



Spin observables in the three-body break-up process near the quasi-free limit in deuteron–deuteron scattering



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ABSTRACT

We have studied spin observables in the three-body break-up reaction in deuteron–deuteron scattering in the phase-space regime that corresponds to the quasi-free deuteron–proton scattering process with the neutron as spectator. The data are compared to measurements of the elastic deuteron–proton scattering process and state-of-the-art Faddeev calculations. The results for iT_{11} and T_{22} for the quasi-free scattering data agree very well with previously published elastic-scattering data. A significant discrepancy is found for T_{20} , which could point to a break-down of the quasi-free assumption.

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1. Introduction

Understanding the exact nature of the nuclear force is one of the long-standing questions in nuclear physics. In 1935, Yukawa successfully described the pair-wise nucleon–nucleon (NN) interaction as an exchange of a boson [1]. Current NN models are mainly based on Yukawa's idea and provide an excellent description of the high-quality data base of proton–proton and neutron–proton scattering [2–6] and of the properties of the deuteron.

Although much has been learned about the interaction between two nucleons, it remains questionable whether this knowledge is sufficient to describe the interaction between more than two nucleons. Already for the simplest three-nucleon system, the triton,

an exact solution of the three-nucleon Faddeev equations employing two-nucleon forces (2NFs) underestimates the experimental binding energy [3], showing that 2NFs are not sufficient to describe the three-nucleon system accurately. In a three-nucleon system, the interaction between two of the nucleons may be influenced by the presence of the third nucleon. This extra effect comes from a force which is beyond the two-nucleon interaction and will be referred to as a three-nucleon force in this Letter (3NF). Most of the current models for the 3NF are based on a refined version of Fujita–Miyazawa's 3NF model [7], in which a 2π -exchange mechanism is incorporated by an intermediate Δ excitation of one of the nucleons [8,9]. More recently, NN and three-nucleon potentials have become available which are derived from the basic symmetry properties of the fundamental theory of Quantum Chromodynamics (QCD) [10–13]. These so-called chiral-perturbation (χ PT) models systematically construct a potential from a low-energy

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expansion of the most general Lagrangian with only the Goldstone bosons, e.g. pions, as exchange particles.

A comparison between experimental data obtained in nucleon–deuteron scattering for the reactions involving more than two nucleons with the corresponding theoretical predictions reveals serious discrepancies, specially in the case of spin observables [14–46]. This implies that the behavior of the systems with more than two nucleons is not completely understood and hints towards a deficiency in the spin structure of 3NFs. Therefore, theoretical calculations for these systems need improvements which could be guided by more experimental data. In particular, channels and observables that show a large sensitivity to the effects of 3NFs are the most advantageous. A detailed review article on our present theoretical and experimental understanding of 3NFs and its implications in the field of nuclear physics can be found in Ref. [47].

Naively one might expect that the 3NF effects increase in the four-nucleon system by the argument that the number of three-nucleon combinations with respect to two-nucleon combinations gets larger as one increases the number of nucleons. For large nuclei, however, the saturation of 3NF effects sets in very quickly. The increase in sensitivity to 3NF effects with increasing the number of nucleons is supported by a comparison between predictions and data for the binding energies of light nuclei [48]. The predictions come from a Green’s function Monte Carlo calculation based on the Argonne V18 [4] NN interaction (AV18) and the Illinois-2 (IL2) 3NF [49,50]. While a calculation which only includes the AV18 NN potential deviates significantly from the experimental results, a calculation which includes as well a 3NF compares much better to the data. Note that the effect of the 3NF on the binding energy for the triton is ~ 0.5 MeV, whereas the effect increases significantly for the four-nucleon system, ${}^4\text{He}$, to ~ 4 MeV. For heavier nuclei, even adding the 3NF as modeled in the present calculations, is not enough to resolve the discrepancies between the theoretical predictions and the measurements. One might argue that the discrepancies for the binding energies of the heavier nuclei stem from four-nucleon force (4NF) effects. These higher-order many-body potentials are, however, predicted by χ PT approaches [10–13] to be negligible compared to 3NF effects. Therefore, it is very unlikely that the large discrepancies can be explained by a missing 4NF or even higher-order nuclear-force effects. This is another evidence which shows that the behavior of the systems with more than two nucleons is not understood yet.

