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Few-body Studies at Nuclotron-JINR

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Abstract Recent results on the deuteron analyzing powers in dp- elastic scattering obtained at Nuclotron (JINR, Dubna) are compared with the calculations performed within relativistic multiple scattering model. The data demonstrate strong deviation form the predictions at large angles in the cms. The preliminary data on the energy dependence of the cross section in the $dp \rightarrow ppn$ reaction at 150–250 MeV/nucleon for different configurations and dp elastic scattering up to 1 GeV obtained at internal target station at Nuclotron are reported. The prospects of the further few-body studies at JINR are discussed.

1 Introduction

The main goal of the Deuteron Spin Structure (DSS) experimental program is to obtain the information on the spin—dependent parts of two-nucleon ($2N$) and three-nucleon ($3N$) forces from two processes: dp- elastic scattering in a wide energy range and dp- nonmesonic breakup with two protons detection at energies 300–500 MeV. The motivation of this program is based on theoretical analysis of the experimental results obtained at low and intermediate energies for the deuteron induced reactions (see recent review [1] and references therein).

Such experimental program at Nuclotron was started by the measurements of the vector A_y and tensor A_{yy} and A_{xx} analyzing powers in dp- elastic scattering at T_d of 880 MeV [2] and 2,000 MeV [3]. The calculations

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performed within relativistic multiple scattering model [4] describes the data on the vector analyzing power A_y. However, there are the problems in the description of the tensor analyzing powers at large angles in the cms.

Here we report the preliminary results on the measurements of the dp- elastic scattering cross section at the deuteron energies 400–2,000 MeV, and dp- nonmesonic breakup at 300, 400 and 500 MeV obtained at internal target station at Nuclotron.

2 Experiment

The measurements were performed using internal target station at Nuclotron [5] with new control and data acquisition system [6]. The 10 μm CH_2 foil and 8 μm carbon wire were used as the targets. The effect on the hydrogen has been obtained using CH_2-C subtraction.

The detection apparatus for the study of dp- elastic scattering consists of 4 scintillation counters with FEU-85 photomultiplier tubes for the detection of the protons and deuterons in coincidence [7]. The amplitudes of the signals and timing information from the detectors were recorded and used in the further data analysis for the dp- elastic scattering events selection. The scintillation counters coupled to Hamamatsu H7416MOD PMTs having better timing and amplitude resolution than FEU-85 PMTs were used for the measurements at $T_d > 1{,}000$ MeV.

The $dp \rightarrow ppn$ reaction will be investigated using ΔE-E techniques for the detection of both protons. The details of the experimental setup with 8 ΔE-E detectors are given in Ref. [8].

3 Results

The measurements of the differential cross section of dp- elastic scattering were performed at 400, 500, 600, 700, 800, 880, 1,000, 1,300, 1,500 and 2,000 MeV. The results obtained at 880 MeV at Nuclotron are given by the solid circles in Fig. 1. They are compared with the data obtained at 850 MeV [9] and 940 MeV [10] given by open circles and triangles, respectively. The dashed and solid lines are the calculation of the relativistic multiple scattering model [11] without and with double scattering taken into account. The model [11] describes the behaviour of the data, however, some deviation at large scattering angles still remains. It has been demonstrated in Ref. [2] that calculations [12] cannot reproduce the cross section data at the angles larger than 70° in the cm Such deviation cannot be explained by the relativistic effects because they are significant only in the region of backward angles and they are small in the region of the differential cross section minimum in the framework of Faddeev calculations [13]. Both approaches cannot reproduce the data at the backward scattering angles, where the essential contribution of the Δ-isobar excitation into the differential cross section at high energies was demonstrated [14]. The agreement between the cross section data and theoretical calculations at the angles larger than 70° in the cm could be improved, if the three-nucleon forces are taking into account. However, theoretical predictions including present 3NF models [12] or an effective 3NF due to explicit Δ-isobar excitation [15] underestimate the data at 250 MeV/nucleon by up to 40 %. Therefore, at high energies, the deviation of the both spin observables and cross sections from the theoretical calculations [12,13,15] demonstrates the

