Letter of Intent for GlueX-III: A path to the luminosity frontier in Hall D

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Executive Summary

The physics program of the GlueX experiment in Hall D has expanded since the inception of the JLab 12 GeV upgrade. While the emphasis on light-quark meson spectroscopy remains, the program has been augmented by unique opportunities for high impact measurements in near-threshold charmonium production with sensitivity to hidden charm pentaquarks and the gluonic structure of the proton, rare $\eta^{(\prime)}$ decays with sensitivity to physics beyond the Standard Model and much more. GlueX has demonstrated the capability to collect a unique photoproduction data set to purse these diverse opportunities, in parallel, using a common data set collected with a general purpose detector to which targeted upgrades have been made to enable new measurements.

In this Letter of Intent, we convey our initial plan to submit a proposal to the PAC next year that details a path to increase the photon beam intensity at GlueX by a factor of three and significantly increase the sensitivity for rare processes with additional beamtime to maximize the scientific output from ongoing and potential future upgrades. In particular, the inner region of the forward calorimeter, closest to the beam axis, is currently being upgraded to a lead-tungstate calorimeter that will have superior acceptance, angular resolution and energy resolution to enable searches for rare η decays. It is scheduled to run for 100 PAC days in the next two years. A future proposal for 200 PAC days with the increased intensity, as described in this LOI, would provide at least a factor of five gain in statistical precision with the upgraded forward calorimeter, which is impractical to achieve with the current beam intensity.

The effects of the increased beam intensity on the GlueX detector was studied in 2023 when the collaboration collected an initial data set at the photon beam intensity described in this LOI. While many detector components were shown to operate well in the high-intensity environment, with some showing small reductions in efficiency, others will require upgrades to maintain data quality. These upgrades include increasing the granularity for portions of the tagger and time of flight detectors and improvements in the trigger to efficiently select the rare processes of interest.

In summary, we outline a selection of unique physics opportunities that can be pursued with additional running of the GlueX detector at three times the beam intensity of previous operations. Making this step in intensity will require targeted upgrades to detector elements that are currently operating at the maximum rate. As we prepare a proposal for a substantial beam time request and needed investment in hardware, we welcome feedback from the PAC on this plan to push to the luminosity frontier in Hall D.

I. MOTIVATION FOR PHOTOPRODUCTION AT THE LUMINOSITY FRONTIER

The initial phase of the GlueX experiment (E12-06-102 [1], referred to as GlueX-I) was completed in 2018, utilizing 120 PAC days to commission and operate the experiment with production running at beam photon rates [2] up to $\sim 2 \times 10^7$ γ/s in the coherent peak. While this proposal was sufficient to make a number of new photoproduction measurements, it was expected to be statistically limited in key hybrid search channels such as $\eta\pi$ and $\eta'\pi$. It also lacked adequate π/K separation to explore hybrids with hidden strangeness.

The second phase of the GlueX experiment (E12-12-002, referred to as GlueX-II) operates at $\sim 5 \times 10^7$ γ/s in the coherent peak and utilizes enhanced π/K separation provided by a DIRC Cherenkov detector [3]. This program began in 2020 and continued in 2023, utilizing 102 of the 220 approved PAC days. The Jefferson Lab Eta Factory (JEF) experiment was approved to run in parallel with GlueX-II for 100 PAC days with an upgraded lead-tungstate (PbWO4) forward calorimeter to search for rare decays of the $\eta^{(\prime)}$ meson [4, 5]. The PbWO4 calorimeter is currently being installed in Hall D and scheduled to be operational in July 2024 to continue the GlueX-II program through March 2025, as described in Table I. The status of these proposals was reviewed in the PAC48 Jeopardy review [6].

TABLE I. A summary of the completed and scheduled GlueX-II experiment.

