EXPERIMENTAL STUDIES OF FEW-NUCLEON SYSTEMS. DYNAMICS OF THE 3*N* INTERACTION IN CROSS SECTIONS*

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(Received December 18, 2017)

Modern nucleon–nucleon (NN) interaction models are able to reproduce the bulk of all NN data with an utmost precision. Their quality can be efficiently probed in the few-nucleon environment by comparing high quality theoretical predictions with the observables measured in precision experiments. The most common experimentally tested systems are those of three nucleons. Systematic studies of elastic nucleon–deuteron scattering and deuteron breakup reactions at intermediate energies show that a proper description of the experimental data cannot be achieved with the use of NN forces alone and has to include additional dynamics like effects of suppressed degrees of freedom, introduced by means of genuine three-nucleon forces, Coulomb interaction between protons or relativistic effects. The most important results, concerning cross sections, of recent experimental studies of $3N$ systems at intermediate energies are discussed.

DOI:10.5506/APhysPolB.49.437

1. Introduction

Description of the nuclear interaction is one of the oldest but still persistent problems in nuclear physics. It is of crucial importance for understanding the basic properties of atomic nuclei and, more general, the strongly interacting hadronic matter. The NN potential is a leading part of the nuclear interactions but it is not sufficient to describe the precise experimental data for systems with more than two nucleons (*e.g.* binding energies of few-nucleon states [1–4]). This discrepancy between experiment and theory strongly indicates the need to include the three-nucleon force (3NF). The existing models of 3NF are usually constructed as refined versions of the Fujita–Miazawa force [5], in which a pion is exchanged between two nucleons leading to an excitation of a Δ isobar, which subsequently decays

* Presented at the XXXV Mazurian Lakes Conference on Physics, Piaski, Poland, September 3–9, 2017.

exchanging the pion with the third nucleon. The modern versions of such a force, such as TM 99 [6], Urbana IX [7], Brazilian [8] or Illinois [9], are combined with the so-called realistic NN potentials (*e.g.* Argonne V18 [10], CD Bonn [11], Nijmegen I and II [12]), and constitute the basis for calculations of binding energies and other observables. An alternative method of generating 3NF is based on the so-called explicit Δ-isobar excitation [13, 14]. Calculations are performed in the coupled-channel approach and the effective 3NF is generated via the explicit treatment of the degrees of freedom of a single Δ. In the Chiral Effective Field Theory, the nuclear forces are constructed systematically in a fully consistent way and the 3NF appears naturally at the next-to-next-to-leading order [15–17].

It is worth to stress that modern *ab initio* calculations of shell structure of neutron-rich nuclei need 3NF for correct description of stability close to the neutron drip line or saturation in nuclear matter (see *e.g.* Refs. [17–19]). The nuclear force used as an input for such calculations should be thoroughly tested. The observables for three-nucleon systems, as a subject of accurate *ab initio* calculations, represent an excellent testing ground for NN + 3NF interactions, constructed in any of the ways mentioned above.

This work discusses successes and failures of the state-of-the-art theoretical calculations in confrontation with precise experimental data. As a sample reference, the cross section results from a series of present-generation studies of the elastic scattering and breakup reaction at intermediate energies are used, supplemented by selected polarization observables.

2. Experimental studies of 3N systems

Studies of the three-nucleon system dynamics are based on measurements of various observables (*e.g.* cross section, vector and tensor analyzing powers) for elastic nucleon–deuteron scattering and breakup of deuteron in its collision with a nucleon. Thanks to detectors covering a big part of the phase space, it is possible to test the effects of various dynamical ingredients (*e.g.* 3NF, Coulomb force and relativistic effects). Such an approach was applied in the experimental studies of Nd system at intermediate energies, where the elastic scattering, breakup and electromagnetic effects can be tested.

2.1. Elastic scattering

In the last decades, the Nd elastic scattering has been extensively tested, with polarized and unpolarized beams, by groups at KVI (Groningen, The Netherlands), RIKEN (Saitama, Japan), RCNP (Osaka, Japan), LANSCE (Los Alamos, USA), and IUCF (Bloomington, USA), providing precise data for cross sections and various spin observables (see Table I).

TABLE I

Recent experiments for *pd* and *nd* elastic scattering at intermediate energies.

System	Beam E [MeV/A]	Observable $\frac{d\sigma}{d\Omega}$	Observable spin	Laboratory	Reference
dp	65	X	X	KVI	[20]
	70	X		RIKEN	[21]
	90	X	X	KVI	[22]
	100		X	RIKEN	[21]
	135	X	X	RIKEN	[21, 23, 24]
	147	X	X	RIKEN	[25]
pd	108	X	X	KVI	[26]
	120	X	X	KVI	[26]
	135	X		RIKEN	[27]
		X	X	KVI	[26]
			X	IUCF	[28]
	146	X	X	Harvard	[29]
	150	X	X	KVI	[26, 30]
	155	X	X	Orsay	[31]
	170	X	X	KVI	[26]
	190	X	X	KVI	[26, 30]
	200		X	IUCF	[28, 32]
	250	X	X	RCNP	[33]
	392	X	X	RCNP	[34]
nd	65	X		PSI	[35]
	95	X		UPSALA	[36]
	135	X		LANSCE	[37]
	150	X		LANSCE	[37]
	160	X		LANSCE	[37]
	170	X		LANSCE	[37]
	180	X		LANSCE	[37]
	190	X		LANSCE	[37]
	200	X		LANSCE	[37]
	210	X		LANSCE	[37]
	220	X		LANSCE	[37]
	230	X		LANSCE	[37]
	240	X		LANSCE	[37]
	248	X	X	RCNP	[38]
	250	X		LANSCE	[37]

