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Future Physics in Hall D with the GlueX Detector

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Executive Summary

Over the past several years, a number of ideas have been presented to the Jefferson Lab Program Advisory Committee (PAC), both as full proposals and letters of intent. In addition a number of physics workshops had been hosted over the last several years to discuss possible future physics programs in Hall D using all or portions of the GlueX detector and beamline. These discussions included topics that could run as part of the normal GlueX spectroscopy program, as well as activities that could require dedicated beam time, and possible modifications to the baseline equipment.

In the late summer of 2018, Jefferson Lab Management asked the GlueX Collaboration to produce a white paper on future physics in Hall D. This should include not only the GlueX spectroscopy program, but other physics opportunities as well. In response to this request, the collaboration organized a brain-storming session during the fall 2018 GlueX Collaboration Meeting. Nine topics were presented during this session, and a summary was made. It was also planned to have a one-half day meeting prior to the February 2019 GlueX Collaboration Meeting where longer presentations would be made, and people would be asked to provide short written summaries of their ideas. During the February meeting, nine presentations were made. These included all the topics from the fall meeting (some consolidated into a broader program) as well as some additional ideas.

In addition to the approved time in Hall D, the potential program summarized in this report represents nearly 900 PAC days of additional beam time. To carry out this program also requires new equipment beyond that currently planned for the detector, and will likely require repairs and possibly replacement of some GlueX equipment due to aging. The GlueX Collaboration finds the diverse physics program presented here to be very exciting and looks forward to seeing many of these ideas more fully developed.

The ideas presented span a large range of both time scales, required beam time, and revisions to the GlueX detector and beamline. The experience of the GlueX Collaboration is that running a successful experiment in Hall D requires the effort of the entire collaboration to be on board in providing manpower and expertise to run the experiment, calibrate the detector, provide simulation and process the large amounts of data. This is not something that could be carried out by a small group of people.

Due to the significant commitment required to run experiments in Hall-D, in fall 2018,GlueX Collaboration revised its bylaws to create the idea of a *GlueX endorsed experiment* and define the procedure for obtaining such an endorsement. Endorsement implies a commitment on the part of the GlueX Collaboration to provide resources to acquire and process data, and a commitment on the part of the proponents conduct a physics program under the auspices of the GlueX Collaboration, including full participation in the running GlueX program. For longer term projects with major new equipment, a GlueX endorsement may not be appropriate at the time of a PAC proposal. As of this writing, only those proposals previously approved by the PAC are "endorsed." In that regard, *this paper represents a survey of ideas for future running, but should not be interpreted as an endorsement or prioritization of particular future programs on the part of the GlueX Collaboration.*

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I. INTRODUCTION

In the late summer of 2018, Jefferson Lab Management asked the GlueX Collaboration to produce a white paper on future physics in Hall D. During the September 2018 GlueX Collaboration meeting, we organized a two-hour session where people made very short presentations followed by discussion. Nine presentations were made in this session. Following the initial meeting, a one-half day meeting was organized just prior to the February 2019 GlueX Collaboration meeting. During thus meeting, we devoted about thirty minutes to each topic presented. Following the 2018 meeting, several of the nine topics coalesced into a larger program, but new ideas also emerged, leading to nine topics again. At the end of the February meeting, the contributors agreed to provide summary text for a white paper. Those documents have been collected and used to generate this white paper.

The topics have been arranged to first cover the currently approved experiments. We then organized the new programs in order of their required modifications to the baseline experiment. There were also several extensions that could run as part of an existing program. These have been placed just following the program with which they could run. Assuming that the concurrency is accurate, these programs would just be part of the normal GlueX data stream and not need to be presented externally for approval.

Beyond the baseline equipment that has been operational in Hall D since 2014, the described programs require the installation of new equipment in Hall D. We identify the larger pieces of equipment here as well as its current status.

- *Compton Calorimeter*: The ComCal is a high-granularity $PbWO_4$ calorimeter located down stream of the GlueX forward calorimeter. It has been commissioned in fall 2018 and is being used during the spring 2019 PrimEx run.

- *GlueX DIRC*: Four of the twelve quartz bar boxes from the BaBar DIRC have been moved to Jefferson Lab from SLAC and will be used for kaon identification in GlueX. A new optical coupling and readout system has been built for GlueX. Half of the system was installed and commissioned in January 2019, while the remainder will be installed in summer 2019. Physics using this new system is planned to start in fall 2019.

- *Forward Muon System*: The forward muon system consists of wire chambers between steel plates, and will be located downstream of the forward calorimeter. It is needed as part of the approved charged pion polarizability experiment. Wire chambres have been tested in Hall-D.

- *Forward Calorimeter Upgrade*:A planned $PbWO_4$ insert for the central part of the forward calorimeter will significantly improve both photon resolution and radiation hardness of the current system. This device is in the Jefferson Lab planned updates and an MRI proposal has been submitted to support this. Installation of this device will require Hall-D to be offline for the scale of a year.

- *Polarized Target*: A longitudinally polarized target is requested for several of the proposed experiments, and could likely find utility in a future GlueX Spectroscopy Program as well. It would most likely be a custom frozen spin target to fit in the current GlueX detector.

- *Compact Photon Source*: The K_L program requires extensive changes to the current Hall-D beamline. This includes a compact photon source to be added to the tagger hall. Such a source would likely require the removal of all tagger electronics and some hardware to avoid radiation damage. In addition, most of the instrumentation in the Hall-D alcove would be removed to accomodate a K_L source.

We estimate over 1200 PAC days would be required to execute all the programs described in this white paper. That includes both the currently approved programs (about 300 PAC days) as well as all of the ideas discussed herein.

We have learned that successfully operating equipment in Hall D requires the efforts of the entire GlueX Collaboration. In addition to the obvious task of manning shifts, there is a large framework of multiple levels of data quality monitoring, extensive calibrations that need to be performed, and the processing of data, either on site at Jefferson Lab, or at off site resources such as NERSC and OSG. Many of these tasks are the responsibility of members of the GlueX Collaboration who are not JLab staff, and they involve non-negligible amounts of time. It seems unreasonable to consider trying to run a successful experiment in Hall D without the commitment of a larger group of people beyond the immediate Hall D staff. As a result of this, the GlueX Collaboration, which has no formal involvement in the PAC or experiment scheduling process, sought to clearly define its intentions with regard to future experiments by creating the idea of a *GlueX endorsed experiment* and a procedure for obtaining such an endorsement.

In particular, since late 2018 a GlueX endorsed experiment is now defined by the following bylaws of the GlueX Collaboration.

1. GlueX endorsed experiments are recognized as distinct experimental directions being pursued under the organization of the GlueX Collaboration.

2. The endorsement of the Collaboration implies a commitment of the entire Collaboration to operate detector equipment, staff shifts, and calibrate and process the data collected.

3. All proponents of such proposed experiments must be members of the GlueX Collaboration, or have a plan approved by the Executive Group and Collaboration Board for joining the Collaboration and participating in ongoing GlueX experiments.

4. All Hall D experiments which were approved by the PAC before 2018 are considered to have the endorsement of the GlueX Collaboration.

The GlueX Collaboration welcomes outside groups to propose new ideas that can be pursued with the Hall D equipment. Endorsement of these proposed programs comes with a level of commitment on the part of the Collaboration to a successful running of the program, and there is a reasonable expectation that outside groups would have a similar commitment to all other GlueX endorsed proposals. The time at which proponents choose to seek endorsement of the collaboration should be made strategically and likely depends on the details of the proposal. Our consensus is that endorsement is likely to be criterion for determining that an experiment is ready to run, and therefore, should be sought, at the latest, prior to the experimental readiness review.

A GlueX endorsement may not be appropriate for long-term projects that represent significant shifts in the physics objectives of the GlueX program, require extend periods of beam time, and/or require major equipment modifications. **Lack of endorsement at the time of a PAC proposal should not be viewed as a lack of support or enthusiasm for these ideas**. It only reflects an inability for the GlueX Collaboration to make a firm commitment of resources for the time scales in question. Choosing to seek endorsement, and the time at which it is done, should be a strategic choice of proponents: GlueX endorsement for such major long-term projects may limit the participation of non-GlueX members as membership of all proponents is a criterion for endorsement. Such projects may grow alongside the existing GlueX Collaboration and then may seek endorsement and merge with GlueX when the relevant commitments and time scales are better defined. Alternatively, it may be appropriate for such activities form as a separate collaboration with intentions of using the Hall D equipment. In such a case, that collaboration would operate independent of the GlueX collaboration under its own governance and it would negotiate directly with JLab to take responsibility for operating the Hall D equipment in such a way to achieve its physics objectives. In this latter operational model no commitment on the part of the GlueX Collaboration membership is needed or implied.

