron counter yielded the neutron time of flight. Typical uncertainties in the measured quantities were ±5 cm in position and ±2 nsec in the time of flight.

The efficiencies of the neutron counters as a function of neutron energy and threshold setting were measured[1] at the Princeton cyclotron. The measured efficiencies ranged from 30% to 60% over the neutron energy range of 2.5 to 19 MeV, with estimated uncertainties of less than 6% of the measured values. A Monte Carlo program which simulated the interaction of neutrons with the scintillator[2] was used to fit the measured efficiencies and extrapolate to larger and smaller neutron energies. The uncertainty in this extrapolation and the statistical uncertainty in the measured efficiencies have been included in the errors in the cross sections.

The trigger requirement was $\bar{A}_0\bar{A}_1\bar{A}_2\bar{A}_3P_1P_2P_3 \times N_i^{\text{up}}N_j^{\text{down}}$, where $N_i^{\text{up}}N_j^{\text{down}}$ indicates that a coincidence was required between the upper end of a neutron counter and the lower end of a counter (not necessarily the same counter). For each event the timing, pulse height, and other neutron-counter information, as well as spark-chamber and monitor-telescope information, were recorded on magnetic tape. Data acquisition and checks on the performance of the experiment were aided by the Brookhaven National Laboratory on-line data facility.

The following procedure was used to select elastic events. Assuming that each event was elastic, we used the measured proton vector momentum to calculate the neutron angles and time of flight. These calculated parameters were compared with the measured ones, and loose cuts were made on the three differences. Those events which survived all three cuts were taken as the elastic sample. The backgrounds in this sample ranged from ~14% at the smallest $|u|$ to ~3% over most of the $|u|$ interval.

A Monte Carlo program was used to calculate the acceptance of the apparatus; such effects as multiple Coulomb scattering of the proton, measurement uncertainties, and energy dependence of the neutron detection efficiency were included. The program also simulated the effects of rescatterings of the recoil neutron in the target, the anti-counters, and the neutron counters themselves.

In order to normalize the cross sections it was necessary to make an independent measurement of the flux and momentum spectrum of the neutron beam. The integral flux was measured to ±5% using a total absorption spectrometer, which is described elsewhere.[3] The spectrum was determined in a separate experiment,[4] namely, neutron diffraction dissociation from carbon, $n + \text{C} \to (p+\pi^-)+\text{C}$. It was *assumed* that the cross section for this reaction is constant for incident neutron momenta between 8 and 29 GeV/c for $p\pi^-$ masses less than 1.5 GeV. This assumption is consistent with current theoretical expectations for this process[5] and with experiments on related processes.[6] In addition, the fact that the angular distributions in the $p\pi^-$ rest frame and the $p\pi^-$ mass distributions were found to be independent, within statistics, of the incident momentum,[4] is also consistent with this assumption.[7]

Combining the data from ~23 000 elastic events and the Monte Carlo information with the measurements of the neutron flux and spectrum, we obtain the cross sections shown in Fig. 2. The errors shown include all known systematic errors as well as statistical errors, but do not include the uncertainties in the neutron flux and spectrum. Uncertainties in absolute normalization are approximately 10% above 12 GeV/c and 15% below 12 GeV/c.

We can make the following observations: (1) The shape of the cross sections agrees very well with recent measurements in or near this momentum interval. Those measurements include those of Manning *et al.*[8] at 8 GeV/c, Miller *et al.*[9] at 3 to 11.75 GeV/c, and Engler *et al.*[10] at 8, 19.2, and 24 GeV/c. (2) The absolute normalizations agree within errors with those of Refs. 9 and 10. (3) The sharp forward peak, characteristic of this reaction, persists apparently unchanged up to at least 29 GeV/c. (4) There is some evidence for structure in the cross sections near $|u|=0.06$ (GeV/c)^2. This structure has appeared in all measurements of the reaction above several GeV/c and is most probably a real property of n-p charge exchange. (5) These data, which extend to higher energy and larger $|u|$ than previous measurements, indicate that the falloff at large $|u|$ is not simple. There appears to be curvature in the $|u|$ distributions for $|u| > 0.5$ $(\mathrm{GeV}/c)^2$.

