N-P Charge Exchange Scattering at FERMILAB*

H.R. Barton, Jr.,[†] N.W. Reay, K. ReibelM. Shaevitz,^{††} and N.R. Stanton

The Ohio State University, Columbus, Ohio 43210

and

M.A. Abolins, P. Brindza,[†]J.A.J. Matthews[#] and R. Sidwell

Michigan State University, East Lansing, Michigan, 48823

and

K.W. Edwards and G. Luxton^{\$}

Carleton University, Ottawa, Ontario K1S 5B6, Canada

and

P. Kitching

University of Alberta, Edmonton, Alberta, Canada

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ABSTRACT

We have measured the neutron-proton charge exchange differential cross-section in the momentum interval 60 to 300 GeV/c, with four-momentum transfers squared 0.002 to 0.8 (GeV/c)². Independent of incident momentum, the data are characterized by a sharp forward peak of width 0.02 (GeV/c)², followed by a shoulder and gentler falloff at higher momentum transfers.

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The differential cross-section for neutron-proton charge exchange scattering below 60 GeV/c is characterized by a "pion exchange" peak of width $M_\pi^2 \sim 0.02 \text{ (GeV/c)}^2$ at small momentum transfers squared (t), followed by a much gentler slope at higher $|t|$.¹ The cross-section has a $(1/P_{\text{LAB}})^{-n}$ dependence on incident momentum, where n is independent of t , but decreases from 2.0 for momenta below 10 GeV/c to 1.5 near 60 GeV/c. Whether the cross-section shape remains invariant and n continues to fall at Fermilab energies is crucial to many models of strong interactions. Further, the N-P charge-exchange cross-section extrapolated to $|t| = 0$ provides a significant bound on the difference between N-P and P-P total cross-sections.

Our data sample of 25,000 events was obtained in the momentum interval 60 to 300 GeV/c and momentum transfers 0.002 to 0.8 (GeV/c)^2 using the apparatus shown in Fig. 1. The Fermilab M3 neutral beam was produced at $3/4$ milliradian from the interactions of 300 GeV/c protons with a beryllium target. Passage through a series of collimators, sweeping magnets, and 3 inches of lead filtering removed charged particles, beam halo, and gamma ray contamination; the K_L^0 flux in the beam was negligible above 60 GeV.² The resulting neutron spectral shape, as shown in Fig. 2, was taken as an average of that determined by the Northwestern-Rochester-SLAC collaboration using coulomb excitation of $\Delta(1238)$,³ and by a Michigan group (and by us) using the Michigan neutron calorimeter.² The total flux was typically 5×10^6 neutrons/second.

Recoil neutrons from the liquid hydrogen target were detected in two banks of neutron counters, each containing 14 counters mounted horizontally. The wide angle bank contained $3'' \times 6'' \times 25''$ 'short' plastic scintillator counters placed radially about 6 feet from the target and set with 0.1 MeV electron equivalent thresholds for detection of slow recoils. The more forward angle

bank contained 4"x12"x60" 'long' counters placed typically 12 feet from the target and had 1.0 MeV thresholds to detect higher energy neutrons. The magnitude of the neutron vector momentum was measured by time of flight, its azimuth by recording which counter fired, and the polar angle by performing timing between the ends of each counter. Timing and spatial resolution were consistent with the measurements presented in a previous paper.⁴

The forward going protons were detected in a magnetic spectrometer containing proportional wire chambers in the upstream leg and magnetostrictive spark chambers in the downstream leg. Sufficient chambers were used to insure a spectrometer efficiency in excess of 99% for charge exchange events.

Non charge-exchange events were suppressed by anti-counters surrounding all but the downstream side of the target, by a series of lead-scintillator aperture anti-counters placed throughout the upstream leg of the spectrometer, and by a trigger requiring a single minimum ionizing pulse height in the scintillation counter just downstream of the target. Non target-associated particles triggering the neutron counters were suppressed by extensive concrete shielding and by an upstream wall of anti-counters.

