# Neutron-Proton Charge-Exchange Scattering, 3-12 GeV/c*

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We report a high-statistics measurement of the neutron-proton charge-exchange differential cross section for incident momenta 3 to 12 GeV/c, and four-momentum transfers 0.003 to 0.85 $(GeV/c)^2$. The data are normalized absolutely to $\pm20\%$. The differential cross section is characterized by a sharp peak at small momentum transfers, with a gentler exponential behavior at large momentum transfers. This shape is remarkably independent of the incident momentum.

We have measured the differential cross section for neutron-proton charge-exchange scattering for four-momentum transfers squared $(-t)$ between 0.003 and 0.85 $(GeV/c)^2$, obtaining approximately 180 000 events in the interval of beam momentum 2.5 to 12 GeV/c. We believe that the absolute normalization of the data is correct to $\pm20\%$, and that the relative normalization of the low- and high-momentum data is correct to $\pm12\%$, allowing both the shape and the energy dependence of the cross section to be studied. Our results thus extend to much higher energy the high-statistics work[1,2] below 2 GeV/c, greatly improving both the statistics and the normalization of the existing high-energy data.[3-5]

This two-arm experiment (Fig. 1) was per-

formed in a continuous-energy neutron beam produced at $\frac{3}{4}°$ from an internal target at the Argonne National Laboratory zero gradient synchrotron. The beam was collimated to a 2-in.-diam spot on a 6-in.-long liquid-hydrogen target. Veto counters (some of them $\gamma$ sensitive) surrounding the target and a pulse-height restriction on the forward-going charged particle minimized triggering on events with higher multiplicity. The momentum vector of the forward proton was measured by a wire-chamber magnetic spectrometer. The slow-recoil neutron was detected by one of thirteen thick scintillation counters, its energy measured by time of flight, its azimuth specified by recording which counter fired, and its production angle determined from timing differences be-
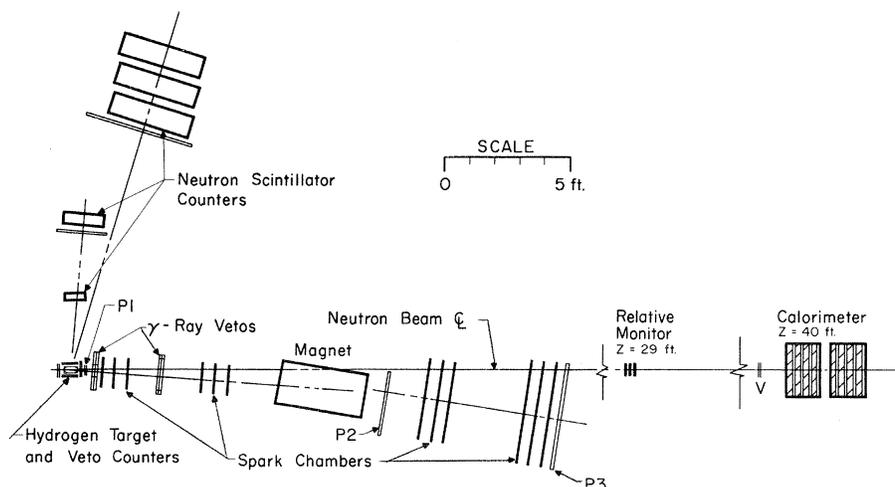


FIG. 1. Schematic layout of the *np* charge-exchange experiment.

tween photomultipliers on both ends of that counter. To reduce accidentals from room background, the neutron counters were of three sizes and were arranged in three banks (Fig. 1). Smaller counters were placed nearer the target and run at lower bias to detect neutrons of lower energy. Both neutron and proton arms were placed on line to a model DDP-24 computer which continuously monitored equipment performance, extracted elastic events, and wrote raw and analyzed data on magnetic tapes.

