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Spin observables in charged pion photo-production from polarized neutrons in solid HD at Jefferson Lab

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E asymmetries have been extracted from double-polarization experiments in Hall-B of the Thomas Jefferson National Accelerator Facility (JLab). Results have been obtained from the E06-101 (g14) experiment, using circularly polarized photon beams, longitudinally polarized Deuterons in solid HD targets, and the CEBAF Large Acceptance Spectrometer (CLAS). The results cover a range in W from 1.48 to 2.32 GeV. Three independent analyses, using distinctly different methods, have been combined to obtain the final values, which have been published recently. Partial wave analyses (PWA), which have had to rely on a sparse neutron data base, have been significantly changed with the inclusion of these g14 asymmetries.

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PoS(Hadron2017)061

1. Introduction

Quark models (QM) that incorporate the symmetries of QCD describe many aspects of particle physics. Both QM and recent results from Lattice QCD predict many N* resonances which have not been observed by the experiments. Some resonances are broad and overlap each other so that simple analyses can not separate them; detailed partial wave analyses (PWA) with spin observables are necessary to resolve overlapping resonances. During the past decade, experimental and theoretical advances have been able to identify some new resonances, although many are still missing.

In order to extract spin observables from the neutron, the g14 experiment was performed from December 2012 to May 2013 in Hall B at JLab using circularly and linearly polarized photon beams, longitudinally polarized deuterium targets, and the CLAS detector [1]. Polarized deuterium was provided as a frozen-spin solid HD target [2]. Data used for this analysis were taken with circularly polarized photons (21 days and 4.1×10^9 trigger events), with energies that ranged from 0.85 to 2.4 GeV.

E asymmetries for the reaction of γ + D $\rightarrow$ p + π^- + (p) have been measured and the results have been published recently in Ref. [3].

2. Experimental conditions and data analysis

Circularly polarized photons were produced as bremsstrahlung from longitudinally polarized electron beams extracted from the Continuous Electron Beam Accelerator Facility (CEBAF). The average polarization of the electron beam during the data taking for this analysis was 85 %. The photon beam energy was measured by tagging the deflected electron with the Hall B bremsstrahlung tagging system [4].

Frozen-spin HD targets were polarized and aged in a dilution refrigerator at 10 mK and 15 T for about 3 months, and subsequently transferred to an InBeam Cryostat (IBC), a horizontal dilution refrigerator that operated at 50 mK with a 0.9 T holding field. The IBC was inserted into the center of the CLAS detector. The target polarizations were calibrated and monitored in the IBC by NMR. The D polarization was flipped by field rotation using a transverse dipole magnet in conjunction with the solenoid magnet. The average deuteron polarization during the data taking period for this analysis was 25 % and the relaxation time was more than a year.

The CLAS consists of drift chambers (DC) built in and around a torus magnet, time-of-flight counters (TOF), gas Cherenkov counters and electromagnetic calorimeters [1]. For experiments using photon beams, a Start Counter surrounding the polarized target is used for the first level trigger and time-of-flight measurement.

The momentum and charge of final-state particles were determined from the curvature of the reconstructed particle tracks in the magnetic field. Protons and charged pions were identified by their momenta and time-of-flight. The energy of these particles was corrected for energy losses in the target and material surrounding the target. Shifts of the reconstructed momentum due to drift-chamber misalignments were also corrected. Events with one π^- and one proton, both identified by CLAS were selected. To remove the ambiguity for events that relate to more than one tagged photon, events were selected for the number of photons in an RF bucket to be one.

PoS(Hadron2017)061

Three independent analyses using different methods were performed. Each applied different techniques to isolate the final state, as described in the subsequent sections.

2.1 Background subtraction (BKsub) method

Backgrounds for this reaction came from the beam-entrance and -exit windows of the cylindrical target cell (pCTFE[C_2CIF_3]), and from thin Aluminum cooling wires inside of the cell. The contributions of the cell background to the spin-asymmetries were subtracted to obtain the yield from pure HD, by measuring the yield from the target cell alone. Subtractions were performed for each angular bin (cosine θ of the π^- in the c.m. system). Events with an azimuthal angle difference between the π^- and the proton of $180^\circ \pm 20^\circ$ were selected. The undetected *spectator* protons were reconstructed from the reaction, γ + D $\rightarrow$ p + π^- + p_s and a cut on missing-mass squared of less than 1.1 GeV^2 was applied.

