# Measurement of the $^1H(\vec{\gamma},\vec{p})\pi^0$ 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. The measurement pioneers a novel polarimetry technique, which can be applied to many other nuclear and hadron physics experiments. The commissioning reaction of $^1H(\vec{\gamma},\vec{p})\pi^0$ in the range $0.4 < E_\gamma < 1.4$ GeV validates the technique and provides essential new data to constrain the excitation spectrum of the nucleon.

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Spin polarization observables are a powerful tool in nuclear and hadronic physics, providing essential constraints on the dynamics of strongly bound systems and ultimately nonperturbative quantum chromodynamics (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 polarimetry that achieves a determination of the spin polarization 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 large-acceptance spin-polarization data in a wide range of future hadronic and nuclear physics experiments including single and multiple meson photoproduction from the nucleon, deuteron photodisintegration, and deeply virtual Compton scattering. The polarimeter is commissioned using a measurement of the $^1H(\vec{\gamma},\vec{p})\pi^0$ reaction. The degree of polarization transfer from the incident circularly polarized photon beam to the recoiling proton can be extracted from the data, an observable referred to as $C_x^*$. There are sparse but accurate data for $C_x^*$ obtained at Jefferson Lab (JLab) [2,3], which can be used to test the new polarimeter.

Large acceptance measurements of beam-recoil observables such as $C_x^*$ are a prerequisite for improving our knowledge of the excitation spectrum of the nucleon, one of the highest priority programs in hadronic physics. A rich spectrum of excited states is expected for the nucleon, reflecting its composite nature as a strongly interacting system of valence quarks, sea quarks, and gluons. Recent theoretical advances such as lattice QCD [4], holographic dual QCD [5], and Dyson-Schwinger approaches [6] reveal the spectrum as a sensitive test of nonperturbative QCD. These complement the phenomenological approaches such as constituent quark models [7]. All theoretical approaches predict many more excited states than currently observed.

Extracting information on the excitation spectrum from meson photoproduction data involves fitting the world database of cross sections and polarization observables with partial wave analyses (PWA). Currently the masses, lifetimes, widths, electromagnetic couplings, and even the existence of many excited states are uncertain due to contradictory results between different PWA [8]. Accurately constraining PWA for pseudoscalar meson photoproduction requires at least seven appropriately chosen cross section or polarization observables [9]. This has led to a significant world-wide effort to produce polarized nucleon targets [10–12]. However, a full constraint on PWA necessitates large-acceptance measurements of double polarization observables, which include the polarization of the recoiling nucleon [13,14].

This experiment was carried out at the Mainz Microtron (MAMI) electron accelerator facility [15,16]. Circularly polarized bremsstrahlung photons were energy tagged in the range 0.4–1.4 GeV by the Glasgow-Mainz tagger [17,18] and impinged on a 5 cm long liquid hydrogen target. Reaction products were detected with the Crystal Ball (CB) [19–21], a highly segmented NaI(Tl) photon calorimeter covering nearly 96% of $4\pi$, and the Two Arm Photon Spectrometer (TAPS) $BaF_2$ array [22,23], which covered polar angles of $\theta = 5°–20°$. The experimental apparatus is shown schematically in Fig. 1. The particle identification detector (PID) [24], a 24 element scintillator barrel 50 cm long and 0.4 cm thick, surrounded the target and provided charged particle identification. The analyzing material for the polarimeter comprised a 2.25 cm thick graphite cylinder covering $\theta \geq 12°$ placed outside the PID and a 7.25 cm thick downstream 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 analyzing material. The spin-orbit term in the nucleon-nucleus potential introduces an azimuthal modulation for the scattered protons [25,26], given by

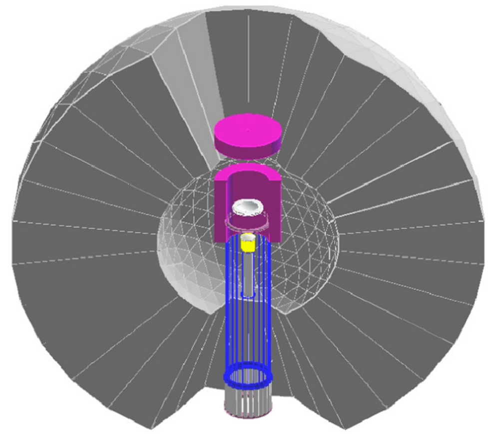

FIG. 1 (color online). Illustration of the experimental setup. The liquid hydrogen target (yellow cylinder), situated at the center of the CB, is surrounded by the PID (blue) and the 2.25 cm thick graphite polarimeter. The 7.25 cm thick downstream cap covers the aperture to TAPS (not pictured). The PID was flush with the cap during production running but has been shifted here for visual clarity.

