Complete pseudoscalar photo-production measurements

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Abstract. Investigations on N^* production generally face large t- and u-channel background and broad, overlapping resonances. In order to disentangle the large variety of contributions, it is necessary to employ not only unpolarized cross section data, but also polarization data. Recent photo-production experiments focus on the extraction of double-polarization observables using linearly and circularly polarized photon beams and longitudinally and transversely polarized targets. Moreover, thanks to the self-analyzing properties of Λ and $\Sigma^{\pm}$, it has become feasible to extract all 15 polarization observables for these channels. Preliminary double-polarization data from Jefferson Lab for the reaction $\gamma p \to K^+\Lambda$ underline the importance of spin observables to constrain the partial-wave analysis of this channel.

Keywords: photoproduction reactions, meson production, baryon production, polarization in interactions and scattering, partial-wave analysis
PACS: 25.20.Lj, 13.60.Le, 13.60.Rj, 13.88.+e, 11.80.Et

MOTIVATION

The study of the nucleon excitation spectrum provides a major tool to understand the dynamics and relevant degrees of freedom within hadrons in the non-perturbative regime of QCD. A large number of baryon resonances has been found through analyses of experimental data, only a few of them, however, are well established as unambiguous states. Resonances like $\Delta(1232)$, N(1520), N(1680), are observed as strong signals with Breit-Wigner shape in single-pion production, but this is the exception: almost all resonant states occur as broad, overlapping structures that are difficult to resolve – even by means of extensive partial wave analyses. Moreover, quark models based on SU(6)$\otimes$O(3) symmetry predict many more states, which have either not been detected or produced only weak signals in the existing data. In order to address this question of “missing resonances”, the properties of established resonances have to be determined more precisely.

The existing data sets for single-pseudoscalar photo-production consist of more than 70% of unpolarized cross section data, the remainders are almost exclusively single-polarization observables. These data sets are insufficient to precisely determine resonance parameters, since unpolarized data does not provide access to relative phases. Resonance parameters for higher-lying states, as well as the parametrization of nonresonant background, are largely model dependent. For example, a comparison of SAID [1] and MAID [2] solutions with experimental data shows an excellent agreement in the description of cross section data for single-pion photoproduction, but large discrepancies in polarization observables, in particular at c.m. energies above 1.7 GeV. Such discrepancies are even more apparent in η and kaon photo-production, which shows that unique extraction of resonance parameters cannot be achieved by partial wave decomposition of cross section data, but requires precise measurements of various polarization observables. The reactions $\gamma p \to \eta p$ and $\gamma p \to K^+\Lambda$ are additionally of special interest in the context of resonance extraction due to their isospin selectivity.

In the framework of helicity amplitudes, it can easily be shown that cross section and single-spin observables (P, T, Σ) only fix the moduli of the helicity amplitudes and that at least four double-polarization observables are necessary to determine the phases. These double-polarization observables have to be chosen from different sets of double-polarization experiments (beam–target, beam–recoil, target–recoil) to form a complete set of measurements [3]. However, fits to the data benefit from a larger number of measured observables, in particular since real measurements have non negligible uncertainties. Algebraic relations between polarization observables, which result from the fact that the observables are not independent, are used to the check for systematics and to constrain the fits [4]. It should be pointed out that partial wave amplitudes cannot unambiguously be constructed from the four independent complex amplitudes, which describe pseudoscalar meson photo-production; higher multipoles have to be fixed by pole terms, and only a truncated multipole analysis (e.g. for $L \leq 3$) can reasonably be performed [5, 6].

POLARIZED BEAM AND POLARIZED TARGET EXPERIMENTS

When a polarized photon beam impinges on a polarized target, the differential cross section for single-pseudoscalar meson production is modulated in the following form [7]:

$$\begin{aligned}\frac{d\sigma}{d\Omega}(E_{cm},\theta,\varphi) \;=\; & \sigma_0\;[1 - P_{lin}\,\Sigma\,\cos(2\varphi) \\ & + P_x\;(\,P_{circ}\,F + P_{lin}\,H\;\sin(2\varphi)\,) \\ & + P_y\;(\,T\;-\;P_{lin}\,P\;\cos(2\varphi)\,) \\ & + P_z\;(P_{circ}\,E + P_{lin}\,G\;\sin(2\varphi)\,)]\;.\end{aligned}$$

Here $\vec{P}_t$=(P_x,P_y,P_z) denotes the polarization vector of the target nucleons, and P_{circ} and P_{lin} denote the degree of circular and linear photon-beam polarization, respectively. For the latter case, φ denotes the angle of the photon polarization vector relative to the production plane. The unpolarized (differential) cross section σ_0, as well as the polarization observables Σ, T, P, E, F, G, H are measured as functions of E_{cm}=$\sqrt{s}$ and the meson production angle θ. Similar spin-dependent cross section formulas can be derived for beam–recoil or target–recoil polarization measurements [8, 7, 3].

