Letter of Intent to Jefferson Lab PAC 22

Pion Photoproduction from a Polarized Target

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Abstract

We propose to study single pion-photoproduction reactions, $p(\gamma,\pi^+)n$ and $p(\gamma,p)\pi^0$, with polarized beam and polarized target using the CLAS detector at Jefferson Lab Hall B. The experiment will measure the unpolarized cross section, $d\sigma/d\Omega$, as well as single- (Σ, T, and P) and four double-polarization observables (E, G, F, and H). The data will greatly constrain partial-wave analyses and reduce model-dependent uncertainties in the extraction of nuclear resonance properties, as well as provide a new benchmark for comparison with theory. The measurement will span $\cos(\theta_{c.m.})$ from -0.9 to 0.9 in a center-of-mass energy range above 1400 MeV.

1 Motivation

1.1 Physics of interest

Through analyses of decades worth of data, from both hadronic and electromagnetic scattering experiments, we have found numerous baryon resonances, and have determined their masses, widths and quantum numbers. Many more states, predicted by quark models, have either eluded detection or have produced only weak signals in the existing data set. Such states provide a natural motivation for future measurements at Jefferson Lab.

A more complete knowledge of the resonance spectrum would be invaluable to studies focused on the grouping [1] of states into Höhler clusters, Regge trajectories and parity doublets, and the possibility of chiral-symmetry restoration exhibited by the high-lying (and poorly determined) states. It is equally important to have precisely determined properties for the well-established resonances, as these are likely to be less model dependent, and existing data already suggest deviations from quark-model predictions for their decay properties.

While a few resonances (such as the $\Delta(1232)$, $N(1520)$, and $N(1680)$) have a strong signal in the cross section, with clear Breit-Wigner behavior in their associated multipole amplitudes, these are exceptional cases. In general, more detailed analyses of the experimental data are required to extract properties of the N^* and Δ^* resonances. As we will demonstrate, having just unpolarized cross sections and single polarization observables alone is not sufficient to resolve discrepancies between the extensive SAID [2] and MAID [3] analyses. The need for the measurement of double polarization observables, which require a polarized target, then becomes obvious.

1.2 Extracting resonance information

Pion photoproduction has long been analyzed in order to extract the photodecay amplitudes associated with the N^* and Δ^* resonances. Extensive fits to elastic pion-nucleon scattering have provided mass and width values for the contributing resonances. Multipole phases are also linked to corresponding pion-nucleon phase shifts, through Watson's theorem, up to the onset of inelasticity.

However, above the two-pion production threshold, multipole analysis becomes increasingly model-dependent. The GW (SAID) and Mainz (MAID) fits to this region attempt to describe the available data, within the constraints obtained from pion-nucleon scattering, employing different phenomenology. In the MAID approach, resonance parameters are varied in fitting the data. The SAID approach is to first obtain multipole amplitudes in a manner as "model-independent" as possible. The extracted multipoles are then refitted to functional forms having both resonance and background contributions.

Differences between these approaches are most evident in predictions for observables not yet measured. Each new measurement provides further constraints related to a different bi-linear combination of helicity amplitudes. Below we outline what types of data are currently available in the database, and consider which measurements are both necessary and best suited to the CLAS detector.

1.3 Observables

There are three objects in the reaction $\gamma N \to N\pi$ that can carry polarization: photon beam, target nucleon, and recoil nucleon. Hence, there are three possible types of double polarization experiments: beam/target, beam/recoil, and target/recoil. The total number of observables is 16. The formalism and definitions of observables commonly used to describe pseudoscalar meson photoproduction can be found in Ref. [4]. Since we cannot measure recoil polarization with the CLAS, it leaves us the beam/target group, and we will discuss only these observables; they are shown in Table 1.

Table 1: Observables in single-pion photoproduction with polarized target and/or polarized photons. See also Ref. [4].

	Photon beam		
Target	unpolarized	circularly polarized	linearly polarized
unpolarized	$d\sigma/d\Omega$	—	Σ
longitudinally	—	E	G
transversely	T	F	H, P

The cross section for the beam/target polarization experiment is expressed as

$$\frac{d\sigma}{dt}\bigg/\frac{d\sigma}{dt}_{\text{unpol}} = 1 - P_T\Sigma\cos(2\phi) + P_X\left[-P_T H\sin(2\phi) + P_\odot F\right] - P_Y\left[-T + P_T P\cos(2\phi)\right] - P_Z\left[-P_T G\sin(2\phi) + P_\odot E\right],$$

for various orientations of the beam and target polarization. In the above expression, $P_\odot$ is the degree of right-circular beam polarization, P_T gives the transverse polarization (at an angle ϕ with respect to the reaction plane), and $P_{X,Y,Z}$ is the target polarization. At present, only $d\sigma/d\Omega$ and Σ could be measured with the CLAS. With these two quantities alone it is impossible to reconstruct even moduli of individual helicity amplitudes. If Hall B would be equipped with the polarized target, then all the observables from Table 1 become measurable.

