K-Long Facility for JLab and its Scientific Potential

Igor I. Strakovsky[1,⋆]

[1] *Institute for Nuclear Studies, Department of Physics, The George Washington University, Washington, D.C. 20052, U.S.A.*

Abstract. Our main interest in creating a secondary high-quality KL-beam is to investigate hyperon spectroscopy through both formation and production processes. We propose to study two-body reactions induced by the KL-beam on the proton target. The experiment should measure both differential cross sections and self-analyzed polarizations of the produced Λ-, Σ-, and Ξ-hyperons using the GlueX detector at the Jefferson Lab Hall D. New data will greatly constrain partial-wave analysis and reduce model-dependent uncertainties in the extraction of strange resonance properties, providing a new benchmark for comparisons with QCD-inspired models and LQCD calculations. The measurements will span c.m. $\cos\theta$ from -0.95 to 0.95 in c.m. range above W = 1490 MeV and up to 4000 MeV.

1 Introduction

At the beginning of February of 2016, Jefferson Lab hosted a Workshop *Physics with Neutral Kaon beam at JLab*. It was dedicated to the physics of hyperons produced by the neutral Kaon beam on both unpolarized and polarized targets [1]. The workshop follows our LoI–12–15–001 [2] (JLab KLF Project) to help to address the comments made by the JLab PAC43 and to prepare the full proposal for PAC45. The emphasis is on the hyperon spectroscopy. Mini-Proceedings of the KL2016 are available at arXiv [3].

The *Excited Hyperons in QCD Thermodynamics at Freeze-Out* (YSTAR2016) Workshop [4] is a successor to the recent KL2016. This workshop will discuss the influence of possible "missing" hyperon resonances on QCD thermodynamics, on freeze-out in heavy ion collisions and in the early universe, and in spectroscopy. Recent studies that compare LQCD calculations of thermodynamic calculations, statistical hadron resonance gas models, and ratios between measured yields of different hadron species in heavy ion collisions provide indirect evidence for the presence of "missing" resonances in all of these contexts. The aim of the workshop is to sharpen these comparisons, advance our understanding of the formation of baryons from quarks and gluons microseconds after the Big Bang and in today's experiments, and to connect these developments to experimental searches for direct, spectroscopic, evidence for these resonances.

The JLab12 energy upgrade, with the new Hall D, is an ideal tool for extensive studies of non-strange and, specifically, strange baryon resonances [5]. Our plan is evolving to take advantage of the existing high quality photon beam line and experimental area in the Hall D complex at Jefferson

---

⋆e-mail: igor@gwu.edu

Lab to deliver a beam of K_L particles onto a liquid hydrogen cryotarget within the GlueX detector. The recently constructed GlueX detector in Hall D is a large acceptance spectrometer with good coverage for both charged and neutral particles that can be adapted to this purpose. Obviously, Kaon beam facility (KLF) with good momentum resolution is crucial to provide the data needed to identify and characterize the properties of hyperon resonances. The masses and widths of the lowest Λ and Σ baryons were determined mainly with Kaon-beam experiments in the 1970s [6]. Pole position in complex energy plane for hyperons has began to be studied only recently, first of all for $\Lambda(1520)\frac{3}{2}^-$ [7].

2 Scope of the Proposed KLF Program

A comparison of recent coupled-channel analyses [8–11] comes to the conclusion that, for most cases, it is only the first excited state in each partial wave whose detailed properties [branching reaction (BRs), helicity amplitudes] are known. Different analyses may agree on the existence of the second state (in each partial wave) but not on their decay properties, while there is no agreement even on the existence of a third state in a particular partial wave. Given the arduous nature of the task involved in obtaining high-quality data that enter these multichannel analyses it is reasonable to address the question as to the final scope of this effort. In other words: How many resonances do we need to identify in order to convince ourselves that we have achieved a solid understanding of the baryon spectrum from QCD? As examples, we examine this question from the viewpoint of lattice gauge and constituent quark model (QM) calculations.

Our current "experimental" knowledge of Λ^*, Σ^*, Ξ^*, and Ω^* resonances is far worse than our knowledge of N^* and Δ^* resonances; though they are equally fundamental. Specifically, the properties of multi-strange baryons (Ξ^* and Ω^* states) are poorly known. For instance the *Review of Particle Physics* lists only two states with BR to $K\Xi$, namely, $\Lambda(2100)\frac{7}{2}^-$ (BR $< 3\%$) and $\Sigma(2030)\frac{7}{2}^+$ (BR $<$ 2%) [6]. Clearly, complete understanding of three-quark bound states requires to learn more about baryon resonances in "strange sector" as well.

