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Dp breakup reaction investigation using polarized and unpolarized deuteron beam

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Abstract. Deuteron Spin Structure (DSS) collaboration program is aimed on few nucleon correlations investigation using unpolarized and polarized deuteron beam at intermediate energy range. Data of the dp breakup reaction have been obtained at energy range from 300 - 500 MeV of deuteron energy for various detector configurations in region where few nucleon correlations and relativistic effects can play significant role. Results are obtained in the form of S-curve and T_{20} and iT_{11} tensor analyzing powers in case of unpolarized and polarized data, respectively. Future plans on extracted deuteron beam of Nuclotron are concerned to tensor analyzing power T_{20} and spin correlation C_{yy} of $^3He(d,p)^4He$ reaction in the kinetic energy range between 1.0 and 1.75 GeV.

1. Introduction

The most used contribution in theoretical models which include three nucleon forces (3NFs) are two pion exchange, e.g. Urbana IX [1] and Tucson-Melbourne [2]. Models can describe binding energies of three and four nucleon systems. Generally, cross section of reactions with few nucleons in which is nucleon unpolarized is better described than for the polarized case. Much worst situation is when the beam or target is polarized, especially in case of polarization observables measurement. Spin structure of the np SRCs has been investigated via the measurements of the tensor analyzing power A_{yy} in deuteron inclusive breakup at various energies in the wide regions of the longitudinal x_F and transverse proton momentum p_T [3]. The A_{yy} data demonstrate the dependence on two internal variables, x_F and p_T or their combinations. However none of used approach [4],[5] describe the data. In the vicinity of the Sagara discrepancy the currently known 3NFs contribute by up to 30% to the dp elastic scattering cross section at intermediate energies [6]. The investigation of dp breakup reaction at deuteron energy of 270 MeV at RIKEN [7] and IUCF [8] reveals that vector analyzing power A_y can be described using NN forces only. But other polarization observables need 3NFs to describe the data. Dp breakup reaction

investigation measured at KVI at energy of 130 MeV [9] shows similar behavior. Inclusion of 3NFs improve the description of a part of the data but breaks other. Relativistic effects for the *nd* elastic scattering cross section at 70 MeV and 250 MeV were investigated in [10]. It was found that relativistic effects contribution is located mainly at backward angles, but their contribution is not large enough to fill discrepancy between experimental data and theory, even in the case when standard three nucleon forces [11] are used. For the d(n,np)n breakup reaction at 200 MeV large relativistic effects were observed in configuration where one arm is fixed and second arm scans the angular range. The contribution which comes from relativistic effects can reach up to 60%.

2. Deuteron breakup reaction investigation using unpolarized and polarized beam

The goal of the Deuteron Spin Structure (DSS) experimental program is to obtain the information about two and three nucleon forces, including their spin dependent parts, from *dp* elastic scattering at the energies between 300 – 2000 MeV and *dp* breakup reactions with registration of two protons at deuteron energies of 300 500 MeV [12].

