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P Thörngren Engblom[1], S Barsov[2], S Bertelli[3], M Contalbrigo[3], D Chiladze[4] , A Kacharava[4] , P Lenisa[3], N Lomidze[5], B Lorentz[4] , G Macharashvili[6], S Merzlyakov[6], S Mikirtytchiants[2], A Nass[4] , D Oellers[4] , F Rathmann[4] , R Schleichert[4] , H Ströher[4] , M Tabidze[5], S Trusov[7,8], C Weidemann[4] for PAX and ANKE Collaborations

[1]Physics Department, Stockholm University, SE-106 91 Stockholm, Sweden
[2]Petersburg Nuclear Physics Institute, RU-188350 Gatchina, Russia
[3]Università di Ferrara, Dipartimento di Fisica, 44100 Ferrara, Italy
[4]Institut für Kernphysik and Jülich Centre for Hadron Physics, Forschungszentrum Jülich, 52425 Jülich, Germany
[5]High Energy Physics Institute, Tbilisi State University, 0186 Tbilisi, Georgia
[6]Laboratory of Nuclear Problems, JINR, RU-141980 Dubna, Russia
[7]Hadron Physics Div. of Forschungszentrum Dresden Rossendorf, D-01328 Dresden, Germany
[8]Skobeltsyn Institute of Nuclear Physics of Lomonosov Moscow State University, Moscow, RU-119991, Russia

E-mail: pia.thorngren@fysik.su.se

Abstract. Spin observables in proton deuteron breakup reactions at low energies offer a rich testing ground for the modern theory of nuclear forces, the chiral effective field theory (EFT). In the three-nucleon continuum the experimental data and the theoretical predictions are today at variance. At the PAX facility at COSY we plan to make an extensive study of analyzing powers and spin correlation parameters in *pd* breakup reactions at low energies between 30 and 50 MeV, an energy range where previous measurements are scarce and limited while three-nucleon effects are expected to be significant. Furthermore it is an ideal energy for the predictive power of chiral EFT to be tested. The longstanding physics question of the nature of three-nucleon forces will be studied with large coverage provided by an optimized silicon detector barrel, and flexibility utilizing the *sampling method*, a technique for direct comparison between experiment and theory developed specifically for the complex analysis of three-particle final states. The proposed experiment will yield an independent determination of the low-energy constants D and E and enable tests of appearing three-nucleon interactions in chiral EFT, with possible implications also for the spectra of light nuclei.

1. Introduction

In general observables at the energy scale relevant to nuclear physics are well described by a nucleon-nucleon (NN) potential. Today there exist several semi-phenomenological NN potentials that reproduce the experimental scattering data below the pion production threshold with a χ^2 close to unity [1, 2, 3]. However, there are nuclear phenomena that cannot be described by averaging over two-nucleon (2N) interactions. There is circumstantial experimental evidence for the existence of a nuclear three-body force, such as the fact that the high precision realistic NN potentials do not reproduce the measured binding energies of ^3H and ^3He. When including theoretical models for the three-nucleon force (3NF) in the calculations Nature's values are reproduced for the bound three-nucleon states [4]. Another instance where additional 3NFs are seen as remedy for lack of agreement between theory and experiment is the *pd* elastic differential cross section minimum, see e.g. [5]. However, in general comparisons between the theoretically calculated predictions and the measurements of the three-nucleon continuum give conflicting messages concerning the validity of the current models for the 3NF, in spite of both experimentally and theoretically intense activities during the past decade. Recent high-precision measurements are reported in [6, 7, 8, 9, 10, 11, 12] and [13, 14] of these proceedings.

The idea that there are many-body forces playing a significant role when there are more than two nucleons interacting [15] goes back to the time when Yukawa presented his seminal paper on meson theory [16]. A new phase in nuclear physics occurs with the advent of the chiral perturbation theory, consistent with the symmetries of QCD and aimed at low energy phenomena in the Goldstone boson and single-baryon sectors (a review can be found in [17]). Treating few nucleon dynamics in a similar manner requires using nonperturbative methods as was originally proposed by Weinberg [18, 19] thereby inciting a rapid theoretical development of the chiral effective field theory (EFT) [20]. Recent reviews are given in [21, 22, 23]. In chiral EFT three- and many-body interactions enter naturally at increasing order explaining the hierarchy of nuclear forces, with three-nucleon effects first appearing at third order, four-nucleon forces show up at fourth order and so forth, see [24] of these proceedings for details.

