POLARIZATION OBSERVABLES IN KAON ELECTROPRODUCTION WITH CLAS AT JEFFERSON LABORATORY

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An extensive program of strange particle production off the proton is currently underway with the CEBAF Large Acceptance Spectrometer (CLAS) in Hall B at Jefferson Laboratory. Precision measurements of ground-state and low-lying excited-state hyperons are being carried out with both electron and real photon beams, both of which are available with high polarization at energies up to 6 GeV. This talk will focus on selected aspects of our strangeness physics program regarding electroproduction measurements of single and double-polarization observables.

1 Introduction

During the last decade there has been considerable effort to develop theoretical models for the kaon electroproduction process. However, the present state of understanding is still limited by a sparsity of data. Model fits to the existing cross section data are generally obtained at the expense of many free parameters, which leads to difficulties in constraining existing theoretical descriptions. Moreover, cross section data alone are not sufficiently sensitive to fully understand the reaction mechanism, as they probe only a small portion of the full response. In this regard, measurements of spin observables are essential for continued theoretical development in this field, as they allow for improved understanding of the dynamics of this process and provide for strong tests of QCD-inspired theoretical models.

The strange particle electroproduction program with CLAS at Jefferson Laboratory focusses on the associated production reaction $ep \rightarrow e'K^+Y$. Individual experiments have measured cross sections and spin observables for $K^+\Lambda$ and $K^+\Sigma^0$ final states at beam energies from 2.5 to 4.8 GeV. With the existing approved program, the present lack of data should soon be remedied with a wealth of very high quality measurements spanning a broad range in invariant energy W and momentum transfer Q^2 .

The large acceptance of the CLAS spectrometer has enabled us to detect the scattered electron and the electroproduced kaon, as well as the proton from the mesonic decay of the final-state Λ hyperon, over a range of Q^2 from 0.4 to 2.7 (GeV/c)² and W from threshold to 2.4 GeV, while providing full angular coverage in the center-of-mass of the kaon. The measured angular

Figure 1. Feynman diagrams for the process $\gamma^* p \rightarrow K^+ Y$ for the s , t , and u channel reactions listing the Born and non-Born terms in the intermediate state.

correlation of the decay proton allows for the determination of the final-state Λ or Σ^0 polarization. The CLAS detector enables simultaneous study of the reactions over kinematical regions where the contributing s , t , and u reaction channels processes (Fig. 1) have varying strengths. By emphasizing specific channel processes we can effectively limit the intermediate hadronic resonances involved in the reaction.

In order to better understand the reaction mechanism of open-strangeness production, it is important to better understand which baryon resonances contribute to the intermediate state, and to allow for a better determination of their associated coupling strengths and form factors. Presently our knowledge on the baryon resonances comes mainly from pion channels^{1,2}. Studies of strange final states could uncover baryonic resonances that do not couple or couple only weakly to the πN channel due to the different hadronic vertices. This allows for insight into the so-called “missing” quark model baryon states. Recent quark model calculations³ have shown that there are several N^* resonances with appreciable photocouplings that also provide for sizeable strength to decay to KY . These resonances, including the $S_{11}(1650)$, $P_{11}(1710)$, $P_{13}(1720)$, and most recently the $D_{13}(1895)$, also appear to be the main s -channel resonances required to fit the data within the framework of some hadrodynamical effective Lagrangian models^{4,5}. However, this phenomenological framework is not without inherent ambiguities in fitting the existing data. Higher quality data, including polarization observables, are important to make progress. Ultimately the data must be analyzed with full partial wave analysis in a coupled-channels framework².

This leads to an important question, namely, in the absence of direct QCD predictions, can effective theories and models allow us to understand the

reaction mechanism for open-strangeness production by providing a framework that describes the full set of available cross section and polarization data? In this regard, polarization observables have been demonstrated to be extremely sensitive to different assumptions about baryonic structure. Polarization effects arise due to interference of amplitudes in the intermediate state, and thus can provide for high sensitivity to resonance-resonance interference, non-resonant components, and small amplitude contributions. In this talk, I will focus on the CLAS beam asymmetry and hyperon single and double-polarization observables, and discuss the preliminary data within the framework of available hadrodynamic models.

2 Experimental Setup

The Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Laboratory is based on a recirculating multi-GeV electron linear accelerator. Located in Experimental Hall B of this facility is the CLAS spectrometer, a detector for use with electron and tagged-photon beams. CLAS is constructed around six iron-free superconducting coils that generate a toroidal magnetic field. The particle detection system (Fig. 2) consists of drift chambers to determine charged-particle trajectories, Čerenkov detectors for electron/pion separation, scintillation counters for flight-time measurements, and calorimeters to identify electrons and high-energy neutral particles.

