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Probing few-nucleon systems using spin

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Abstract. Understanding the few-nucleon system remains one of the challenges in modern nuclear and hadron physics. Observables in few-nucleon scattering processes are sensitive probes to study the two and many-body interactions between nucleons in nuclei. In the past decades, several facilities provided a large data base to study in detail the three-nucleon interactions below the pion-production threshold by exploiting polarized proton and deuteron beams and large-acceptance detectors. This paper gives a brief overview of the experimental results and their interpretation exploiting ab-initio calculations derived from the state-of-the-art nucleon-nucleon forces. In particular, the role of spin in the proton-deuteron break-up channel is being highlighted.

1. Introduction

Understanding the exact nature of the nuclear force is one of the long-standing questions in nuclear physics. In 1935, Yukawa successfully described the pair-wise nucleon-nucleon (NN) interaction as an exchange of a boson [1]. Current NN models are mainly based on Yukawa's idea and provide an excellent description of the high-quality data base of proton-proton and neutron-proton scattering [2] and of the properties of the deuteron. However, for the simplest three-nucleon system, the triton, three-body calculations employing NN forces clearly underestimate the experimental binding energies [3], demonstrating that NN forces are not sufficient to describe the three-nucleon system accurately. Some of the discrepancies between experimental data and calculations solely based on the NN interaction can be resolved by introducing an additional three-nucleon force (3NF). Most of the current models for the 3NF are based on a refined version of Fujita-Miyazawa's 3NF model [4], in which a 2π-exchange mechanism is incorporated by an intermediate Δ excitation of one of the nucleons [5, 6]. More recently, NN and three-nucleon potentials have become available which are derived from the basic symmetry properties of the fundamental theory of Quantum Chromodynamics (QCD) [7, 8]. These so-called chiral-perturbation (χPT) driven models construct systematically a potential from a low-energy expansion of the most general Lagrangian with only the Goldstone bosons, e.g. pions, as exchange particles. The validity of the χPT-driven models for the intermediate energies remains, however, questionable and depends strongly on the convergence of results at higher terms in the momentum expansion.

2. Nucleon-deuteron elastic scattering

In the last decade, high-precision data at intermediate energies in elastic Nd and dN scattering [9–21, 23, 24, 26–28] for a large energy range together with rigorous Faddeev calculations [29] for the three-nucleon system have proven to be a sensitive tool to study the 3NF. In particular, a large sensitivity to 3NF effects exists in the minimum of the differential cross section [30,31]. The results of a systematic study of the energy dependence of all available cross sections in elastic proton-deuteron scattering with respect to state-of-the-art calculations by the Hannover-Lisbon theory group are depicted in Fig. 1. The top panel shows the relative difference between the model predictions excluding the Δ-isobar contribution and data taken at a fixed center-of-mass angle of $\theta_{\text{c.m.}}$=140°. The data points were extracted from a polynomial fit through each angular distribution. The error bars correspond to a quadratic sum of the statistical and systematic uncertainties of each measurement. Note that the discrepancies, reflecting the 3NF effects, increase drastically with incident energy and reach values of more than 100% at energies equal or larger than 200 MeV. The bottom panel in Fig. 1 shows a similar comparison between data and model predictions including the Δ-isobar as mediator of the 3NF effects. Clearly, a large part of the discrepancies is resolved. However, a smaller but significant deficiency remains which increases with energy to values of about 30% at an energy of 200 MeV.