Deuterons are accelerated by Nuclotron up to required energy. *Dp* breakup reaction has been investigated at 300 MeV, 400 MeV and 500 MeV of deuteron energy. Polyethylene and Carbon targets are enclosed in a spherical hull of Internal Target Station (ITS) [13]. Up to six various targets can be placed inside of ITS. The *dp* breakup reaction is investigated by the simultaneous registration of two protons by two detectors – the two detectors work in coincidence. Up to eight $\Delta E - E$ detectors can be used in experiment. Effect on protons is obtained by subtracting Carbon spectra from Polyethylene one. Various detector setups were used for *dp* breakup reaction investigation. Details of the $\Delta E - E$ detector construction can be found in [14]. Reasonable agreement was obtained in comparison of energy spectra and missing mass distributions of *dp* breakup reaction between experiment and GEANT4 simulation which give us opportunity to handle with the signal and background in more flexible way [15]. The stability of amplitude of all photomultiplier tubes (PMTs) were monitored during all data acquisition. Mean values of LED amplitudes have been obtained at 200 MeV/n data taking. All PMT amplitudes from calibration and physical data obtained on Polyethylene and Carbon targets were corrected by multiplied factor defined as a ratio between mean LED amplitude value at 200 MeV/n to mean LED amplitude one between two closest LED runs in time to calibration or physical ones. By this procedure possible temperature dependence of ΔE detectors was suppressed. Detailed description of LED system of PMTs can be found in [14]. Detectors used for *dp* breakup investigation at intermediate energy range from 300 to 500 MeV have been calibrated using following procedure. Amplitude and time information from all PMTs are used to reconstruct amplitude spectra of ΔE detectors. Assuming linear dependence of amplitudes on particle energy, calibration coefficients for particular ΔE and E detector is obtained by solving of the set of linear equation. For this purpose detectors have been placed under *pp* quasi elastic kinematics at 300 MeV, 400 MeV and 500 MeV where energies can be calculated from kinematics. Good agreement between experimental and simulated ΔE vs. E plot is observed. Obtained missing mass and energy spectra were compared with results obtained form GEANT4. Satisfactorily agreement is obtained, see Fig.1. Missing mass spectra obtained by subtracting of Carbon content from Polyethylene one at angles of 31° and 43° for the particles which are stopped in detector at deuteron energy of 200 MeV/n is shown in Fig.2. Energy resolution of the detector can be found with gaussian fit. Obtained mean value of the missing spectra (941 MeV) is in agreement with neutron missing mass, with energy resolution of 11 MeV. Detailed information about calibration procedure can be found in [16].

The largest part of *dp* breakup data obtained at 200 MeV/n in 2014 follows inverse kinematics of the reaction in which relativistic effects can play a role [10]. The *dp* breakup data have been obtained under condition when one arm is fixed and and second scans the angular interval allowed

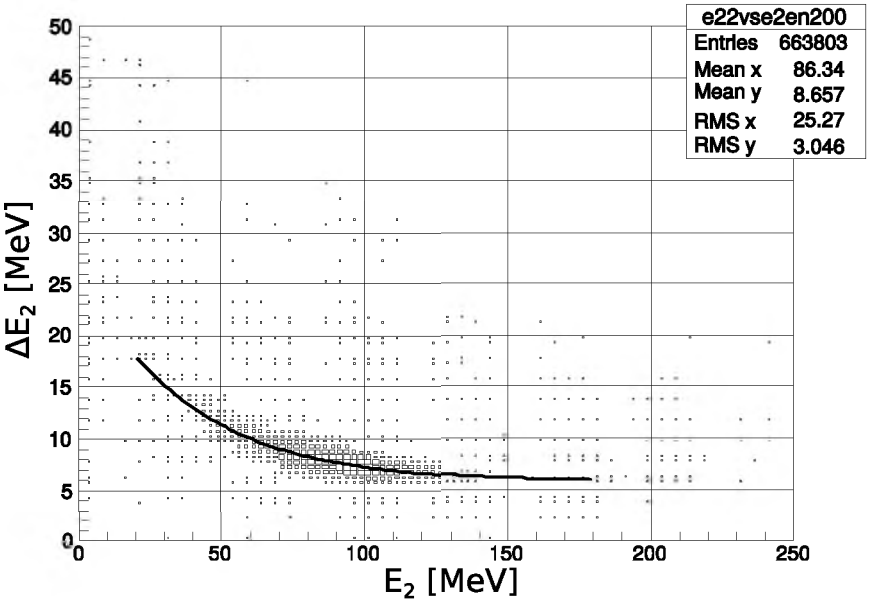

Figure 1. $\Delta E - E$ correlation obtained for one of arm in the pp quasi elastic kinematics at 90° cm and deuteron energy of 200 MeV/n. Curve represents the $\Delta E - E$ correlation obtained from GEANT4 simulation [17] at the same kinematic configuration.