In order to achieve a conclusive experimental description of 3N interactions and particularly their spin dependence, a majority of possible observables need to be measured with large phase space coverage and high accuracy. A great amount of experimental effort from several laboratories has gone into this endeavor. In *pd* elastic scattering reactions vector and tensor analyzing powers, spin transfer coefficients and spin correlation coefficients have been measured covering a large part of phase space. Still, the results have led to conflicting messages with respect to available 3NF models.

For *pd* breakup reactions considerably fewer studies have been carried out, in particular in the energy range where chiral EFT is considered to give a valid description and where 3NF effects are expected to show up. There are a few very specific geometrical configurations of polarization observables measured at 65 MeV/A [25, 26, 27, 28, 29, 30]. The most coverage in phase space so far at low to intermediate energies was reported for cross sections at 65 MeV/A [9, 14]. Vector and analyzing powers were also measured at this energy and at 50 MeV/A by the same research group [12, 13]. The conclusions from these high-precision investigations were that both the dynamics and the spin part of the 3N models are insufficient to account for the phenomena.

So called axial observables forbidden by parity in elastic scattering and predicted to have a certain kind of sensitivity to 3N forces [31] were measured in two experiments that were initiated to test this argument, at 135 and 9 MeV/A [7, 32]. At the lower energy the nucleon longitudinal analyzing power A_z, turned out to be consistent with zero. At the higher energy the axial observables measured were sizeable but the message concerning the effect on including current 3N forces was mixed. A further test of the theoretical argument would be a comparison of predictions by the chiral EFT to experimental data of axial observables. For a brief summary and an easily accessible compilation of previous experimental 3NF studies, see [33].

In response to this rather confused situation the RIKEN group choose to go to somewhat higher energy, as in [10] and [34], also studying relativistic effects. At KVI they have shown the feasibility of identifying three-body break up reactions in *dd* collisions [35]. The argument behind this novel approach is that 3N effects would sum up to be relatively larger in 4N reactions and thus presumably easier to detect. So far there are no theoretical calculations available nor foreseen in an immediate future at the relevant energies.

With the main objective to offer a laboratory for the development of the modern theory for nuclear forces, the chiral EFT, we plan to measure *pd* breakup reactions in the energy range 30-50 MeV [36]. At this energy the predictive power for NN interactions is well established and 3NF effects are expected to appear and be significant. In addition an independent cross check of the low energy constants D and E and a possible impact on calculations of the spectra of light nuclei are foreseen. The scarcity of in particular polarized experimental data in this region increases the urgency of the experiment outlined in detail in a letter-of-intent [36] for the COSY accelerator. In the following the formalism for spin $\frac{1}{2}$ and 1 reactions is introduced, we describe the PAX experimental setup and our systematic approach aimed at exploring the richness of three-nucleon final state and facilitating a direct comparison between theory and experiment.

2. Formalism and observables in spin $\frac{1}{2}$ and spin 1 collisions

The most general expression for the spin dependent cross section for spin 1/2 and spin 1 including the terms forbidden by parity in elastic scattering, and the vector and tensor moments using the formalism developed by Ohlsen [37], are given in Eqs.1 - 3. The traditional coordinate system is used according the Madison convention with the beam in the z-direction, the y-axis pointing upwards, and the x-axis sideways completing a right hand coordinate system [38].

The notation for the observables and spin alignment components are as follows: The vector and tensor analyzing powers are A_i and A_{jk}, respectively, with $i, j, k = x, y, z$. Vector correlation parameters are $C_{i,j}$, tensor vector correlation parameters are denoted $C_{ik,j}$, with the first index referring to the deuteron polarization, and the second represents the proton polarization state. The proton vector moments are denoted $p_{x,y,z}$. The deuteron vector components are given by $q_{x,y,z}$ and the tensor moments are q_{jk} with $j, k = x, y, z$.

