Future Physics using GlueX in Hall-D

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Abstract

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1 The GlueX Spectroscopy Program

1.1 Introduction

The primary goal of the GlueX experiment is to search for gluonic excitations of mesons, the so called hybrid mesons. [1][2] Of particular interest are exotic-quantum-number hybrids, where the J^{PC} of the hybrid is not an allowed J^{PC} of normal mesons: 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, ... Lattice QCD predicts several nonets of these exotic hybrids with masses in the 2 GeV mass range, and photoproduction with simple t-channel exchanges can, in principle, couple to all of them. In addition, the likely decay modes of several of these should be easily seen in the GlueX experiment. Unknown are the production cross sections and the branching fractions to the interesting modes. However, these are expected to be similar to ordinary mesons in the same mass range. Key to this program is sufficient statistics, and we hope that the full data set from the initial GlueX experiment (now in the can) will provide information on some exotic hybrids.

Betond the search for exotic hybrids, GlueX will also carry out a broad spectroscopy program. In particular, with the addition of the DIRC in 2019, the large program involving strange quarks, both $s\bar{s}$ and open strangeness should be very interesting. One open question relates to whether there are counterparts of the charmonium X, Y, Z states in the strange sector. Another particularly promising area will be strange baryons. This includes the double-strange Xi states, as well as studies of hyperons.

1.2 Summary of GlueX Experiments

The GlueX program was originally presented to Jefferson Lab PAC 30 in 2006 [3], with and update presented to PAC 36 in 2010 [4]. From the initial presentation, the first phase of GlueX running was approved as **E12-06-102** for a total of 120 PAC days, 30 days for Engineering and Commissioning and 90days for physics. In 2012, we presented a proposal to extend the GlueX program to include strange quarks using an undefined forward kaon identification system [5]. This proposal was deferred until the kaon-identification system was defined. This was followed by a proposal to PAC 40 in 2013 [6] that defined a strangeness program that could be carried out with the baseline GlueX equipment and high-intensity running. This was approved as **E12-13-003** for 200 PAC days of physics running. Finally, in 2014 we made a presentation to PAC 42 for a strangeness program using part of the BaBar DIRC detector as the forward kaon-identification system in GlueX [7]. This was approved as **E12-12-002** for 220 PAC days, 20 for DIRC Commissioning and 200 for physics running. This approved running is summarized in table 1.

Experiment	Name	Approved Time (PAC Days)		
		Commissioning	Physics	Total
E12-06-102	Phase I GlueX Running	30	90	120
E12-13-003	Phase II GlueX: High Intensity		200	200
E12-12-002	Phase II GlueX: High Intensity & DIRC	20	200	220

Table 1: *The approved experiments that are part of the GlueX spectroscopy program.*

GlueX operations started in fall 2014 with a two-month run engineering run that satisfied the key performance parameters of GlueX/Hall D. A short run occurred in the spring of 2015 when the accelerator was operating at 6 GeV energy. A full engineering an commissioning run took place in the spring of 2016, during which physics quality running occurred at the end. These data resulted in the first GlueX physics paper [8]. The first full physics run took place in spring 2017, followed by a long physics run in spring 2018 and a follow-up physics run in fall 2018. This running completed the data taking for the Phase I program in GlueX, and is summarized in table 2. Data are scaled by *triggers*, which include both physics events and calibration events. The mix between these two was not uniform over the four run periods, with the largest fraction of calibration events occurring in the latter half of the spring 2018 run period[1].

Based on this run history, we estimate that if the two approved Phase II programs run concurrently, the program would complete by the end of 2024. Assuming that the average of 2017 and 2018 is typical, then to get 200 PAC days of running would take just shy of four and one-half years. Accounting for the 20 PAC days of DIRC commissioning in 2019, we come up with the conservative date of late 2024.

