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THE STUDY OF EXCITED BARYON RESONANCES*

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Nucleons are complex systems of confined quarks and exhibit characteristic spectra of excited states. Highly excited nucleon states are sensitive to details of quark confinement which is poorly understood within Quantum Chromodynamics (QCD), the fundamental theory of strong interactions. Observing and understanding these higher-mass resonances is crucial, but they are difficult to observe since they are broad and overlapping. Very often, these higher-lying states reveal themselves more clearly through interference with dominant amplitudes. The interference terms can be isolated via polarization observables. At Jefferson Lab, extensive data sets on photo- as well as electro-production of pseudo-scalar mesons (π, 2π, η, K) and vector mesons (ρ, ω, ϕ) have been accumulated over the last few years using the CLAS spectrometer. The current efforts with CLAS focus on utilizing highly-polarized hydrogen and deuterium targets in combination with polarized photon beams toward a complete measurement of a large number of reaction channels. This contribution discusses recent results on single- and double-pion photoproduction.

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1. Introduction

The mass spectrum of hadrons is clearly organized according to flavor content, spin and parity. For intermediate and long-distance phenomena such as hadron properties, the full complexity of QCD emerges, including nonlinearity and confinement, and is a strong obstacle to understanding hadronic phenomena at a fundamental level. Lattice-QCD studies are making progress towards the solution of the QCD Lagrangian in the low-energy regime and for bound states, but more development is required. In the meantime, quark models have been developed to predict the properties of

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hadronic states. Thus, the primary goals of hadron physics are to determine the relevant degrees of freedom at different scales, to relate them to each other, and ultimately to the parameters and fundamental fields of QCD.

Models based on three constituent quark degrees of freedom predict many more states in the baryon mass spectra than have been seen experimentally. Consequently, these states are called *unobserved* or *missing*. The majority of the known non-strange baryon resonances stems from πN scattering experiments and the hitherto unobserved resonances have been predicted to couple only weakly to this channel. Although photoproduction of a single-pion is less likely to detect states not seen in pion–nucleon studies, it is the most well-developed of the meson-photoproduction programs, having an extensive database for which many single- and multi-channel fits are available. For this reason, studying the production of a single-π in photo-induced reactions will greatly enhance our understanding of the nature and also of the properties of well-known nucleon excitations.

2. Photoproduction of a single π-meson at CLAS

Cross-section data on the photoproduction of a single pion measured with the CEBAF Large Acceptance Spectrometer (CLAS) [1] and the photon-tagging facility [2] in Hall B of the Thomas Jefferson National Accelerator Facility (JLab) have been presented recently as part of a broader program of meson photoproduction measurements. In [3], results for the reaction $\gamma p \to p\pi^0$ were discussed; resonance couplings were extracted in the SAID analysis framework. A strong excitation of the $N(1720)P_{13}$ resonance was observed, consistent with an analysis of $\pi^+\pi^-$ electro-couplings. No new nucleon resonances were needed to describe the data. Fig. 1 shows differential cross-sections for the reaction $\gamma p \to n\pi^+$ [4]. With the addition of these recent cross-section data to the world database, the new SAID solution is more satisfactory at higher energies. However, resonance couplings have not changed significantly and no new resonances are needed.

In general, cross-section data are still sparse above an incident photon energy $E_\gamma = 1.7\,\mathrm{GeV}$, and have come from untagged bremsstrahlung measurements in many cases. As a result, all photo-decay amplitudes for the higher N^* states have an inherent uncertainty beyond any model due to the background-resonance extraction process. While some theory-based model dependence is unavoidable, cross-sections measured using a tagged-photon beam, with incident photon energies covering the full resonance region, will provide tighter and more reliable constraints for future analyses of the properties of excited nucleons.

