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Measurement of *np* Charge Exchange for Neutron Energies 150-800 MeV

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The s and u variations of the *np* charge-exchange ($np \rightarrow pn$) cross section are measured to be relatively smooth and without structure at intermediate energies—in sharp contast to previous results.

During the 1960's it was noted[1] that the shape of the *np* charge-exchange (CEX) cross section could be fitted by an empirical double exponential in the square of the invariant four-momentum transfer u: $d\sigma/du = \alpha_1 \exp(\beta_1 u) + \alpha_2 \exp(\beta_2 u)$. Although it was certain that the very sharp peak at the extreme back angles ($-u \leq 0.02$) was due to one-pion exchange (OPE), in Born approximation the OPE amplitude yields a dip at $u = 0$ instead of the observed peak. Phillips[2] suggested that the sharp peak could be caused by a destructive interference between the OPE amplitude and a slowly varying background term. Further developments of this idea considered absorption corrections[3] to the OPE amplitude in both the initial and final states caused by competing inelastic channels. These improvements indeed turned the dip into a spike but also predicted a secondary maximum in the cross section which was simply not observed. Other ways of handling the background terms have been developed,[4] but none have been completely successful in fitting the s and u variations of the *np* CEX cross section at medium energies (s is the square of the total c.m. energy).

During the past few years two experiments have produced large amounts of new data relating to *np* CEX at medium energy. In 1969, the group[5] from the Princeton-Pennsylvania Accelerator (PPA) reported a large peak in both the cross section and its logarithmic derivative at $u = 0$. The peak was centered about an incident neutron momentum (P_n) of about 850 MeV/c, and the experiment covered the range $600 < P < 1730$. In 1975 the data from an experiment[6] at Saclay were published and, while disagreeing with PPA data[5] rather markedly for $P_n > 1.2$ GeV/c, the data for the lower momenta (down to their minimum 0.98

GeV/c) were consistent with the existence of both peaks mentioned above.

The present experiment was designed to span the region of the peak and to study in some detail the s and u variations of the np CEX cross section over the range $575 \leq P_n \leq 1429$. This was accomplished by using a continuum beam of neutrons incident on a liquid-hydrogen target and detecting the recoiling protons with a multiwire proportional-chamber spectrometer. The spectrometer is described in previous publications.[7,8] Briefly, the 800-MeV proton beam at LAMPF (Clinton P. Anderson Meson Physics Facility) passes through a 2-cm-thick aluminum target and after deflection through 60° is transported to a beam dump several meters away. Neutrons emerging at 0° are collimated to form a neutron beam which is then cleared of charged particles by a sweeping magnet. The spectrum of neutrons thus obtained is characterized by a strong narrow peak above 1400 MeV/c and a broad continuum of neutrons at lower momenta. Charged particles emerging from the interaction of the neutron beam with a liquid-hydrogen target are momentum analyzed in the spectrometer. Particle identification is accomplished by a simultaneous measurement of their time of flight through the spectrometer, which allows a calculation of the particle mass by the usual relation $M=P/\beta\gamma$. Particle identification is unambiguous for greater than 99% of the events.

Once the protons are identified, then for the elastic events the proton momentum and angle uniquely specify the incident neutron momentum associated with each event. Inelastic events (such as $np\to pn\pi^0$, $np\to pp\pi^-$) destroy this one-to-one correspondence. However, the incident-neutron time of flight is measured in addition to the proton momentum. This allows the elastic and inelastic events to be easily separated—thus restoring the correspondence between proton and neutron momentum. Since the accuracy of the proton momentum determination is ~1%, this translates into an uncertainty in the neutron momentum determination of about the same amount. This technique has also been used for a measurement[9] of backward nd scattering over the incident energy range 200–800 MeV.

After the neutron momentum is calculated from the measured elastic proton momentum and angle, the events are sorted into 30-MeV/c-wide bins. The highest-momentum bin, containing the peak of the spectrum, is treated somewhat differently. All events with $P_n > 1400$ MeV/c are put into that bin and the average value of P_n for the bin was determined to be 1429 MeV/c. Therefore we have 29 relative angular distributions for P_n from 575 to 1429 MeV/c extending from 0° laboratory proton angle to about 30°. The angular resolution varied from about 4 to 8 mrad and the data for each incident momentum bin were sorted into angular bins 5 mrad wide.