It is important to note that, with the exception of those proposals that have already been approved by the PAC, *none of the extensions to the Hall D program presented in this white paper have been endorsed by the GlueX Collaboration.* This document is an attempt by the Collaboration to survey the ideas of the community. It does not represent a tentative commitment on the part of the GlueX Collaboration to run the presented programs. Independent of the outcome of any PAC proposal, the commitment of resources on the part of the collaboration to collect and process data will eventually require an endorsement according to the procedure defined in the bylaws of the GlueX Collaboration.

II. THE GLUEX SPECTROSCOPY PROGRAM

A. 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.

Beyond 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.

B. 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 I.

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

TABLE I. *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 II. 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 II. *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.*

C. 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.

$$\begin{aligned}
\eta'\pi \text{ in } \gamma p &\to p\eta\pi^+\pi^-\pi^0 \text{ and } \gamma p \to \Delta^{++}\eta\pi^+\pi^-\pi^- \\
\pi\pi\pi \text{ in } \gamma p &\to p\pi^+\pi^-\pi^0 \\
\eta\pi\pi \text{ in } \gamma p &\to p\eta\pi^+\pi^- \text{ and } \gamma p \to p\eta\pi^0\pi^0 \\
\omega\pi\pi \text{ in } \gamma p &\to p\pi^+\pi^+\pi^-\pi^-\pi^0 \\
K^*K \text{ in } \gamma p &\to pK^+K^-\pi^0
\end{aligned}$$

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] This was to obtain TPOL data with two different radiator thicknesses, when the 750 μm radiator was used, about 50% of the triggers were calibration.

D. 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.

E. Summary of the Spectroscopy Program

In table III 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 $PbWO_4$. 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 III. *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.*

III. CHARMONIUM PROGRAM WITHIN GLUEX

A. Introduction

The upgraded 12 GeV JLab accelerator provides a unique opportunity to study the near threshold production of charmonium states below the $D\bar{D}$ threshold. It has the right energy and high intensity that is needed to perform measurements as close as possible to the threshold.

TABLE IV. Analogy between electromagnetic and gluonic form factors

	e.m. FF	gluonic FF
reaction	$ep \to ep$	$J/\psi p \to J/\psi p$
transverse size of probe	0	$\ll$ 1 fm
effective mass scale m_0	0.84 GeV (vector meson)	$\sim$ 1.1 GeV (two-gluon mass)

Thanks to their large mass, the charm quarks are almost static, which allows the application of non-relativistic methods that describe the charmonium states very successfully. In addition to these conventional states there are numerous candidates for exotic states that involve charm quarks which were discovered and extensively studied in the last 15 years. The LHCb pentaquark candidates, $P_c^+(4380)$ and $P_c^+(4450)$, are of special interest for JLab as they can be produced in the s-channel of the J/ψ photoproduction at a beam energy of $\sim$ 10 GeV, i.e. within the reach of the 12 GeV accelerator.

In photoproduction, the heavy quark charmonium interacts with the nucleon via gluon exchange. The transverse size of the $c\bar{c}$ system is much smaller than the proton radius which makes it an excellent probe to study the color charge distribution of the nucleon. The charmonium production near threshold is of particular interest since it is sensitive to the high-x gluonic content of the nucleon. The J/ψ photoproduction near threshold is dominated by the real part of the $J/\psi p$ elastic amplitude, which is critically important as it contains a term (trace anomaly) related to the fraction of the nucleon mass arising from gluons.

Hall D is the only hall to which a beam of energy higher than 11 GeV can be delivered which is critical for the threshold production of the high mass charmonium states. The full acceptance of the GlueX detector, starting at very small forward angles, is another advantage compared to the other halls, allowing the study of exclusive reactions very close to the threshold.

B. J/ψ near-threshold photoproduction

At the present moment, the main interest in the J/ψ photoproduction comes from its direct relation to the two pentaquark candidates, $P_c^+(4380)$ and $P_c^+(4450)$, reported by LHCb [9] in the $J/\psi p$ channel of the $\Lambda_b^0 \to J/\psi K^- p$ decay. The existence of these resonances implies they should be seen also in the s-channel photoproduction, $\gamma p \to P_c^+ \to J/\psi p$, at $\sim$ 10 GeV beam energy. Almost immediately after the pentaquarks have been reported it was realized [10–12] that this reaction can be described using the $P_c^+ \to J/\psi p$ decay plus its time inversion and the addition of the $J/\psi - \gamma$ coupling based on Vector Meson Dominance (VMD). The Breit-Wigner expression for the cross-section includes the measured width of the pentaquark, the VMD coupling obtained from the leptonic decay of the J/ψ, and only one unknown parameter, the branching fraction of the $P_c^+ \to J/\psi p$ decay, which enters squared in the expression for the cross section. Thus, by measuring the J/ψ photoproduction cross-section one can estimate this branching fraction.

Studying the J/ψ-nucleon interaction is another important aspect of the charmonium program. In [13] using dimensional scaling, the energy dependence of this reaction is predicted depending on the number of hard gluons that are exchanged. In [14] it is argued that the t-dependence of $J/\psi N$ elastic scattering is defined by the proton gluonic form-factor describing the color charge distribution, which is analogous to the electromagnetic form factors (see Table IV) though with a different mass scale. According to [15] the J/ψ photoproduction near threshold is dominated by the real part of the $J/\psi p$ elastic amplitude, which contains the trace anomaly term related to the fraction of the nucleon mass arising from gluons. It was demonstrated [16] that near threshold, the energy dependence of the cross-section and especially the t-dependence is sensitive to the gluon contribution to the mass of the proton.

C. Searches for other Charmonium states

In addition to J/ψ, there are several other charmonium states accessible within the GlueX energy reach. GlueX is an excellent place to search for these states, with its large acceptance and wide range of particle

Reaction	Threshold	Suggested Decays (Branching Fractions)
$\gamma p \to p\,\eta_c(1S)$	7.7 GeV	$\eta_c(1S) \to K_S K\pi(2.3\%), K^+K^-\pi^0(2.3\%),\ \eta\pi\pi(1.7\%)$
$\gamma p \to p\,J/\psi(1S)$	8.2 GeV	$J/\psi(1S) \to e^+e^-(6\%)$
$\gamma p \to p\,\chi_{c0}(1P)$	9.6 GeV	$\chi_c 0(1P) \to \pi^+\pi^-\pi^+\pi^-(2.3\%)$
$\gamma p \to p\,\chi_{c1}(1P)$	10.1 GeV	$\chi_{c1}(1P) \to \gamma J/\psi(34\%)$
$\gamma p \to p\,h_c(1P)$	10.1 GeV	$h_c(1P) \to \gamma\eta_c(1S)(51\%)$
$\gamma p \to p\,\chi_{c2}(1P)$	10.3 GeV	$\chi_{c2}(1P) \to \gamma J/\psi(19\%)$
$\gamma p \to p\,\psi(2S)$	10.9 GeV	$\psi(2S) \to \pi^+\pi^- J/\psi(35\%)$

TABLE V. Production thresholds and suggested decay modes for charmonium searches described in the text.

identification abilities. A summary of the possible states to search for is given in Table V.

The charmonium state with the largest phase space available for its production is the ground state, $\eta_c(1S)$, with a production threshold of $E_\gamma = 7.7$ GeV. It is the widest of the bound charmonium states ($\Gamma = 32.0 \pm 0.8$ MeV), and decays almost entirely into light hadrons, with its largest decays into multi-pion (4,6,8) final states. It is likely difficult to extract a small signal in these multi-pion final states, which are copiously produced at GlueX. However, some of the larger branching fractions of the $\eta_c(1S)$ are to 3-body final states which are of interest in hybrid and other light meson searches, for example $\eta_c(1S)$ decays to $K_S K^\pm \pi^\mp$ and $K^+K^-\pi^0$ 2.3% of the time, and to $\eta\pi\pi$ 1.7% of the time. The intermediate resonances in these decays should help reduce background contributions, and it is possible that $\eta_c(1S)$ could be observed in amplitude analyses of these final states, or perhaps as a peak if a method for enhancing the production of high-mass resonances is identified.

