Extensive high-precision studies of proton deuteron breakup reactions at COSY

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We plan to measure the spin dependence of proton deuteron breakup at 30 and 49 MeV proton beam energy where previous measurements are few and limited. The physics objective is to test the predictive power of the chiral effective field theory in the three nucleon continuum by measuring analyzing powers and double spin observables with high precision over large areas of phase space at relevant energies for the theoretical interpretation. The experiment will be done at a newly installed and commissioned low-β section and interaction point in the COSY ring utilizing the PAX Multipurpose Detection System that is presently in the design stage.

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1. Introduction

Presently the spin structure of the three nucleon continuum exhibits disparate results when comparing experimental data to theoretical predictions based on two-nucleon potentials either with or without three nucleon interactions. The inclusion of three-nucleon forces in the calculations does not consistently improve the agreement between data and theory [1, 2, 3, 4, 5, 6]. A recent review on the current status of the research on the nature of three-nucleon forces (3NF) can be found in [7] considering aspects from both experiment and theory.

The rich kinematical region in proton deuteron breakup reactions at low to intermediate energy offers a versatile laboratory for the chiral effective field theory (EFT), the modern theory of nuclear forces in the low-energy regime; see [8, 9] and references therein. In the framework of chiral EFT nucleon-nucleon potentials have been developed to next-to-next-to-next-to leading order (N3LO) reproducing two-nucleon observables with high accuracy [10, 11]. Three-nucleon forces (3NF) have been analyzed up to next-to-next-to-leading order (N2LO) with persistent discrepancies and inconclusive results as to specifically how the presence of a third nucleon affect the interaction in few-nucleon systems. In order to remedy this situation both the long-range [12] and short-range contributions [13] to the 3N forces were derived up to N3LO. Thus the calculations of two-, three- and four-nucleon forces at this order in the chiral expansion (without explicit $\Delta(1232)$ degrees of freedom) is completed and the implementation into the theoretical calculations for scattering observables at low to intermediate energy of three nucleon configurations is in progress [14].

Precise measurements of the majority of the spin observables over large areas of phase space would provide a data base for the characterization of the non-vanishing contributions from the chiral 3NF appearing at third and fourth order. To this aim we plan an experiment at the COSY cooler synchrotron and storage ring, measuring proton deuteron breakup reactions at proton beam energies from 30 to 50 MeV where few previous data exist. This is also an ideal energy range for testing the predictive power of chiral EFT. In addition the only two low energy constants (LECs) needed for both N2LO and N3LO, D and E, could be independently determined from a multitude of scattering spin observables[1].

The experiment will be carried out in one of the straight sections in the COSY ring, where a low β section has been installed for the commissioning of the spin filtering experiment [15] with the objective of polarizing a stored antiproton beam *in situ* that is proposed by the PAX Collaboration to be done at the AD ring at CERN [16]. The experimental details and the plans for a PAX Multipurpose Detection System, barrel shaped with layers of silicon double sided strip detectors, are given in [17]. A precursor *pd* breakup experiment using vertically polarized beam, an unpolarized deuterium target and the ANKE silicon telescopes is currently being analyzed.

2. Observables and Theoretical Predictions from Chiral EFT

The formalism for polarization in nuclear reactions was worked out in detail by G.G. Ohlsen in the seventies [18]. The general expression for the double polarized proton deuteron breakup reaction can be found in [19]. Here is shown in table form the independent observables categorized

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[1]These LECs are currently deduced from the ^3H binding energy and the *nd* doublet scattering length, the properties of light nuclei, the triton β decay or the ^4He binding energy.

by the spin alignment directions of the proton beam and the deuterium target required to access the specified observable, see Table [1].

2.1 Grid studies

In order to facilitate a theoretical investigation for the optimization of the measurements of all the spin observables, grids were created based on chiral EFT at N2LO, one for each observable[2], with the theoretical predictions as functions of the five kinematically independent parameters, p, θ_p, θ_q, ϕ_p and ϕ_q; where p and q are the jacobi momenta in the center-of-mass. The grids are thus large matrices spanning the available phase space. Using *the sampling method*, thoroughly explained in [20] and applied in [3, 21], enables a systematic study of any three-particle final state. For the current study the *sampled events* are isotropically generated in a phase space simulation of *pd* breakup. Then multidimensional linear interpolation is used to retrieve the theoretical prediction for each event. In the following figures a few examples of the application are given, all for a proton beam energy of 49 MeV. Some aspects are displayed of the tensor analyzing power A_{xz} in Figs. 1 − 4, the tensor-vector correlation coefficient $C_{yy,y}$ in Figs. 5 − 7 and the vector-vector spin correlation $C_{x,x}$ in Figs. 8 and 9.