Reviewing analyses decades worth of data, from both hadronic and EM experiments, we have found numerous baryon resonances, and determined their masses, widths, and quantum numbers. There are 112 baryons in PDG2014 Listings [6] (including both non-strange and strange states) and only 58 of them are 4^* and 3^*. Many more states have been predicted by QMs. For example in case of $SU(6) \times O(3)$, it would be required 434 resonances, if all revealed multiplets were completed (three 70^- and four 56^-).

Three light quarks can be arranged in 6 baryonic families, N^*, Δ^*, Λ^*, Σ^*, Ξ^*, and Ω^*. Number of members in a family that can exist is not arbitrary [12]. If $\mathrm{SU}(3)_F$ symmetry of QCD is controlling, then for the octet: N^*, Λ^*, and Σ^*, and for the decuplet: Δ^*, Σ^*, Ξ^*, and Ω^*. Number of experimentally identified resonances of each baryon family in PDG2014 summary tables is 17 N^*, 24 Δ^*, 14 Λ^*, 12 Σ^*, 7 Ξ^*, and 2 Ω^*. Constituent QMs, for instance, predict existence of no less than 64 N^* and 22 Δ^* states with mass less than 3 GeV. Seriousness of "missing-states" problem [13] is obvious from these numbers. To complete $\mathrm{SU}(3)_F$ multiplets, one needs no less than 17 Λ^*, 41 Σ^*, 41 Ξ^*, and 24 Ω^*.

3 Observables

There are two particles in the reactions $K_L p \to \pi Y$ and KY that can carry polarization: the target and recoil nucleon/hyperon. Hence, there are two possible double-polarization experiments: target/recoil. While a formally complete experiment requires the measurement, at each energy and angle, of at least three independent observables, the current database for $K_L p \to \pi Y$ and KY is populated mainly by unpolarized cross sections. Figure 1 illustrates this quite clearly.

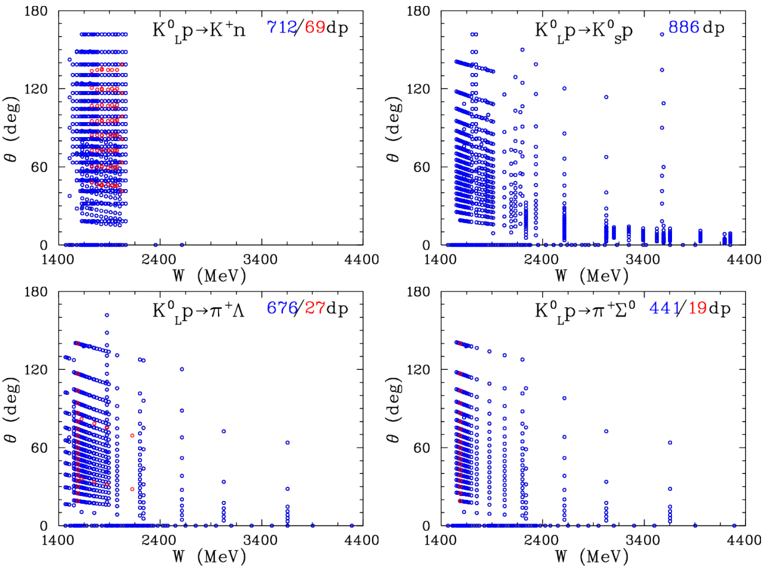

Figure 1. Experimental data available for $K_Lp \to K^+n$, $K_Lp \to K_Sp$, $K_Lp \to \pi^+\Lambda$, and $K_Lp \to \pi^+\Sigma^0$ as a function of c.m. energy W [14]. The number of data points (dp) is given in the upper righthand side of each subplot [blue (red) shows amount of unpolarized (polarized) observables]. Total cross sections are plotted at zero degrees.

The experiments using unpolarized LD_2 (to get "neutron" data) and polarized target (aka FROST) for both hydrogen and deuteriun components, we will leave for the following proposals. Obviosly, it will open up a new avenue to the complete experiment. Note that the "neutron" data are critical to determine parameters of neutral Λ^*s and Σ^*s hyperons which were considered recently [15].