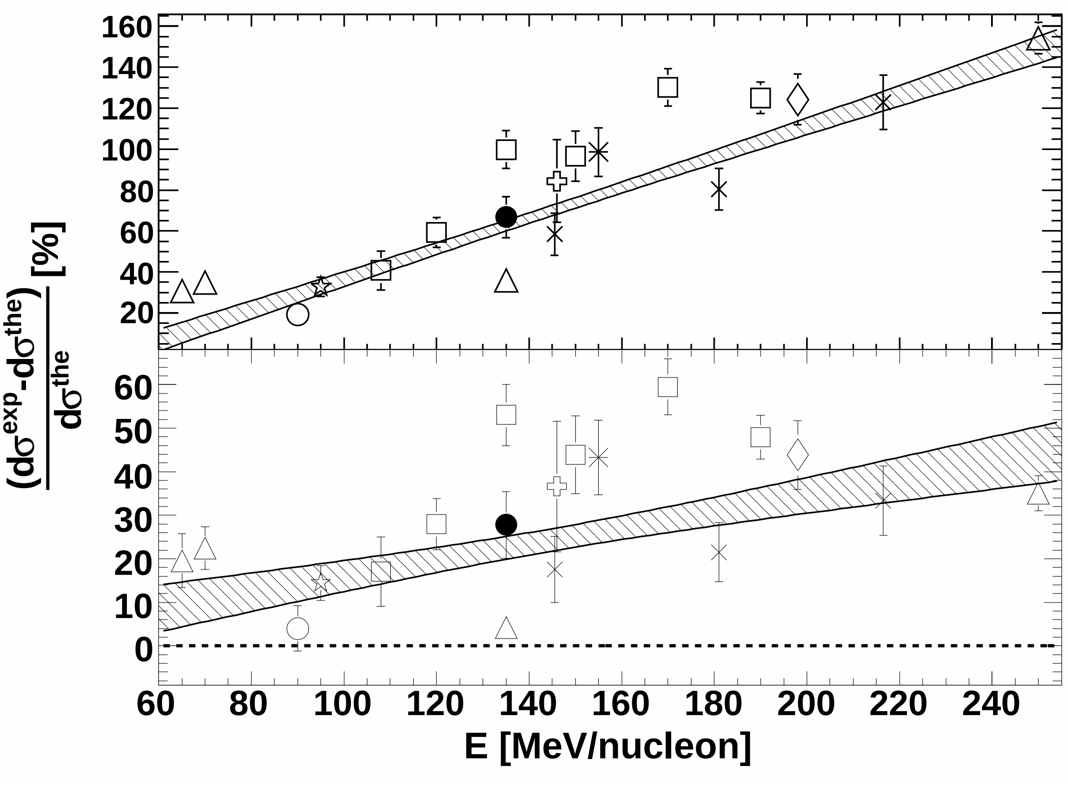

Figure 1. The relative difference between the calculations by the Hannover-Lisbon theory group and the measured cross sections for the elastic $p+d$ reaction as a function of beam energy for $\theta_{\text{c.m.}} = 140°$. The top panel shows the differences with a calculation based on the CD-Bonn potential and the Coulomb interaction, whereas for the bottom panel an additional Δ isobar has been taken into account. Open squares are data from Ref. [11], open triangles are data from Refs. [13,14,26,27], the open circle is from [17], the open star is from [19], crosses are from [20], the star is from [18], the open cross is from [16], the diamond is from [21] and the filled circle is from [22]. The shaded band represents the result of a line fit through the data excluding the results obtained at KVI, RIKEN and RCNP. The width of the band corresponds to a 2σ error of the fit.

3. Nucleon-deuteron break-up

Complementary to the elastic scattering experiments, three-nucleon studies have been performed exploiting the nucleon-deuteron break-up reaction. The phase space of the break-up channel is much richer than that of the elastic scattering. The final state of the break-up reaction is described by five kinematical variables, as compared to just one for the elastic scattering case. Therefore, studies of the break-up reaction offer a way of much more detailed investigations of the nuclear forces, in particular of the role of 3NF effects. Predictions show that large 3NF effects can be expected at specific kinematical regions in the break-up reaction. Results of the cross sections and tensor analyzing powers have already been published for a deuteron-beam energy of 130 MeV on a liquid-hydrogen target [32–34]. These experiments were the first ones of its type which demonstrated the feasibility of a high-precision measurement of the break-up observables and they confirmed that sizable influences of 3NF and Coulomb effects are visible in the break-up cross sections at this energy. In the last years, more data at several beam energies and other observables have been collected to provide an extensive data base at intermediate energies.