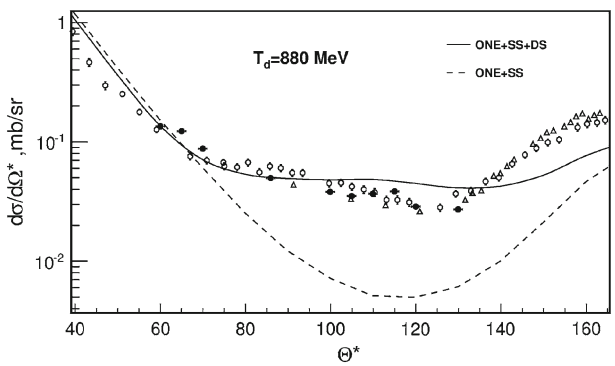

Fig. 1 The differential cross section of dp- elastic scattering obtained at 880 MeV at Nuclotron (*solid circles*), at 850 MeV [9] (*open circles*) and at 940 MeV [10] (*open triangles*). The *lines* are explained in the text

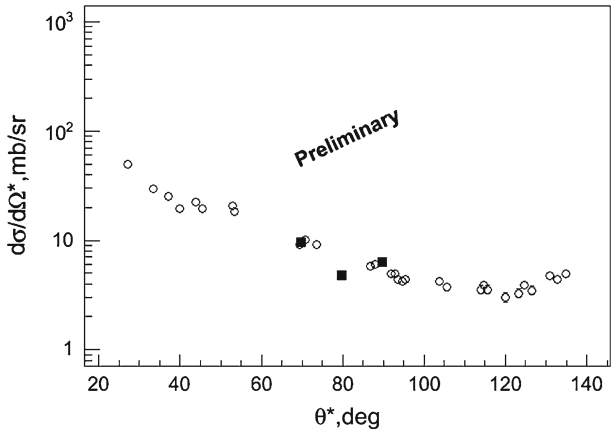

Fig. 2 The differential cross section of dp- elastic scattering at 2,000 MeV: ANL data [16] (*open circles*) and preliminary Nuclotron data (*solid squares*)

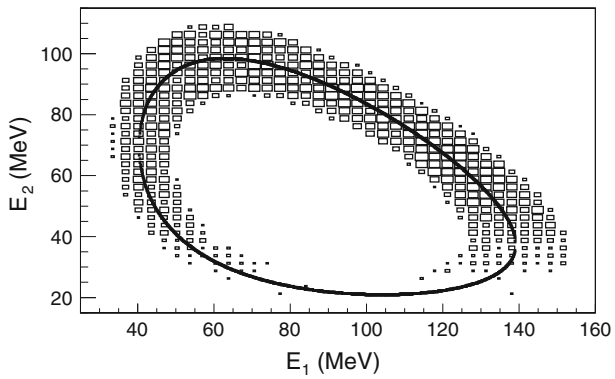

Fig. 3 The $dp \rightarrow ppn$ reaction at T_d=400 MeV (θ_1=25°, θ_2=33.7° and ϕ=44.6°)

deficiencies of the present 3NF models and relativistic description of the dp -elastic scattering process. This might indicate that additional short-range 3N forces should be added to the 2π -exchange type forces [13].

The preliminary data on the differential cross section of dp- elastic scattering obtained at Nuclotron at 2,000 MeV and given in Fig. 2 by the solid squares are compared with the data obtained previously at ANL [16] (open circles). The Nuclotron data are normalized to the ANL data at 70° in the cms. One can see the reasonable angular behaviour of the relatively normalized Nuclotron data. The final analysis will be based on absolute normalization to the luminosity.

The data for different kinematic configuration for the $dp \rightarrow ppn$ reaction have been obtained at 300, 400 and 500 MeV. The preliminary results for the $dp \rightarrow ppn$ events selection obtained at $T_d = 400$ MeV for the $\theta_1 = 25°$, $\theta_2 = 33.7°$ and $\phi = 44.6°$ are presented in Fig. 3. The data analysis is in progress.

4 Conclusions

The data on the analyzing powers in dp- elastic scattering have been measured at internal target stationat the Nuclotron at the energies of 880 and 2,000 MeV [2,3].

The data on the energy dependence of the dp- elastic scattering cross section have been accumulated at 400–2,000 MeV. The data analysis is in progress.

The data on dp- nonmesonic breakup have been obtained at 300, 400 and 500 MeV for different kinematic configurations.