The dependence of the detection efficiency of one of the neutron counters on energy and bias setting was calibrated at the Carnegie-Mellon synchrocyclotron,[6] and a Monte Carlo program was written to permit extension of the measurements to different energies and counter geometries. The predictions of the program generally agree with our calibration and those of others[6] to better than 5% of the efficiency which ranged from 0.21 to 0.70 with our bias settings. An additional efficiency check was provided during the experiment by the extensive overlap in $t$ of counters of the various types; in the regions of overlap the cross sections from all counters agreed to 6%.

A three-constraint fit to each event was performed off line, resulting in a confidence-level distribution which was flat from 0.05 to 1.0. The background subtraction performed after fitting was typically 4 to 10%.

The continuous momentum spectrum of the beam allowed simultaneous measurement of charge-exchange cross sections for the entire range of incident momenta, but required that the spectrum be measured in an independent experiment. Using the same beam, target, and beam monitor, measurements were made of the forward $np$ elastic-scattering angular distribution. Knowledge of the yield per monitor count for this reaction in each bin of beam momentum allows the determination of the absolute neutron beam flux in each bin, provided that the cross section for forward $np$ elastic scattering is known. We have assumed equality of $np$ and $pp$ forward elastic differential cross sections for momentum transfers of 0.15 to 0.50 $(\text{GeV}/c)^2$ and for beam momenta of 3 to 12 GeV/$c$.

For the measurement of the forward $np$ elastic-scattering yield, the slow, sideward proton was detected by an array of wire chambers followed by a bank of stopping scintillators; and the stopping pulse height, time of flight, and direction were recorded by the on-line computer. The di-

rection of the fast, forward neutron was measured using an assembly of steel plates, scintillators, and wire chambers. The efficiency of this wire shower-chamber system was calibrated with proton-initiated showers and separately by using forward elastically scattered neutrons tagged by the trigger from the recoil protons and veto counters. Neutron beams of 4-, 8-, and 12-GeV/$c$ maximum momenta were used in an attempt to measure possible inelastic contributions to the tag. For example, 4-GeV/$c$ neutrons tagged from a neutron beam with maximum momentum 12 GeV/$c$ should contain more contamination than if tagged from a 4-GeV/$c$-maximum beam. All methods of obtaining the efficiency agreed to better than 5%. The experimental beam-momentum resolution for the forward elastic experiment (worst case, 1 GeV/$c$ full width at half-maximum) was unfolded from the measured spectrum. Below 10 GeV/$c$, measured and unfolded spectra differ by less than 10%, independent of the unfolding technique applied.

As an independent check, the integral beam flux was measured using a total absorption calorimeter and found to be 12% larger than that determined from forward elastic scattering. An average of the two normalization methods was used to calculate the charge-exchange cross sections. The good agreement between the two types of integral-flux determinations indicates that on the average the assumption of equality of $np$ and $pp$ forward elastic scattering is correct.

Our measured differential cross sections for $np$ charge exchange are presented in Fig. 2(a). Only statistical errors are shown; systematic uncertainties are described below:

(1) A ±3% uncertainty in subtracting background.

(2) An uncertainty of at most ±3% in the correction for absorption of slow-recoil neutrons in the hydrogen target.

(3) A ±5% uncertainty in the efficiency of the neutron scintillators at any given momentum transfer; the shape of the angular distribution may be distorted by this amount.

(4) Uncertainties in the determination of the beam flux: (a) statistical errors in the forward elastic measurement, ±3%; (b) uncertainty in the relative energy dependence of $np$ and $pp$ forward elastic scattering, ±10%; (c) uncertainty in the integral flux determination, ±15%; (d) uncertainty in unfolding the beam spectrum near the end point, ±12% at 11 GeV/$c$, ±18% at 11.75 GeV/$c$.

