η Decay Program at GlueX

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The GlueX detector in the experimental Hall D at Jefferson Lab provides a unique capability to perform a precision measurement of the $\eta \to \gamma\gamma$ decay width via the Primakoff effect and study rare decays of η mesons. Measurement of the η decay width is essential for the determination of fundamental properties, such as the ratios of the light quark masses and the η-η' mixing angle, and will provide an important test of chiral symmetry breaking in QCD. Physics of rare η decays ranges from critical tests of the chiral perturbation theory to the search for lepto-phobic dark matter candidates. We will give an overview of the ongoing PrimEx η experiment and physics program of rare η decays.

Keywords: Radiative decay width of η meson, Rare η decays

1. Introduction

The GlueX detector in the experimental Hall D at Jefferson Lab was originally designed to search for gluonic excitations in the spectra of light mesons using photon beams. The detector provides good reconstruction of both neutral and charged particles and allows for identifications of multi-particle final states. The detector started collecting data in the Spring of 2016 and has acquired a data sample of about 300 fb^{-1} since then. Two new experiments to study various decays of eta mesons with the GlueX detector have been recently approved: an experiment to perform a precision measurement of the $\eta \to \gamma\gamma$ decays width via the Primakoff effect (the PrimEx η experiment), and an experiment to study η rare decays, the Jefferson Eta Factory (JEF). These experiments will be described below.

2. PrimEx η Experiment

The PrimEx η experiment will measure the cross section of the $\eta \to \gamma\gamma$ decays as a function of the η production angle. The resonant production of mesons in the Coulomb field of a nucleus by photons is known as the

Primakoff effect. The cross section of this process on a zero-spin nucleus is related to the η decay width, $\Gamma_{\gamma\gamma}$. The two-photon decay width will be extracted from the cross section measurement with a precision of 3.2%. The PrimEx η results will have a significant impact on various physics topics:

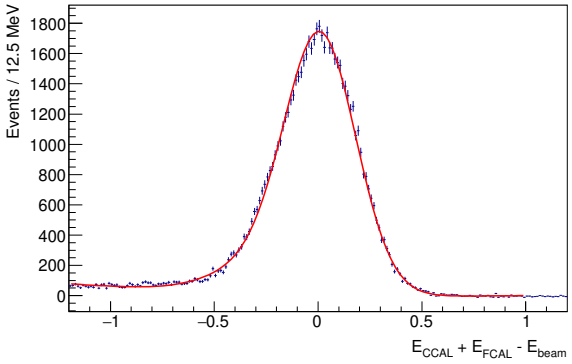

Fig. 1. Elasticity distribution of reconstructed Compton candidates.

- The measurement will significantly improve the world's average value of $\Gamma_{\gamma\gamma}$ [1] and will help to understand some discrepancies between $\Gamma_{\gamma\gamma}$ obtained from e^+e^- collider experiments and the Primakoff experiment at Cornell [2].
- The measurement will improve partial widths of all other η decays, which are determined using the measured $\Gamma_{\gamma\gamma}$ and the corresponding branching ratios. The branching ratios are typically known with a relatively good precision.
- Extraction of the partial width of $\eta \to \pi^0\pi^0\pi^0$ and $\eta \to \pi^+\pi^-\pi^0$ decays is of particular interest. These decays proceed through the isospin breaking generated by the mass difference $m_d - m_u$ and can be used for the determination of the light-quark mass ratio $(m_u - m_d)/m_s$ [3].
- The SU(3) symmetry breaking induced by m_s gives rise to the mixing of η and η'. The precision measurement of the η radiative decay width will provide an important input for the determination of the $\eta - \eta'$ mixing angle.

The PrimEx η experiment started collecting data in Spring of 2019 using a He target and has acquired about 30% of the required statistics. The

cross section will be normalized using the Compton process, which will also be used to monitor the luminosity and control the detector stability during the run. In order to reconstruct electrons and photons at small angles originating from Compton events, the GlueX detector was instrumented with a small (24 cm x 24 cm) lead tungstate ($PbWO_4$) calorimeter, positioned downstream of the GlueX forward calorimeter (FCAL). The elasticity distribution, defined as the energy of two reconstructed clusters minus the beam energy, for Compton candidates is presented in Fig. 1. The Compton calorimeter was also the prototype of a large-scale calorimeter, which will be used to upgrade the FCAL. This upgrade is required for the JEF experiment, described in Section 3.