Recent and interesting results have been obtained at KVI using a 4π detection system BINA, which provides a unique tool to study a large part of the phase space of the break-up reaction. Figure 2 presents some results of the vector analyzing powers in proton-deuteron break-up for an incident proton beam of 190 MeV and for two symmetric kinematical configurations (θ_1, θ_2)=$(25°, 25°)$ and $(28°, 28°)$ for three different values of ϕ_{12}. Here, the angles θ_1 and θ_2 refer to the polar angles of the two final-state protons and ϕ_{12} to the relative azimuthal angle between these protons. The parameter S is directly related to the energies of the two final-state protons and is a measure of their energy correlation. The data are compared with calculations based on different models for the interaction dynamics as described in detail in the caption of the figure. For these configurations and observable, the effects of relativity and the Coulomb force are predicted to be small with respect to the effect of three-nucleon forces. At ϕ_{12}=180°, the value of A_y is predicted to be completely determined by two-nucleon force effects with only a very small effect of 3NFs, which is supported by the experimental data. A surprising discrepancy between the measured analyzing powers and theoretical predictions can be observed at small relative azimuthal opening angles ϕ_{12}=20°. This configuration corresponds to a relative energy between the two protons of less than 10 MeV. Note that this deficiency even increases when including three-nucleon force effects such as the TM' potential or the implicit inclusion of the Δ isobar by the Hannover-Lisbon theory group. The relative energy between the two protons varies as a function of S and, for symmetric configurations, $\theta_1 = \theta_2$, it reaches a very low value at the center of S of less than 1 MeV. A comparison between differential cross section data and corresponding Monte Carlo studies has shown unambiguously that, in these cases, the two protons move very close to each other in a relative angular momentum S state with an isospin of one, which is similar to the configuration of a ^{2}He.

The observed discrepancies in the vector-analyzing power in proton-deuteron break-up as shown in Fig. 2 could point to a deficiency in the spin-isospin structure of the description of the many-nucleon forces in the present-day state-of-the-art calculations. This is demonstrated by the data shown in Fig. 3. Here, the analyzing powers for the break-up reaction, $^2\mathrm{H}(\vec{p},^2\mathrm{He})n$ (left panel), are compared to the analyzing power of the elastic $^2\mathrm{H}(\vec{p}, d)p$ reaction (right panel). In the elastic channel, the total isospin of the initial and final state is exclusively 1/2, whereas in the former case, the final state might couple to an isospin 3/2 as a consequence of the isospin violating Coulomb force. The analyzing powers in the left panel are selected from the symmetric break-up configurations in which ($\theta_1 = \theta_2$, $\phi_{12} = 20°$); see the lower panels of Fig. 2 for example. The data points in the left panel of Fig. 3 are obtained from a fit using a second-order polynomial to the analyzing power data as a function of S. We have taken the fit value and its error for the central value of S, corresponding to the smallest relative energy. The center-of-mass angles

