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Hyperon photoproduction in the nucleon resonance region

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Hyperon photoproduction in the nucleon resonance region

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High-statistics cross sections and recoil polarizations for the reactions $\gamma + p \rightarrow K^+ + \Lambda$ and $\gamma + p \rightarrow K^+ + \Sigma^0$ have been measured at CLAS for center-of-mass energies between 1.6 and 2.3 GeV. In the $K^+\Lambda$ channel we confirm a resonance-like structure near $W = 1.9$ GeV at backward kaon angles. Our data show more complex *s*- and *u*- channel behavior than previously seen, since structure is also present at forward angles, but not at central angles. The position and width change with angle, indicating that more than one resonance is playing a role. Large positive Λ polarization at backward angles, which is also energy dependent, is consistent with sizable *s*- or *u*-channel contributions. Presently available model calculations cannot explain these aspects of the data.

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Characterizing the nonstrange baryon resonances is of fundamental interest in nonperturbative QCD. The masses, quantum numbers, and decay branches of the higher-mass baryon resonances have remained difficult to establish, both experimentally and theoretically. Experimentally, most information comes from the use of pion beams interacting with nucleon targets, combined with detection of one or more pions or the nucleon. For increasing masses, both the energy overlap of resonances and meson production (e.g., ρ) make it more difficult to separate the resonance contributions. The long list of poorly established higher-mass resonances [1] illustrates this problem above the strangeness threshold near $W = 1600$ MeV. Theoretically, there is an apparent oversupply of baryons predicted in quark models, the so-called "missing baryons" problem [2]. Various ways have been suggested whereby dynamical effects such as diquarks could reduce the number of states to something closer to what has been already observed [3].

Photoproduction of nonstrange resonances detected via decay into strange particles offers two benefits in this field. First, two-body KY final states are easier to analyze than the three-body $\pi\pi N$ final states that dominate decays at higher masses. So, while the cross sections for strangeness production tend to be small (on the order of 1 or 2 μb in electromagnetic production), the energy and angular distributions are simpler. Also, the recoil polarization observables are readily accessible via hyperon decays. Second, couplings of nucleon resonances to KY final states are expected to differ from coupling to πN or $\pi\pi N$ final states [2]. Therefore, looking in the strangeness sector casts a different light on the resonance excitation spectrum, and thus may emphasize resonances not revealed in πN scattering. Some "missing resonances" may only be "hidden" by the character of the channels studied previously. To date, however, the PDG compilation [1] gives poorly known $K\Lambda$ couplings for only five well-established resonances, and no $K\Sigma$ couplings for any resonances. The most widely available model calculation of the $K\Lambda$ photoproduction, the Kaon-MAID code [4], includes merely three well-established resonances: the $S_{11}(1650)$, the $P_{11}(1710)$, and the $P_{13}(1720)$. Thus it is timely and interesting to have additional good-quality photoproduction data of these channels to see what additional resonance formation and decay information can be obtained. Here we report the global features of our results [5] which are new, and compare them to published reaction models.

Differential cross section and hyperon recoil polarization data were obtained with the CLAS [6] system in Hall B at the Thomas Jefferson National Accelerator Facility. A beam of tagged photons from a bremsstrahlung beam spanned energies from threshold at $E_\gamma = 0.911$ GeV ($W = 1.609$ GeV) up to 2.325 GeV ($W = 2.290$ GeV). The event trigger required an electron signal from the photon tagger, and at least one charged-track coincidence between the time-of-flight "start" counters near the 18-cm liquid-hydrogen target and the time-of-flight "stop" counters surrounding the drift chambers. Kaons were identified using momentum and time-of-flight measurements to compute their mass, and were the only particles detected in CLAS to obtain the cross sections. The Λ and Σ^0 yields were separated from the background due to misidentified pions using line shape fits to missing-mass spectra in each of over 900 kinematic bins of photon energy and kaon angle. The results are binned in 25 MeV steps in E_γ and in 18 bins in the center-of-mass (c.m.) angle of the kaons, $-0.9 < \cos(\theta_K^{\text{c.m.}}) < +0.9$. Consistency among several variations of kaon selection cuts and background shapes was demanded in extracting the hyperon yields, with χ^2_ν always less than 1.75 and signal-to-background ratios of greater than 2.5. A hyperon missing-mass resolution of $\sigma = 6.1$ MeV was obtained when averaged over all detection angles and photon energies. The estimated method-dependent yield uncertainties are included bin by bin in our results, and average 6%. A

