Measurement of the $^{1}H(\vec{\gamma},\, \vec{p})\pi^0$ reaction using a novel nucleon spin polarimeter

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We report the first large-acceptance measurement of polarization transfer from a polarized photon beam to a recoiling nucleon, pioneering a novel polarimetry technique with wide application to future nuclear and hadronic physics experiments. The commissioning measurement of polarization transfer in the $^{1}H(\vec{\gamma},\vec{p})\pi^0$ reaction in the range $0.4 < E_\gamma < 1.4$ GeV is highly selective regarding the basic parameterizations used in partial wave analyses to extract the nucleon excitation spectrum. The new data strongly favor the recently proposed Chew-Mandelstam formalism.

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I. INTRODUCTION

Spin polarization observables are a powerful tool in nuclear and hadronic physics, providing essential constraints on the dynamics of strongly bound systems and ultimately non-perturbative QCD. Previous measurements of nucleon spin polarization have been limited by small detector acceptances, resulting in the need for long beam times and sequential experimental measurements. This is generally due to the polarimeters employed in such experiments, which rely on accurately measuring the nucleon momentum before and after a spin-dependent nucleon-nucleus scattering interaction using charged particle tracking detectors. The high cost of these detector systems restricts the solid angular coverage.

In this letter, we present a novel approach to nucleon polarimetery that achieves a determination of the spin

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directions of protons with large acceptance, a goal that has remained elusive for many decades. The technique utilizes a reconstruction of the kinematics of the nucleon-nucleus scattering processes in the analyzing medium without the need for tracking detectors. Detailed polarized particle tracking simulations built on the Geant4 [1] framework are used to isolate and characterize the analyzing reaction. The polarimeter concept presented here has the potential to provide spin-polarization data for a wide range of future hadronic and nuclear physics experiments including single and multiple meson photoproduction, deuteron photodisintegration and Deeply Virtual Compton Scattering. The polarimeter will provide neutron spin transfer observables in future approved experiments [2]. The commissioning reaction for the polarimeter is taken as the beam-recoil double polarization observable ${C_x}^*$ in the $^1H(\vec{\gamma},\vec{p})\pi^0$ reaction. This observable measures the degree of circular polarization transferred from the incident photon beam to the recoiling nucleon. There are sparse but accurate data for this reaction obtained at Jefferson Lab (JLab) using the spectrometer facilities at Hall A [3] and Hall C [4], which can be used as a verification of the new polarimeter concept.

Measurements of beam-recoil observables in meson photoproduction with large acceptance are a prerequisite for improving our knowlege of the excitation spectrum of the nucleon, one of the highest priority programs in hadronic physics. A rich spectrum of excited states are expected for the nucleon, reflecting its composite nature as a tightly bound strongly interacting system comprising valence quarks, sea quarks, and gluons. Recently, theoretical predictions of this spectrum have emerged directly from Quantum Chromodynamics (QCD) via the lattice [5], Holographic Dual [6], and Dyson-Schwinger approaches [7]. These reveal the spectrum as a sensitive test of non-perturbative QCD as a complete theory to describe light quark bound systems. The spectrum also guides phenomenological QCD based approaches such as constituent quark models [8].

To extract information on the excitation spectrum, cross sections and polarization observables measured in meson production data are fit with Partial Wave Analyses (PWA), based on amplitudes that include couplings to intermediate nucleon resonant states as well as non-resonant background terms. The current determination of the nucleon excitation spectrum is incomplete with masses, lifetimes, and widths of many states not conclusively measured. Even the existence of some states is in doubt due to contradictory results between different PWA [9]. Accurately constraining PWA requires at least seven appropriately chosen cross section and polarization observables [10] to determine the reaction amplitudes up to an overall phase. This has led to a significant effort to produce polarized nucleon targets at ELSA [11], MAMI [12] and JLab [13]. However, a full constraint on PWA necessitates large-acceptance measurements of double polarization observables including recoil polarization [14, 15].