The foreseen final result for the planned *pd* breakup experiment is a compilation of the data from all measured observables leading to an overall evaluation of the degree of agreement between experiment and theory.

3. Summary

Measurements of proton deuteron breakup at energies between 30 and 49 MeV are planned at the COSY accelerator and storage ring, motivated by the development of the chiral EFT for describing low-energy phenomena in hadron physics. Using a new experimental approach the aim is to obtain conclusive constraints for the chiral 3NFs, and to form a data base of analyzing powers and spin correlation coefficients at low energy thus contributing to a fuller understanding of few-nucleon interactions.

Acknowledgements

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[2]The theory grids were created by A. Nogga

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

Table 1: Tabulated here are the 7 analyzing powers and 15 spin correlation observables possible in proton deuteron breakup showing the required polarization alignment directions of beam and target and some combinations thereof. 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). The last two columns refer to the situation when the deuteron target spin alignment axis is at 45 degrees which can be accomplished by running current through two target guide field coils simultaneously. With the longitudinal ($\pm z$) and vertical ($\pm y$) guide field coils on, denoted dAU, and switched in $\pm$ polarity, four directions are achieved. Another four alignments are obtained with the longitudinal and sideways ($\pm x$) combinations, denoted dAS. There are five observables (here marked in bold font) that are parity forbidden in elastic scattering and goes to zero in breakup reactions in coplanar kinematical configurations. In the last two columns also a few observables are included requiring longitudinally polarized beam in addition to a target spin alignment at 45 degrees. E.g. the tensor-vector correlation coefficient $C_{yz,z}$ is accessible only using longitudinally polarized beam and diagonal target spin alignment.
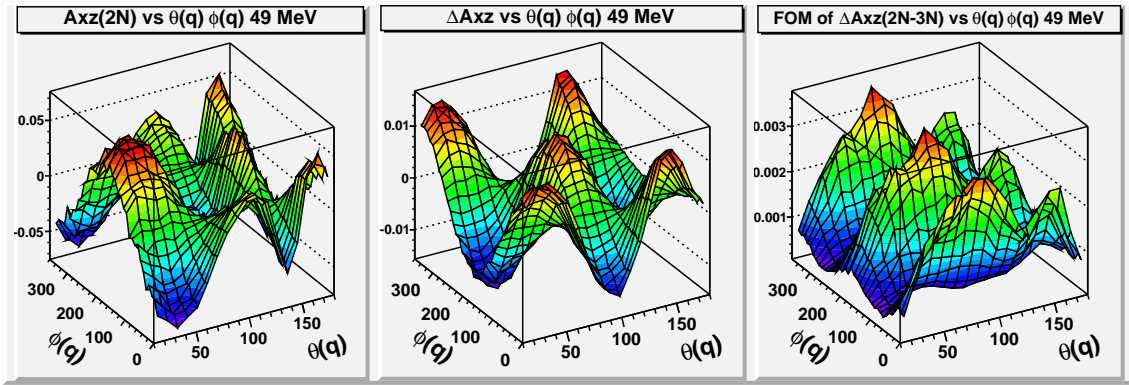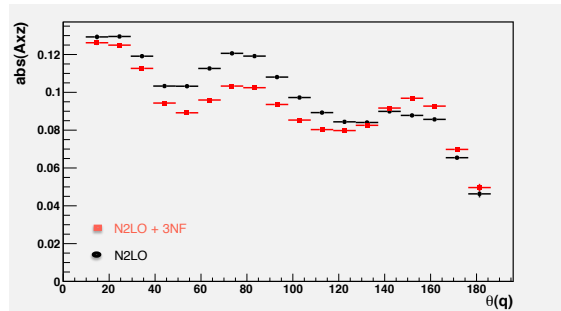
Figure 1: The tensor analyzing power A_{xz} (2N) *(left)*, the difference between the 2N and 3N predictions (middle), the figure-of-merit (right) as function of θ_q and ϕ_q.
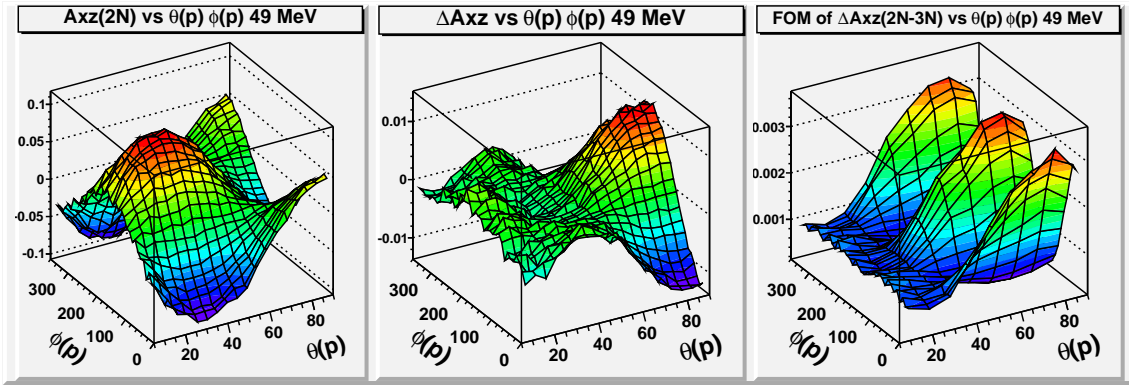

