THE STRANGENESS PHYSICS PROGRAM AT CLAS

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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. This talk will emphasize strangeness photo- and electro-production in the baryon resonance region between \( W = \)1.6 and 2.5 GeV, where indications of \( s \)-channel structure are suggestive of high-mass baryon resonances coupling to kaons and hyperons in the final state. Precision measurements of cross sections and polarization observables 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.

1. Introduction

A key to understanding the structure of the nucleon is to understand its spectrum of excited states. However understanding nucleon resonance excitation provides a serious challenge to hadronic physics due to the non-perturbative nature of QCD at these energies. Recent symmetric quark model calculations predict more states than have been seen experimentally. Mapping out the spectrum of these excited states will provide for insight into the underlying degrees of freedom of the nucleon.

Most of our present knowledge of baryon resonances comes from reactions involving pions in the initial and/or final states. A possible explanation for the so-called missing resonance problem could be that pionic coupling to the intermediate \( N^* \) or \( \Delta^* \) states might be weak. This suggests a search for these hadronic states in strangeness production reactions. Beyond different coupling constants (e.g. \( g_{KNY} \) vs. \( g_{\pi NN} \)), the study of the exclusive production of \( K^+\Lambda \) and \( K^+\Sigma^0 \) final states has other advantages in the search for missing resonances. The higher masses of the kaon and hyperons, compared to their non-strange counterparts, kinematically favor a two-body decay mode for resonances with masses near 2 GeV, a situation
that is experimentally advantageous. In addition, baryon resonances have large widths and are often overlapping. Studies of different final states can provide for important cross checks in quantitatively understanding the contributing amplitudes. Note that although the two ground-state hyperons have the same valence quark structure \((uds)\), they differ in isospin, such that intermediate \(N^*\) resonances can decay strongly to \(K^+\Lambda\) final states, while both \(N^*\) and \(\Delta^*\) decays can couple to \(K^+\Sigma^0\) final states.

The search for missing resonances requires more than identifying features in the mass spectrum. QCD cannot be directly tested with \(N^*\) spectra without a model for the production dynamics. The \(s\)-channel contributions are known to be important in the resonance region in order to reproduce the invariant mass \((W)\) spectra, while \(t\)-channel meson exchange is also necessary to describe the diffractive part of the production and \(u\)-channel diagrams are necessary to describe the backward-going processes. Thus measurements that can constrain the phenomenology for these reactions are just as important as finding one or more of the missing resonances.

Theoretically, there has been considerable effort during the past decade to develop models for the \(KY\) photo- and electroproduction processes. 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 theories. 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 models.

In this talk I focus on the strangeness physics program in Hall B at Jefferson Laboratory using the CLAS detector. Presently there is very limited knowledge of \(N^*, \Delta^* \rightarrow KY\) couplings. With the existing CLAS program, the present lack of data will be remedied with a wealth of high quality measurements spanning a broad kinematic range.

2. \(KY\) Photoproduction

Photoproduction measurements for \(K^+\Lambda\) and \(K^+\Sigma^0\) made with CLAS have provided both differential cross sections and hyperon polarizations. The data shown here were collected at electron beam energies of 2.4 and 3.1 GeV. This gives rise to measurements spanning photon energies from threshold
\( E_\gamma = 0.911 \text{ GeV} (W = 1.61 \text{ GeV}) \) up to \( E_\gamma = 2.95 \text{ GeV} (W = 2.53 \text{ GeV}) \). The final state hyperons were reconstructed from the \((\gamma, K^+)\) missing mass. Detection of the decay proton from the hyperon was also required. The average hyperon mass resolution was \( \sigma = 8.5 \text{ MeV} \). The \( \Lambda \) and \( \Sigma^0 \) events were separated from the pion mis-identification background using lineshape fits to the missing mass spectra in each bin of photon energy and kaon angle.

CLAS has already published photoproduction data from another analysis where only the final state \( K^+ \) was detected. The results shown here represent a new analysis with very different systematics. The two separate analyses are now in good agreement within the associated uncertainties, giving us full confidence in the CLAS results.