In Phase I running, photon fluxes started at about $10^7\,\gamma/s$ in the coherent peak of the primary photon beam (about 8.2 to 8.8 GeV under current accelerator conditions). In the latter half of the 2017 run, this was approximately doubled to $2\times10^7\,\gamma/s$, and in 2018, we pushed this to about $3\times10^7\,\gamma/s$. We estimate that the average flux for all of phase I was probably slightly below $2\times10^7\,\gamma/s$. The plan is to run phase II at close to $5\times10^7\,\gamma/s$. We also note that while GlueX Phase II will start running in fall of 2019, it will be required to make a jeopardy presentation to PAC 48 in 2020. This would be the logical time to request an extension to the Phase II physics program, but probably premature to request other GlueX spectroscopy running as outlined later.

Run Period	Triggers	Fraction of Data
Spring 2016 Engineering Run	7×10^9	0.024
Spring 2017 Physics Run	50×10^9	0.179
Spring 2018 Physics Run	145×10^9	0.518
Fall 2018 Physics Run	78×10^9	0.279

Table 2: *A summary of the physics data collected in the Phase I physics program in GlueX. Triggers to not match precisely with physics events as they include events taken for calibration purposes.*

1.3 Analysis of GlueX Data

At this time, the 2016 and 2017 data are in active physics analysis (about 20% of the phase I sample), and this provides our best estimates of physics cross sections and reconstruction efficiencies in GlueX. We anticipate that the full Phase I data set will be ready for physics analysis by fall 2019. We anticipate that the best data are likely to the the Fall 2018 data, and systematics of running conditions were under the best control during that run period.

While no full analysis of any promising hybrid meson channel has been performed, many channels have been looked at. In particular the following channels have been looked at with varying degrees of rigor.

$$\begin{array}{lcl} \eta'\pi & \text{in} & \gamma p \;\rightarrow\; p\eta\pi^+\pi^-\pi^0 \text{ and } \gamma p \;\rightarrow\; \Delta^{++}\eta\pi^+\pi^-\pi^- \\ \pi\pi\pi & \text{in} & \gamma p \;\rightarrow\; p\pi^+\pi^-\pi^0 \end{array}$$

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[1] This was to obtain TPOL data with two different radiator thicknesses, when the $750\mu m$ radiator was used, about 50% of the triggers were calibration.

$$\begin{array}{rcl} \eta\pi\pi & \text{in} & \gamma p \;\to\; p\eta\pi^+\pi^- \text{ and } \gamma p \;\to\; p\eta\pi^0\pi^0 \\ \omega\pi\pi & \text{in} & \gamma p \;\to\; p\pi^+\pi^+\pi^-\pi^-\pi^0 \\ K^*K & \text{in} & \gamma p \to pK^+K^-\pi^0 \end{array}$$

Except for the $\pi\pi\pi$ case, the full Phase I statistics will be needed to carry out an initial analysis. For the case of $\pi\pi\pi$, the full statistics will also be needed in order to be competitive with other measurements. In channels where we have done a more detailed study, the intermediate states that are expected for hybrid decays are present in the data. This does not imply there are hybrids, only that the correct data exists to be able to carry out the search.

1.4 Possible Additional GlueX Running

Based on data rates and efficiencies that we have observed to date, it seems very likely that the GlueX Phase II strangeness program will require an extension beyond the 200 approved days. At this time, the best guess would be an additional 200 days of running. Such a request is almost certainly guaranteed. Beyond this simple extension, what we find in the current data will likely dictate other requests.

I. If we see any of the isospin 1 hybrids in a charge exchange reaction, running on a deuterium target could be of interest.

II. Mapping out the energy dependence of production cross sections of hybrids may be interesting. This would require running with the coherent energy peak at a lower energy. This option will be informed by low-energy data that was collected in Fall of 2018.

III. More speculative, but there may be a compelling threshold charmonium program that could justify trying to enhance the highest-energy part of the photon beam.

IV. If there are counterparts to the X, Y, Z charmonium states in the $s\bar{s}$ sector, there may be some desired enhancements to the detector and additional running requested.

V. There could well be a case for other targets. This includes both polarized targets, as well as other nuclear targets beyond hydrogen and deuterium.