The polarization observables can be extracted using a Fourier analysis or moment analysis of the azimuthal variation of the cross section (or corrected yield) in each $(E_{cm}, \cos\theta)$ bin. In practice, the extraction is hindered by the effective dilution present in polarized targets. Currently, the CLAS collaboration as well as CBELSA [9] and CB@MAMI [10] are using frozen-spin butanol (C_4H_9OH) targets, polarized in longitudinal or transverse direction. The subtraction of background from reactions on bound nucleons is facilitated through special runs on an unpolarized butanol target or an additional thin target, on which data is taken simultaneously to the production data on the polarized butanol target.

The FROST experiment at the Thomas Jefferson National Accelerator Facility (JLab) used the Hall-B Frozen-Spin Target (FROST) together with the CEBAF Large Acceptance Spectrometer (CLAS) [11] to collect data on longitudinally and transversely polarized protons in 2007/8 and 2010, respectively. The butanol target was operated at a base temperature of 30 mK and with holding fields of about 0.5 T. The average polarization was about 82% in 2007/8 and 85% in 2010, with a relaxation time of more than 2000 hours. During both run periods, circularly and linearly polarized photon beams were employed. The effective dilution factor was determined by subtracting the (scaled) yield from reactions on a ^{12}C foil, positioned downstream of the target. Data analysis and preliminary results on pion and eta production are reported elsewhere in these proceedings.

In this context it should be mentioned that the upcoming CLAS experiment in winter/spring 2011/12 will utilize a modified HDice target in order to extract a large number of observables for pion, η, and kaon production on longitudinally polarized neutrons without significant nuclear background [12]. This upcoming experiment is a crucial component in the effort to obtain complete sets of measurements, since neutron data are essential to separate the isoscalar and isovector components of photon field couplings to the nucleon.

HYPERON PHOTO-PRODUCTION

Measurements of double-polarization observables involving the spin orientation of the recoiling baryon require either a recoil polarimeter (with comparatively low analyzing power) or, in the case of KΛ and KΣ production, a measurement of the decay distribution thanks to the parity violating weak decay of Λ and $\Sigma^{\pm}$.

CLAS has collected a large sets of double-polarization data for the reactions $\gamma p \rightarrow K^+\Lambda$ and $\gamma p \rightarrow K^+\Sigma^0$. Besides the published data for the beam–recoil observables C_x, C_z for circularly polarized beam [13], preliminary data are available for O_x, T, O_z for linearly polarized beam [14], and new beam–target and target–recoil data using FROST. A coarse energy binning of these new results has been chosen due to limited statistics, in particular in the context of subtraction of bound-nucleon background. Here a short report is given on the $K^+\Lambda$ analysis for circularly polarized photons on the longitudinally polarized target [15]. The progress of the $K^+\Lambda$ analysis for linearly polarized beam is reported elsewhere [16].

About 3.4 billion events were collected with circularly polarized photons impinging on FROST in 2007/8. The beam polarization was determined from the helicity transfer of longitudinally polarized electrons accelerated to E_0=1.65 and 2.48 GeV with average polarization of about 85%. The helicity state was flipped pseudo-randomly at a rate of 30 Hz with negligible beam-charge asymmetry. In the process of the analysis, events were selected with detected K^+ and proton, where the K^+ originated from the butanol target (cf. Fig. 1, *left*) or from the ^{12}C foil. The bound-nucleon background was subtracted by scaling the yield of pK^+ events produced on the ^{12}C foil. The effective dilution factor D in the missing mass range of $\pm 2\sigma$ about the Λ mass amounted to $D \approx 1.45$. Identified pK^+ events not originating from the reactions $\gamma p \rightarrow K^+\Lambda$ or $K^+\Sigma^0$ were accounted for by fitting to the Λ and Σ^0 peaks in the missing-mass distribution $MM(\gamma p \rightarrow K^+X)$ as shown in Fig. 1, *right*.

