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The study of the elementary proton-proton interaction at intermediate energies, rather well known now after the extensive measurements of spin observables\textsuperscript{1} these last years, has brought very interesting results, especially through Phase-Shift Analyses (P.S.A.)\textsuperscript{2,4} which have shown resonance-like behavior for the $3_T^3$ and $1_{12}$ waves in elastic scattering. It has often been suggested\textsuperscript{5} that this behavior is determined by the excitation of the $\Delta_{33}$ resonance which largely dominates the proton-proton interaction from 400 to 800 MeV. The situation is different for the neutron-proton interaction, which is isospin-mixed $I=0.1$ instead of $I=1$ only for $p-p$. Indeed, for the $I=0$ part, the excitation of the $\Delta$ is forbidden by isospin conservation. This means that other features could emerge in this $I=0$ component of the nucleon-nucleon interaction, while being invisible in the $\Delta$-dominated $I=1$ $p-p$ channel. It would thus be of great interest to undertake a detailed study of the $n-p$ interaction in this energy domain, and also at higher energies, where the excitation of the $I=1/2 N^*$ resonances is expected to play a role in both the $I=0$ and $I=1$ components of the $N-N$ interaction.

Unfortunately, the experimental situation is much worse for the $n-p$ interaction than for the $p-p$ case. Data are scarce: the spin-averaged total cross section $\sigma_c$ is known, but, for elastic scattering, the differential cross-section and analyzing power are poorly known (especially at small transfers) and very few spin observables have been measured. For inelastic channels, only a very limited set of data is available. Moreover, existing experiments have often been done by quasi-free scattering of neutrons bound inside a deuteron (beam or target) instead of using a free neutron beam. We have measured free $n-p$ elastic differential cross sections and analyzing powers at small transfer, where, it must be noted, there was no previous data. Analyzing powers have already been published\textsuperscript{6}. We present here cross sections

Abstract:

The differential cross section in free np forward elastic scattering has been measured for incident neutron energies of 378, 481, 582, 683, 784, 884 and 1085 MeV and for momentum transfer $0.01 <|t| < 0.08$ (GeV/c)$^2$. The experiment used a recoil detector ionization chamber which served at the same time as a gas target. Special care has been taken to obtain a precise absolute normalization.

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13.75.Cc ; 21.30.+y ; 25.40.Dn
The connection (a point of contact) of a particle to a target is made by the collision of the particle with the target. The collision occurs when the particle (target) and the target (particle) come into contact. The collision causes the particle to change its direction and momentum. The collision process is described by the law of conservation of momentum. The law of conservation of momentum states that the total momentum of a system remains constant, regardless of the interactions within the system. This is a fundamental principle in physics that governs the behavior of particles at the subatomic level.

The connection (a point of contact) of a particle to a target is made by the collision of the particle with the target. The collision occurs when the particle (target) and the target (particle) come into contact. The collision causes the particle to change its direction and momentum. The collision process is described by the law of conservation of momentum. The law of conservation of momentum states that the total momentum of a system remains constant, regardless of the interactions within the system. This is a fundamental principle in physics that governs the behavior of particles at the subatomic level.

Let us now recall the principle of the connection of a particle with a target.

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forward and recoil protons were detected. The coefficient \( k \) is determined from range-energy tables using information from recoil protons which stop at the limits between two anodes. Protons of energy greater than 15 MeV leave the chamber, so we compute their total energy \( T_r \) from their energy loss in the gas. Correlations between the amplitudes of the anode signals allow us to know whether the proton stopped inside the chamber or not, and permit identification of the recoiling particle as a proton. Correlations between amplitudes and times (i.e. between \( T_r \) and \( \theta_r \)) allow separation of free elastic scattering events from the quasi-free scattering off protons in \( \text{CH}_2 \). The forward neutron detectors visible in fig. 1, needed for the analyzing power measurements, were not used in obtaining the results presented here.

Having obtained, for each good elastic scattering event, the transfer \( t \) by the formula (valid for elastic scattering) \( t = 2aT_r \), we can extract the absolute differential cross-section. Our results are presented in Fig. 2, where the (small) errors bars are statistical only. The other main sources of error are the background subtraction and monitor calibration. The uncertainty in background subtraction causes a 2.5% uncertainty in the measured n-p yields. The absolute monitor calibration, as stated above, is done by comparing n-^4_He yields with previously measured absolute p-^4_He cross sections. The experimental differences between the two measurements have been well studied and are not expected to introduce large uncertainties. We estimate the uncertainty in beam normalization to be between 2.5% and 6%, depending on energy. Including other small uncertainties in the determination of efficiencies, target thickness, etc., we obtain overall normalization uncertainties of the cross-sections presented in Fig. 2 of 4 to 7 percent, depending on the energy.

In Fig. 2, we also present the results of the Phase-Shift Analyses made by Arndt and Bystricky et al. before the inclusion of our normalized data. For Bystricky et al., a preliminary unnormalized version of our data was included in the fit, which somewhat constrains the slope. In these analyses, the normalization of \( \frac{d\sigma}{dt} \) is mainly governed by the size of the n-p total cross-section \( \sigma_t \), which is well-known. This means that the agreement of our data with the F.S.A. predictions indicates a good experimental consistency between our normalization and those of the experiments giving \( \sigma_t \). It must be noted, however, that our results at 378 MeV are higher than those predicted by more than the experimental error.

In high energy physics, the Regge pole theory predicts an exponential behavior of the elastic p-p cross-section angular distribution at small transfers. Experimental results show that it is still true at our energies, and one usually parametrizes the cross-section using the slope parameter \( b \) of the diffraction cone:

\[
\frac{d\sigma}{dt} = e^{-bt}
\]

For the present experiment, fits for \( b \) have been done for \( 0.01 < |t| < 0.08 \text{ (GeV/c)}^2 \). For fits made with different \( t \) ranges, \( b \) remains approximately the same, provided that the range is not so small that the fit is dominated by experimental fluctuations. Fig. 3 shows the variation with incident neutron energy of \( b \) for the differential cross-sections presented in Fig. 2, together with the corresponding variation of the same quantity for the p-p system.

It is interesting to see in Fig. 3 that the slope parameter \( b \) does not differ significantly in the p-p and n-p cases. This means that the I=0 component, which makes the difference between the p-p and n-p interactions, is negligible, or has the same behavior as the I=1 component for this
Figure captions

1. Schematic picture of the experimental set-up; A1, A2, R1-R3, and L1-L3 are scintillation counters.

2. Absolute differential cross section for n-p elastic scattering. The curves are from the phase shift analyses of refs. 2 and 3. The open points are from refs. 12 and 13.

3. Slope parameter b of the elastic scattering differential cross section versus energy.