Vector and tensor analyzing powers in deuteron-proton breakup reaction

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Abstract. High precision data for vector and tensor analyzing powers of the $^1$H($\vec{d},pp)n$ breakup reaction at 130 and 100 MeV deuteron beam energies have been measured in a large fraction of the phase space. They are compared to the theoretical predictions based on various approaches to describe the three nucleon (3N) system dynamics. Theoretical predictions describe very well the vector analyzing power data, with no need to include any three-nucleon force effects for these observables. Tensor analyzing powers can be also very well reproduced by calculations in most of the studied region, but locally certain discrepancies are observed. At 130 MeV for $A_{xy}$ such discrepancies usually appear, or are enhanced, when model 3N forces are included. Predicted effects of 3NFs are much lower at 100 MeV and at this energy equally good consistency between the data and the calculations is obtained with or without 3NFs.

1. Introduction

Understanding the interaction between nucleons is fundamental for nuclear physics and a starting point for describing properties of nuclei and reactions involving nucleons. Observables for three-nucleon (3N) systems constitute an important basis for testing modern theories of these interactions. The deuteron-nucleon breakup reaction, leading to a final state with three free particles, offers the possibility of testing the theoretical predictions on continuous set of kinematical configurations of the outgoing nucleons. In order to fully exploit the research potential of this process, experiments covering a significant part of its phase space are indispensable.

Experimental studies of the $^1$H($\vec{d},pp)n$ breakup reaction were performed at KVI Groningen, The Netherlands, with the use of polarized deuteron beams with energies of 130 and 100 MeV, and two detection systems, respectively SALAD [1] and BINA [2]. High precision cross section data for the breakup reaction at 130 MeV provided important information on the significance of 3N and Coulomb forces on this observable [3, 4, 5]. In the next step, a complete set of vector ($A_x, A_y$) and tensor ($A_{xx}, A_{xy}, A_{yy}$) analyzing powers attainable with the transversally polarized deuteron beam was determined for about 800 kinematical points (for each observable), covering large part of the phase space of the $^1$H($\vec{d},pp)n$ breakup reaction at 130 MeV. The set of data for the same reaction at 100 MeV comprises so far $A_x, A_y$ and $A_{xy}$ analyzing powers, each determined at over 400 kinematical points. All the results were obtained on a systematic grid of kinematical variables, for polar angles, $\theta_1, \theta_2$, of the outgoing protons between 15° and 30° and
Figure 1. Examples of vector analyzing powers for the d-p breakup reaction obtained for four geometries of outgoing protons, as specified in the panels. Left side: The results obtained at 130 MeV compared to calculations performed with the realistic potentials without (cyan/light gray band) and with (magenta/dark gray band) TM99 3N force, as well as with predictions obtained within the coupled-channel framework with the CD Bonn+∆ potential without (dashed line) and with (solid line) inclusion of the Coulomb force. Right side: The results obtained at 100 MeV compared to calculations with the CD Bonn potential only (dashed lines) and when the TM99 3NF is included into the calculations (solid lines). Dotted lines represent CC calculations with Coulomb interaction included.

for the full range of their azimuthal angles. For each geometry, defined by $\theta_1$, $\theta_2$ and the relative azimuthal angle $\varphi_{12}$, the energy dependence of the studied observables was described by means of variable $S$, denoting the arc-length along the kinematical curve. The system of coordinates applied for description of 3-body final state and definitions of the kinematical variables can be found in Ref. [6].

Established large effects of the Coulomb interaction in cross section motivated the experimental exploration especially in the region with a very low energy of relative motion between the two breakup protons ($E_{\text{rel}}$), where these effects dominate. The region corresponds to forward laboratory polar angles and small relative azimuthal angles of the protons. The measurement was carried out at Forchungszentrum Jülich with the use of external beam of COSY accelerator and GeWall detection system [7]. The vector ($A_x$, $A_y$) analyzing powers were determined for 6 combinations of polar angles from the range between 6 and 12° and 4 different relative azimuthal angles $\varphi_{12}$: 60°, 100°, 140° and 180°.