While a formally complete experiment requires the measurement at each energy and angle of at least eight observables [5], the current database for pion photoproduction is populated mainly by unpolarized cross sections. Table 2 illustrates this quite clearly. The fraction of double polarization data is on the level of 2–3%.

Table 2: Relative weight of unpolarized and polarized data in the database.

	$p(\gamma,p)\pi^0$	$p(\gamma,\pi^+)n$
unpolarized	76%	70%
single-polarized	22%	27%
double-polarized	2%	3%

1.4 The influence of polarization measurements

As is evident in Fig. 1, cross section data alone is insufficient to isolate resonance contributions and distinguish between the various analyses. The resonance region may include on the order of 100 resonances, but has only three distinct "bumps".

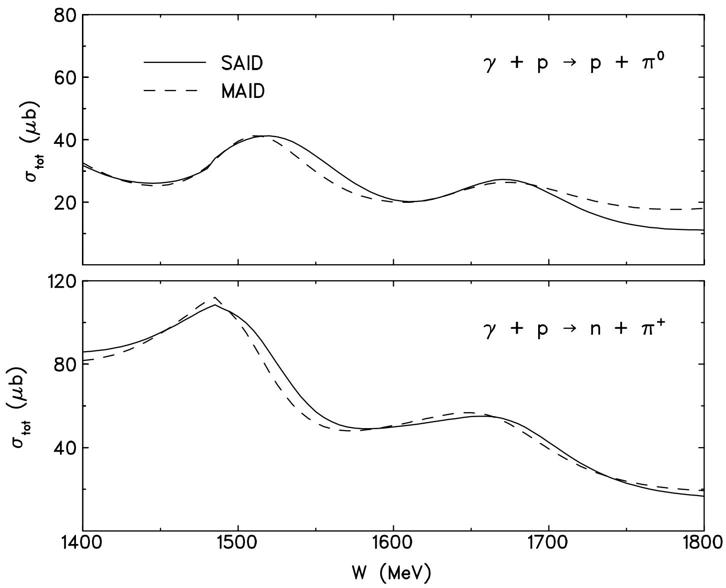

Figure 1: Total cross section for the π^0 and π^+ photon-production on the proton. The solid and dashed curves show SAID and MAID predictions respectively.

The beam polarization, Σ has been useful in isolating resonance components in the $\Delta(1232)$ region, and more recently at higher energies [6]. Whereas both SAID and MAID analyses agree reasonably well for Σ (top part of Fig. 2), there is substantial difference in their predictions for G. This, perhaps, is not so surprising. Single polarization observables are sensitive to the moduli of helicity

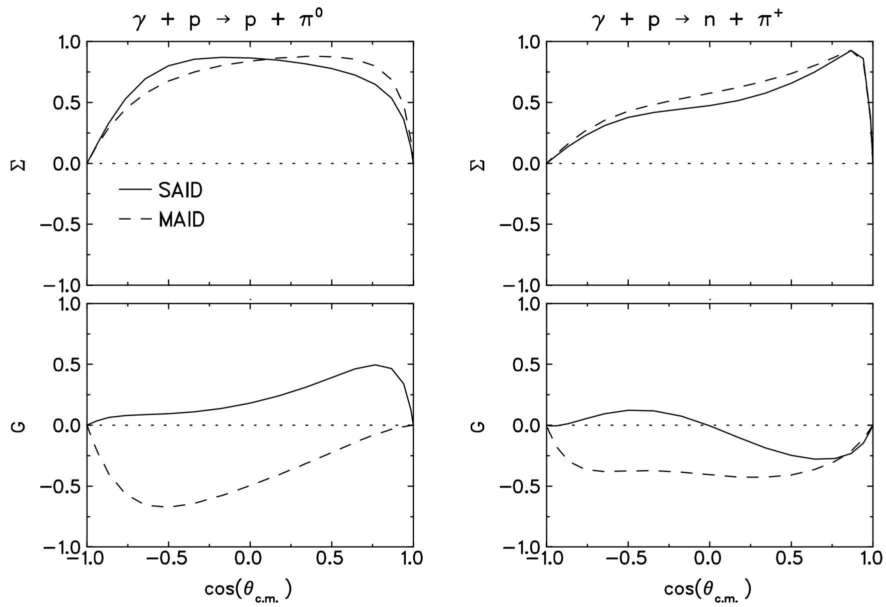

Figure 2: Polarization observables Σ and G in the $p(\gamma,p)\pi^0$ reaction (left panel) and $p(\gamma,\pi^+)n$ reaction (right panel) at $W = 1500$ MeV along with SAID (solid curve) and MAID (dashed curve) results.

