Cross section of the deuteron–proton breakup as a probe of three-nucleon system dynamics

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Abstract. Modern nucleon-nucleon interaction models can be probed quantitatively in the three-nucleon environment by comparing predictions based on rigorous solutions of the Faddeev equations with the measured observables. Proper description of the experimental data can be achieved only if the dynamical models include subtle effects of suppressed degrees of freedom, effectively introduced by means of genuine three-nucleon forces. A large set of high precision, exclusive cross-section data for the \(^1\text{H}(d,pp)n\) breakup reaction at 130 MeV, contributes significantly to constrain the physical assumptions underlying the theoretical interaction models. Comparison of nearly 1800 cross section data points with the predictions using nuclear interactions generated in various ways, allowed to establish for the first time a clear evidence of importance of the three-nucleon forces in the breakup process. Moreover, the results, supplemented by a set of cross sections from another dedicated experiment, confirmed predictions of sizable Coulomb force influences in this reaction.

1. Introduction

Detailed knowledge of the nucleon-nucleon (\(NN\)) interaction is one of the most demanded pieces of information in the field of nuclear physics. An exact understanding of all features of the two nucleon (\(2N\)) system dynamics would provide a natural basis for description of properties and interactions of nuclei. This optimistic presumption has to be verified by applying models of the \(NN\) interaction to reproduce properties of many-nucleon systems with increasing complexity. Obviously, the least complicated non-trivial environment is the one composed of three nucleons.

Dynamics of the three-nucleon (\(3N\)) system can be comprehensively studied by means of the nucleon-deuteron (\(Nd\)) breakup reaction. Its final state, constrained by only general conservation laws, provides a rich source of information to test the \(3N\) Hamiltonian details. It is of particular importance when components of the models which account for subtle effects, like three-nucleon force (3NF) contributions to the potential energy of the \(3N\) system, are under investigation. Nowadays precise predictions for observables in the \(3N\) system can be obtained via exact solutions of the \(3N\) Faddeev equations for any nucleon-nucleon interaction, even with the inclusion of a 3NF model [1, 2].

The most widely used in few-nucleon studies, so called realistic \(NN\) potentials (RP) are Argonne \(v_{18}\) (AV18), charge dependent Bonn (CD Bonn) or Nijmegen I and II forces. Extension
of that picture is provided by the baryon coupled-channel potential (CCP), in which one Δ-isobar degrees of freedom are allowed on top of purely nucleonic ones [3, 4, 5]. The most basic approach, however, stems from the effective field theory applied to the $NN$ system. The resulting expansion scheme for nuclear systems is called chiral perturbation theory (ChPT). For the $3N$ system it is numerically developed in full at the next-to-next-to-leading (NNLO) order [6, 7, 8, 9]. All the above approaches can also be supplemented by model 3NF’s. In the RP case semi-phenomenological 3NF’s are used, most commonly the Tucson-Melbourne (TM99) or Urbana IX (UIX) models. In the CCP and ChPT frameworks this additional dynamics is generated naturally, together with the $NN$ interactions. The predicted effects are, however, smaller than for the TM99 or UIX forces.

There are additional difficulties in interpretation of the experimental results by means of theoretical calculations. The most important, until recently missing feature is the Coulomb interaction: The experiments are performed mainly for the deuteron-proton system while all calculations are strictly neglecting any long-range forces. Only in the last years a significant step forward has been made in including the Coulomb force effects for the breakup reaction. It was first tried within the coupled-channels approach [10, 11] and recently applied also for the AV18+UIX potential [12]. Contrary to the former expectations, the influence of the Coulomb force on the breakup observables can be quite significant.

2. New generation breakup experiment

To allow for conclusive comparisons between the experimental data and theoretical predictions large sets of data are required. Unfortunately, precise measurements of the breakup reaction are very demanding. The experimental coverage is concentrated at lower energies, below 30 MeV nucleon energy – see Refs. [2, 13] for references. In the recent years some revival of the activity can be noticed (see Ref. [14] for listing of papers), but again only few kinematical configurations are usually studied.

Our new approach to the breakup research assumed a simultaneous measurement in a large part of the phase space by using high acceptance position-sensitive detection system. Measurements of the $^1H(d,pp)n$ reaction were carried out at KVI at 130 MeV beam energy, providing worldwide first extensive set of the breakup cross-section data, spanned on a systematic grid of kinematical variables. Cross section values were extracted for about 80 kinematical configurations [15, 16], defined by the polar angles of the two outgoing protons, $\theta_1$, $\theta_2$, and their relative azimuthal angle $\varphi_{12}$, and presented as functions of the arc-length variable $S$, giving in total nearly 1800 experimental points. The data covered a substantial fraction of the phase-space and allowed to conclude on importance of the 3NF effects for the breakup reaction – only inclusion of this additional dynamics in the calculations leads generally to a better description of the cross sections.

