Polarization observables in few nucleon systems with CLAS

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Polarization observables in few nucleon systems with CLAS

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Abstract. The CEBAF Large Acceptance Spectrometer (CLAS), housed in Hall-B at the
Thomas Jefferson National Accelerator Facility provides us with the experimental tools to
study strongly-interacting matter and its dynamics in the transition from hadronic to partonic
degrees of freedom in nuclear interactions. In this paper we discuss the progress made
in understanding the relevant degrees of freedom using polarisation observables of deuteron
photodisintegration in the few-GeV photon-energy region. We also address progress made in
studying the interaction between Hyperons and Nucleons via polarisation observables, utilising
high-statistics experiments that provided us with the large data samples needed to study final-
state interactions, as well as perform detailed studies on initial-state effects. The polarisation
observables presented here provide us with unique experimental tools to study the underlying
dynamics of both initial and final-state interactions, as well as the information needed to
disentangle signal from background contributions.

1. Introduction

Photoproduction experiments, using polarized beams incident on few-nucleon systems, provide
us with unique experimental tools to 1) study the underlying dynamics of strongly interacting
matter and investigate the relevant degrees of freedom, and 2) study initial- and final-state
effects. Hadron interaction at low and high energies has been extensively studied and it is
currently well understood in terms of hadronic and partonic degrees of freedom, respectively.
What governs this interaction at medium energies has been, however, a long standing problem
in nuclear physics. This transition region has been extensively studied over the past 20 years
in deuteron photodisintegration, which provides us with the simplest two-body system. Here
we present recent polarization measurements on deuteron photodisintegration, that provide
stringent constraints on the underlying dynamics.

Understanding initial- and final-state effects allows us to reduce model-dependent
interpretation of experimentally accessible phenomena on bound nucleon targets, as well as study
in detail interactions that are otherwise experimentally difficult to perform. Understanding the
hyperon-nucleon (YN) interaction is crucial in obtaining a comprehensive picture of the strong
interaction. On one hand, the nucleon-nucleon interaction has been extensively studied for
many decades and a good understanding of this system at energies beyond the pion production
threshold exists. On the other hand, direct studies of interactions between other members of
the octet – namely the hyperons – remain scarce and inaccurate due to the challenges imposed
by the short-lived hyperon. Reliable and precise data on the interaction between hyperons and

nucleons will allow us to address the "Hyperon Puzzle", which reflects how theoretical models cannot predict the role of hyperons in neutron stars in a manner that is consistent with the most recent observations of massive neutron starts [1]. Here we present a new approach that utilizes final-state interactions (FSI) in exclusive hyperon photoproduction reactions to obtain a clear insight of the dynamics of the YN interaction.

The studies presented here were performed using data collected at the Jefferson Lab (JLab) using the CEBAF Large acceptance Spectrometer (CLAS) [2] from experiment E06-103 [3]. During this experimental run, data were collected using a circularly and linearly polarized tagged photon beam incident on a 40 cm long liquid deuterium target.

2. Hall B and the CLAS detector

The Continuous Beam Accelerator Facility (CEBAF) at JLab provided the continuous electron wave beams up to 6 GeV used for the nuclear and particle physics scientific program [4]. The injector was able to produce polarized beams with polarizations > 80%, which allowed polarization experiments to be performed. The beam was simultaneously delivered to three end stations (Halls A, B, and C) to conduct complementary experiments. The CLAS detector, which was the main scientific instrument for experiments performed in Hall B until 2012, provided a nearly hermetic acceptance. The CLAS detector was split into six sectors – each comprising of identical mass spectrometers – by six kidney-shaped superconducting coils, which produced a toroidal magnetic field primarily in the ϕ direction. Each sector was composed of three layers of drift chambers to measure charged-particle trajectories, scintillators to measure time-of-flight, a Čerenkov counter to separated electrons from π^-s, and electromagnetic calorimeters primarily used for photon and neutron identification (see left panel of Fig. 1). This system allowed for an efficient charged-particle tracking between $8°$ and $144°$ polar angles and a neutral particle detection between $8°$ and $70°$ polar angles with momentum and angular resolutions of $\sim 0.5\%$ and 2 mrad, respectively. These detector characteristics allowed for a reliable particle identification between protons and pions below 3.5 GeV/c, and between pions and kaons below 2 GeV/c. The entire detector system has since been upgraded for the new scientific programme at JLab and will receive beams with energies up to 10.6 GeV [5].