In summary, for the data below 11 GeV/$c$ the estimated *relative* systematic uncertainty is ±6%
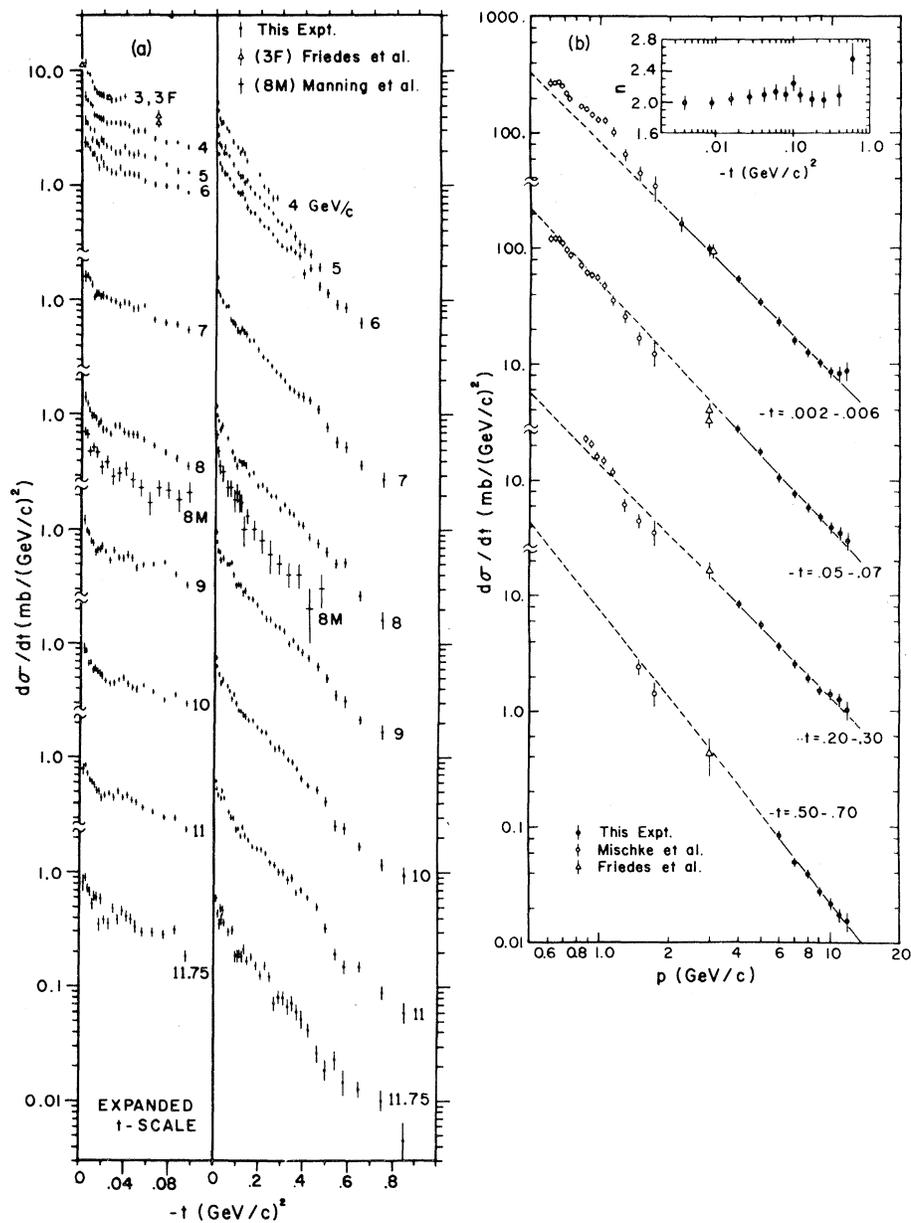
FIG. 2. Differential cross sections $d\sigma/dt$ for $np$ charge exchange. (a) Dependence of $d\sigma/dt$ on momentum transfer $t$ at fixed laboratory beam momentum $p$. The expanded scale on the left-hand side provides magnification of the structure at small $|t|$. The data of Refs. 3 and 4 are included for comparison. Error bars are statistical. (b) Dependence of $d\sigma/dt$ on $p$ at fixed $t$. The solid lines are fits to our data at four values of $t$ by the form $d\sigma/dt = A(t)p^{-n}$; the dashed lines extrapolate the fits through the data of Refs. 2 and 3. The inset shows the fitted values of $n$ (from our data alone) for all $t$. Error bars include an estimate of the systematic uncertainty in each point (see text).