This Letter presents the results of a recent measurement of spin observables in the three-body break-up reaction in deuteron–deuteron scattering, $\vec{d} + d \rightarrow d + p + n$. We are particularly interested in the regions of phase space for which the neutron acts as a spectator particle. These data can directly be compared to spin observables in the elastic scattering process, $\vec{d} + p \rightarrow d + p$, which are measured using the same setup and with the same beam by replacing the liquid deuterium target with a solid (CH_2) target containing hydrogen atoms. Furthermore, the data can be interpreted using ab-initio Faddeev calculations that are based upon modern two- and three-nucleon potentials. The feasibility of identifying and measuring spin observables in the three-body break-up reaction in deuteron–deuteron scattering has been reported recently in Refs. [51,52].

2. Experiments

We performed two scattering experiments at KVI using the Big Instrument for Nuclear-polarization Analysis (BINA) [51]. A large part of the setup, in particularly the wall part, consisted of elements that were used by the former SALAD detection system [53]. The polarized beam of deuterons for both experiments was produced by a polarized ion source (POLIS) [54,55] at KVI and was

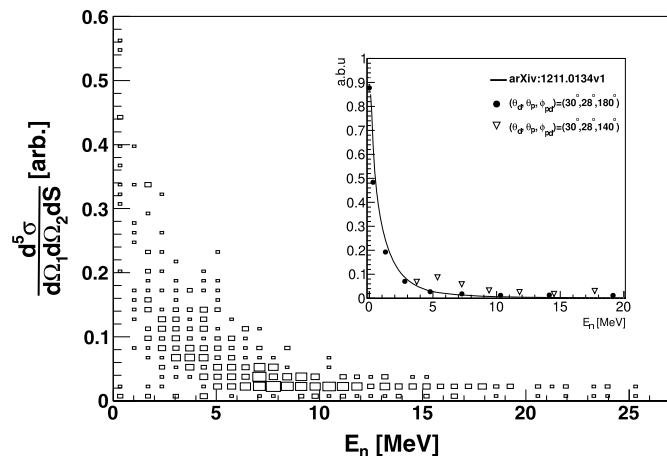


Fig. 1. Relative cross sections for all of the analyzed configurations of the three-body break-up reaction in $\vec{d} + d$ scattering as a function of the outgoing neutron energy. The size of each box corresponds to the number of configurations that fall in that bin. Inset: The reconstructed neutron-energy distribution for a few selected configurations. The solid line represents the expected energy distribution (normalized to the data) of the neutron for the quasi-free scattering process.

accelerated by AGOR (Accélérateur Groningen ORsay). In the first experiment, a polarized beam of deuterons with a kinetic energy of 65 MeV/nucleon was impinged on a liquid deuterium target [56]. The elastic channel, the neutron transfer channel, and break-up channels leading to three- and four-body final states were uniquely identified using the information on the energies of the outgoing particles, their scattering angles, and their time-of-flight (TOF) [51, 52]. We note that the three-body break-up channel in deuteron–deuteron scattering is extremely rich in phase space even more than the $\vec{p} + d$ reaction since its final state is composed of non-identical particles. These data contain a wealth of information that can be exploited to study many-body forces. The measured differential cross sections, vector- and tensor-analyzing powers for a large number of kinematical configurations of the three-body break-up reaction are reported in Ref. [51].

In the second experiment, the elastic reaction ${}^1\text{H}(\vec{d}, dp)$ was studied using a deuteron-beam energy of 65 MeV/nucleon and a solid CH_2 target. We made use of this reaction to check the systematic uncertainties and also to measure the polarization of the beam of deuterons [52]. The vector and tensor polarizations of the beam was determined by combining measurements of the azimuthal asymmetries of the reaction yield and the published data for iT_{11} and T_{22} . The polarization of the deuteron beam was measured as well in the low-energy beam line with a Lamb-Shift Polarimeter (LSP) [57]. The polarization values obtained with the LSP were found to be in an excellent agreement with the ones measured with BINA [52]. For a part of phase space in the $\vec{d}p$ elastic reaction in which both particles are scattered to the forward angles, data on T_{20} were compared with the results of the three-body reaction in the deuteron–deuteron scattering.

We were interested in studying the quasi-free process with the neutron as spectator, e.g. $\vec{d} + d \rightarrow d + p + n_{\text{spec}}$ which can be compared to the elastic reaction $\vec{d} + p \rightarrow d + p$. For each coincidence event, we measured the scattering angles and energies of the outgoing deuteron and proton. Using the known beam energy, we calculated the angle and energy of the unobserved neutron. Fig. 1 represents the cross sections in arbitrary units obtained for all analyzed configurations of the first experiment as a function of the energy of the outgoing neutron, E_n . Each configuration corresponds to a small region in the scattering angles of the deuteron and proton, their relative azimuthal angle, and their relative energy represented by the variable S as explained in detail in Ref. [52].

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