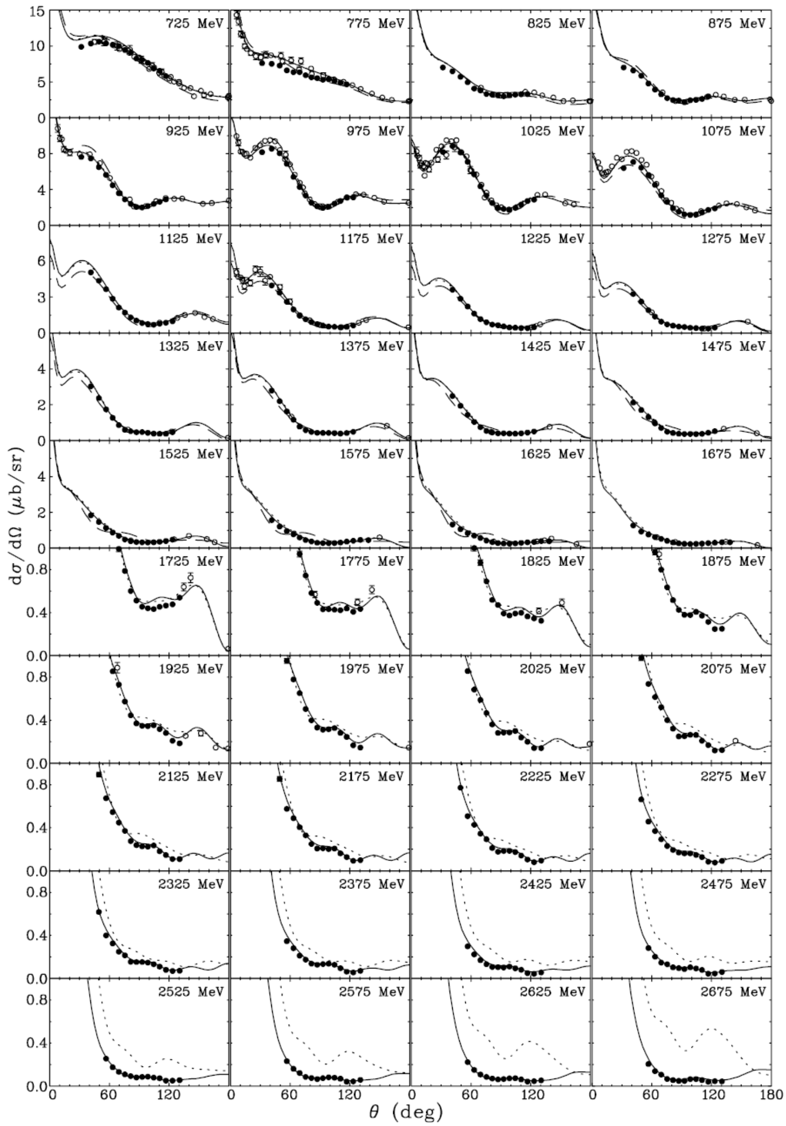

Fig. 1. The differential cross-section for $\gamma p \to \pi^+ n$ below $E_\gamma = 2.7\,\mathrm{GeV}$ *versus* pion center-of-mass scattering angle [4]. Solid (dotted) lines correspond to the SAID FA08 (FA07) solution. Dashed lines give the MAID07 [5] predictions. Experimental data are from the current (filled circles) and previous measurements (open circles). The plotted points from previously published experimental data are those data points within 3 MeV of the photon energy indicated on each panel. Plotted uncertainties are statistical.

3. Double-pion photoproduction: $\gamma p \to p\pi^+\pi^-$

In recent years, results in the spectroscopy of baryon resonances have indicated that 3-body final states are very likely key for the discovery of higher-lying missing states because they account for most of the cross-section above $W \approx 1.7$ GeV. Highly excited baryon states are predicted to decay into particles with higher masses, *i.e.* excited intermediate states rather than a ground-state nucleon and a meson. Calculations of decays for those resonances into two-particle channels like $N\pi$, $N\eta$, and $N\omega$ yield very small partial widths. However, high-mass states have total widths of at least 150 MeV, thus the remaining decay strength must lie in reactions with higher thresholds. Two-body final states have been largely explored. Nonetheless, many questions in the field of single-meson production are still awaiting an answer and the JLab-FROST (double-polarization) experiment will help shed light on many open issues.

