Dynamics of three-nucleon system studied via deuteron breakup

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Abstract. Three-nucleon system dynamics, determined mainly by pairwise nucleon-nucleon (NN) interaction, can be investigated quantitatively by comparing predictions based on rigorous solutions of the Faddeev equations with results of precise measurements. Proper description of the experimental data can be achieved only if the dynamical models include, in addition to the NN potential, subtle effects of suppressed degrees of freedom, effectively introduced by means of genuine three-nucleon forces. Another dynamical effect which is needed for correct reproducing of the measured observables is the long-time neglected Coulomb force. A large set of high precision, exclusive cross-section data for the $^1$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 importance of including both, the three-nucleon and the Coulomb forces to significantly improve description of the whole data set.

1. Introduction

Three-nucleon ($3N$) system dynamics can be thoroughly 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. Such studies are 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 ($NN$) interaction, even with the inclusion of a 3NF model [1].

The most commonly 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 ∆-isobar degrees of freedom are allowed on top of purely nucleonic ones [2, 3]. 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 [4, 5]. All the above approaches can also be supplemented by model 3NF’s. In the RP case semi-phenomenological
3NF’s are used, most frequently 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 attempted within the coupled-channels approach [6] and recently applied also for the AV18+UIX potential [7]. Contrary to the former expectations, the influence of the Coulomb force on the breakup observables can be quite significant at certain kinematical regions, even in measurements with beam energies of hundreds MeV.

2. New Generation Breakup Experiments

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 and were usually limited to studies of a few isolated kinematical configurations.

Our new approach to the breakup investigations assumed a simultaneous measurement in a large part of the phase space by using high acceptance position-sensitive detection systems. Such measurements of the $^1$H(d,pp)$^n$ reaction were started 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 [8, 9], 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 additional (more than just the leading $NN$ force) dynamics in describing the whole data set.

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 AV18 potential with the UIX 3NF (Fig. 1, left panel, triangles) 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.

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 calculations in the coupled-channels approach, they were mostly explained and removed [10]. A consistent theoretical treatment of phenomenological 3NF and Coulomb force has been achieved only recently [7] and allows to investigate the role of both effects on the same level of accuracy. In Fig. 1 (left panel, squares) impact of the Coulomb force effects on the breakup cross sections can be inspected. While at large $E_{\text{rel}}$ the long-range electromagnetic force essentially does not influence the data, it strongly reduces the disagreements at small $E_{\text{rel}}$ values. Only with such a large set of the breakup data significance of the Coulomb force effects could has been proven and their behavior traced over the phase space [10]. It has been also established that even after including the Coulomb force there is still room for 3NF effects. The resulting total action of both dynamical ingredients supplementing the pure $NN$ interaction can be seen in Fig. 1, right panel. One observes that at small $E_{\text{rel}}$ values too strong action of the Coulomb force is compensated by 3NF effects, leading to a very good agreement between the data and the theoretical cross sections. The discrepancies remaining at large $E_{\text{rel}}$ values hint at some still unresolved problems in our understanding of the 3N system dynamics, e.g. non-complete modeling of 3NF structure.
The first calculations of the Coulomb force influences for the breakup reaction pointed to some quite spectacular effects at 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 the $S$-range. This behavior has been confirmed by a subset of KVI data, for configurations at the acceptance edge of the detection system [10].

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. The cross section values have been obtained at almost 2400 points, with the upper angular limit overlapping the acceptance of the KVI experiment. An excellent agreement between the two data sets is achieved [11], although they stem from completely different measurements and normalization procedures. Examples of the breakup cross section distributions at four kinematical configurations, compared to various predictions, are shown in Fig. 2. Obviously, only the approaches which do include the Coulomb interaction are able to correctly reproduce the data. This agreement can be considered as a proof of certain maturity of including the Coulomb force effects in the theoretical calculations.

3. 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 (see e.g. Ref. [13]). They present a general success of 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.
Figure 2. Examples of the breakup cross section distributions for four kinematical configurations (specified in the panels). Predictions obtained by various theoretical approaches are shown as bands and lines (see legend).

The cross-section data are supplemented with equally large sets of various analyzing powers and measurements of even higher-order polarization observables (see Refs. [14, 15] and references therein). Certain discrepancies observed in those observables are hints of problems in the spin (and isospin) 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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