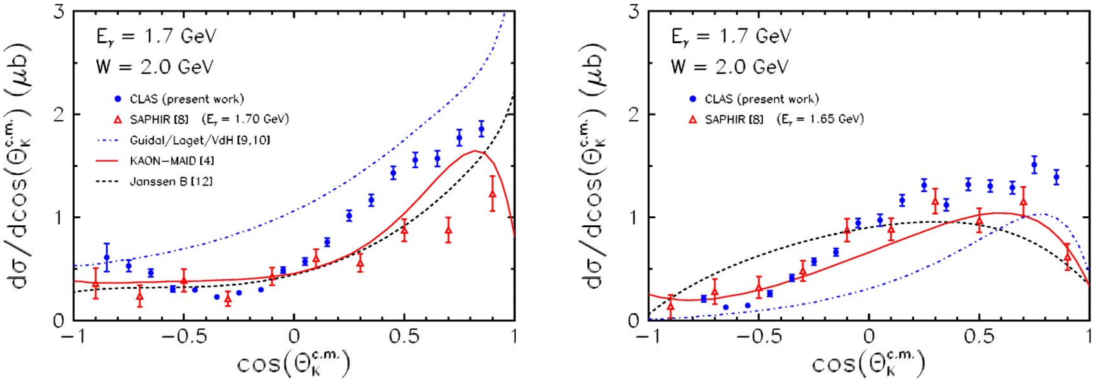

FIG. 1. (Color online) Angular distributions for Λ (left) and Σ^0 (right) hyperon photoproduction measured at CLAS (solid circles) at $W=2.01$ GeV. The error bars combine statistical and estimated point-to-point systematic errors. Data from SAPHIR [8] (open triangles) are also shown. The curves are for effective Lagrangian calculations computed by Kaon-MAID [4] (solid) and Janssen *et al.* [12] (dashed), and a Regge-model calculation of Guidal *et al.* [9,10] (dot-dashed).

total of 427 000 $K^+\Lambda$ events and 354 000 $K^+\Sigma^0$ events were accumulated.

The acceptance and efficiency for CLAS were modeled twice, using two independent Monte Carlo models. One was a full GEANT-based simulation involving hit digitizations, while the other was a faster parametric simulation that modeled detector effects starting at the level of reconstructed tracks. The results were in good agreement overall, and analysis of the remaining variations led to an estimated global systematic uncertainty of 7%. This was the dominant systematic uncertainty in the experiment.

The photon flux was determined by integrating the tagger rate. The rate was sampled by counting hits from accidental photons in the tagger TDC's. Photon losses due to beam collimation were determined using a separate total-absorption counter downstream of CLAS. As a check on our results, the $p(\gamma,\pi^+)n$ cross section was measured using the same analysis chain as the $p(\gamma,K^+)Y$ data. The pion cross section was found to be in agreement with the SAID [7] parametrization of the world's data between 0.6 and 1.6 GeV, albeit low by an overall scale factor of 0.92. In energy and angle the variation in the ratio of CLAS to SAID pion cross sections was small, $\approx\pm 3\%$. This shows that the yield extractions, acceptance calculations, and photon flux determinations were all consistent, but the overall normalization of the kaon results was made relative to the world's pion photoproduction data. The final global systematic uncertainty on our cross sections is 8.2% for the Λ data and is 7.7% for the Σ^0 data.

Figure 1 (left) shows the differential cross section for Λ hyperon photoproduction at $W=2.0$ GeV. It is forward peaked, as has been seen in previous experiments [8]. However, we also see a backward rise in the cross section for this and similar high values of W. This can be due either to u-channel components of the reaction mechanism or to the interference of s-channel resonances. The agreement between CLAS and previous data from SAPHIR at Bonn [8] varies: generally the measurements agree within the estimated uncertainties at back angles and near threshold energies, but CLAS measures consistently larger $K^+\Lambda$ cross sections at forward kaon angles.

The Λ and Σ^0 hyperons have isospin 0 and 1, respectively, and so intermediate states leading to the production of Λ's can only have isospin $1/2$ (N^* only), whereas for the Σ^0's intermediate states with both isospin $1/2$ and $3/2$ (N^* or Δ) can contribute. Figure 1 (right) shows the data for Σ^0 production at the same W as above, showing the more central strength of the Σ^0 cross sections induced by differing resonance structure.

The Regge-model calculation [9,10] shown in Fig. 1 uses only K and K^* exchanges, with no s-channel resonances. The prediction was made using a model that fit high-energy kaon electroproduction data well, and could be expected to reproduce the average behavior of the cross section in the resonance region. However, extrapolated down to the resonance region, the model overpredicts the size of the Λ cross section and underpredicts that of the Σ^0. Since it is a t-channel reaction model, it cannot produce a rise at back angles as seen for the Λ, and illustrates the need for s- and u-channel contributions to understand that feature. Two hadrodynamic models based on similar effective Lagrangian approaches [4,11,12] are also shown. Both emphasize the addition of a small set of s-channel resonances to the nonresonant Born terms, and differ in their treatment of hadronic form factors and gauge invariance restoration. Both were fit to the previous data from SAPHIR [8], and therefore do not agree well with our results.