Future studies of the deuteron-induced reactions like $dp \rightarrow pd$, dp- breakup, $dd \rightarrow {}^3Hp({}^3Hen)$ and $d^3He \rightarrow p^4He$ at Nuclotron are related with new polarized ion source developed at LHEP-JINR [17]. These new experimental data and further development in theoretical approaches will be important for adequate description of the short-range light nuclei spin structure.

Project "Baryonic Matter at Nuclotron" [18] will allow to measure spin and polarization effects in a GeV region with the extracted beams.

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References

1. Kalantar-Nayestanaki, N., Epelbaum, E., Messchendorp, J.G., Nogga, A.: Signatures of three-nucleon interactions in few-nucleon systems. Rep. Prog. Phys. **75**, 016301 (2012)
2. Kurilkin, P.K., et al.: Measurement of the vector and tensor analyzing powers for dp- elastic scattering at 880 MeV. Phys. Lett. **B715**, 61–65 (2012)
3. Kurilkin, P.K., et al.: Investigation of the angular dependence of the analyzing powers in the deuteron–proton elastic scattering at the nuclotron. Phys. Part. Nucl. Lett. **8**, 1081–1083 (2011)
4. Ladygina, N.B.: Deuteron–proton elastic scattering at intermediate energies. Phys. Atom. Nucl. **71**, 2039–2051 (2008)
5. Malakhov, A.I., et al.: Potentialities of the internal target station at the Nuclotron. Nucl. Instrum. Methods Phys. Res. **A440**, 320–329 (2000)
6. Isupov, A.Yu., Krasnov, V.A., Ladygin, V.P., Piyadin, S.M., Reznikov, S.G.: The Nuclotron internal target control and data acquisition system. Nucl. Instrum. Methods Phys. Res. **A698**, 127–134 (2013)
7. Gurchin, Yu.V., et al.: Detection equipment for investigating dp elastic scattering at internal target of nuclotron in the framework of DSS project. Phys. Part. Nucl. Lett. **8**, 950–958 (2011)
8. Piyadin, S.M., et al.: ΔE-E detector for proton registration in nonmesonic deuteron breakup at the Nuclotron internal target. Phys. Part. Nucl. Lett. **8**, 107–113 (2011)
9. Booth, N.E., et al.: Proton–deuteron elastic scattering at 1.0 GeV/c. Phys. Rev. **D4**, 1261–1267 (1971)
10. Alder, J.C., et al.: Elastic pd scattering at 316, 364, 470, and 590 MeV in the backward hemisphere. Phys. Rev. **C6**, 2010–2019 (1972)
11. Ladygina, N.B.: Differential cross section of dp- elastic scattering at intermediate energies. Eur. Phys. J. **A42**, 91–96 (2009)
12. Witala, H., Glöckle, W., Golak, J., Nogga, A., Kamada, H., Skibinski, R., Kuros-Zolnierczuk, J.: Nd elastic scattering as a tool to probe properties of three nucleon forces. Phys. Rev. **C63**, 024007 (2001)
13. Witala, H., Glöckle, W., Golak, J., Kamada, H.: Relativistic effects in neutron–deuteron elastic scattering. Phys. Rev. **C71**, 054001 (2005)
14. Kaptari, L.P., Kämpfer, B., Dorkin, S.M., Semikh, S.S.: Pion exchange effects in elastic backward proton deuteron scattering. Few Body Syst. **27**, 189–206 (1999)
15. Deltuva, A., Chmielewski, K., Sauer, P.U.: Nucleon–deuteron scattering with delta isobar excitation: Perturbation theory. Phys. Rev. **C67**, 034001 (2003)
16. Bennett, G.W., et al.: Proton-deuteron scattering at 1 BeV. Phys. Rev. Lett. **19**, 387–390 (1967)
17. Fimushkin, V.V., et al.: Source of polarised deuterons. Eur. Phys. J. Special Topics **162**, 275–280 (2008)
18. Ladygin, V.P.: Study of strange matter production in the heavy ion collisions at NUCLOTRON. In: Proceedings of the 21st International Baldin Seminar on High Energy Physics Problems: Relativistic Nuclear Physics and Quantum Chromodynamics (ISHEPP 2012), Dubna, Russia, 10–15 September 2012, PoS Baldin-ISHEPP-XXI:038 (2012)