The unpolarized cross section is denoted σ_0, and the polarized cross section σ is given by

$$\begin{aligned}
\sigma \;=\; & \sigma_0(1 + p_yA_y(p) + p_zA_z(p) + \frac{3}{2}q_yA_y(d) + \frac{3}{2}q_zA_z(d) \\
& + \frac{3}{4}(q_xp_x + q_yp_y)(C_{x,x} + C_{y,y}) + \frac{3}{4}(q_xp_x - q_yp_y)(C_{x,x} - C_{y,y}) \\
& + \frac{3}{4}(q_yp_x - q_xp_y)(C_{y,x} - C_{x,y}) + \frac{3}{2}q_xp_zC_{x,z} + \frac{3}{2}q_zp_x\ C_{z,x} + \frac{3}{2}q_zp_zC_{z,z} \\
& + \frac{1}{6}(q_{xx} - q_{yy})(A_{xx} - A_{yy}) + \frac{1}{2}q_{zz}A_{zz} + \frac{2}{3}q_{xz}A_{xz} \\
& + \frac{1}{6}(q_{xx} - q_{yy})p_y(C_{xx,y} - C_{yy,y}) + \frac{1}{2}q_{zz}p_zC_{zz,z} + \frac{1}{2}q_{zz}p_yCzz, y \\
& + \frac{2}{3}q_{xy}p_xC_{xy,x} + \frac{2}{3}q_{xz}p_yC_{xz,y} + \frac{2}{3}q_{yz}p_xC_{yz,x} \\
& + \frac{2}{3}q_{xy}p_zC_{xy,z} + \frac{2}{3}q_{yz}p_zC_{yz,z} + \frac{1}{3}(q_{xz}p_x + q_{yz}p_y)(C_{xz,x} + C_{yz,y})) \qquad (1)
\end{aligned}$$

We label the absolute polarization of the proton P, and the magnitude of the vector polarization of the deuteron Q. The azimuthal and polar angles of the proton spin alignment is (Φ_p, β_p), The azimuthal of the outgoing particle is denoted ϕ, or in the case of elastic scattering it refers to the scattering plane. The vector moments of the proton spin:

$$p_x = P\ \sin(\beta_p)\ \cos(\Phi_p - \phi) \qquad (2a)$$

$$p_y = P\ \sin(\beta_p)\ \sin(\Phi_p - \phi) \qquad (2b)$$

$$p_z = P\ \cos(\beta_p) \qquad (2c)$$

Analogous for the vector moments of the deuteron spin, with the direction of the deuteron spin alignment given by (Φ_d, β_d):

$$q_x = Q \sin(\beta_d) \cos(\Phi_d - \phi) \tag{3a}$$
$$q_y = Q \sin(\beta_d) \sin(\Phi_d - \phi) \tag{3b}$$
$$q_z = Q \cos(\beta_d) \tag{3c}$$

The six tensor moments of the deuteron polarization are given as follows:

$$q_{xx} = \frac{1}{2} Qt \left(3 (\sin(\beta_d))^2 (\cos(\Phi_d - \phi))^2 - 1\right) \tag{4a}$$
$$q_{yy} = \frac{1}{2} Qt \left(3 (\sin(\beta_d))^2 (\sin(\Phi_d - \phi))^2 - 1\right) \tag{4b}$$
$$q_{zz} = \frac{1}{2} Qt \left(3 (\cos(\beta_d))^2 - 1\right) \tag{4c}$$
$$q_{xy} = \frac{3}{2} Qt (\sin(\beta_d))^2 \sin(\Phi_d - \phi) \cos(\Phi_d - \phi) \tag{4d}$$
$$q_{xz} = \frac{3}{2} Qt \sin(\beta_d) \cos(\beta_d) \cos(\Phi_d - \phi) \tag{4e}$$
$$q_{yz} = \frac{3}{2} Qt \sin(\beta_d) \cos(\beta_d) \sin(\Phi_d - \phi) \tag{4f}$$

