A Letter of Intent to Jefferson Lab PAC-43.

Physics Opportunities with a Secondary K_L^0 Beam at JLab.

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We express our interest in creating a secondary K_L^0 beam in Hall D to be used with the GlueX experimental setup for spectroscopy of excited hyperons through formation as well as production processes.

At first stage an electron beam from CEBAF, with a current in the range $I_e = 3 - 5\ \mu A$, will interact with a radiator to produce bremsstrahlung photon beam. The collimated photon beam, impinging on secondary 1-2 radiation length Be target installed 85 m downstream the tagger radiator will produce a flow of K_L^0 mesons, which then interacts with a physics target installed 16 m further downstream. To stop the photon beam a thick lead absorber ($l \approx 30$ radiation lengths) will be inserted into the beamline and will be followed by a sweeping magnet to deflect produced charged particles flow. Our preliminary simulations show that neutron rate on physics target will be less than the kaon rate for $p_{K_L} > 2$ GeV/c, this neutron rate will only be an order of magnitude larger than the K-long rate for momenta in the range of $1 < P < 2GeV/c$ and increase at very low momenta, which will be cut out with the time-of-flight. This is one of the great advantages of K_L^0 production in electromagnetic interactions, as opposed to the case of primary proton beams, where the rate of neutrons is about 10^3 times higher than that of K_L^0 [1], which creates a huge rate of neutron initiated events.

We estimated the flux of K_L^0 beam on the GlueX physics target in the range of few times 10^3/sec up to 10^4/sec, to be compared to about $10^2 K_L$/sec used at SLAC in LASS experiment [2] and almost comparable to charged kaon rates obtained at AGS [3] and elsewhere in the past. Momenta of neutral kaons will be measured using time-of-flight technique. Our studies show $\Delta p/p \approx 0.5\%$ of K_L^0 momenta can be achieved.

These measurements will allow studies of very poorly known multiplets of Λ, Σ, Ξ, and Ω hyperons with unprecedented statistical precision, and have a potential to observe dozens of predicted (but heretofore unobserved) states and to establish the quantum numbers of already observed hyperons listed in PDG [4].

The possibility to run with polarized target (e.g. FROST) , and measuring recoil polarization of hyperons will open up a new avenue to the complete experiment.

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Contents

I. INTRODUCTION

Our current understanding of strong interactions is embedded in Quantum Chromodynamics (QCD). However, QCD being a basic theory, extremely successful in explaining the plethora of experimental data in the perturbative regime, faces significant challenges to describe the properties of hadrons in non-perturbative regime. Constituent Quark Model (CQM) is surprisingly successful in explaining spectra of hadrons, especially in the ground state; however, CQM appears to be too naive to describe properties of excited states. It is natural that excited states are not simply explained with spatial excitations of constituent quarks, but it is an effective representation revealing complicated interactions of quarks and gluons inside. Hadron spectroscopy aims to provide a comprehensive description of hadron structure based on quark and gluon degrees of freedom. Despite many successes in observing hundreds of meson and baryon states experimentally we haven't succeeded to either observe or rule out existence of glueballs, hybrids and multi quark systems; although it is tempting to explain recently observed X, Y, Z [4] states as first evidences of tetra-quarks. An extensive experimental program is developed to search for hybrids in the GlueX experiment at JLab. Over the last decade, significant progress in our understanding of baryons made of light (u, d) quarks have been made in CLAS. However, systematic studies of excited hyperons are very much lacking with only decades old very scarce data filling the world database in many channels. In this experiment we propose to fill this gap and study spectra of excited hyperons using the modern CEBAF facility with the aim to use proposed secondary K_L^0 beam the physics target of the GlueX experiment in Hall D. The goal is to study $K_L - p$ and $K_L - d$ interactions and do the baryon spectroscopy for the strange baryon sector.

Our current experimental knowledge of strange resonances is far worse than our knowledge of N and Δ resonances; however, within the quark model, they are no less fundamental. Clearly there is a need to learn about baryon resonances in the "strange sector" to have a complete understanding of three-quark bound states.

Unlike in the cases with pion or photon beams, kaon beams are crucial to provide the data needed to identify and characterize the properties of hyperon resonances.

The masses and widths of the lowest mass baryons were determined with kaon-beam experiments in the 1970s [4]. First determination of pole positions, for instance for $\Lambda(1520)$, were obtained only recently from analysis of Hall A measurement at JLab [5]. An intense kaon beam would open a window of opportunity not only to locate missing resonances, but also to establish properties including decay channels systematically for higher excited states.

A comprehensive review of physics opportunities with meson beams is presented in a recent paper [6]. Importance of baryon spectroscopy in strangeness sector was discussed in Ref. [7].

II. REACTIONS THAT COULD BE STUDIED WITH K_L^0 BEAM

1. *Elastic and charge-exchange reactions*

$$K_L^0 p \to K_S^0 p \tag{1}$$
$$K_L^0 p \to K^+ n \tag{2}$$

2. *Two-body reactions producing $S = -1$ hyperons*

$$K_L^0 p \to \pi^+ \Lambda \tag{3}$$
$$K_L^0 p \to \pi^+ \Sigma^0 \tag{4}$$

3. *Three-body reactions producing $S = -1$ hyperons*

$$K_L^0 p \to \pi^+ \pi^0 \Lambda \tag{5}$$
$$K_L^0 p \to \pi^+ \pi^0 \Sigma^0 \tag{6}$$
$$K_L^0 p \to \pi^0 \pi^0 \Sigma^+ \tag{7}$$
$$K_L^0 p \to \pi^+ \pi^- \Sigma^+ \tag{8}$$
$$K_L^0 p \to \pi^+ \pi^- \Sigma^- \tag{9}$$