amplitudes, while double polarization observables are sensitive to their relative phases. A small variation of amplitude may have little effect on single polarization observables, but at the same time the interference could be rather large. To resolve this ambiguity the analysis must be constrained by the experimental data on double polarization, which are not available.

Whereas both codes agree reasonably well for Σ, there is a substantial difference in G. This highlights the incompleteness of the present dataset and as a result an ambiguity in the underlying helicity amplitudes.

An overview comparison of SAID and MAID calculations for selected single- and double-polarization observables is shown in Fig. 3. Plotted is the squared difference between the SAID and MAID summed over 19 scattering angles from $0°$ to $180°$. Figure 4 shows another way to look at the sensitivity of observables to the presence or absence of certain resonances. Three different results of MAID are plotted for the differential cross section and the double-polarization observable G for π^+ photo-production at $W = 1500$ MeV. The MAID full calculation includes the $P_{33}(1232)$, $P_{11}(1440)$, $D_{13}(1520)$, $S_{11}(1535)$, $S_{31}(1620)$, $S_{11}(1650)$, $F_{15}(1680)$, and $D_{33}(1700)$ resonances and is shown as solid curve. The dashed curve results if one excludes the $P_{11}(1440)$ resonance; the dotted curve excludes the $S_{11}(1535)$ resonance. These different model results have little effect on the differential cross section (upper panel of Fig. 4), but are significantly different

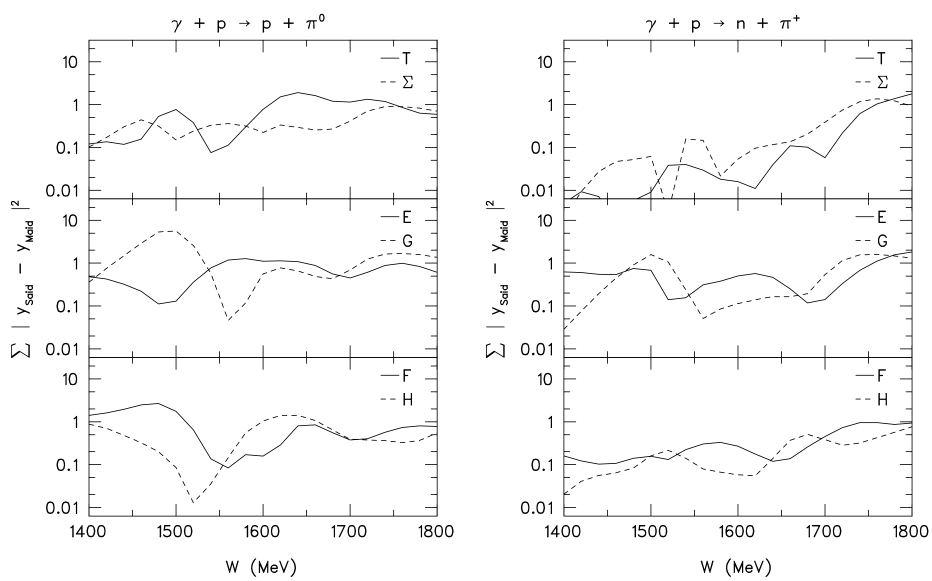

Figure 3: Comparison between SAID and MAID calculations for selected polarization observables in the $p(\gamma,p)\pi^0$ reaction (left panel) and $p(\gamma,\pi^+)n$ reaction (right panel). Plotted is the squared difference between the SAID and MAID results summed over 19 scattering angles from $0°$ to $180°$.

