Measurement with a Free Neutron Beam of Absolute Neutron-Proton Forward Elastic-Scattering Differential Cross Section at Intermediate Energies

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The differential cross section in free n-p forward elastic scattering has been measured for incident neutron energies of 378, 481, 582, 683, 784, 884, and 1085 MeV and for momentum transfer $0.01 < |t| < 0.08$ $(\mathrm{GeV}/c)^2$. 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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The study of the elementary proton-proton interaction at intermediate energies, rather well known now after the extensive measurements of spin observables[1] these last years, has brought very interesting results, especially through phase-shift analyses (PSA)[2-4] which have shown resonancelike behavior for the $^3F_3$ and $^1D_2$ waves in elastic scattering. It has often been suggested[5] that this behavior is determined by the excitation of the Δ_{33} resonance which largely dominates the proton-proton interaction from 400 to 800 MeV. The situation is different from 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 Δ 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 Δ-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 $I=\frac{1}{2}$ 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 σ_t 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 quasifree scattering of neutrons bound inside a deuteron (beam or target) instead of with a free neutron beam. We have measured free n_{pol}-p elastic differential cross sections and analyzing powers at small transfer, where, it must be noted, there were no previous data. Analyzing powers have already been published.[6] We present here cross sections at incident energies $T_n=378$, 481, 582, 683, 784, 884, and 1085 MeV. In the framework of the physical ideas explained above, we did this experiment to provide data for PSA. It must be noted that our data are also essential to determine the free n-p amplitude, which is an important input in any microscopic calculation of nuclear reactions.

The experiment was performed at the SATURNE synchrotron at Saclay. The incident neutron beam was obtained by breakup of deuterons[7] on a 20-cm-thick Be target. This leads to a neutron energy width $\sigma=25$ to 50 MeV between 378 and 1085 MeV. The beam was collimated in such a way that its diameter at the target did not exceed 2 cm. We used an intensity of about 10^5 neutrons/burst, with a frequency ranging from 0.7 burst/s at 378 MeV to 0.25 burst/s at 1085 MeV. In Fig. 1, which shows a schematic picture of the apparatus, one can see that the intensity of the beam was monitored by means of a double left-right telescope of plastic scintillators. To obtain the absolute cross sections presented here, we had to calibrate this monitor carefully. Not having the possibility with our apparatus to measure the charge-exchange reaction $p(n,p)n$, which is one way[7] to calibrate a neutron beam, we have used an original method. Having demonstrated that nuclear differential cross sections for n-^{4}He and p-^{4}He can be considered as equal within (1–2)% in the range of smaller transfers,[8] we have used our detector IKAR[9] to measure relative n-^{4}He elastic-scattering cross sections with our uncalibrated monitor. The comparison with the previously measured absolute p-^{4}He elastic-scattering cross sections[10] has thus given an absolute calibration of our device.

Let us briefly recall here the principle of the experiment, of which a complete description will be given elsewhere. The chamber IKAR[9] is filled with CH_4 gas at

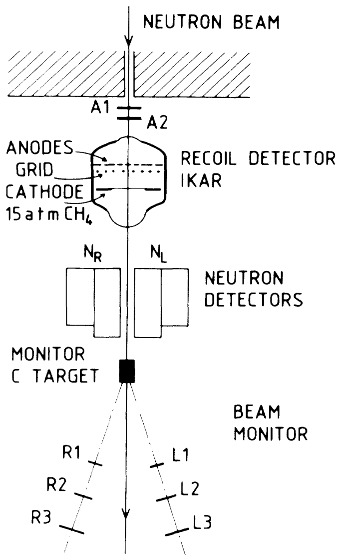

FIG. 1. Schematic picture of the experimental setup; $A1$, $A2$, $R1-R3$, and $L1-L3$ are scintillation counters.