Figure 1. Differential cross sections for \( K^+\Lambda \) (top) and \( K^+\Sigma^0 \) (bottom) vs. \( W \) for three kaon angle bins (solid circles). Data from Bonn/SAPHIR (open triangles) are also shown. The curves are calculations from KAON-MAID (solid), Ireland (dashed), Janssen (dashed), and Guidal (dot-dashed).

Figure 1 shows a sample of the CLAS differential cross sections for \( K^+\Lambda \) and \( K^+\Sigma^0 \) photoproduction as a function of the invariant energy \( W \) for angle bins at \( \cos \theta_K^* = 0.8, 0.6, \) and -0.5. The different angle bins allow us to vary the relative contributions to the \( s, t, \) and \( u \) reaction channels. Existing data from SAPHIR at Bonn are also included. The data are compared with effective Lagrangian calculations from Mart/Bennhold, Ireland, and Janssen, which are based on adding the non-resonant Born terms with a number of resonances and leaving their coupling constants as free parameters bounded loosely by SU(3) predictions. These models have been developed from fits to the Bonn data, however they only reproduce the
threshold region of the data. Much beyond about 200 MeV above threshold
the calculations do not reflect the CLAS data. The data are also compared
with a Reggeon exchange model\cite{10} that uses only $K$ and $K^*$ exchanges,
with no resonance contributions. The prediction was made using a model
that fit higher energy kaon electroproduction data well.

For the $K^+\Lambda$ data the broad structure just above the threshold region
is typically accounted for by the known $S_{11}(1650)$, $P_{11}(1710)$, and $P_{13}(1720)$
resonances. Centered at roughly 1.9 GeV is another broad structure, first
seen in the Bonn data, that remains unexplained, whose position and width
vary with kaon angle. This has been interpreted by Mart and Bennhold\cite{11}
as evidence for a missing $D_{13}(1900)$ resonance, where the assignment was
consistent with the measured angular distributions, as well as a predicted
quark model state.\cite{11} However, other groups have shown that the same data
can also be explained by accounting for $u$-channel hyperon exchanges\cite{12}
or with an additional $P$-wave resonance.\cite{9} Interestingly, the Regge model fully
saturates the strength in the reaction, leaving no room for significant $s$ and $u$
channel contributions.

For the $K^+\Sigma^0$ data, there is a single peak in the differential cross sections
at about 1.9 GeV. This has been associated with a cluster of $\Delta$ resonances
in this mass range. However both isospin $1/2$ ($N^\ast$) and isospin $3/2$
($\Delta^\ast$) resonances can contribute to this final state. These data, as well as the
Bonn data, show evidence for resonant decays to $K^+\Sigma^0$. The Regge model
here now provides only a fraction of the reaction strength with significant
contributions possible from the $s$ and $u$ reaction channels.

Another part of the photoproduction analysis program is to measure
the induced hyperon polarization with an unpolarized beam and target.
An attractive feature of the hyperon decay is its well known self-analyzing
nature. The hyperon polarization is revealed by the asymmetry in the
angular distribution of the protons from the mesonic decay of the hyperon.
From parity conservation, the only allowed polarization component is along
the axis perpendicular to the $K^+\Sigma$ reaction plane. Measurement of this
observable is important since it is related to interferences of the imaginary
part of resonant amplitudes with other amplitudes, including Born terms.
These data are shown in Fig.\cite{12} as a function of $W$ for two kaon angle bins
at $\cos\theta_K^{\ast}=0.3$ and $-0.3$.\cite{4} The CLAS data provide the first precision data
for this observable. The data show a sizeable negative $\Lambda$ polarization for
forward-going kaons, and an equally sizeable positive polarization when the
kaons go backward. The basic trend is reversed in the $\Sigma^0$ data. The CLAS results
are consistent with some older data points from Bonn.\cite{6} CLAS has
also completed measurements of the beam recoil polarization observables $C_x$ and $C_z$.

![Figure 2. Induced polarization of the Λ and Σ^0 hyperon as a function of W for two kaon angle bins.](image)

The curves are calculations from KAON-MAID (solid), Janssen (dashed), and Guidal (dot-dashed).