Taking advantage of the e^+e^- signature of J/ψ, the 1^3P_1 χ_{c1} can be identified by its favorable (34%) radiative decay into J/ψ. Also, as a spin-1 particle, it can be expected to be well produced in photoproduction, and initial evidence for its production has been seen with the data analyzed so far. The remaining members of the $1P$ spin-triplet, the 1^3P_0 χ_{c0} and 1^3P_2 χ_{c2} are expected to be more difficult to identify than the χ_{c1}. The χ_{c0} decays primarily into light hadrons, with its largest decay into 4 charged pions. The χ_{c2} has a favorable radiative branching fraction to J/ψ of 19%, but the production of this spin-2 state is expected to be suppressed compared to the spin-1 χ_{c1}, and is indeed not yet seen in the $\gamma J/\psi$ final state.

Other possibilities include the singlet P-wave state h_c, which radiatively decays roughly half the time to $\eta_c(1S)$ with a ~ 500 MeV photon. This monoenergetic photon is likely the best signature for identifying this state. The radial excitation of the J/ψ, the $\psi(2S)$, mostly decays to lighter charmonia, including roughly half the time into J/ψ via a dipion transition. This is a clear signature for this state, but unfortunately the threshold for its production is $E_\gamma \sim 10.9$ GeV, leaving little phase space available at current CEBAF energies.

D. Additional Opportunities

The spectrometer halls at JLab (A and C) are able to study the inclusive J/ψ production at high intensity under the assumption that it is purely elastic: $\gamma p \to J/\psi p$, The GlueX detector can verify the exclusiveness of charmonium production at these energies. We can search for the reaction $\gamma p \to p\pi^0 J/\psi$ which has the largest available phase space of the multibody hadronic channels. One can also use this final state to search for the production of J/ψ in additional isospin channels, such as $\gamma p \to \Delta^0 J/\psi$, $\Delta^0 \to p\pi^0$. Such studies are critical for the validation of the results from the other halls and for the full understanding of charmonium production mechanisms.

E. Experimental conditions and compatibility with the GlueX experiment

In 2016 and 2017 running periods together we have accumulated ~ 450 J/ψ. We expect a factor of 4 more in the 2018 data based on the measured luminosity. If the conditions of the GlueX experiment remain the same we expect of the order of $10k$ J/ψ events collected through the end of the GlueX program. This amount of data will allow us to measure the differential cross-section near threshold as a function of energy and t. We have observed already, from 2016 and 2017 data, ~ 16 χ_{c1} particles in the $\gamma p \to \chi_{c1} p \to \gamma J/\psi p \to \gamma e^+ e^- p$ reaction. Including the 2018 data will result in ~ 60 events, and we expect for the whole GlueX program about 200-300 detected χ_{c1} particles.

Therefore, the default plan is to collect charmonium data opportunistically during GlueX running. However, if there is a compelling physics case, the GlueX detector allows running with higher intensity, using a special charmonium trigger with a high threshold on the sum of the two calorimeters. This will require also lowering the HV in the inner part of the drift chambers and TOF. Adding a Transition Radiation Detector (TRD), outside of the magnet and in front of the DIRC detector, will help to suppress the pion background. This is not needed for J/ψ, but is very important for the Bethe-Heitler process $\gamma p \to e^+ e^- p$ which is critical for the J/ψ normalization the study of the systematics of the charmonium photoproduction. Tests with prototype TRDs have been performed for several years already.

The charmonium program will benefit from the addition of the DIRC detector and the increase of the intensity in the next phases of the GlueX experiment. As discussed, reaching the maximum beam energy is very important for the charmonium production. In addition, high energies are needed for comparison to the higher energy measurements at SLAC, which start at 13 GeV. In the spring of 2016 the maximum tagged photon energy was 11.85 GeV, while for the later running it was lowered to 11.4 GeV. Therefore, the 2016 data is the only one so far (and will remain the only for several more years) that can give valuable information in the high energy region next to the SLAC measurements.

IV. THE JLAB η-FACTORY EXPERIMENT (JEF)

A. 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 [17] to run concurrently with the GlueX Spectroscopy Program. The JEF experiment will perform precision measurements of various η and η' decays with emphasis on rare neutral modes to test fundamental symmetries and to search for new physics Beyond the Standard Model (BSM).

Compared to all existing and planned η/η' experiments in the world, the unique features of the JEF experiment are: (1) simultaneous productions of η and η' with up to two orders of magnitude of background suppression in the rare neutral decay modes; and (2) large statistics and significantly improved systematics with a uniform detection efficiency over the meson decay phase space. JEF will improve the branching ratio upper limits for various rare η/η' decays up to two orders of magnitude per 100 days of beam time, and have a sufficient sensitivity for the first time to map the Dalitz distribution of $\eta \to \pi^0 2\gamma$ to probe the scalar meson dynamics in ChPT and to search for new physics beyond the Standard Model.

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

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

B. Special Conditions

In order for the JEF experiment to run, the GlueX forward calorimeter (FCAL) needs to be upgraded with a $PbWO_4$ 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 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.

C. The Physics of JEF

The JEF program will address a broad range of important physics topics. Table VII summarizes various η decays in the scope of JEF program and the physics highlight. The priority physics campaigns for the JEF experiment are:

Mode	**Branching Ratio**	**Physics Highlight**	**Photons**
priority:			
$\gamma + B'$	beyond SM	leptophobic dark vector boson	4
$\pi^0 + \phi'$	beyond SM	electrophobic dark scalar boson	4
$\pi^0 2\gamma$	$(2.7 \pm 0.5) \times 10^{-4}$	χPTh at $\mathcal{O}(p^6)$	4
$3\pi^0$	$(32.7 \pm 0.2)\%$	$m_u - m_d$	6
$\pi^+\pi^-\pi^0$	$(22.9 \pm 0.3)\%$	$m_u - m_d$, CV	2
3γ	$< 1.6 \times 10^{-5}$	CV, CPV	3
ancillary:			
4γ	$< 2.8 \times 10^{-4}$	$< 10^{-11}$[23]	4
$2\pi^0$	$< 3.5 \times 10^{-4}$	CPV, PV	4
$2\pi^0\gamma$	$< 5 \times 10^{-4}$	CV, CPV	5
$3\pi^0\gamma$	$< 6 \times 10^{-5}$	CV, CPV	7
$4\pi^0$	$< 6.9 \times 10^{-7}$	CPV, PV	8
$\pi^0\gamma$	$< 9 \times 10^{-5}$	CV, Ang. Mom. viol.	3
normalization:			
2γ	$(39.4 \pm 0.2)\%$	anomaly, η-η' mixing E12-10-011	2

TABLE VII. The η decays highlighted in the JEF experiment, plus related ancillary channels [24]. The $\eta \to 2\gamma$ will be measured by the PrimEx-eta experiment (E12-10-011).

- A search for a leptophobic dark vector boson (B') [18] coupled to baryon number is complementary to ongoing worldwide effort for a dark photon focusing mainly on signatures involving leptons. The decay $\eta \to \gamma + B'(\to \gamma + \pi^0)$, will cover the B' mass range 0.14-0.54 GeV. The JEF experiment will improve the existing bounds by two orders of magnitude, with sensitivity to the baryonic fine structure constant α_B as low as 10^{-7}, indirectly constraining the existence of anomaly cancelling fermions at the TeV-scale.

- A search for an electrophobic dark scalar (ϕ') in the mass range of 0.01-0.4 GeV through $\eta \to \pi^0 + \phi'(\to \gamma + \gamma)$ or $\eta \to \pi^0 + \phi'(\to e^+ + e^-)$. A positive signal in the JEF search may solve the puzzles of the proton charge radius and the anomalous magnetic moment of muon (g-2) simultaneously [19, 20].

- A search for the C-violating η decays (such as $\eta \to 3\gamma$ and $\eta \to 2\pi^0\gamma$) and a mirror asymmetry in the Dalitz distribution of $\eta \to \pi^+\pi^-\pi^0$ will offer the best direct constraints on new C violating, P conserving reactions (CVPC). As pointed out by M. Ramsey-Musolf, the Electric Dipole Moment (EDM) searches place no constraint on CVPC in the presence of a conspiracy or new symmetry; only the direct searches for CVPC are unambiguous [21].

- A low-background measurement of the rare decay $\eta \to \pi^0 2\gamma$ provides a clean, rare window into $\mathcal{O}(p^6)$ in chiral perturbation theory [22]. This is the only known meson decay which proceeds via a polarizability type mechanism. With sufficient precision to explore the role of scalar meson dynamics in this channel for the first time, this measurement will model independently determine two Low Energy Constants (LEC) in the $\mathcal{O}(p^6)$ chiral Lagrangian and test the ability of models such as meson resonance saturation to calculate many other unknown $\mathcal{O}(p^6)$ LEC's.

