Excerpt from Jefferson Lab PAC 42 Proposal: "A study of decays to strange final states with GlueX in Hall D using components of the BaBar DIRC"

M. Dugger,[1] B. Ritchie,[1] I. Senderovich,[1] E. Anassontzis,[2] P. Ioannou,[2] C. Kourkoumeli,[2] G. Vasileiadis,[2] G. Voulgaris,[2] N. Jarvis,[3] W. Levine,[3] P. Mattione,[3] W. McGinley,[3] C. A. Meyer,[3] R. Schumacher,[3] M. Staib,[3] F. Klein,[4] D. Sober,[4] N. Sparks,[4] N. Walford,[4] D. Doughty,[5] A. Barnes,[6] R. Jones,[6] J. McIntyre,[6] F. Mokaya,[6] B. Pratt,[6] W. Boeglin,[7] L. Guo,[7] E. Pooser,[7] J. Reinhold,[7] H. Al Ghoul,[8] V. Crede,[8] P. Eugenio,[8] A. Ostrovidov,[8] A. Tsaris,[8] D. Ireland,[9] K. Livingston,[9] D. Bennett,[10] J. Bennett,[10] J. Frye,[10] M. Lara,[10] J. Leckey,[10] R. Mitchell,[10] K. Moriya,[10] M. R. Shepherd,[10] O. Chernyshov,[11] A. Dolgolenko,[11] A. Gerasimov,[11] V. Goryachev,[11] I. Larin,[11] V. Matveev,[11] V. Tarasov,[11] F. Barbosa,[12] E. Chudakov,[12] M. Dalton,[12] A. Deur,[12] J. Dudek,[12] H. Egiyan,[12] S. Furletov,[12] M. Ito,[12] D. Mack,[12] D. Lawrence,[12] M. McCaughan,[12] M. Pennington,[12] L. Pentchev,[12] Y. Qiang,[12] E. Smith,[12] A. Somov,[12] S. Taylor,[12] T. Whitlatch,[12] B. Zihlmann,[12] R. Miskimen,[13] B. Guegan,[14] J. Hardin,[14] J. Stevens,[14] M. Williams,[14] V. Berdnikov,[15] G. Nigmatkulov,[15] A. Ponosov,[15] D. Romanov,[15] S. Somov,[15] I. Tolstukhin,[15] C. Salgado,[16] P. Ambrozewicz,[17] A. Gasparian,[17] R. Pedroni,[17] T. Black,[18] L. Gan,[18] S. Dobbs,[19] K. Seth,[19] X. Ting,[19] A. Tomaradze,[19] T. Beattie,[20] G. Huber,[20] G. Lolos,[20] Z. Papandreou,[20] A. Semenov,[20] I. Semenova,[20] W. Brooks,[21] H. Hakobyan,[21] S. Kuleshov,[21] O. Soto,[21] A. Toro,[21] I. Vega,[21] N. Gevorgyan,[22] H. Hakobyan,[22] and V. Kakoyan[22]

(The GlueX Collaboration)

[1] *Arizona State University*
[2] *University of Athens*
[3] *Carnegie Mellon University*
[4] *Catholic University of America*
[5] *Christopher Newport University*
[6] *University of Connecticut*
[7] *Florida International University*
[8] *Florida State University*
[9] *University of Glasgow*
[10] *Indiana University*
[11] *ITEP Moscow*
[12] *Jefferson Lab*
[13] *University of Massachusetts Amherst*
[14] *Massachusetts Institute of Technology*
[15] *MEPhI*
[16] *Norfolk State University*
[17] *North Carolina A&T State*
[18] *University of North Carolina Wilmington*
[19] *Northwestern University*
[20] *University of Regina*
[21] *Santa Maria University*
[22] *Yerevan Physics Institute*

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We propose to enhance the kaon identification capabilities of the GlueX detector by constructing an FDIRC (Focusing Detection of Internally Reflected Cherenkov) detector utilizing the decommissioned BaBar DIRC components. The GlueX FDIRC would significantly enhance the GlueX physics program by allowing one to search for and study hybrid mesons decaying into kaon final states. Such systematic studies of kaon final states are essential for inferring the quark flavor content of hybrid and conventional mesons. The GlueX FDIRC would reuse one-third of the synthetic fused silica bars that were utilized in the BaBar DIRC. A new focussing photon camera, read out with large area photodetectors, would be developed. We propose operating the enhanced GlueX detector in Hall D for a total of 220 days at an average intensity of 5×10^7 γ/s, a program that was conditionally approved by PAC39.

