Cross Sections for Neutron–Deuteron Elastic Scattering in the Energy Range 135–250 MeV

Few-Body Syst (2013) 54:1339–1341
DOI 10.1007/s00601-013-0638-9

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Received: 2 October 2012 / Accepted: 11 January 2013 / Published online: 8 February 2013

Abstract We report new measurements of the neutron–deuteron elastic scattering cross section at energies from 135 to 250 MeV and center-of-mass angles from 80° to 130°. Cross sections for neutron-proton elastic scattering were also measured with the same experimental setup for normalization purposes. Our *nd* cross section results are compared with predictions based on Faddeev calculations including three-nucleon forces, and with cross sections measured with charged particle and neutron beams at comparable energies.

1 Introduction

The study of 3N systems has been enhanced by the growing database of precise measurements on two-nucleon systems [1], and the ability of modern potential models to provide accurate predictions of nucleon–nucleon scattering observables [2–5]. Furthermore, modern computational techniques have made it possible to calculate scattering cross sections and spin observables in three-nucleon systems for any kinematical configuration using the Faddeev formalism [6], allowing the identification of experiments with strong sensitivity to the effects of three-nucleon forces (3NF).

Most of the previous experiments have been carried out with charged particle beams, necessitating the consideration of Coulomb effects on the cross section. Also, with the exception of the KVI work [7,8] and the early work of Igo et al. [9], previous measurements have been performed at a single energy. Moreover, there are still some lingering uncertainties in the magnitude and shape of the differential cross section at 135 MeV [10].

These factors have motivated the present measurement: a study of the neutron–deuteron elastic scattering cross section, at large angles where the sensitivity to 3NF is greatest, over a broad range of incident neutron energies.

Presented at the 20th International IUPAP Conference on Few-Body Problems in Physics, 20–25 August, 2012, Fukuoka, Japan.

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Since the absolute normalization of neutron scattering experiments can be a difficult problem, the *np* scattering cross section was also measured using the same experimental setup. The *np* data were then used to normalize the measured *nd* cross sections.

2 The Experiment

The experiment was carried out at the Los Alamos Neutron Science Center (LANSCE) at the Los Alamos National Laboratory, Los Alamos, New Mexico. Neutrons were produced as spallation products from an 800 MeV H^- beam incident on a bare tungsten target. The beam passes through a ^{238}U foil fission ionization chamber [11] that monitored the beam flux as a function of neutron energy. Approximately 1 m downstream from the fission chamber, the beam impinged on a cryogenic target cell containing either liquid deuterium (LD_2) or liquid hydrogen (LH_2). Scattered neutrons and recoiling charged particles were observed in coincidence. Protons and deuterons were detected by five telescopes, each consisting of a thin ΔE plastic scintillator backed by a pure CsI calorimeter. These detectors were positioned with their front faces 100 cm from the center of the target, at mean laboratory angles of $\theta_{\mathrm{lab}} = 24°,\ 30°,\ 36°,\ 42°$ and 48°. The scattered neutrons were detected with five plastic scintillator bars, each 10 cm high × 10 cm thick × 200 cm wide which spanned a laboratory angle range from 34° to 108°. Empty-target runs were interspersed throughout the experiment to provide a measure of background. The target was filled with LD_2 for the *nd* elastic scattering cross-section measurements and with LH_2 for normalization purposes.

3 Data Analysis

The analysis was performed in two phases: neutron–proton and neutron–deutron elastic cross-section analysis. For the former, LH_2 target was used and the data were analyzed with the proton-singles trigger. Thus, the neutron information was not used which eliminated any uncertainty in neutron detection efficiency. The background subtraction was achieved using empty target data. Then the obtained cross-sections were normalized

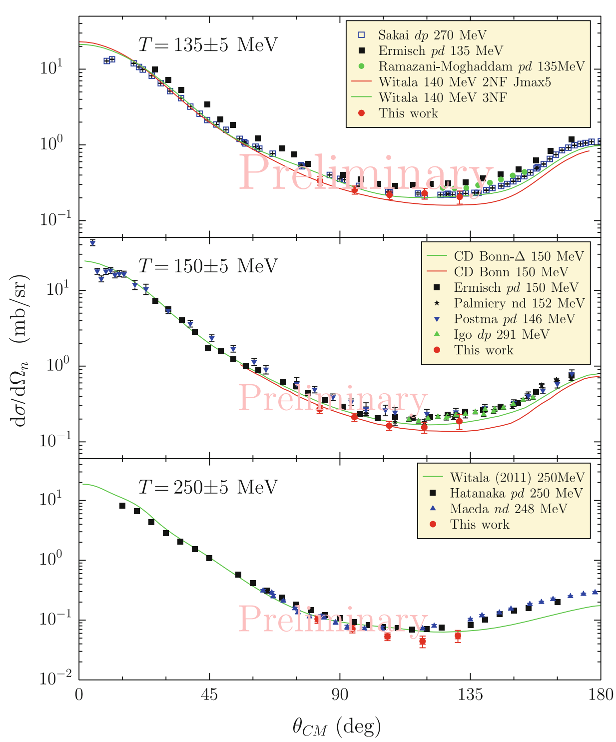

Fig. 1 The cross-section results. The experimental data and the theoretical work prior to this study is taken from [12,8,10,13,14,9,15,16] and [17,4,5,18], respectively.

with respect to the SAID multi-energy partial wave analysis [1] to handle the uncertainties arising from target thickness and unknown uranium fission cross-section. This normalization factor was later used in the deuteron analysis for which the target is LD_2. This time the coincidence data were used since the timing information of the neutrons is crucial in order to get rid of the background. As a side note, the needed neutron efficiencies for coincidence analysis was also measured using the experimental data and the measurements are in good agreement with the Monte Carlo simulations. Lastly, the correction due to the weak polarization of the beam was applied.

4 Results

The results for 135, 150 and 250 MeV incident beam energy are presented in Fig. 1 along with the previous experiments and theoretical predictions for the corresponding energies. In addition to the statistical errors, systematic errors varied from 16 to 24%. The latter were due to uncertainties in the *np* normalization, the measured neutron detection efficiency, the polarization correction, and the interpolation procedure used to obtain the uranium fission cross-section.

5 Conclusion

In this study, the differential cross section for *nd* elastic scattering was extracted in a continuous incident neutron energy range from 135 to 250 MeV, by detecting scattered neutrons and recoil deuterons in coincidence, with the aim of elucidating the contribution of three-nucleon forces (3NF), in particular the energy dependence of this effect. The current data are in good agreement with previous measurements. At angles near the cross section minimum, where the 3NF contribution is most important, our results generally favor calculations which include three-nucleon forces. The 3NF effect could be further tested by confronting the present data with theoretical predictions for the differential cross section at fixed angles as a function of incident neutron energy.

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