4. Two- and three-body reactions producing $S = -2$ hyperons

$$K_L^0 p \to K^+ \Xi^0 \tag{10}$$
$$K_L^0 p \to \pi^+ K^+ \Xi^- \tag{11}$$
$$K_L^0 p \to K^+ \Xi^{0*} \tag{12}$$
$$K_L^0 p \to \pi^+ K^+ \Xi^{-*} \tag{13}$$

5. Three-body reactions producing $S = -3$ hyperons

$$K_L^0 p \to K^+ K^+ \Omega^- \tag{14}$$
$$K_L^0 p \to K^+ K^+ \Omega^{-*} \tag{15}$$

Reactions 10-15 will be discussed in more detail below.

III. THE K_L^0 BEAM IN HALL D

In this chapter we describe photo-production of secondary K_L^0 beam in Hall D.

At the first stage, $E_e = 12$ GeV electrons produced at CEBAF will scatter in a radiator in the tagger vault, generating intensive beam of bremsstrahlung photons. At the second stage, bremsstrahlung photons interact with Be target placed on a distance 16 m upstream of liquid hydrogen (LH_2) target of GlueX experiment in Hall D producing K_L^0 beam. To stop photons a 30 radiation length lead absorber will be installed in the beamline followed by sweeping magnet to deflect the flow of charged particles. The flux of K_L on (LH_2) target of GlueX experiment in Hall D will be measured with pair spectrometer upstream the target. Momenta of K_L particles will be measured using the time-of-flight between RF signal of CEBAF and start counters surrounding LH_2 target. Schematic view of beamline is presented in Fig.1. The bremsstrahlung photons, created by electrons at a distance about 85 m upstream, hit the Be target and produce K_L^0 mesons along with neutrons and charged particles. The lead absorber of $\sim$30 radiation length is installed to absorb photons exiting Be target. The sweeping magnet deflects any remaining charged particles (leptons or hadrons) remaining after the absorber. The pair spectrometer will monitor the flux of K_L^0 through the decay rate of kaons at given distance about 10 m from Be target.

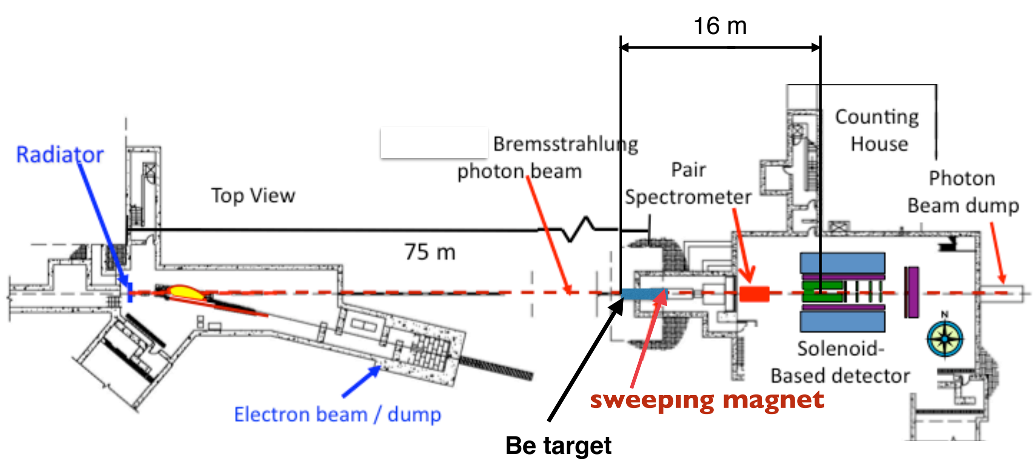

FIG. 1: Schematic view of Hall D beamline. See a text for explanation.

Here we outline experimental conditions and simulated flux of K_L^0 based on GEANT4 and known cross sections of underlying subprocesses [8–10].

- An electron beam with energy $E_e = 12$ GeV and current $I_e = 5\ \mu A$ (maximum possible, limited by the Hall D beam dump).
- A thickness of radiator 5 % radiation length (10 %).
- Primary Be target with $R = 4$ cm, $L = 40$ cm (60 cm).
- LH_2 target with $R = 2$ cm, $L = 30$ cm ($R = 3$ cm).
- Distance between Be and LH_2 targets 16 m.

The expected flux of K_L^0 mesons integrated in the range of momenta $P = 0.3 - 10 GeV/c$ will be $\approx 2000\ K_L^0/sec$ on the physics target of the GlueX setup.

In a more aggressive scenario with

- A thickness of radiator 10%.
- Be target with a length $L = 60$ cm.
- LH_2 target with $R = 3$ cm.

The expected flux of K_L^0 mesons integrated over the same momentum range will increase to $\approx 10^4 K_L^0/sec$.

In addition to these requirements it will require lower repetition rate of electron beam with ~ 40 ns spacing between bunches to have enough time to measure time-of-flight of the beam momenta and to avoid an overlap of events produced from alternating pulses. Lower repetition rate was already successfully used by G0 experiment in Hall C at JLab [11].

The radiation length of the radiator needs further studies in order to estimate the level of radiation and required shielding in the tagger region. During this experiment all photon beam tagging detector systems and electronics will be removed.

The final flux of K_L^0 is presented with 10% radiator, corresponding to maximal rate .

