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Precision Measurement of *n-p* Charge-Exchange Cross Section at 647 MeV*

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The differential cross section for *n-p* elastic scattering in the angular region $145° < \theta_{c.m.} < 180°$ has been measured with high statistical accuracy using the monoenergetic neutron beam at Clinton P. Anderson Meson Physics Facility. The results differ significantly from previous Dubna and Princeton-Pennsylvania Accelerator results but agree reasonably well with recent Saclay data except at extreme backward angles.

In spite of much experimental effort in the study of neutron-proton scattering near 640 MeV, the nucleon-nucleon interaction in isospin-0 states remains undetermined. The most recent energy-independent phase-shift analysis by Glonti *et al.*[1] yields several solutions, in which the $^3S_1$ phase shift varies from $-17°$ to $35°$, and similar variations are found in the other low-order partial waves. Resemblance to the results of the earlier analysis by MacGregor, Arndt, and Wright[2] (LRL VIII and IX) is qualitative at best. At the experimental level, there is considerable discrepancy between the three previous measurements of so elementary an observable as the elastic *n-p* differential cross section $d\sigma/d\Omega$ (shown by open symbols in Fig. 1). The Dubna values[3] at 630 MeV are much higher than the recent Princeton-Pennsylvania Accelerator (PPA) values[4] at 649 MeV, while Saclay measurements[5] at 649 MeV fall in between. The disagreement is well beyond the normalization uncertainty assigned to each experiment. It cannot be attributed purely to normalization errors since the relative shapes of the angular distributions are different. In order to resolve these discrepancies, we have begun a long-range program for experimental investiga-

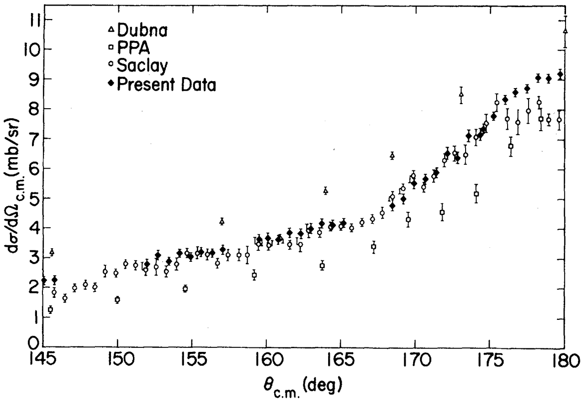

FIG. 1. Differential-cross-section data for n-p charge-exchange scattering near 640 MeV: Dubna (630 MeV), Ref. 3; PPA (649 MeV), Ref. 4; Saclay (649 MeV), Ref. 5; present experiment (647 MeV).

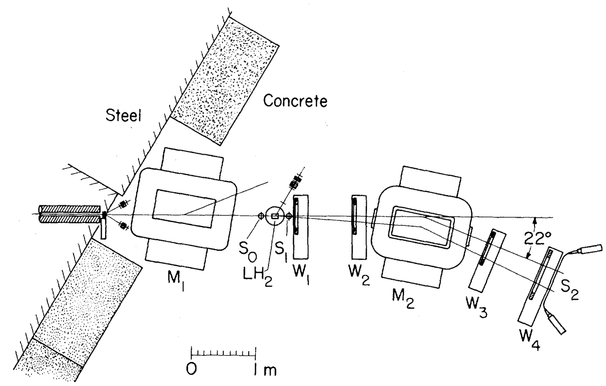

FIG. 2. Layout of experimental apparatus.

tion of the n-p interaction at the Clinton P. Anderson Meson Physics Facility (LAMPF) by studying n-p charge-exchange scattering (CEX) at 647 MeV. In this paper we compare our measurements of $d\sigma/d\Omega$ in the angular region $145° \leq \theta_{c.m.} < 180°$ with the previously published data.