Neither the hadrodynamic nor Regge calculations reproduce the magnitudes or the trends seen in the hyperon polarization data across the broad kinematic region covered. The significant discrepancies between the calculations and the data imply that these data can serve to provide for significant new constraints on the model parameters.

A recent coupled-channels analysis of photoproduction data from SAPHIR and CLAS, as well as beam asymmetry data from SPring-8/LEPS for $K^+Λ$ and data from π and η photoproduction, reveals evidence for new baryon resonances in the high $W$ mass region. The full suite of data can only be satisfactorily fitted by including a new $P_{11}$ state at 1840 MeV and two $D_{13}$ states at 1870 and 2130 MeV. The only Δ state that contributed significantly to the $K^+Σ^0$ final state is the $D_{33}(1940)$. This analysis has certain ambiguities that can be resolved or better constrained by incorporating the expansive set of electroproduction data from CLAS.

3. KY Electroproduction

CLAS has measured exclusive $K^+Λ$ and $K^+Σ^0$ electroproduction on the proton for a range of momentum transfer $Q^2$ from 0.5 to 4.5 (GeV/c)^2 with electron beam energies from 2.6 to 5.7 GeV. For this talk I will focus attention on our 2.6 GeV data set. The final state hyperons were reconstructed from the $(e, e'K^+)$ missing mass. The average hyperon resolution was about
8 MeV, similar to what was found for photoproduction. The hyperon yields were extracted using Monte Carlo templates with a background determined from the data associated with pions misidentified as kaons.

The most general form for electroproduction cross section of the kaon from an unpolarized-proton target is given by:

$$d^4\sigma \over dQ^2dWd\Omega^*_K \equiv \sigma_0 = \Gamma_v[\sigma_T + \epsilon\sigma_L + \epsilon\sigma_{TT}\cos 2\Phi + \sqrt{2\epsilon(\epsilon + 1)}\sigma_{LT}\cos \Phi].$$

In this expression, the cross section is decomposed into four structure functions, $\sigma_T$, $\sigma_L$, $\sigma_{TT}$, and $\sigma_{LT}$, which are in general functions of $Q^2$, $W$, and $\theta^*_K$ only. $\Gamma_v$ represents the virtual photon flux factor, $\epsilon$ is the virtual photon polarization, and $\Phi$ is the angle between the electron scattering and hadronic reaction planes. One of the goals of the electroproduction program is to provide a detailed tomography of the structure functions vs. $Q^2$, $W$, and $\cos \theta^*_K$. In a first phase of the analysis at CLAS, we have measured the unseparated cross section ($\sigma_U = \sigma_T + \epsilon\sigma_L$) and, for the first time in the resonance region away from parallel kinematics, the interference cross sections $\sigma_{TT}$ and $\sigma_{LT}$. At the amplitude level, these interference responses are related to real photon measurements of the polarized beam asymmetry, and so they are sensitive to some of the same structure information. Exploiting the $\Phi$ dependence of the reaction allows us to extract these responses from the CLAS data. The $Q^2$ dependence of the data provides sensitivity to the associated form factors.

A small sample of the available results from this analysis is shown in Fig. 3 vs. $W$ for each of our six angle bins for the kaon. The kinematic dependence of the unpolarized structure functions shows that $\Lambda$ and $\Sigma^0$ hyperons are produced very differently. $\sigma_U$ at forward angles for $K^+\Lambda$ is dominated by a structure at $W=1.7$ GeV. For larger kaon angles, a second structure emerges at about 1.9 GeV, consistent with the signature in photoproduction. $\sigma_{TT}$ and $\sigma_{LT}$ are clearly non-zero and reflect the structures in $\sigma_U$. The fact that $\sigma_{LT}$ is non-zero is indicative of longitudinal strength. For the $K^+\Sigma^0$ final state, $\sigma_U$ is centrally peaked, with a single broad structure at 1.9 GeV. This is consistent with the photoproduction data. $\sigma_{TT}$ reflects the features of $\sigma_U$, with $\sigma_{LT}$ consistent with zero everywhere, indicative of $\sigma_L$ being consistent with zero.