For neutron momenta greater than 800 MeV/c, the relative angular distributions can be made absolute by normalizing to the deuterons detected simultaneously from the reaction $np\to d\pi^0$. The kinematics for this reaction enables the forward-going deuterons (in the center of mass) to be easily distinguished from those going backwards by utilizing the incident neutron time of flight in conjunction with the measured deuteron momentum. Hence the incident neutron momentum can be calculated uniquely from the deuteron momentum and angle. These events are binned as before in P_n. Since the cross section for $np\to d\pi^0$ is assumed from charge symmetry to be one-half that for the well-known[10] reaction $pp\to d\pi^+$, it is possible to calculate from the detected deuterons the product of the number of incident neutrons in each bin and the number of target atoms per unit area. Given this product, the absolute differential cross section for those bins with $P_n > 800$ MeV/c can be obtained. For the data reported here, the angular distributions for $P_n < 800$ MeV/c are relative, not absolute.

Corrections to the data included the usual ones for dead-time effects in the data acquisition system (≤10%) and deuteron loss resulting from collisions in the scattering target and spectrometer (3.5%–2.5%). Spectrometer inefficiencies were measured to be substantially less than 1% and were ignored. We estimate the overall systematic errors, including normalization error, to be in the range of 5 to 10%.

Typical distributions are shown in Fig. 1 along with the double-exponential fit obtained by the method of least squares for each distribution. Only those data with the $|u| < 0.16$ (GeV/c)^2 were used in the fitting procedure since it was found that the function did not fit the data very well for $|u| \gtrsim 0.2$. The values of the extracted parameters were insensitive to the u cutoff as long as it was less than about 0.2. The suitability of the double exponential for describing the present data set is indicated by an overall χ^2 of 1718 for 1593 degrees of freedom ($\chi^2/\nu = 1.078$) —a remarkable result.

From similar fits to the 29 distributions, val-

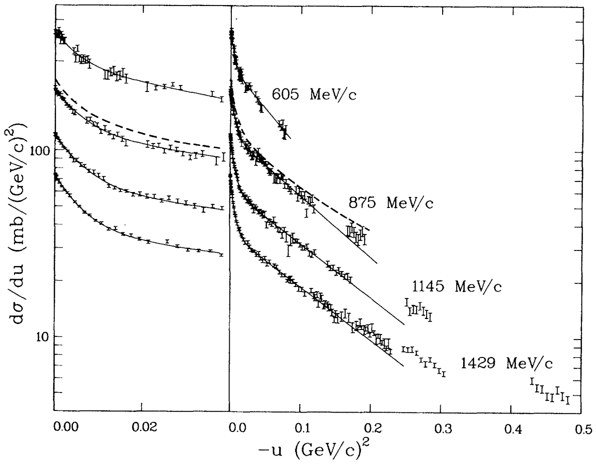

FIG. 1. Typical angular distributions for np charge-exchange scattering plotted as a function of $-u$, the square of the invariant four-momentum transfer. The solid curves are the result of the double-exponential fit to the data with $|u| < 0.16$. The dashed curve is the prediction of a recent phase-shift analysis (Ref. 11).

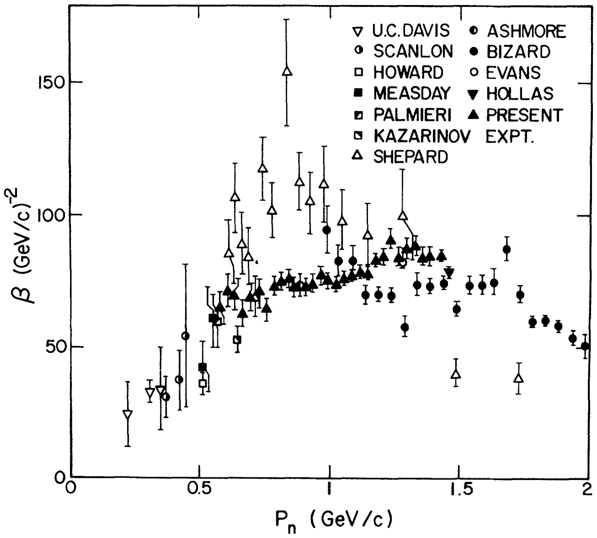

FIG. 2. Momentum dependence of the logarithmic slope, β, at $u = 0$ determined from the present 29 angular distributions compared to previous measurements. References to previous results are listed in the order 12, 13, 14, 15, 16, 17, 5, 18, 6, 7, and 19.