Figure 2: The tensor analyzing power A_{xz} (2N) *(left)*, the difference between the 2N and 3N predictions (middle), the figure-of-merit (right) as function of θ_p and ϕ_p.
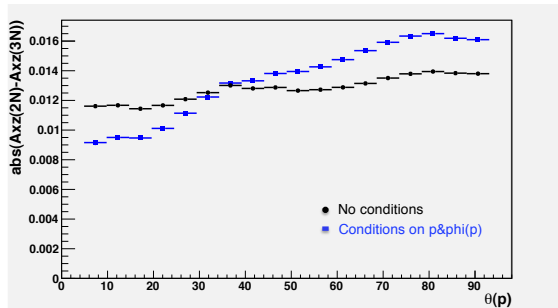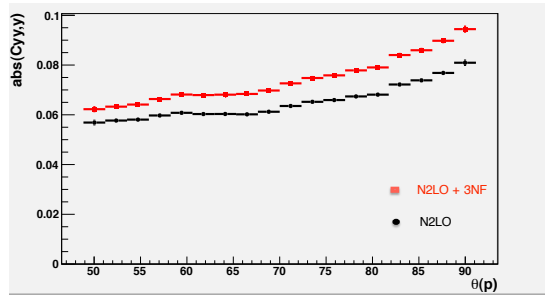

Figure 3: The absolute magnitude of the difference of the tensor analyzing power $A_{xz}(2N) - A_{xz}(3N)$ as function of θ_p in a profile histogram. The dots (black) represent no selection but integration over all independent variables. The squares (blue online) represent conditions set on p and ϕ_p. For $\theta_p > 45°$ a larger difference is observed between 2N and 3N calculations.