4 Phenomenology / Partial-Wave Aanalysis

Following Höhler [16], the differential cross section and polarization for $K_Lp \to \pi Y$ and KY are given by

$$\frac{d\sigma}{d\Omega} = \lambda\!\!\!^{-2}(|f(W,\theta)|^2 + |g(W,\theta)|^2), \quad P\frac{d\sigma}{d\Omega} = 2\lambda\!\!\!^{-2}\mathrm{Im}(f(W,\theta)\, g(W,\theta)^*), \tag{1}$$

where $\lambda\!\!\!^{-} = \hbar/k$, with k the magnitude of c.m. momentum for the incoming meson. Here $f(W,\theta)$ and $g(W,\theta)$ are the usual spin-nonflip and spin-flip amplitudes at c.m. energy W and meson c.m. scattering angle θ. In terms of partial waves, $f(W,\theta)$ and $g(W,\theta)$ can be expanded as

$$f(W,\theta) = \sum_{l=0}^{\infty}[(l+1)T_{l+} + lT_{l-}]P_l(\cos\theta), \quad g(W,\theta) = \sum_{l=1}^{\infty}[T_{l+} - T_{l-}]P_l^1(\cos\theta), \tag{2}$$

where l is the initial orbital angular momentum, $P_l(\cos\theta)$ is a Legendre polynomial, and $P_l^1(\cos\theta)$ is an associated Legendre function. The total angular momentum for the amplitude T_{l+} is $J = l + \frac{1}{2}$, while that for the amplitude T_{l-} is $J = l - \frac{1}{2}$. For hadronic scattering reactions, we may ignore small

CP-violating terms and write

$$K_L^0 = \frac{1}{\sqrt{2}}(K^0 - \overline{K^0}), \quad K_S^0 = \frac{1}{\sqrt{2}}(K^0 + \overline{K^0}). \tag{3}$$

We may generally have both $I = 0$ and $I = 1$ amplitudes for KN and $\overline{K}N$ scattering, so that the amplitudes $T_{l\pm}$ can be expanded in terms of isospin amplitudes as

$$T_{l\pm} = C_0 T^0_{l\pm} + C_1 T^1_{l\pm}, \tag{4}$$

where $T^I_{l\pm}$ are partial-wave amplitudes with isospin I and total angular momentum $J = l \pm \frac{1}{2}$, with the appropriate isospin Clebsch-Gordan coefficients C_I.

We plan to do a coupled-channel PWA with new GlueX KLF data in combination with available and new J-PARC K^-p measurements when they will be available. Then the best fit will allow to determine data driven (model independent) partial-wave amplitudes and associated resonance parameters as the SAID group does, for instance, for analysis of πN-elastic, charge-exchange, and $\pi^-p \to \eta n$ data [17]. With the new GlueX KLF data, the quantitative significance of resonance signals can be determined. Additionally, new PWA with new GlueX data will allow to look for "missing" hyperons via looking for new poles in complex plane positions. It will provide a new benchmark for comparisons with QCD-inspired models and LQCD calculations.

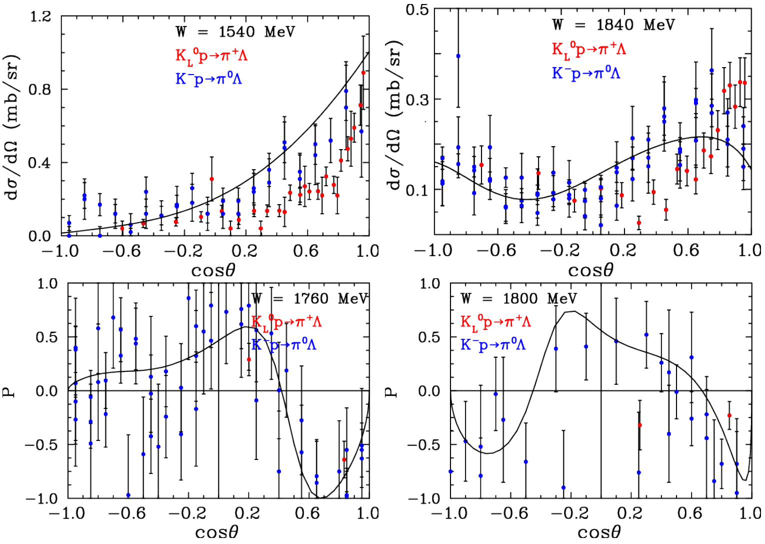

Figure 2. Comparison of selected differential cross section data for $K^-p \to \pi^0\Lambda$ and $K_Lp \to \pi^+\Lambda$ at W = 1540 MeV and 1840 MeV and selected polarization data at W = 1760 MeV and 1800 MeV from previous measurements are those data points within 20 MeV of the Kaon c.m. energy indicated on each panel [14]. The curves are from the recent PWA of $K^-p \to \pi^0\Lambda$ data [8].