I. PREAMBLE

In 2012, the GlueX Collaboration submitted a proposal to PAC39 titled "A study of meson and baryon decays to strange final states with GlueX in Hall D" [1]. The proposal requested 220 days of data taking with the GlueX detector operating at an intensity of 5×10^7 γ/s on target. A necessary component of the broad physics program put forth in this proposal was an upgrade to the

GlueX particle identification (PID) capability. At the time of the proposal, a design for an upgraded PID system had not been finalized. The PAC granted conditional approval stating in its summary document:

> GlueX is the flagship experiment in Hall D; the theoretical motivation for the proposed extension of running is very sound. However, the success of the experiment depends crucially on the final design of the kaon identification system. The PAC39 therefore recommends C2 conditional approval, contingent upon the final design of the particle ID system.

In 2013, the GlueX Collaboration returned to PAC40 with a proposal [2] demonstrating that some states with hidden and open strangeness were accessible with the baseline GlueX design, provided that the statistical precision of the data sample was sufficient. PAC40 approved an additional 200 days of running at 5×10^7 γ/s on target with an "A" scientific rating for this program. The PAC40 report noted:

> The PAC was impressed by the level of sophistication of the GlueX software and analysis which is essential for the achievement of a significant kaon and hyperon program even in the absence of dedicated hardware. Still the complete mapping of the spectrum of conventional and exotic hadrons will ultimately require the implementation of dedicated particle ID in the forward direction, extending the kaon identification capability to 10 GeV/c. The PAC therefore encourages the collaboration to move forward with the design of such system and aim at an early installation, if at all possible.

The 10 GeV/c momentum cutoff cited by the PAC was motivated by preliminary designs for a dual-radiator RICH discussed in our previous proposals rather than any specific physics requirement. Concurrently with our preparation for PAC40, it became apparent that there was an opportunity to utilize components of the BaBar DIRC detector[1]. In fall of 2013, a team of five members of the GlueX Collaboration visited SLAC to understand the condition of the DIRC components and details about their utilization. The conclusion of this visit was that there are no insurmountable technical challenges in utilizing the BaBar DIRC; the opportunity presents a unique and cost-effective solution to upgrade the PID capability of GlueX, providing a significant enhancement in our kaon identification capability.

[1] At the time of our original proposal the BaBar DIRC was to be used in Super$B$, a next-generation B-factory experiment. The cancellation of Super$B$ in late 2012 made the DIRC components available for reuse.

In December 2013, members of the collaboration submitted a detailed conceptual design for utilizing the DIRC to SLAC for consideration. As this was precisely the request of PAC39, a final design of the particle ID system, we present this design in the document that follows. The physics case remains largely the same from that presented in our PAC39 proposal [1] and is repeated in part here for completeness.

II. INTRODUCTION AND MOTIVATION

The GlueX experiment, currently under construction and scheduled to start running in Hall D at Jefferson Lab in 2015, will provide the data necessary to construct quantitative tests of non-perturbative QCD by studying the spectrum of light-quark mesons. The primary goal of the GlueX experiment is to search for and study the spectrum of so-called hybrid mesons that are formed by exciting the gluonic field that couples the quarks. QCD-based calculations predict the existence of hybrid meson states, including several that have exotic quantum numbers that cannot be formed from a simple quark/anti-quark pair. To achieve its goal, GlueX must systematically study all possible decay modes of conventional and hybrid mesons, including those with kaons. The addition of a Cherenkov-based particle identification system utilizing the BaBar DIRC (Detection of Internally Reflected Cherenkov) components will dramatically increase the number of potential hybrid decay modes that GlueX can access and will reduce the experimental backgrounds from misidentified particles in each mode. This enhanced capability will be crucial in order for the GlueX experiment to realize its full discovery potential.

In this section we motivate the GlueX experiment and discuss the importance of kaon identification in the context of the GlueX physics program. The subsequent section discusses the baseline GlueX design and run plan. Both of these sections are largely reproduced from Refs. [1, 2], documents that were developed jointly by the GlueX Collaboration.

A. The GlueX experiment

A long-standing goal of hadron physics has been to understand how the quark and gluonic degrees of freedom that are present in the fundamental QCD Lagrangian manifest themselves in the spectrum of hadrons. Of particular interest is how the gluon-gluon interactions might give rise to physical states with gluonic excitations. One class of such states is the hybrid meson, which can be naively thought of as a quark anti-quark pair coupled to a valence gluon ($q\bar{q}g$). Recent lattice QCD calculations [3] predict a rich spectrum of hybrid mesons. A subset of these hybrids has an exotic experimental signature: angular momentum (J), parity (P), and charge conjugation (C) that cannot be created from just a quark-antiquark pair. The primary goal of the GlueX experiment in Hall D is to search for and study these mesons.