The elastic scattering results for cross sections and polarization observables, which depend on the energy and the angular range, show that the experimental data are well-described by the calculations which include the 3NF. The effects of this force are significant, especially at the minimum of the cross section distributions, and could not be neglected.

However, at the extreme angles, a disagreement between the data and the calculations is visible. For the very forward angles, these differences are cancelled when the Coulomb interaction between protons is taken into account [39]. At very backward angles, where the exchange processes by the NN interactions are dominant, the discrepancies between the experimental data and theoretical predictions increase with increasing incident energy [40] and they are not remedied even if the relativistic effects are taken into consideration [41, 42]. This feature strongly suggests that in theoretical predictions additional important components are needed.

In general, the results for elastic scattering show a picture that is not completely clear, so there is still much to investigate, including complementary studies. In addition, the weak Coulomb and relativistic effects are visible at a very forward and backward angles, respectively.

2.2. Breakup reaction

For better understanding of the $3N$ systems dynamics, the dp (pd) breakup reactions were measured at beam energies in the range from 50 to 200 MeV/nucleon (see Table II). A significant amount of these experimental data was collected at KVI, where the $^1\mathrm{H}(\vec{d}, pp)n$ and $^2\mathrm{H}(\vec{p}, pp)n$ reactions were studied at five beam energies from 50 to 190 MeV/nucleon using the SALAD [50] and BINA [20] detectors. The differential cross sections and vector and tensor analyzing powers were studied in a wide phase space regions.

TABLE II

Recent experiments for pd breakup reaction at intermediate energies.

System	Beam E [MeV/A]	Observable $\frac{d\sigma}{d\Omega}$	spin	Laboratory	Reference
dp	50	X	X	KVI	[43]
	65	X	X	KVI	[20]
		X	X	FZ-Jülich	[44]
	80	X	X	KVI	
	135		X	IUCF	[45]
	170	X		FZ-Jülich	[46]
	190			FZ-Jülich	
	200			FZ-Jülich	
pd	135	X	X	RIKEN	[47]
		X	X	KVI	[48]
	190	X	X	KVI	[49]

In order to test the Coulomb interaction, an additional experiment was conducted at the deuteron energy of 65 MeV/nucleon at FZ-Jülich with the use of the GeWall detector [20, 44, 51, 52]. The vector and tensor analyzing powers were extensively measured at 135 MeV at IUCF [45] and RIKEN [47]. Recently, the differential cross sections have been measured with the use of the 4π WASA detector. Deuteron beams were accelerated at the COSY ring of FZ-Jülich to energies from 170 to 200 MeV/nucleon [46]. A combination of high precision experimental data with exact theoretical calculations for a selected kinematic configuration gives the opportunity to study subtle 3NF, Coulomb force or relativistic effects.

Figure 1 presents the experimental breakup cross sections at 130 MeV in four selected kinematic configurations. Black circles represent experimental data. Dashed and solid lines are the predictions for realistic CD Bonn potential with and without TM99 three-nucleon force included, respectively. The other lines present the results obtained by calculations with the coupled-channel potential, CD Bonn + Δ, without (dotted) and with (dash-dotted) Coulomb force included [53]. One can see that for this type of reaction, the calculations show that there are regions (see bottom panel of Fig. 1) where