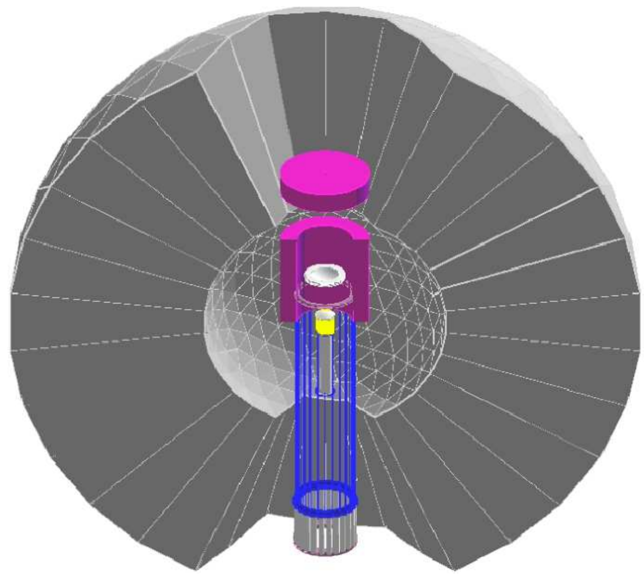

FIG. 1: (Color online) Illustration of the experimental setup. The liquid hydrogen target (yellow cylinder), situated at the center of the CB, is surrounded by the PID (blue) and the 2.25 cm thick graphite polarimeter. The 7.25 cm thick upstream cap covers the upstream aperture to TAPS (not pictured). The PID was flush with the upstream cap during data acquisition, however for this picture, the PID has been shifted for clarity.

II. EXPERIMENTAL DETAILS

This experiment took place at the Mainz Microtron (MAMI) electron accelerator facility [16, 17] in a total beamtime of 600 hours. Circularly polarized bremsstrahlung photons were energy tagged by the Glasgow Tagger [18, 19] and impinged on a 5 cm long liquid hydrogen target. Reaction products were detected with the Crystal Ball (CB) [20–22], a highly segmented NaI(Tl) photon calorimeter covering nearly 96% of 4π, and the TAPS [23, 24] BaF_2 array, which covered the forward angle region for $\theta = 5 - 20°$. The experimental apparatus is shown schematically in Fig. 1. A 24 element 50 cm long scintillator barrel (PID) surrounded the target to assist in charged particle identification. For this experiment, additional analyzing material for the polarimeter was placed inside the CB, comprising a 2.5 cm thick graphite cylinder covering $\theta \geq 12°$ placed outside the PID and a 7.25 cm thick upstream cap covering $\theta < 12°$.

The events of interest are those for which the proton has undergone a nuclear scatter with a ^{12}C nucleus in the polarimeter. The successful operation of the polarimeter requires such events to be cleanly identified for a wide range of incident proton angles and energies. The analysis utililizes a kinematic reconstruction of the scattering of final state protons in the graphite analyzer, exploiting the accurate measurement of the incident photon, final state pion and the interaction point of the proton in the CB. For the $^1H(\vec{\gamma},\vec{p})\pi^0$ events, three particles are detected in the final state: the proton and the two photons from the fast $\pi^0 \to 2\gamma$ decay. The two particles whose invariant mass was closest to the π^0 mass of 135 MeV were identified as photons, with an additional check for anti-coincidences in the PID. A missing mass cut was then used to identify the recoiling proton and to reconstruct its 4-vector $\mathbf{p_{rec}}$. A correlation in the azimuthal angle of the reconstructed proton and a hit in the appropriate PID element were also required. Particle identification was confirmed using ΔE-E analysis of the reconstructed proton energy with the PID energy signal offering clean identification up to proton energies of 650 MeV, well above the energy at which protons are stopped within the CB crystals.