Figure 2. Three dimensional representation of CLAS with a portion of the system cut away to highlight the elements of the detector system.

CLAS was designed to track charged particles emerging from the target with momenta greater than 200 MeV/c over polar angles from 8° to 142° , while covering up to 80% of the azimuth. The average acceptance of CLAS for detecting the final state e' and K^+ is about 30%, and drops to 5% when also requiring detection of the decay proton. The electron beam longitudinal polarization is roughly 70%, with typical beam-target luminosities of $6\text{--}7 \times 10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$.

Figure 3. Missing-mass spectra (GeV) for the reactions (a) $p(e, e' K^+)X$ and (b) $p(e, e' K^+ p)X$. (c) The hyperon distribution after cutting on the low-mass peak in (b). Reconstructions from 4.247 GeV CLAS data.

Hyperon final-state identification with CLAS relies on missing-mass reconstructions to identify neutral particles in exclusive reactions. Shown in Fig. 3a is the missing-mass distribution at 4.247 GeV for $p(e, e' K^+)X$ after reconstructing the scattered electron and kaon. This spectrum shows substantial, well-separated peaks for the low-lying hyperon states. Fig. 3b shows the missing mass for the reaction $p(e, e' K^+ p)X$. The final-state proton in this case can come from the decay of the $\Lambda(1115)$ (missing π^-), the $\Sigma^0(1192)$ (missing $\gamma\pi^-$), or the $\Lambda(1520)$ (missing K^-). Fig. 3c shows the resulting spectrum from a cut on the low-mass peak in Fig. 3b. The width of the hyperon peaks in this spectrum, summed over all Q^2 and W , is about 14 MeV.

3 Physics Results

3.1 Formalism

The most general form for the virtual photo-absorption cross section of the kaon from an unpolarized-proton target, allowing for both a polarized-electron

beam and recoil hyperon is given by⁶:

$$\frac{d^2\sigma_v}{d\Omega_K^*} = \sigma_0 \left[1 + hA_{TL'} + \sum_{i=t,n,l} (P_i^0 + hP_i') \right], \quad (1)$$

$$\sigma_0 = K_f \left[R_T^{00} + \epsilon_L R_L^{00} + \sqrt{2\epsilon_L(1+\epsilon)} R_{TL}^{00} \cos \Phi + \epsilon R_{TT}^{00} \cos 2\Phi \right]. \quad (2)$$

Here σ_0 represents the unpolarized cross section, $A_{TL'}$ the polarized-beam asymmetry, and P_i refers to the hyperon polarization. The R_i terms represent the longitudinal, transverse, and interference response functions that account for the dynamics of the hadronic system. Here ϵ (ϵ_L) is the degree of transverse (longitudinal) polarization of the virtual photon, h is the electron beam helicity, K_f is a kinematic factor given by the ratio of CM momenta of the outgoing kaon and the virtual photon, and Φ is the relative angle between the electron and hadron planes.

Each of the hyperon polarization components (P_t, P_n, P_l) is further split into the induced polarization P^0 , and the helicity-dependent transferred polarization P' , defined with respect to a particular set of spin-quantization axes. In the (t, n, l) coordinate system defined in Fig. 4, the three induced and transferred polarization components are given by⁶:

$$\begin{aligned} P_t^0 &= -K_f \left(\sqrt{2\epsilon_L(1+\epsilon)} R_{TL}^{x'0} \sin \Phi + \epsilon R_{TT}^{x'0} \sin 2\Phi \right) / \sigma_0 \\ P_n^0 &= K_f \left(R_T^{y'0} + \epsilon_L R_L^{y'0} + \sqrt{2\epsilon_L(1+\epsilon)} R_{TL}^{y'0} \cos \Phi + \epsilon R_{TT}^{y'0} \cos 2\Phi \right) / \sigma_0 \\ P_l^0 &= -K_f \left(\sqrt{2\epsilon_L(1+\epsilon)} R_{TL}^{z'0} \sin \Phi + \epsilon R_{TT}^{z'0} \sin 2\Phi \right) / \sigma_0, \end{aligned} \quad (3)$$

$$\begin{aligned} P_t' &= -K_f \left(\sqrt{2\epsilon_L(1-\epsilon)} R_{TL}^{x'0} \cos \Phi + \sqrt{1-\epsilon^2} R_{TT}^{x'0} \right) / \sigma_0 \\ P_n' &= K_f \sqrt{2\epsilon_L(1-\epsilon)} R_{TL}^{y'0} \sin \Phi / \sigma_0 \\ P_l' &= -K_f \left(\sqrt{2\epsilon_L(1-\epsilon)} R_{TL}^{z'0} \cos \Phi + \sqrt{1-\epsilon^2} R_{TT}^{z'0} \right) / \sigma_0. \end{aligned} \quad (4)$$