2.2 Kinematic fitting (KinFit) method

Applying a hypothesis to the fitter, γ + (n) $\rightarrow$ π^- + p and assuming a moving target neutron with unknown Fermi momentum, kinematic fitting was applied and the confidence level was calculated for each event. Requiring the confidence level to be greater than 0.05 removed events from high-momentum neutrons in the deuteron, target cell background, and backgrounds from other reactions such as multi-pion production, γ + n $\rightarrow$ π^- + p + π^0 [5].

2.3 Boosted Decision Tree (BDT) method

To reject backgrounds from the target cell and other reactions such as multi-pion productions, the algorithm was *trained* with Monte Carlo signals of the CLAS response to the reaction γ + (n) $\rightarrow$ π^- + p, including CLAS geometries and performances, and with background data from the empty cell [6]. BDT cut with multi-dimensional selected parameters for each event separates the signal and background.

2.4 Common cut for all three methods

A common cut in these three methods, requiring a missing (proton) momentum of $p_{missing} <$ 0.1 GeV/c, was used in order to select quasi free neutron reaction events. (This cut was determined from the data to show that $|E|$ starts decreasing for $p_{missing} > 0.1$ GeV/c, while $|E|$ is stable for $p_{missing} < 0.1$ GeV/c [3].) Deuteron D-state corrections were negligible for events that passed this cut [7].

3. Results

E asymmetries obtained from the three methods have been compared, observed to be consistent, and combined. The results, with their statistical uncertainties, are shown in Figure 1 as a function of $\cos\theta_{\pi^-}$ for twenty-one W bins. Systematic variations of the data have been studied by changing parameter values for each of the three analysis methods and the results are summarized in Table 1. The systematic uncertainty associated with analysis and event processing enter the three methods in different ways, but total about 4% in each case. Nonetheless, the systematic

PoS(Hadron2017)061

Contribution to σ_{sys}	σ_{sys}		
	BkgSub	KinFit	BDT
Analysis Parameter variation:	3.7%	3.5%	3.5%
Extrapolation to $\lvert\vec{p}_{miss}\rvert$=0:	2.2%	2.2%	2.2%
σ_{sys} (cuts):	4.3%	4.1%	4.1%
Photon beam polarization:	3.4%	3.4%	3.4%
Target polarization:	6.0%	6.0%	6.0%
σ_{sys} (polarization):	6.9%	6.9%	6.9%
σ_{sys} (total):	8.1%	8.0%	8.0%

Table 1: Estimated systematic uncertainties of E for each of the three analysis methods, and for beam and target polarizations. (All uncertainties are relative.)

polarization uncertainty dominates (6.9%) and leads to a total systematic uncertainty of 8% for the experiment.

New partial wave analyses (PWA) including these g14 results have been performed by the George Washington University data-analysis group (SAID) [8]; red shaded bands with energy variations in Figure 1. New PWA by the Bonn-Gacthina (BnGa) group are shown as black curves [9]. Comparing these new PWA results with previous PWA solutions, plotted as dotted and dashed curves shown in three W bins (1580, 1900 and 2220 MeV), demonstrate the impact of these new neutron data on PWA solutions. Red-dotted curves from SAID[CM12] are based on data up to the year 2012 [10], while red-dashed ones from SAID[AS25] include all previously published data. Grey-dashed curves are based on the data up to the year 2014 [11] from BnGa[2014-02] and black short-dashed ones used all previously published data from BnGa. These previous PWA cannot describe the new data at higher energies.

As a measure of γnN* couplings, the transverse helicity amplitudes, A_n^h, have been extracted from the BnGa and SAID PWA analyses, with the inclusion of the new g14 data. The amplitudes are compared with previous determinations in Table 2 [3]. The uncertainties in the extracted helicity amplitudes have been reduced sufficiently with the inclusion of the new asymmetries. For the N(1720)3/2$^+$, $A_n^{1/2}$ and $A_n^{3/2}$ from SAID are significantly different, while $A_n^{1/2}$ from BnGa has also changed substantially for the N(2190)7/2$^-$.