$$N(\theta_s,\phi_s) = N_0(\theta_s)[1 + A(\theta_s)(P\cos\phi_s - C_x^* P_\gamma^\odot \sin\phi_s)]. \tag{1}$$

$\theta_s$ and $\phi_s$ are the polar and azimuthal scattering angles of the proton in the frame where $\mathbf{z}'$ points in the direction of the incident nucleon and $\mathbf{x}'$, $\mathbf{y}'$ are defined from the plane containing the photon and the reaction products [27]. $N_0(\theta_s)$ gives the polar angle dependence of the scattering distribution for unpolarized protons. The bracketed term results in an azimuthal modulation of the scattering distribution in the case of polarized protons. This produces a cosine modulation with magnitude proportional to $P$, the single polarization observable describing the induced polarization, and a sine modulation proportional to $C_x^*$, the transferred polarization. $A(\theta_s)$ is the analyzing power for $p$-$^{12}C$ scattering, which influences the magnitude of the modulation. $P_\gamma^\odot$ is the degree of circular polarization of the photon beam. Successful operation of the polarimeter requires the scattered events to be cleanly identified for a wide range of incident proton angles and energies.

This analysis utilizes a kinematic reconstruction of the scattering of the protons in the graphite analyzer. The momentum of the proton from the $^1H(\vec{\gamma},\vec{p})\pi^0$ reaction, $\mathbf{p}_{\rm rec}$, was reconstructed using the measured momenta of the incident photon and the $\pi^0$. The $\pi^0$ decays inside the target and its momentum is reconstructed by detecting the photons from the $\pi^0 \to 2\gamma$ decay [28]. The proton momentum reconstruction was checked by requiring a hit in the PID element on the path of the reconstructed proton. Further checks on the particle identification were obtained from the correlation of the energy deposited in the struck PID element, $\Delta E$, and the reconstructed proton energy $E$. This $\Delta E$-$E$ analysis gave clean identification up to proton energies of 650 MeV.

The location of the point ($A$) where the proton scattered in the analyzer was determined from $\mathbf{p}_{\rm rec}$, assuming it was emitted from the target center and that the scatter took place half way through the analyzer. The point ($B$) where the proton entered the CB or TAPS was obtained from an energy weighted average of the locations of the struck crystals. The vector **AB** was taken as the direction of the scattered proton and together with $\mathbf{p}_{\rm rec}$ gave $\theta_s$ and $\phi_s$.

During the experiment the circular polarization, or helicity, of the incident photon was flipped randomly every second. An azimuthal asymmetry was formed between the yields for positive and negative helicities $N^+$ and $N^-$,

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

where $A_e$ is the effective analyzing power for the accepted events. $A_e$ was determined via the simulation, which required a realistic parametrization of polarized proton-$^{12}$C scattering. Two methods were used for this to provide an estimate of systematic uncertainties. For the first method the world data set of proton-$^{12}$C scattering data [29–32] was fitted with the parametrization given in Ref. [32]. For the second method quasifree scattering events were identified in the simulation, using the event information available in GEANT4. These events arise from scattering on a quasifree nucleon in $^{12}$C rather than the $^{12}$C nucleus. Their scattering was modeled using nucleon-nucleon scattering amplitudes extracted from experimental data [33], while non-quasi-free events were modeled using the former parametrization.

$A_e$ was obtained from the simulation by generating $p\pi^0$ events with $P = 0$, $C_x^* P_\gamma^\odot = \pm 1$ and a reaction vertex randomized within the target cell. With these conditions the asymmetry, which is fitted to give $A_e$ for each kinematic bin is

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

Figure 2 demonstrates the excellent agreement between the polar scatter angle distributions for simulated events and the experimental data. Below 12° the yield of nuclear scatter events is negligible and little information can be extracted on the recoil proton polarization. The width of the distribution reflects the angular resolution of the reconstruction. The simulation was used to define the scatter angle regions where the statistical uncertainty on $A_e$, and, thus, the polarization measurement, was minimized [34]. The two models used for calibrating the analyzing power were averaged to give the final results for $C_x^*$. The variation in the analyzing power is illustrated in the top panel of Fig. 2. The resulting mean variation in $C_x^*$ was 0.04.