- Reduction of the uncertainty on the quark mass ratio, $\mathcal{Q} = (m_s^2 - \hat{m}^2)/(m_d^2 - m_u^2)$ with $\hat{m} = (m_u + m_d)/2$, will be achieved by a high statistics measurement in the Dalitz distributions of $\eta \to 3\pi$ while controlling systematic uncertainties due to relatively flat acceptance and detection efficiency over the phase space, in addition to a new measurement of $\Gamma(\eta \to \gamma\gamma)$ from the on-going PrimEx-eta experiment (E-10-011).

V. THE PRIMEX EXPERIMENT

A. Introduction

The PrimEx η experiment was presented to and approved by Jefferson Lab PAC 35 in 2010 [27]. The experiment will measure the η radiative decay width at a precision of $\sim 3\%$ via the Primakoff effect on two light targets, hydrogen and ^4He, using the GlueX apparatus in Hall D with additional $PbWO_4$ crystal calorimeter to control the experimental systematics.

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

TABLE VIII. *The approved PrimEx experiment.*

B. Special Conditions

The PrimEx experiment requires a 12×12 $PbWO_4$ 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.

C. Physics of PrimEx

The η meson is of great importance for understanding fundamental QCD symmetries at confinement scale. It is one of the Goldstone bosons due to spontaneous chiral symmetry breaking. The chiral anomaly [29] primarily drives its decay into two photons. The explicit breakings of chiral symmetry, isospin, and SU(3) by the light-quark masses are manifested in its decay as well. The SU(3) symmetry breaking gives rise to the mixing of π^0, η and η'. The precision measurement of the η radiative decay width will improve all partial decay widths in the η-sector and offer critical input for model independent determinations of the light quark-mass ratio and the $\eta - \eta'$ mixing angle. It will have profound importance in our understanding the QCD symmetry structure at low energy as well as the origin and dynamics of QCD confinement.

D. Future Measurement of the η' Radiative Decay Width

The planned extension of the PrimEx-η experiment with GlueX is to measure the η' radiative decay width via the Primakoff effect. All existing measurements were carried out by using the e^+e^- collision and the experimental uncertainty for the individual experiment is in the range of 7.3%-27%. We will perform the first Primakoff measurement with the projected uncertainty of 4% for $\Gamma(\eta' \to \gamma\gamma)$. The precision measurement of $\eta' \to \gamma\gamma$ will not only provide additional input for determination of the η-η' mixing angle and the decay constants of those mesons, but also help us to understand the nature of η'. It is well-known that the mass of η' is not zero in the chiral limit due to the U(1) anomaly, the same anomaly that is responsible for the strong CP-violation. The theoretical analyses imply that the mass of η' would vanish at large N_c limit. Is η' an approximate Goldstone Boson or not? More precise experimental measurements together with the theoretical framework in place would help to answer this question via a global analysis of different processes involving both η and η'. It is clear that a new measurement of the two-photon decay width of η' will have important impact on our understanding of fundamental issues of QCD.

E. Summary

The $\eta \to \gamma\gamma$ measurement is the first project among a series of measurements proposed in the Primakoff 12 GeV program [36, 37] that includes the two-photon decay widths of η and η' and the transition form factors of π^0, η and η' at small four-momentum transfer ($Q^2 \sim 0.001$–0.5 GeV^2/c^2). It was initially submitted to PAC18 in 2000 for the JLab 12 GeV science special review. This program was included in the executive summary of CEBAF 12 GeV upgrade white paper "Science Driving the 12 GeV CEBAF Upgrade" [37]. The PrimEx-η experiment [27] was approved by PAC35 in 2010 and updated by PAC37 for 79 days of the approved beam time; and it was reviewed by PAC41 in 2014 to select a high priority subset of approved experiments for the first 3-5 years of 12 GeV running. This experiment received recommendation from PAC41 that "The PAC believes this is very compelling physics and hopes it will be scheduled in a timely fashion" [38].

VI. THE CHARGED PION POLARIZABILITY EXPERIMENT

A. Introduction

The charged pion polarizability (CPP) experiment was presented to Jefferson Lab PAC 40 in 2013 [40]. The goal of the experiment is to measure the charged pion polarizability $\alpha_\pi - \beta_\pi$. The polarizability is a fundamental property of the lightest charged meson making it an important quantity in chiral perturbation theory. The polarizability is obtained by measuring the cross section of the Primakoff reaction $\gamma p \to p\pi^+\pi^-$. This requires the polarized photon beam source in Hall-D to distinguish it from backgrounds, primarily ρ production. Another major background will be $\mu^+\mu^-$ pair production. Standard GlueX detectors cannot distinguish between pions and muons so another detector is needed (see below).

Running condition	
Days for production running	20
Days for calibrations	5
Target	^{208}Pb
Photon intensity in coherent peak	10^7 photons/s
Edge of coherent peak	6 GeV

TABLE IX. Beam request and running conditions. Note that at the time of the proposal, there was a preference for a ^{116}Sn target.

B. Special Conditions

The CPP experiment will run with the coherent edge at 6 GeV, use a solid (lead) target, and muon chambers interleaved with iron absorbers downstream of the forward calorimeter. The experiment is also studying the use of a trigger using the time-of-flight counters instead of the usual calorimeter-based trigger of GlueX.

In fall 2018 a full-scale prototype, largely unshielded muon chamber, was installed on the Hall-D beam line downstream of the FCAL, with the photon beam going through the center of the chamber. Given that the actual installation of the muon chambers in CPP will have tens of cm of iron absorber in front of the chambers, the test chamber performed remarkably well, running at the design gain of x 10^5 with few chamber trips. The most problematic aspect of detector performance was electronic noise due to an oscillating ground plane in the electronics. The problem is fixable, and will be corrected in the eight detectors being readied for the experiment.

The fabrication of the eight muon chambers for the CPP experiment is nearing the final steps. The chambers with 144 wires each are under construction at the University of Massachusets and will be completed and delivered to JLab in the summer of 2019. All chamber frames have been assembled, the preamp electronics tested and attached to frames, and the central group of 10 sense wires and 11 field wires installed in all detectors. The central group of sense wires required special tools and installation techniques because they intersect the photon beam line. For that reason the 10 central sense wires were ''deadened" for a length of approximately 10 cm in the middle of the wires. For the CPP detectors this was done by threading the sense wires through .028" OD x .011" ID carbon tubes, about 10 cm long, and then bonding the tubes to the wires with a carbon based adhesive. The increased conductor diameter at the center of the detector, 28 mil as compared to .8 mil elsewhere (20 micron), drops the gas gain in the central region to x1. The next steps are to complete the sense and field wire stringing for the detectors, and then commission the detectors at operating voltage.

Triggering in GlueX is based upon EM calorimetry. To minimize bias in the trigger against $\pi^+\pi^-$ events, the CPP group is developing a trigger for the experiment based on the fast identification of two charged tracks in the TOF system. A test run with the TOF was completed in mid-February. The TOF singles rate is dominated by the rates in the central paddles near the beam line. To minimize accidentals in the two-hadron trigger, data were taken with and without one and two radiation-length lead plates covering the central 60 cm x 60 cm region of the TOF. The data are currently under analysis.

Discussions are underway with the Hall D engineering group as to the most efficient and cost-effective way to install the muon chambers and approximately 35 tons of iron on the platform behind FCAL. This installation will require significant modifications to the downstream platform, including removing and re-installing all of the FCAL cabling, which is expected to take about six months. The current preference is to not install the detectors permanently. Rather, the idea would be to move the platform into position for CPP, add non-movable auxiliary supports to the platform to handle the increased weight of the detectors and absorbers, and then do the installation. When CPP completes running, the detectors, absorbers, and auxiliary supports are removed. Cabling for FCAL must be re-routed because electronics racks must be moved to make way on the platform for the muon chambers. However, it appears that new cables for FCAL do not need to be made, and the current cables are sufficiently long.

The CPP group anticipates requesting a Readiness Review for the experiment in late summer 2019. Following that, there will be a jeopardy PAC in summer 2020. Contingent on engineering support for the installation, the CPP group expects that the experiment could be ready to run in late 2021.

C. Summary

The goal of the CPP experiment is to measure the charged pion polarizability, which is a fundamental property of the lightest charged meson, by measuring the cross section of the Primakoff reaction $\gamma p \to p\pi^+\pi^-$. This experiment uses the baseline equipment in Hall D with some important modifications. These include the use of a thin solid lead target, implementation of a new trigger using the time-of-flight counters, and the building of a muon detector downstream of the FCAL. The muon chambers are being fabricated, the new trigger is being studied and we are starting the design effort to install the muon detector onto the downstream platform.