The role of additional dynamics in the breakup cross section is recapitulated in a global approach in Fig. 1. The relative difference of the experimental and theoretical cross sections, $(\sigma_{\text{exp}} - \sigma_{\text{th}})/\sigma_{\text{exp}}$, was determined and plotted as a function of $E_{\text{rel}}$, the kinetic energy of the relative motion of the two protons. Combining the CD Bonn potential with the TM99 3NF (left panel) significantly improves the data description in almost the whole range of $E_{\text{rel}}$ but the smallest relative energies, where it drives the predictions away from the data. The overall improvement of the data description due to inclusion of the TM99 3NF in the calculations (compared to the ones with the pure CD Bonn $NN$ potential) is expressed by a reduction of the global $\chi^2$ by about 40% [16].

In comparisons of our results we were faced with quite substantial disagreements at low values of $E_{\text{rel}}$. Only with the inclusion of the Coulomb force into the calculations in the coupled-channels approach they were mostly explained and removed - see Fig. 1, middle panel. Only with such a large set of the breakup data significance of the Coulomb effects could have been
Figure 1. Relative discrepancies between the experimental data and the theoretical predictions of the breakup cross sections as a function of the relative energy of the two breakup protons. Left panel: Action of TM99 3NF with respect to the pure $NN$ CD Bonn potential. Middle panel: Action of the Coulomb interaction within the CCP approach. Right panel: Combination of the above two effects, when treated as fully independent (see text).

proved and their behavior traced over the phase space [17]. It has been also established that even after including Coulomb effects there is still room for 3NF effects. Since the coherent calculations with both, phenomenological 3NF and Coulomb force are available only now [12], the reasoning has been based on an approximate “correcting” of the data (measured in the $d−p$ system) for the Coulomb effect (defined as the difference of cross sections calculated with and without the Coulomb force included in the CCP) at every experimental point. In this way the data were changed to “equivalent” to the $d−n$ system, for which calculations with the realistic potentials and phenomenological 3NF are strictly applicable. The resulting total effect can be seen in Fig. 1, right panel. One observes that at small $E_{rel}$ values to strong action of the Coulomb force is compensated by 3NF effects, leading to a nearly perfect agreement between the data and the theoretical cross sections. Those conclusion will be now checked by employing the full, consistent calculations.

3. Breakup experiment at forward angles

The first calculations of the Coulomb force influences for the breakup reaction pointed to some quite spectacular effects for small emission angles of the two protons. The cross section is not only strongly suppressed but its distribution is distorted, with a local minimum enforced in the middle of $S$-range. This behavior has been confirmed by a subset of KVI data, for configurations at the acceptance edge of the detection system [17].

To study this effects in some depth, a new experiment has been performed at the Research Center Jülich (FZJ), using the deuteron beam of 130 MeV extracted from the COSY synchrotron and the detection system covering the range of very forward polar angles. An example of the cross section data for one of the kinematical configurations common to both experiments is shown in Fig. 2. The results from FZJ are still preliminary, lacking the absolute normalization,
thus they have been adjusted to match the KVI data. One can observe a very good agreement of the shapes of both data sets and their proper description by theoretical calculations including the Coulomb force [18].

It should be noted that for a relatively sharp structures in the cross section the theoretical calculations have to be appropriately averaged over the angular and energy regions, corresponding to the ones used in the data evaluation procedure. Only then they can be confronted with the experimental data - the size of the effect can be inspected in Fig. 2. A larger sample of the preliminary results showing the distortion effect of the cross section distribution due to the Coulomb force is presented in Fig. 3.

4. Summary

Studies of the breakup reaction performed in a large part of the phase space are shedding light on the role of various aspects of the 3N system dynamics. After the pioneering experiments, further data sets are being acquired at several beam energies [19, 20]. They present a general success of the modern calculations in describing the data, however, possibly complete theoretical treatments, including all important ingredients (3NF, Coulomb interaction, relativistic effects), as well as developments in ChPT are very important for better understanding of the three-nucleon system dynamics.

The cross-section data are supplemented with equally large sets of various analyzing powers and measurements of even higher-order polarization observables (see Refs. [21, 22] and references therein). Certain discrepancies observed in those observables are a hint of problems in the spin part of the current models of 3NF. More experiments to study 3N system dynamics are planned at several laboratories, including the next step - continuation of the few-body system studies in the four-body environment.

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Figure 3. Preliminary cross section data for the breakup reaction measured at FZJ for six kinematical configurations specified in the panels. The lines show the results of the appropriately averaged calculations of CCP with the Coulomb force included.

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