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Studies of the Three-Nucleon System Dynamics in the Deuteron-Proton Breakup Reaction

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Abstract. One of the most important goals of modern nuclear physics is to contruct nuclear force model which properly describes the experimental data. To develop and test predictions of current models the breakup $^1H(\vec{d},pp)n$ reaction was investigated experimentally at 100 and 130 MeV deuteron beam energies. Rich set of data for cross section, vector and tensor analyzing powers was obtained with the use of the SALAD and BINA detectors at KVI and Germanium Wall setup at FZ-Jülich. Results are compared with various theoretical approaches which describe the three-nucleon (3N) system dynamics. For correct description of the cross section data both, three-nucleon force (3NF) and Coulomb force, have to be included into calculations and influence of those ingredients is seizable at specific parts of the phase space. In case of the vector analyzing powers very low sensitivity to any effects beyond nucleon-nucleon interaction was found. At 130 MeV, the A_{xy} data are not correctly described when 3NF models are included into calculations.

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1 Introduction

The models most commonly used in few-nucleon studies of few-nucleon systems are based on the meson exchange theory and phenomenology. These so-called realistic nucleon-nucleon (NN) potentials, like CD Bonn, Nijmegen or Argonne AV18 are able to predict observables for two nucleon (2N) systems with very high precision. Now one can verify if the models are also valid for more complex systems, in particular the ones composed of three nucleons (3N). For the purpose to study details of the 3N Hamiltonian and the system dynamics the nucleon-deuteron breakup reaction has been chosen, which is the simplest nontrivial environment. The process with its 3N final state serves as unique laboratory in which even very subtle dynamical effects like the 3NF, Coulomb force or relativistic component can be studied. Nowadays precise predictions for observables in the 3N systems are available throughout exact solutions of the 3N Faddeev equations for any NN interaction, also with the inclusion of a 3NF model (TM99 3NF or Urbana IX 3NF). Other than realistic NN potentials and supplementing them with 3NF models, the 3N system dynamics can be described within the coupled-channels (CC) approach [1]. This method is based on explicit treatment of a single Δ-isobar degrees of freedom, which generates also certain 3NF effects. Within the CC formalism the Coulomb interaction was implemented into calculations for the first time [2]. Recently, a consistent theoretical treatment of phenomenological 3NF and of Coulomb force has been achieved also for the AV18+UIX potential [3] that allows to investigate the role of both effects on the high level of accuracy. An alternative way to describe 3N systems is based on chiral perturbation theory (ChPT), an effective field theory representing more basic approach to describe nuclear forces than realistic potentials. Here, the nuclear potential is obtained in a way of a systematic expansion in terms of momentum, and the many-body interactions appear naturally at growing orders. The non-vanishing 3NF appears at the next-to-next-to-leading (NNLO) order [4, 5], which is numerically fully developed.

The deuteron breakup reaction can be used as a valuable experimental tool for verification of the theoretical models. The final state of the reaction is complex enough to test different ingredients of few-nucleon system dynamics, appearing with varying strength in certain phase space regions.

2 Experimental setup

The $^1H(\vec{d},pp)n$ breakup reaction was studied in broad phase space regions with the use of three detection systems: the SALAD and BINA at KVI and the Germanium Wall (GeWall) at FZ-Jülich. Results of the analyzing powers were obtained with the use of the BINA and SALAD apparatuses at polarized deuteron beam energies of 100 [6] and 130 MeV [7], respectively. The cross sections [8–12] were measured using the SALAD and GeWall detectors at deuteron beam energy of 130 MeV. The BINA detector offered access to the almost full phase space, whereas the SALAD and GeWall setups covered only forward polar angles.

The SALAD detector consisted of a three-plane multi-wire proportional chamber (MWPC) and two layers of a segmented scintillator hodoscope: horizontal ΔE and vertical stopping E detectors. The acceptance of the setup covered the region of the polar angles from 12° to 40° and the full range of the azimuthal angles. The liquid hydrogen target was placed inside the scattering chamber. BINA apparatus was constructed as an upgraded version of SALAD and is composed of two main parts called Wall and Ball. Wall inherited most parts and features from SALAD, covering the same angular range and built of the same MWPC and modified ΔE and E hodoscopes. The backward part is ball-shaped and consists of 149 phoswich detectors which cover polar angles between 40^0 and 160^0. The Ball plays two roles: of particle detector and scattering chamber. In the measurements liquid LH_2 target was used.

The GeWall setup at the Research Center in Jülich (FZJ) consisted of three high-purity semiconductor position sensitive germanium detectors. Two different types of the detectors were used: a thin transmission detector "Quirl" with an excellent spatial resolution used to determine the position and energy loss (ΔE detector) of the passing charged particles, and two thick energy detectors E1 and E2 with excellent energy resolutions. The angular acceptance of the apparatus was $5° - 14°$ for the polar and 2π for the azimuthal angles.

