The Physics Opportunities with $K^0_L$ Beam at

Jefferson Lab

Moskov Amaryan

ODU Nuclear Group Seminar, June 23, 2016
A Letter of Intent to Jefferson Lab PAC-43.

Physics Opportunities with a Secondary $K^0_L$ Beam at JLab.

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Outline

• Introduction

• Baryon Multiplets

• Reactions with $K^0_L$ beam on proton target

• Experimental Arrangement

• $K^0_L$ Beam at GlueX

• Expected rates

• Summary
Constituent Quark Model

Octet

\[ Q = I_3 + \frac{B + S}{2} \]

Gell-Mann Nishidjima

Decuplet

The nonexistent is whatever we have not sufficiently desired.
Franz Kafka
(In some cases it may be true M.A.)

But there are many more states predicted, where are they?
Where are hybrids, glueballs, multiquark states?
Well, some of them may already have been observed?
FIG. 4 (color online). Results for baryon excited states using the ensemble with $m/C_{25} = 391$ MeV are shown versus $J^P$. Colors are used to display the flavor symmetry of dominant operators as follows: blue for $8F$ in $N$, $\lambda_3$, $\lambda_6$, and $\lambda_4$; beige for $1F$ in $\lambda_3$; yellow for $10F$ in $\lambda_1$, $\lambda_6$, $\lambda_4$, and $\lambda_{10}$. The lowest bands of positive- and negative-parity states are highlighted within slanted boxes. The eight excited states of $\lambda_6$, with $J^P = 3^2$, that are shown within a slanted box, are $H_g$ states 1, 2, 4, 5, 7, 8, 13, and 15. Fits for the same states are shown in Fig. 1, and identifications of their spins and flavors are noted in Fig. 3.
Lattice QCD calculations

Edwards, Mathur, Richards and Wallace
and Karl [3]. The 12 excited states were predicted up to 2 GeV/c, whereas only $\Xi(1820)$ is identified as $J^P = 3/2^+$. Recently it is pointed out that there are two distinct excitation modes when a baryon contains one heavy flavor inside, and the separation of these two modes possibly good enough even at the strange quark mass [4]. Baryons which contain single (Qqq) and double (QQq) strange and/or charm flavors might be understood as a "dual" system based on the spatial parametrization concerning a diquark contribution of (qq) and (QQ). In this sense, it should be noted that cascades and charmed baryons are expected to be closely related.

The $\Xi^*$ states were intensively searched for mainly in bubble chamber experiments using the $Kp$ reaction in '60s-'70s. The cross section was estimated to be an order of $10^3 \mu b$ at the beam momentum up to $\sim 10$ GeV/c. In '80s-'90s, the mass or width of ground or some excited states were measured with a spectrometer in the CERN hyperon beam experiment. There has been a few experiments to study cascade baryons with the missing mass technique. In 1983, the production of $\Xi^*$ resonances up to 2.5 GeV/c were reported from the missing mass measurement of the $p(^K, K^+)$ reaction, using multi-particle spectrometer at the Brookhaven National Laboratory [5]. Figure 2 shows squared missing mass spectra of $p(^K, K^+)$ reaction. With ten times intense kaon beam combined with 5 times better resolution, each states is expected to be clearly stated even without tagging any decay particles in the $p(^K, K^+)$ reaction.

II. THE PHYSICS CASE

The physics case and experimental method are reviewed in the following.
The spectroscopy of $$\Omega^*$$ resonances to confirm known three states and to search for missing states can be performed in early stage of the $$S = -3$$ program at J-PARC. The production cross-sections of $$\Omega$$($$2250$$) and $$\Omega$$($$2470$$) are 0.63 µb [16] and 0.29 µb [17], respectively, for the $$K^-$$ beam momentum of 11 GeV/c. If we use an identical target with the thickness of 1g/cm$$^2$$, and assume that the 11 GeV/c $$K^-$$ beam intensity is $$1 \times 10^5$$/spill and overall detection efficiency is 10%, the numbers of measured $$\Omega$$($$2250$$) and $$\Omega$$($$2470$$) are expected to be about 22/day and 10/day, respectively.