ues of the four parameters were extracted for each incident-momentum bin. We present here the results on the momentum dependence of the logarthmic slope and the intercept at $u = 0$. In Fig. 2 the present results are compared to previous measurements[5-7,12-19] of the logarithmic slope β, defined as

$$\beta = \left[\frac{d}{du}\ln\frac{d\sigma}{du}\right]_{u=0} = \frac{\alpha_1\beta_1 + \alpha_2\beta_2}{\alpha_1 + \alpha_2}.$$

The values plotted for previous measurements were obtained from the same fitting procedure used for the present results. The large peak around 850 MeV/c indicated by the PPA[5] and Saclay[6] results is replaced by a smooth increase from a value of about 65 at 600 MeV/c (in good agreement with the lower-energy measurements) to a value of 85 at our highest momenta. The present results, obtained with the continuum-neutron-beam technique described above, are also in good agreement with previous measurements from this group using nearly monoenergetic neutron beams of energy 647 (Ref. 7) and 800 (Ref. 19) MeV. The statistically precise measurement of Ashmore *et al.*[18] at 353 MeV is also in excellent agreement with the present results.

As mentioned above, previous measurements[5,6] had also indicated the presence of a peak in the value of the 180° cross section as a function of neutron energy. From the aforementioned fits to the charge-exchange region, we have derived values of the quantity $[d\sigma/du]_{u=0} = \alpha_1 + \alpha_2$. In Fig. 3 we plot this quantity (multiplied by P_n^2) as a function of the neutron momentum P_n. Again the present results are consistent with a flat momentum dependence in disagreement with the previous measurements. The excellent overlap with the previous results of this group[7,19] is also apparent. The lower-energy measurements, with the ex-

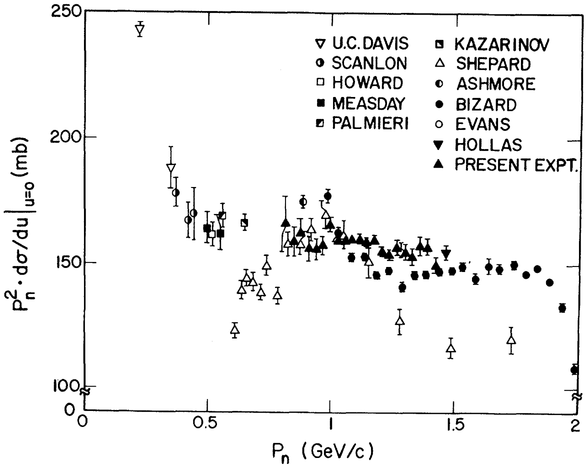

FIG. 3. Momentum dependence of the cross section at $u = 0$ (multiplied by P_n^2) determined from the present experiment compared to previous measurements. References to previous results are the same as in Fig. 2.

ception of Ref. 5, are also consistent with a constant value of about 160 mb for the quantity $[P_n^2\, d\sigma/du]_{u=0}$ over the entire energy region from 100 to 800 MeV.

Recently published[20] results at 325 MeV on the polarization and the triple-scattering parameter D_t in *np* scattering have apparently resolved the long-standing ambiguity in the $T=0$ phase-shift solutions that have been found at that energy. In Fig. 1 is plotted the prediction from the solution of Bryan, Clark, and Verwest[11] for the *np* CEX cross section at 875 MeV/*c* compared to the results from the present experiment at this momentum (not included in their analysis). Aside from an overall normalization difference of about 10%, the agreement is impressive and incorporation of the present results at this and other nearby energies should indeed sharpen the phase-shift solution even further. The agreement at this energy also lends support to the validity of the present results over the wide range covered by this experiment.

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