Topic	Proposal Number	Approved	Completed (2020-2023)	Scheduled (2024-2025)
GlueX II with DIRC	E12-12-002	220	102	107
JEF	E12-12-002A	100	0	107
Total Unique	-	220	102	107

In this Letter of Intent we propose to enhance the GlueX physics program through an upgrade of the experiment to operate with tagged photon beam intensities at least three-times larger than currently approved experiments. The increased luminosity will significantly extend the physics program in the search for and study of rare processes in three critical domains:

- **Near-threshold charmonium photoproduction:** precision J/ψ measurements and unique capabilities for χ_{c1} and $\psi(2S)$

- **η and η' decays:** search for rare neutral decays in exclusive $\eta^{(\prime)}$ production made possible by a new PbWO4 calorimeter insert

- **Light-quark meson spectroscopy:** search for a *pattern* of mesons with exotic quantum numbers through the production of rare final states

Near-threshold charmonium photoproduction

Measurements of J/ψ photoproduction by GlueX [7, 8] and the J/ψ-007 experiment [9] probe the near-threshold region with unprecedented precision for the total and differential cross sections. These measurements are sensitive to the direct production of hidden charm pentaquarks, probe the $J/\psi-$proton interaction and provide new insights on the gluonic structure of the proton. The approved GlueX-II program will provide 4-5 times larger statistics for the J/ψ cross section measurement than the GlueX-I results shown in Fig. 1. A program to extend the current GlueX-II running with the addition of a Transition Radiation Detector for e/π separation would expand the opportunities in these e^+e^- final states as described in a separate Letter of Intent submitted to this PAC [10]. Combined with the increased intensity described in this LOI, this would be a unique program to study the J/ψ production mechanism, including polarization observables with linear photon beam polarization.

Beyond precision J/ψ studies, increased luminosity at GlueX would provide the opportunity to study near-threshold photoproduction of χ_{c1} and $\psi(2S)$ states. Theoretical predictions for the near-threshold production cross sections for these states are shown in Fig. 1 (left) with thresholds of 10.1 and 10.9 GeV, respectively [11]. The $\psi(2S)$ is complementary to the J/ψ in studying the system size and model dependence of the $\psi - p$ scattering to probe the gluonic content of the proton.

Preliminary results from the exclusive reaction $\gamma p \to J/\psi\gamma p$ shown in Fig. 1 (right) demonstrate the capability of GlueX to study threshold charmonium with non-vector quantum numbers such as the χ_c states. Such measurements would shed new light on the dynamics of charmonium production and provide a critical baseline for models of the production of more exotic charmonium systems such as the $X(3872)$, which could be studied with upgrade of the CEBAF energy to 17 or 22 GeV.

Studying the production of these states requires the highest electron beam energies currently available at JLab, making them uniquely accessible in Hall D with energies up to 12 GeV. The χ_{c1} can be detected through the $J/\psi\gamma, J/\psi \to e^+e^-$ decay mode with a branching fraction of 34.3% that is well matched to calorimeter coverage at GlueX, while the $\psi(2S)$ can be detected through the e^+e^- or $\pi\pi J/\psi(\to e^+e^-)$, decay modes with branching fractions of 0.79% and 3.18%. With the

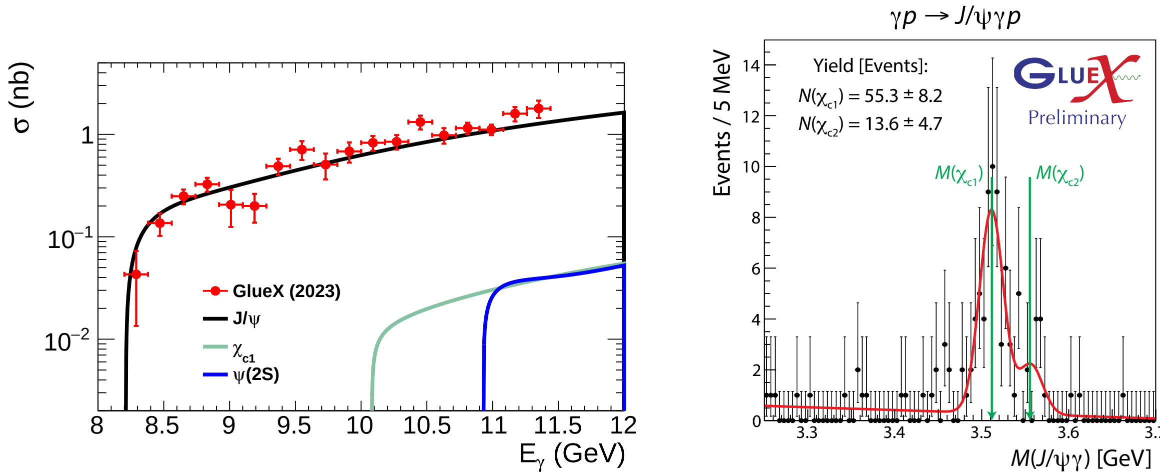

FIG. 1. (left) Near-threshold charmonium photoproduction cross sections as a function of photon beam energy from GlueX-I [8] and predictions from JPAC [11] where $E_\gamma > 11$ GeV is only accessible at GlueX with the existing CEBAF. (right) Preliminary results from all currently available GlueX data showing the capability to make a first measurement of the χ_{c1} photoproduction cross section.