3. Beam lines

Since the threshold of the elementary process $$K^-p \rightarrow \Omega^-K^+K^0$$ is 3.1 GeV/c, charged secondary beam with the higher momentum than that of existing K1.8 beam line is required to carry out $$\Omega^-$$ experiments. The construction of a new primary proton beam line (Fig. 2) is scheduled to be completed in 2016. The beam line "high-p" is branched from the existing primary beam line at the middle of the beam-switching yard between the Main Ring and the HD-hall. H. Noumi proposed to modify it to a secondary beam line "$$\pi^15$$" in the next a few years by replacing beam-splitting magnets with a production target and by installing several additional beam-transport magnets [18]. The $$\pi^15$$ beam line is designed to provide high-resolution ($$dp/p \sim 0.1\%$$) beams with the momentum up to 15 GeV/c. Secondary beams are generated by production target with equivalent to 15-kW beam loss and delivered to the HD-hall. The beams are dispersively focused just after the entry to the hall, where their momenta are measured with some tracking devices, and then transported and focused to a target in the experimental area. In order to achieve high resolution, second-order aberrations are eliminated at the dispersive focus by using three sextupole....
• **Three light quarks** can be arranged in 6 baryonic families, \( N^*, \Delta^*, \Lambda^*, \Sigma^*, \Xi^* \), & \( \Omega^* \).

• **Number of members** in a family that can exist is not arbitrary.

• If \( SU(3)_F \) symmetry of QCD is controlling, then:

  \[ \text{Octet: } N^*, \Lambda^*, \Sigma^*, \Xi^* \]
  \[ \text{Decuplet: } \Delta^*, \Sigma^*, \Xi^* \text{, & } \Omega^* \]

• Number of experimentally identified resonances of each baryon family in \cite{PDG} summary tables is 17 \( N^* \), 24 \( \Delta^* \), 14 \( \Lambda^* \), 12 \( \Sigma^* \), 7 \( \Xi^* \), & 2 \( \Omega^* \).

• **Constituent Quark** models, for instance, predict existence of no less than 64 \( N^* \), 22 \( \Delta^* \) states with mass < 3 GeV.

• Seriousness of “missing-states” problem is obvious from these numbers.

• To complete \( SU(3)_F \) multiplets, one needs no less than 17 \( \Lambda^* \), 41 \( \Sigma^* \), 41 \( \Xi^* \), & 24 \( \Omega^* \).
Recourse to the Neutral Kaon System

Strangeness eigenstates with \( J^{PC} = 0^{-+} \)

\[
|K^0\rangle = |d\bar{s}\rangle, \quad |\bar{K}^0\rangle = |\bar{d}s\rangle
\]

\( S = +1 \) \quad \( S = -1 \)

Party eigenstates with intrinsic \( P = -1 \)

\[
P|K^0\rangle = -|K^0\rangle, \quad P|\bar{K}^0\rangle = -|\bar{K}^0\rangle
\]

Effect of C-Party can be taken to be

\[
C|K^0\rangle = |\bar{K}^0\rangle, \quad C|\bar{K}^0\rangle = |K^0\rangle
\]

However not CP eigenstates

\[
CP|K^0\rangle = -|\bar{K}^0\rangle, \quad CP|\bar{K}^0\rangle = -|K^0\rangle
\]
CP eigenstates can be formed

\[ |K_1\rangle \equiv \frac{1}{\sqrt{2}} (|K^0\rangle - |\bar{K}^0\rangle) \; ; \; \text{CP} |K_1\rangle = + |K_1\rangle \]

\[ |K_2\rangle \equiv \frac{1}{\sqrt{2}} (|K^0\rangle + |\bar{K}^0\rangle) \; ; \; \text{CP} |K_2\rangle = - |K_2\rangle \]
$K^0$ and $\bar{K}^0$

are unstable particles decaying via WI

$K_S(K - \text{short})$ and $K_L(K - \text{long})$

propagate as free particles and have distinct lifetimes

$\tau_S = 0.9 \times 10^{-10} s ~ \text{and} ~ \tau_L = 0.5 \times 10^{-7} s ~ (c\tau = 15 \text{ m})$

\[ |K_S\rangle \equiv \frac{1}{\sqrt{1 + |\epsilon|^2}} (|K_1\rangle + \epsilon |K_2\rangle) \approx |K_1\rangle \]

\[ |K_L\rangle \equiv \frac{1}{\sqrt{1 + |\epsilon|^2}} (|K_2\rangle + \epsilon |K_1\rangle) \approx |K_2\rangle \]