We have fitted the cross sections with the standard two exponentials—$d\sigma/d|u| = Ae^{-B|u|} + Ce^{-D|u|}$. Since the data at large $|u|$ appear to be more complicated than this simple parametrization would imply, we have restricted the fits to $|u| \leq 0.5$ $(\mathrm{GeV}/c)^2$. As can be seen in Fig. 3(a) there is little evidence for a momentum dependence of the parameters. The weighted average over the entire momentum interval, assuming no momentum dependence, yields

$$d\sigma/d|u| = \mathrm{const}[e^{-(57.4\pm 8.4)|u|} + (0.92\pm 0.10)e^{-(4.26\pm 0.11)|u|}].$$

The $|u| = 0$ cross sections extracted from this parametrization are shown in Fig. 3(b) and demonstrate a $P_{\mathrm{lab}}^{-(2.02\pm 0.22)}$ dependence. We have also examined the momentum dependence of the cross sections at fixed $|u|$, fitting the data with $d\sigma/d|u| = F(|u|)P_{\mathrm{lab}}^{-n}$. The results of the fit are shown in Fig. 3(c). The weighted average n, assuming no $|u|$ dependence, is 1.82 ± 0.04. This value is sensitive to the low-momentum points. When the data of Miller *et al.*[9] from 7 to 11 GeV/c and the data of Engler *et al.*[10] are included, the average n changes to approximately 2.0 ± 0.1. In those fits our 12.6-GeV/c point falls slightly below the fitted line. The fit is improved somewhat, but the average value of n is unchanged if we assume that there is a small momentum dependence in the diffraction dissociation process—e.g., $P_{\mathrm{lab}}^{-0.2}$.

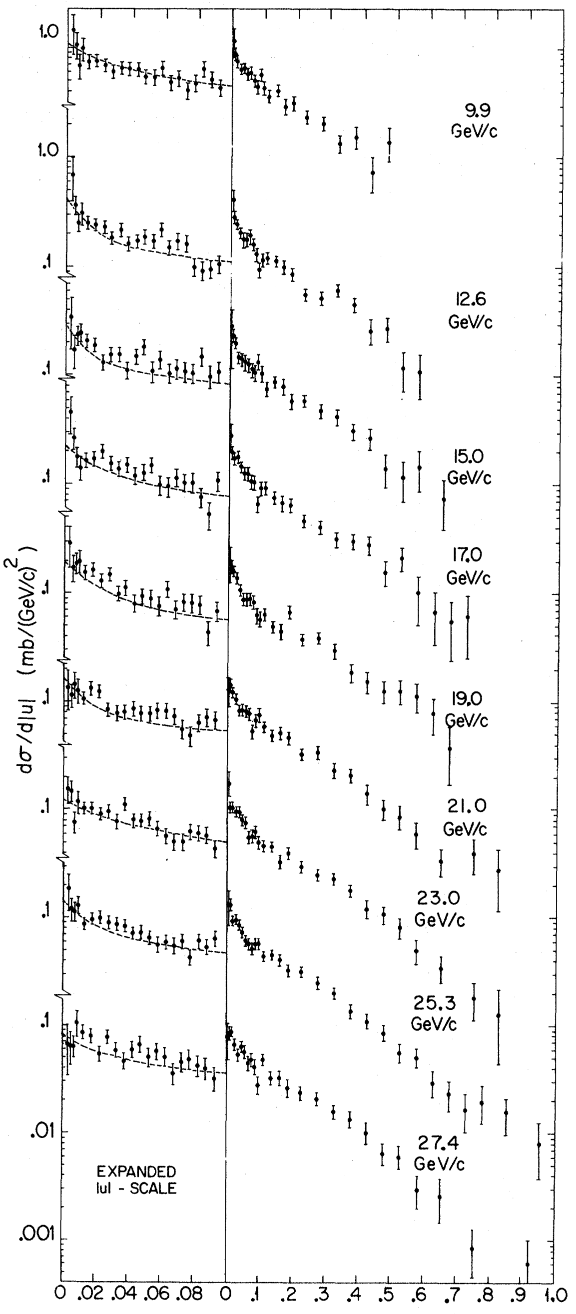

FIG. 2. Differential cross sections for neutron-proton charge-exchange scattering. The low-$|u|$ region is shown with an expanded scale, with the two-exponential fits indicated.