GlueX I and II data, the χ_{c1} and $\psi(2S)$ measurements will be statistically limited by these low cross sections and small branching fractions, motivating additional running with higher intensities.

η and η' rare decays

The Jefferson Lab Eta Factory (JEF) experiment aims to explore rare decays of the $\eta^{(\prime)}$ meson through exclusive photoproduction, providing comparable statistical samples to other facilities worldwide. The high energy photon beam results in a significant Lorentz boost in the lab frame for the rare decay products to suppress backgrounds and optimally utilize the high precision PbWO4 calorimeter currently being installed in Hall D with GlueX, referred to as the FCAL 2. The $\eta^{(\prime)}$ meson, with the quantum numbers of the vacuum, provides a unique, flavor-conserving laboratory to probe the isospin-violating sector of low-energy QCD and to search for new physics Beyond the Standard Model (SM) [12].

One of the highlighted rare decays is the $\eta \to \pi^0\gamma\gamma$, which in the area of low-energy QCD provides a unique opportunity to study $\mathcal{O}(p^6)$ contributions in chiral perturbation theory [13] through a measurement of the $M_{\gamma\gamma}$ dependence of the decay width. The same decay also provides a search for gauge bosons coupling the SM to the dark sector. A leptophobic vector boson (B') [14] coupling to baryon number can be searched for via $\eta, \eta' \to B'\gamma \to \pi^0\gamma\gamma$ for $0.14 < m_{B'} < 0.62$

GeV and a hadrophilic [15, 16] scalar can be probed in $\eta \to \pi^0 S \to \pi^0\gamma\gamma$ for $m_S < 2m_\pi$.

Since the PAC approval of the JEF experiment, three significant developments impact the expected sensitivity of these measurements relative to the proposal:

- The η photoproduction cross section measured at GlueX is smaller than the estimate used in the proposal
- Recent measurements of $BR(\eta \to \pi^0\gamma\gamma)$ by the KLOE experiment [17] are a factor of two smaller than previous measurements
- The FCAL 2 insert was reduced in area from the originally proposed $1.18 \times 1.18\ m^2$ to $0.8 \times 0.8\ m^2$, limiting the fraction of neutral decays where the boosted photons are detected in the high resolution PbWO4 crystals.

While operational experience with the FCAL 2 detector in GlueX will not be obtained until 2024, the developments described above clearly demonstrate that additional beamtime will be required to meet the statistical precision of the original JEF proposal. This Letter of Intent describes an opportunity to improve the statistical precision for the JEF program by future operation at higher luminosities than originally proposed. The feasibility to study rare η decays strongly depends on the performance of the GlueX detector systems (such as the time of flight and FCAL 2) and background levels. Detailed studies will be performed to evaluate the impact of the detector material and performance of the detectors on the reconstruction of rare decays and to optimize the experimental conditions for JEF. A new type of trigger capable of operating at high intensity and accepting η decays into charged pions should be developed and studied in order to fully exploit the JEF physics program.

Light-quark hadron spectroscopy

The motivation for the exotic hadron spectroscopy program has continued to develop since the PAC approved the GlueX-II program. Observations of the $\eta\pi$ and $\eta'\pi$ final states using data from COMPASS [18, 19] and Crystal Barrel [20, 21] have definitely determined the resonance parameters of the lightest hybrid meson, the isovector $\pi_1(1600)$. While this has been the primary focus of light-quark hybrid studies for many years, a rich spectrum of both isovector and isoscalar exotics are predicted by lattice QCD which requires a much broader experimental search to complete the multiplet [22]. A first step in this direction was provided by the BESIII collaboration who recently reported the observation of an isoscalar exotic 1^{-+} known as the $\eta_1^{(\prime)}(1855)$ in radiative $J/\psi \to \gamma\eta\eta'$ decay [23] displayed in Fig. 3 (left). The interpretation of this state is still not fully understood, but it opens the path to experimentally observing the complete multiplet of exotic and conventional quantum number hybrid mesons.