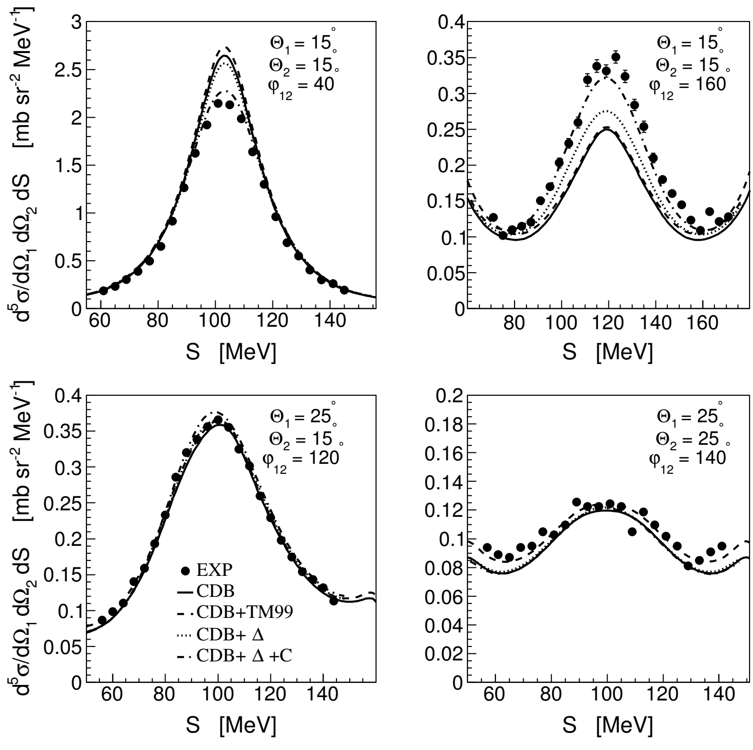

Fig. 1. Cross section distributions for *dp* breakup reaction at 130 MeV in four selected configurations (see the text).

3NF effects are pronounced and their importance is confirmed by the measured cross sections. For the very forward part of the phase space (upper panel of Fig. 1), one finds that the disagreement between the predictions of the realistic potential supplemented or not by 3NF (solid and dashed lines) and the experimental cross section changes with relative azimuthal angle. For small values of φ_{12}, the data are overestimated, while for large ones they are underestimated. This discrepancy between experimental and theoretical cross section for the very forward part of phase space (bottom panel of Fig. 1) is reduced when the calculations are supplemented by the Coulomb force.

With increasing the beam energy, the relativistic effects start playing an important role. There are theoretical calculations [54] which predict the relativistic effects at the level of 60% for *pd* breakup at the energy of 200 MeV for the quasi-free scattering (QFS) configurations. A dedicated experiment to test this phenomenon is being prepared at CCB PAN, Kraków.

In order to perform a systematic study of dynamical effects (*e.g.* 3NF, Coulomb force) of such a large database, the kinematics of breakup reaction was presented in regime of invariant coordinates [20, 55]. For that purpose, the Mandelstam variables were rewritten in a convenient way for a breakup reaction, $p + d \longrightarrow p^{(1)} + p^{(2)} + n$. Using this representation, the effects of 3NF and the Coulomb force have been analyzed.

Figure 2 presents the net effects of the Coulomb force in function of the kinetic energy transferred to a proton, $E^p_{\rm tr}$ and the energy of relative motion of proton–neutron pair, $E^{pn}_{\rm rel}$ coordinates. Shapes of these spectra correspond

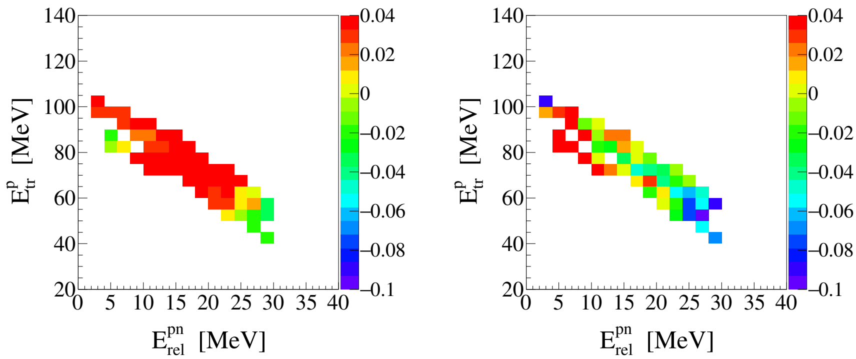

Fig. 2. (Color online) Net effects of the Coulomb force in the differential cross section of the *dp* breakup at 130 MeV, presented as a function of two invariants. Left panel: Difference of theoretical predictions (by Deltuva *et al.* [53]) obtained for Argonne V18 potential combined with UIX 3NF with and without Coulomb force, relatively normalized to AV18+UIX calculations. Right panel: Difference between experimental data and calculations with AV18+UIX alone, normalized in the same way.

to the selected phase space of the dp breakup experiment at 130 MeV, while their colors code a magnitude of the effect calculated as $\frac{\sigma_i - \sigma_{\mathrm{AV18+UIX}}}{\sigma_{\mathrm{AV18+UIX}}}$, where σ_i denotes the theoretical (with the Coulomb force included) or experimental differential cross section. These results are consistent with the previous analysis of the Coulomb effect based on data originating from a dedicated dp breakup experiment with a beam of energy 130 MeV, which has been done at FZ-Jülich, using the Germanium Wall (GeWall) setup.

3. Summary

The $3N$ system studies at intermediate energies are still continued thanks to recent progress in experimental techniques and calculations including 3NF and other dynamical effects. The studies of elastic scattering and breakup reactions at various energies are necessary for a complete description of 3NF dynamics. It is worth to underline that the existing experimental data indicate the need of including in the state-of-the-art theoretical predictions the Coulomb and the relativistic effects. Moreover, these data also show that some significant components are missing in the calculations at higher energies.

The breakup reaction data collected in a wide range of phase space make feasible a systematic analysis of breakup observables as a function of kinematic variables. For the sake of comparing data obtained at various energies and learning more about the dynamics of the process, the analyses in invariant coordinates are pursued.

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