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MINI-REVIEW

Kaon Photoproduction: From an Experimental Point of View

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Abstract

Today, laboratory experiments conducted worldwide continue to search for undiscovered excited states of the nucleon. The database has been continually updated over the past years to allow for nearly model-independent partial wave analyses (PWA) to be carried out in the search for such undiscovered states. The photoproduction of mesons, such as kaons, has been studied extensively in the past. However, there is still much information that can be gathered and learned from the photoproduction of the kaon. Recent coupled-channel analyses have found strong sensitivity of the $K^+\Lambda$ channel to several higher mass nucleon resonances. Various experiments have provided new and interesting results that are discussed in this short review.

Introduction

Quantum Chromodynamics (QCD) theory describes strong interactions, the dynamics of the fundamental constituents of most matter, as the interaction between quarks and gluons [1]. At higher energies, the strong interaction becomes weaker and easier to describe. However, at low-to-medium energies (a few GeV in the c.m. energy regime), the strong interactions are considered an interesting, but puzzling force. At these energies, QCD equations cannot be simplified due to the degrees of freedom of mesons and baryons that dominate the physics. Lattice QCD has made advances towards finding direct solutions of QCD, but these calculations are computationally intensive computationally and still not close enough to current experimental data [2]. Interestingly, the lattice spacing is still rather wide and only corresponds to pion masses of 300-400 MeV, instead of the correct value of 140 MeV. Currently, there is no simple analytic solution to QCD at medium energies.

Due to the lack of calculations of QCD at intermediate energies, models and calculation tools have been developed. By making these approximations, QCD then allows for detailed predictions of the spectrum of excited states of the nucleon. The direct comparison of experimental data to the calculations allows for tuning and testing of the models and tools. Baryon spectroscopy programs at many facilities are attempting to provide the necessary experimental data for these comparisons. The baryon spectrum has many resonances, or excited states, that are closely spaced in energy and overlap. These excited states are identified by their quantum numbers and masses. Baryon spectroscopy is the
detailed program of mapping out the nucleon resonant states that are excited in a given reaction. The mapped out resonant states can then decay into quasi-stable baryons and mesons which are detected experimentally and which allow for their masses and quantum numbers (e.g. spin and parity) to be determined.

The baryon spectrum can be probed in experiments involving the scattering of p mesons from the proton. Intermediate $N^*$ states are produced and then decay into detectable hadrons, mainly a nucleon and one or more pions. The biggest complication in baryon spectroscopy is due to the width of the nucleon resonances. Many of the states are broad and overlapping, which makes a complete identification of the states based on energy alone not possible.

The next issue is the “missing resonance” problem. A discrepancy exists between the number of states that have been predicted and those that have actually been observed. Some resonant states have properties that have been observed in many experiments. However, for some, there is no experimental evidence, and these are viewed as “missing”. Various theories exist to explain why the states are missing. The most rational explanations are that not all of the predicted resonances exist, or that they do exist, but have not been detected in current experiments. If the predicted resonances do not exist, this implies that the model predicts too many states and does not predict the interaction of the valence quarks of the states correctly. However, if the states do exist, but have not yet seen experimentally, the experiments are incomplete, and the missing resonances couple weakly or do not couple at all to these reaction channels. Pion production has been studied in the past, but now kaon photoproduction can be used as a valuable tool, which can provide insights into the nucleon that pion production cannot.

Capstick and Roberts [3,4,5] have theorized in their quark model calculations that some missing resonances couple strongly to hyperon final state channels in photoproduction reactions. Their model also predicts that a number of negative-parity states from the $N = 3$, 4, and 5 bands will appear clearly in the final state reaction of $K^+\Lambda$. Figure 1 shows the Capstick and Roberts predictions for the coupling of resonances up to 2200 MeV to $\pi N$, $\gamma N$, and $K^+\Lambda$ for $N^*$ resonances. There is also a similar prediction for $K^+\Sigma^0$ for $\Delta$ resonances and can be found in Ref. [5]. This figure shows that most predicated states with masses above 1850 MeV have not been seen experimentally.

Figure 1. Capstick–Roberts Predicted Amplitudes for $N^*$ Resonances. For most States with Masses above 1850 MeV there is Poor or no Experimental Evidence
Results of the Experiments

The early results in kaon photoproduction were only cross-section results. With the development of large acceptance spectrometers, more data and results became available. A large experimental effort has been conducted at several electron accelerators (JLab, GRAAL, and MAMI) in recent years, attempting to advance the study of kaons. Many polarization observables have yet to be published, but some of the recent works will be highlighted here. In addition, much research is still being done on the $\Lambda(1405)$ despite having a 4-star PDG rating.

Polarization Observables. The photoproduction of single pseudoscalar mesons can be described by four complex amplitudes, which can be fully determined when a complete set of measurements is performed. The four complex amplitudes can be combined to account for the cross section, complemented by polarization observables including beam, target, and recoil asymmetries and combinations of beam-target, beam-recoil, and target-recoil polarization asymmetries.

Recently, published results based on the CEBAF Large Acceptance Spectrometer (CLAS) [6] include the beam asymmetry $\Sigma$, target asymmetry $T$, and the beam-recoil double polarization observables $O_x$ and $O_z$ for both $\gamma p \rightarrow K^0\Lambda$ and $K^0\Sigma^0$. Only the beam asymmetry $\Sigma$ is shown here in Figs. 2 and 3. The authors conclude that, in comparison with models, the data will hopefully provide some evidence of new resonances; unfortunately, there is not enough information to deduce the quantum numbers or masses of these states or to verify whether they actually exist [6].
Figure 4. Preliminary Polarization Observable $F$ Results for $\gamma p \rightarrow K^*\Lambda$. Red Data Points are CLAS g9b. Dotted Red Curves are from RPR-Ghent Model [11]; Solid Blue Curves are from KAON-MAID [12]; and Dashed Magenta Curves are from Bonn-Gatchina [13]
Figure 5. Preliminary Polarization Observable $F$ Results for $\gamma p \rightarrow K^0\Sigma^0$. Red Data Points are CLAS g9b. Dotted Red Curves are from RPR-Ghent Model; Solid Blue Curves are from KAON-MAID; and Dashed Magenta Curves are from Bonn-Gatchina
The $\Lambda(1405)$ hyperon. The $\Lambda(1405)$ hyperon was first seen in bubble chamber experiments in the 1960s [14], but has not been measured often since then. Since the mass of the state is below the $NK$ threshold, it is not possible to produce it in kaon beam experiments, which makes it difficult compared to other strange baryon resonances. However, the line shapes were recently measured by CLAS [15] using $\Sigma\pi$ final states in photoproduction. The state does not fit well within the constituent quark model, which normally works well for understanding the masses of low-lying baryon resonances [16]. The measured lines shapes include all three charge combinations and the authors’ primary conclusion is that they are significantly different from each other and that none are well represented by a simple Breit-Wigner line shape. They conclude that the interference of $I = 0$ and $I = 1$ isospin channels could be the explanation for the different line shapes for the three $\Sigma\pi$ final states.

Conclusion

An overview of recent results in kaon photoproduction has been presented. Despite new results being published, it is clear that there is still much work to be done and many channels with kaon photoproduction can still be explored. Kaons can help in accessing properties of $N^*$ and $\Delta^*$ states. Kaon data is valuable to the world database, as these results will help in providing answers in constraining current PWA models. There can also be insight into extracting undiscovered states of the nucleon. Data from many experiments such as the FROST experiment in CLAS include additional polarization observables and other channels not discussed here. These are important in order to untangle and decipher the full spectrum of $N^*$ and $\Delta^*$ resonances.

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