The reaction $^2H(p,n)pp$ was used to generate the neutron beam used in this experiment. The LAMPF proton beam passed through a liquid-deuterium neutron-production target[6] of thickness 1.80 g/cm^2 and after magnetic deflection was buried in a heavily shielded beam stop. The proton beam was monitored by integration of the output of a toroid beam-current monitor. The neutron beam was formed by collimation of the neutrons at a production angle of 0° to a half angle of 0.1°. The energy spectrum of this neutron beam is almost ideal for n-p experiments in that it is dominated by a high-energy peak of nearly monoenergetic neutrons ($\langle T_n \rangle = 647$ MeV; $\delta T_n \leq 13$ MeV, full width at half-maximum) almost isolated from a relatively small background of lower-energy neutrons.[7] The neutron beam was monitored by viewing a polyethylene radiator at the collimator exit (see Fig. 2) with counter telescopes positioned at 25° to left and right of the beam. Contaminant charged particles not swept from the neutron beam by magnet M_1 were vetoed by scintillator S_0. A liquid-hydrogen (LH_2) target of thickness 0.94 g/cm^2 was placed in the path of the neutron beam. (The product of neutron flux and target thickness was monitored by a range telescope placed to detect protons scattered at 45°.) Recoil charged particles were detected in a multiwire-proportional-chamber (MWPC) spectrometer,[8] which could be rotated about a vertical axis through the center of the target. The spectrometer consisted of a large magnet (M_2) and four horizontal-vertical pairs of MWPC planes (W_1–W_4) which provided the coordinates of four points of the particle trajectory, determining the path before and after the magnetic deflection with angular precision of ~0.06°. Typical bend angles were ~22°, which gave a momentum determination of accuracy ~0.5%. The angular acceptance in the horizontal plane was ~4°. Protons, deuterons, and pions of the same momentum were distinguished by their different times of flight t_{12} between scintillators S_1 and S_2. Multiple scattering was reduced by placing helium-filled plastic bags between the MWPC's. The criterion for acceptance of an event was coincidence of signals from S_1, S_2, and a majority of both horizontal and vertical MWPC's in the absence of a veto from S_0. For such events, analog signals for S_1, S_2, and t_{12} and digital signals identifying the "hit wires" in the MWPC's were read into a PDP-11 computer. The data-acquisition program[9] provided flexible on-line monitoring and stored all data for each event on tape.

In the off-line analysis, an estimate of the particle momentum was obtained from the angle of deflection. The path of a particle of this momentum through the spectrometer was computed using known magnetic field values, and the optimum momentum p was determined by a χ^2 minimization procedure. This p value and other data on the event were written on another tape which was used in all further analysis.

The geometric acceptance of the spectrometer is a function of the polar and azimuthal angles of scattering θ and φ, the momentum p, the magnet current, and the origin of the scattering (within the overlap of the neutron beam and the LH_2 target). With our spectrometer geometry and beam size, there was negligible probability of a particle striking a magnet pole if $\sin\theta \sin\varphi < 0.02$. Within this restriction, the fraction of azimuthal angle accepted when $\sin\theta > 0.02$ is $\epsilon = (2/\pi) \times \arcsin(0.02/\sin\theta)$. The possibility of a particle missing one of the MWPC's was determined empirically from plots of θ versus hit-wire position in each of the MWPC's for various momentum bands and all magnet currents. Regions of θ were found in which all particles passed through all MWPC's. Only events within these θ regions and having $\sin\theta \sin\varphi \leqslant 0.02$ were used in the final analysis.

The discreteness of the coordinate information provided by the MWPC's causes artificial discontinuities in the distributions of θ and φ values calculated from these coordinates. This instrumental "granularity" was removed by redistributing the discrete coordinates randomly with a trapezoidal distribution function. The occasional occurrence of multiple hits in the MWPC planes was resolved by considering all possible trajectories through individual hits in the different wire planes and selecting the one with the best χ^2 value. Events with a missing x or y coordinate due to MWPC inefficiency (typically ~0.3%) caused no problem because three x and three y coordinates determine the trajectory unambiguously.

The number of deuterons which were detected along with the $^1H(n,p)n$ protons was used to determine the absolute normalization of the n-p cross section. This is possible because by isospin invariance the cross section for $^1H(n,d)\pi^0$ is one half the cross section for $^1H(p,d)\pi^+$, and the latter cross section is well known.[10] The estimated accuracy of this normalization is ± 7%.[11] The same method of normalization was used by the Saclay group.[5]

The data were obtained in two sets of runs, some six months apart, in which different methods were used to vary the scattering angle accepted by the spectrometer. In the first set the spectrometer was positioned at 0°, and data of high statistical accuracy were obtained for three different magnet currents. As the current was lowered, the θ-acceptance region of the spectrometer shifted to larger θ values, providing the data on $d\sigma/d\Omega$ for $174.5° < \theta_{c.m.} < 180°$. In the second set of runs the spectrometer was positioned at 0°, 4°, 8°, 12°, and 16° in the laboratory with the magnet current fixed at 600 A, giving data on $d\sigma/d\Omega$ for $145° < \theta_{c.m.} < 180°$. Every foreground run made with a filled LH_2 target was matched by a background run with the target emptied. Relative normalization of individual runs was provided by both the proton-beam integrator and the neutron-beam monitor, which were consistent within 1.6%. A background subtraction for the contribution from the LH_2-target walls was made for each foreground run. The results obtained with different magnet currents in the first set of runs were self-consistent and agreed very well with those obtained six months later in the second set of runs. Although the beam energy was ~2% lower in the first set of runs, the difference could be ignored because the CEX cross section is practically independent of energy in this energy region. The final $d\sigma/d\Omega$ values, shown in Fig. 1, were obtained by pooling all of the data from both sets of runs. The energy quoted is that for the second set of runs. The error bars are statistical only and do not include the 7% normalization uncertainty.

