The GLUEX JLab Eta Factory (JEF) Experiment at JLAB Hall D *

W.J. Briscoe

The George Washington University

The GLUEX Collaboration

The Thomas Jefferson National Accelerator Facility

Received October 26, 2024

The JEF program aims to perform precision measurements of various η and η' decays with emphasis on rare neutral decays. Since the production rates of η and η' are similar under the JEF experimental conditions, the same data set will offer sensitive probes for decay modes. Compared to existing and planned η/η' experiments worldwide, the unique feature of the JEF program is to offer a clean data set in the rare neutral decays of both η and η' with a significant reduction in background. The JEF data will offer significantly different systematics compared to other $\eta^{(\prime)}$ programs.

1. Introduction

The η meson provides a unique, flavor-conserving laboratory to probe the isospin-violating sector of low-energy QCD and search for physics beyond the Standard Model (BSM). Measurements of $\eta \to 3\pi$ has been running in parallel during the GlueX experiment to improve our understanding of the light-quark mass ratio. Our priorities in the JEF program are centered around neutral rare decays of the η following key signal channels:

- A search for a leptophobic dark boson B' coupled to baryon number is complementary to searches for a dark photon or invisible decay searches for dark sector particles.
- A low-background measurement of the rare decay $\eta \to \pi^0\gamma\gamma$ provides a clean window into $\mathcal{O}(p^6)$ in Chiral Perturbation Theory (ChPT). With sufficient precision in Dalitz distribution, we will be able to make a first model-independent determination of two $\mathcal{O}(p^6)$ Low Energy Constants (LEC) and to explore the role of scalar meson dynamics in ChPT.

* Presented at Workshop at 1GeV scale: from mesons to axions

- A search for the SM forbidden decay $\eta \to 3\gamma$ (as well as $\eta \to 2\pi^0\gamma$ and $\eta \to 3\pi^0\gamma$) lead to constraints on C violating, P conserving reactions: a largely unexplored area of fundamental symmetry tests [1].

2. Physics Interests

The Standard Model (SM) is successful in describing a range of phenomena in nuclear/particle physics, crowned with the discovery of the Higgs boson at CERN in 2012. However, there are strong indications that the SM is incomplete; the theory needs 19 input parameters and does not explain the origin of the three fermion families, nor why their masses are widely different. Furthermore, the SM fails to explain the dominance of matter over anti-matter in the universe or the dark matter relic density. Resolving these questions is a high priority.

Another interest is the understanding of the rich complexity of confinement QCD *e.g.* to confirm predictions for low-energy phenomenology such as the meson spectrum with explicit gluonic degrees of freedom, or to correct for strong re-scattering well enough to determine basic SM parameters such as $m_u - m_d$. A theoretical framework used to address these issues is Chiral Perturbation Theory (ChPT), based on the chiral symmetry of QCD in the massless quark limit. Tests of ChPT predictions and understanding its links to underlying QCD are important.

Decays of the neutral and long-lived η meson provide a unique, flavor-conserving, laboratory to probe the isospin violating sector of low-energy QCD and search for BSM physics. Spontaneously broken chiral symmetry in QCD gives birth to the η as a Goldstone Boson. The η is an eigenstate of P, C, CP, and G ($I^G J^{PC} = 0^+0^{-+}$) whose strong and electromagnetic decays are either anomalous or forbidden in lowest order due to P, C, CP, G-parity and angular momentum conservation [2]. This enhances the relative importance of higher-order contributions, making η decays a sensitive probe for searching for rare processes or testing discrete symmetries.

We will test low-energy QCD and search for new BSM physics in η decays using the high-energy photon tagging facility and the GlueX detector in Hall D at Jefferson Lab. Table 1 summarizes various η decays in the scope of this experiment. While data for SM-allowed decay channels have been accumulating since 2015, the upgraded Forward Calorimeter (FCAL-II) affords an improvement of about 1 to 2 orders of magnitude for rare or SM-forbidden channels leading to all-neutral final states.

3. Motivation for sub-GeV dark gauge boson

About 80% of matter in the Universe is Dark Matter (DM)—whose constituents and interactions are unknown other than for its gravitational

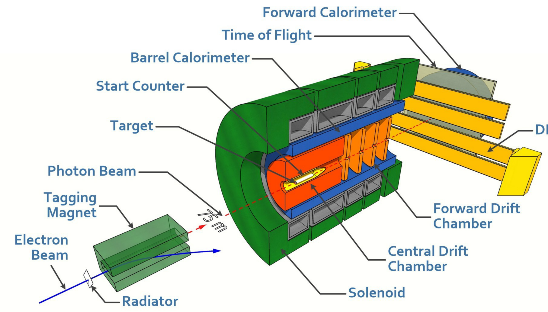
Mode	Branching Ratio	Physics Highlight	Photons
priority:			
$\gamma + B'$	beyond SM	leptophobic dark boson	4
$\pi^0 2\gamma$	$(2.7 \pm 0.5) \times 10^{-4}$	χPTh at $\mathcal{O}(p^6)$	4
$3\pi^0$	$(32.7 \pm 0.2)\%$	$m_u - m_d$	6
$\pi^+\pi^-\pi^0$	$(22.9 \pm 0.3)\%$	$m_u - m_d$, CV	2
3γ	$< 1.6 \times 10^{-5}$	CV, CPV	3
ancillary:			
4γ	$< 2.8 \times 10^{-4}$	$< 10^{-11}$[3]	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 1: The η decays to be studied by the JEF experiment, plus related ancillary channels [5]. The $\eta \to 2\gamma$ is being measured by the JLab Hall D Primakoff experiment (E12-10-011) and will be used for normalization.