where the notation conforms to what is previously used for the spin alignment direction and Qt is the magnitude of the tensor polarization alignment. In order to link the polarized cross section formula Eq. 1 to a particular spin observable to be measured in an actual experiment, one has to specify the polarization alignment of the beam and target particle ensembles. As an example consider a longitudinally polarized proton beam and a vertically polarized deuterium target. We then have a proton alignment along the beam, i.e. $\Phi_p = \frac{\pi}{2}$ and $\beta_p = 0$, and a deuteron alignment direction with spin up, i.e. $\Phi_d = \frac{\pi}{2}$ and $\beta_d = \frac{\pi}{2}$. When inserting these values into the expressions for the vector and tensor moments and of the cross section (Eq. 1), we acquire the observables measurable with that particular configuration of beam and target. In Table 1 a compilation is done for the spin alignment directions for which most of the observables appear in terms of the cross section equation. Among those not included is e.g. A_{xz} that requires a spin alignment for the deuterons *non-parallel* to any axis of the fixed coordinate system.

3. Experimental setup

The experiment will take place at the PAX facility in the recently commissioned low β section in the COSY ring [39]; the setup for the breakup experiment is here briefly described.

The number of protons in a stored vertically polarized COSY beam is expected to be $4 \cdot 10^9$ ($5 \cdot 10^9$) at 30 MeV (45 MeV), reduced by a factor two by electron cooling. For longitudinally polarized protons, there are additional injection losses due to the phase space couplings with the solenoid fields with a resulting intensity of $6.7 \cdot 10^8$ ($8.3 \cdot 10^8$) at 30 MeV (45 MeV) [40]. The proton beam polarization will be calibrated using the method that was applied in Ref. [41]. A polynomial fit to the the measured asymmetries A_y at 30 MeV [42, 43, 44] and at $49 - 50$ MeV [45, 46] will together with a clean selection of *pd* elastic events provide the polarization using the cross-ratio method [47]. To provide longitudinally polarized protons at the PAX interaction point, a full solenoid snake in the opposite straight section at the considered energies of 30 MeV to 50 MeV an integrated strength of the solenoids of 0.894 through 1.16 Tm is required.

Polarized internal targets (PIT) represent a well established technique and have been used extensively at the TSR–ring in Heidelberg [48], at HERA/DESY [49] and at Indiana University Cyclotron Facility [50]. A PIT is presently in operation at ANKE–COSY [51, 52]. A recent

Table 1. Tabulated here are the majority of the correlation observables and analyzing powers accessible in proton deuteron breakup using the PAX facility. For p (proton) and d (deuteron); U means alignment up (vertical), S is sideways (parallell to the x-axis) and A is along the beam direction (longitudinal).

PolObs	pU dU	pU dS	pU dA	pA dU	pA dS	pA dA
$A_y(p)$	X	X	X			
$A_z(p)$				X	X	X
$A_y(d)$	X	X		X	X	
$A_z(d)$			X			X
$A_{xx} - A_{yy}$	X	X		X	X	
A_{zz}	X	X	X	X	X	X
$C_{x,x} + C_{y,y}$	X					
$C_{x,x} - C_{y,y}$	X	X				
$C_{y,x} - C_{x,y}$		X				
$C_{x,z}$				X	X	
$C_{z,x}$			X			
$C_{z,z}$						X
$C_{xx,y} - C_{yy,y}$	X	X				
$C_{zz,z}$				X	X	X
$C_{zz,y}$	X	X	X			
$C_{xy,x}$	X	X				
$C_{xy,z}$				X	X	

review of polarized targets can be found in Ref. [53]. Typical target densities range from a few 10^{13} to 2×10^{14} atoms/cm^2 [49, 50]. The PAX target comprises an Atomic Beam Source (ABS) [54, 55] a thin-walled openable storage cell, and a Breit–Rabi polarimeter (BRP). Hydrogen or deuterium atoms in a well–defined hyperfine–state are injected into the storage cell. A small sample of the target gas propagates from the centre of the cell into the BRP where the atomic polarization is measured. The sampled gas enters simultaneously the Target Gas Analyzer (TGA) where the ratio of atoms to molecules in the gas is determined. Helmholtz coils provide weak magnetic holding fields of $\sim 10\,\text{G}$ around the storage cell defining the quantization axis for the target atoms be oriented along the horizontal (x), vertical (y), or longitudinal (z) directions.