The neutron counter thresholds and efficiencies were determined by methods described elsewhere.^{4,5,6} Cross-sections from each of the counters of a given bank agreed within statistics, and changed less than 10% when thresholds were raised a factor of 2.4 and efficiencies lowered correspondingly. In the region of overlap between .04 and .08 (GeV/c)²,

cross-sections from the two types of counters agreed to better than 8%, and were statistically averaged.

In off-line analysis, potential proton tracks were formed by linking elevation view points within roads defined by the target and H1 and H2 hodoscopes. The correspondence with plan view points was then established by means of several 45° angle chambers spaced throughout the spectrometer. Approximately one million triggers yielded about 500,000 reconstructed tracks.

Extraction of 3-constraint elastic events from background relied mainly on coplanarity and $P_\perp$ momentum balance between neutron and proton arms. The proton arm alignment was performed to 10^{-5} radians using straight-through muons from the neutron beam production target; the 3rd constraint (a relation between the angle and momentum of the neutron) was used to adjust the end-to-end timings of the individual neutron counters.

A full kinematic fit was made using the neutron and proton vector momenta with errors calculated from the resolution of the proton spectrometer and the neutron time of flight errors. In the event that more than one neutron counter fired, all possibilities were tried and the combination with lowest χ^2 kept.

Fits to the χ^2 distribution were then performed to estimate the background contamination in the final data sample of 25,000 events. Such backgrounds were typically 5% for the large neutron counters, rising to 12% at the highest momentum transfers, and 10% for the small neutron counters, rising to 27% in the smallest momentum transfer bin.

Corrections were applied for anti-overkill (typically 10%), losses from the proton pulse-height cut (7%), and absorption (largely in the target) of the recoil neutron before reaching the neutron counters, 37% for the smallest momentum transfer bin to 2% for the highest. Proton absorption losses were compensated by losses in the neutron beam before it arrived at the downstream beam monitor. A small correction (1 to 2%) was applied for events in which the time of flight was stopped by randoms in the neutron counter, and a 2% correction was applied for losses due to the χ^2 cut in the kinematic fitting.

The data are shown in Fig. 3 and Table I. The errors shown are statistical only and include neither the $\pm 6\%$ point to point uncertainty in neutron counter efficiency nor the $\pm 15\%$ error in absolute normalization. The latter error was derived equally from the differences of up to 10% between the various methods of measuring the beam spectrum, and from uncertainties in calibration and stability of the downstream beam monitor. The smallest momentum transfer bin has an additional $\pm 10\%$ error due to uncertainties in thresholds and absorption corrections.

A detailed discussion of the data is presented in a companion paper.

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- * Work supported in part by ERDA, NSF and NRC, Canada.
- + Present address, Fermilab, Batavia, Ill. 60510.
- ++ Present address, California Institute of Technology, Pasadena, California 91109.
- # Present address, Johns Hopkins University, Baltimore, Md. 21218.
- \$ Present address, Dept. of Radiology, Sanford University, Stanford, California 94305.

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FIGURE CAPTIONS

Figure 1. Experimental layout. Not shown are the neutron beam and upstream anti-counter.

Figure 2. Relative incident neutron beam intensity as a function of incident momentum.

Figure 3. N-P charge-exchange absolute cross sections in microbarns/ $(\text{GeV}/c)^2$. The data are shown using the binning of Table I, and the errors shown are statistical only. Small momentum transfer data are shown in an expanded $|t|$ scale for ease in viewing.

Table I. N-P charge exchange differential cross-section presented as a function of momentum transfer in six bins of incident momentum. The $\pm 6\%$ point to point uncertainty in efficiency and the overall $\pm 15\%$ uncertainty in absolute normalization are not included.