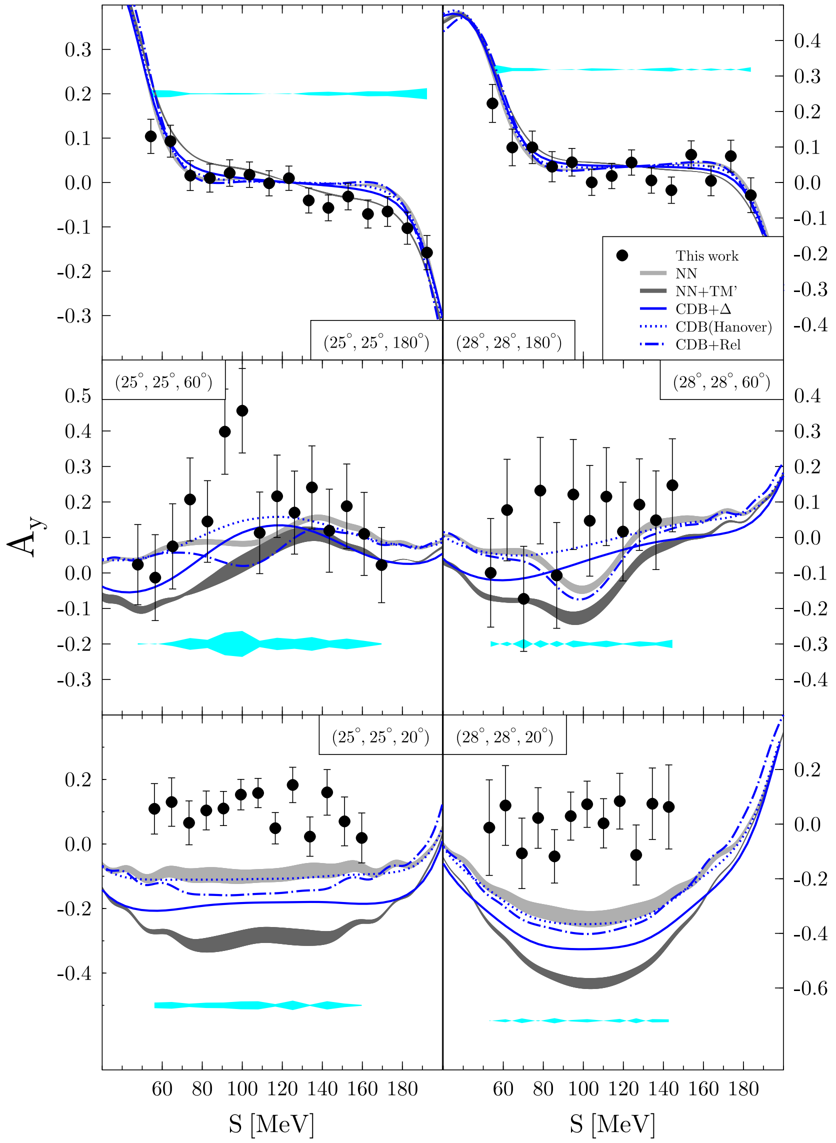

Figure 2. A comparison between the results of the analyzing power measurements for a few selected break-up configurations with various theoretical predictions. The light gray bands are composed of various modern two-nucleon (NN) force calculations, namely CD-Bonn, NijmI, NijmII, and AV18. The dark gray bands correspond to results of the calculations with the same NN forces including the TM' (3N) potential. The lines represent the predictions of calculations by the Hannover-Lisbon group based on the CD-Bonn potential (dotted) and CD-Bonn potential extended with a virtual Δ excitation (solid blue). The blue dash-dotted lines are derived from calculations by the Bochum-Cracow collaboration based on the CD-Bonn potential including relativistic effects [35]. The errors are statistical and the cyan band in each panel represents the systematic uncertainties (2σ).

are obtained by assuming that the *pp* pair with a small relative energy corresponds to one body, namely a ^{2}He state scattering at an angle $\theta_1 = \theta_2$. The theory curves depicted in the left panel were obtained from calculations for the symmetric configuration of the break-up reaction,

($\theta_1 = \theta_2$, $\phi_{12} = 20^\circ$), and taken at the center of S. Note that at center-of-mass angles of less than 135°, there is a large discrepancy between the state-of-art calculations and the experimental data for the $^2\mathrm{H}(\vec{p},^2\mathrm{He})n$ reaction, whereas the same calculations deviate significantly less with the analyzing power results in the $^2\mathrm{H}(\vec{p},d)p$ channel at the same incident energy. The current modeling of two and three-nucleon forces is not sufficient to describe consistently polarization data for the two isospin states, which hints towards a deficiency in the spin-isospin structure of the forces. A more detailed discussion can be found in Ref. [25].

