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Spin–isospin selectivity in three-nucleon forces

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A B S T R A C T

Precision data are presented for the break-up reaction, ^{2}H$(\vec{p}, pp)n$, within the framework of nuclear-force studies. The experiment was carried out at KVI using a polarized-proton beam of 190 MeV impinging on a liquid-deuterium target and by exploiting the detector, BINA. Some of the vector-analyzing powers are presented and compared with state-of-the-art Faddeev calculations including three-nucleon forces effect. Significant discrepancies between the data and theoretical predictions were observed for kinematical configurations which correspond to the ^{2}H$(\vec{p}, ^2$He$)n$ channel. These results are compared to the ^{2}H$(\vec{p}, d)p$ reaction to test the isospin sensitivity of the present three-nucleon force models. The current modeling of two and three-nucleon forces is not sufficient to describe consistently polarization data for both isospin states.

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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 database of proton–proton and neutron–proton scattering [2] and of the properties of the deuteron. However, for the simplest three-nucleon system, 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].

The structure of the 3NF can be studied via a measurement of observables in three-nucleon scattering processes. More detailed information on the spin dependence of the 3NF can be obtained by measuring polarization observables such as the analyzing powers. For this, a series of extensive studies of 3NF effects in elastic-scattering reactions have been performed at KVI and other laboratories. Precision measurements of the vector analyzing power of the proton in elastic proton–deuteron scattering have been performed at various beam energies ranging from 90 to 250 MeV [7–12]. Also, vector and tensor analyzing powers in elastic deuteron–proton scattering have been obtained at various beam energies ranging from 75 to 270 MeV [13–18]. Moreover, a rich set of spin correlation coefficients have been measured in the elastic proton–deuteron process at incident energies of 135 and 200 MeV [19,20]. In all these measurements, systematic discrepancies between data and theoretical predictions which rigorously solve the Faddeev equations and using only NN potentials were ob-
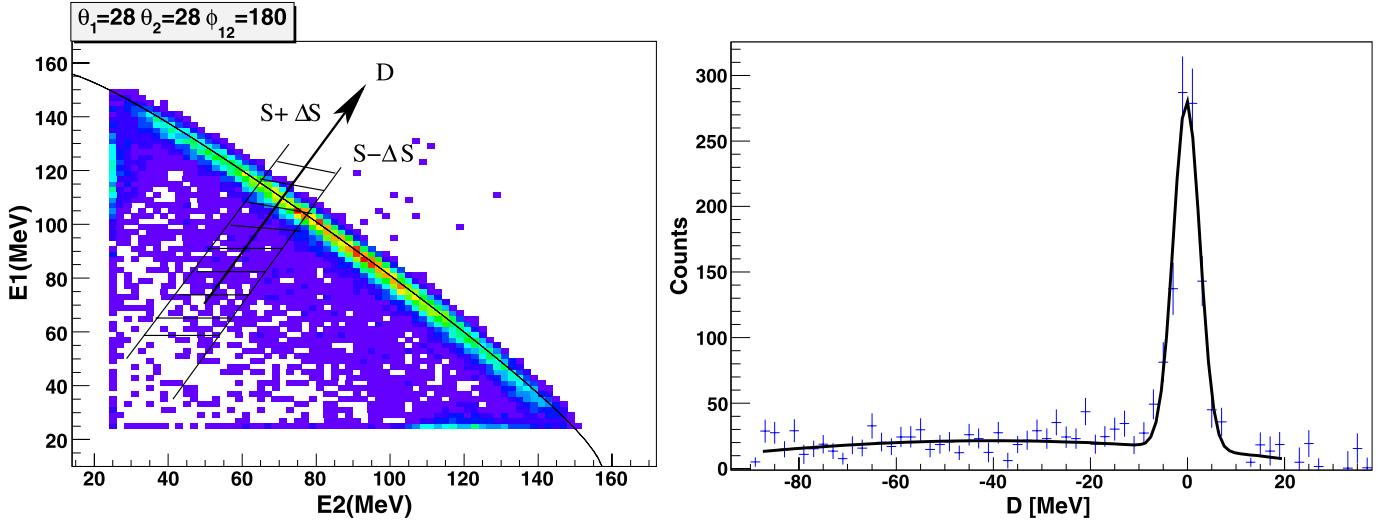
Fig. 1. The left panel shows the energy correlation between the two protons for the kinematical configuration $(\theta_1, \theta_2, \phi_{12}) = (28° \pm 2°, 28° \pm 2°, 180° \pm 4°)$, together with the kinematical S-curve. In the right panel, a projection of events from a sample gate indicated in the left panel, $S = 150 \pm 5$ MeV, onto an axis D perpendicular to the S-curve is shown as crosses. The solid line depicts a fit to that spectrum, composed of a Gaussian and a polynomial background model.

served. A large part of the discrepancies, in particular at the minimum of the differential cross sections, were removed by adding a 3NF to the NN potentials. Nevertheless, there are still unresolved problems specially for the differential cross sections at higher energies, above 150 MeV/nucleon, and for various polarization observables calling for more detailed investigations. So far, none of the existing precision calculations has produced a consistent explanation for all the experimental observables in the intermediate energy range.