$|\epsilon| \approx 2.3 \times 10^{-3}$

defines the level of CP violation
\[ K_S \to \pi^+\pi^- \quad \text{BR} = 68.6\% \]
\[ \to \pi^0\pi^0 \quad \text{BR} = 31.4\% \]
\[ K_L \to \pi^+\pi^-\pi^0 \quad \text{BR} = 12.6\% \]
\[ \to \pi^0\pi^0\pi^0 \quad \text{BR} = 21.1\% \]
\[ \to \pi^-e^+\nu_e \quad \text{BR} = 19.4\% \]
\[ \to \pi^+e^-\bar{\nu}_e \quad \text{BR} = 19.4\% \]
\[ \to \pi^-\mu^+\nu_\mu \quad \text{BR} = 13.6\% \]
\[ \to \pi^+\mu^-\bar{\nu}_\mu \quad \text{BR} = 13.6\% \]

**CP conserving decays**

**CP violating decays observed in 1964**

\[ K_L \to \pi^+\pi^- \quad \text{BR} = 2.1 \times 10^{-3} \]
\[ \to \pi^0\pi^0 \quad \text{BR} = 9.4 \times 10^{-4} \]
What if we have a $K^0_L$ beam?

List of reactions:

Elastic and charge-exchange

Two-body with $S=-1$

Two-body with $S=-2$

Three-body with $S=-2$

Three-body with $S=-3$
Very Limited World Data with $K_L$ beam

(mainly low stat. bubble chamber data compilation by I. Strakovsky)

blue points: $d\sigma/d\Omega$

red points: Polarization

we are not aware of any data on Neutron target
Data for $K_L p \rightarrow K_S p$

Courtes of Mark Manley, KL2016

- Many details in KL2016 Workshop Proceedings
- arXiv: 1604.02141
How to make a kaon beam?

Thomas Jefferson National Accelerator Facility
Hall D Beamline
Current setup
Hall D Tagger Area

- Design beam current limits: 5 μA (60 kW) max
- Design radiator thickness: ~0.0005 Radiation Lengths max
- Challenge: Increase radiator thickness to 0.05-0.10 R.L.?!
GEANT3 Model, 2000 electrons at 12 GeV
Compact $\gamma$ Source

- Tungsten radiator 0.1 R.L.
- 60 kW beam power contained
Compact Photon Source Concept

- Strong magnet after radiator deflects exiting electrons
- Long-bore collimator lets photon beam through
- Electron beam dump placed next to the collimator
- Water-cooled Copper core for better heat dissipation
- Hermetic shielding all around and close to the source
- High Z and high density material for bulk shielding
- Borated Poly outer layer for slowing, thermalizing, and absorbing fast neutrons still exiting the bulk shielding
- No need in tagging photons, so the design could be compact, as opposed to the Tagger Magnet concept
CPS: PR12-15-003 Proposal at JLab

Application example: CPS concept for new experiment in Hall A

Distance to target ~200 cm
 photon beam diameter on the target ~ 0.9 mm

Distance: 200 cm

2mm opening

1.2 μA e^-
8.8 GeV

B ~ 2.5T

e^-

10%X0

3cm NH₃

Beam Dump in the magnet

MC simulation and direct calculations show acceptable background rates on SBS and NPS.

B. Wojtsekhowski

PAC43, July 7, 2015
CPS at the Hall D Tagger Area

- Tungsten radiator
- Permanent magnet
- Beam diagnostics volume
- Dump entrance
- Collimator
- Beam dump

Shielding: Copper-Tungsten bulk, Borated Poly layer

CEBAF Hall D Tagger
Cut plane at x = 0 m
CPS, vertical plane cut

Tungsten radiator
Permanent magnet
Beam diagnostics volume
Dump entrance
Beam dump

Shielding: Copper-Tungsten bulk, Borated Poly layer

CEBAF HallD Tagger
Cut plane at x = 0 m

(axis view expanded by factor 4)
CPS, horizontal plane (1)

Tungsten radiator
Permanent magnet
Beam diagnostics volume
Dump entrance
Collimator

Shielding: Copper-Tungsten bulk, Borated Poly layer

(axis view expanded by factor 4)
CPS, 50 electrons at 12 GeV

Tungsten radiator 0.1 R.L.