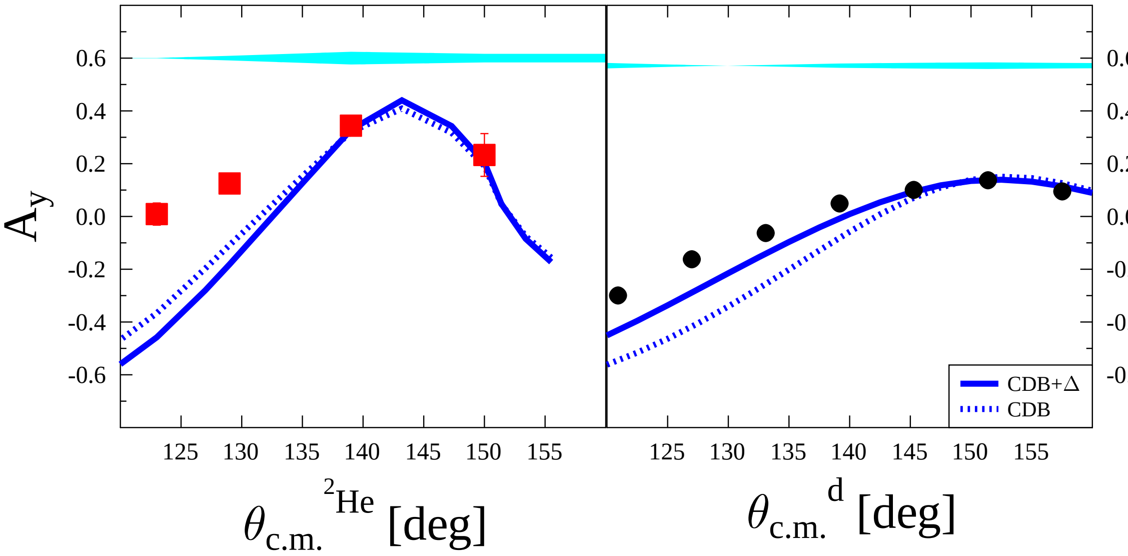

Figure 3. The analyzing power as a function of the center of mass angle for two reactions $^2\mathrm{H}(\vec{p},^2\mathrm{He})n$ (left panel) and $^2\mathrm{H}(\vec{p},d)p$ (right panel). For a description of the lines and bands, see Fig. 2 and for a description of the data points, see the text. The data of the $^2\mathrm{H}(\vec{p},d)p$ reaction are taken from Refs. [10, 12]. The results of both reactions were obtained with a proton-beam energy of E_p=190 MeV.

A more global analysis of the Nd break-up reaction is presently conducted in which the deficiencies with the state-of-the-art calculations are being systematically studied for all the available break-up data. These results will soon become available within a review article. For this paper, I present one of the preliminary outcomes of this analysis. In Fig. 4 a summary plot is depicted for all the available vector-analyzing data points in proton-deuteron break-up for two incident proton energies, namely 135 MeV and 190 MeV. The figure depicts the deviations with respect to calculations from the Hannover-Lisbon theory group. The y-axis represents the deviation with a calculation based upon the CD-Bonn potential and excluding the effect of the 3NF, whereas the x-axis represents the deviation with the same calculation including 3NF effects. Here, the Δ resonance within a coupled-channel framework mimics the 3NF effects. The calculation takes into account the effect of the Coulomb force. The color intensity on the z-axis represents the number of kinematical configurations, e.g. data points, that fall into the corresponding bin. Note that a large amount of data points are close to the origin. For those cases, the calculations predict a negligible 3NF effect and the data agrees well with the model predictions. In the ideal case, one hopes that all the data would lie on the horizontal line, implying that the 3NF effects are correctly incorporated in the model. Data that fall on the diagonal line away from the origin would imply that the calculations predict only a small 3NF effect, whereas the data are incompatible with this assumption. The vertical line indicates the worse case scenario, e.g. the inclusion of a 3NF effect makes the discrepancy with the experimental data larger. Strikingly, a large fraction of the break-up data fall within the diagonal and vertical line, indicating that our present understanding of 3NF effects is not under control for this channel and observable.