Complementary to the elastic scattering experiments, three-nucleon studies have been performed exploiting the proton–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 5 kinematical variables, as compared to just one for the elastic scattering case. Theoretical predictions show that large 3NF effects can be expected at specific kinematical regions in the break-up reaction [21].

Results of the cross sections and tensor analyzing powers have already been published [22,23,18] for a deuteron-beam energy of 130 MeV on a liquid-hydrogen target. These experiments were the first ones of its type which demonstrated the feasibility of a high-precision measurement of the break-up observables together with a large coverage of the phase space. 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 systematically to provide an extensive database at intermediate energies. Here, we report on results obtained at relatively large energies below the pion-production threshold.

This Letter addresses a particular phase space region that corresponds to the reaction $\vec{p} + d \rightarrow (pp) + n$ where the proton pair, (pp), moves with a very small relative energy and a small opening angle in a $^1S_0$ state. A large 3NF sensitivity of the polarization observable, A_y, is expected which would provide crucial information on its spin structure. Moreover, a comparison is made with polarization data of the reaction $\vec{p} + d \rightarrow d + p$ to provide a deeper understanding of the spin–isospin structure of the forces. The reported analysis was inspired by an earlier experiment performed by the ANKE Collaboration in which analyzing powers of the reaction $\vec{p} + d \rightarrow (pp) + n$ were measured at much larger incident beam energies of 500 MeV and 800 MeV with the detection of

a fast forward proton pair at a small excitation energy of less than 3 MeV [24]. Intriguing deviations were observed between A_y data obtained at 500 MeV with a model taking into account one-nucleon exchange, single scattering, and the $\Delta(1232)$ excitation in the intermediate state, whereas the same model fairly describes the data at 800 MeV.

The proton–deuteron break-up experiment reported here was performed at KVI using a polarized proton beam with an energy of 190 MeV impinging on a liquid-deuterium target [25]. The reaction channel has been identified using a 4π, highly symmetric detector system Big Instrument for Nuclear-polarization Analysis abbreviated as BINA [26,27,12]. The relatively high energy used in this experiment offered a unique chance to study 3NF effects, since their magnitude are predicted to increase with energy. In this Letter, we present a set of selected analyzing power results, preceded by a brief description of the methods used in the data analysis. We focus specifically on results of the analyzing power at symmetric configurations including those with very small azimuthal opening angles. Results are compared with predictions of the modern Faddeev calculations.