The tagger spectrometer, also housed in Hall B, allowed tagged real-photon experiments to be performed, with photon energies between 20% and 95% of the incident electron energy E_0. The right panel of Fig. 1 shows a schematic of the photon tagger. The tagger hodoscope design provided an energy resolution of $0.001E_0$ and a timing resolution of 110 ps. Circularly and linearly polarized photon beams were generated with the use of amorphous and crystal radiators placed upstream of the tagger, with polarizations reaching 80% and 75% respectively. These capabilities were utilised in a plethora of experiments performed in Hall B and here we report recent measurements on the study of few nucleon systems to obtain detailed understanding of the underlying dynamics in transition region and the hyperon-nucleon interaction.

3. Studies of the transition region

Studies of the transition region were initially employed searching for experimentally accessible phenomena, such as dimensional scaling and hadron helicity conservation, as an attempt to search and identify the onset of quark-gluon dynamics. Historically, these dimensional scaling rules have been derived first in the framework of perturbative QCD (pQCD) and predict a scaling of the energy dependence of the invariant cross section, $d\sigma/dt \propto s^{-n+2}$, where n is the number of elementary fields involved in the interaction, and s and t are the usual Mandelstam variables [6]. Extensive experimental efforts in many reactions were performed to search for the onset of scaling. CLAS data from experiment E93-017 allowed a detailed study of the two-body deuteron photodisintegration differential cross section at photon energies between 0.5 and 3.0 GeV. The results were consistent with the power-law dependence $\propto s^{-11}$ above proton transverse
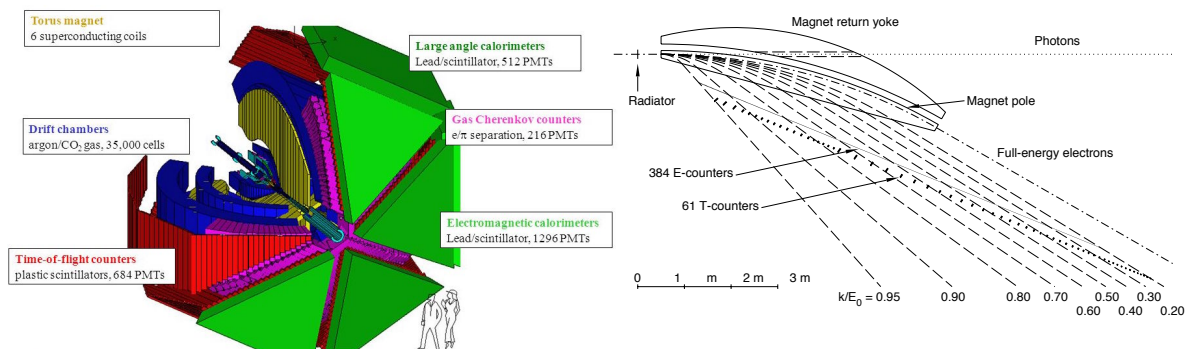
Figure 1. Left: schematic CLAS detector. The kidney-shaped superconducting coils are shown in yellow, drift chambers in blue, Čerenkov counters in magenta, time-of-flight scintillators in red, and electromagnetic calorimeters in green. Right: Hall-B photon tagging system located upstream of the CLAS detector.

momenta of $p_\perp = 1.1$ GeV/c [7]. It was thus, initially claimed that the quark-gluon regime is reached above these energies.