Resonance structure in the s channel should appear most clearly in the W dependence of the cross sections. In Fig. 2 (top) we show the $K^+\Lambda$ cross section at our most forward kaon angle, showing a sharp rise from threshold up to 1.72 GeV, a slow decline, and then a structure at 1.95 GeV with a full-width of about 100 MeV. The peak in the threshold region is understood in model calculations as due to the known $S_{11}(1650)$, $P_{11}(1710)$, and $P_{13}(1720)$ resonances. At a moderate forward angle, shown in Fig. 2 (middle), the higher-mass structure near 1.95 GeV is not visible. At a moderate backward angle, shown in Fig. 2 (bottom), we again see clear structure, but it is broader, centered near 1.90 GeV, and is about 200 MeV wide. These structures are prominent at forward and backward angles; for most intermediate angles the energy dependence near 1.9 GeV falls

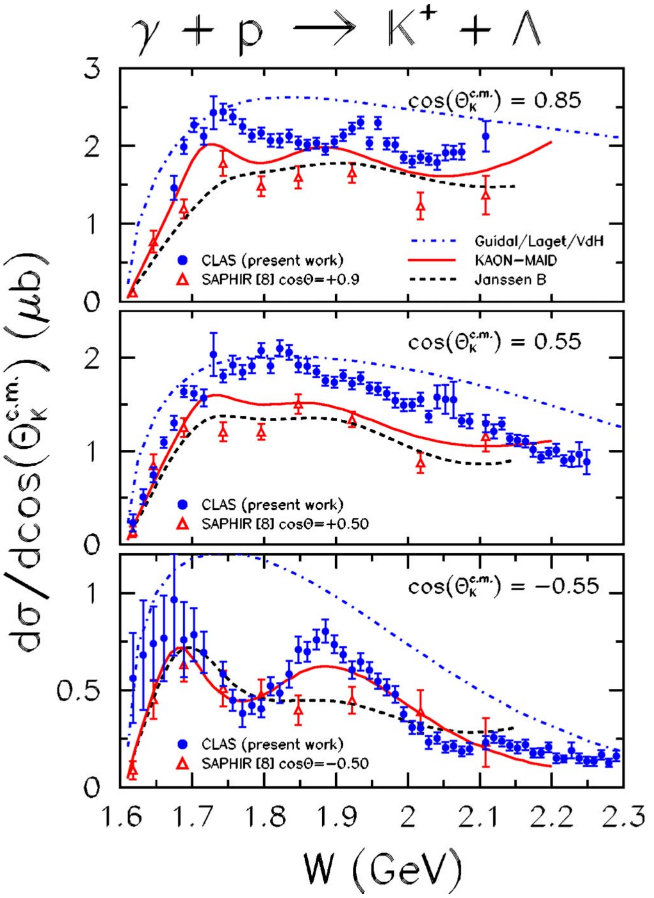

FIG. 2. (Color online) Energy dependence of the Λ cross section at the most forward angle measured (top), and at intermediate forward and backward angles (middle), (bottom). The error bars combine statistical and estimated point-to-point systematic errors. The curves and other data are the same as in Fig. 1.

smoothly. In contrast, our corresponding measured $\pi^+ n$ cross sections are featureless throughout this angle and energy range [5].

Indications of the structure near 1.9 GeV were first seen in data from SAPHIR [8], which was interpreted by some [11] as evidence for a "missing" resonance at this mass. Based on theoretical guidance from one particular quark model [2], an assignment of $D_{13}(1895)$ seemed consistent with the angular distributions. However, other groups [12,13] showed that the same data could be accommodated using u-channel hyperon exchanges, an extra P-wave resonance, or alternative hadronic form factors. CLAS data, which show a structure that varies in width and position with kaon angle, suggests an interference phenomenon between several resonant states in this mass range, rather than a single well-separated resonance. This should be expected, since many s-resonances occupy this mass range. The best modeling of the backward-angle structure near 1.9 GeV is given in Ref. [11] by incorporating a $D_{13}(1895)$. We see, however, that the resulting fixed position and width in this model is not consistent with the variation with angle seen in the data.