Conventionally, in the $\vec{p} + d$ break-up reaction, the kinematics are determined by using the scattering angles of the two final-state protons, $(\theta_1, \theta_2, \phi_{12} = \phi_1 - \phi_2)$ where θ_1, θ_2 are the polar scattering angles of the first and second proton, respectively, and ϕ_{12} is the azimuthal angle between the two protons. The left panel in Fig. 1 shows the correlation between the energies of the two protons for a sample geometry, namely $(\theta_1, \theta_2, \phi_{12}) = (28° \pm 2°, 28° \pm 2°, 180° \pm 4°)$. The expected correlation according to the relativistic kinematics for the break-up reaction, referred to as the S-curve, is shown as the solid line. The kinematical variable, S, is defined as the arc-length along this curve, starting from the minimum value of E_1. It is customary to present the cross sections and analyzing powers as a function of the variable S. We note that for most of the data, both of the protons are stopped inside the scintillator. Only protons with energies larger than 140 MeV will punch through the detector, corresponding to the data in the corners of the left panel in Fig. 1. For the further analysis, only configurations are considered for which both protons are stopped in the forward wall. The right panel in Fig. 1 depicts a projection of the spectrum onto an axis D perpendicular to the S-curve and for a window of $\Delta S = \pm 5$ MeV. The solid line depicts a fit to that spec-
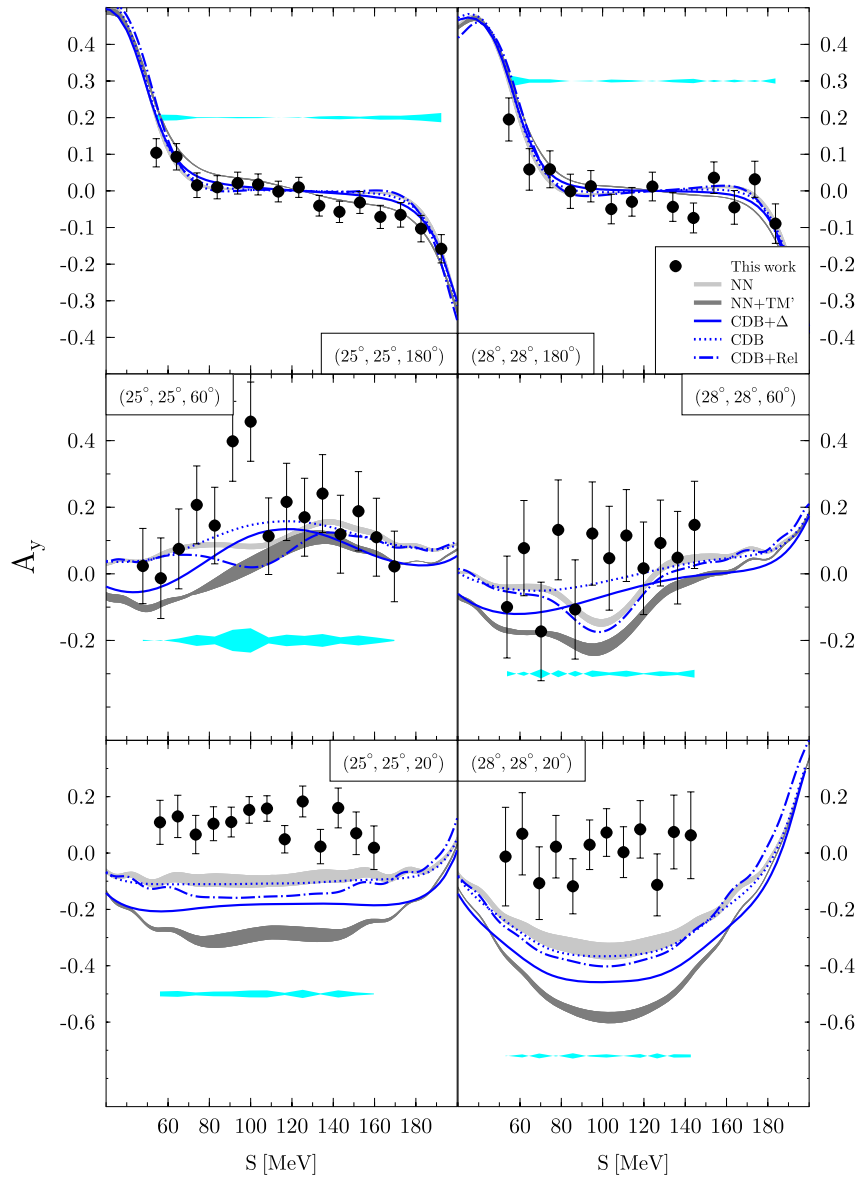
Fig. 2. A comparison between the results of the analyzing power measurements for a few selected break-up configurations with various theoretical predictions. The light gray bands are composed of various modern two-nucleon (NN) force calculations, namely CD-Bonn, NijmI, NijmII, and AV18. The dark gray 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 [28]. The errors are statistical and the cyan band in each panel represents the systematic uncertainties (2σ). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this Letter.)

trum, composed of a Gaussian and a second-order polynomial. The low-energy tail corresponds predominantly to events in which one of the protons of the break-up reaction undergoes a hadronic interaction inside the plastic scintillator of BINA, thereby depositing only a fraction of its energy. The fraction of protons that undergoes a hadronic interaction has been estimated using GEANT-3 to be about 8–10% per proton. For the extraction of the analyzing powers, only events are taken that fall within two standard deviations from the expected kinematics to have a well defined measure of the energies of both protons. The background from pile-up events was studied by using the relative time-of-flight between the two protons and found to be negligible.