Figure 4: The absolute magnitude of the tensor analyzing power A_{xz} as function of θ_q in a profile histogram. The dots (black) represents predictions according the 2N calculation, the squares (red online) includes 3N interactions. Cuts have been made on p, θ_p, ϕ_p and ϕ_q in order to visualize one part of phase space where significant deviations might appear, roughly 0.02 between 60 and 90 degrees.
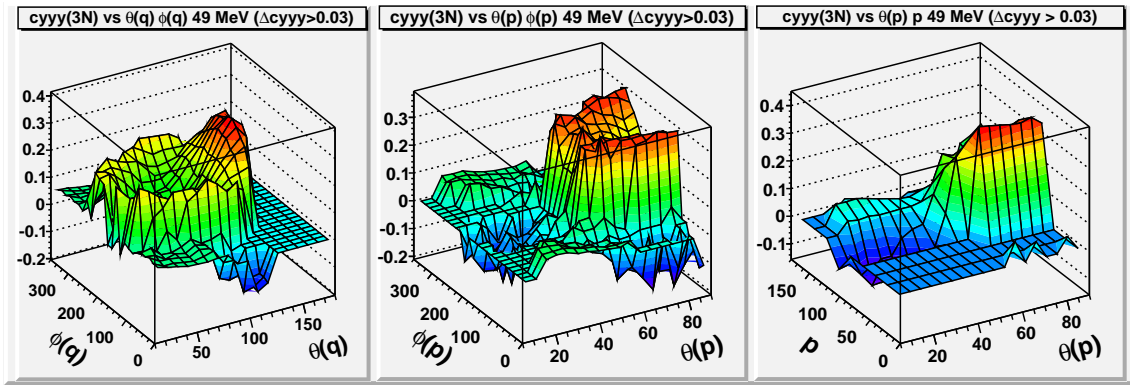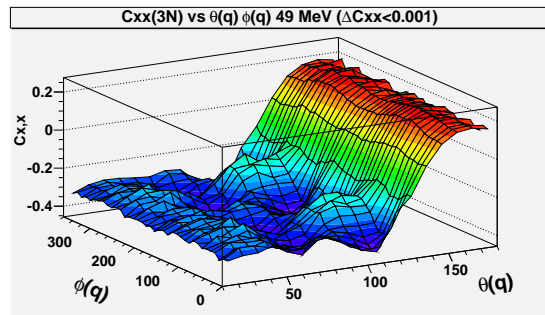
Figure 5: The tensor-vector correlation coefficient $C_{yy,y}$ (2N) as function of θ_q and ϕ_q (left), θ_p and ϕ_p (middle), θ_p and p (right), depicted in two dimensional profile histograms under the condition that the absolute difference between the 2N and 3N calculations correspond to $\Delta(abs(3N - 2N) \geq 0.03$.


Figure 6: The absolute magnitude of the tensor-vector correlation coefficient $C_{yy,y}$ as function of θ_p in a profile histogram using conditions on p, θ_p, ϕ_p and ϕ_q.
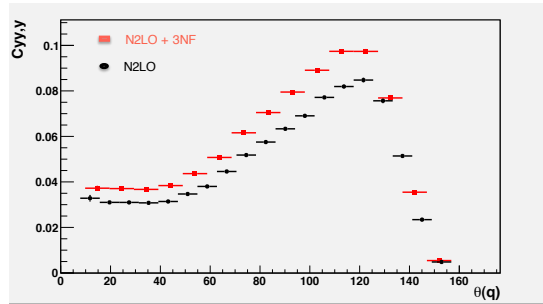
Figure 7: The tensor-vector correlation coefficient $C_{yy,y}$ as function of θ_q in a profile histogram using conditions on p, θ_p, ϕ_p and ϕ_q, yielding a deviation of roughly 0.02 at 120 degrees.

Figure 8: The vector-vector correlation coefficient $C_{x,x}$ (3N) as function of θ_q and ϕ_q at 49 MeV with a condition applied on the absolute difference between the 2N and 3N theoretical predictions; $\Delta(abs(3N - 2N) \leq 00.1$. From this graph one of the conditions is deduced in order to find areas in phase space where the theory predicts similar behavior for 2N and 3N calculations
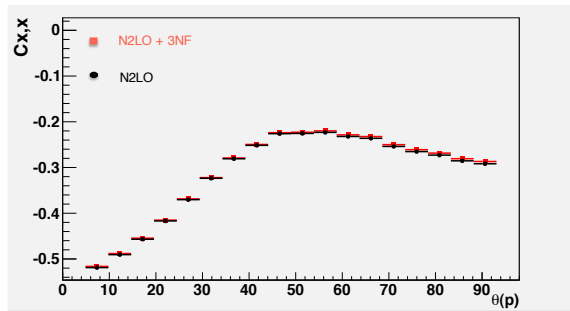
Figure 9: The vector-vector correlation coefficient $C_{x,x}$ predicted from 3N (squares, red online) and 2N (dots, black online) calculations as function of θ_p in a profile histogram integrated over all other parameters except for selected cuts. In this graph aimed at showing no or insignificant 3NF effects for a consistent description, the cuts were made on $\theta_q \leq 100°$, $q \geq 60$ and p in $[30, 130]$ MeV/c.

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