The PAX silicon detector system is being designed to meet the following requirements: to measure effectively polarization observables in both pp, pd [39] (at COSY) and $\bar{p}p$ [56] (at AD) scattering; work in vacuum to detect low momentum particles in the kinetic energy range from few to few tens of MeV; have large dimensions to fit beam envelope at injection and allow target cell operation at AD (to be opened during injection); provide wide acceptance along the cell to cope with the 40 cm long interaction volume. To measure pd breakup reactions a third layer of thickness 1.5 mm is introduced in order to provide enough stopping power for the two outgoing protons and thus enable complete kinematical reconstruction of the event.

4. Systematic approach to the three-particle phase space

A prerequisite for a possible interpretation of the data is the existence of computationally exact solutions of the 3N system. To meet this requirement the Krakow-Bochum group has performed Faddeev calculations up to the pion production threshold [57]. The analysis of the dp breakup observables has traditionally been limited to small phase space regions using the kinematically

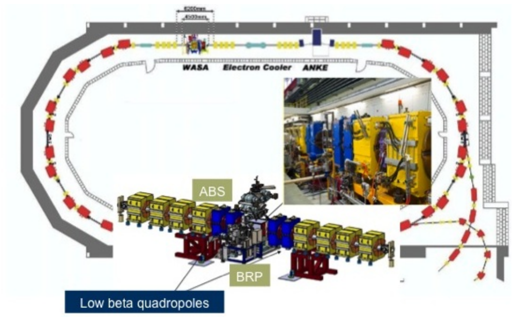

Figure 1. Layout of the COSY synchrotron accelerator with the new low β section inserted: the blue quadropoles are from CELSIUS, the ABS is placed above the target chamber.

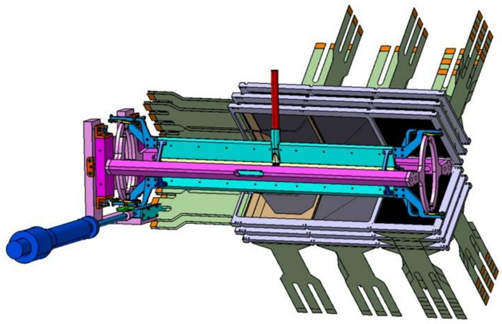

Figure 2. The silicon sensors (grey) with the frames and the kapton connections to the front-end electronics surrounding the target cell (cyan). Shown is also the openable cell support (magenta).

allowed locus in the plane of the energies of the two detected nucleons as the independent variable (the so called S-curve [58]). In order to make full use of the nowadays large coverage of phase space by the detection systems and a kinematically complete knowledge of the final states of the reactions, we developed a novel method for analysis, the so called *sampling method* [59]. For

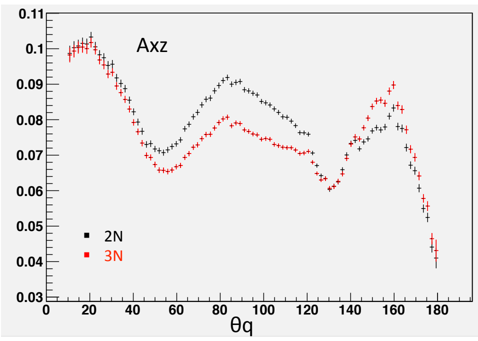

Figure 3. Profile histogram of the (positive) tensor analyzing power A_{xz} versus θ_q, the polar angle of the neutron center-of-mass momentum.