In the production of a beam of neutral kaons, an important factor is the rate of neutrons as background. As it is well known, the ratio $R = N_n/N_{K_L^0}$ is on the order 10^3 from primary proton beams [1], the same ratio with primary electromagnetic interactions is much less. This is illustrated in Fig.2, which presents the rate of kaons and neutrons as a function of the momentum, which resembles similar behavior as it was measured at SLAC [2].

IV. EXPECTED RATES

In this section we discuss expected rates of events for some selected reactions. The production of Ξ hyperons has been measured only with charged kaons with very low statistical precision and never with primary K_L^0 beam. In Fig.3 left and middle panels show existing data for the octet ground state Ξ's with theoretical model predictions for W (the reaction center of mass energy) distribution. On the right panel, a similar model prediction [13] is presented with expected experimental points and statistical error for 10 days of running with our proposed setup with a beam intensity $2000 K_L$/sec is presented using missing mass of K^+ in the reaction $K_L^0 + p \to K^+ \Xi^0$ without detection of any decay products of Ξ.

The physics of excited hyperons is not well explored, remaining essentially at the pioneering stages of '70s-'80s. This is especially true for $\Xi^*(S = -2)$ and $\Omega^*(S = -3)$ hyperons. For example, the $SU(3)$ flavor symmetry allows as many $S = -2$ baryon resonances, as there are N and Δ resonances combined (≈ 27); however, until now only three [ground state $\Xi(1382)1/2^+$, $\Xi(1538)3/2^+$, and $\Xi(1820)3/2^-$] have their quantum numbers assigned and few more states have been observed [4]. The status of Ξ baryons is summarized In a table presented in Fig.4 together with quark model predicted states [14].

Historically the Ξ^* states were intensively searched for mainly in bubble chamber experiments using the $K^- p$ reaction in '60s-'70s. The cross section was estimated to be on the order of 1-10 μb at the beam momenta up to 10 GeV/c. In '80s-'90s, the mass or width of ground and some of excited states were measured with a spectrometer in the CERN hyperon beam experiment. Few experiments have studied cascade baryons with the missing mass

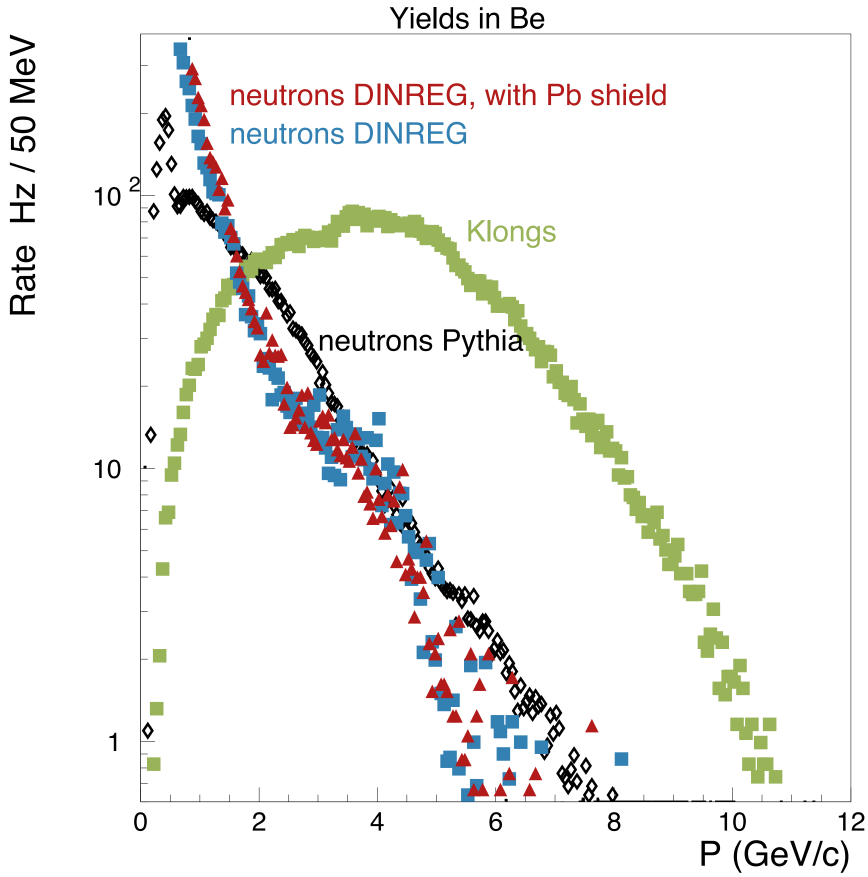

FIG. 2: The rate of neutrons (open symbols) and K_L^0 (full squares) on LH_2 target of Hall D as a function of their momenta simulated with different MC generators with $10^4 K_L^0$/sec.

technique. In 1983, the production of Ξ^* resonances up to 2.5 GeV were reported from $p(K^-, K^+)$ reaction from the measurement of the missing mass of K^+ [15]. In Fig.5, missing mass squared of K^+ from the reaction $p(K^-, K^+)$ is presented for two different spectrometer settings.

The experimental situation with Ω^{-*}'s is even worse than the Ξ^* case, there are very few data for excited states. The main reason for such a scarce dataset in multi strange hyperon domain is mainly due to very low cross section in indirect production with pion or in particular photon beams. In Fig.6 on the left panel, we present cross section of Ω production with K^- beam [16].

The current status of Ω hyperons is summarized in Fig.7. Observed states are grouped in the rightmost column showing that essentially only ground state Ω^- quantum numbers are identified. One also has to mention significant progress made recently by lattice QCD calculations of excited baryon states [23, 24].