Our cross-section values are seen to fall between those from Dubna and PPA. They are in reasonable agreement with the Saclay values but are of higher statistical accuracy, especially for $\theta_{c.m.} > 175°$. It is noteworthy, however, that the shape of the backward peak in our measurements is different from that shown by the Saclay results. This shape is conventionally parametrized by expressing the differential cross section as $d\sigma/du$, where u is the square of the four-momentum transfer between incoming neutron and outgoing proton, and least-squares fitting the values with the double exponential $d\sigma/du = \alpha_1 \exp(\beta_1 u) + \alpha_2 \times \exp(\beta_2 u)$. Such a fit to our data is shown in Fig. 3. The values obtained for the fitting parameters are $\alpha_1 = 47.5 \pm 0.3$, $\beta_1 = 162.5 \pm 4.5$, $\alpha_2 = 47.9 \pm 0.2$, and $\beta_2 = 6.80 \pm 0.1$, with $\chi^2 = 0.92$. The values we get for the Saclay data are $\alpha_1 = 38.5 \pm 1.2$, $\beta_1 = 119.1 \pm 6.1$, $\alpha_2 = 45.7 \pm 0.5$, and $\beta_2 = 7.73 \pm 0.2$, with $\chi^2 = 1.85$.

The plausibility of the shape of the backward peak in the angular distribution can be tested using the pole-extrapolation method of Chew[12] to extract the pion-nucleon coupling constant from this shape. In this energy region the method should give a value which is reasonably accurate.[13] The value obtained when this is done is $f^2 = 0.073 \pm 0.003$, which agrees with the value obtained in a phase-shift analysis of p-p data[2] (LRL VII). When we apply the same procedure to the Saclay data, a reasonable value of f^2 is not obtained unless the points at extreme back angles (≥ 176°) are excluded from the analysis.

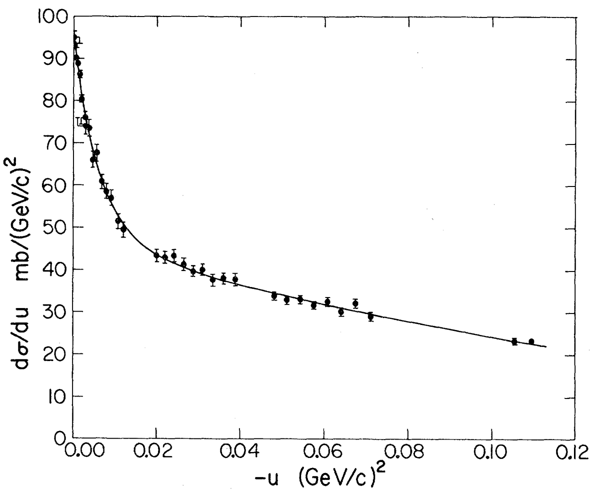

FIG. 3. Double exponential fit to $d\sigma/d\Omega$ values for present data.

In conclusion, we believe that the validity of our results is supported by the high degree of internal consistency in our data and the good value for the pion-nucleon coupling constant derived from the shape of the backward peak. This coupled with the excellent statistical accuracy and the large number of points should be of great value in obtaining a meaningful phase-shift analysis for *n-p* scattering at this energy.

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Interplay of Confinement and Decay in the Spectrum of Charmonium*

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The spectrum of charmonium in the presence of a charmed-meson continuum is investigated. Radiative rates are in considerably better agreement with data than for the naive model, the largest discrepancy being a factor 2–3 for $\psi' \rightarrow \gamma + {}^3P_0$. The model accounts for the peak at ~ 4.2 GeV in $\sigma(e\bar{e} \rightarrow \text{had})$, and predicts a further peak at ~ 3.75 GeV due to 1^3D_1. The latter would be the most favorable location for a charm search in $e\bar{e}$ collisions.

The interpretation[1] of the ψ resonances as bound states of charmed quark pairs ($c\bar{c}$) has enjoyed considerable success. In particular, the prediction[2-4] that P states lie between ψ and ψ' may be confirmed by recent observations,[5,6] and the expected ${}^1S$ ground state η_c may also have been discovered.[7] Nevertheless, the naive model must be modified substantially near and above the charm threshold W_c due to coupling to decay channels. We have generalized the model to incorporate such effects.[8] Our method provides a comprehensive approach to the interplay between