Physics Letters B 687 (2010) 149–153

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Spin–isospin selectivity in three-nucleon forces

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ARTICLE INFO

Article history:
Received 9 November 2009
Received in revised form 14 February 2010
Accepted 6 March 2010
Available online 11 March 2010
Editor: V. Metag

Keywords:
Nuclear forces
Proton–deuteron break-up
Three-nucleon force
Polarization phenomena

ABSTRACT

Precision data are presented for the break-up reaction, $^2\mathrm{H}(\vec{p}, pp)n$, within the framework of nuclear-force studies. The experiment was carried out at KVI using a polarized-proton beam of 190 MeV impinging on a liquid-deuterium target and by exploiting the detector, BINA. Some of the vector-analyzing powers are presented and compared with state-of-the-art Faddeev calculations including three-nucleon forces effect. Significant discrepancies between the data and theoretical predictions were observed for kinematical configurations which correspond to the $^2\mathrm{H}(\vec{p}, {}^2\mathrm{He})n$ channel. These results are compared to the $^2\mathrm{H}(\vec{p}, d)p$ reaction to test the isospin sensitivity of the present three-nucleon force models. The current modeling of two and three-nucleon forces is not sufficient to describe consistently polarization data for both isospin states.

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 database of proton–proton and neutron–proton scattering [2] and of the properties of the deuteron. However, for the simplest three-nucleon system, triton, three-body calculations employing NN forces clearly underestimate the experimental binding energies [3], demonstrating that NN forces are not sufficient to describe the three-nucleon system accurately. Some of the discrepancies between experimental data and calculations solely based on the NN interaction can be resolved by introducing an additional three-nucleon force (3NF). Most of the current models for the 3NF are based on a refined version of Fujita–Miyazawa's 3NF model [4], in which a 2π-exchange mechanism is incorporated by an intermediate Δ excitation of one of the nucleons [5,6].

The structure of the 3NF can be studied via a measurement of observables in three-nucleon scattering processes. More detailed information on the spin dependence of the 3NF can be obtained by measuring polarization observables such as the analyzing powers. For this, a series of extensive studies of 3NF effects in elastic-scattering reactions have been performed at KVI and other laboratories. Precision measurements of the vector analyzing power of the proton in elastic proton–deuteron scattering have been performed at various beam energies ranging from 90 to 250 MeV [7–12]. Also, vector and tensor analyzing powers in elastic deuteron–proton scattering have been obtained at various beam energies ranging from 75 to 270 MeV [13–18]. Moreover, a rich set of spin correlation coefficients have been measured in the elastic proton–deuteron process at incident energies of 135 and 200 MeV [19,20]. In all these measurements, systematic discrepancies between data and theoretical predictions which rigorously solve the Faddeev equations and using only NN potentials were ob-

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0370-2693/$ – see front matter
doi:10.1016/j.physletb.2010.03.021

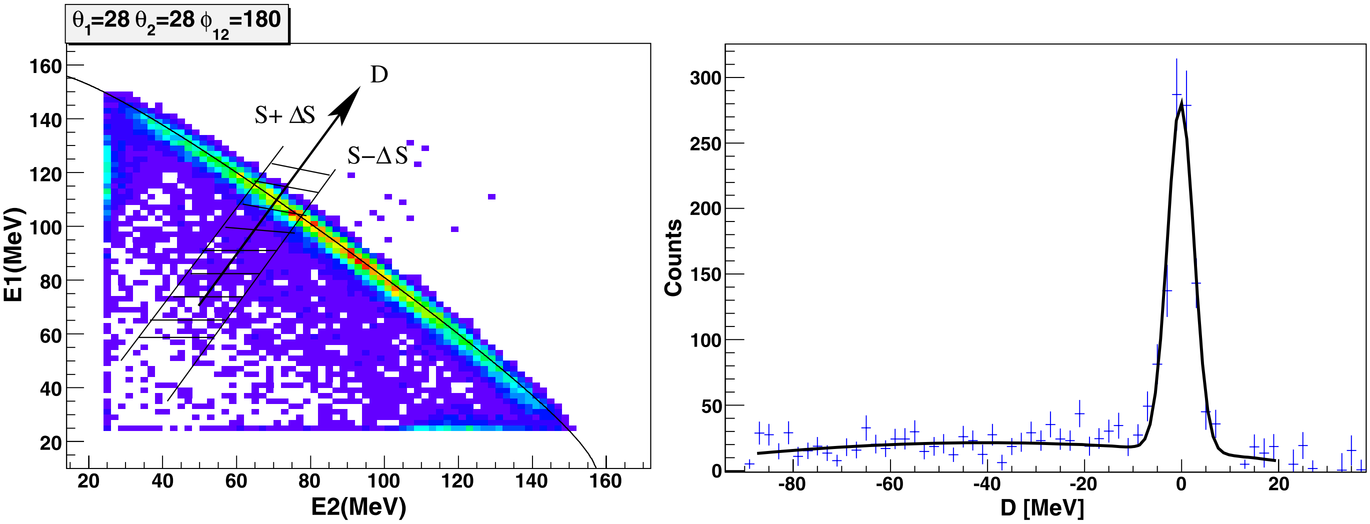

Fig. 1. The left panel shows the energy correlation between the two protons for the kinematical configuration $(\theta_1, \theta_2, \phi_{12}) = (28^\circ \pm 2^\circ, 28^\circ \pm 2^\circ, 180^\circ \pm 4^\circ)$, together with the kinematical S-curve. In the right panel, a projection of events from a sample gate indicated in the left panel, $S = 150 \pm 5$ MeV, onto an axis D perpendicular to the S-curve is shown as crosses. The solid line depicts a fit to that spectrum, composed of a Gaussian and a polynomial background model.