More recent theoretical efforts, however, using the correspondence between string theories in Anti-de-Sitter space-time and conformal field theories in physical space time, have predicted the same cross-section scaling in a very different dynamical regime [8]. This was done by using the scale invariance of the interaction between hadron constituents at very large distance scales in the so-called "conformal window", where the effective coupling is large but constant. Therefore, the onset of dimensional scaling alone, does not provide with direct evidence of quark-gluon dynamics. In this respect, polarization observables provide us with the tools needed to probe the underlying dynamics in the few-GeV region. Several theoretical models have been developed in an attempt to describe these dynamics. The main models for deuteron photodisintegration are based on nonperturtbative phenomenological approaches. The two models that provide us with predictions for polarization observables, are the Hard Rescattering Mechanism (HRM) [9], which is described as a phenomenological extension of pQCD, and the Quark- Gluon-String-Model (QGSM) [10], which is a purely non-perturbative partonic model. Both of these models describe the available cross-section data with the same degree of success [11], however predictions on the beam-spin asymmetry, Σ, which is more sensitive to the reaction mechanism, differ by about 40% between the two models [12].

Experiment E06-103 allowed a precise determination of Σ for a wide range of proton angles ($30° < \theta_p^{c.m.} < 145°$) and photon energies from 1.1 to 2.3 GeV [13]. The results from this study are shown in Fig. 2, with the left panel showing the energy dependence of Σ at proton $c.m.$ angle around 90° and the right panel showing the angular dependence for six photon energy bins 200-MeV wide from 1.1 to 2.3 GeV.

The energy dependence of the measured Σ values shows a clear transition from lower to higher values around 1.7 GeV, that might be described by the HRM model. Neither model predicts, however, the magnitude of the observable. The angular dependence of Σ shows rich structures especially at lower photon energies. Such rich structures are predicted by the QGSM; however, none of the models is able to adequately describe the angular dependence of the CLAS data. The polarization results from CLAS provide stringent constraints for the available theoretical models, as they significantly extend the existing database to a much broader kinematic range, with significantly improved precision compared to previous measurements. Theoretical efforts are needed to better describe our data, and obtain a clear understanding of hadron dynamics in the few-GeV region.
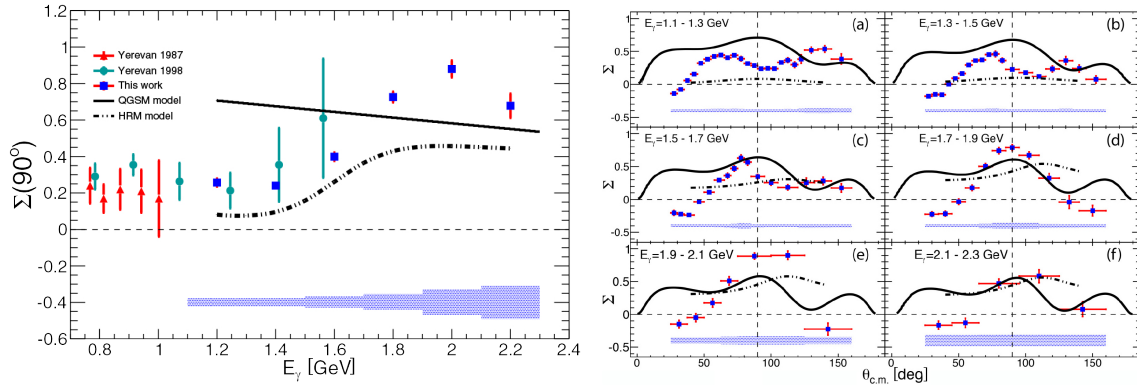
Figure 2. Recent published data from CLAS on the beam-spin asymmetry of the reaction $\gamma d \rightarrow pn$ [13]. The left panel shows the energy dependence of the 90° data (blue squares) compared to previous measurements from Yerevan. Theoretical predictions from QGSM and HRM are shown with solid and dashed line respectively. The right panel shows the angular dependence for six photon-energy bins 200-MeV wide.