A major effort in lattice gauge calculations of the spectrum of QCD is dealing with inelastic and multi-hadron scattering amplitudes, and the first calculation to study an inelastic channel has recently been performed [26] and [27]. An advantage of baryons containing one or more strange quarks for lattice calculations is that then number of open decay channels is in general smaller than for baryons comprising only the light u and d quarks.

In Fig.8, baryon spectra from [23] are presented in units of Ω mass from lattice QCD calculations from ensemble with $m_\pi = 391$ MeV. The experimental situation for higher excited states is essentially unknown and it requires significant efforts to map out these states. Moreover, lattice calculations show that there are many states with strong gluonic content in positive parity sector for all baryons, presented by symbols with thick borders. The reason why hybrid baryons have not attracted the same attention as hybrid mesons is mainly due to the fact that they lack manifest "exotic" character. Although it is difficult to distinguish hybrid baryon states, there is significant theoretical insight to be gained from studying spectra of excited baryons, particularly in a framework that can simultaneously calculate properties of hybrid mesons [23, 25]. Therefore this program will be very much complementary to the GlueX

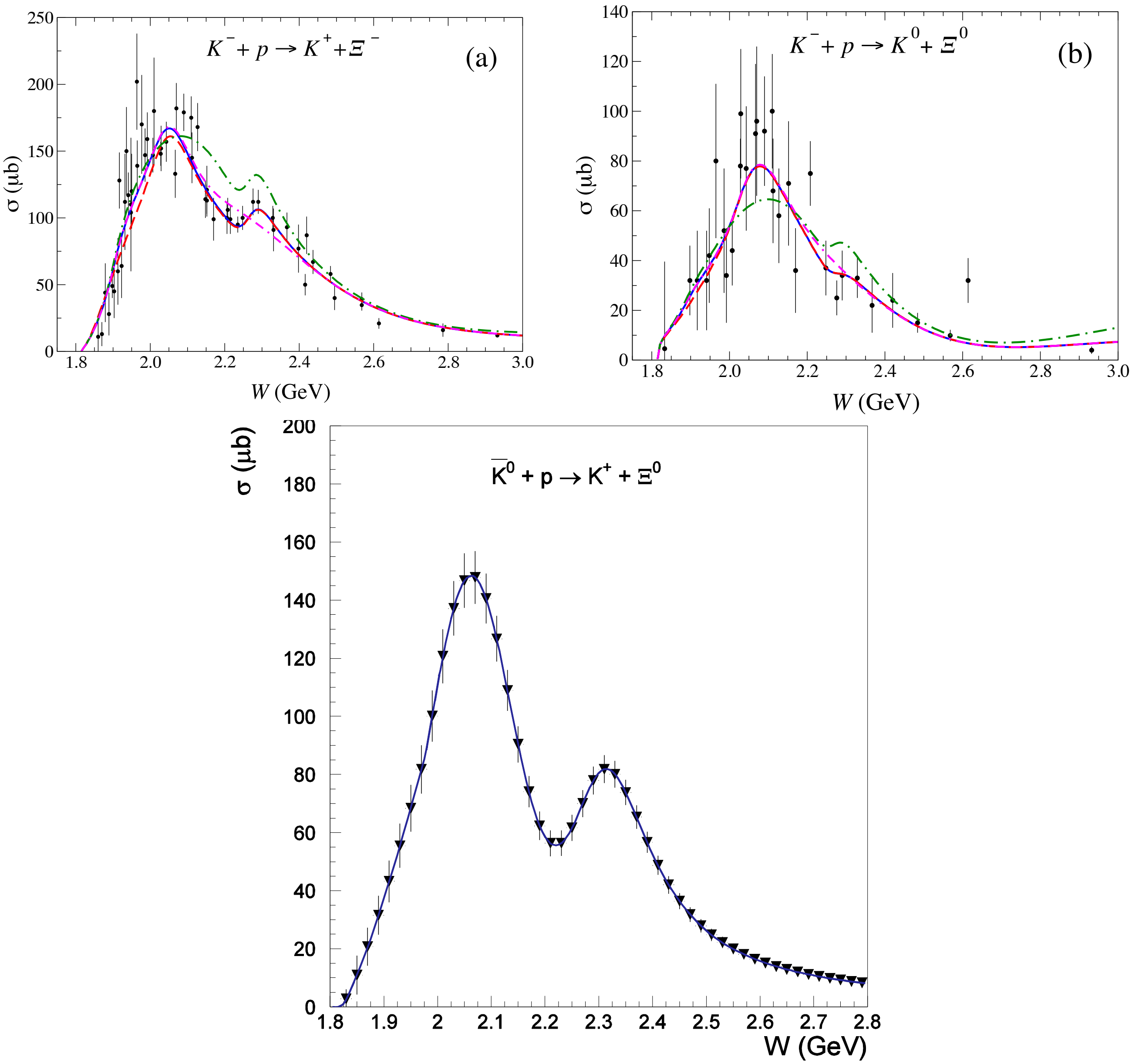

FIG. 3: Upper panel: a) cross section for existing world data for $K^- + p \to K^+\Xi^-$ reaction; b) the same for the reaction $K^- + p \to K^0\Xi^0$ as a function of W with theoretical curves from [12]. The blue lines represent the full results. The red dashed lines, the result with $\Lambda(1890)$ switched off. The green dash-dotted lines, that with $\Sigma(2030)$ switched off and the magenta dash-dash-dotted lines represent the result with $\Sigma(2250)5/2^-$ switched off. On the lower panel we show our expected measurements of the reaction $K_L^0 + p \to K^+\Xi^0$ with statistical errors for 10 days of running with a beam intensity $2000 K_L$/sec overlaid on theoretical prediction [13].

physics program for hybrid mesons.