3.2 Hyperon Polarization

An attractive feature of the mesonic decay $\Lambda \rightarrow p\pi^-$ comes from its self-analyzing nature. From the decay-proton angular distribution, the average hyperon polarization about each of the three spin axes can be determined. The decay distribution in the Λ rest frame is of the form:

$$dN/d\Omega_p^{RF} \propto 1 + \alpha P_\Lambda \cos \theta_p^{RF}. \quad (5)$$

In this expression, $\alpha=0.642$ is the weak-decay asymmetry parameter and θ_p^{RF} is the decay-proton polar angle relative to the spin-quantization axes. To improve the statistical precision, our analysis has proceeded by summing over all relative Φ angles. In this case, the polarization components P_t^0 , P_l^0 , and P_n^0 vanish and our definitions (with $K_I = (R_T^{00} + \epsilon_L R_L^{00})^{-1}$) become:

$$P_n^0 = K_I(R_T^{y'0} + \epsilon_L R_L^{y'0}) \quad (6)$$

$$P_t' = -K_I \sqrt{1 - \epsilon^2} R_{TT}^{x'0}, \quad P_l' = -K_I \sqrt{1 - \epsilon^2} R_{TT}^{z'0}. \quad (7)$$

Figure 4. Center-of-mass (CM) coordinate systems used in the polarization analysis.

For polarization observables, the (t, n, l) coordinate system is not a unique choice. Other choices for the spin-quantization axes, shown in Fig. 4, could include an axis along the virtual photon direction (z, z'') or perpendicular to the electron scattering plane (y'') . The Φ -integrated polarization observables will then be sensitive to a different subset of response functions.

3.3 Theoretical Models

A comprehensive theoretical framework has been developed for the electromagnetic production of low-lying Λ and Σ^0 hyperons^{4,5}. Model parameters are determined by a simultaneous fit to the low-energy γp and $\gamma^* p \rightarrow K^+ Y$ photo- and electroproduction data, along with the $K^- p \rightarrow \gamma Y$ radiative capture data. In this hadrodynamical effective Lagrangian approach, several different elementary models have been developed from fits to the data by adding Born terms with a number of resonances and leaving their coupling constants as free parameters. Different models have markedly different ingredients and coupling constants. The different resonances in the various models include:

t chan.: $K^*(893)$, $K_1(1270)$	$ $	s chan.: $P_{11}(1440)$, $S_{11}(1650)$,
u chan.: $\Lambda(1405)$, $\Lambda(1670)$, $\Lambda(1800)$	$ $	$P_{11}(1710)$, $P_{13}(1720)$, $D_{13}(1895)$.

Beyond selecting different elementary models of the production process that incorporate different intermediate resonant states, the theoretical framework also allows for the selection of different forms for the Q^2 dependence of the electromagnetic form factors of the kaon and the hyperon. In the results that follow in this paper, simple dipole form factors have been employed and the results for different elementary models have been compared. These models were developed by Bennhold and Mart (BM)⁴, Williams, Ji, and Cotanch (WJC)⁸, and Adelseck and Wright (AW)⁹.

3.4 Beam Asymmetry

The polarized-beam asymmetry $A_{TL'}$ for the $K^+\Lambda$ final state provides direct access to the fifth response function $R_{TL'}^{00}$. This asymmetry is given by:

$$A_{TL'} = \frac{1}{P_e} \frac{N^+ - N^-}{N^+ + N^-} = \frac{K_f}{\sigma_0} \sqrt{2\epsilon_L(1-\epsilon)} R_{TL'}^{00} \sin \Phi. \quad (8)$$

Here the N^+ and N^- helicity-gated yields are extracted by selecting events in the $e'K^+$ missing-mass spectrum consistent with a final-state Λ . This term allows for separation of the reaction mechanisms that contribute to the intermediate-state excitations from non-resonant processes. This observable accesses imaginary parts of interfering longitudinal and transverse amplitudes. These imaginary parts vanish identically if the resonant state is determined by a single complex phase, which is the case for an isolated resonance.