CEBAF HallD Tagger
Cut plane at x = 0 m
Dose Rate Evaluation and Comparison

- The dose rates in the Tagger vault for the CPS setup with 10% R.L. radiator are close to Standard XD ops
- The radiation spectral composition is different; most of the contribution in the CPS setup is from higher energy neutrons
Dose Rate Evaluation and Comparison

- The plots show comparison of dose rate estimates in the Tagger Area in two conditions: (1) nominal Hall D operation with the standard amorphous radiator at 0.0005 R.L., - with (2) radiator at 0.1 R.L., used as part of the Compact Photon Source setup.
- The comparison indicates that at equal beam currents, gamma radiation dose rates are much smaller for the CPS run (~order of magnitude), and neutron dose rates in the area are comparable.
- Design and shielding optimization may improve the comparison further in favor of the CPS solution.
- Electron beam with \( I_e = 5 \mu A \)

- Delivered with 60ns bunch spacing avoids overlap in the range of \( P=0.35\text{-}10.0 \text{ GeV/c} \)

- Momentum measured with TOF

- \( K^0_L \) flux measured with pair spectrometer

- Side remark: Physics case with polarized targets is under study and feasible
Implementation Advantages

• Most of all present Tagger Area equipment stays in place; CPS is assembled around the gamma line
• Re-use of the available permanent magnet (pending thermal engineering analysis, $\sim 1.5$ kW to dissipate)
• Re-use of the dump cooling system (max 60 kW)
• No extra prompt irradiation or extra beam line activation for existing structures in the area
• No problem switching between the two modes of Hall D operations: low intensity tagged photon beam, and high intensity photon beam from CPS
• Disassembly and decommissioning could be postponed until radioactive isotopes decay inside to manageable levels (self-shielded in place)
Detailed Design and Cost Estimate

- We do not see show-stoppers for implementation of the CPS concept in the experiment.
- 60 kW Copper-core dump will have characteristics close to the one installed already.
- To make long and narrow photon beam collimation we propose to build the core using two symmetric flat plates, left and right, and make matching grooves in them for the beam entry cones, beam line, and the aperture collimator.
- Cost would include detailed iterative modeling and simulation to optimize operation parameters, design, engineering and production, plus the choice and cost of bulk shielding material.
- Crude cost expectation: within $0.5M
Conclusions

- Compared to the alternative, the proposed CPS solution presents several advantages, including much less disturbance of the available infrastructure at the Tagger Area, and better flexibility in achieving high-intensity photon beam delivery to the Hall D.
- The proposed CPS solution will satisfy proposed $K^0_L$ beam production parameters.
- We do not envision big technical or organizational difficulties in the implementation of the conceptual design.
$K_L$-beam line

sweeping magnet

16...20m to target

Collimator area

Hall D

spectromter

Liquid hydrogen target

collimators

Be

Pb

L 40cm

L 15cm
Rate of neutrons and $K^0_L$ on GlueX target

- **JLAB**

  ![Plot of Yields in Be vs. Momentum (GeV/c)](image)

  - Neutrons DINREG, with Pb shield
  - Neutrons Pythia

- **PRL22.996 (1969) Brody et al.**

  ![Comparison of Particle Incident at HBC](image)

  FIG. 2. Comparison of the neutron and $K^0_L$ fluxes at the hydrogen bubble chamber for $2^\circ$ production with 16-GeV electrons.