The $K^-p \to \pi^0\Lambda$ and $K_Lp \to \pi^+\Lambda$ amplitudes imply that observables for these reactions measured at the same energy should be the same except for small differences due to the isospin-violating mass differences in the hadrons. No differential cross section data for $K^-p \to \pi^0\Lambda$ are available at c.m.

energies $W < 1540$ MeV, although data for $K_L p \to \pi^+ \Lambda$ are available at such energies due to longer K_L life time. At 1540 MeV and higher energies, differential cross section and polarization data for both reactions are in fair agreement, as shown in Fig. 2. Meanwhile, the quality of avilable P measurements do not have a sensitivity to the fit.

5 Proposed Measurements

We propose to use a Hall D Facility with the GlueX spectrometer, to perform precision measurements of two-body reactions induced by the K_L-beam on the liquid hydrogen cryotarget in the resonance region, W = 1490 – 4000 MeV and c.m. $\cos\theta$ from -0.95 to 0.95. This ability of the GlueX provides an ideal environment for these experiment.

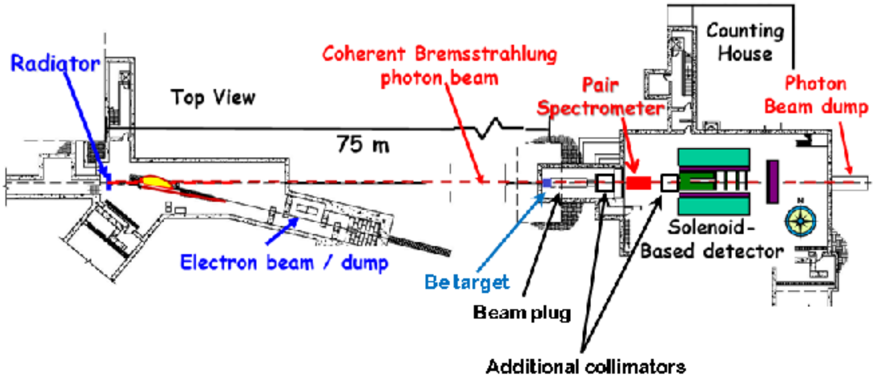

Figure 3. Schematic view of Hall D beamline on the way $e \to \gamma \to K_L$.

There is an advantage factor for $K_L p$ vs. $K^- p$ experiment. The mean lifetime of the K_L is 51.16 ns ($c\tau$ = 15.3 m) whereas the mean lifetime of the K^- is 12.38 ns ($c\tau$ = 3.7 m) [6]. For this reason, it is much easier to perform measurements of $K_L p$ scattering at low beam energies compared with $K^- p$ scattering [18].

The recently constructed GlueX detector in Hall-D is a large acceptance spectrometer with good coverage for both charged and neutral particles that can be adapted to this purpose [5]. Schematic view of the Hall D beamline is presented in Fig. 3. At the first stage, E_e = 12 GeV electrons produced at the CEBAF will scatter in a radiator in the target vault, generating intensive beam of bremsstrahlung photons (we will not need in the Hall D Broadband Tagging Hodoscope). At the second stage, bremsstrahlung photons, created by electrons, hit the Be-target and produce K_L-mesons along with neutron and charged particles. Finaly, K_L will reach the LH$_2$ cryogenic target within GlueX settings.

We estimated the flux of K_L beam on the GlueX LH$_2$ target is about 10^5 K_L/s, to be compared to about 10^3 K_L/s used at NINA [19] and SLAC [20], almost comparable to charged Kaon rates obtained at AGS and elsewhere in the past and expected for J-PARC [18]. Momenta of neutral Kaons at JLab will be measured applying the time-of-flight technique using a time structure of 60 ns. The count rate estimates carried out assuming 100 days of data taking are presented in Fig. 4.

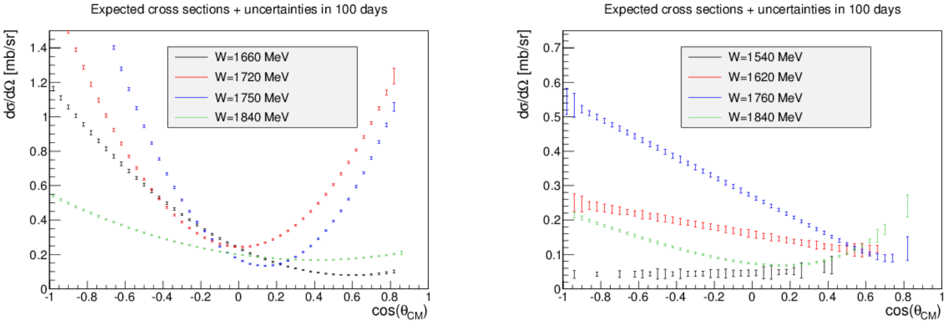

Figure 4. The cross section uncertainty estimates (statistics only) for $K_Lp \to pK_S$ (left) and for $K_Lp \to \pi^+\Lambda$ (right).