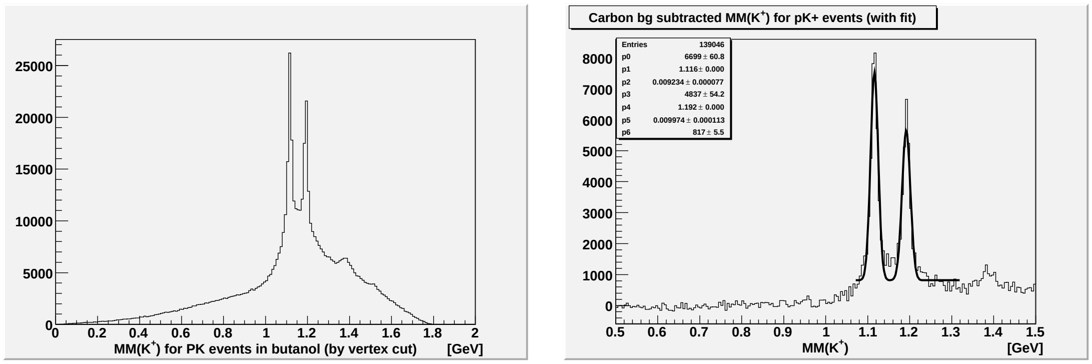

FIGURE 1. Missing mass $MM(\gamma p \rightarrow K^+X)$ for detected K^+p events with K^+ originating from the butanol target: *left* uncorrected yield, *right* after subtraction of bound-nucleon background (fit to two Gaussians and a constant).

The helicity asymmetry E for each kinematic bin was determined from the number of $K^+\Lambda$ events from the butanol target for anti-aligned ($N_{\frac{1}{2}}$) and aligned ($N_{\frac{3}{2}}$) spins of beam photon and target proton, the dilution factor, and the beam and target polarizations:

$$E = \frac{D}{P_{circ}P_z} \frac{N_{\frac{1}{2}} - N_{\frac{3}{2}}}{N_{\frac{1}{2}} + N_{\frac{3}{2}}} \,. \tag{1}$$

As example, preliminary results for two energy bins together with predictions from SAID (KL20) [1], kaonMAID [2], and the Bonn-Gatchina analysis [17] are shown in Fig. 2. None of the predictions describe the strength of aligned helicity production ($N_{\frac{3}{2}}$) at forward angles. In addition, the polarization-transfer observables L_x, L_z have been extracted, for which systematic checks are still being performed.

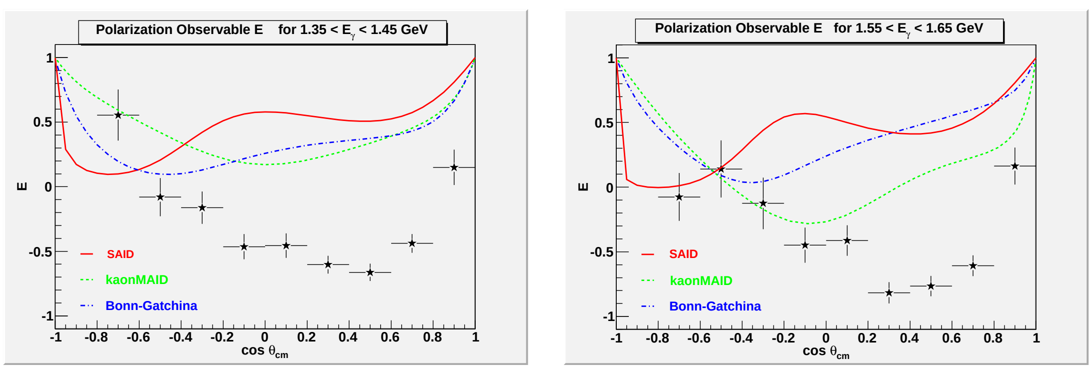

FIGURE 2. Preliminary results for the helicity asymmetry E for $1.35 < E_\gamma < 1.45$ GeV (left) and $1.55 < E_\gamma < 1.65$ GeV (right) together with model predictions: SAID (*solid line*), kaonMAID (*dashed line*), and Bonn-Gatchina (*dashed–dotted line*).

ACKNOWLEDGMENTS

Work at Jefferson Lab is supported in parts by the U.S. National Science Foundation: NSF PHY-0969434. Jefferson Science Associates operates the Thomas Jefferson National Accelerator Facility under DOE contract DE-AC05-06OR23177.

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