All the experimentally measured analyzing powers were compared to the results of rigorous Faddeev calculations [8] performed with the use of modern realistic nucleon-nucleon potentials (CD Bonn, AV18, Nijm I and Nijm II) only, referred to in the following by 2N, as well as including the Tucson-Melbourne three nucleon force model (2N+TM99). The experimental data were also confronted with the results of the coupled channel (CC) approach with the CD-Bonn+∆ potential, without and with Coulomb interaction included [9]. The data for 130 MeV beam energy were also compared with predictions of Chiral Perturbation Theory (ChPT) [10, 11].
2. Results
Confronting the calculated observables with the experimental data shows no sensitivity of the deuteron vector analyzing powers of the breakup reaction at 100 and 130 MeV to any additional dynamics beyond the pure NN interactions (see examples in Fig. 1). The calculations based on NN forces alone are sufficient to provide a very good description of the whole data sets. The phase space region covered by the GeWall is characterized with very low values of the analyzing powers and their complete insensitivity to any details of dynamics: The theoretical curves shown in Fig. 2, all show identical and small vector analysing powers which is consistent with the data.

![Graph showing vector analyzing powers](image)

Figure 2. Examples of vector analyzing power distributions obtained for the $d$-$p$ breakup at 130 MeV for three angular configurations of outgoing protons with the relative azimuthal angle $\varphi_{12} = 60^\circ$ and different combinations of the polar ($\theta_1$, $\theta_2$) angles, specified in the upper panels. Green and orange bands represent calculations based on the chiral theories, dashed maroon line - calculations based on the realistic AV18 potential combined with the Urbana IX 3NF, rest of the bands and lines are the same as in the Fig. 1, left side.

Tensor analyzing powers of the breakup reaction at the same beam energies are very well reproduced by calculations in the majority of the studied region, but locally certain discrepancies are observed [12, 6]. For $A_{xy}$ such discrepancies usually appear, or are enhanced, when model 3N forces, TM99 or UIX, are included, see examples in Fig. 3, left side. Problems exist for all theoretical approaches with describing $A_{xx}$ and $A_{yy}$ in kinematical regions characterized with the lowest relative momenta of the two protons. At 100 MeV no sizable 3NF effect is predicted for $A_{xy}$ (Fig. 3, right side), while the Coulomb interaction between protons starts to play the role in certain phase space regions.

3. Summary
Precise results obtained for the deuteron vector analyzing powers at 100 and 130 MeV demonstrate that this observable is sensitive to the pure nucleon-nucleon potential alone. This conclusion can be contrasted with results of the experiments performed at much higher beam energy of 270 MeV. There certain, though rather moderate, effects of 3NF are predicted: For $A_z$ these effects are partially, but not fully confirmed by the data [13]. For $A_p$ the results obtained
in several angular configurations [14] demonstrate, that this observable is described properly by
the pure $NN$ force predictions and relativistic effects are negligible, while including 3NFs leads
to a deterioration of this agreement.

Tensor analyzing powers, when studied at 130 MeV, reveal a sensitivity to subtle ingredients
of the dynamics. On the other hand the modern 3NF models do not describe the $A_{xy}$ data in
certain ranges of phase space. The sensitivity to dynamics beyond pure NN almost vanishes at
the energy of 100 MeV, with exception of Coulomb interaction, which starts to play important
role.

The conclusion of negligible 3NF effects in the vector analyzing power and problems with the
description of the tensor analyzing powers also emerge from analysis of the d-p elastic scattering
in the similar range of energies, see Refs [15, 16, 17]. The discrepancies, observed both in the
elastic scattering and breakup reaction, clearly depend on beam energy, and must be considered
as indications of deficiencies in the spin part of the assumed models of the 3N system dynamics.

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