by mechanics. Relativistic effects can play more significant role in the cross section under this condition as it was investigated in [10]. In our case one arm was fixed at polar angle (θ_2) of 43.0° and second was placed at angle (θ_1) of 27.0°, 31.0°, 35.0°, 39.0° and 43.0°. The kinematic variable S corresponds to the arc-length along the kinematic curve with zero point chosen closest to axis origin. Points of kinematic S-curve are calculated with energy step of 5 MeV for the detector arms placed at polar angles of $\theta_1 = 39.0°$, $\theta_2 = 43.0°$ and azimuthal angle between arms of 179.2° at deuteron energy of 400 MeV. The S is increasing in anti-clockwise direction. The number of breakup events in an interval $S - \Delta S/2$, and $S + \Delta S/2$ was obtained by projecting the events on a line perpendicular to the S-curve. Preliminary energy distribution of deposited energy and S distribution (with the step of 5 MeV) in the first (E_1) and second arm (E_2) placed

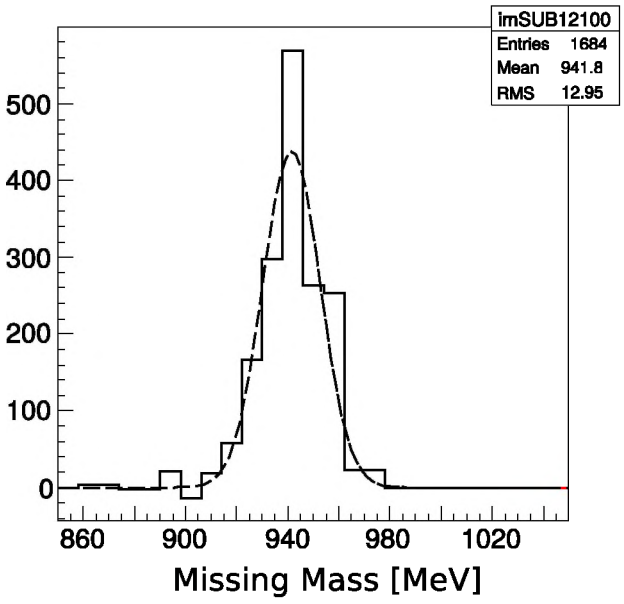

Figure 2. Missing mass spectra with gauss fit (941 ± 11 MeV) obtained by subtracting of Carbon content from Polyethylene one at angles of 31° and 43° for the particles which are stopped in detector at deuteron energy of 200 MeV/n.

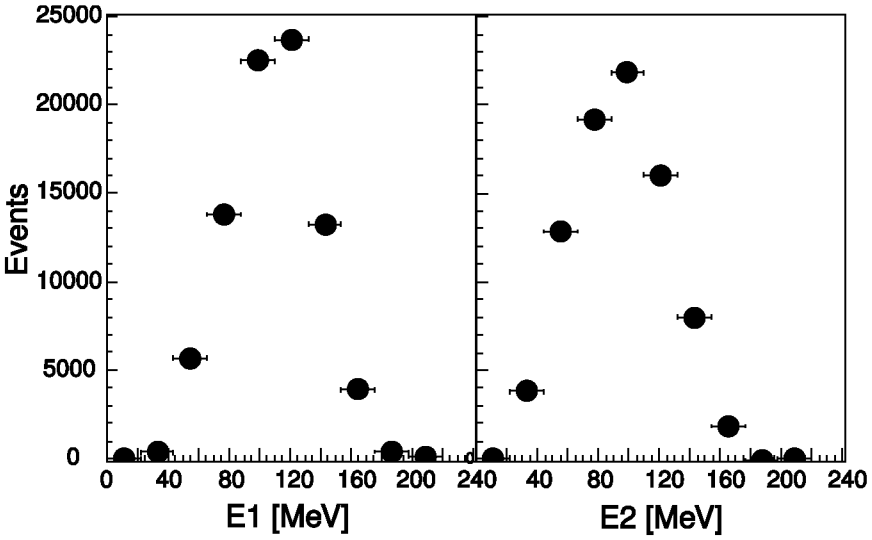

Figure 3. Energy distribution of deposited energy in the first (E_1) and second arm (E_2) placed at polar angles of 39° and 43°, respectively. Difference in azimuthal angles is 179.2°.

at polar angles of 39° and 43° are shown in Fig.3 and Fig.4, respectively. Difference in azimuthal angles is 179.2°. The energy resolution is taken from the detector calibration.