The proposed experiment with a beam intensity $10^4 K_L$/sec will result in about 2×10^5 Ξ^*'s and 4×10^3 Ω^*'s per month.

A similar program for KN scattering is under development at J-PARC with charged kaon beams [28]. The current maximum momentum of secondary beamline of 2 GeV/c is available at the K1.8 beamline. The beam momentum of 2 GeV/c corresponds to $\sqrt{s}$=2.2 GeV in the K^-p reaction which is not enough to generate even the first excited Ξ^* state predicted in the quark model. However, there are plans to create high energy beamline in the momentum range 5-15 GeV/c to be used with the spectrometer commonly used with the J-PARC P50 experiment which will lead to

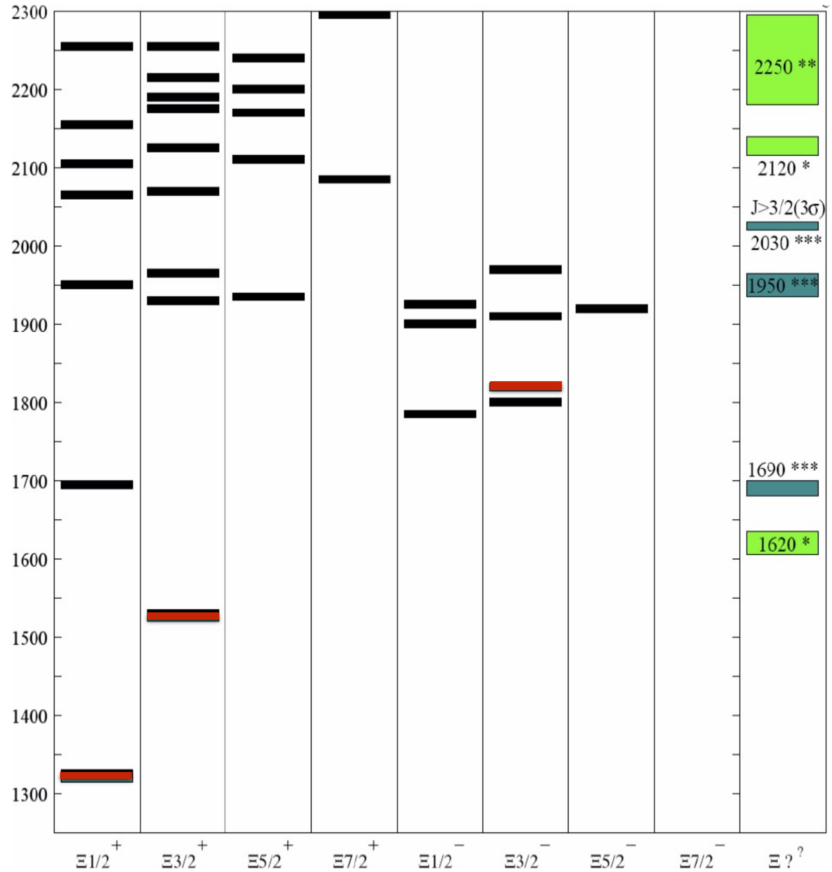

FIG. 4: Black bars: Predicted Ξ spectrum based on the quark model calculation [14]. Colored bars: Observed states. The two ground octet and decuplet states together with $\Xi(1820)$ in the column $J^P = 3/2^-$ are shown in red color. Other observed states with unidentified spin-parity are plotted in the rightest column.

expected yield of $(3-4)\times 10^5$ Ξ^*'s and 10^3 Ω^*'s per month.

As one can see our proposed experiment with K_L beam will be of similar statistical power as that in J-PARC with charged kaons.

An experimental program with kaon beams will be much richer and allow to perform a complete experiment using polarized target and measuring recoil polarization of hyperons. This studies are under way to find an optimal solution for GlueX setup.

V. SUMMARY

In summary we intend to create high intensity K_L beam using photoproduction processes from a secondary Be target. A flux as high as $10^4 K_L$/sec could be achieved. Momenta of K_L beam particles will be measured with TOF with $\Delta P/P \approx 0.5\%$. The flux of kaon beam will be measured through partial detection of $\pi^+\pi^-$ decay products from their decay to $\pi^+\pi^-\pi^0$ by exploiting similar procedure used by LASS experiment at SLAC [2]. Besides using unpolarized LH_2 target currently installed in GlueX experiment additional studies are needed to find the optimal choice of polarized targets. This proposal will allow to measure KN scattering with different final states including production of strange and multi strange baryons with unprecedented statistical precision to test QCD in non perturbative domain. It has a potential to distinguish between different quark models and test lattice QCD predictions for excited baryon states with strong hybrid content.