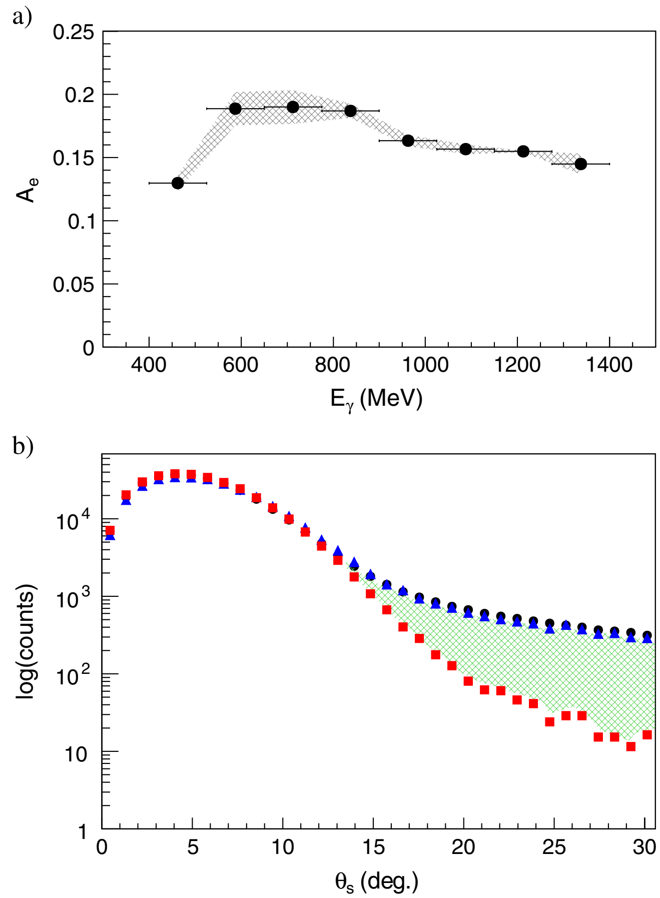


FIG. 2 (color online). Top: the effective analyzing power, obtained by averaging the results from each scattering model, integrated over $\theta_{\rm CM}$, the pion angle defined in the center-of-mass frame of the photon and $^1H$ target. The shaded band indicates the systematic error, obtained from the difference between the two models. Bottom: comparison of $\theta_s$ distributions from experiment (circles) and simulation with (triangles) and without (squares) hadronic interactions. Nuclear scattered events lie in the shaded region.

Using the optimized scatter angle regions described above, the azimuthal distribution of accepted scatter events was extracted for both real and simulated data. The contribution of the analyzing power was then removed by dividing the real by the simulated azimuthal distributions to get

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

The circular polarization of the MAMI photon beam $P_\gamma^\odot$ can be calculated analytically [35] and varied from 30%–85% over the $E_\gamma$ range of the experiment. Values of $P$ were taken bin by bin from the current SAID PWA [36,37] and multiplied by the fits to $A_e$ from the simulation.

