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JLab Eta Factory Experiment in Hall D

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The new experiment, JLab Eta Factory (JEF), in the experimental Hall D at Jefferson Lab will extend the physics potential of the GlueX detector beyond the main spectroscopy program and perform precision measurements of various $\eta^{(\prime)}$ decays with emphasis on rare neutral modes. The physics program of the experiment spans from precision tests of low-energy QCD to search of gauge bosons in the mass range below 1 GeV coupling the SM sector to the dark sector. Photoproduction of highly boosted $\eta^{(\prime)}$ mesons using a tagged photon beam, good detection of recoil proton and multi-photon final states will allow to suppress background and collect high-statistics data sample of η mesons. All these provide many advantages over other $\eta^{(\prime)}$ experiments. The JEF experiment requires to upgrade the inner part of the forward lead glass calorimeter of the GlueX detector with high-granularity, high-resolution lead tungstate $PbWO_4$ scintillating crystals. The calorimeter insert is currently under construction at Jeffeson Lab. The detector will be ready to take data in 2024. An overview of the JEF project will be presented.

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1. Introduction

The GlueX detector [1] in experimental Hall D at Jefferson Lab (JLab) was designed to carry out experiments using a photon beam. The detector has a large and flat acceptance for both neutral and charged particles and allows good identification of multi-particle final states. The detector was commissioned in 2016 and has been collecting data since then.

The new experiment, JLab Eta Factory (JEF) [2] with the GlueX detector is currently under construction. The main goal of the JEF experiment is to study various decays of eta mesons with emphasis on rare neutral modes using a beam of photons with energies of between 9 GeV and 12 GeV. Eta and $\eta^{'}$ mesons will be produced in the reaction $\gamma + p \rightarrow \eta^{(\prime)} + p$, where the energy of a beam photon is determined by GlueX tagging detectors, and the recoil proton is detected using tracking drift chambers positioned inside the solenoid magnet. Detection of photons and leptons originating from $\eta^{(\prime)}$ decays is performed by forward and barrel calorimeters. The experiment requires an upgrade of the inner part of the GlueX lead glass Forward Calorimeter (FCAL) with high-granularity, high-resolution $PbWO_4$ scintillating crystals. The lead tungstate insert of the FCAL consists of the 1596 crystals. It will improve the shower energy and position resolutions and the separation of showers in the forward direction.

The JEF experiment will produce a competitive sample of $\eta^{(\prime)}$ mesons compared to other existing facilities, the expected production rate is about 6×10^7 and 5×10^7 η and η' mesons per 100 days, respectively. Production of $\eta^{(\prime)}$ mesons with large boost, along with the good reconstruction of photons in the new calorimeter will result in a significantly smaller background compared to other low-energy experiments, and provide a unique capability to study rare η decays. The installation of the FCAL $PbWO_4$ insert is scheduled for the spring of 2023. The JEF experiment will start collecting data in the beginning of 2024. We will give an overview of main physics topics of the JEF program in Section 2 and will briefly describe the FCAL upgrade in Section 3.

2. JEF physics program

The JEF experiment will allow to study a broad variety of physics topics [3], such as tests of low-energy QCD via precision measurements, determination of the quark mass ratio, constraints on new C-violating, P-conserving reactions (CVPC), and search for gauge bosons coupling the SM sector to the dark sector. Some selected topics from the JEF program are listed below:

- Perform measurements of the Dalitz distribution of the $\eta \rightarrow \pi^0\gamma\gamma$ decays. The measurements will allow to better understand the contribution of scalar resonances in the calculation of $O(p^6)$ low-energy constants (LEC) and to determine some LECs in the chiral Lagrangian [4]. Recently, $\eta \rightarrow \pi^0\gamma\gamma$ decays have been measured by several low-energy experiments [5][7][6], where η's were produced with small boost. The large background from $\eta \rightarrow 3\pi^0$ and $\eta \rightarrow 2\pi^0$ limits the precision on measurement of $d\Gamma/dM_{\gamma\gamma}$, which is essential to distinguish among various production mechanisms. The highly boosted η's produced in Hall-D is expected to have significantly smaller background.