The GlueX spectroscopy program provides data from polarized photoproduction to search for these exotic and conventional mesons through a complementary production mechanism to previous experiments. The statistical precision of the first phase of GlueX (GlueX-I) is shown in Fig. 2, where the charged and neutral $\eta\pi$ and $\eta'\pi$ yields are shown. Through a separate analysis of the $\omega\pi\pi$ system and predictions for the $\pi_1(1600)$ branching fractions from Lattice QCD [24], an upper limit was determined for the photoproduction of this state with the projection of that maximal possible contribution to these final states [25]. The statistical precision of the $\eta\pi$ and $\eta'\pi$ will clearly exceed the state of the art from COMPASS once the GlueX-II program is completed in 2025.

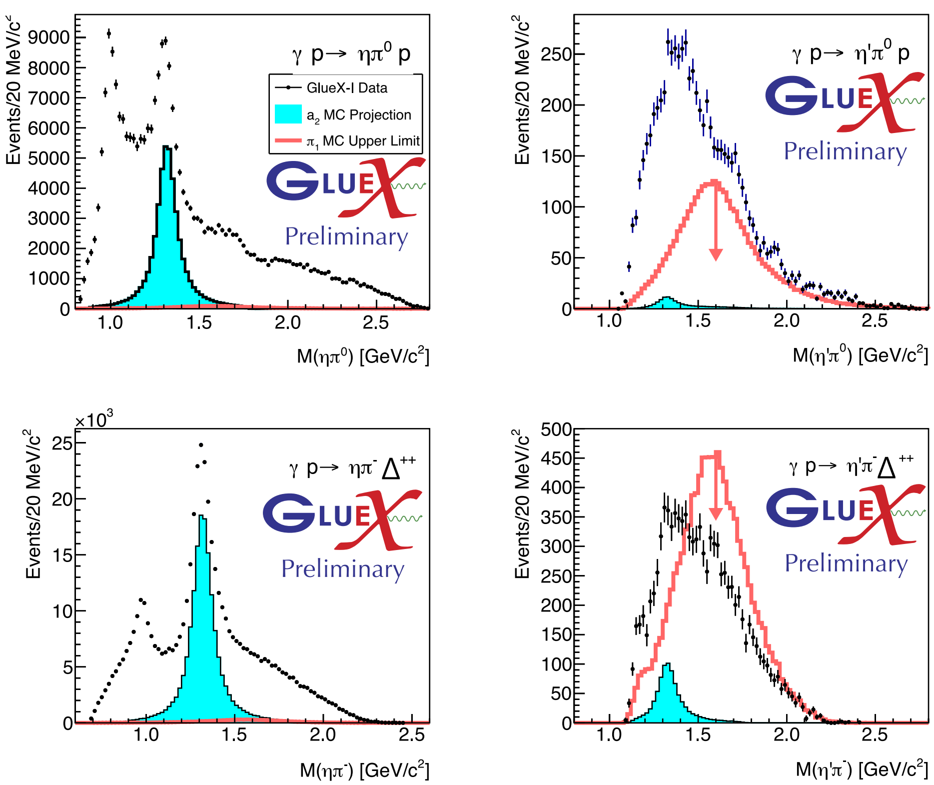

FIG. 2. GlueX-I data (points), $\sigma(a_2(1320))$ projection (blue), and π_1 upper limit projection (red) for $\eta\pi^0$ (top left), $\eta'\pi^0$ (top right), $\eta\pi^-$ (bottom left), and $\eta'\pi^-$ (bottom right).

To search for exotic mesons beyond the isovector $\pi_1(1600)$, even more rare final states should be studied. The ongoing GlueX-II program utilizes the improved kaon identification provided by the DIRC to search in final states with kaons [3], and three-body decays including kaons are expected to be the primary decay mode of the isoscalar exotic hybrid $\eta_1^{'}$. However, BESIII has observed an $\eta_1^{(')}(1855)$ candidate in the $\eta'\eta$ system (Fig. 3 (left)) and we are building experience in amplitude analysis of two-body decays such as $\eta\pi$ and $\eta'\pi$ that bolster interest in studying $\eta'\eta$ production at GlueX. Figure 3 shows the comparison of the $\eta'\eta$ mass distribution from BESIII and the GlueX-I data, which indicates this final state will be statistically limited even with an additional factor of ∼3-4 larger data set expected from GlueX-II. Therefore, additional beamtime with higher luminosity would provide the opportunity to more fully explore the production of these rare final states and other potential rare decays of conventional and exotic mesons.