The spin-orbit term in the nucleon-nucleus potential introduces an azimuthal modulation for the scattered proton given by [25, 26]

$$N(\theta_{sc},\phi_{sc}) = N_0(\theta_{sc})\left[1 + A(\theta_{sc})(P\cos\phi_{sc} - C_x^* P_\gamma^\odot \sin\phi_{sc})\right] \quad (1)$$

θ_{sc} and ϕ_{sc} describe the scattering of the protons off the carbon nuclei in a lab coordinate frame defined by $\mathbf{z'}$ along the initial proton momentum $\mathbf{p_{rec}}$; $\mathbf{y'}$ along $\mathbf{k}_\gamma \times \mathbf{k}_\pi$; and $\mathbf{x'}$ along $\mathbf{y'} \times \mathbf{z'}$. $N_0(\theta_{sc})$ is the unpolarized scattering distribution, $A(\theta_{sc})$ is the p-^{12}C analyzing power, P is the single polarization observable describing the induced polarization in the y-direction of the scattering frame, and $P_\gamma^\odot$ is the degree of circular polarization of the photon beam. To determine the scattering angles, the hit position in the graphite and CB were required. The latter was determined by averaging the positions of the struck CB crystals, weighted by the energy in each cystal. The former was approximated by assuming the proton with momentum $\mathbf{p_{rec}}$ initiated from the center of the target and scattered at the mid-point of the graphite scatterer. The vector between the two positions was then rotated into the coordinate frame described above.

During the experiment, the helicity of the photon was flipped randomly every second, and an asymmetry was formed between the azimuthal yields for positive and negative helicities N^+ and N^-,

$$\frac{N^- - N^+}{N^- + N^+} = \frac{A_e C_x^* P_\gamma^\odot \sin\phi_{sc}}{1 + A_e P\cos\phi_{sc}}. \quad (2)$$

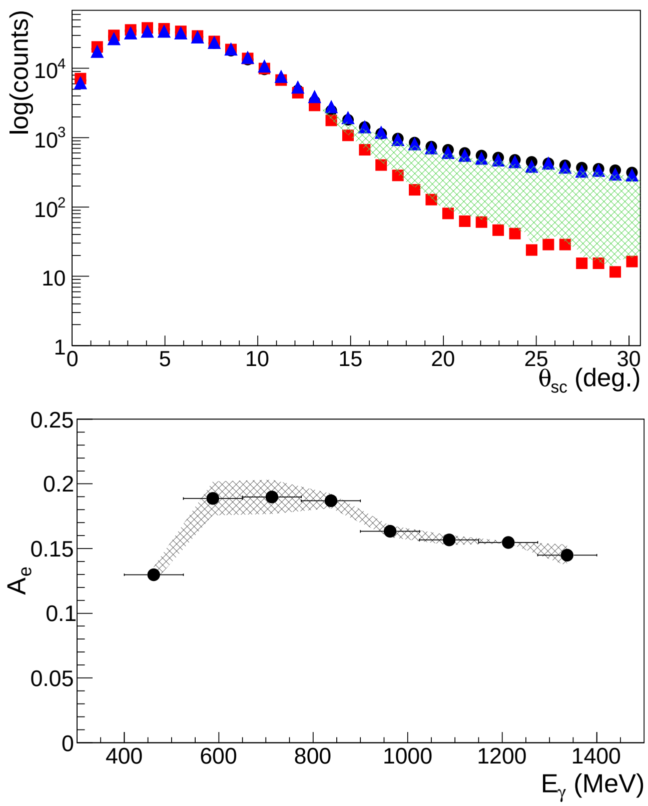

FIG. 2: (Color online) (Top) Comparison of θ_{sc} for data (circles), simulation (triangles), and the simulation with no hadronic interaction (squares). Nuclear scattered events lie in the shaded region. (Bottom) The average of the effective analyzing powers obtained from each model, integrated over θ_{CM}. The shaded region indicates the systematic error.