Our understanding of how gluonic excitations manifest themselves within QCD is maturing thanks to recent results from lattice QCD. This numerical approach to QCD considers the theory on a finite, discrete grid of points in a manner that would become exact if the lattice spacing were taken to zero and the spatial extent of the calculation, *i.e.,* the "box size," was made large. In practice, rather fine spacings and large boxes are used so that the systematic effect of this approximation should be small. The main limitation of these calculations at present is the poor scaling of the numerical algorithms with decreasing quark mass. In practice most contemporary calculations use a range of artificially heavy light quarks and attempt to observe a trend as the light quark mass is reduced toward the physical value. Trial calculations at the physical quark mass have begun, and regular usage is anticipated within a few years.

The spectrum of eigenstates of QCD can be extracted from correlation functions of the type $\langle 0|\mathcal{O}_f(t)\mathcal{O}_i^\dagger(0)|0\rangle$, where the $\mathcal{O}^\dagger$ are composite QCD operators capable of interpolating a meson or baryon state from the vacuum. The time-evolution of the Euclidean correlator indicates the mass spectrum ($e^{-m_\mathfrak{n} t}$) and information about quark-gluon substructure can be inferred from matrix-elements $\langle \mathfrak{n}|\mathcal{O}^\dagger|0\rangle$. In a series of recent papers [4–7], the Hadron Spectrum Collaboration has explored the spectrum of mesons and baryons using a large basis of composite QCD interpolating fields, extracting a spectrum of states of determined $J^{P(C)}$, including states of high internal excitation.

As shown in Fig. 1, these calculations show a clear and detailed spectrum of exotic J^{PC} mesons, with a lightest 1^{-+} state lying a few hundred MeV below a 0^{+-} and two 2^{+-} states. Through analysis of the matrix elements $\langle \mathfrak{n}|\mathcal{O}^\dagger|0\rangle$ for a range of different quark-gluon constructions, $\mathcal{O}$, we can infer [3] that although the bulk of the non-exotic J^{PC} spectrum has the expected systematics of a $q\bar{q}$ bound state system, some states are only interpolated strongly by operators featuring non-trivial gluonic constructions. One may interpret these states as non-exotic hybrid mesons, and by combining them with the spectrum of exotics, it is possible to isolate the lightest hybrid supermultiplet of $(0,1,2)^{-+}$ and 1^{--} states at a mass roughly 1.3 GeV heavier than the ρ meson. The form of the operator that has the strongest overlap onto these states has an S-wave $q\bar{q}$ pair in a color octet configuration and an exotic gluonic field in a color octet with $J_g^{P_g C_g} = 1^{+-}$, a *chromomagnetic* configuration. The heavier $(0,2)^{+-}$ states, along with some positive parity non-exotic states, appear to correspond to a P-wave coupling of the $q\bar{q}$ pair to the same chromomagnetic gluonic excitation.

A similar calculation for isoscalar states uses both $u\bar{u} + d\bar{d}$ and $s\bar{s}$ constructions and is able to extract both the spectrum of states and also their hidden flavor mixing. (See Fig. 1.) The basic experimental pattern of significant mixing in the 0^{-+} and 1^{++} channels and small mixing elsewhere is reproduced, and for the first time, we are able to say something about the degree of mixing for exotic-J^{PC} states. In order to probe this mixing experimentally, it is essential to be able to reconstruct decays to both strange and non-strange final state hadrons.

B. The importance of kaon identification

The primary goal of the GlueX experiment is to conduct a definitive mapping of states in the light meson sector, with an emphasis on searching for exotic mesons. Ideally, we would like to produce the experimental analogue of the lattice QCD spectrum pictured in Fig. 1, enabling a direct test of our understanding of gluonic excitations in QCD. In order to achieve this, one must be able to reconstruct strange final states, as observing decay patterns of mesons has been one of the primary mechanisms of inferring quark flavor content. An example of this can be seen by examining the two lightest isoscalar 2^{++} mesons in the lattice QCD calculation in Fig. 1. The two states have nearly pure flavors, with only a small (11°) mixing in the $\ell\bar{\ell}$ and $s\bar{s}$ basis. A natural experimental assignment for these two states are the $f_2(1270)$ and the $f_2'(1525)$. An experimental study of the branching ratios shows that $\mathcal{B}(f_2(1270) \to KK)/\mathcal{B}(f_2(1270) \to \pi\pi) \approx 0.05$ and $\mathcal{B}(f_2'(1525) \to \pi\pi)/\mathcal{B}(f_2'(1525) \to KK) \approx 0.009$ [8], which support the prediction of an $f_2(1270)$ ($f_2'(1525)$) with a dominant $\ell\bar{\ell}$ ($s\bar{s}$) component. By studying both strange and non-strange decay modes of mesons, GlueX hopes to provide similarly valuable experimental data to aid in the interpretation of the hybrid spectrum.