for the neighboring data points and ±12 % for points widely separated in beam momentum. The estimated *absolute* systematic uncertainty in any datum point is ±20%, and the normalization is known best near 8 GeV/$c$.

The differential cross sections are plotted against $-t$ in Fig. 2(a); the data of Refs. 3 and 4 are included for comparison. A sharp forward

peak of width $\delta t \approx m_\pi^2 = 0.02$ (GeV/$c$)$^2$ and a more gradual falloff with slope of about 5 (GeV/$c$)$^{-2}$ at larger $|t|$ are evident at all momenta; a weak second maximum or shoulder near $|t| = 0.04$ (GeV/$c$)$^2$ is also discernable. There is good normalization agreement with the data of Friedes et al.[3] (taken with a single-arm spectrometer) at 3 GeV/$c$. At 8 GeV/$c$, our data agree in shape

but are a factor of $2\frac{1}{2}$ larger than the data of
Manning et al.[4] and Engler et al.[5] (not shown),
both obtained by a single-arm technique. This
discrepancy is large and unexplained. However,
Engler et al. have stated[5] that systematic errors
inherent in the overall normalization of the sin-
gle-arm technique could be as large as a factor
of 2.

The dependence on beam momentum $p$ of $d\sigma/dt$
at fixed $t$ is shown in Fig. 2(b) for our data and
those of Friedes et al.[3] and Mischke et al.[1,2] The
error bars in Fig. 2(b) include the estimated rel-
ative systematic uncertainty discussed above for
our data, and a conservative estimate[7] of the
normalization uncertainty in the data of Ref. 2.
The solid lines in Fig. 2(b) are the result of fits
to our data at four values of $t$ by the form $d\sigma/dt$
$=A(t)p^{-n(t)}$; the dashed lines extrapolate the fits
to lower momenta, where they are seen to de-
scribe quite well the average $p$ dependence of the
Mischke data. The values of $n$ resulting from the
fits are shown for all $t$ in the inset to Fig. 2(b).
Our data are consistent with a constant value of
$n \approx 2.1$ for all $|t|$ between 0.002 and 0.50 $(\text{GeV}/c)^2$.
Within errors, there is no indication that the
shape of the angular distribution is changing.

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of Ref. 2; see also the discussion on p.90 of Ref. 2.

## Coincidence Measurements of Single π+ Electroproduction*

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We have studied the reaction $e^- + p \rightarrow e^- + \pi^+ + n$ by detecting the final electron and pion
in coincidence. Data are presented in the region of virtual photon mass squared from
−0.18 to −1.2 $\text{GeV}^2$, and virtual photoproduction center-of-mass energy and angle from
1.85 to 2.50 GeV and 0 to 20°, respectively.

We have performed a series of experiments at
the Cambridge Electron Accelerator (CEA) to
study electroproduction by detecting a charged
hadron in coincidence with the scattered electron.
This Letter presents our results for the reaction
$e^- + p \rightarrow e^- + \pi^+ + n$.

To lowest order in the electromagnetic inter-
action this process can be treated as photopro-

duction by a virtual photon whose mass, energy,
direction, and polarization density matrix are
tagged by the detected electron. The cross sec-
tion can then be written[1]

$$\frac{d^3\sigma}{dE' d\Omega_e d\Omega_\pi} = \Gamma \frac{d\sigma}{d\Omega_\pi}, \tag{1}$$

where $\Gamma$ represents the flux of virtual photons,