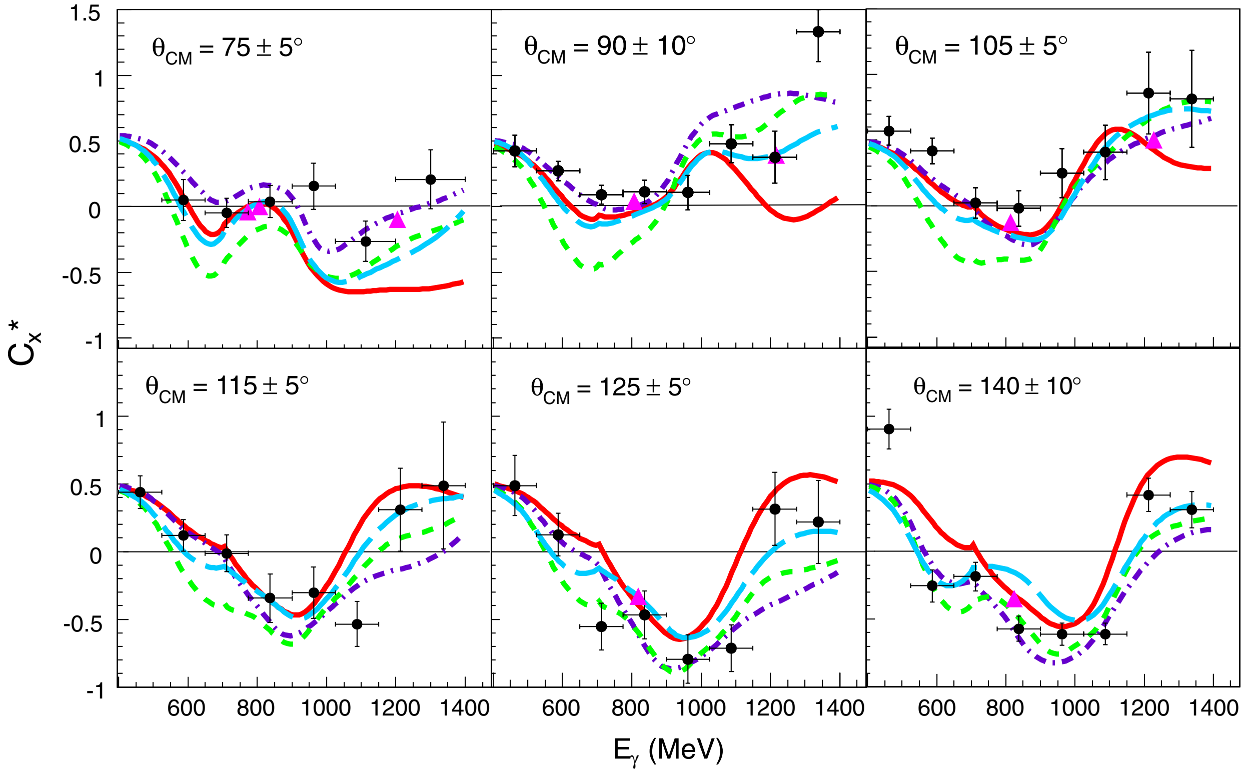


FIG. 3 (color online). $C_x^*$ excitation functions for $\vec{\gamma}p \to \pi^0\vec{p}$ (black circles) for fixed pion polar angles $\theta_{\rm cm}$. Previous data came from JLab [2] (magenta triangles). The PWA solutions shown are SAID CM12 [36] (cyan long-dash line), SAID SN11 [37] (green short-dash line), BnGa2011-2 [38] (solid red line), and MAID07 [39] (violet dash-dotted line).

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.

In Fig. 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 JLab [2]. The JLab data are limited in kinematic coverage because of the small acceptance of the polarimeter but are precise. The new data and JLab measurements are consistent where they overlap, providing a convincing verification of the new technique.

The data cover a center-of-mass energy ($W$) range of 1275–1870 MeV, and therefore give new constraints on the properties of a substantial section of the nucleon excitation spectrum. Further interpretation of the results is obtained from comparison with the MAID [39], SAID [36,37], and Bonn-Gatchina (BnGa) [38] PWA. The last two analyses include the full available database of meson photoproduction reactions and meson-nucleon scattering data. Currently two parametrizations of SAID are available that describe the world database with similar accuracy but use different PWA formalism. From Fig. 3 it is clear that our $C_x^*$ data are better described by the new Chew-Mandelstam formalism [36] (CM12) over that of SN11 [37], with a respective $\chi^2$ per degree of freedom of 1.7 and 3.9. The CM12 formalism includes rescattering effects in the meson photoproduction amplitude, which influences the extracted nucleon resonance properties [36]. The current MAID and Bonn-Gatchina [38] solutions are also shown in Fig. 3. These solutions agree with the overall trends in the new $C_x^*$ data, although with clear discrepancies for certain kinematic regions.

Future PWA will clearly benefit from the constraints provided by these new data, which highlight the importance of new polarization observables in providing a stringent test of PWA, even in kinematic regions where a large number of cross section and polarization observables are already present in the world database. An accurate partial wave analysis 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. In this regard future experiments to measure the spin polarization of neutrons are already planned at MAMI [40].

In summary, a new polarimeter concept has enabled the first large-acceptance measurement of the spin polarization of protons produced in nuclear reactions. 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, Jefferson

Lab, and FAIR where measurements of spin observables would enhance a range of physics programs. The commissioning measurement of $^1H(\vec{\gamma},\vec{p})\pi^0$ for $E_\gamma = 0.4$–$1.4$ GeV provides a comprehensive data set on the transfer of polarization from a circularly polarized photon beam to the recoiling proton ($C_x^*$). Measurements of such observables with large acceptance are crucial to the world program aiming to determine the excitation spectrum of the nucleon.

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