1. *Exotic $s\bar{s}$ states*

While most experimental efforts to date have focused on the lightest isovector exotic meson, the $J^{PC} = 1^{-+}$ $\pi_1(1600)$, lattice QCD clearly predicts a rich spectrum of both isovector and isoscalar exotics, the latter of which may have mixed $\ell\bar{\ell}$ and $s\bar{s}$ flavor content. A compilation of the "ground state" exotic hybrids is listed in Table I, along with theoretical estimates for masses, widths, and key decay modes. It is expected that initial searches with the baseline GlueX hardware will target primarily the π_1 state. Searches for the η_1, h_0, and b_2 may be statistically challenging, depending on the masses of these states and the production cross sections. With increased statistics and kaon identification, the search scope can be broadened to include these heavier exotic states in addition to the $s\bar{s}$ states: η_1', h_0', and h_2'. The η_1' and h_2' are particularly interesting because some models predict these states to be relatively narrow, and that they should decay through well-established kaon resonances.

Observations of various π_1 states have been reported in the literature for over fifteen years, with some anal-

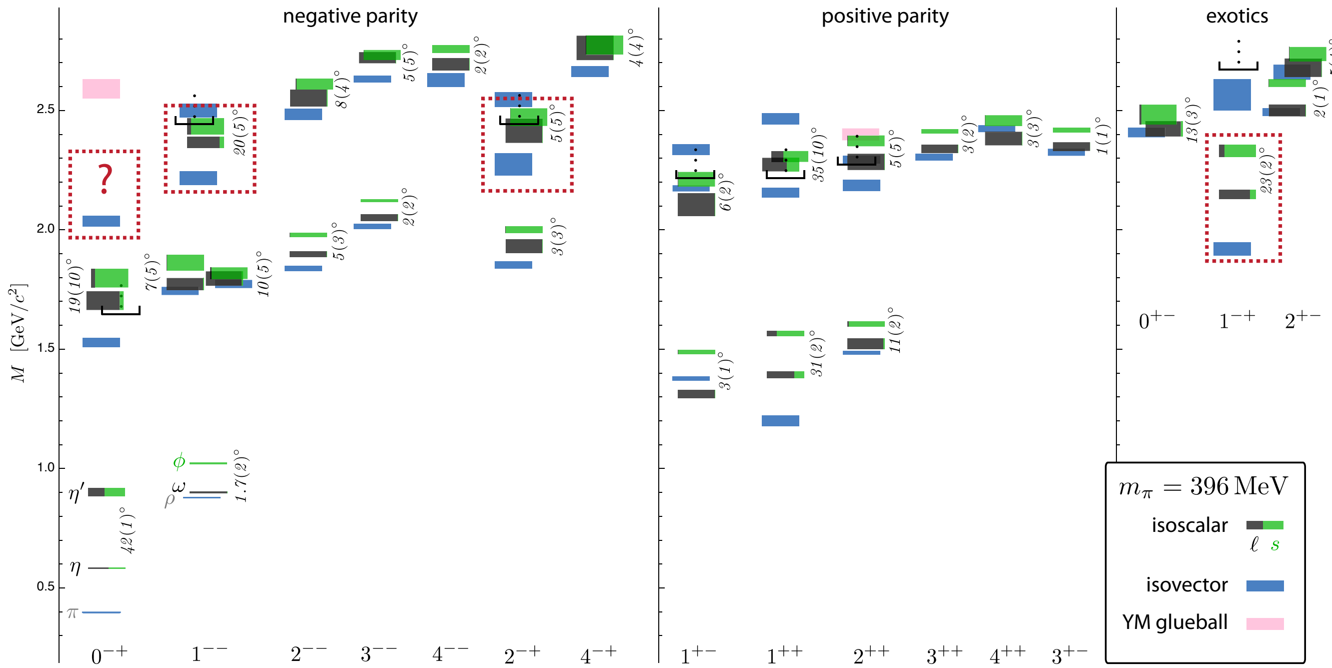

FIG. 1. A compilation of recent lattice QCD computations for both the isoscalar and isovector light mesons from Ref. [3], including $\ell\bar{\ell}$ $\left(|\ell\bar{\ell}\rangle \equiv (|u\bar{u}\rangle + |d\bar{d}\rangle)/\sqrt{2}\right)$ and $s\bar{s}$ mixing angles (indicated in degrees). The dynamical computation is carried out with two flavors of quarks, light (ℓ) and strange (s). The s quark mass parameter is tuned to match physical $s\bar{s}$ masses, while the light quark mass parameters are heavier, giving a pion mass of 396 MeV. The black brackets with upward ellipses represent regions of the spectrum where present techniques make it difficult to extract additional states. The dotted boxes indicate states that are interpreted as the lightest hybrid multiplet – the extraction of clear 0^{-+} states in this region is difficult in practice.