VII. MEASURING THE NEUTRAL PION POLARIZABILITY

A. Introduction

Measurements of hadron polarizabilities provide an important test for effective field theories, dispersion theory, and lattice calculations. Among the hadron polarizabilities, the neutral pion polarizability ranks of paramount importance because it tests fundamental symmetries, in particular chiral symmetry, and its realization in QCD. Indeed, the non-trivial (non-perturbative) vacuum properties of QCD result in the phenomenon of spontaneous chiral symmetry breaking, giving rise to the Goldstone Boson nature of the pions. In particular, the Goldstone Boson nature of the π^0 manifests itself most notably in its decay into $\gamma\gamma$ and also in its electromagnetic polarizabilities, which according to ChPT can be predicted to leading order in the expansion in the quark masses.

Hadron polarizabilities are best measured in Compton scattering experiments where one looks for a deviation of the cross section from the prediction of Compton scattering from a structureless particle.

The short lifetime of the neutral pion requires an indirect study of low energy Compton scattering via measurements of the process $\gamma\gamma \to \pi^0\pi^0$, a method that can also be applied to the charged pion (CPP) and for which a proposal in Hall D is already approved [40].

We are formulating a plan to make a precision measurement of the $\gamma\gamma^* \to \pi^0\pi^0$ cross section using the GlueX detector in Hall D. The measurement is based on the Primakoff effect which allows one to access the low $W_{\pi^0\pi^0}$ invariant mass regime with a small virtuality of the γ^* representing the Coulomb field of the target. The central aim of the measurement is to drastically improve the determination of the cross section in that domain, which is key for constraining the low energy Compton amplitude of the π^0 and thus for extracting its polarizability. At present, the only accurate measurements exist for invariant masses of the two π^0s above 0.7 GeV, way above the threshold 0.27 GeV. The existing data at low energy were obtained in $e^+e^- \to \pi^0\pi^0$ scattering in the early 1990's with the Crystal Ball detector at the DORIS-II storage ring at DESY [41].

Meanwhile, theory has made significant progress over time, with studies of higher chiral corrections [42]and also with the implementation of dispersion theory analyses which serve to make use of the higher energy data. It is expected that the experimental data from this proposal, together with those theoretical frameworks, will allow for the most accurate extraction of the π^0 polarizabilities to date.

B. Theoretical predictions for the neutral pion polarizability

In the case of the neutral pion, the polarizabilities are determined by the one loop chiral contributions which are calculable, free of unknown parameters, given only in terms of the fine structure constant, the pion mass and the pion decay constant:

$$\begin{aligned}\alpha_{\pi^0} + \beta_{\pi^0} &= 0 \\ \alpha_{\pi^0} - \beta_{\pi^0} &= -\frac{\alpha}{48\pi^2 M_\pi F_\pi^2} \simeq -1.1 \times 10^{-4}\ \text{fm}^3\end{aligned} \tag{1}$$

Accurate measurements of the cross section near threshold combined with data for $W_{\pi\pi} > 0.7$ GeV will provide the necessary input for performing a full theoretical analysis, combining dispersion theory[43] with and without inputs from ChPT at low energy. This is a well established method which has been used to analyze $\pi\pi$ scattering. Through such an analysis it will be possible to determine, via combination with ChPT, the low energy Compton amplitude and extract the polarizability combination $\alpha_\pi - \beta_\pi$.

C. Past Measurements

Past measurements of the $\gamma\gamma \to \pi^0\pi^0$ cross section can be summarized as follows:

1. In the early 1990's measurements were made in e^+e^- collisions at DESY with the XBall detector at the DORIS-II storage ring, which are the only available data for $W_{\pi\pi} < 0.6$ GeV[41].

2. In 2008-9, measurements were carried out by BELLE for 0.6 GeV $< W_{\pi\pi} <$ 4.0 GeV [44].

D. Experimental conditions

The measurement of the neutral pion polarizability is expected to run concurrently with the experiment to measure the charged pion polarizability (CPP) [40] in Hall D. Essentially all the optimizations for that experiment are expected to improve the sensitivity of this experiment also. We briefly summarize the configuration for CPP.

The diamond radiator will be adjusted to set the coherent peak of the photon beam between 5.5 and 6 GeV. This enhances the polarization significantly and also the tagging ratio. The experimental target will be placed upstream of the nominal GlueX target by 64 cm (z=1 cm in the Hall D coordinate system). These changes benefit the present experiment. In addition, the CPP experiment will add multi-wire proportional chambers downstream for muon identification, but these do not impact this measurement one way or another.

E. Expected signal

In order to estimate rates, resolution and acceptance due to the Primakoff reaction on lead, $\gamma^{208}\text{Pb} \to \pi^0\pi^0\,\text{Pb}$, we take the reaction process to be the same as for charged pion production and given in Eq. 8 of the Proposal for the Charged Pion Polarizability experiment [40], where the $\gamma\gamma$ cross section for charged pions has been substituted with the cross section for neutral pions.

The cross section for $\sigma(\gamma\gamma \to \pi^0\pi^0)$ has been measured by the Crystal Ball Collaboration [41], albeit with limited statistical precision. We have parametrized the cross section for $W_{\pi\pi} < 0.8$ GeV. We can then estimate cross section on lead. The integrated cross section is $0.35\,\mu$b/nucleus.

The Primakoff signal was generated according to the cross section described above. One hundred thousand events were generated with $M_{\pi\pi}$ <0.5 GeV and with no background. They were passed through a full detector simulation and then reconstructed and analyzed using standard GlueX software.

F. Sensitivity

We expect to collect approximately 3000 events during the approved 20 PAC days of the CPP experiment and the anticipated statistical uncertainties on the signal are quite small. The effort to understand the backgrounds and extract a clean signal is ongoing.

Calculations by Dai and Pennington[45] indicate that a 1.3% determination of $\sigma(\gamma\gamma \to \pi^0\pi^0)$ will determine the combination of $\alpha_{\pi^0} - \beta_{\pi^0}$ to a precision of 10%. Initial estimates give a measurement of this never-before-measured quantity to 30 to 40%.

VIII. PHOTOPRODUCTION ON NUCLEAR TARGETS

Several LOIs and proposals discussing the use of nuclear targets in GlueX have been presented to PACS 43, 45 and 46 [46],[47].

A. Introduction

We propose to extend the main GlueX Spectroscopy program to study photoproduction on nuclear targets with the GlueX detector. Several physics topics have been considered so far:

- Photoproduction of light vector mesons using a set of nuclear targets: ^{12}C, ^{28}Si, ^{120}Sn, and ^{208}Pb in a wide beam energy range from 6 GeV to 12 GeV [46]
- Primakoff production of $\eta\prime$ mesons
- Color transparency [47]
- Short range Correlations

a. Photoproduction of light vector mesons In the proposed experiment we will extract the nuclear transparency ($A_{eff} = \frac{\sigma_A}{\sigma_N}$, where σ_A and σ_N are production cross sections on nuclei and free nucleon, respectively) and the spin density matrix element (ρ^A_{00}) of light vector mesons. The primary goals of the experiment are:

- To study hadronic structure of the photon by measuring the dependence of the nuclear transparency on the beam energy
- To extract the ω-nucleon cross section ($\sigma_L(\omega_L N)$) of longitudinally polarized ω mesons for the first time

Decrease of the nuclear transparency with energy is predicted for both electroproduction and photoproduction [48, 49], and is related to the energy-dependent coherence length ($l_c = 2E_\gamma/m^2_V$), which characterizes the onset of nuclear shadowing (the propagation distance of a quark-antiquark fluctuation). This energy dependence was measured and confirmed in the electroproduction of ρ mesons [50]. However, the observed decrease of the nuclear transparency in photoproduction of π^0 mesons is smaller than theoretically predicted [51, 52]. The same discrepancy takes place in ρ meson photoproduction, where experimental data are scarce [53]. The GlueX beam energy range is well suited to study photon shadowing because the coherence lengths overlap with the sizes of nuclei. Nuclear transparencies of light mesons extracted from the GlueX data (with the precision of $\sim 5\%$) will also provide a sensitive probe to the degree of photon shadowing in nuclear matter. Measurement of nuclear transparency in the wide energy range is also important for understanding results from other experiments, specifically the abnormally large nuclear absorption of ω mesons recently measured by the CLAS experiment [54].