The above expression introduces A_e, the effective analyzing power of the events selected for analysis in that kinematic bin. A_e was averaged via the simulation over the accepted events. This required a realistic parameterization of polarized proton-Carbon scattering. Two methods were used for this to provide an estimate of the systematic uncertainty. In the first, the world dataset of proton-Carbon data [27–30] was fitted with the parameterization given in [30]. In the second, quasi-free scattering, which is dominant at these energies, was selected in the simulation and modelled using the SAID nucleon-nucleon scattering amplitudes [31], while non-quasi-free events were given the former parameterization. The resulting analyzing powers differed by ∼13%. This was however found to be the dominant uncertainty in the final results. A_e was obtained from the simulation by generating events with $P = 0$ and $C_x^* P_\gamma^\odot = \pm 1$. With these conditions the asymmetry, which is fitted to give

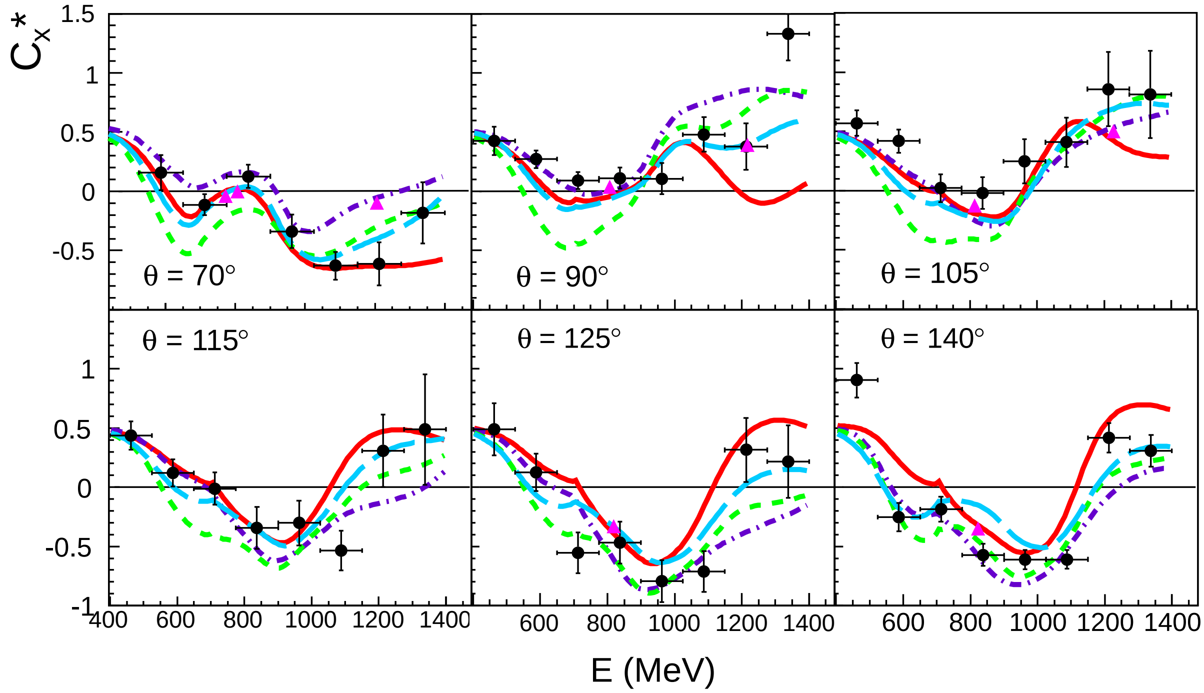

FIG. 3: (Color online) $C_x{}^*$ excitation functions for $\vec{\gamma}p \rightarrow \pi^0\vec{p}$ (black circles) for fixed pion CM polar angles. Previous data came from JLab Hall A [3] (magenta triangles). The PWA solutions shown are: SAID CM12 [33] (cyan long-dash line), SAID SN11 [34] (green short-dash line), BnGa2011-2 [35] (solid red line), and MAID07 [36] (violet dash-dotted line).

A_e, is:

$$\frac{N^- - N^+}{N^- + N^+} = A_e \sin\phi_{sc}. \quad (3)$$

Figure 2 demonstrates the excellent agreement between the simulated proton scatter angle and the distribution reconstructed in the experiment. Below 13° almost no events undergo a nuclear scatter and hence provide little information on the polarization, and the width of the distribution reflects the resolution of the angular reconstruction. Therefore the polarized scattering simulation was used to define the scatter angle acceptance where the figure of merit was greatest, i.e., where the statistical uncertainty on A_e, and thus the polarization measurement, was minimized. This was done for each kinematic bin, yielding the effective analyzing powers shown in Figure 2.