yses based on millions of events [9]. However, it is safe to say that there exists a fair amount of skepticism regarding the assertion that unambiguous experimental evidence exists for exotic hybrid mesons. If the scope of exotic searches with GlueX is narrowed to only include the lightest isovector π_1 state, the ability for GlueX to comprehensively address the question of the existence of gluonic excitations in QCD is greatly diminished. On the other hand, clear identification of all exotic members of the lightest hybrid multiplet, the three exotic $\pi_1^{\pm,0}$ states and the exotic η_1 and η_1', which can only be done by systematically studying a large number of strange and non-strange decay modes, would provide unambiguous experimental confirmation of exotic mesons. A study of decays to kaon final states could demonstrate that the η_1 candidate is dominantly $\ell\bar{\ell}$ while the η_1' candidate is $s\bar{s}$, as predicted by initial lattice QCD calculations. Such a discovery would represent a substantial improvement in the experimental understanding of exotics. In addition, further identification of members of the 0^{+-} and 2^{+-} nonets as well as measuring the mass splittings with the 1^{+-} states will validate the lattice QCD inspired phenomenological picture of these states as P-wave couplings of a gluonic field with a color-octet $q\bar{q}$ system.

2. *Non-exotic $s\bar{s}$ mesons*

As discussed above, one expects the lowest-mass hybrid multiplet to contain $(0,1,2)^{-+}$ states and a 1^{--} state that all have about the same mass and correspond to an S-wave $q\bar{q}$ pair coupling to the gluonic field in a P-wave. For each J^{PC} we expect an isovector triplet and a pair of isoscalar states in the spectrum. Of the four sets of J^{PC} values for the lightest hybrids, only the 1^{-+} is exotic. The other hybrid states will appear as supernumerary states in the spectrum of conventional mesons. The ability to clearly identify these states depends on having a thorough and complete understanding of the meson spectrum. Like searching for exotics, a complete mapping of the spectrum of non-exotic mesons requires the ability to systematically study many strange and non-strange final states. Other experiments, such as BESIII or COMPASS, are carefully studying this with very high statistics data samples and have outstanding capability to cleanly study any possible final state. While the production mechanism of GlueX is complementary to that of charmonium decay or pion beam production and is thought to enhance hybrid production, it is essential that the detector capability and statistical precision of the data set be competitive with other contemporary

TABLE I. A compilation of exotic quantum number hybrid approximate masses, widths, and decay predictions. Masses are estimated from dynamical LQCD calculations with $M_\pi = 396$ MeV/c^2 [3]. The PSS (Page, Swanson and Szczepaniak) and IKP (Isgur, Kokoski and Paton) model widths are from Ref. [22], with the IKP calculation based on the model in Ref. [23]. The total widths have a mass dependence, and Ref. [22] uses somewhat different mass values than suggested by the most recent lattice calculations [3]. Those final states marked with a dagger (†) are ideal for experimental exploration because there are relatively few stable particles in the final state or moderately narrow intermediate resonances that may reduce combinatoric background. (We consider η, η', and ω to be stable final state particles.)

	Approximate Mass (MeV)	J^{PC}	Total Width (MeV) PSS	IKP	Relevant Decays	Final States
π_1	1900	1^{-+}	$80-170$	120	$b_1\pi^\dagger$, $\rho\pi^\dagger$, $f_1\pi^\dagger$, $a_1\eta$, $\eta'\pi^\dagger$	$\omega\pi\pi^\dagger$, $3\pi^\dagger$, 5π, $\eta 3\pi^\dagger$, $\eta'\pi^\dagger$
η_1	2100	1^{-+}	$60-160$	110	$a_1\pi$, $f_1\eta^\dagger$, $\pi(1300)\pi$	4π, $\eta 4\pi$, $\eta\eta\pi\pi^\dagger$
η_1'	2300	1^{-+}	$100-220$	170	$K_1(1400)K^\dagger$, $K_1(1270)K^\dagger$, $K^*K^\dagger$	$KK\pi\pi^\dagger$, $KK\pi^\dagger$, $KK\omega^\dagger$
b_0	2400	0^{+-}	$250-430$	670	$\pi(1300)\pi$, $h_1\pi$	4π
h_0	2400	0^{+-}	$60-260$	90	$b_1\pi^\dagger$, $h_1\eta$, $K(1460)K$	$\omega\pi\pi^\dagger$, $\eta 3\pi$, $KK\pi\pi$
h_0'	2500	0^{+-}	$260-490$	430	$K(1460)K$, $K_1(1270)K^\dagger$, $h_1\eta$	$KK\pi\pi^\dagger$, $\eta 3\pi$
b_2	2500	2^{+-}	10	250	$a_2\pi^\dagger$, $a_1\pi$, $h_1\pi$	4π, $\eta\pi\pi^\dagger$
h_2	2500	2^{+-}	10	170	$b_1\pi^\dagger$, $\rho\pi^\dagger$	$\omega\pi\pi^\dagger$, $3\pi^\dagger$
h_2'	2600	2^{+-}	$10-20$	80	$K_1(1400)K^\dagger$, $K_1(1270)K^\dagger$, $K_2^*K^\dagger$	$KK\pi\pi^\dagger$, $KK\pi^\dagger$