Polarization of deuteron beam is provided by new polarization ion source (PIS). Ideal values of polarizations were $p_z, p_{zz} = (-1/3, \pm 1)$. PIS can provide unique opportunity for the studies of the spin effects and polarization phenomena in few body systems at ITS and also on extracted beam with the BM@N setup. Commissioning of the upgraded DSS setup has been performed at 270 MeV using unpolarized and polarized deuteron beam in June-July 2016. Good values of vector and tensor polarizations [18] were obtained at low energy polarimeter. The polarization was flipped each spill between "spin-up" and "spin-down" (perpendicular to the plane of the accelerator) and no polarization. Polarization of deuteron beam was monitored continuously during whole experiment. Vector and tensor polarizations are obtained from the asymmetries and known values of analyzing powers of dp elastic reaction at energy of 270 MeV. Measured values of polarization for "+ mode" when tensor component is positive are: $p_z = -0.190 \pm 0.009$, $p_{zz} = 0.533 \pm 0.017$ and for "- mode": $p_z = -0.230 \pm 0.007$, $p_{zz} = -0.705 \pm 0.013$. Statistical

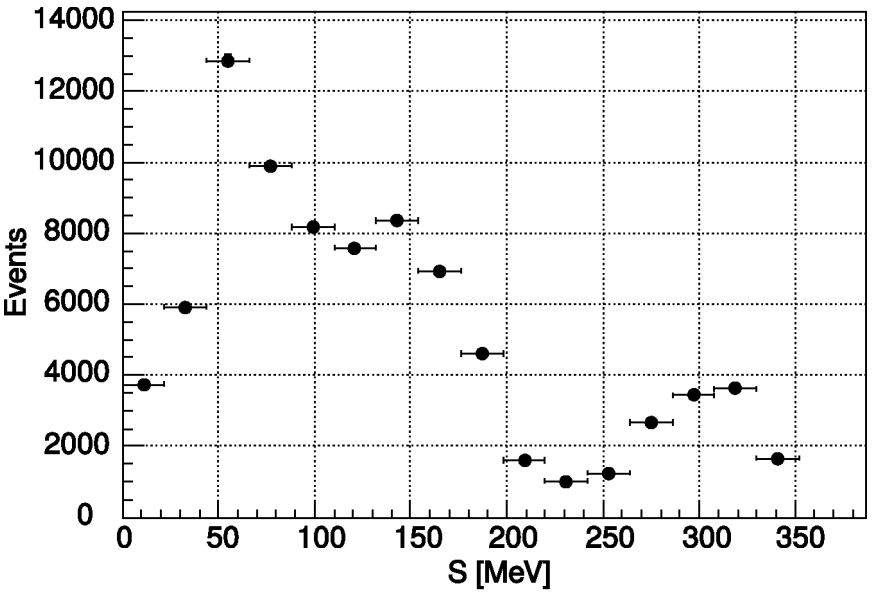

Figure 4. S distribution for the detector configuration of 39° and 43°. Difference in azimuthal angles is 179.2°.