- **With a proton beam ratio $n/K_L = 10^3-10^4$**
**$K^0_L$ beam**

- **Electron beam** \( E_e = 12\text{GeV} ; I_e = 5\mu\text{A} \)
- **Radiator (rad. length)** \( 10\% \)
- **Be target (R=3cm)** \( L = 40\text{cm} \)
- **LH2 target (L=30cm)** \( R = 3\text{cm} \)
- **Distance Be-LH2** \( 16\text{m} \)
- **$K_L$ Rate/sec** \( \sim 10^4 \)
Neutron Background

Neutron calculations for the KLF Project using MCMP6
Results:

Tally #1: 3200 n/(s cm²)
Tally #2: 40 n/(s cm²)
Tally #3: 140 n/(s cm²)
Tally #4: 3 n/(s cm²)

• Conclusion: Neutron Flux in Hall D is tolerable

Neutron Flux $10^{10}/4\pi\text{s}$
• Talk by Onishi at KL2016

J-PARC
Japan Proton Accelerator Research Complex

Two beam lines are under operation
K1.1 & High-p beam lines are under construction

\[
\pi^\pm, K^\pm, p, \bar{p} \\
(1.5 \times 10^5 K^- / 5.52 \text{s})
\]

\[
\pi^\pm, K^\pm, p, \bar{p} \\
(5 \times 10^5 K^- / 5.52 \text{s})
\]

\[
\pi^\pm, K^\pm, p, \bar{p} \\
(1.5 \times 10^5 K^- / 5.52 \text{s})
\]

unseparated beam
(> 10^7 \pi^- / 5.52 \text{s})

\[
10^{11} p / 5.52 \text{s} \\
@30 \text{GeV}
\]
• ProjectX (Fermi Lab) arXiv:1306.5009

**Table III-2:** Comparison of the $K_L$ production yield. The BNL AGS kaon and neutron yields are taken from RSVP reviews in 2004 and 2005. The Project X yields are for a thick target, fully simulated with LAQGSM/MARS15 into the KOPIO beam solid angle and momentum acceptance.

<table>
<thead>
<tr>
<th>Beam energy</th>
<th>Target ($\lambda_I$)</th>
<th>$p(K)$ (MeV/c)</th>
<th>$K_L/s$ into 500 $\mu$sr</th>
<th>$K_L : n (E_n &gt; 10 \text{ MeV})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BNL AGS</td>
<td>24 GeV</td>
<td>1.1 Pt</td>
<td>300-1200</td>
<td>$60 \times 10^6$</td>
</tr>
<tr>
<td>Project X</td>
<td>3 GeV</td>
<td>1.0 C</td>
<td>300-1200</td>
<td>$450 \times 10^6$</td>
</tr>
</tbody>
</table>

**KL beam can be used to study rare decays**

**However it will be impossible to use for hyperon spectroscopy because of momentum range and $n/K$ Ratio**
Momentum and $W$ Resolution

The left graph shows the momentum resolution ($\Delta p / p$ in percent) as a function of $K_L$ momentum (GeV/c). The right graph illustrates the $W$ resolution ($\Delta W / W$ in percent) as a function of $W$ (GeV).
W-Resolution

$\sigma(W)$ vs. $W$, (GeV)

Missing mass

Invariant mass

see more from Simon Taylor’s talk
Simulated with GlueX
10^4 K/τ/sec, one day of running

Jackson, Oh, Haberzettl, Nakayama
Status of $\Xi^*$

Very poorly measured at AGS (BNL) 32 years ago

Cross Sections

\[ K^- p \rightarrow \Xi^- X \]

\[ K^- p \rightarrow \Omega^- X \]

J.K. Hassal et al., NPB 189 (1981)
## Expected rates

<table>
<thead>
<tr>
<th>Production</th>
<th>J-PARC*</th>
<th>Jlab (this proposal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>flux/s</td>
<td>$3 \times 10^4 K^-$</td>
<td>$10^4 K^0_L$</td>
</tr>
<tr>
<td>$\Xi^*/$month</td>
<td>$3 \times 10^5$</td>
<td>$2 \times 10^5$</td>
</tr>
<tr>
<td>$\Omega^{-*}/$month</td>
<td>600</td>
<td>4000</td>
</tr>
</tbody>
</table>

*H.~Takahashi, NP A 914, 553 (2013)*  
*M.~Naruki and K.~Shirotori, LOI-2014-JPARC*
**Missing states and freezout in heavy ion collisions**

Close to $T_c$ relaxation rates become small compared to the expansion rates and the system created in heavy ion collisions freezes out. The freeze-out is characterized by: $(T^f, \mu^f_B, \mu^f_S)$ and hadron abundances can be calculated from HRG.