experiments in order to maximize the collective experimental knowledge of the meson spectrum.

Given the numerous discoveries of unexpected, apparently non-$q\bar{q}$ states in the charmonium spectrum, a state that has attracted a lot of attention in the $s\bar{s}$ spectrum is the $Y(2175)$, which is assumed to be an $s\bar{s}$ vector meson (1^{--}). The $Y(2175)$ (also denoted as $\phi(2170)$) has been observed to decay to $\pi\pi\phi$ and has been produced in both J/ψ decays [10] and e^+e^- collisions [11, 12]. The state is a proposed analogue of the $Y(4260)$ in charmonium, a state that is also about 1.2 GeV heavier than the ground state triplet (J/ψ) and has a similar decay mode: $Y(4260) \to \pi\pi J/\psi$ [13–16]. The $Y(4260)$ has no obvious interpretation in the charmonium spectrum and has been speculated to be a hybrid meson [17–20], which, by loose analogy, leads to the implication that the $Y(2175)$ might also be a hybrid candidate. It should be noted that the spectrum of 1^{--} $s\bar{s}$ mesons is not as well-defined experimentally as the $c\bar{c}$ system; therefore, it is not clear that the $Y(2175)$ is a supernumerary state. However, GlueX is ideally suited to study this system. We know that vector mesons are copiously produced in photoproduction; therefore, with the ability to identify kaons, a precision study of the 1^{--} $s\bar{s}$ spectrum can be conducted with GlueX. Some have predicted [21] that the potential hybrid nature of the $Y(2175)$ can be explored by studying ratios of branching fractions into various kaonic final states. In addition, should GlueX be able to conclude that the $Y(2175)$ is in fact a supernumerary vector meson, then a search can be made for the exotic 1^{-+} $s\bar{s}$ member of the multiplet (η_1'), evidence of which would provide a definitive interpretation of the $Y(2175)$ and likely have implications on how one interprets charmonium data.

III. EXPECTED FDIRC PERFORMANCE

A. Strangeness reactions of interest

As described in section II B, to fully explore the spectrum of hybrid mesons, a systematic study of many hadronic final states is necessary, including those with kaons. The hybrid mesons with exotic quantum-number states that decay to kaons include the η_1', h_0', the h_2', which are all expected to couple to the $KK\pi\pi$ final state, while both the η_1' and the h_2' are expected to couple to the $KK\pi$ final state. To study the GlueX sensitivity to these two final states, we have modeled two decay chains. For the $KK\pi$ state, we assume one of the kaons is a K_S, which leads to a secondary vertex and the $K^+\pi^-\pi^+\pi^-$ final state:

$$\begin{aligned}\eta_1'(2300) &\to K^*K_S \\ &\to (K^+\pi^-)(\pi^+\pi^-) \\ &\to K^+\pi^-\pi^+\pi^-. \end{aligned} \quad (1)$$

For the $KK\pi\pi$ state we assume no secondary vertex:

$$\begin{aligned}h_2'(2600) &\to K_1^+K^- \\ &\to (K^*(892)\pi^+)K^- \\ &\to K^+K^-\pi^-\pi^+. \end{aligned} \quad (2)$$

In addition to the exotic hybrid channels, there is an interest in non-exotic $s\bar{s}$ mesons. In order to study the sensitivity to conventional $s\bar{s}$ states, we consider an excitation of the normal ϕ meson, the known $\phi_3(1850)$, which decays to $K\bar{K}$

$$\phi_3(1850) \to K^+K^- . \quad (3)$$

The detection efficiency of this state will be typical of ϕ-like states decaying to the same final state. Finally, as noted in Section II B, the $Y(2175)$ state is viewed as a potential candidate for a non-exotic hybrid and has been reported in the decay mode

$$Y(2175) \to \phi f_0(980) \to (K^+K^-)(\pi^+\pi^-)\,. \quad (4)$$

While this is the same $KK\pi\pi$ state noted in reaction 2 above, the intermediate resonances make the kinematics of the final state particles different from the exotic decay channel noted above. Therefore, we simulate it explicitly. The final-state kaons from the reactions 1 - 4 will populate the GlueX detector differently, with different overlap of the region where the time-of-flight system can provide good K/π separation.