3 Theoretical predictions and experimental results

New generation measurements of the ${}^1H(\vec{d}, pp)n$ breakup reactions in a wide phase space region provided a very rich set of data for differential cross section, vector A_x, A_y and tensor A_{xx}, A_{xy}, A_{yy} analyzing powers collected at the deuteron beam energies of 130 and 100 MeV.
To trace various dynamical effects more globally dependencies of χ^2 (calculated as the squared difference between experimental cross section value and the theoretical one and divided by an uncertainty of the experimental point) per degree of freedom (d.o.f.) and relative cross sections (theoretical and/or experimental) were studied in a function of the relative energy E_{rel} of the two breakup protons. For A_x and A_y analyzing powers the χ^2/d.o.f. was analyzed in function of E_{rel} (see Fig. 1, left panel). The obtained results at 65 [7] and 50 MeV/nucleon [6] are well reproduced by 2N calculations in the whole studied phase space. That implies the observables are practically insensitive to any aspects of the nuclear dynamics. In case of the tensor analyzing powers [7] at 130 MeV certain discrepancies are observed. The theory predicts quite large effects of TM99 3NF, however there are configurations in which inclusion of the TM99 3NF leads to a worse agreement with the experimental data. Such discrepancies were found especially for A_{xy} tensor analyzing power. This suggests an existence of some missing ingredients in the spin part of the 3NF model.
The results of the cross sections [8–12] for the energy of 65 MeV/nucleon were obtained for about 225 kinematical configurations, defined by the polar angles of the two outgoing protons, θ_1, θ_2, and their relative azimuthal angle φ_{12}. In case of the data measured with the SALAD detector quite seizable 3NF effects were observed [8, 9]. Inclusion of the 3NF into the calculations leads generally to a better description of the cross section data. Figure 1, central panel, presents seize of the predicted

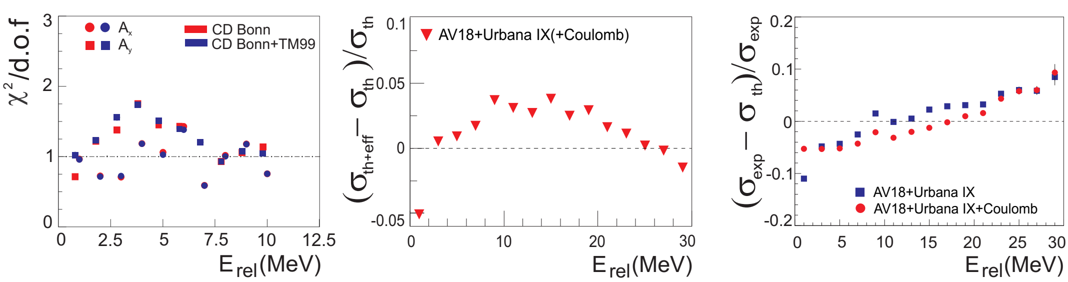

Figure 1. *Left panel*: quality of description of the vector analyzing powers at 50 MeV/nucleon given by various models (as indicated in the panel), presented as dependence of χ^2/d.o.f on kinetic energy of the relative motion of the two breakup protons (E_{rel}). *Central panel*: net effects of Coulomb force in the breakup cross sections at 65 MeV/nucleon presented as function of E_{rel} variable. *Right panel*: relative discrepancies between the experimental data and the theoretical predictions of the breakup cross sections as a function of the E_{rel} variable. The results obtained for the Av18 potential combined with the Urbana IX 3NF (*blue squares*) and compared to results of the similar calculations but with Coulomb force included (*red dots*).

relative Coulomb effect in the cross sections (relative difference of the results obtained with (σ_{th+eff}) and without (σ_{th}) Coulomb force) in a function of E_{rel}. The same two types of calculations confronted with the experimental cross section data (σ_{exp}) are shown in the right panel. The strongest influence of Coulomb interaction is observed at the smallest values of E_{rel}. For the data obtained with the GeWall apparatus at very small polar angles, the Coulomb effects are a dominant component of the dynamics, which become extremely strong in a region defined by very small relative azimuthal angles [10–12]. In general adding the Coulomb force into the models significantly improves the quality of the data description at the small values of the relative energies. Taking into account the whole studied region of the breakup phase space one can conclude that only calculations including both ingredients, the Coulomb interaction and the 3NF, provide the best description of the data [10, 11].

4 Summary and outlook

Precise and systematic studies of the breakup reaction in a large part of the phase space are very important for understanding of the interaction between nucleons in few nucleon systems. Currently available theoretical approaches which try to model the interaction need very precise and large experimental database to be verified and further developed. Within these predictions different pieces of the dynamics can be studied separately and also their mutual interplay can be investigated. The obtained data in general confirmed the modern calculations, however, there are still some problems with description of certain details, in particular in the sector of analysing powers. Moreover, there is still strong need to have possibly complete theoretical treatments including all ingredients of the 3N system dynamics (3NF, Coulomb interaction, relativistic effects). The future studies of the 3N system dynamics in the deuteron breakup reaction at not too high energies are planned to be performed at the Cyclotron Center Bronowice in Cracow, Poland. This scientific center equipped with a new cyclotron offers possibility to continue the experimental program started at KVI and focuesd on investigation of the few nucleon systems dynamics. The measurements will be carried out with the use of the BINA detector, which is now under installation.

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