4. Studies of the hyperon-nucleon interaction and initial state effects

Information on the YN interaction was accessed through final-state interactions (FSI) in the reaction $\gamma d \rightarrow K^+\Lambda n$ using data from experiment E06-103. Figure 3 illustrates the four main mechanisms that contribute to our reaction. These includes the quasi-free hyperon photoproduction off the bound proton (panel a) – which dominates the cross-section, and three FSI: the pion-mediate reaction (panel b), the kaon rescattering (panel c), and the hyperon-nucleon rescattering reaction (panel d). The large acceptance of CLAS and the tagged photon beam allowed for kinematically selecting events in which FSI effects dominate, permitting the extraction of information on the dynamics of YN interaction in a model-dependent way. The FSI contributions were enhanced by selecting events in which the momentum of the final-state neutron was inconsistent with the typical Fermi motion. This corresponded to a cut of the spectator momentum above 200 MeV/c. While this selection significantly reduced contributions from the quasi-free mechanism to the FSI sample, the relative contributions between the three mechanisms remained unknown.
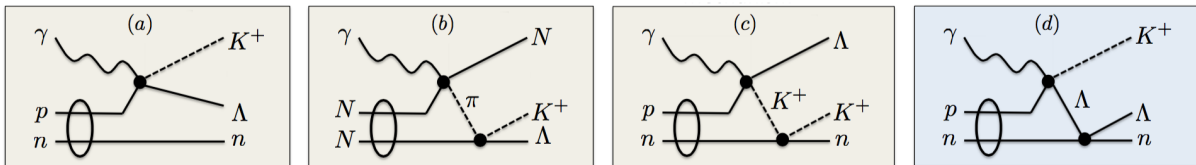

Figure 3. Four main mechanisms that contribute to the reaction $\gamma d \rightarrow K^+\Lambda n$ according to theoretical models [14, 15]: (a) quasi-free Λ photoproduction on the proton; (b) pion mediated production; (c) K^+ rescattering on spectator neutron; (d) Λ rescattering on spectator neutron.

Polarization observables allow us to obtain estimates of the contributions from the three FSI mechanisms in a relatively model-independent way, or even identify kinematical regimes where the YN mechanism dominates. The self-analyzing nature of the Λ hyperon allows a simultaneous determination of several polarization observables, utilizing both the linearly and circularly polarized photon beam. Equation (1) shows the polarization observables accessible to

4

our experiment

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_0 [1 - P_{lin}\Sigma\cos 2\phi + \alpha\cos\theta_x(-P_{lin}O_x\sin 2\phi - P_{circ}C_x)$$
$$-\alpha\cos\theta_y(-P_y + P_{lin}T\cos 2\phi) - \alpha\cos\theta_z(P_{lin}O_z\sin 2\phi + P_{circ}Cz)\dots], \qquad (1)$$

where $\left(\frac{d\sigma}{d\Omega}\right)_0$ is the cross section obtained from an unpolarised photon beam, P_{lin} and P_{circ} are the degree of linear and circular photon polarisation, respectively, and Σ, O_x, O_z, C_x, C_z, P_y, and T are the polarisation observables. The kaon azimuthal angle ϕ is measured from the photon-polarization plane and $\cos\theta_{x,y,z}$ are the direction cosines of the Λ decay products in the Λ rest frame. The self-analysing power of Λ, which allows the determination of the Λ polarisation by studying the distribution of its decay products, is denoted by α. The beam-spin asymmetry can be obtained using the azimuthal distribution of the kaon or the hyperon. In a pure quasi-free data sample the two polarization observables Σ_{K^+} and Σ_Λ are consistent as the two particles fall in the same plane. However, FSI effects dilute the magnitude of Σ. Specifically, events that originate from the pion-mediate reaction are expected to significantly dilute the beam-spin asymmetry Σ_{K^+} and Σ_Λ, whereas kaon rescattering samples will dilute Σ_{K^+} but leave Σ_Λ unchanged. In a very similar manner YN samples will dilute Σ_Λ but leave Σ_{K^+} unchanged. Similar arguments can be made for the set of polarization observables accessed in this experiment. Figure 4 shows the preliminary result from CLAS for Σ_{K^+} and Σ_Λ as a function of photon energy, for a quasi-free dominate sample (right panel) and an FSI dominated sample (left panel). Kinematic regimes
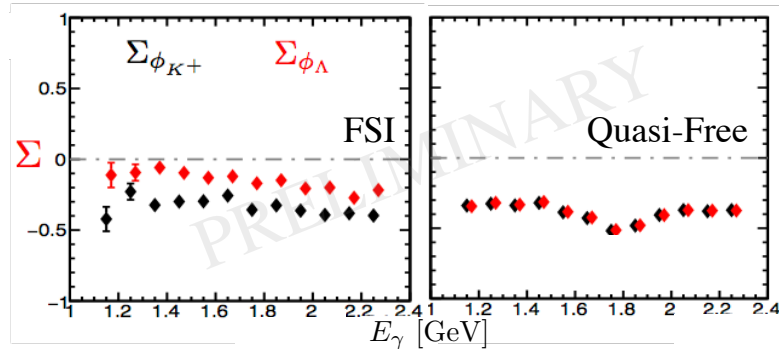