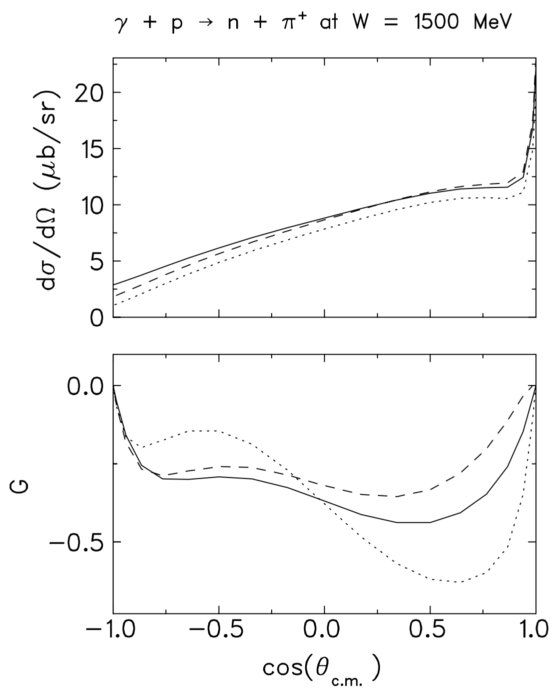

Figure 4: MAID calculations of the differential cross section and double-polarization observable G in the $p(\gamma, \pi^+)n$ reaction at $W = 1500$ MeV; full calculation (solid curve), full calculation with $P_{11}(1440)$ resonance removed (dashed line), full calculation with $S_{11}(1535)$ resonance removed (dotted line).

for G (lower panel). Despite the simplicity of this comparison — normally the removal of a resonance in any model requires a refitting of the remaining model parameters — it demonstrates the very different sensitivities of cross section and polarization observables.

A second example, using measurements related to the beam-target polarization quantity E, is provided by a recent Mainz study [7]. There a variation in the $N(1520)$ photo-decay couplings was suggested in order to explain deviations of the new measurement from predictions of the MAID analysis.

The high sensitivity of the double polarization observable to resonance parameters makes them an indispensable tool for further progress in baryon spectroscopy.

1.5 What can we add with an experiment at CLAS?

Above the second resonance region (1520 MeV), the existing database for pion photoproduction is quite sparse, with few experiments covering large angular ranges at fixed energies. This shortcoming, coupled with the need to simultaneously analyze data from several laboratories (with different inherent systematic errors), often measured decades apart, has necessarily led to highly model-dependent analyses.

The CLAS detector, with its ability to measure both $\theta_{c.m.}$ and ϕ distributions in a broad angular range, combined with the Photon Tagger Facility in Hall B at Jefferson Lab, is uniquely positioned to host a new generation of high-quality photoproduction experiments, with small statistical uncertainties and well understood systematic uncertainties, see for example Ref. [10] for pion photoproduction with an unpolarized target. The full potential of CLAS can be achieved with the addition of a polarized target.

2 Proposed measurements

We propose to use the Photon Tagging Facility [8] with the large acceptance detector CLAS, in Hall B at the Jefferson Laboratory, to perform precision measurements of pion-photoproduction from a polarized proton target in the resonance region. The ability of CLAS to measure over wide ranges in $\theta_{c.m.}$ and ϕ, together with the photon energy information from the tagging facility, provide an ideal environment for these measurements. The plan outlined in this LoI leads to future experiments of photoproduction from the neutron - this will require development of a polarized deuterium (neutron) target.

2.1 Tagged photon beams

The tagging facility in Hall B has reliably provided all of unpolarized, circularly polarized and linearly polarized tagged photon beams. Most of the experiments to date have used unpolarized tagged photon beams, at energies, E_γ, from 20% to 95% of the incident electron beam energy, E_e.

Circularly polarized photon beams are produced using a beam of longitudinally polarized electrons incident on the bremsstrahlung radiator. The degree of circular polarization of the photon beam depends on the ratio E_γ/E_e, and ranges from 60% to 99% of the incident electron beam polarization for photon energies of 50% to 95% of the incident electron energy [9].

Linearly polarized photon beams are produced using coherent bremsstrahlung from a thin diamond radiator. This technique has been successfully employed for the first part of the CLAS-g8 run period. The degree of polarization can reach 80%-90% and is a function of the fractional photon beam energy and collimation.