3. JEF Experiment

The primary goal of the JEF experiment is to perform precision measurements of various η and η' decays mainly reconstructed in neutral modes. The experiment requires an upgrade of the inner part (80 cm x 80 cm) of the GlueX lead glass forward calorimeter with high-granularity, high-resolution $PbWO_4$ crystals. The calorimeter will improve the separation of clusters in the forward direction and the energy resolution of reconstructed photons by about a factor of two. The experiment is tentatively scheduled to start data taking in 2023 and will run concurrently with the GlueX spectroscopy program. The main physics topics considered for JEF are listed in Table 1 and described below:

Table 1. The η decays highlighted in the JEF experiment.

Mode	**Branching Ratio**	**Physics Highlight**	**Photons**
$\gamma + B'$	beyond SM	dark vector boson	4
$\pi^0 + \phi'$	beyond SM	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
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4γ	$< 2.8 \times 10^{-4}$	$< 10^{-11}$	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

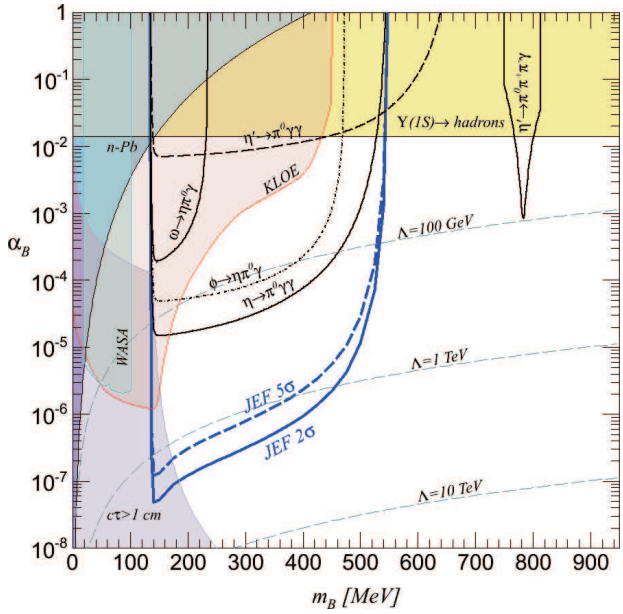

Fig. 2. Limits on leptophobic gauge B-boson coupling α_B as a function of the mass $m_{\rm B}$, described in Ref. 5. Projected JEF search regions are superimposed on the plot.

- A search of the leptophobic dark B boson, which couples predominantly to quarks. The search will be performed using $\eta \to \gamma + B(\to \gamma + \pi^0)$ channel[4,5], which will cover the B boson mass range 0.14 - 0.54 GeV. The JEF sensitivity to the baryonic fine structure constant $\alpha_{\rm B}$ is about two orders of magnitude better than the existing bound and corresponds to 10^{-7} (see Fig. 2). In the η' mass range, the B-boson will be searched using $\eta' \to B\gamma(\to \pi^+\pi^-\pi^0)$ decays.
- A search of the electrophobic dark scalar[6] ϕ' in the decays $\eta \to \pi^0 + \phi'(\to \gamma + \gamma)$ in the mass range between 0.01 GeV and 0.4 GeV.
- Perform measurements of the Dalitz distribution of the $\eta \to \pi^0\gamma\gamma$ decays. The measurements will allow to determine two low-energy constants in the $O(p^6)$ chiral Lagrangian[7] and study the contribution of scalar resonances in this channel. The highly boosted $\eta's$ produced in Hall D is expected to have significantly smaller background compared with the previous measurements by low-energy experiments. The projected invariant mass distribution of the reconstructed 4γ events is shown in Fig. 3.

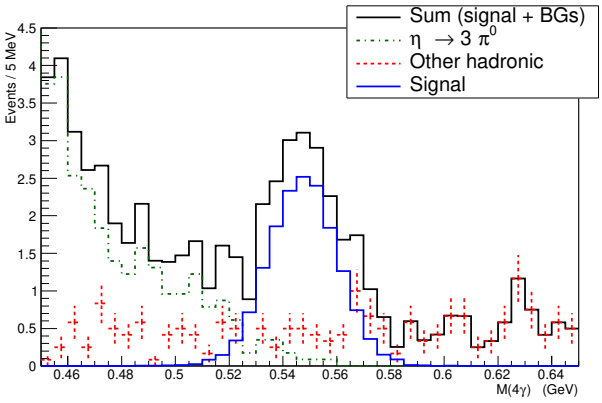

Fig. 3. Four photon invariant mass distributions for the signal $\eta \to \pi^0\gamma\gamma$ events (blue solid curve), $\eta \to 3\pi^0$ background (dash-dotted curve), and the hadronic background predicted by PYTHIA (red dashed curves). The black solid curves correspond to the sum of the signal and backgrounds. All yields are normalized to 1 day of taking data with GlueX.

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