For particles with nonzero spin, such as vector mesons V (ρ, ω, ϕ), interactions with nucleons are represented by a set of polarization-dependent amplitudes and can result in different cross sections for transversely (σ_T) and longitudinally (σ_L) polarized vector mesons with nucleons. Indications that the interaction of a vector meson with a nucleon depends on the meson polarization have been known for many years, but there have been no direct extraction of σ_L so far. The meson-nucleon cross sections of longitudinally and transversely polarized mesons can be extracted by measuring the absorption of mesons in production off nuclei. The total cross section of longitudinally polarized ω mesons on a nucleon, $\sigma_L(\omega N)$, will be extracted from the two independent measurements of A_{eff} and ρ^A_{00} in the incoherent ω photoproduction [55]. These two different methods will provide a cross check of systematic uncertainties. The knowledge of $\sigma_L(\omega N)$ is important for many theoretical models. It will also provide important information for understanding the color transparency in the electroproduction of vector mesons.

b. Primakoff production of η′ mesons Measurement of the radiative decay with of $\eta\prime \to \gamma\gamma$ using the Primakoff effect will complement already approved Primakoff program in GlueX. A precision measurement of the $\eta\prime$ decay width will provide information for the determination of the $\eta - \eta\prime$ mixing angle and decay constants, which is important for studying QCD symmetries and symmetry breaking at low energy. So far, the decay width was measured in collider experiments, with the best precision of 6.9 % (the PDG fitted value has 3.2 % uncertainty). GlueX will perform the first measurement of the decay width using the Primakoff reaction in two decay channels $\eta\prime \to \gamma\gamma$ and $\eta' \to \pi^+\pi^-\eta(\gamma\gamma)$, with the estimated total uncertainties of $\sim 3.4\%$ and $\sim 4\%$, respectively.

c. Search for Color Transparency at large momentum transfer Color Transparency (CT) is a fundamental prediction of QCD based on the assumption that the hadron produced in exclusive reactions at high momentum transfer will have significantly less interactions with nuclei due to the reduced transverse size. Color transparency has not yet been observed for baryons. We propose to study Color Transparency using binary reactions $\gamma + p \to \pi^0 + p$, $\gamma + p \to \rho^0 + p$, etc. at large momentum transfers. Recent theoretical calculations for GlueX beam energies predict the impact of the CT on the experimentally measured nuclear transparency [56]. The GlueX spectrometer capabilities are enough to clearly separate the standard Glauber model from the onset of CT.

d. Study Short-Range-Correlations Short-Range Correlations (SRC) are brief fluctuations of two nucleons with high and opposite momenta, where each of them is higher than the Fermi momentum for the given nucleus, and the center of mass momentum is less than the corresponding Fermi momentum. Recent work have shown that SRC could have significant implications on the quark distributions in nuclei (EMC effect). Studying SRC in photoproduction has a complementary reaction mechanism (to electron and proton scattering), that was never studied before. A set of exclusive and semi exclusive measurements of SRC at Hall D would measure reactions of type $A(\gamma, X)$ and $A(\gamma, XN_{\text{recoil}})$. Here X stands for the leading meson or baryon, and N_{recoil} stands for a correlated recoil nucleon emitted in the case of photon-absorption on a nucleon that is part of a 2N-SRC pair. The use of a real photon beam also allows probing the neutron in the pairs by measuring a charged final state.

B. Run Conditions

Although, the run conditions for the proposed physics topics are rather different, some optimization of the conditions is possible in order to share the beam request time.

Photoproduction of light vector mesons will be studied using a wide beam energy range of 6-12 GeV and four nuclear targets, ^{12}C, ^{28}Si, ^{120}Sn, and ^{208}Pb. The experiment has to run at a relatively small luminosity in order to control accidental hits in the tagging detector and provide clean reconstruction of mesons. We propose to take data for 28 days, including 10 days on the lead target. Run conditions for the $\eta\prime$ experiment are rather similar. We propose to run about 60 days with a Carbon target; using heavier targets is currently being investigated. The relatively small cross sections of reactions proposed to study the color transparency and short range correlations will require to run the experiment at higher luminosity and perform reconstruction in a small beam energy range of 8-9 GeV because of the large fraction of accidental hits in the tagging detectors. The experiment is expected to run for 40 days and will use four light targets D, ^{4}He, ^{12}C, and ^{40}Ca.

C. Special Conditions

No modifications of the GlueX detector is required, except for installing nuclear targets.

D. Summary

Photoproduction on nuclear target will extend the physics potential of the GlueX experiment beyond the main spectroscopy program. Several physics topics to study photoproduction on nuclear targets are considered and will be organized to the GlueX physics program on nuclear targets.

IX. THE GERASIMOV-DRELL-HEARN SUM RULE

A. Introduction

The Gerasimov-Drell-Hearn (GDH) sum rule [57] is a fundamental relation of quantum field theory whose validity depends on the internal dynamical properties of the particle to which the sum rule is applied. It relates the anomalous magnetic moment κ of a particle to its helicity-dependent photoproduction cross sections:

$$I = \int_{\nu_0}^{\infty} \frac{\Delta\sigma(\nu)}{\nu} d\nu = \frac{4\pi^2 S \alpha \kappa^2}{M^2}, \tag{2}$$

where ν is the probing photon energy, ν_0 is the pion production threshold energy, S is the spin of the particle, M is its mass, and α the QED coupling. $\Delta\sigma \equiv \sigma_P - \sigma_A$, where σ_P and σ_A are the photoproduction cross sections for which the photon spin is parallel and antiparallel to the target particle spin, respectively. Eq. (2) reveals that the excitation spectrum of composite particles is related to their non-zero κ. A saturation of the sum rule beyond a given ν indicates the scale at which the object structure or mass scales become irrelevant. Thus, while resonances contribute most to the nucleon GDH sum, the high-energy part is equally important since it may reveal possible substructure or unknown structural process. Possible causes for a GDH sum rule violation are reviewed in [59]. The ones most considered are the existence of non-zero quark anomalous moments, the existence of a $J = 1$ pole of the nucleon Compton amplitude, and the chiral anomaly. All proposed mechanisms would manifest themselves at high-ν.

B. Experimental Overview

We summarize here a proposal to measure for the first time the high-ν behavior of the GDH integrand $\Delta\sigma/\nu$. The experiment would run in Hall D, using a FROST-type target and a polarized beam on an Aluminum radiator. The measurement would be on both protons and neutrons, to allow for an isospin analysis of their high-ν behavior. The high-ν domain is where the sum rule may fail. In fact, the unpolarized equivalent of the GDH integral converges neither for the proton nor for the neutron, a fact clear only from high-ν data ($\nu > 3$ GeV) greater than the present upper reach of 2.9 GeV for measurement of the GDH integrand. On its left panel, the red line marks the current highest $\sqrt{s}$ at which the GDH integrand $\Delta\sigma/\nu$ has been measured. There would be no sign of potential divergence for the unpolarized equivalent of the GDH sum rule, $\int(\sigma_P + \sigma_A)d\nu$, if its measurement had stopped at this limit. On the right panel, the magenta line indicates the highest $\sqrt{s}$ reachable in Hall D. It is clear that the persistent flat dependence of $\sigma_P + \sigma_A$ represents a convergence problem for the unpolarized sum.

The proposed measurement, up to $\nu = 12$ GeV, would allow to study the convergence property of the GDH sum rule. This depends on two conditions: A) the spin-dependent forward Compton amplitude $f_2(\nu)$ must vanish at large ν; and B) the imaginary part of $f_2(\nu)$ must decrease with ν faster than $\approx 1/\ln(\nu)$. With a possible violation of the sum rule interpreted in terms of quark compositeness (among other causes proposed for a putative violation), the proposed experiment would constrain quark compositeness at the TeV-level.

Regardless of the convergence and sum rule validity, the data will constrain our knowledge of diffractive QCD, whose phenomenology is unverified in the spin sector. To quote the review [61]: *"above the resonance region, one usually invokes Regge phenomenology to argue that the integral converges [...] However, these ideas have still to be tested experimentally. [...] the real photon is essentially absorbed by coherent processes, which require interactions among the constituents such as gluon exchange between two quarks. This behavior differs from DIS, which refers to incoherent scattering off the constituents."* As pointed out in [59], not even a model prediction is available for the magnitude of the $J = 1$ pole effect, due to our absence of knowledge of polarized diffractive QCD. In fact, results from fits of photoproduction data and of DIS data independently disagree with the Regge theory expectation for the sign of the Regge intercept driving the isovector part of

$\Delta\sigma$. The proposed experiment would clarify this problem. Given the success of Regge theory to describe unpolarized diffractive scattering data, this problem may well illustrate Bjorken's oft-quoted statement that *"Polarization data has often been the graveyard of fashionable theories. If theorists had their way, they might well ban such measurements altogether out of self-protection."* [62]

Analyzing $\Delta\sigma(\nu)$ using dispersion relation techniques will provide $f_2(\nu)$. This will further clarify the convergence property of the GDH sum rule, which depends on both the real and imaginary parts of f_2, and will test Chiral Effective Field Theory (χEFT). The latter is especially important since tests of χEFT with polarized observables by the JLab experimental program on low-Q^2 spin sum rule revealed that currently, χEFT has difficulties to consistently describes spin observables [63].