The remainder of this section describes a study of the sensitivity of the baseline GlueX detector to these reactions of interest involving kaons (Sec. III A 1), and the expected increase in sensitivity with the proposed FDIRC detector in GlueX (Sec. III A 3). The studies were performed using a larger scale PYTHIA simulation of γp collisions processed through a complete GEANT model of the baseline GlueX detector and fully reconstructed with the GlueX analysis software. Signal samples were obtained from PYTHIA events with the generated reaction topology, and the remainder of the inclusive photoproduction reactions were used as the background sample. Since many of the cross sections of interest are unknown we use PYTHIA to predict the size of signal topologies of interest.

1. *Performance of the baseline* GlueX *detector*

The baseline GlueX detector does not contain any single detector element that is capable of providing discrimination of kaons from pions over the full-momentum range of interest for many key reactions. However, the hermetic GlueX detector is capable of exclusively reconstructing all particles in the final state. In the case where the recoil nucleon is a proton that is detectable by the tracking chamber, this exclusive reconstruction becomes a particularly powerful tool for particle identification because conservation of four-momentum can be checked, via a kinematic fit, for various mass hypotheses for the final state particles. Many other detector quantities also give an indication of the particle mass, as assumptions about particle mass (pion or kaon) affect interpretation of raw detector information.

An incomplete list of potentially discriminating quantities include:

- The confidence level (CL) from kinematic fitting that the event is consistent with the desired final state.
- The CL(s) from kinematic fitting that the event is consistent with some other final states.
- The goodness of fit (χ^2) of the primary vertex fit.
- The goodness of fit (χ^2) of each individual track fit.
- The CL from the time-of-flight detector that a track is consistent with the particle mass.
- The CL from the energy loss (dE/dx) that a track is consistent with the particle type.
- The change in the goodness of fit ($\Delta\chi^2$) when a track is removed from the primary vertex fit.
- Isolation tests for tracks and the detected showers in the calorimeter system.
- The goodness of fit (χ^2) of possible secondary vertex fits.
- Flight-distance significance for particles such as K_S and Λ that lead to secondary vertices.
- The change in goodness of fit ($\Delta\chi^2$) when the decay products of a particle that produces a secondary vertex are removed from the primary vertex fit.

The exact way that these are utilized depends on the particular analysis, but it is generally better to try to utilize as many of these as possible in a collective manner, rather than simply placing strict criteria on any one of them. This means that we take advantage of correlations between variables in addition to the variables themselves. One method of assembling multiple correlated measurements into a single discrimination variable, which has been used in this study, is a boosted decision tree (BDT) [26]. Traditionally, analyses have classified candidates using a set of variables, such as a kinematic fit confidence level, charged-particle time of flight, energy loss (dE/dx), *etc.*, where cuts are placed on each of the input variables to enhance the signal. In a BDT analysis, however, cuts on individual variables are not used; instead, a single classifier is formed by combining the information from all of the input variables.

A BDT is a multivariate classifier which is trained on a sample of known signal and background events to select signal events while maximizing a given figure of merit. The event selection performance is validated using an independent data sample, called a validation sample, that was not used in the training. If the performance is found to be similar when using the training (where it is maximally biased) and validation (where it is unbiased) samples, then the BDT performance is predictable. Practically, the output of the BDT is a single number for each event that tends towards one for signal-like events but tends towards negative one for background-like events. Placing a requirement on the minimum value of this classifier, which incorporates all independent information input to the BDT, allows one to enhance the signal purity of a sample. For a pedagogical description of BDTs, see Ref. [27]. The BDT algorithms used are contained within ROOT in the TMVA package [28].

Here we only consider the case where the recoil proton is reconstructed. A missing recoil nucleon reduces the number of constraints in the kinematic fit, and, consequently, dramatically diminishes the capability of the fit to discriminate pions from kaons. One can build a BDT for the reaction of interest, and look at the efficiency of selecting true signal events as a function of the sample purity. These studies do not include the efficiency of reconstructing the tracks in the detector, but start at the point where a candidate event containing five charged tracks has been found. In all cases we set the requirement on the BDT classifier in order to obtain a fixed final sample purity. For example, a purity of 90% implies a background at the 10% level. Any exotic signal in the spectrum would likely need to be larger than this background to be robust. Therefore, with increased purity we have increased sensitivity to smaller signals, but also lower efficiency. In Table II we present the signal selection efficiencies (post reconstruction) for our four reactions of interest for the baseline GlueX detector and including a FDIRC detector in GlueX (more in Section III A 3). As noted earlier, these assume that the tracks have been reconstructed and do not include that efficiency. With the baseline GlueX detector, higher signal purities of 95% to 99%, which may be necessary to search for more rare final states, result in the signal efficiency dropping dramatically. This exposes the limit of what can be done with the baseline GlueX hardware.