14.2 atm, and serves as both target (hydrogen) and detector. (For the monitor calibration measurement, He gas replaces CH_4.) IKAR has been used many times previously associated with an external trigger, for example in the measurement of p-p elastic differential cross sections.[11] It is a ionization chamber with a cathode, a grounded grid, and, for this experiment, five concentric anodes set perpendicular to the beam direction. For elastic scattering at small transfers, recoil protons are emitted at slightly less than 90°, and thus almost parallel to the anode plane. In the volume between the cathode and the grid, electrons created along the proton track migrate towards the grid under the action of an electric field parallel to the beam direction, and are collected by the anodes. The anode signals thus appear only after the electrons have drifted past the grid. The cathode signal appears immediately by induction and is used as a trigger, this autotriggering mode of operation of IKAR being used for the first time. The time difference between the inner anode and cathode signals (8 μs maximum) permits us to determine the Z coordinate (parallel to the beam) of the interaction vertex in the grid-cathode space. Cuts are placed to eliminate tracks which are very close to either the grid (the signal induced on the cathode is too small) or the cathode (the recoil track can pass through the cathode and leave the active region). This eliminates dependence of the effective target thickness on recoil angle. The small differences between the times of the anodes are related to the recoil angle of the proton. For recoil protons which stop inside the active volume, the sum S of the amplitudes of the corresponding anode signals is related to the recoil energy T_r by the equation $T_r = E_0 + kS$. The (small) pedestal energy E_0 is due to the usual physical effect of

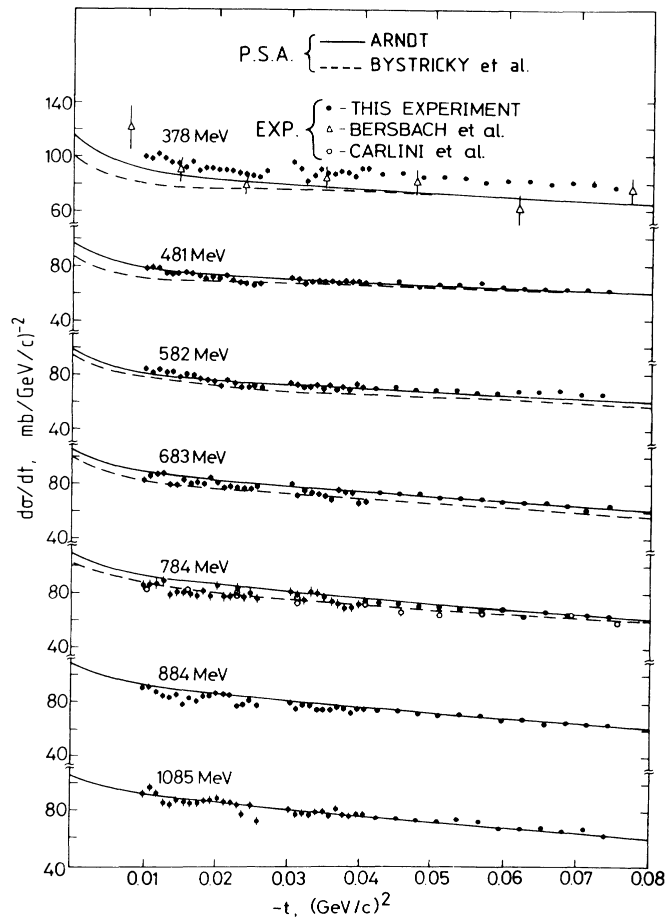

FIG. 2. Absolute differential cross section for n-p elastic scattering. The curves are from the phase-shift analyses of Refs. 2 and 3. The open symbols are from Refs. 12 and 13.

quenching of the ionization occurring at the end of the recoil proton track, just before it stops. E_0 has been measured at the Leningrad Nuclear Physics Institute (Gatchina) in a special experiment of p-p elastic scattering where both forward and recoil protons were detected. The coefficient k is determined from range-energy tables with use of information from recoil protons which stop at the limits between two anodes. Protons of energy greater than 15 MeV leave the chamber, and 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 θ_r) allow separation of free elastic-scattering events from the quasifree scattering off protons in CH_4. The forward neutron detectors visible in Fig. 1, needed for the analyzing-power measurements,[6] were not used in obtaining the results presented here.