served. A large part of the discrepancies, in particular at the minimum of the differential cross sections, were removed by adding a 3NF to the NN potentials. Nevertheless, there are still unresolved problems specially for the differential cross sections at higher energies, above 150 MeV/nucleon, and for various polarization observables calling for more detailed investigations. So far, none of the existing precision calculations has produced a consistent explanation for all the experimental observables in the intermediate energy range.

Complementary to the elastic scattering experiments, three-nucleon studies have been performed exploiting the proton–deuteron break-up reaction. The phase space of the break-up channel is much richer than that of the elastic scattering. The final state of the break-up reaction is described by 5 kinematical variables, as compared to just one for the elastic scattering case. Theoretical predictions show that large 3NF effects can be expected at specific kinematical regions in the break-up reaction [21].

Results of the cross sections and tensor analyzing powers have already been published [22,23,18] for a deuteron-beam energy of 130 MeV on a liquid-hydrogen target. These experiments were the first ones of its type which demonstrated the feasibility of a high-precision measurement of the break-up observables together with a large coverage of the phase space. They confirmed that sizable influences of 3NF and Coulomb effects are visible in the break-up cross sections at this energy. In the last years, more data at several beam energies and other observables have been collected systematically to provide an extensive database at intermediate energies. Here, we report on results obtained at relatively large energies below the pion-production threshold.

This Letter addresses a particular phase space region that corresponds to the reaction $\vec{p} + d \to (pp) + n$ where the proton pair, (pp), moves with a very small relative energy and a small opening angle in a $^1S_0$ state. A large 3NF sensitivity of the polarization observable, A_y, is expected which would provide crucial information on its spin structure. Moreover, a comparison is made with polarization data of the reaction $\vec{p} + d \to d + p$ to provide a deeper understanding of the spin–isospin structure of the forces. The reported analysis was inspired by an earlier experiment performed by the ANKE Collaboration in which analyzing powers of the reaction $\vec{p} + d \to (pp) + n$ were measured at much larger incident beam energies of 500 MeV and 800 MeV with the detection of a fast forward proton pair at a small excitation energy of less than 3 MeV [24]. Intriguing deviations were observed between A_y data obtained at 500 MeV with a model taking into account one-nucleon exchange, single scattering, and the $\Delta(1232)$ excitation in the intermediate state, whereas the same model fairly describes the data at 800 MeV.

The proton–deuteron break-up experiment reported here was performed at KVI using a polarized proton beam with an energy of 190 MeV impinging on a liquid-deuterium target [25]. The reaction channel has been identified using a 4π, highly symmetric detector system Big Instrument for Nuclear-polarization Analysis abbreviated as BINA [26,27,12]. The relatively high energy used in this experiment offered a unique chance to study 3NF effects, since their magnitude are predicted to increase with energy. In this Letter, we present a set of selected analyzing power results, preceded by a brief description of the methods used in the data analysis. We focus specifically on results of the analyzing power at symmetric configurations including those with very small azimuthal opening angles. Results are compared with predictions of the modern Faddeev calculations.

Conventionally, in the $\vec{p} + d$ break-up reaction, the kinematics are determined by using the scattering angles of the two final-state protons, $(\theta_1, \theta_2, \phi_{12} = \phi_1 - \phi_2)$ where θ_1, θ_2 are the polar scattering angles of the first and second proton, respectively, and ϕ_{12} is the azimuthal angle between the two protons. The left panel in Fig. 1 shows the correlation between the energies of the two protons for a sample geometry, namely $(\theta_1, \theta_2, \phi_{12}) = (28^\circ \pm 2^\circ, 28^\circ \pm 2^\circ, 180^\circ \pm 4^\circ)$. The expected correlation according to the relativistic kinematics for the break-up reaction, referred to as the S-curve, is shown as the solid line. The kinematical variable, S, is defined as the arc-length along this curve, starting from the minimum value of E_1. It is customary to present the cross sections and analyzing powers as a function of the variable S. We note that for most of the data, both of the protons are stopped inside the scintillator. Only protons with energies larger than 140 MeV will punch through the detector, corresponding to the data in the corners of the left panel in Fig. 1. For the further analysis, only configurations are considered for which both protons are stopped in the forward wall. The right panel in Fig. 1 depicts a projection of the spectrum onto an axis D perpendicular to the S-curve and for a window of $\Delta S = \pm 5$ MeV. The solid line depicts a fit to that spec-