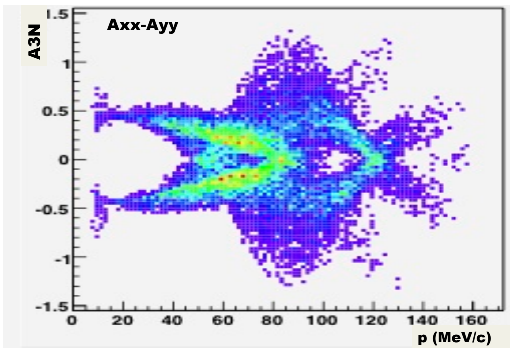

Figure 4. $A_{xx} - A_{yy}$ versus the jacobi momentum p, with a condition applied that $|2N - 3N| > 0.05$.

a three-particle final state to be kinematically fully determined, five parameters are required. When extracting observables one has to choose which independent variable to use and what regions of phase space to integrate over. The acceptance and any significant efficiency variation has to be well known, most often this is accomplished by advanced monte carlo simulations. In contrast, with the complete kinematical information of an event as input, the theoretical prediction for the sought observable can be directly calculated for that particular event. That is, a given experimental data set containing the phase space points used as input to a theoretical model calculation, can then be compared directly to theory by taking the mean of the calculated theoretical predicted values. The sampling method has so far been implemented for the analysis of axial observables [7] and tensor analyzing powers [60] in dp breakup at 135 MeV/A. In order to avoid time consuming repeated Faddeev calculations we adopt multidimensional linear interpolation on a grid of precalculated stored theoretical values, for details see [59]. The *sampling method using a grid* is particularly useful in planning experiments and in governing a complex data analysis of polarization observables. The five independent variables required to determine the three-particle final state were chosen to be $\{p, \theta_p, \phi_p, \theta_q, \phi_q\}$, with the jacobi momenta p and q defined according

$$p = \frac{1}{2}(p_1 - p_2) \tag{5a}$$

$$q = -(p_1 + p_2) \tag{5b}$$

where p_1 and p_2 are the momenta of the two protons in the center of mass ordered such that $p_1 > p_2$ and thus the polar angle θ_p lies in the interval $[0, 90]$ degrees, and q is the center of mass momentum of the neutron. The polar and azimuthal angles are denoted by $\theta_{p(q)}$ and $\phi_{p(q)}$, respectively. For the technique of the interpolation scheme see App. A of [59]. The present choice of grid size for five independent variables is over $4 \cdot 10^6$ mesh points.

Grid studies are in progress using theoretical grids provided by A. Nogga. Some typical results are shown in Figs. 3 – 4 and a sensitivity study in Table 2.

Table 2. *Sensitivity study at 49.3 MeV proton beam energy:* A phase space generated event sample of 10^6 was used. Conditions were applied on the absolute magnitude of the sampled 2N observable plus a minumum 2N cross section. Here the columns represent the RMS of the histogrammed absolute difference between the 2N and 3N calculations, and the percentage of the events left with the applied condition given in the heading. *Note:* The longitudinal analyzing power $A_z(p)$ is predicted to be one order of magnitude smaller than the other listed observables and the conditions were adjusted to $|A2N| > 0.01$ and $|A2N| > 0.05$ respectively.

A2N cond	$\|A2N\| > 0.05$		$\|A2N\| > 0.1$	
Polobs	$RMS\|\Delta(3N - 2N)\|$	Percentage	$RMS\|\Delta(3N - 2N)\|$	Percentage
$A_{xx} - A_{yy}$	0.020	75	0.021	57
$A_{xx} + A_{yy}$	0.019	62	0.021	36
A_{xz}	0.021	56	0.025	29
$A_y(d)$	0.009	31	0.010	13
$A_y(p)$	0.014	52	0.016	27
$A_z(p)$	0.002	55	0.002	5

5. Summary

We plan to measure analyzing powers and spin correlation parameters in proton deuteron breakup at 30 and 49 MeV proton beam energy, in an energy range where previous measurements are rather limited. The experiment will be done at the PAX facility in the COSY ring.

The physics objective is to test the predictive power of the chiral perturbation theory in the three nucleon continuum. In particular we will study the effects of current schemes for three nucleon forces that recently were implemented at third order in the calculations and diagrams appearing at fourth order.

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