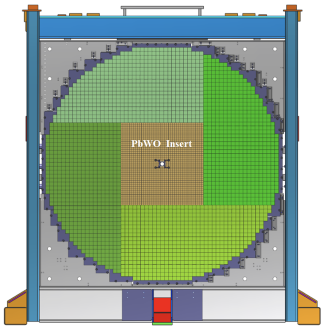
properties. The simplest model for dark matter is a stable Weakly Interacting Massive elementary Particle (WIMP). This has motivated a broad experimental program to detect non-gravitational DM interactions, including direct searches for DM-nucleus scattering, indirect searches for DM annihilation products, and accelerator-based searches for missing energy. Due to the absence of evidence for WIMPs at the LHC and direct detection experiments, there is a strong consensus among the physics community [6] about the vital importance of broadening the scope of searches, both in the dark sector parameter space and in experimental approaches. Particularly, fixed-target experiments at high intensity frontiers offer a complementary approach to DM detection, with superior sensitivity to the sub-GeV dark sector. The search for a sub-GeV leptophobic B'-boson is a top priority physics goal for JEF. It will be complementary to the searches based on the dark photon or the other leptophilic models.

4. Unique Features of JEF Experiment in η Decays

Compared to other η experiments, the unique features of JEF at JLab Fig.1a are: (1) highly-boosted η's produced by a $\sim$12 GeV tagged pho-



(a) A cut-away drawing of the GlueX detector in Hall D, not to scale.



(b) FCAL-II schematic.

Fig. 1: GlueX overview (left) and FCAL II schematic (right)

ton beam through the $\gamma p \to \eta p$ reaction; (2) η's are tagged by measuring recoil protons; and (3) the electromagnetic particles from η decays (γ, or e^+ and e^- in some cases) are measured by our state-of-the-art, high-resolution, FCAL-II calorimeter with a central insert of high-granularity Lead Tungstate (PWO) crystals. The decayed products from a highly-boosted η have relatively high energies, thus their detection will be significantly less sensitive to detector threshold effects compared to experiments where the η's have relatively low kinetic energies in the lab frame. The η decay particles in JEF will be mostly concentrated in the forward direction and be detected by FCAL-II. Using the existing Barrel CALorimeter (BCAL) as a veto will help to reject background channels for e.g. the $\eta \to \pi^0\gamma\gamma$ channel with more than four final-state photons (such as $\eta \to 3\pi^0$) migrating into signal channels with fewer final-state photons. The combination of these experimental techniques in JEF offer lower backgrounds for η rare decays, particularly for neutral decay modes, with up to a factor of about two orders of magnitude reduction in background compared to other existing or planned experiments. The result from JEF will provide a stringent constraint for B' in the mass range of 140–550 MeV through the $\eta \to \gamma B' \to \gamma\gamma\pi^0$ reaction. The GlueX apparatus, a solenoid magnet with tracking detectors and time-of-flight walls, offers excellent capability to detect charged particles, such as pions and electrons.

One can also search for new physics in complementary processes, such as searching for B' with a mass $m_B < m_\pi$ through $\eta \to \gamma B' \to \gamma e^+e^-$ since $B' \to e^+e^-$ will dominate in this mass region [7]. In the event of a discovery for $m_B < m_\pi$, one can distinguish the B' from the dark photon A' by studying ω decays: $\omega \to \pi^0 A'$ can occur while $\omega \to \pi^0 B'$ is highly suppressed by isospin conservation, according to Tulin [8]. A light pseudoscalar or scalar meson can also be probed through $\eta \to \pi^0 H \to \pi^0 e^+ e^-$ [9]. In addition, the same experimental data will also offer an opportunity to search for B' in the direct photo-production $\gamma p \to B' p$ process, as pointed out by C. Fanelli and M. Williams [10].

The projected η production rate for JEF is at the level of $\sim 6 \times 10^7$ per 100 days (assuming photon beam energy $E_\gamma > 8$ GeV). It will not be the highest η production rate compared to some other experiments, such as the REDTOP experiment. However, it will be competitive, particularly in the η neutral decay mode. The JEF experiment will run in parallel to the other experiments in Hall D using a hydrogen target. This offers the possibility to continuously accumulate data throughout the JLab 12 GeV era. In addition, the production rate for η' is about the same as η for the beam energy range planned for the JEF program. The same data set will allow studies of both η and η' decays in the same setting. The results from these comprehensive studies of η-η' sector will have a great potential to make a significant impact in our understanding of low energy QCD and new physics beyond SM.