Furthermore, the experiment will provide a $Q^2 = 0$ baseline for Electron Ion Collider (EIC) studies [64]. This will be helpful in particular for the study of the transition between the DIS regime characterized by partonic degrees of freedom to the diffractive regime characterized by effective degrees of freedom such as the pomeron and the reggeon. Finally, the data will constraint the polarizability contribution to the muonic hydrogen hyperfine splitting.

We propose to focus primarily on measuring the yield difference $\Delta y(\nu) = N^+ - N^-$ (where $N^{+(-)}$ is the number of events in a bin ν for positive (negative) beam helicity), rather than the absolute $\Delta\sigma$. This eliminates uncertainties coming from normalization factors, such as polarimetry and acceptance, which are typically dominant in experiments measuring cross-sections. Furthermore, uncertainties from unpolarized contributions (target dilution) cancel in the Δy. Measuring $\Delta y(\nu)$ is sufficient to establish the convergence of the integral. As an example, supposing that $\Delta\sigma = a\nu^b$, the primary goal of the present experiment is to measure b, without need of an accurate measurement of a.

C. Special Conditions

The three main ingredients needed for measuring $\Delta y(\nu)$ are: A) a circularly polarized photon beam; B) a longitudinally polarized target; and C) a large solid-angle detector.

Highly circularly polarized photons can be generated using CEBAF's polarized electrons with an amorphous radiator. No beam polarimetry is needed since we are concerned about measuring a yield. It can nevertheless be measured at 5% level using the injector Mott polarimeter or the polarimeters in Hall A, B or C.

Two polarized target systems suited for the experiment exist at JLab: the HDice and the FROST systems. The proposed experiment is short and thus investing in the demanding HDice system is not needed. The FROST butanol target is best suited. The Target Group indicated its preference to build a dedicated Hall D FROST target rather than using that of Hall B. Their estimated building cost is $0.5M. Two months will be necessary to install the target in the hall and test it. No commissioning beam time is needed. To switch from the deuteron to proton data taking takes about half a day.

Hall D is the best suited hall at JLab to measure the total photoproduction cross-section thanks to its large solid angle and high luminosity. The standard Hall D detector package plus the Compton Calorimeter is assumed. It provides detection of neutral and charged particles over polar angles from 0.2° to 145° with a nearly complete azimuthal coverage. It can be compared to the 7° to 145° coverage of the LEGS detector at BNL and to the 1.6° to 174° coverage of the GDH-detector at ELSA.

The expected rates from butanol are 36 kHz or 40 kHz for proton and deuteron respectively,. This yields a useful proton rate of 5 kHz and a deuteron rates 10 kHz. The butanol rates are well below the current 60 kHz DAQ limit of Hall D. Hence, there will be no deadtime or other DAQ limitation.

If $\Delta\sigma$ obeys the presumed Regge behavior, the experiment would determine the relevant Regge intercepts at the level of 1 to 2%, to be compared to the 30 to 50% level at which they are presently known.

D. Summary

This will be enough to assess the convergence of the GDH sum rule. It will also clarify the problem that results from fits of photoproduction and DIS data disagree with the Regge theory expectation. In Regge theory, the high-energy behavior of the isovector and isoscalar cross-section differences are driven by the $a_1(1260)$ and $f_1(1285)$ Regge trajectories such that

$$\Delta\sigma^{(p-n)} \sim s^{\alpha_{a_1}-1}\,, \qquad \Delta\sigma^{(p+n)} \sim s^{\alpha_{f_1}-1}\,.$$

Photoproduction and DIS data fits both yield $\alpha_{a_1} \approx +0.45$, while the Regge expectation is $\alpha_{a_1} = 1-\alpha' m_{a_1}^2 \approx -0.34$, where $\alpha' = 1/(2\pi\sigma) \approx 0.88\,\mathrm{GeV}^{-2}$ and σ is the string tension, which is known to be approximately $0.18\,\mathrm{GeV}^2$. If α_{a_1} were indeed ≈ 0.45, this would imply a string tension more than twice as high as the commonly accepted value. The problem at the root of the discrepancy is partly that $a_1(1260)$ is the only $I^G(J^{PC}) = 1^-(1^{++})$ meson to form a "trajectory", while the second candidate, the $a_1(1640)$, has been omitted from the PDG Summary Tables as it still needs confirmation. A precise measurement of $\Delta\sigma$ at high ν for both proton and neutron targets would help to remove this uncertainty.

In all, three weeks of beam time are needed to reach these goals. Once a polarized target is available in Hall D, a rich experimental program will open [65]. It is sensible to initiate it with the simplest experiment and a robust observable.

X. AN N^* PROGRAM IN GLUEX

A. Introduction

For a better understanding of the interaction inside baryons, their excitation spectra need to be measured and results compared to constituent quark models [66] or lattice QCD calculations [67]. This comparison reveals a major difference between the theoretical models and the experimentally measured states: at higher masses, more resonances are predicted than have been measured so far. This is the *missing resonance* problem, and to tackle it, more measurements at higher masses and different final states are needed. A valuable contribution can be made by experiments using polarized photon beams, polarized targets and by measuring the recoil polarization, giving access to several different polarization observables [68, 69], and providing the opportunity to study weak resonance contributions.

In the easiest case, the photoproduction of a single pseudoscalar meson, 16 observables are accessible [68]. Depending on the selection of the beam polarization (linear or circular) and the target polarization (longitudinal or transverse), different observables can be accessed. If vector mesons or even multiple mesons are investigated, the number of measurable observables increases [69].

The excitation spectrum of the baryons has been investigated in the recent years by several different experiments, like the A2@MAMI [70], CBELSA/TAPS [71] and CLAS experiment [72]. A large data base has been acquired, including different reaction channels and photon energies up to 2.3 GeV.

- Single polarization observables (particularly photon beam asymmetry) have been measured with very good statistics for variety of channels.
- Double polarization observables have been measured with varying statistical precision - those with recoiling hyperons taking advantage of the self-analyzing property of the hyperons.
- Double polarization measurements based on polarized targets tend to have poor statistics.
- Channels requiring detection of neutrals in the final state are difficult or impossible to access.
- For linear polarization measurements the statistical precision becomes poorer as photon energy approaches 2 GeV due to lower beam polarization and less data.
- There are very few data points with $E_\gamma > 2$ GeV and previous measurements of observables at higher photon energies [74] included large error bars and only sparse data points.

Note. There is also strong current interest in the α_- weak decay constant, where there is disagreement with the *accepted* value and the recent measurement at BESIII [75]. GlueX would be able to make a definitive measurement of this as part of a baryon spectroscopy experiment.

B. Experimental conditions

a. GlueX detector The GlueX detector itself is ideal for this proposal: it can detect charged and neutral, multi-particle final states, and will have excellent K/Pi separation with the addition of the DIRC. The linearly polarized photon beam is already world leading and would provide very high (>80%) polarization in the range of interest. Additional requirements for this program would be:

b. Polarized Beams Both linearly and circularly polarized photons would be essential for this program. The introduction of a circularly polarized beams would also serve the GDH proposal. A Moeller polarimeter making use of the hodoscope counters (as in Mainz) might be an option.

c. Pair Polarimeter The triplet polarimeter (TPOL) does an excellent job, but at the lower rates required for this work the time for measurement would be long. The coherent peak will be close to the bottom end of the tagger, so using the CBSA will also be limiting from the point of systematics. We propose adding a pair polarimeter of the type currently being developed for Mainz [76], which would require the addition of a scattering foil in the pair spectrometer (PS) and Timepix3 pixel detectors (see below) between the beamline and the PS counter.

d. Polarized Target A longitudinally polarized target would be required and would be the same as needed for the GDH measurement (See section IX). This is likely to be a FROST type target. A transverse polarized target would also desireable - however, this is not practical with the GlueX setup.

e. Tagging The current Hodoscope / Microscope arrangement is such that high rate capability is only available in the 8-9 GeV range of the (fixed) Microscope, and in the lower photon energy range of interest the rate is limited by the hodoscope, which is only intended for *sampling* purposes. The ideal solution would be a travelling microscope, which could be positioned at any point along the focal plane to provide full coverage, high resolution and improved rate capability over a window covering the coherent peak. The Glasgow group is investigating the use of Timepix3 based modules (Section (see below) for this purpose, and will test these in Mainz over the next year.

f. CEBAF Energy It will be neccessary for most of this program to be scheduled at times where the CEBAF energy will be less than the standard 12 GeV. Ideally we would repeat some of the CLAS measurements to test consistency and improve statistical precision. The current lower tagging range is 25%, so to have the coherent edge as low as 2 GeV would require a CEBAF energy of about 6GeV. Clearly this would have to be scheduled well in advance, in agreement with other halls.

g. Timepix3 for polarimetry and microscopy The Timepix3 ASIC has been developed by the CERN-based, Medipix3 collaboration [78]. The Glasgow group is currently developing a modular detector and readout system based on the Timepix3 chip with a silicon sensor. It will be tested in the Mainz pair polarimeter project, where the position resolution ($< 50\mu$m in x and y) is the crucial feature, and on the tagger focal plane, where rate capibility is more important (40MHz / cm^2). This project is in collaboration the UK's Nuclear Physics Cross Community Support Group, who have wide ranging expertise in detector development, electronics, FPGA and DAQ. The same components could have potential for both tagging and polarimetry at GlueX and the UK groups will consider bidding for funds for this activty in the forthcoming Jlab2 upgrade project (The first UK Jlab Upgrade project was funded at a level of £1.5M [77].