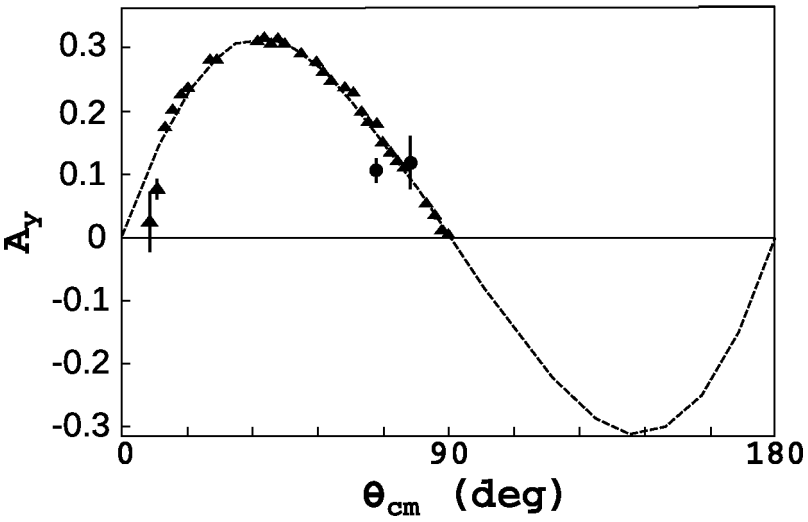

Figure 5. Angular dependence of the vector analyzing power A_y at energy of 200 MeV/n. Data obtained at Nuclotron at 72.3° and 76.5° in cm are represented by full circle symbols, triangle symbols represent data from [19].

and systematical errors are taken into account. Statistical error comes from ratio of dp elastic to pp quasi elastic events.

Analyzing power iT_{11} at 72.3° and 76.5° in cm was measured under pp quasi conditions. Obtained values at 72.3° and 76.5° are 0.10 ± 0.02 and 0.11 ± 0.06, respectively. Results are in agreement with world pp- elastic scattering data within experimental errors , see Fig.5. Values of the vector iT_{11} and tensor T_{20} analyzing powers at polar angles of 34.8° and 36.8° and difference in azimuthal angles of 135° are 0.47 ± 0.10 and 0.02 ± 0.20 [20].

3. $d^3He \to p^4He$ reaction investigation at Nuclotron

Polarization correlation coefficient $C_{//}$ for the $d^3He \to p^4He$ reaction can be a unique probe to the D-state admixture in deuteron in one nucleon exchange approximation [21]. Measurement of tensor analyzing power T_{20} can give the key for understanding its behaviour in dp- backward elastic scattering. The possibility to perform the $d^3He \to p^4He$ reaction at extracted beam of Nuclotron at BM@N area was investigated using GEANT4 and ROOT simulation package at energy of 1.5 GeV. Proposed experiment is assumed to be performed in energy range from 1.0 – 1.75 GeV. The simulation [22] has been performed for the initial deuteron kinetic energy $T_d = 1.5$ GeV and 30 cm of the ^3He target cell. In simplified model deuteron beam hits the ^3He target which is placed in the one of the focuses of the beam transportation line of Nuclotron. Quartz radiator which can serve as a TOF start counter spreads the size of beam and the number of scattered particles in the secondary beam due to additional scattering on it in comparison with the option without TOF, however, the number of scattered events is quite small for both cases. The further simulation used quartz radiator. The momentum reconstruction of particles is based on the information derived from 12 GEM stations placed in the inhomogeneous magnetic field defined by a field map. From obtained result follows that protons passed through 12 GEM tracker stations can be tracked from 0.4 T to maximal magnetic field of 0.9 T. Simplified BM@N setup with 12 stations of GEM tracker situated in the magnet can provide the momentum resolution of few percents. The time difference between mRPC and start detector is about 20 ns which is good enough to separate protons from the background deuterons.

4. Conclusion

Energy and S distributions of dp breakup reaction obtained in coplanar kinematics at 200 MeV/n were discussed. Obtained values of vector analyzing power at 72.3° and 76.5° in cm measured under pp quasi conditions are in agreement with world data within experimental accuracy.

Values of the vector iT_{11} and tensor T_{20} analyzing powers at polar angles of 34.8° and 36.8° and difference in azimuthal angles of 135° are 0.47 ± 0.10 and 0.02 ± 0.20, respectively. In order to substantially decrease errors of analyzing powers beam luminosity needs to be increase at least 10 times. Study of $^3He(d,p)^4He$ reaction at 1.5 GeV was performed using ROOT and GEANT4 package. Suitability of experiment performed on extracted beam was investigated using maximal and one half of maximal magnetic field. Experiment can be performed at extracted beam under investigated conditions.

Acknowledgments

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