6 Conclusion and Perspectives

Precise new data (both differential cross section and recoil polarization of hyperons) for K_Lp scattering with good kinematic coverage could significantly improve our knowledge on Λ^* and Σ^* resonances. Clearly, complete understanding of three-quark bound states requires to learn more about baryon resonances in "strange sector". Polarization data are very important to be measured in addition to differential cross sections to help remove ambiguities in PWAs.

Unfortunately, the current database for K_Lp scattering includes very few polarization data. As noted here, several K_Lp reactions are isospin (I=1) selective, which would provide a useful constraint for a combined PWA of K_Lp and K^-p reactions. Finally, the long lifetime of the K_L compared with the K^- would allow K_Lp measurements to be made easier at lower energies compared with K^- beams. It would be advantageous to combine all K_Lp data in a new coupled-channel PWA with available and new J-PARC K^-p data when they will be available. The proposed KL facility potentially may unravel many "missing" hyperons. To complete SU(3)$_F$ multiplets, one needs no less than 17 Λ^*, 41 Σ^*, 41 Ξ^*, and 24 Ω^*.

Measurements of "missing" hyperon states with their spin-parity assignments along with the "missing" non-strange baryons will provide very important ingredients to test QM and LQCD predictions thereby improving our understanding of QCD in a non-perturbative regime.

I thank Moskov Amaryan, Yakov Azimov, William Briscoe, Eugene Chudakov, Ilya Larin, Mark Manley, James Ritman, and, Simon Taylor for comments on the feasibility of future measurements. This work is supported, in part, by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under Award Number DE–SC0014133.

References

[1] Workshop on *Physics with Neutral Kaon Beam at JLab*, JLab, VA, USA, Feb. 2016.

[2] *Physics opportunities with secondary K_L beam at JLab*, Spokesperson: M. Amaryan (GlueX Collaborations), JLab LoI12–15–001, Newport News, VA, USA, 2015.

[3] M. Albrow *et al. Mini-Proceedings of the Workshop on Physics with Neutral Kaon Beam at JLab* (KL2016), JLab, VA, USA, Feb. 2016, edited by M. Amaryan *et al.*; arXiv:1604.02141 [hep–ph].

[4] Workshop on *Excited Hyperons in QCD Thermodynamic at Freeze-Out*, JLab, VA, USA, Nov. 2016.

[5] H. Al Ghoul *et al.* (GlueX Collaboration), AIP Conf. Proc. **1735**, 020001 (2016), Proceedings of the *16th International Conference on Hadron Spectroscopy* (Hadron2015), Newport News, VA, Sept. 2015, edited by M. Pennington.

[6] K.A. Olive *et al.* (Particle Data Group), Chin. Phys. C **38**, 090001 (2014).

[7] Y. Qiang *et al.*, Phys. Lett. B **694**, 123 (2010).

[8] H. Zhang *et al.*, Phys. Rev. C **88**, 035204 (2013); *ibid.* **88**, 035205 (2013).

[9] H. Kamano *et al.*, Phys. Rev. C **90**, 065204 (2014); *ibid.* **92**, 025205 (2015).

[10] B. C. Jackson *et al.*, Phys. Rev. C **91**, 065208 (2015).

[11] C. Fernandez-Ramirez *et al.*, Phys. Rev. D **93**, 034029 (2016).

[12] B.M.K Nefkens, πN Newsletter, **14**, 150 (1997).

[13] R. Koniuk and N. Isgur, Phys. Rev. Lett. **44**, 845 (1980).

[14] The Durham HEP Reaction Data Databases (UK) (Durham HepData): http://durpdg.dur.ac.uk/hepdata/reac.html .

[15] B.S. Zou, *Mini-Proceedings of the Workshop on Physics with Neutral Kaon Beam at JLab*, see Ref. [3].

[16] G. Höhler, *Pion-Nucleon Scattering*, Landoldt-Börnstein, Vol. **I/9b2**, edited by H. Schopper (Springer-Verlab, Berlin, 1983).

[17] R. A. Arndt *et al.*, Phys. Rev. C **74**, 045205 (2006).

[18] H. Noumi, *Mini-Proceedings of the Workshop on Physics with Neutral Kaon Beam at JLab*, see Ref. [3].

[19] M.G. Albrow *et al.*, Nucl. Phys. B **23**, 509 (1970).

[20] G.W. Brandenburg *et al.*, Phys. Rev. D **7**, 708 (1973).