Having obtained, for each good elastic-scattering

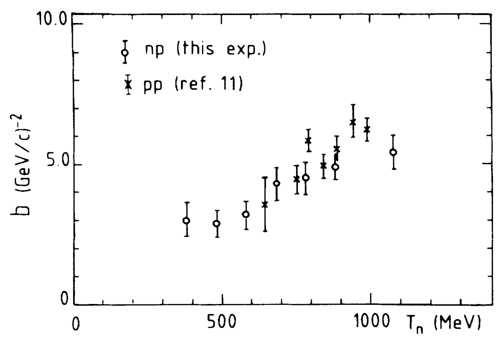

FIG. 3. Slope parameter b of the elastic-scattering differential cross section vs energy.

event, the transfer $-t$ by the formula (valid for elastic scattering) $-t=2mT_r$, we can extract the absolute differential cross section. Our results are presented in Fig. 2, where the (small) error 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 comparison of n-^{4}He yields with previously measured[9] 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%, depending on the energy.

In Fig. 2, we also present the results of the PSA made by Arndt *et al.*[2] and Bystricky, Lechanoine-Leluc, and Lehar[3] before the inclusion of our normalized data. For Bystricky, Lechanoine-Leluc, and Lehar, a preliminary unnormalized version of our data was included in the fit, which somewhat constrains the slope. In these analyses, the normalization of $d\sigma/dt$ is mainly governed by the size of the n-p total cross section σ_t, which is well known. This means that the agreement of our data with the PSA predictions indicates a good experimental consistency between our normalization and those of the experiments giving σ_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, Regge-pole theory[14] 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:

$$d\sigma/dt \propto e^{-bt}.$$

For the present experiment, fits for b have been done for $0.01<|t|<0.08$ $(\mathrm{GeV}/c)^2$. 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. Figure 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 observable. However, more experimental studies are needed, especially at energies around 1 GeV or above, where the excitation of N^* resonances becomes possible, and can contribute in both $I=0$ and $I=1$ terms.

Further investigations on the inclusion of our data in PSA are in progress.

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[1]F. Lehar, J. Phys. Soc. Jpn. Suppl. **55**, 284 (1986).

[2]R. A. Arndt *et al.*, Phys. Rev. D **28**, 97 (1983); R. A. Arndt, J. S. Hyslop, III, and L. D. Roper, Phys. Rev. D **35**, 128 (1987).

[3]J. Bystricky, C. Lechanoine-Leluc, and F. Lehar, J. Phys. (Paris) **48**, 199 (1987).

[4]Y. Higuchi, in *Proceedings of the 1983 Institute for Nuclear Study International Symposium on High Energy Photo Nuclear Reaction and Related Topics,* edited by S. Homma and F. Sakata (Institute for Nuclear Study, Tokyo, 1983), p. 124.

[5]See M. Aguilar-Benitez *et al.* (Particle Data Group), Phys. Lett. **170B**, 1 (1986), p. 337, and references therein.

[6]G. A. Korolev *et al.*, Phys. Lett. **165B**, 262 (1985).

[7]G. Bizard, *et al.*, Nucl. Instrum. Methods **111**, 451 (1973).

[8]Y. Terrien and F. Wellers, J. Phys. (Paris) **46**, 1873 (1985).

[9]A. A. Vorobyov *et al.*, Nucl. Instrum. Methods **119**, 509 (1974).

[10]G. N. Velichko *et al.*, Yad. Fiz. **42**, 1325 (1985) [Sov. J. Nucl. Phys. **42**, 837 (1985)].

[11]A. V. Dobrovolsky *et al.*, Nucl. Phys. **B214**, 1 (1983).

[12]A. J. Bersbach *et al.*, Phys. Rev. D **13**, 535 (1976).

[13]R. Carlini *et al.*, Phys. Rev. Lett. **41**, 1341 (1978).

[14]See, for example, Martin L. Perl, *High Energy Hadron Physics* (Wiley, New York, 1974), Chap. 17.