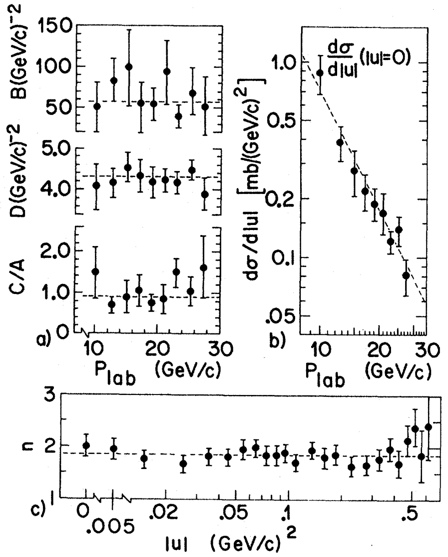

FIG. 3. Results of fits to n-p charge-exchange cross sections. (a) Parameters of the two-exponential fit described in text. Weighted average values indicated by dashed lines. (b) Momentum dependence of $|u| = 0$ cross sections. Dashed line shows fit described in text. (c) Values of n from a fit of $d\sigma/d|u| = F(|u|)P_{\mathrm{lab}}^{-n}$ to our data alone.

Our results indicate that π exchange apparently dominates the cross sections at all $|u|$. If ρ or A_2 exchange dominated, one would expect a much different momentum dependence. In addition, there appears to be very little or no momentum dependence of the shape of the cross sections. Most phenomenological models seem to agree with the shape at small $|u|$, but tend to disagree regarding the behavior at large $|u|$. We are currently investigating various theoretical explanations of our data.

We would like to thank the alternating gradient synchrotron staff and the members of the on-line data facility for their assistance during the experiment. T. McCorriston is to be thanked for his invaluable programming assistance with the on-line program. We would also like to thank N. Albers, T. Baker, C. Burch, W. Davidson, O. Haas, F. Ringia, and S. Wilson for their help during various phases of the experiment. In addition, we would like to thank A. Ramanauskas for the loan of some read-out logic.

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[3] L. W. Jones, M. J. Longo, T. P. McCorriston, E. F. Parker, S. T. Powell, and M. N. Kreisler, Phys. Lett. 36B, 509 (1971).

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[5] See, for example, H. Lesniak and L. Lesniak, Phys. Lett. 34B, 135 (1971); G. Cohen-Tannoudji, G. Kane, and C. Quigg, Nucl. Phys. B37, 77 (1972).

[6] Measurements of $p+p\to p+N^*$ in this momentum region indicate little or no momentum dependence—at most $P_{\rm lab}^{-0.2}$; E. W. Anderson *et al.*, Phys. Rev. Lett. 16, 855 (1966); F. Turkot, private communication.

[7] We emphasize that even if there is a significant momentum dependence in the diffraction dissociation cross section, it would have very little effect on our absolute normalizations between 18 and 26 GeV/c, near the peak in the neutron spectrum.

[8] G. Manning *et al.*, Nuovo Cimento 41, 167 (1966).

[9] E. L. Miller *et al.*, Phys. Rev. Lett. 26, 984 (1971).

[10] J. Engler *et al.*, Phys. Lett. 34B, 528 (1971).

ERRATA

LINEWIDTH OF SPONTANEOUS SPIN-FLIP LIGHT SCATTERING IN InSb. S. R. J. Brueck and F. A. Blum [Phys. Rev. Lett. 28, 1458 (1972)].

Equations (2) and (3) contain incorrectly written terms of the form $\langle G(k_z)\rangle^{-1}$, where G is a function of k_z and the angular brackets denote an average over k_z. These terms should read $\langle G^{-1}(k_z)\rangle$.

TIGHT BINDING MODEL OF ELECTRONIC STATES IN A LIQUID METAL. L. M. Roth [Phys. Rev Lett. 28, 1570 (1972)].

In Eqs. (4) and (5), φ_j should read φ_l. In Eq. (10) $H_{\vec{k}}'$ should read $\tilde{H}_{\vec{k}}'$. In the second of Eqs. (13) $\tilde{H}_{\vec{k}}'\tilde{H}_{\vec{k}}'$ should read $\tilde{H}_{\vec{k}'}'H_{\vec{k}'}'$, and in the third of Eqs. (13), $H_{\vec{k}}'$ should read $H_{\vec{k}''}'$.