	$A_n^{1/2}$	(10^{-3} GeV$^{-1/2}$)	$A_n^{3/2}$	(10^{-3} GeV$^{-1/2}$)
	g14 PRL 118 [3]	Previous [12, 13]	g14 PRL 118 [3]	Previous [12, 13]
SAID				
N(1720)3/2$^+$	-9 ± 2	-21 ± 4	+19 ± 2	-38 ± 7
N(2190)7/2$^-$	-6 ± 9	–	-28 ± 10	–
BnGa				
N(2190)7/2$^-$	+30 ± 7	-15 ± 12	-23 ± 8	-33 ± 20

Table 2: γnN^* couplings with g14 neutron data and from previous PWA solutions

PoS(Hadron2017)061

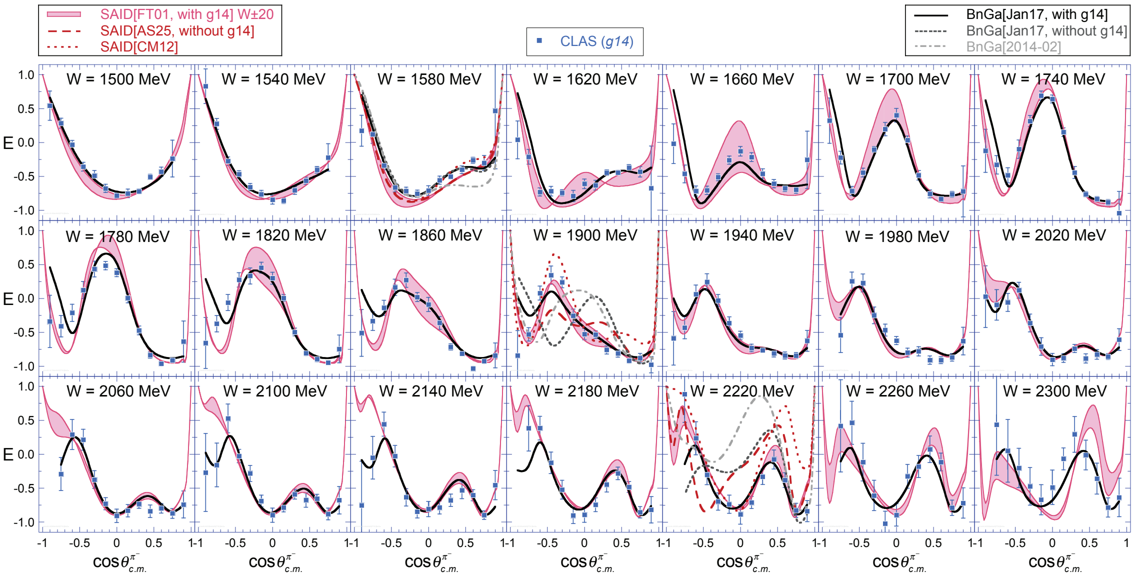

Figure 1: E asymmetries from the E06-101 (*g14*) experiment as a function of cos θ_{π^-} are plotted (blue squares) in invariant mass (W) bins of $\pm$ 20 MeV [3]. Recent PWA fits including the new neutron g14 data are shown in solid black curves (BnGa) [9], and as red shaded bands (SAID) [8] showing variations across the energy bins. The previous PWA solutions as shown in three selected energy bins (1580, 1900 and 2220 MeV) from SAID (red-dotted and -dashed) and BnGa (grey-dashed and black short-dashed) do not describe the new g14 data at higher energies.

Data analyses are ongoing for the G asymmetry measured in the π^-p channel with linearly-polarized beams, as well as asymmetries in $K^0\Lambda$, $K^+\Sigma^-$ and two-pion final states. These will likely result in further modifications to PWA analyses.

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PoS(Hadron2017)061

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PoS(Hadron2017)061