Figure 4. Beam-spin asymmetry Σ determined using the kaon (black points) and the Hyperor (red points) azimuthal distribution for an FSI dominated sample (left panel) and a a quasi-free dominate sample (right panel).

where the Σ_{K^+} determined in the FSI data is consistent with the observable determined in the quasi-free data, reflect regimes in which the YN interaction dominates. The determination of a large set of polarization observables in such kinematical regimes places very stringent constraints on the underlying dynamics of the YN interaction and allows us to tune the existing and largely unconstraint YN potentials [14, 16]. The available statistics from CLAS allows us to obtain these set of observables and their kinematical dependence for FSI, not only for the one-fold differential observables as shown here, but differential up to three kinematic variables, providing an unprecedented insight on the bare YN interaction.

It has been shown recently that exclusive meson photoproduction off the neutron is mportant for the research of the excited nucleon spectrum and the search for missing resonances, as some resonances are predicted to couple strongly to the neutron. However, since no free neutron targets exist, bound neutron targets, the simplest of which is deuterium, are typically employed. The information extracted from such targets is modified by both initial and final state effects. The method discussed above allows us to establish the contributions of FSI. Initial state effects, can be determined by studying the dependence of the observables with the momentum of the target nucleon. Studies performed with CLAS indicated that such effects can be well understood in a model independent way [17]. The left panel of Fig. 5 shows the evolution

of Σ for K^+ photoproduction off the bound proton, with the target proton momentum, and the right panel shows the results obtained from a polynomial extrapolation (red points) as compared to results from a free-proton target (black points). It has been shown that selecting a quasi-free sample (in which the target nucleon momentum is less than 150 MeV/c), the determination of observables by neglecting any target-nucleon momentum dependence, leads to biased estimates compared to ones that are determined by extrapolation to the free-nucleon point of 0 MeV/c. The extrapolated results are consistent with the free-proton data, providing confidence of the method employed.
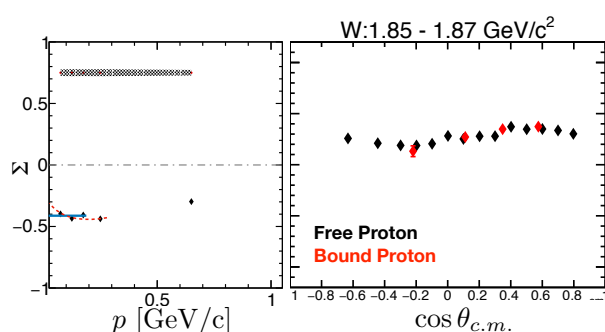

Figure 5. Evolution of Σ with target proton momentum determined using exclusive kaon photoproduction off the bound proton (left panel) and a comparison of results obtained through extrapolation with results from a free proton target.

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