5. Extension to η' physics

Multiple ongoing GlueX analyses have confirmed that photo-production rates for the η and η' are similar, suggesting that GlueX could become a competitive facility for η' studies. While BES-III has recently measured the non-resonant part of $\eta' -> \pi^0 2\gamma$ branching ratio (excluding $\eta' -> \omega\gamma$, with $\omega -> \pi^0\gamma$) [4], other rare but allowed, photon-rich decays of the η' have not to date been observed such as the $\eta 2\gamma$ and $4\pi^0$. [5] Although the acceptance in FCAL-II for photons from η' decays will be smaller than for the lighter η, FCAL-II will improve measurements of rare, photon-rich decays of the η' by reducing backgrounds from missing and combinatorial photons.

An η' physics program could search for the four-photon decay channels, $\pi^0 2\gamma$ and $\eta 2\gamma$. As in the case of $\eta \to \pi^0 2\gamma$, scalars are expected to make significant contributions in these decays [11]. The calculated branching ratios are near current experimental limits. A background that will be important due to missing photons is $\eta' \to \eta 2\pi^0$ (BR=22.3%)$\to 6\gamma$. The $\eta' \to 4\pi^0$ decay leading to 8 photons is not expected to be accessible in GlueX since one calculation estimates the branching ratio to be 4×10^{-8} [12]. Here the goal would be to lower the BR upper limit below the current 3.2×10^{-4} to test the prediction that this decay is indeed heavily D-wave suppressed (i.e., that there are no unexpectedly large contributions from a pair of tensor mesons, for example). It should be possible to avoid the large potential background from $a_0(980) \to \pi^0\eta$ by excluding events with combos in which $M(3\pi^0) \sim M(\eta)$. Finally, a photon-rich decay of the η'

that is effectively SM forbidden is $\eta' \to 3\gamma$ ($BR < 1.0 \times 10^{-4}$) [5] – a test of C invariance. Again, FCAL-II would reduce what are almost certainly important backgrounds from $\eta' \to \eta 2\pi^0$ (BR=22.3%) with missing photons.

6. Summary

The JEF experiment will run in parallel to GlueX with the upgraded FCAL-II. Under the GlueX-IV running conditions, the numbers of tagged meson are $\sim 6 \times 10^7$ for η and $\sim 5 \times 10^7$ for η' per 100 days of beam time. The availability of significantly boosted mesons in Hall D, in combination with the lead tungstate upgrade to the forward calorimeter, improves the signal to background ratio for rare $\eta^{(\prime)}$'s decays to neutral channels with 3-5 photons by up to 2 orders of magnitude. This represents a unique η and η' factory with little competition in the rare neutral decay modes. This allowa us to address a broad range of important physics topics, from a precision test of low energy QCD, to a sensitive probe for a sub-GeV leptophobic dark B' boson and the C-violating, P-conserving new forces that extend our knowledge to the dark sector and explore new sources of CP violation needed to explain the matter/anti-matter asymmetry in the universe. The discovery of such new forces beyond SM would have far-ranging implications into our understanding of symmetry and dark matter.

REFERENCES

[1] M.J. Ramsey-Musolf, talk at workshop on "Hadronic Probes of Fundamental Symmetries", the Amherst Center for Fundamental Interactions (ACFI), University of Massachusetts, Amherst, MA, March 6-8, 2014.

[2] B.M.K. Nefkens and J.W. Price, Phys. Scr. **T99** , 114 (2002).

[3] E.L. Bratkovskaya *et al.*, Phys. Lett. B **359**, 217 (1995).

[4] https://arxiv.org/abs/1612.05721 (Phys.Rev.D 96 (2017) 1, 012005)

[5] C. Patrignani, et al. (Particle Data Group), Chin. Phys. C **40**, 100001 (2016).

[6] J. Alexander et al., Dark Sector 2016 Workshop: Community Report, arXiv:1608.08632.

[7] S. Tulin, Phys. Rev. D **89**, 114008 (2014).

[8] S. Tulin, private communication.

[9] M. Pospelov, A. Ritz and M. Voloshin, Phys. Rev. D **78**, 115012 (2008).

[10] C. Fanelli and M. Williams, J.Phys., G **44(1)**, 014002 (2016).

[11] R. Escribano, PoS QNP **2012**, 079 (2012) [arXiv:1207.5400 [hep-ph]].

[12] F. K. Guo, B. Kubis and A. Wirzba, Phys. Rev. D **85**, 014014 (2012) doi:10.1103/PhysRevD.85.014014 [arXiv:1111.5949 [hep-ph]].