1.5 Summary of the Spectroscopy Program

In table 3 we summarize the various extensions to the approved GlueX program and estimate the chance of each one being requested. In terms of scheduling, we also note that there is a planned upgrade to the forward calorimeter (FCAL) that will replace the central crystals with BGO. This will likely have the experiment off line for a year. Longer term, there will likely be other maintenance issues in the detector that will require upgrading or replacing other GlueX hardware. Finally, in this discussion we have not included the allocated beam time for the other two approved experiments in Hall D: PrimEX and the charged pion polarizability measurement. Folding these in will likely extend the baseline GlueX program past 2025.

Name	Requested Time (PAC Days)			Chance
	Commissioning	Physics	Total	
Phase II GlueX: High Intensity & DIRC Extension	0	200	200	100 %
GlueX Deuterium Running (I.)	5	120	125	70%
GlueX lower coherent peak(II.)	0	100	100	50%
GlueX other targets (polarized, nuclear) (V.)	20	100	120	50%
GlueX specialized running (III., IV.)	0	100	100	25%

Table 3: *The possible extensions to the GlueX spectroscopy program. We anticipate that the currently approved GlueX experiment will run through 2024, and these add-ons would occur after that.*

2 The PrimEx Experiment

2.1 Introduction

The PrimEx η experiment was presented to Jefferson Lab PAC 35 in 2010 [9]

Experiment	Name	Approved Time (PAC Days)		
		Commissioning	Physics	Total
E12-10-011	PrimEx η	0	79	79

Table 4: *The approved PrimEx experiment.*

2.2 Special Conditions

The PrimEx experiment requires a 12 × 12 BGO crystal calorimeter (COMCAL) to be installed down stream of the current forward calorimeter. This device will detect Compton Scattering events. The experiment also needs a liquid helium target. Finally, the experiment will run with no magnetic field and the GlueX drift chambers turned off.

The COMCAL was commissioned in December 2018 and the liquid helium target was built and installed in GlueX for the latter part of the spring 2019 Hall-D running. This running, from late February on was the first run period of PrimEx. Assuming that the experiment runs well, it is anticipated that the second run period will occur in late 2020.

2.3 Summary

3 The Charged Pion Polarizability Experiment

3.1 Introduction

The charged pion polarizability experiment was presented to Jefferson Lab PAC 40 in 2013 [10]

Experiment	Name	Approved Time (PAC Days)		
		Commissioning	Physics	Total
E12-13-008	CPP	0	25	25

Table 5: *The approved Charged Pion Polarizability experiment.*

3.2 Special Conditions

The CPP experiment requires the installation of muon chambers interleaved with iron absorber downstream of the forward calorimeter. It will also require some shielding in front of the time-of-flight wall and will run with a solid (lead) target. Installation of the down stream equipment is a major operation, and is expected to take several (up to six) months.

Prototype muon chambers have been tested during the fall 2018 run of GlueX, and additional shielding and trigger tests have been performed in January 2019.

3.3 Summary

4 The JLab η-Factory Experiment (JEF)

4.1 Introduction

The JLab η-Factory Experiment was presented to Jefferson Lab PACs 39, 40, 42 and 45; it was approved in 2014 by PAC 45 [11] to run concurrently with the GlueX Spectroscopy Program. The goal of the experiment is to study rare decays of the η meson.

Experiment	Name	Approved Time (PAC Days)		
		Commissioning	Physics	Total
E12-14-004	JEF	0	0	0

Table 6: *The JEF experiment is approved to run concurrently with the normal GlueX Spectroscopy program. No additional time has been allocated*

4.2 Special Conditions

In order for the JEF experiment to run, the GlueX forward calorimeter (FCAL) needs to be upgraded with a BGO crystal insert to improve the photon energy resolution for the most-forward going photons in GlueX. Members of the JEF group have submitted an NSF MRI proposal in early 2019 and Jefferson Lab has allocated funds for this work. There is also some substantial design work needed for this insert as it requires a new frame and a cooling system for the crystals. It may also require modifications to the current FCAL frame and support structure.