- Measurement of the quark mass ratio $Q = (m_s^2 - \hat{m})/(m_d^2 - m_u^2)$, where $\hat{m} = (m_u + m_d)/2$, using $\eta \rightarrow 3\pi$ decays [8][9]. The combination of JEF and GlueX running will acquire more than 15 million reconstructed events for each $\eta \to \pi^+\pi^-\pi^0$ and $\eta \to \pi^0\pi^0\pi^0$ decays, which is significantly larger than existing worlds datasets. Large statistics and the relatively flat acceptance of GlueX will allow significant reduction of the statistical error over the Dalitz distribution.

- Perform a search of gauge bosons in the decay of $\eta^{(\prime)}$ mesons in the mass range below 1 GeV. The gauge boson is a mediator particle which can couple the Standard Model sector with the dark sector. They will be probed in three portals: the vector (B boson), scalar (S scalar) , and pseudoscalar (Axion-like particles). A list of reactions considered for the search is presented in Table 1.

	Vector B boson [10]	
$\eta, \eta' \to \gamma B$	$B \to \pi^0\gamma$	$(0.14 < \mathrm{m_b} < 0.62)$ GeV
	$B \to \pi^+\pi^-\pi^0$	$(0.62 < \mathrm{m_B} < 1$ GeV)
	Scalar [11, 12]	
$\eta \to \pi^0 S$	$S \to \gamma\gamma, e^+e^-$	$(\mathrm{m_S} < 2\ \mathrm{m}_\pi)$
$\eta, \eta' \to \pi^0 S$	$S \to \pi\pi$	$(\mathrm{m_S} > 2\ \mathrm{m}_\pi)$
$\eta' \to \eta S$		
	Axion-Like Particle [13–15]	
$\eta, \eta' \to \pi\pi a$	$a \to \gamma\gamma$	
	$a \to e^+e^-$	

Table 1: List of reactions considered for the search of gauge bosons in JEF.

3. Upgrade of the GlueX forward calorimeter

The forward calorimeter of the GlueX detector is positioned about 6 m downstream of the target and covers a polar angle of photons produced from the target between 1° and 11°. The calorimeter can detect electromagnetic showers with energies between 0.1 GeV and 8 GeV and the typical energy resolution of $\sigma_\mathrm{E}/E = 6.2\%/\sqrt{E} \oplus 4.7\%$ [1]. The FCAL consists of 2800 lead glass modules, each with the size of 4 cm × 4 cm × 45 cm. The Cherenkov light produced by showers in the modules is detected by FEU-84-3 photomultiplier tube.

The inner part of the FCAL will be replaced by high-resolution, high-granularity $PbWO_4$ scintillating crystals. Lead tunstate crystals have better radiation resistance compared to lead glass, which is important for the long term operation of the detector at high luminosity. The insert consists of 1596 lead tungstate crystals, which will form an array of 40×40 modules with a beam hole of 2×2 modules in the middle. Each crystal has the following dimension: 2.05 cm×2.05 cm×20 cm. The

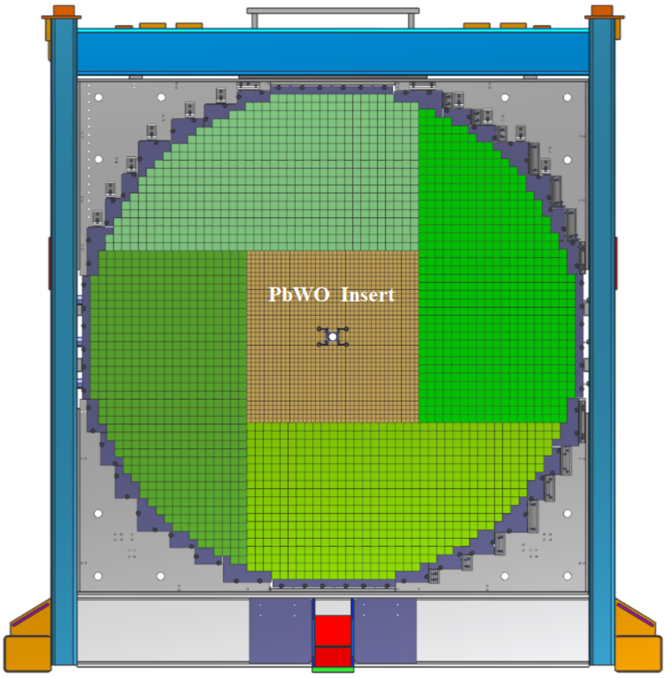

Figure 1: FCAL frame with calorimeter modules installed: $PbWO_4$ crystals (brown area), lead glass blocks (green). The photon beam passes through the hole in the middle of the calorimeter.

small Molière radius (R_M = 2.19 cm) of $PbWO_4$ results in about a factor of two smaller transverse size of the crystal compared to the lead glass module. In combination with the larger light yield from the scintillating material, the insert will improve the separation of clusters in the forward direction and the energy resolution of reconstructed photons by about a factor of two. A schematic view of the FCAL frame with the lead tungstate insert is presented in Fig. 1. Lead tungstate crystals are purchased from two vendors: SICCAS (China) and CRYTUR (the Czech Republic). Properties of recently produced crystals have been studied in detail and can be found in Ref. [16].