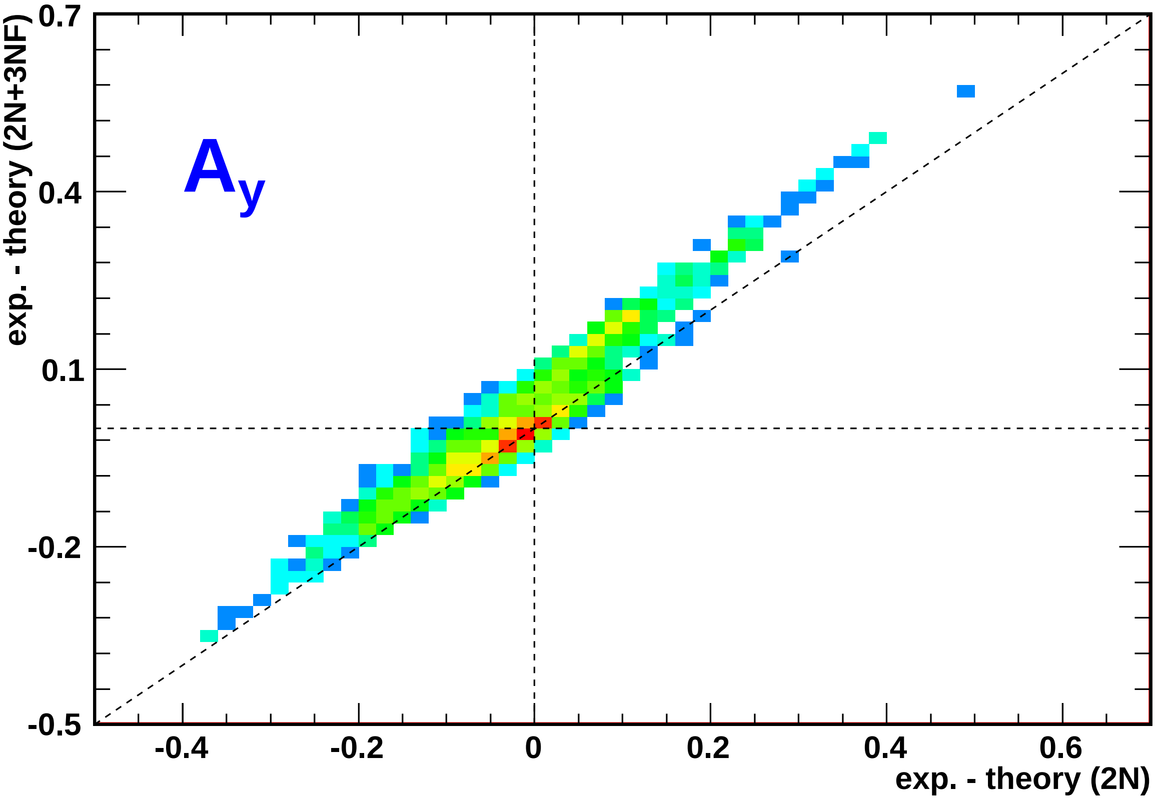

Figure 4. A global analysis of the proton-deuteron break-up data on the vector analyzing power, A_y, for two incident proton-beam energies of 135 MeV and 190 MeV. The figure includes about 2500 data points for a large range in kinematics. The data are compared with predictions by the Hannover-Lisbon theory group. For a more detailed description, see text.

4. Conclusions

In the past decades, our understanding of the nuclear forces has drastically improved. These developments can be attributed to the enormous progress made in theory and in experiment. In particular, in the three-nucleon sector, the theoretical descriptions are ab-initio, based on high quality potentials, and (partly) able to include effects like Coulomb and relativity. Also, the experimental techniques have significantly improved in the course of time and have provided a huge data base with high-precision data and covering a huge part of the phase space.