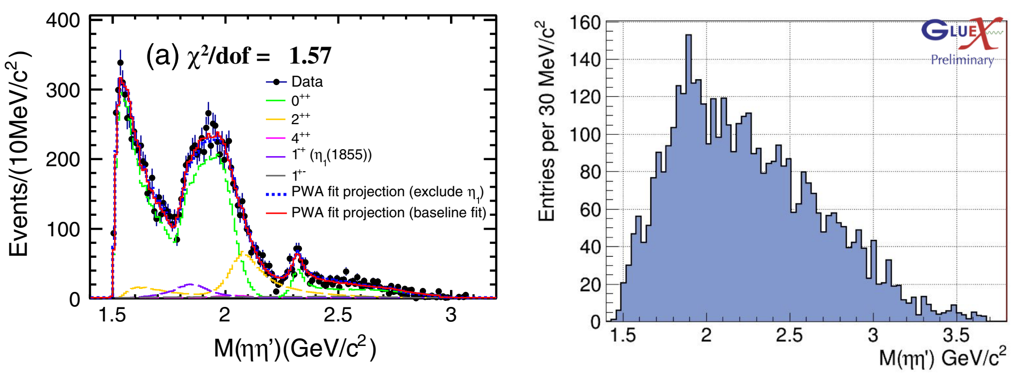

FIG. 3. BESIII $\eta'\eta$ mass distribution observed in $J/\psi \to \gamma\eta\eta'$ (left) and GlueX-I data for the same $\eta'\eta$ mass distribution in the reaction $\gamma p \to \eta\eta' p$. In the BESIII distribution the exotic η_1 from the fit result is shown by the purple dashed line and is distinguished by its contribution to the moments of angular distributions (see Ref. [23], Figure 3). The production mechanisms are quite different between J/ψ radiative decay and photoproduction, therefore it is not necessarily expected that the shapes of the distributions should be the same.

II. DETECTOR PERFORMANCE REQUIREMENTS FOR INCREASED LUMINOSITY

The GlueX detector [26] was originally designed to operate with a photon flux of 10^8 γ/s in the coherent peak, which is a factor of two larger luminosity than the current GlueX-II program operates. However, there are several subsystems which could be potential bottlenecks for increasing the luminosity for future experiments. To understand these potential limitations and study the detector performance with increased luminosity, the GlueX collaboration collected data up with a factor of 3 larger beam current to obtain a photon flux of 1.5×10^8 γ/s in the coherent peak over several days in February and March 2023.

Performance of existing hardware during high luminosity tests in 2023

Trigger and Data Acquisition

During nominal GlueX-II production the main physics trigger requires a minimum energy sum in a combination of the forward and barrel calorimeters, with the goal of a low-bias trigger on the energy deposited by multiple minimum ionizing particles. This rather-loose trigger condition results in an event rate of $\sim$ 100 kHz and a data rate of $\sim$ 1 GB/s, which is well within the capabilities of the existing data acquisition. The recorded event rate is currently limited by a small number of readout crates with high channel density like the DIRC.

To compensate for the increased luminosity proposed in this LOI, the trigger requirements must be more selective to identify the rare processes of interest. The simplest implementation of a more selective trigger would be to raise the thresholds on the energy sum in the calorimeters. A scan of the trigger thresholds required to operate at the proposed luminosity was performed in 2023. Figure 4 shows the correlation of summed energy in BCAL vs FCAL for the nominal GlueX-II trigger conditions (left) and conclusion of the thresholds scan (right) with the red line indicating the more restrictive requirement that achieves the desired rate reduction.

In reactions with multiple final state e^+, e^- or photons these thresholds may be sufficient to maintain an acceptable trigger efficiency, and this will be studied by emulating these thresholds with existing GlueX-II data. More sophisticated trigger requirements, such as the identification of high energy calorimeter clusters or additional correlations between detectors would likely require both hardware upgrades and algorithm development which is beyond the scope of this LOI, but will be considered to maximize the potential of this program.