The interaction of a polarized beam with an unpolarized target produces an azimuthal asymmetry in the scattering cross section. BINA has a complete azimuthal coverage and can, therefore, unambiguously determine the magnitude of the asymmetry, $\frac{\sigma^\downarrow - \sigma^\uparrow}{\sigma^\uparrow p_Z^\downarrow - \sigma^\downarrow p_Z^\uparrow}$

with p_Z the polarization of the incident beam and $\sigma^\downarrow$, $\sigma^\uparrow$ the 5-fold differential cross section in the case of beam polarizations pointing "down" and "up", respectively. This asymmetry corresponds to $A_y \cdot \cos(\phi)$ with ϕ the azimuthal angle of the reaction plane, understood as the plane spanned by the momentum vectors of the beam and of the "first" emitted proton, and A_y the vector analyzing power. Note that, in first order, the polarization observable, A_y, does not suffer from uncertainties in detection efficiencies and acceptances, since these cancel out in the calculation of this observable. The dominant part of the systematic uncertainty stems from the polarizations $p_Z^\uparrow$ and $p_Z^\downarrow$. These polarizations were determined from combining the well-known analyzing powers in proton–deuteron elastic scattering with measurements of the corresponding cross section asymmetry with the same setup, BINA, as was used for the break-up experiment. In addition, the polarizations were checked independently via asymmetry studies of
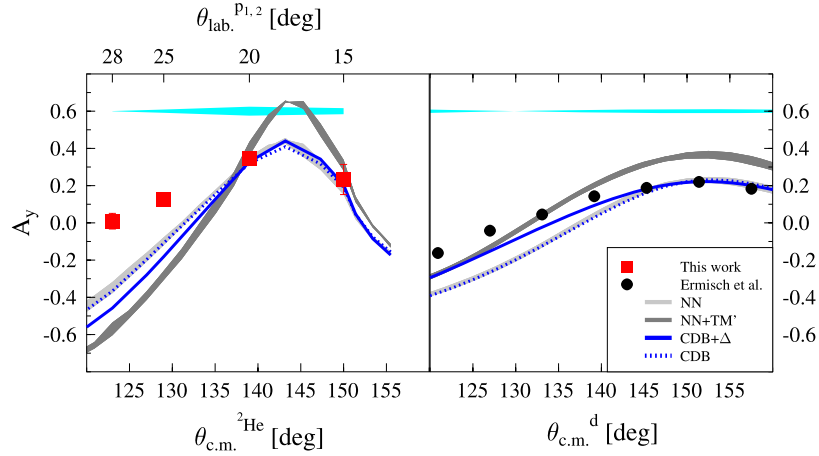
Fig. 3. The analyzing power as a function of the center of mass angle for two reactions $^2\mathrm{H}(\vec{p},{}^2\mathrm{He})n$ (left panel) and $^2\mathrm{H}(\vec{p},d)p$ (right panel). For a description of the lines and bands, see Fig. 2 and for a description of the data points, see the text. The data of the $^2\mathrm{H}(\vec{p},d)p$ reaction are taken from Refs. [11,8]. The results of both reactions were obtained with a proton-beam energy of $E_p = 190$ MeV.

the proton–proton elastic scattering process using the in-beam polarimeter, IBP [29]. The two methods were in agreement and the deviations were at most 3%. Typically, the beam polarization varied gradually between 0.5–0.7 for $p_Z^\uparrow$ and $p_Z^\downarrow$ during the course of the experiment. The changes were taken into account by the concurrent asymmetry measurements with BINA. The statistical and systematical uncertainties were 6% and 3%, respectively. This uncertainty in the polarization translates into a systematic uncertainty of $\sim 7\%$ in the analyzing power measurement.

Fig. 2 presents results of the analyzing powers for two symmetric kinematical configurations $(\theta_1, \theta_2) = (25°, 25°)$ and $(28°, 28°)$ for three different values of ϕ_{12}. The bin sizes for $\theta_{1,2}$, ϕ_{12}, and S are $\pm 2°$, $\pm 4°$, and ± 5 MeV, respectively. 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 $\phi_{12} = 180°$, 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. Note, however, that the effect of 3NFs increases with decreasing the relative azimuthal angle ϕ_{12}, corresponding to a decrease in the relative energy between the two final-state protons.

A surprising discrepancy between the measured analyzing powers and theoretical predictions can be observed at small relative azimuthal opening angles $\phi_{12} = 20°$. 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 $^2\mathrm{He}$. The analyzing power for the corresponding reaction, $^2\mathrm{H}(\vec{p},{}^2\mathrm{He})n$, can be compared to the analyzing power of the elastic $^2\mathrm{H}(\vec{p},d)p$ reaction. 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. For a com-

parison, we extracted the analyzing power, A_y, for the $^2\mathrm{He}$ state at a kinematics corresponding to a value in the middle of the S-curve where the relative energy is at its minimum.

Fig. 3 depicts the resulting analyzing power as a function of the center-of-mass angle for the two reactions $^2\mathrm{H}(\vec{p},{}^2\mathrm{He})n$ (left panel) and $^2\mathrm{H}(\vec{p},d)p$ (right panel). The analyzing powers in the left panel are selected from the symmetric 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 are obtained by assuming that the pp pair with a small relative energy corresponds to one body, namely a $^2\mathrm{He}$ 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 $(\theta_1 = \theta_2, \phi_{12} = 20°)$, 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.