The installation of this insert is a major operation. The insert will replace the inner crystals of the current FCAL, requiring that the FCAL will need to be dismantled, and then reassembled around the insert. As part of this, it is expected that many of the FCAL parts will need to be refurbished. This work will likely lead to a 9-12 month shutdown of physics in Hall D.

4.3 Summary

5 Strange Hadron Spectroscopy with Secondary K_L Beam

5.1 Introduction

This White Paper summarizes unresolved issues in hadron physics and outlines the vast opportunities and advances that only become possible with the KL facility. This KL facility would revolutionize our understanding of bound-systems containing strange quarks, providing the long sought, quality experimental data to reach deeper into the strange quark sector. This will enable the tremendous recent progress in spectroscopy in both theory and experiment with electromagnetic beams to continue into a new frontier.

5.2 Theoretical Motivation

The experiment [12] will measure both differential cross sections and self-analyzed polarizations of the Λ, Σ, Ξ, and Ω hyperons. These new data will significantly constrain the partial wave analyses for the extraction of the properties and pole positions of the strange hyperon resonances. They will finally determine the orbitally excited multiplets in the spectra of these hyperons, which with the exception of the Λ remain very poorly known. Comparison with the corresponding multiplets in the spectra of charm and bottom hyperons will illuminate the approach to heavy flavor symmetry and eventually the accuracy of QCD based calculations.

The proposed facility will have a defining impact in the strange meson sector through measurements of the final state $K\pi$ system up to 2 GeV invariant mass by determination of pole positions and widths of all $K^*(K\pi)$ P-wave resonances. It will settle the question of the possible existence or nonexistence the of scalar meson $K_0^*(700)$ (κ). This resonance would be the strange counterpart of the σ (or $f_0(500)$) meson, which is now rather well established from πN scattering. Knowledge of the resonance spectra of the strange hyperons is a crucial ingredient in strange resonance enhancements in relativistic heavy ion collisions.

The physics case for the experiments is aligned with the 2015 Long Range Plan for Nuclear Science: "....a better understanding of the role of strange quarks became an important priority" [13]. The determination of the strange hyperon spectra in combination with the current measurements of the spectra of the charm and beauty hyperons at the LHCb experiment at CERN will provide an understanding of soft QCD matter and the approach to heavy quark symmetry. In the spectrum of the Λ hyperon only the lowest negative parity doublet and the positive parity singlet are well established, but their structure remains unsettled. In the spectra of the Σ and Ξ hyperons only the lowest decuplet states $\Sigma(1385)$ and $\Xi(1530)$ are well established. It is a priority determine whether the indication for several low lying negative parity Σ hyperon around 1500 MeV are real.

The mass of the lowest positive-parity resonance in the spectrum of Σ hyperons is experimentally known, but their structure is not. In the case of the Ξ hyperon, the lowest positive-parity resonance remains unobserved. To settle the nature of these hyperon resonances, their main decay modes have to be determined by experiment. Heavy quark symmetry provides a powerful tool for analyzing the structure of strange hyperons by comparison to the corresponding heavy flavor hyperons. Heavy quark symmetry is a consequence of the fact that the strength of quark spin-orbit couplings scale with the inverse of the constituent mass. In the case of the hyperons, this implies that the spin-orbit splittings in the hyperon spectra decrease with increasing quark mass. In the case of hyperons with light and heavy quarks this implies that the heavy quark spin decouples from that of the light quarks. Heavy quark symmetry suggests, that the ratio of the sizes of such spin-orbit splittings in the corresponding multiplets in the spectra of the strange, charm and beauty hyperons should approximately correspond to the ratio of the inverses of the corresponding constituent quark (or approximately) meson (K, D, B) masses. Where the spin-orbit splittings conform to this scaling law the implication is that the quark structure of the corresponding hyperon resonances in the different flavor sectors are similar.