Using the optimized scatter angle cuts described above, the azimuthal distribution of accepted scatter events was produced for both real and simulated data. The contribution of the analyzing power was then removed by dividing the real by simulated distribution. The resulting asymmetry is given by dividing eq. (2) by eq. (3) :

$$A(\phi_{sc}) = \frac{C_x^* P_\gamma^\odot}{1 + A_e P \cos\phi_{sc}}. \quad (4)$$

The circular polarization of the MAMI photon beam P_{beam} can be calculated analytically [32] and varied from 30–85% over the E_γ range of the experiment. Values of P were taken bin-by-bin from the current SAID PWA and multiplied by the fits to A_e from the simulation. The extracted $C_x{}^*$ results show little sensitivity to the value taken for P, which gives a typical systematic uncertainty of ∼0.01. Background processes passing the analysis cuts were assessed through simulation to contribute less than 3.5% to the yield.

III. RESULTS

In Figure 3 the new $C_x{}^*$ data are presented as a function of incident photon energy for a range of fixed pion angles alongside the existing measurements from the Hall A Collaboration [3] at JLab. The data cover a center-of-mass energy (W) range of 1277−1872 MeV, and therefore give constraints on the properties of a large section of the nucleon resonance spectrum. The JLab data are limited in kinematic coverage because of the small acceptance of the polarimeter but are precise. The new data and Hall A measurements are consistent where they overlap, providing a convincing verification of the new technique.

Further interpretation of the results is obtained from comparison to the most recent predictions from the SAID PWA. These include the full available database of photomeson production reactions and meson-nucleon scattering data. Currently two parameterizations are available and have been used to extract information on the resonance spectrum. From Fig. 3 it is clear that our data are much better described by the newer SAID Chew-Mandelstam parameterization, shown as solution CM12, using a technology presented in Ref. [33], with $\chi^2/N = 1.7$, while the SN11 solution, using a formalism presented in Ref. [34], gives a relatively poor $\chi^2/N = 3.9$. It should be noted that both these parameterizations give a good description of the previous world database with a χ^2/N of $\sim$2. The differences in the extracted partial wave multipoles from adopting the different parameterizations are reported elsewhere [33] and include significant changes to phase of the $E_{0+}^{1/2}$. The CM12 fit more correctly incorporates the effect of opening quasi-two-body channels above the two-pion threshold. The current MAID [36] and Bonn-Gatchina [35] solutions are also shown on Fig. 3. These solutions agree with the overall trends in the new ${C_x}^*$ data, although with clear discrepancies for certain kinematic regions. All PWA models will clearly benefit from the constraints provided by this new data.

These results highlight the importance of new polarization observables in providing a stringent test of PWA methods and in producing new sensitivities, even in kinematic regions where a large number of cross section and polarization observables are already present in the world database. An accurate PWA must ultimately describe a complete set of observables. The current data and future experiments exploiting these polarimetry developments at large acceptance detectors will be a key part to achieving this complete measurement.

IV. SUMMARY AND CONCLUSION

A new polarimeter concept has been developed to determine the spin of the proton produced in nuclear and hadronic reactions with large acceptance and kinematic coverage. This novel, cost effective method for large acceptance spin-polarimetry could also find application at many other facilities with large acceptance particle detectors such as ELSA, JLab, and FAIR where new possibilities for spin observable measurements in meson spectroscopy, baryon spectroscopy and nuclear structure physics are possible.

In the commissioning experiment a comprehensive set of data for the transfer of polarization to the recoiling nucleon (${C_x}^*$) was obtained for neutral-pion photoproduction on the proton at incident photon energies from 0.4 to 1.4 GeV using the MAMI-C tagged-photon beam. The data are a central piece of the ongoing nucleon resonance program and give strong evidence that the Chew-Mandelstam formalism should be used if reliable information on the excitation spectrum is to be obtained.

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