To date we have completed analysis of data sets at 2.6 and 4.2 GeV and have performed a Rosenbluth separation for several $W$ bins over the full kaon angular range for a single bin at $Q^2=1.0$ (GeV/c)$^2$ where the data sets overlap. A crucial part in this analysis of extracting absolute cross sections...
Figure 3. Preliminary separated structure functions $\sigma_U$, $\sigma_{LT}$, and $\sigma_{TT}$ for the $K^+\Lambda$ (top) and $K^+\Sigma^0$ final state (bottom) at 2.6 GeV and $Q^2=0.65$ (GeV/$c$)$^2$. The curves correspond to the calculations of Janssen, Guidal, and Mart/Bennhold.

is to minimize the physics model dependence of the detector acceptance function, radiative corrections, and bin-centering factors. We estimate an average absolute systematic uncertainty on these data points of about 15%.

The polarized-beam asymmetry provides access to the fifth structure function $\sigma_{LT}$. This observable probes imaginary parts of the interfering $L$ and $T$ amplitudes (as opposed to the real parts of the interference from $\sigma_{LT}$). These imaginary parts vanish identically if the resonant state is determined by a single complex phase, which is the case for an isolated resonance. A representative sample of our data at 2.6 GeV and $Q^2=0.65$ (GeV/$c$)$^2$ is shown in Fig. 4 for the $K^+\Lambda$ final state. The calculations shown are not able to reproduce the features seen in the data.
The first measurements of spin transfer from a longitudinally polarized electron beam to the Λ hyperon produced in the exclusive \( p(e, e' K^+)\bar{\Lambda} \) reaction have recently been completed at CLAS. A sample of the results highlighting the angular dependence of \( P' \) summed over all \( Q^2 \) for three different \( W \) bins is shown in Fig. 5 at 2.6 GeV. The polarization along the virtual photon direction \( P'z' \) decreases with increasing \( \cos\theta^*_K \), while the orthogonal component in the hadronic reaction plane \( P'x' \) is constrained to be zero at \( \cos\theta^*_K = \pm 1 \) due to angular momentum conservation, and reaches a minimum at \( \theta^*_K \sim 90^\circ \). The component normal to the hadronic reaction plane \( P'y' \) is statistically consistent with zero as expected.
The transferred polarization data are compared with three effective Lagrangian models that include a different subset of resonances. It is interesting that the model with the best agreement includes the $D_{13}(1900)$ resonance. 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.

The transferred polarization data have also been used to measure the ratio $R = \sigma_L/\sigma_T$. This can be done by extrapolating the $P'$ data to $\theta_K = 0^\circ$, where $R = (1/\epsilon)(c_0/P'_z - 1)$. Here $c_0$ represents a kinematic factor. This method provides a complementary approach from the standard Rosenbluth measurement in a situation with different systematics. Existing data from Hall C have remained controversial. The new results, shown in Fig. 6, are consistent with, although systematically smaller than, the latest Hall C results. They indicate that $R$ is reasonably constant with $Q^2$ with small values for $\sigma_L$.

4. Summary and Conclusions

In this talk I have reviewed some of the key reasons why the photo- and electroproduction processes of open-strangeness production are important for the investigation of baryonic structure and missing quark model states. I have discussed several aspects of the CLAS strangeness physics program highlighting the breadth and quality of our data sets. Results were presented for cross sections and single and double-polarization observables for $K^{+}\Lambda$ and $K^{+}\Sigma^0$ photo- and electroproduction. Our analyses 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 production dynamics for $K^+\Lambda$ and $K^+\Sigma^0$ are also seen to be very different.

Work on publication of the full set of hyperon cross section and polarization data sets reported here is in progress. The main qualitative conclusion seems clear: these data show significant unexplained baryon resonance structure at higher masses. While the comparison of the effective Lagrangian calculations to the data is illustrative to highlight the present deficiencies in the current models and their parameter values, the next step in the study of the reaction mechanism is to include our data in the available data base and to refit the set of coupling strengths. Additionally new amplitude-level analyses are called for to more fully unravel the contributions to the intermediate state.

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