One of the key experiments in the search for yet unobserved states is the investigation of double-pion photoproduction. Quark models predict large couplings of those states to $\Delta\pi$, for instance. In the case of a linearly-polarized photon beam and an unpolarized target, the cross-section for the photoproduction of two pseudoscalar mesons can be written in the form:

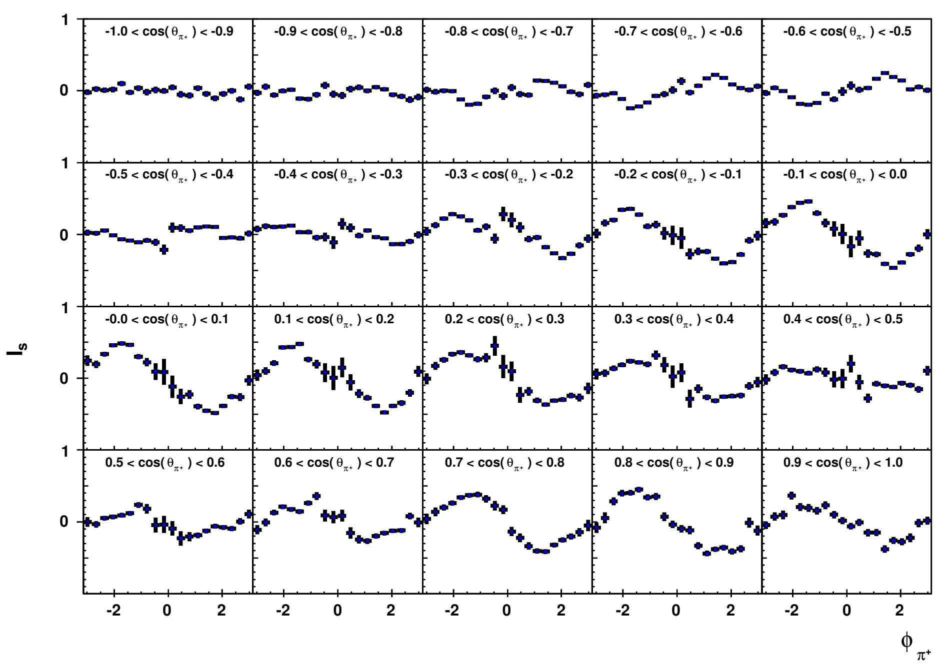

Fig. 2. Preliminary beam asymmetry $\boldsymbol{I}^{\rm s}$ for $E_\gamma \in [1.10, 1.15]$ GeV for the reaction $\gamma p \to p\pi^+\pi^-$. Surprisingly big values for the observable have been observed.

$$I = I_0(1 + \delta_l\,(\boldsymbol{I}^{\rm s}\sin 2\beta + \boldsymbol{I}^{\rm c}\cos 2\beta))\,, \tag{1}$$

where I_0 denotes the unpolarized cross-section, δ_l the degree of linear polarization of the photon beam, and $\boldsymbol{I}^{\rm s}$, $\boldsymbol{I}^{\rm c}$ the beam asymmetries. The two observables occur for two mesons in the final state since the reaction is no longer restricted to a single plane. Fig. 2 shows an example for the observable $\boldsymbol{I}^{\rm s}$ in $\gamma p \to p\pi^+\pi^-$ from the CLAS g8b run group. The variables ϕ and θ denote the azimuthal and polar angle of the π^+ in the rest frame of the two mesons. The expected odd behavior of the distribution is clearly visible.

4. The double-polarization program

The g9-FROST program at JLab anticipates to take data for all four combinations of beam and target polarization, thus providing (almost) complete sets of measurements for π^0, π^+, η, η', and $\pi^+\pi^-$ photoproduction. The program using a longitudinally-polarized target has been completed successfully in the spring of 2008. The additional determination of the recoil polarization in hyperon production, completes polarization measurements for the reactions $\gamma p \to K\Sigma$ and $\gamma p \to K\Lambda$. At the time of this writing, data using a transversely-polarized target are being accumulated. The FROST program was awarded beam time to determine all observables over a large range in production angle and energy with anticipated statistical errors between ± 0.05 and ± 0.07.