The hyperon recoil polarization provides another test of reaction models. This observable is related to interferences of the imaginary parts of the resonant amplitudes with the real part of other amplitudes, including the nonresonant Born terms. Unpolarized photons on an unpolarized target can only produce hyperons that are polarized along the axis $(\hat{\gamma}\times\widehat{K^+})$ normal to the production plane. The parity-violating weak decay asymmetry in hyperon decays enables us to determine this polarization by measuring the angular distribution of the decay protons. The large acceptance of CLAS made it straightforward to detect protons from the decay of hyperons in coincidence with the K^+ mesons.

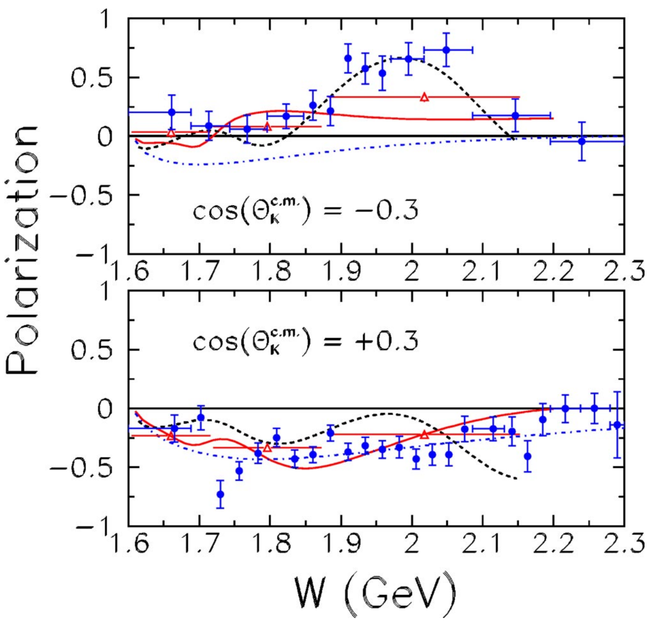

FIG. 3. (Color online) Recoil polarization of Λ hyperons as a function of W for the center-of-mass kaon angle of $\cos(\theta_K^{\mathrm{c.m.}}) = -0.3$ (top) and $\cos(\theta_K^{\mathrm{c.m.}}) = +0.3$ (bottom). Vertical bars on CLAS data (solid points) combine statistical and systematic errors and horizontal error bars span regions of weighted averaging. The curves and other data are the same as in Figs. 1 and 2.

Figure 3 shows the Λ recoil polarization as a function of W for representative kaon angles in the backward and the forward directions. The data have been binned such that the statistical uncertainty on each datum is less than ± 0.15. The error bars combine statistical and estimated systematic uncertainties arising from the yield extraction. Our results are generally consistent with a few older data points from SAPHIR [8], but our energy binning is finer and reveals more structure. The data show negative polarization of the Λ hyperons when kaons go forward in the center-of-mass frame and a comparably strong positive polarization when kaons go backward.

Of the three models tested here, only the model of Janssen *et al.* [12] (dashed line) predicts the large back-angle polarization seen in the data near 2.0 GeV. This prediction is strongly influenced by u-channel Y^* contributions in that model which are added to a $D_{13}(1895)$ s-channel component. At the forward angle, however, this model does not perform better than the other hadrodynamic calculation or the Regge-based model. The positive back-angle polarization arises in the Kaon-MAID [4] calculation from the presence of a

$D_{13}(1895)$, but the strength is too small. The Regge-based model [9,10] can provide only very weak back-angle polarization, since by construction it has only a *t*-channel (forward-angle) production mechanism, leading here to the wrong sign. Near threshold energy the hadrodynamic models show the most structure due to interference of the known resonances cited earlier; but here our data have limited precision and cannot distinguish among these models.

In summary, we present results from an experimental investigation of hyperon photoproduction from the proton in the energy range where nucleon resonance physics should dominate. Our $K^+\Lambda$ cross section data reveal an interesting W dependence: double-peaked at forward and backward angles, but not at central angles. For the first time we see that the structure near 1.9 GeV shifts in position and shape from forward to backward angles. This finding cannot be explained by a *t*-channel Regge-based model or by the addition of a single new resonance in the *s* or *u* channel. Our polarization data show large values of polarization that change from negative values at forward angles to positive for backward kaon angles. Since a *t*-channel Regge model is unable to explain the backward, positive polarization, it appears that additional *s*- or *u*-channel resonances are needed to explain the data. Our results show that hyperon photoproduction can reveal resonance structure previously “hidden” from view, thereby improving our understanding of nucleonic excitations in the higher-mass region where data are sparse. Comprehensive partial wave analysis and amplitude modeling for these data can therefore be hoped to firmly establish the mass and possibly the quantum numbers of these states.

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