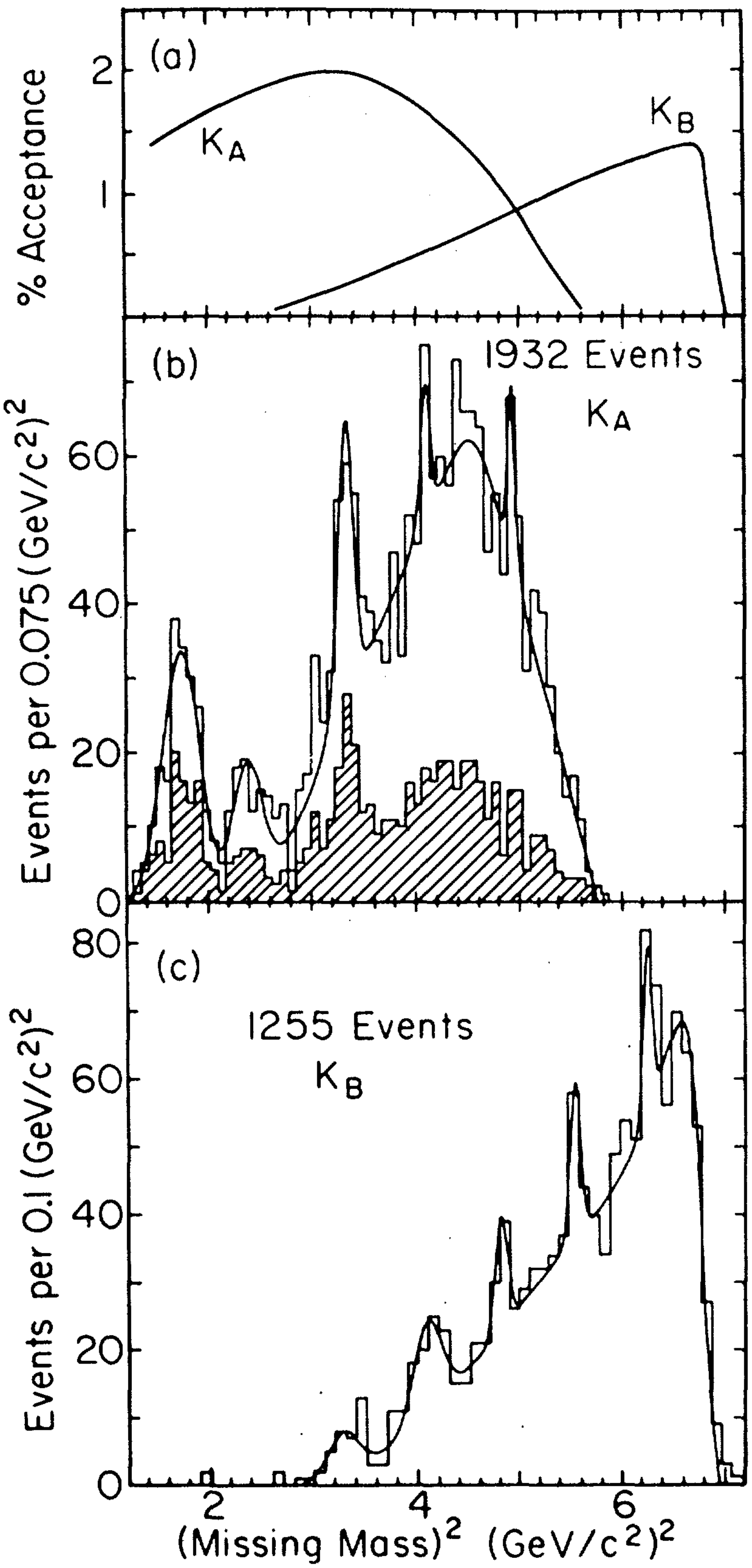

FIG. 5: Missing mass squared of K^+ from the reaction $p(K^-, K^+)$ [15]: a) the acceptance for two different settings of the spectrometer; b) and c) missing mass squared for these two different settings.

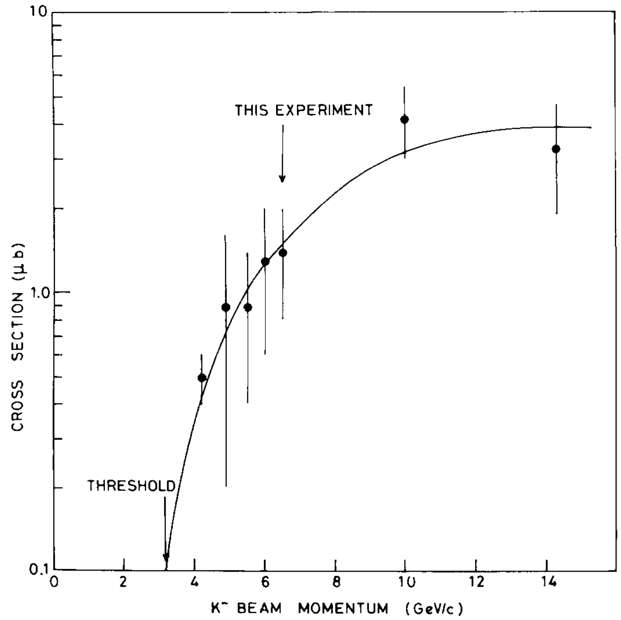

FIG. 6: Cross section of Ω^- production, $K^- p \to \Omega^- K^+ K^0$, as a function of the beam particle momentum [16].