4.1. The FROzen-Spin Target (FROST)

For the recent double-polarization measurements, the frozen-spin (butanol) target was positioned in the geometrical center of CLAS with a minimum amount of material in the path of outgoing particles. The target cryostat is of horizontal type with a pipe of about 200 cm in length and 25 cm in diameter. Since CLAS is a magnetic spectrometer, its operational characteristics are very sensitive to the additional magnetic field produced by the target. For this reason, the target material was dynamically polarized by microwave irradiation in a strong magnetic field of 5 T at a temperature of about 1 K outside of CLAS. After maximum polarization had been reached, the cryostat was switched to *holding* (or *frozen-spin*) mode using a much lower magnetic field of 0.5 T and moved back into CLAS. The proton polarization decreased very slowly with a relaxation time of typically several days. This was sufficiently long for a useful polarized-target experiment.

In a first series of measurements using a longitudinally-polarized target, the performance of the frozen-spin target in its first operation exceeded expectations. A *beam-on* temperature of 30 mK was achieved in frozen-spin mode (design goal was $< 50\,$mK) attaining degrees of polarization of more than $80\,\%$. Re-polarization coincided for most of the time with physically-required flips of the target polarization avoiding losses of valuable beam time. Fig. 3 shows very preliminary results for the helicity difference $P_z^{\odot}$ in $\pi^+\pi^-$ photoproduction.

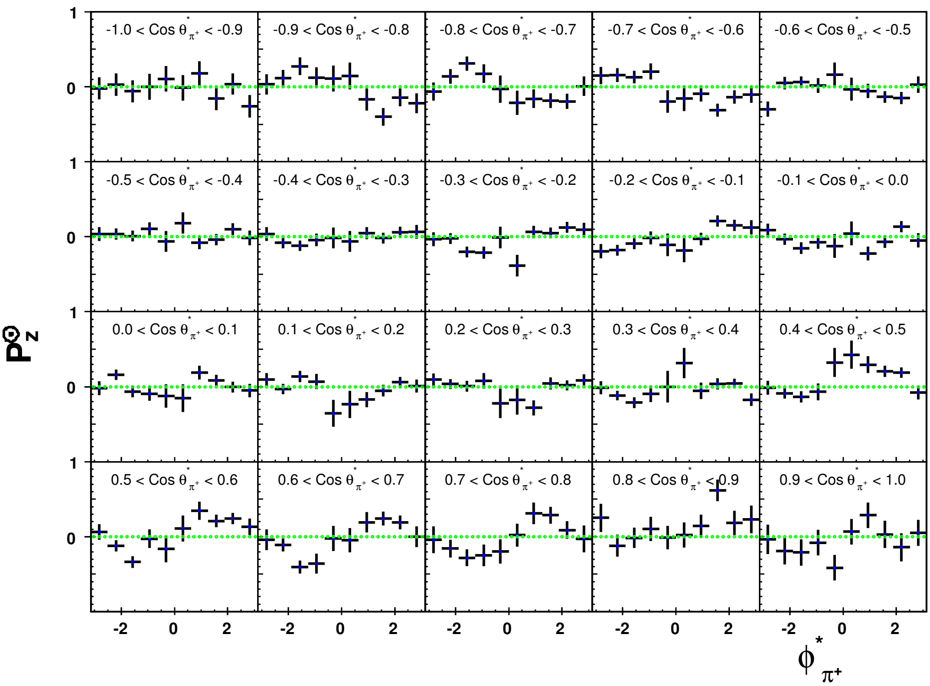

Fig. 3. Preliminary helicity difference $P_z^{\odot}$ for the reaction $\gamma p \rightarrow p\pi^+\pi^-$.

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