2.2 Polarized target

A frozen spin target for CLAS would complete the requirements for this new generation of experiments. A longitudinally polarized target will provide measurements of G using linearly polarized photons, and measurements of E using

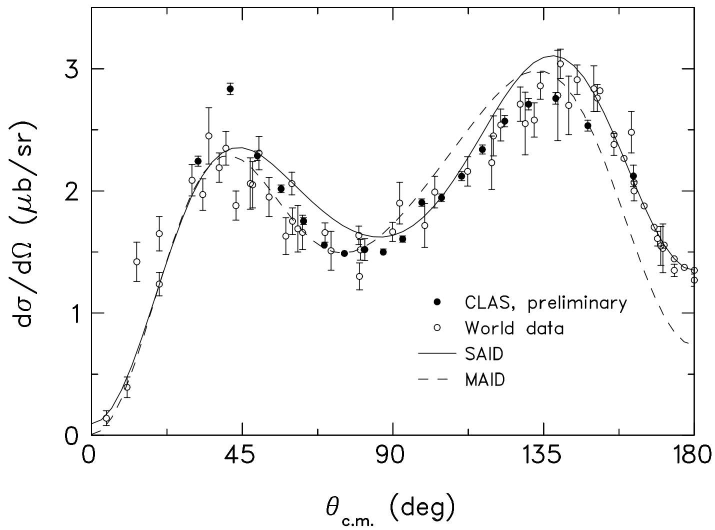

Figure 5: Preliminary differential cross section data in the $p(\gamma,p)\pi^0$ reaction at $E_\gamma = 1000$ MeV from the CLAS g1c run group (solid circles) [10], analysis by M. Wood. These data are compared to other world data (open circles), along with SAID (solid line) and MAID (dashed line) predictions.

circularly polarized photons, producing information to improve existing multipole analyses. With the eventual availability of a transversely polarized target, the measurements could be extended to T, H, P, and F, to provide an almost complete set of observables for (γ,π) reactions.

The dynamically polarized target currently used for electron-beam experiments with CLAS has the disadvantage of requiring the target to be located inside a strong and very uniform magnetic field. The magnet needed to produce this field occupies a large fraction of the space around the target sample, leaving a relatively small acceptance for outgoing particles. A frozen spin target would thus be the only choice for the proposed measurements.

2.3 Analysis technique

The analysis of the reaction $\gamma p \to \pi^0 p$ and $\gamma p \to \pi^+ n$ will be done using standard particle identification procedure for protons and positive pions detected in CLAS. Undetected π^0 and neutron will be reconstructed using missing mass technique assuming two body kinematics. This method was developed and proven successful for unambiguous selection of the reaction channel in the analysis of CLAS-g1 data [10]. Preliminary results of CLAS g1c differential cross section data are shown in Fig. 5 along with old data and SAID and MAID predictions. The preliminary CLAS data show reasonable agreement with SAID and MAID results, though not included in both analyses.

The important difference between the proposed experiment and previous photoproduction experiments with CLAS is an extra source of a background, the background associated with the reaction on bound nucleons. This effect constitutes additional sources of the systematic uncertainty. In order to keep it under control, we plan to place additional carbon target downstream of the main target and collect data from both targets simultaneously.

3 Summary

We propose to use the CLAS detector and photon tagging facility in Hall B at Jefferson Laboratory, together with a frozen spin-polarized target to perform high-precision measurements of the observables $d\sigma/d\Omega$, Σ, T, P, E, G, F, and H in pion photoproduction for W in the range above 1400 MeV and covering $\cos(\theta_{c.m.})$ from -0.9 to 0.9; utilizing the full angular acceptance of CLAS. These measurements will provide a high-precision data set, with small statistical uncertainties and well-understood systematic uncertainties, which will be used in Partial-Wave Analyses of photoproduction data to improve the quality of the global fits and reduce the model dependence uncertainties when extracting resonance parameters from the data.

This proposed experimental program is a natural continuation of the measurements already made on pion photoproduction from the nucleon, performed with CLAS in experiments E94-103 [10]. In addition, a number of other proposals to study photoproduction of other mesons $(K, \eta, \eta', \rho, \omega, \ldots)$ using a spin-polarized target are being prepared. It is likely that the experimental requirements for these other measurements would be similar to those for the present proposed measurements, permitting the data to be taken concurrently for all the meson photoproduction experiments. The experimental conditions for the part of the proposed experiment, which requires a circularly polarized beam incident on a longitudinally polarized target, are similar to approved experiment E01-104 [11]. It may be feasible to take part of the data for both experiments in one run.

The preparations for running the experiment will require extensive Monte-Carlo simulation in order to understand the background contributions to the reaction channels of interest, to determine the optimal experimental conditions (CLAS field setting, electron beam energy, target dimensions) and to estimate the final uncertainties and the required beam time.

If there is interest in the experimental program outlined in this Letter of Intent, we believe that a full proposal could be prepared for the next PAC meeting.

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