2. *Limitations of existing kaon identification algorithms*

It is important to point out that the use of kinematic constraints to achieve kaon identification, without dedicated hardware, has limitations. By requiring that the recoil proton be reconstructed, we are unable to study charge exchange processes that have a recoil neutron. In addition, this requirement results in a loss of efficiency of 30%-50% for proton recoil topologies and biases the event selection to those that have high momentum transfer, which may make it challenging to conduct studies of the production mechanism. Our studies indicate that it will be difficult to attain very high purity samples with a multivariate analysis alone. In channels with large cross sections, the GlueX sensitivity will not be limited by acceptance or efficiency, but by the ability to suppress and parameterize backgrounds in the amplitude analysis; thus, we need high statistics and high purity. Finally, it is worth noting that our estimates of the kaon selection efficiency using kinematic constraints depends strongly on our ability to model the performance of the detector. Although we have constructed a complete simulation, the experience of the collaboration with comparable detector systems indicates that the simulated performance is often better than the actual performance in unforeseen ways.

3. *Performance with FDIRC detector in* GlueX

As described in the Technical Design Report [29], the single track particle identification of the FDIRC in GlueX is expected to provide 3σ K/π separation up to momentum of ≈ 4 GeV/c. This provides vital, independent information to the multivariate analysis that has a very high discrimination power. The FDIRC information is included in the BDT by converting the measured Cherenkov angle into a probability for each particle mass hypothesis (π, K, and p). We define a χ^2 for each particle mass hypothesis as

$$\chi_i^2 = \frac{\left(\theta_{C,i}^{exp} - \theta_C^{reco}\right)^2}{\sigma_{\theta_C}^2}, \tag{5}$$

where $\theta_{C,i}^{exp}$ is the expected Cherenkov angle for mass hypothesis i using the measured track momentum from the drift chambers, θ_C^{reco} is the "reconstructed" Cherenkov angle, and σ_{θ_C} is the Cherenkov angle resolution.

As we do not yet have a full FDIRC reconstruction algorithm, we use Eq. 5 as a proxy for the FDIRC performance. We use $\sigma_{\theta_C} = 2.5$ mrad for all tracks (this is an upper bound on the expected resolution; see Technical Design Report [29] for more details). The track momentum resolution is included in $\theta_{C,i}^{exp}$. The "reconstructed" Cherenkov angle is obtained by generating a random number from a Gaussian distribution whose mean is the expected Cherenkov and width is σ_{θ_C}. A confidence level for each particle mass hypothesis (π, K, p) is computed from Eqn. 5. These three values for each track are included in the BDT training, and the performance is evaluated in the same way as the baseline GlueX detector and shown in Table II. We note that, depending on the choice of readout, the FDIRC may provide an improvement in time-of-flight measurements for charged particles over our baseline design. Further study is needed to quantify this improvement; therefore, we neglect it in the studies presented below.

At 95% purity, the signal efficiencies are typically about twice as high including the FDIRC into GlueX. Reaching 99% purity is not possible for several of these channels without the FDIRC. It is important to stress here that the purity levels are defined as correctly identified final state candidates divided by all candidates. In the case that exotic contributions to some channel are at the percent level, extracting such signals will require reaching 99% purity, which helps ensure that the backgrounds are smaller than the small signal of interest. Without the FDIRC, this will not be possible for many channels of interest. Finally, as noted above, the baseline numbers are dependent on the reliability of the simulation. For example, the discrimination power of the kinematic fit confidence level will decrease drastically if the GlueX detector resolution is worse than expected. The simulation of the FDIRC performance is based only on the Cherenkov-angle resolution. The value of 2.5 mrad

TABLE II. Efficiencies for identifying several final states in GlueX excluding reconstruction of the final state tracks.

	$\eta_1'(2300) \to K^* K_S$		$h_2'(2600) \to K_1^+ K^-$		$\phi_3(1850) \to K^+ K^-$		$Y(2175) \to \phi f_0(980)$	
Purity	Baseline	FDIRC	Baseline	FDIRC	Baseline	FDIRC	Baseline	FDIRC
0.90	0.36	0.48	0.33	0.49	0.67	0.74	0.46	0.65
0.95	0.18	0.33	0.16	0.34	0.61	0.68	0.20	0.55
0.99	0.00	0.05	0.00	0.08	0.18	0.38	0.03	0.28

is expected to be achievable; thus, the real-world performance enhancement obtained by adding the FDIRC is likely to be even greater than what is shown in Table II.

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