This Letter presents a study of the vector analyzing power, A_y, in the proton–deuteron break-up reaction with an incident proton-beam energy of 190 MeV. The data were obtained exploiting a detection system, BINA, which covers nearly the full kinematical phase space of the break-up reaction. In particular, it features a complete azimuthal coverage which provides a well-controlled measure of spin observables. The analyzing power, A_y, has proven to be a unique probe to study 3NF effects, especially since the effect of the Coulomb force and relativity are expected to be small. For kinematical configurations at which the relative azimuthal opening angle between the two final-state protons is small, 3NF effects are predicted to be large. These regions in phase space can, therefore, be studied rigorously by a comparison with experimental data. Here, we concentrate on the spin–isospin structure of the three-nucleon force, which can be tested by a comparison between the break-up channel mimicking the, $^2\mathrm{H}(\vec{p},{}^2\mathrm{He})n$ reaction, and the elastic scattering channel, $^2\mathrm{H}(\vec{p},d)p$. For this, we analyzed the break-up reaction at configurations at which the relative en-

ergy between the two final-state protons is at its minimum within the experimental acceptance and for which the S-wave character of the proton pair was established. Strikingly, Faddeev calculations, which are based on modern two and three-nucleon potentials, fail to describe the analyzing powers in the $^2\text{H}(\vec{p}, ^2\text{He})n$ channel, whereas the same calculations compare well to polarization data in the analogous elastic channel. Such an inconsistency points 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.

Acknowledgements

References

[1] H. Yukawa, Proc. Phys. Math. Soc. Jpn. 17 (1935) 48.
[2] V.G.J. Stoks, R.A.M. Klomp, C.P.F. Terheggen, J.J. de Swart, Phys. Rev. C 49 (1994) 2950.
[3] R.B. Wiringa, V.G.J. Stoks, R. Schiavilla, Phys. Rev. C 51 (1995) 38.
[4] J. Fujita, H. Miyazawa, Prog. Theor. Phys. 17 (1957) 360.
[5] A. Deltuva, R. Machleidt, P.U. Sauer, Phys. Rev. C 68 (2003) 024005.
[6] S.A. Coon, H.K. Han, Few-Body Sys. 30 (2001) 131.
[7] R. Bieber, et al., Phys. Rev. Lett. 84 (2000) 606.
[8] K. Ermisch, et al., Phys. Rev. Lett. 86 (2001) 5862.
[9] K. Hatanaka, et al., Phys. Rev. C 66 (2002) 044002.
[10] K. Ermisch, et al., Phys. Rev. C 68 (2003) 051001.
[11] K. Ermisch, et al., Phys. Rev. C 71 (2005) 064004.
[12] A. Ramazani-Moghaddam-Arani, et al., Phys. Rev. C 78 (2008) 014006(R).
[13] M. Garçon, et al., Nucl. Phys. A 458 (1986) 287.
[14] H. Wit ała, T. Cornelius, W. Glöckle, Few-Body Sys. 15 (1993) 67.
[15] R.V. Cadman, et al., Phys. Rev. Lett. 86 (2001) 967.
[16] K. Sekiguchi, et al., Phys. Rev. C 65 (2002) 034003.
[17] H. Mardanpour, et al., Eur. Phys. J. A 31 (2007) 383.
[18] E. Stephan, et al., Phys. Rev. C 76 (2007) 057001.
[19] H.O. Meyer, et al., Phys. Rev. Lett. 93 (2004) 112502.
[20] B.v. Przewoski, et al., Phys. Rev. C 74 (2006) 064003.
[21] J. Kuroś-Żołnierczuk, et al., Phys. Rev. C 66 (2002) 024003.
[22] S. Kistryn, et al., Phys. Lett. B 641 (2006) 23.
[23] A. Biegun, et al., Acta Phys. Pol. B 371 (2006) 213.
[24] S. Yaschenko, et al., Phys. Rev. Lett. 94 (2005) 072304.
[25] N. Kalantar-Nayestanaki, J. Mulder, J. Zijlstra, Nucl. Instr. Meth. A 417 (1998) 215.
[26] H. Mardanpour, et al., Nucl. Phys. A 790 (2007) 426c.
[27] H. Mardanpour, Ph.D. thesis, University of Groningen, 2008.
[28] R. Skibiński, H. Wit ała, J. Golak, Eur. Phys. J. A 30 (2006) 369.
[29] R. Bieber, et al., Nucl. Instr. Meth. Phys. Res. A 457 (2001) 12.