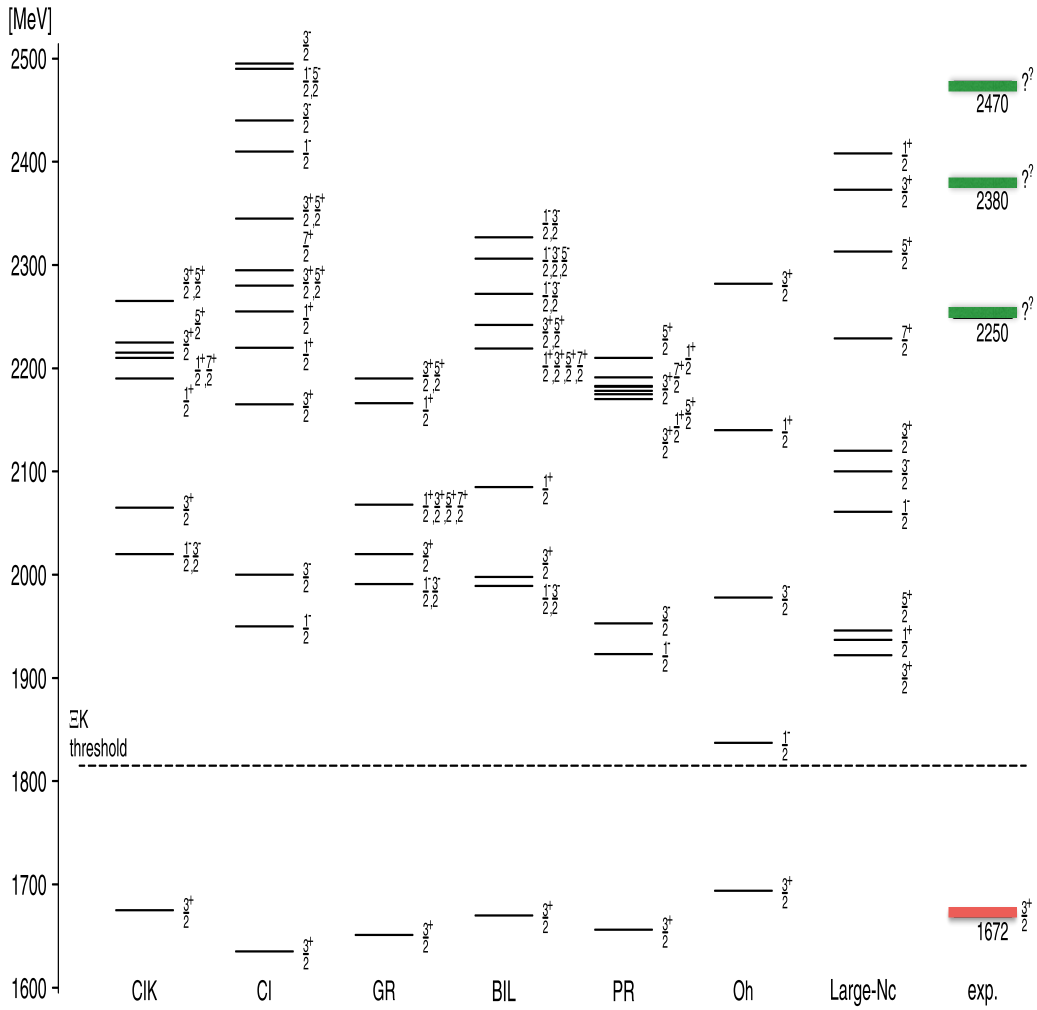

FIG. 7: Low-lying Ω baryon spectrum predicted by the non-relativistic model (CIK) [14], the relativized quark model (CI) [17], The Glozman-Riska model (GR) [18], the algebraic model (BIL) [19], the recent non-relativistick quark model (PR) [20], the Skyrme model (Oh) [21], and large N_c analysis [22]. The experimental data are from the particle listings by the PDG [4].