Given hyperons with only one light flavor quark shall be exceptionally important to compare the spin-orbit splittings between the Ξ hyperons in the different flavor sectors, once these are determined experimentally. Hitherto the comparable splittings are only known for the lowest negative parity doublets in the strange, charm and beauty hyperon spectra, with two light-flavor and only one single heavy quark.

Current QCD lattice calculations are able to give good qualitative information on the structure of the hadron spectra, but still are computational constrained to unphysically large pion mass values.

The application to baryons is far more limited. In an approach in which the excited-state hadrons are treated as stable particles, a spectrum of baryons at least as rich as that of the quark model has been revealed and evidence has been presented for "hybrid" baryon states, beyond those of the quark model, in which gluon degrees of freedom are essential. Notably, this picture extends to the spectrum of the Λ, Σ, Ξ, and Ω states where the counting of states reflects $SU(6) \times O(3)$ symmetry.

The calculations for the baryon sector are incomplete, in that the momentum-dependent scattering amplitudes characterizing multi-hadron states have not been extracted. In comparison with the calculations for mesons cited above, the challenges are more computational than theoretical or conceptual. The first direct calculation of the $I = 3/2$ $N\pi$ system in the P-wave has now been performed and reveals a Breit-Wigner description of the amplitude commensurate with a phenomenological description of the $\Delta(1232)$ resonance. According to the general trend in lattice QCD, it is likely that the progress made in the meson sector will be reflected for the case of baryons in the coming years. Quantitative first principle lattice calculations with the physical pion mass of the positive parity resonances beyond the lowest decuplet states do, however, remain beyond reach for the time being. This emphasizes the need for phenomenological determination of the strange hyperon spectra at GlueX in parallel with the current work at LHCb at CERN.

5.3 Experimental Details

The tertiary neutral kaon beam to be used for these experiments will consist of four main components:

- In the first stage, 12 GeV electrons will scatter in a copper radiator (10% X_0) inside the Compact Photon Source (CPS), thereby generating an intense beam of untagged bremsstrahlung photons.

- In the second stage, the photon beam will interact with a Be target located 67 m downstream of the CPS. Directly behind the Be target there will be collimation and a sweep magnet to strongly enhance the relative contribution of neutral kaons transported along the beam line.

- In the third stage a flux monitor will register in-flight decays of the K_L over a 2 m path length.

- In the fourth and final stage, the momentum-tagged K_L (via time-of-flight) will interact with the existing GlueX liquid hydrogen target modified to accept a larger diameter target cell.

A brief overview of each of these components is provided below, together with an overview of the experimental conditions that this facility will be able to provide. Further details of the devices and experimental conditions can be found in the proposal and supplemental materials to PAC46 [12].

CPS: The CPS design combines in a single properly shielded assembly all elements necessary for the production of the intense photon beam, such that the overall dimensions of the setup are limited and the operational radiation dose rates around it are acceptable. The CPS with a weight of 100 t is to be located in the Hall D tagger vault, 11 m downstream of the current radiator. Consequently, the Hall D tagger does not need to be modified to implement the CPS. The CPS will contain a 10% X_0 radiator capable of handling up to 60 kW of power deposited from the 12 GeV electron beam. The enclosed magnet will enable the CPS to concurrently serve as the beam dump for the primary electron beam. The active elements will be surrounded by sufficient shielding for radiation protection. At the full 60 kW beam operation, the dose rates will be comparable to nominal conditions in the vault.

Be target: The K_L will be produced with forward emission kinematics in the interaction of the photon beam with a Be target. Be is used because lighter element provide higher photoproduction yield per unit radiation length. The Be-target will be a cylinder of 6 cm diameter and 40 cm length. The Be will be surrounded radially and downstream by a tungsten absorber with an overall length of 70 cm and an outer diameter of 75 cm. This will be surrounded by lead (diameter 100 cm, length 130 cm) and then a 10 cm shell of borated polyethylene. The weight of the Be-target assembly is 14.5 t. Changeover from the photon to K_L beamline and vice versa is expected to take about half a year or less , and thus should fit well into beam breaks of the current CEBAF schedule. Water cooling will be required to dissipate the 6 kW deposited by the photon beam. Directly downstream of the target there will be a magnet with a field integral of 0.8 $T \cdot m$ to clean up the charged particle component from the beam.