In spite of the progress made in experimental and theoretical techniques to study the many-nucleon system, there are still various open questions which urgently need to be addressed. A large part of these questions point to our present understanding of 3NF effects, in particular to its spin structure. This paper discusses some results of few-nucleon scattering experiments taken at intermediate energies. In general, the overall comparison between data and theory improve significantly by taking into account 3NF effects. This holds in particular for the differential cross sections in Nd elastic scattering. There are, however, various spin observables which show huge discrepancies. Therefore, the existing data base for few-nucleon scattering observables provide an ideal basis to develop a better understanding of the spin-structure of many-body forces in few-nucleon interactions.

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[1] Yukawa H 1935 *Proc. Phys. Math. Soc. Jap.* **17** 48.
[2] Stoks V G J, Klomp R A M, Terheggen C P F, and de Swart J J 1994 *Phys. Rev. C***49** 2950.
[3] Wiringa R B, Stoks V G J, and Schiavilla R 1995, *Phys. Rev. C***51** 38.
[4] Fujita J and Miyazawa H 1957 *Prog. Theor. Phys.* **17** 360.
[5] Deltuva A, Machleidt R, and Sauer P U 2003 *Phys. Rev. C***68** 024005.
[6] Coon S A and Han H K 2001, *Few-Body Syst.* **30** 131.
[7] Epelbaum E, Glöckle W, and Meißner U G 1998 *Nucl. Phys. A***637** 107.
[8] Epelbaum E, Glöckle W, and Meißner U G 2000 *Nucl. Phys. A***671** 295.
[9] Bieber R *et al.* 2000 *Phys. Rev. Lett.* **84** 606.
[10] Ermisch K *et al.* 2001 *Phys. Rev. Lett.* **86** 5862.
[11] Ermisch K *et al.* 2003 *Phys. Rev. C***68** 051001(R).
[12] Ermisch K *et al.* 2005 *Phys. Rev. C***71** 064004.
[13] Sakai H *et al.* 2000 *Phys. Rev. Lett.* **84** 5288.
[14] Sekiguchi K *et al.* 2002 *Phys. Rev. C***65** 034003.
[15] Sekiguchi K *et al.* 2005 *Phys. Rev. Lett.* **95** 162301.
[16] Postma H and Wilson R 1961 *Phys. Rev.* **121** 1129.
[17] Amir-Ahmadi H *et al.* 2007 *Phys. Rev. C***75** 041001(R).
[18] Kuroda K *et al.* 1966 *Nucl. Phys.* **88** 33.
[19] Mermod P *et al.* 2005 *Phys. Rev. C***72** 061002(R).
[20] Igo G *et al.* 1972 *Nucl. Phys. A***195** 33.
[21] Adelberger R E and Brown C N 1972 *Phys. Rev. D***5** 2139.
[22] Ramazani-Moghaddam-Arani A *et al.* 2008 *Phys. Rev. C***78** 014006.
[23] Mardanpour H *et al.* 2007, *Eur. Phys. J. A***31** 383.
[24] Stephan E *et al.* 2007 *Phys. Rev. C***76** 057001.
[25] Mardanpour H *et al.* 2010 *Phys. Lett. B***687** 149.
[26] Shimizu H *et al.* 1982 *Nucl. Phys. A***382** 242.
[27] Hatanaka K *et al.* 2003 *Eur . Phys. J. A***18** 293.
[28] Stephenson E J, Witała H, Glöckle W, Kamada H, and Nogga A 1999 *Phys. Rev. C***60** 061001.
[29] Glöckle W *et al.* 1996 *Phys. Rep.* **274** 107.
[30] Witała H, Glöckle W, Huber D, Golak J, and Kamada H 1998 *Phys. Rev. Lett.* **81** 1183.
[31] Nemoto S, Chmielewski K, Oryu S, and Sauer P U 1998 *Phys. Rev. C***58** 2599.
[32] Kistryn S *et al.* 2006 *Phys. Lett. B***641** 23.
[33] Biegun A *et al.* 2006 *Acta Phys. Pol. B***371** 213.
[34] Stephan E *et al.* 2007 *Phys. Rev. C***76** 057001.
[35] Skibiński R, Witała H, and Golak J 2006 *Eur. Phys. J. A***30** 369.