Photon tagger

The photon tagger is composed of two subsystems, the Tagger Hodoscope (TAGH) and Tagger Microscope (TAGM). The TAGM instruments the photon beam energy region where the coherent bremsstrahlung is enhanced and photons have a large degree of linear polarization. The enhanced flux in this region requires a finely segmented array of scintillators read out through fibers and

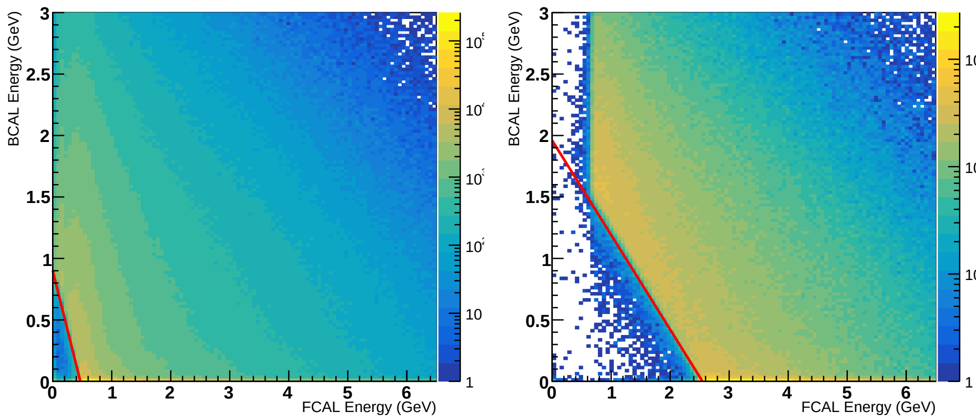

FIG. 4. Correlation of summed energy in BCAL vs FCAL, where the red line indicates the trigger requirement on the energy correlation between calorimeters. The nominal GlueX-II trigger condition is shown on the left, with a more restrictive trigger condition on the right that achieved the necessary rate reduction to operate at the proposed intensity.

SiPMs. This fine segmentation allowed the TAGM to operate successfully throughout the high luminosity tests with single channel rates up to several MHz. However, the occupancy is large enough at these rates that there are often multiple signal pulses within a readout window leading to pileup that will at a minimum require improvements to the FPGA algorithms used to identify signal hits.

The remainder of the photon beam energy is instrumented by the TAGH with traditional hodoscope scintillators readout by PMTs. The width of the scintillators is larger for these channels than the TAGM array, leading to rates of several MHz. To preserve the PMT lifetime these TAGH channels were turned off during the tests. To instrument the beam energy range of interest, $E_\gamma > 8$ GeV, it is likely that the TAGH would need to be upgraded to a finer segmentation to accommodate the observed rates.

Charged particle tracking

The detection and reconstruction of charged particles is provided by the Central and Forward Drift Chambers, CDC and FDC respectively, which are sensitive to the higher rates at the proposed luminosities. The FDC was able to maintain stable operation (i.e. low trip rate and stable current draw) at the highest beam current tested 900 nA, corresponding to a flux of 1.5×10^8 γ/s in the coherent peak. For the CDC the high voltages on wires near the beamline were required to be reduced by $\sim 4\%$ for stable operation. While this results in a reduction in the gain that degrades the dE/dx performance for particle identification, the efficiency for detecting a hit is only reduced by $\sim 1\%$ which negligibly impacts the track reconstruction efficiency.

A more significant impact on the track reconstruction is caused by increased rate of pileup tracks and beam-induced backgrounds, which challenge the track pattern recognition and fitting algorithms. During GlueX-I beam-induced backgrounds were mitigated by the addition of a thin Tungsten foil in the photon beamline to remove some low energy X-ray photons. In 2023, additional foils with varying X-ray absorption profiles were tested, but did not show a significant improvement over the existing Tungsten foil.

Particle identification

In the forward angular region of GlueX the time of flight and DIRC detectors provide charged hadron identification. The time of flight is a two-plane array of scintillator paddles readout by standard PMTs to provide ~ 100 ps timing for charged hadron identification. Although the paddles are narrow in the region around the beamline, the background from e^+e^- pair production in this region results in hits rates of many MHz rendering this region inoperable at the proposed photon beam intensities. Replacing the eight paddles in the region near the beamline for both planes with finer segmentation would provide the required rate capabilities. In addition, the proposed Transition Radiation Detector [10] for improved e/π separation in the charmonium program uses GEM technology, which is fully capable of operating at intensity proposed in this LOI.