FIGURE 1

TABLE I

I [(GeV/c) ²]	INCIDENT MOMENTUM (GEV)					
	60-90	90-120	120-160	160-200	200-240	240-300
.0030	18.01 ± 3.04	10.94 ± 2.10	13.76 ± 1.79	9.34 ± 1.28	9.67 ± 1.17	6.14 ± .93
.0050	18.41 ± 2.98	17.55 ± 2.58	10.54 ± 1.52	10.45 ± 1.31	7.49 ± 1.00	6.32 ± .92
.0070	21.95 ± 3.23	13.15 ± 2.22	8.43 ± 1.35	7.19 ± 1.08	5.01 ± .81	5.43 ± .84
.0090	14.00 ± 2.55	9.19 ± 1.87	8.04 ± 1.30	6.23 ± .99	5.54 ± .84	3.62 ± .88
.0115	16.55 ± 2.29	12.53 ± 1.77	8.22 ± 1.08	7.52 ± .90	4.39 ± .62	4.24 ± .50
.0145	16.01 ± 2.28	8.74 ± 1.50	8.44 ± 1.11	5.25 ± .76	5.23 ± .68	4.26 ± .62
.0180	12.85 ± 1.80	12.11 ± 1.55	7.88 ± .94	5.95 ± .71	4.11 ± .53	4.33 ± .55
.0225	15.08 ± 1.81	11.19 ± 1.38	8.12 ± .89	5.23 ± .62	4.47 ± .51	4.24 ± .50
.0275	15.43 ± 1.87	12.15 ± 1.47	7.51 ± .87	5.05 ± .62	5.39 ± .58	4.66 ± .54
.0325	13.41 ± 1.76	9.83 ± 1.33	7.02 ± .85	4.98 ± .62	5.43 ± .58	4.36 ± .52
.0375	16.32 ± 1.99	10.93 ± 1.44	8.72 ± .98	5.50 ± .67	4.91 ± .57	5.34 ± .60
.0450	11.83 ± .89	10.12 ± .73	7.89 ± .49	5.65 ± .36	3.80 ± .26	4.41 ± .28
.0550	12.34 ± .92	8.86 ± .69	6.81 ± .46	5.48 ± .36	4.80 ± .30	3.87 ± .27
.0650	12.84 ± .95	8.43 ± .68	6.20 ± .44	4.66 ± .33	4.01 ± .27	3.80 ± .27
.0750	10.71 ± .87	9.08 ± .71	5.97 ± .44	4.74 ± .34	4.45 ± .29	3.86 ± .27
.0900	10.70 ± .63	8.79 ± .51	6.79 ± .34	4.72 ± .24	3.70 ± .19	3.64 ± .19
.1125	10.68 ± .60	7.90 ± .45	5.69 ± .29	4.31 ± .22	3.61 ± .18	3.50 ± .18
.1375	9.73 ± .76	7.56 ± .59	5.11 ± .38	3.88 ± .28	3.40 ± .23	3.06 ± .22
.1625	9.84 ± .80	7.23 ± .61	4.97 ± .38	3.52 ± .28	2.95 ± .23	2.91 ± .23
.1875	6.69 ± .67	5.81 ± .56	3.97 ± .35	3.28 ± .27	2.70 ± .22	2.54 ± .22
.2250	7.04 ± .50	4.72 ± .36	4.08 ± .25	2.74 ± .18	2.12 ± .14	2.04 ± .14
.2750	5.55 ± .46	4.07 ± .35	2.55 ± .21	1.94 ± .15	1.22 ± .11	1.23 ± .11
.3250	3.70 ± .38	2.79 ± .29	2.00 ± .19	1.25 ± .13	.84 ± .09	.81 ± .09
.3750	2.06 ± .28	1.88 ± .24	1.08 ± .14	.95 ± .11	.57 ± .08	.52 ± .07
.4500	1.20 ± .15	.84 ± .11	.54 ± .07	.41 ± .05	.28 ± .04	.28 ± .03
.5500	.49 ± .09	.34 ± .07	.31 ± .05	.14 ± .03	.11 ± .01	.11 ± .02
.6500	.16 ± .05	.14 ± .04	.08 ± .02	.08 ± .02	.02 ± .01	.05 ± .01
.7500	.08 ± .03	.08 ± .03	.03 ± .01	.02 ± .01	.004 ± .004	.004 ± .004

TABLE II

TABLE III