C. Count Rate Estimate

- 1 GlueX hour $\sim$ 1 CLAS day (with current GlueX hodoscope)

The above approximation was made by taking numbers from the g8 run period at CLAS as a baseline, using the $\gamma p \to K\Lambda$ where detection of K^+p was required, and the missing pion reconstructed in the analysis. The coherent edge was at an energy of $E_\gamma = 2.1$ GeV resulting in photons with a mean polarization of about 60%. A total number of 6 days was spent at this setting, with the aim of having good statistical errors and good enough binning in W and $\cos(\theta_{cm})$ for PWA calculations [72]. The numbers used for the comparision are shown in the table below. GlueX rates are based on the current configuration, including the existing hodoscope. In both CLAS and GlueX cases, the limit was the rate capability of the hodoscope counters.

	CLAS	Gluex
Max Tagger Rate (MHz per 100MeV)	1	6
Mean degree of linear polarization	0.6	0.9
K^+p acceptance	0.5	1.0

A comparison of the GlueX to the CLAS quality was estimated based on the following equation:

$$\frac{GlueXquality}{CLASquality} = \frac{GlueXrate}{CLASrate} \cdot \frac{GlueXpol.^2}{CLASpol.^2} \cdot \frac{GlueXacceptance}{CLASacceptance} \approx 24$$

This means that an hour of data taking with the GlueX experiment, using the current detector and hodoscope, without any additions, would be equivalent to one day of data taking with the CLAS experiment. Within a few days, one could measure several peak settings to cover a large energy range - at least for our *benchmark* reaction: $\gamma p \to K\Lambda$.

a. Beamtime request The main limit in the above calculation is the present hodoscope. We have proposed the addition of a microscope (Timepix3 based or otherwise) to improve the coverage, resolution and rate capability. Improving the coverage alone would double the rate capability per MeV, and we conservatively assume another factor of 2 increase from the increased segmentation of a Microscope. This would give an improvement of a factor of $\sim$100 over CLAS, for our benchmark channel. Hence, to get equivalent quality to the 6 days of CLAS data shown, the production running would be 6/100 days $\sim$ 1.5 h! This does not take into account the overhead of setting up the coherent peak, measuring beam polarization, empty target running etc - nor does it consider the rate implications for having polarized proton and neutron targets, or the measurement of channels with lower cross-sections than our *benchmark*. For those reasons, we propose 1 day of beam time per coherent peak setting for linearly polarized photons, with equivalent for circulaly polarized photons. Ideally, both polarized photon and neutron targets will be available, and we propose the same amount of running with each. The numbers are summarised in the table below.

Note Detailed calculations need to be done to improve these estimates. Also, we anticipate that there will be the possibility to run some of the circularly polarized beamtimes in parallel with the GDH beamtime.

CEBAF Energy (GeV)	Target	Beam	Coh Edge Settings (GeV)	Total Days
6, 6, 10, 10, 10	p pol+	lin pol	2.0, 2.5, 3.0, 3.5, 4.0	5
6, 6, 10, 10, 10	p pol-	lin pol	2.0, 2.5, 3.0, 3.5, 4.0	5
6, 6, 10, 10, 10	p pol+	circ pol		5
6, 6, 10, 10, 10	p pol-	circ pol		5
6, 6, 10, 10, 10	^{12}C Foam	lin pol	2.0, 2.5, 3.0, 3.5, 4.0	2.5
6 or less	^{12}C Foam	lin pol		2.5
6, 6, 10, 10, 10	n pol+	lin pol	2.0, 2.5, 3.0, 3.5, 4.0	5
6, 6, 10, 10, 10	n pol-	lin pol	2.0, 2.5, 3.0, 3.5, 4.0	5
6 or less	n pol+	circ pol		5
6 or less	n pol-	circ pol		5
			Total	**45**

D. Summary

GlueX can be the perfect experiment to continue the baryon spectroscopy program at JLab. It would allow the measurement of many single and double polarization observables with high statistics for many different reaction channels, and can prove the high energy continuation of the previously taken data. Furthermore, it can access many channels with neutral final state particles which were not accessible with CLAS. The combination of high statistics, full angular coverage and polarization can make the GlueX experiment one of the leading contributors to the field of baryon spectroscopy.

XI. STRANGE HADRON SPECTROSCOPY WITH SECONDARY K_L BEAM

A. Introduction

There are many unresolved issues in hadron physics and 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.

B. Theoretical Motivation

The experiment [79] 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" [80]. 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.

C. 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 [79].

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.

D. Summary

The current KLF proposal has been tested in four international workshops with more than 100 talks given, supporting the KLF physics program [81–84]. 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.

XII. SUMMARY

In this white paper, we have identified between 1200 and 1400 PAC days of potential physics that coud be carried out in Hall D using portions of the GlueX appartus. In Table X we summarize the remaining approved beam time in Hall D. At the time of compiling this note, PrimEx is running, so some fraction of the approved 79 days will have been performed in the spring of 2019. We also note that the two large blocks of time approved for GlueX could potentially run concurrently. The initial approval fo E-13-003 was made prior to the identification of the DIRC as the forward kaon identification system in GlueX. It is expected that E12-12-002 will start running in fall of 2019.

Experiment	Name	Section	Approved Time (PAC Days)		
			Commissioning	Physics	Total
E12-10-011	PrimEx η	Section V	0	79	79
E12-12-002	Phase II GlueX: High Intensity & DIRC	Section II	20	200	220
E12-13-003	Phase II GlueX: High Intensity	Section II		200	200
E12-13-009	CPP	Section VI	5	20	25
E12-14-004	JEF	Section IV	0	0	0
Total			324 (524)		

TABLE X. *Approved beam time associated with experiments that have not yet run in Hall D. We note that PrimEx will have completed some part of its program by summer 2019. Also, the two approved GlueX times may be run concurrently.*

In addition to the approved experiments, several interesting physics programs that could run in Hall D. These are summarized in table XI. Two of these could likely run concurrently with approved experiments so no additional beam time is listed. The η' extension to PrimEx would likely need no additional modifications to the equipment in Hall D. The nuclear targets program would only require nuclear targets, but care would need to be taken to assess the potential radiation damage to the equipment, particularly the silicon photomultipliers used to read out the BCAL are damaged by neutron exposure. The GDH sum rule experiment would require a frozen-spin target built to fit in GlueX. The low-energy N^* program, requires that the accelerator run at reduced energy, where 6 GeV is cited. It also requires the polarized target as well as a new photon polarization monitoring detector. Finally, the K_L program requires substantial reworking of the Hall D beamline.

Experiment	Section	Anticipated Beam Time (PAC Days)
GlueX Spectroscopy Program	Section II	200
GlueX Spectroscopy Extensions	Section II	200
GlueX Charm	Section III	Concurrent with GlueX Spectroscopy
PrimEx $\eta\prime$ Extension	Section V	80
Neutral Pion Polarizability	Section VII	Concurrent with CPP
GlueX Nuclear Targets	Section VIII	128
GDH Sum Rule	Section IX	25
Low-energy N^* program	Section X	45
Strange Physics with K_L Beams	Section XI	200
Total		878

TABLE XI. *Possible physics programs that could run in Hall D using components of the GlueX detector or beamline.*

While many of these programs will require new equipment, aging may require replacement of some of the existing GlueX equipment during this time frame. Degradation in performance has been noted in several detectors since the first beam in 2014, and this situation will continue to be monitored by the GlueX Collaboration.

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