Summary

Despite these challenges of the high rate environment for many subsystems, the standard reconstruction algorithms were used to analyze data collected at beam currents from 300 nA (current GlueX-II conditions) to 900 nA (intensity proposed in this LOI) to reconstruct the exclusive reactions $\gamma p \to \rho p, \rho \to \pi^+\pi^-$ and $\gamma p \to \omega p, \omega \to \pi^+\pi^-\pi^0$. The normalized yields of exclusive ρ and ω photoproduction are shown in Fig. 5 as a function of beam current, demonstrating the increased statistical precision that would be obtained with increased beam current. The $\sim 10-20\%$ reduction in reconstruction efficiency can be seen from the deviation between the linear extrapolated curves and measured yields at 900 nA. These preliminary studies demonstrate the ability for much of the

GlueX detector to operate at the photon beam intensity proposed in this LOI with a significant gain in statistical precision.

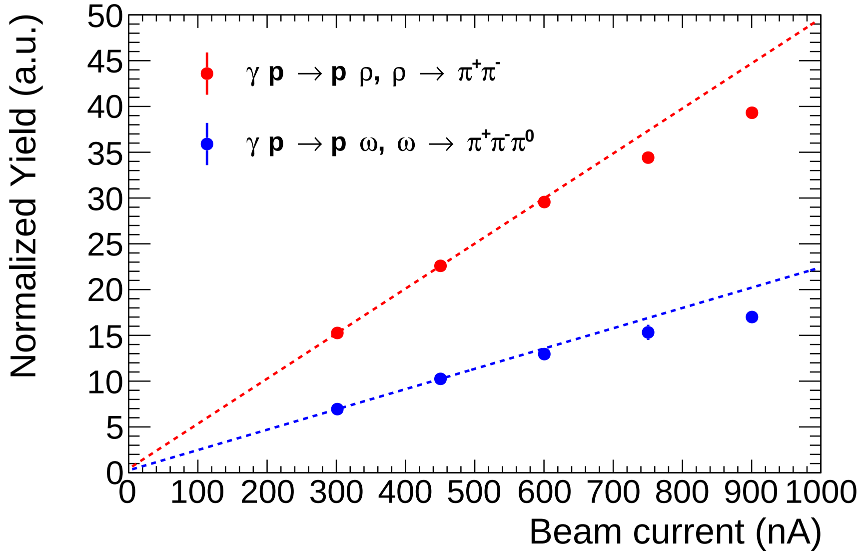

FIG. 5. Normalized yields of exclusive ρ and ω photoproduction for beam currents from 300 nA (current GlueX-II conditions) to 900 nA (intensity proposed in this LOI). The measured yields are divided by the photon flux and scaled by the beam current, demonstrating the gain in observed yield per unit time with increasing beam current. The dashed curves represent a linear extrapolation, showing a $\sim 10-20\%$ reduction in overall reconstruction efficiency at the highest beam currents.

Priorities for detector upgrades

From these studies we identify three clear priorities for detector upgrades required to operate with luminosities higher than the current GlueX-II conditions:

- Higher granularity tagger detectors over the full beam energy range of interest $E_\gamma > 8$ GeV will be required to replace the TAGH

- Higher granularity section of the time of flight detectors at forward angles will be required to replace portions of the current system

- Trigger optimization and potential upgrades required to maintain high efficiency for the rare processes described in this LOI

III. SUMMARY

We propose to study the unique opportunities and detector upgrades required to operate GlueX with three times the photon beam intensity from previous experiments. A selection of the diverse physics topics enabled by this program include near-threshold charmonium, rare $\eta^{(\prime)}$ decays and light-quark hadron spectroscopy. Preliminary studies from limited data collected in 2023 at the proposed photon beam intensity demonstrate that much of the detector is capable of operating under these conditions, and we have identified the targeted detector upgrades that will be required to operate at these rates. Further investigations are necessary to understand the impact of the trigger conditions required for the proposed intensity and potential backgrounds for identifying rare processes. We welcome feedback from the PAC on the physics program and hardware investment as we prepare a proposal for a substantial beam time request.

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