The design of the FCAL $PbWO_4$ module is described in Ref. [17]. An assembled calorimeter module is shown in Fig. 2. The lead tungstate crystal is wrapped with a specular reflector foil produced by $3M^{TM}$ company and light-tight Tedlar film. Light from the crystal is detected using Hamamatsu PMT 4125. In order to reduce the fringe field of the GlueX solenoid magnet present in the FCAL region to the level suitable for the PMT operation, the PMT is located inside the soft iron housing (made of AISI 1020 steel) and is surrounded by a 350 μm thick mu-metal foil. A 3.5 cm long acrylic cylindrical light guide is used to extend the magnetic shield above the face of the PMT. One end of the light guide is glued to the PMT using Dymax 3094 UV curing glue, the other end is coupled to the crystal using a 1.8 mm thick transparent silicon rubber (a silicon cookie). Two flanges are positioned at the crystal and PMT housing ends and are connected together using brass straps, which are brazed to the flanges. Four screws on the PMT housing flange provide strap tension and hold the assembly together. The PMT is read out using an active base (a divider with an amplifier), which was designed at JLab. Signal pulses are digitized using a twelve-bit 16-channel flash ADC electronics module operated at a sampling rate of 250 MHz. The ADC was designed at

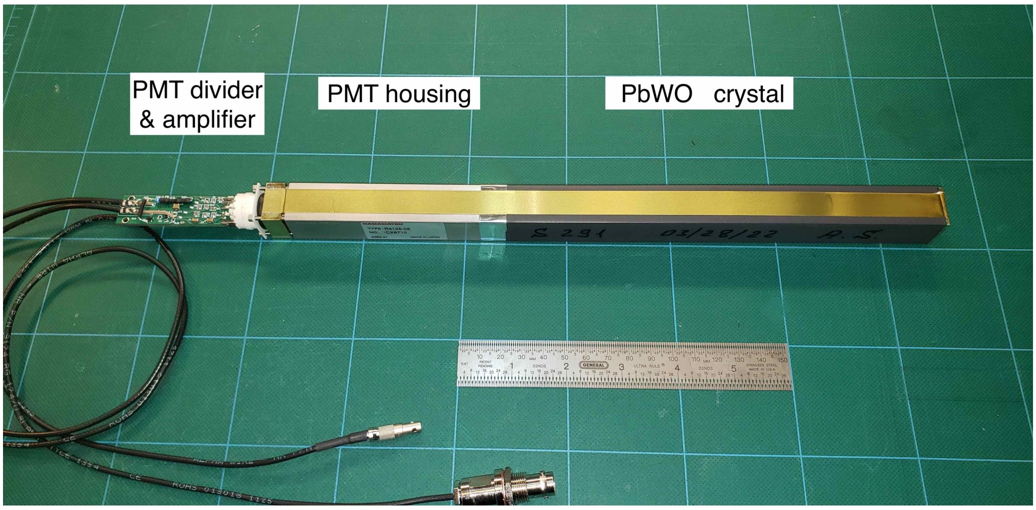

Figure 2: FCAL insert module showing main components: the $PbWO_4$ crystals wrapped with the ESR reflective foils and light-tight Tedlar, PMT housing, PMT divider, and high-voltage and signal cables.

JLab [18]. Prior to the FCAL insert construction we built a prototype which comprises an array of 12×12 lead tungstate modules. The prototype was successfully used in the PrimEx-η experiment in Hall D to reconstruct Compton scattering events. It was also used to study the energy resolution and performance of the PMT active base [17].

Fabrication of the FCAL insert modules is currently ongoing in the lab. The installation of the FCAL insert is tentatively schedules for the spring of 2023. The JEF experiment will start collecting data in the beginning of 2024.

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