Figure 5. Preliminary CLAS beam asymmetry for $\bar{e}p \rightarrow e'K^+\Lambda$ as a function of Φ for $W=1.7$ GeV (left) and $W=1.9$ GeV (right) summed over Q^2 at 4.247 GeV. The curves correspond to different hadrodynamical models: AW-solid, WJC - dashed, BM - dotted.

The preliminary CLAS results at 4.247 GeV are shown in Fig. 5 for two different W bins. These asymmetries have been acceptance corrected and had the dominant background subtracted. This dominant background arises from misidentification of final-state pions as kaons. The results are compared with three different hadrodynamic models. The models are in reasonable agreement with the low- W data, but underpredict the data for the higher- W bin. One of the models (WJC) even comes in at higher W with the wrong phase.

3.5 Induced Polarization

For the induced Λ polarization measurements, the acceptance-corrected decay-proton yields have been summed over both electron helicity states and fit with the form of eq(5) to extract P_n^0 . P_n^0 represents the only Φ -integrated induced polarization component that is not required to vanish. Results have been summed together from data sets at 2.567 and 4.247 GeV as the data show essentially no ϵ dependence.

Figure 6. Preliminary CLAS induced polarization for $ep \rightarrow e' K^+ \Lambda$ as a function of $\cos \theta_K^*$ for two different W bins summed over Q^2 (left) and as a function of W summed over Q^2 and $d\Omega_K^*$ (right) from the combined 2.567 and 4.247 GeV CLAS data. The curves correspond to different hadrodynamic models: AW-solid, WJC - dashed, BM - dotted.

The preliminary CLAS results are shown vs. $\cos \theta_K^*$ and W in Fig. 6. The dependence of P_n^0 with respect to W is very similar to what has been found from analysis of photoproduction data at SAPHIR⁷. However the angular dependence is quite different, indicating an important Q^2 dependence. The results are compared with three different hadrodynamic model calculations

to show how well the models are doing relative to the data, as well as the spread in their predictions. Clearly there is not much spread between the calculations, indicating a possible commonality in their disagreement.

3.6 Transferred Polarization

The transferred Λ polarization is determined from the acceptance-corrected yield asymmetries:

$$A_i = \frac{N^+ - N^-}{N^+ + N^-} = \frac{\alpha P_e \cos \theta_p^{RF} P_i'}{1 + \alpha \cos \theta_p^{RF} P_i^0}, \quad i = t, n, l. \quad (9)$$

This asymmetry is formed separately from the decay-proton helicity-gated yields with respect to the (t, n, l) axes. With this method, we are quite insensitive to the CLAS acceptance function. In forming these asymmetries and summing over Φ , A_n must vanish, but A_l and A_t can be non-zero. Fig. 7 shows results of our preliminary analysis at 4 GeV as a function of both $\cos \theta_K^*$ and W . The results for P_l' and P_t' are compared with three different hadrodynamic models. The accuracy of the measurements, coupled with the spread in the theory predictions, clearly indicates that these data are sensitive to the resonant and non-resonant structure of the intermediate state.

Figure 7. Preliminary CLAS transferred polarization from $\bar{e}p \rightarrow e' K^+ \bar{\Lambda}$ vs. $\cos \theta_K^*$ (left) summed over Φ and Q^2 and vs. W (right) summed over Q^2 and $d\Omega_K^*$ at 4 GeV. The curves correspond to different hadrodynamic models: AW-solid, WJC - dashed, BM - dotted.

4 Summary and Conclusions

In this talk I have reviewed some of the key reasons why electroproduction processes of open-strangeness production are important for the investigation of baryonic structure and "missing" quark model states. I have highlighted several aspects of the CLAS strangeness physics program regarding $ep \rightarrow e' K^+ Y$ focussing on single and double-polarization observables with polarized beam and/or polarized hyperon recoils. Detailed analysis of data sets at 2.5 and 4 GeV have shown sizeable Λ polarization signatures with very little W or Q^2 dependence. The polarization data have been studied within the framework of hadrodynamic models. The results indicate that the data are highly sensitive to the ingredients of the models, including the specific baryonic resonances included, along with their associated form factors and coupling constants.

The CLAS program is presently ongoing with a polarized-electron beam at 6 GeV. This will extend the W range of the polarization data to nearly 3.5 GeV. This will allow for study of the dynamics of open-strangeness production beyond the resonance region, where the effective degrees of freedom are expected to evolve from mesons and baryons to quarks and gluons.

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