**Lattice QCD Calculations**

\[
dU = TdS - PdV + \sum_{i=1}^{n} \mu_i dN_i
\]

\[
\mu_i = \frac{\partial U_i}{\partial N_i}
\]

*APS, April 2016, Peter Petreczky*

*Bazavov et al., PRL 113(2014) 072001*
### 12 GeV Approved Experiments by PAC Days

<table>
<thead>
<tr>
<th>Topic</th>
<th>Hall A</th>
<th>Hall B</th>
<th>Hall C</th>
<th>Hall D</th>
<th>Other</th>
<th>Total</th>
</tr>
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<tbody>
<tr>
<td>The Hadron spectra as probes of QCD</td>
<td></td>
<td></td>
<td>540</td>
<td></td>
<td></td>
<td>659</td>
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<td>The transverse structure of the hadrons</td>
<td>145.5</td>
<td>85</td>
<td>102</td>
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<td>357.5</td>
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<td>The longitudinal structure of the hadrons</td>
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<td></td>
<td></td>
<td>460</td>
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<td>The 3D structure of the hadrons</td>
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<td>872</td>
<td>212</td>
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<td>1493</td>
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<tr>
<td>Hadrons and cold nuclear matter</td>
<td>180</td>
<td>175</td>
<td>201</td>
<td>14</td>
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<td>570</td>
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<td>Low-energy tests of the Standard Model and Fundamental Symmetries</td>
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<td>180</td>
<td>79</td>
<td>60</td>
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<td>Total Days</td>
<td>1346.5</td>
<td>1661</td>
<td>680</td>
<td>644</td>
<td>74</td>
<td>4405.5</td>
</tr>
<tr>
<td>Total Days – Without MIE Days</td>
<td>697.5</td>
<td>1661</td>
<td>680</td>
<td>644</td>
<td>28</td>
<td>3710.5</td>
</tr>
<tr>
<td>Total Approved Run Group Days (includes MIE)</td>
<td>1346.5</td>
<td>826</td>
<td>637</td>
<td>424</td>
<td>74</td>
<td>3307.5</td>
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<tr>
<td>Total Approved Run Group Days (without MIE)</td>
<td>528.5</td>
<td>826</td>
<td>637</td>
<td>424</td>
<td>28</td>
<td>2443.5</td>
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<td>Total Days Completed</td>
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<td>15</td>
<td>0</td>
<td>25</td>
<td>0</td>
<td>60</td>
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<tr>
<td>Total Days Remaining</td>
<td>508.5</td>
<td>811</td>
<td>637</td>
<td>399</td>
<td>28</td>
<td>2383.5</td>
</tr>
</tbody>
</table>

- Bob McKeown’s talk at 2016 UG meeting

60 weeks
• During FY01-FY12, CEBAF ops averaged 34.5 weeks/year (best year FY05 at 42 weeks)

• For 12 GeV era we estimate “optimal” operations at 37 weeks per year

• FY17 Pres. Budget includes JLab ops at $104M
  - would fund 23 weeks (+ 3 weeks from 12 GeV project)

• FY18+ at cost of living implies 23 weeks/year running (62% of optimal)

• We propose FY18+ at 30 weeks/year (81%), will require ~$6M increase in operations budget.

• Slide from Mont’s talk at 2016 UG meeting

• Hall D Physics Program will be completed in 2-3 years
Summary

- KN scattering still remains very poorly studied

- lack of data on excited hyperon states requires significant experimental efforts to be completed

- Our preliminary studies show that few times $10^4 K^0_L/s$ at Jlab is feasible with GlueX setup in Hall D

- Proposed setup will have highest intensity $K^0_L$ beam ever used for hadron spectroscopy two orders of magnitude higher than in LASS (SLAC) experiment

- Data obtained at Jlab will be unique and partially complementary to charged kaon data

- The possibility to run with polarized H and D targets is possible (see talk by C. Keith at KL2016 Workshop)
Thank You!