Flux Monitor: In order to normalize the cross section of the recorded data, the K_L flux will be determined with a relative precision of better than 5% by a dedicated Flux Monitor (FM). This device will measure pairs of charged decay products from the in-flight decay of the K_L. The K_L flux will be measured upstream of the GlueX detector, using the Hall D pair spectrometer as shielding against decays that have occurred further upstream. The fiducial volume will encompass the 2 m downstream of the Pair Spectrometer. The FM will consist of tracking devices directly before and after a solenoid magnet and will be surrounding by scintillating endcaps. A potential extension of the system would further increase performance by instrumenting the inner wall of the magnet and add a start counter surrounding the beamline. Detailed studies indicate that a statistical precision to measure the K_L flux of 1% is achievable in less than one day.

CryogenicTarget: The existing GlueX liquid hydrogen cryogenic target will be used and modified to accept a larger diameter target cell. The radius of the kapton cell will be increased from 2 cm to 6 cm and the length will increase from 30 cm to 40 cm, corresponding to a volume of 1.1 liter. There will be cooperation with the JLab Target Group to investigate alternative materials and construction techniques to increase the strength of the cell and to enable operation with both LH_2 and LD_2.

Beam Luminosity/Background: Detailed simulation studies of the beam properties have been performed. The main mechanism of K_L production in this energy range is via ϕ-meson photoproduction. Total and differential cross sections including angular distributions of intermediate decays have been taken into account, as well as absorption in the target and surrounding shielding. The K_L flux incident upon the cryogenic target will increase with momentum and reach a broad plateau at about 4 GeV/c, beyond which the flux will drop rapidly. Due to the contribution of hyperons, the flux of K^0 will be larger than that of the $\overline{K^0}$ by about 30%. In total about 1×10^4 K_L /s will be incident on the cryogenic target.

Beam background from muons, neutrons and photons have been studied. Most muons are produced in the photon dump and will be swept out of the K_L beamline; thus, they are not inherently a significant background for the measurement. Detailed studies show that they are also not a significant radiation load outside of the shielding. The neutron and gamma flux along the beamline and the neutron dose rate in the experimental hall from scattered neutrons and gamma were determined using the MCNP6 N-Particle (MCNP) Transport code. The neutron dose rate calculated is 0.11 ± 0.04 $mrem/h$, which is acceptable by RadCon. The neutron flux on the face of the LH_2/LD_2 cryogenic target is 1.7×10^4 $n/(s \cdot cm^2)$. This flux peaks at about 400 MeV and drops exponentially to 10 GeV. The flux is not sufficient to provide a significant background in the case of np or nd interactions in the cryogenic target.

The momentum of the K_L beam will be measured using time-of-flight (TOF) - the time between the accelerator bunch (RF signal from CEBAF) and the reaction in the LH_2/LD_2 target as detected by the GlueX spectrometer. Since the accelerator signal has a time resolution of about 1 ps, the TOF resolution will be defined by GlueX. With a beam bunch separation of 64 ns, there will be no bunch misidentification for momenta above about 320 MeV/c. The beam momentum resolution will vary from about 1.5% at 1 GeV/c to 5% at 2 GeV/c, corresponding to a W resolution of better than 30 MeV over this momentum range. At higher momenta, exclusive reconstruction of final states will enable ΔW to be limited to about 30 MeV by exploiting over-constraints in the event reconstruction.

5.4 Summary

The current KLF proposal has been tested in four international workshops with more than 100 talks given, supporting the KLF physics program [14, 15, 16, 17]. Currently this proposal is signed by 200 physicists from 61 institutions of 20 countries, with some distinguished world experts in the field. It is the largest collaboration ever to submit a proposal to the JLab PAC. The submitted proposal reflects the collective wisdom of the broad community.

6 Summary

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