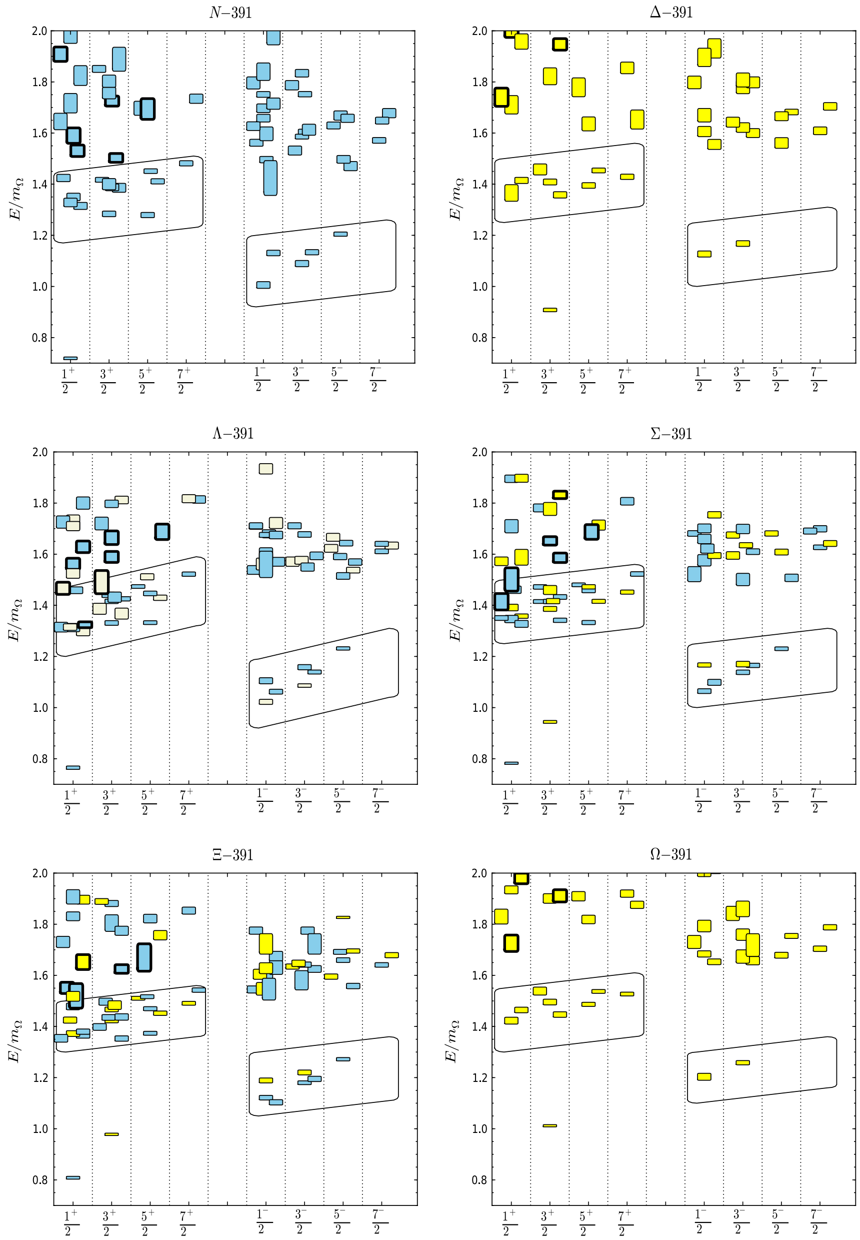

FIG. 8: Results for baryon excited states using ensemble with $m_\pi = 391$ MeV are shown versus J^P. Colors are used to display the flavor symmetry of dominant operators as follows: blue for $\mathbf{8_F}$ in N, Λ, Σ and Ξ; beige for $\mathbf{1_F}$ in Λ; yellow for $\mathbf{10_F}$ in Δ, Σ, Ξ, and Ω. The lowest bands of positive- and negative-parity states are highlighted within slanted boxes. Hybrid states, in which the gluons play a substantive role, are shown for positive parity by symbols with thick borders [23].

[1] W.E. Cleland *et al.*, Phys. Rev. D **12** 1247 (1975).
[2] G.W. Brandenburg *et al.*, Phys. Rev. D **7**, 708 (1973).
[3] S. Prakhov *et al.*, Phys. Rev. C **80**, 025204 (2009).
[4] K.A. Olive *et al.* (Particle Data Group), Chin. Phys. C **38**, 090001 (2014).
[5] Y. Qiang *et al.*, Phys. Lett. B **694**, 123 (2010)].
[6] W.J. Briscoe *et al.*, arXiv:1503.07763 [hep-ph].
[7] A.S. Kronfeld and R.S. Tschirhart (Editors). *Project X: Physics Opportunities*, arXiv:1306.5009.
[8] H. Seraydaryan *et al.*, Phys. Rev. C **89**, 055206 (2014).
[9] A. Titov and T.-S. H. Lee, Phys. Rev. C **67**, 065205 (2003).
[10] G. McClellan *et al.*, Phys. Rev. Lett. **21**, 1593, (1971).
[11] D. Androic *et al.*, Nucl. Instrum. Meth. A **646**, 59 (2011).
[12] B. Jackson *et al.*, arXiv:1503.00845 [nucl- th].
[13] H. Haberzettl. Private communication. The curve is based on the work reported in [12]; it will be included in an updated version of that work.
[14] K.T. Chao and N. Isgur, and G. Karl, Phys. Rev. D **23**, 155 (1980).
[15] C.M. Jenkins *et al.*, Phys. Rev. Lett. **51**, 951 (1983).
[16] J.K. Hassall *et al.*, Nucl. Phys. B **189**, 397 (1981).
[17] S. Capstick and N. Isgur, Phys. Rev. D **34**, 2809 (1986).
[18] L.Ya. Glozman and D.O. Riska, Phys. Rep. **268**, 263 (1996).
[19] R. Bijker, F. Iachello, and A. Leviatan, Ann. Phys. **284**, 89 (2000).
[20] M. Pervin and W. Roberts, Phys. Rev. C **77**, 025202 (2008).
[21] Y. Oh, Phys. Rev. D **75**, 074002 (2007).
[22] C.E. Carlson and C.D. Carone, Phys. Lett. B **484**, 260 (2000);
C.L. Schat, J.L. Goity, and N.N. Scoccola, Phys. Rev. Lett. **88**, 102002 (2002);
J.L. Goity, C. Schat, and N.N. Scoccola, Phys. Lett. B **564**, 83 (2003);
N. Matagne and Fl. Stancu, Phys. Rev. D **71**, 014010 (2005);
N. Matagne and Fl. Stancu, Phys. Rev. D **74**, 034014 (2006).
[23] R.G. Edwards, N. Mathur, D.G. Richards, and S.J. Wallace [Hadrons Spectrum Collaboration], Phys. Rev. D **87**, 054506 (2013).
[24] G.P. Engel, C.B. Lang, D. Mohler, and A. Schaefer (Bern-Graz-Regensburg Collaboration), Phys. Rev. D **87**, 074504 (2013).
[25] J.J. Dudek and R.G. Edwards, Phys. Rev. D **85**, 054016 (2012).
[26] D. J. Wilson, J. J. Dudek, R. G. Edwards and C. E. Thomas, Phys. Rev. D **91**, no. 5, 054008 (2015).
[27] J.J. Dudek *et al.* [Hadron Spectrum Collaboration], Phys. Rev. Lett. **113**, no. 18, 182001 (2014)
[28] H. Takahashi, Nucl. Phys. A **914**, 553 (2013),
M. Naruki and K. Shirotori, LOI-2014-JPARC.