Update on

A Precision Measurement of the η Radiative Decay Width via the Primakoff Effect

(Proposal PR12-10-011)

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Abstract

The proposal PR12-10-011 had been approved by PAC35 in January, 2010 to perform a precision measurement of the $\eta \rightarrow \gamma\gamma$ decay width via the Primakoff effect in Hall D with the GlueX experimental setup. The decay width will be extracted from the measured differential cross sections at forward angles on two light targets, proton and ^{4}He with a 11.5 GeV tagged photon beam. This result will not only potentially resolve a long standing discrepancy between the Primakoff and collider measurements, but will also reduce the experimental uncertainty by a factor of two of the current PDG average on this important quantity, which will result in a direct improvement on all other η partial decay widths. A high precision measurement of the $\eta \rightarrow \gamma\gamma$ decay width will have significant impact on the experimental determination of the fundamental parameters, such as the ratios of light quark masses (m_u, m_d, m_s) and the $\eta - \eta^{'}$ mixing angle. It will provide a sensitive test of QCD symmetries in the chiral limit. It will also deliver the first cross section measurement on the $\gamma p \rightarrow \eta p$ elementary process at the forward angles for this energy range. In this document we are updating the scientific progress made in the past one year, and addressing the issues regarding the beam time planning, which was raised by the PAC35.

1 Physics Motivation of the Proposed Experiment

The goal of the proposed experiment (PR12-10-011) is to perform a precision measurement (at the 3 % level) of the $\eta \to \gamma\gamma$ decay width via the Primakoff effect on two targets, proton and ^{4}He using the GlueX standard experimental setup in Hall D.

The η meson is of great importance for the understanding of fundamental symmetries and their partial breaking effects in QCD. In the chiral limit, the condensation of quark-anti-quark pairs in the QCD vacuum spontaneously breaks $SU_L(3) \times SU_R(3)$ symmetry down to the flavor $SU(3)$ symmetry. As a result, there are eight massless Goldstone Bosons (GB) corresponding to the eight spontaneously broken symmetry generators. These states are identified with the octet of pseudoscalar mesons (π^o, $\pi^\pm$, $K^\pm$, K^0, $\bar{K}^0$, and η). In reality, the quark masses are non zero (albeit small), thus breaking the chiral symmetry explicitly and giving rise to masses for the GBs. As the heaviest member in the octet the η plays a special role. It has an interesting feature that all its strong and electromagnetic decays are forbidden in lowest order due to P, PC, C, G-parity symmetries and angular momentum conservation. The width of the η is about five orders of magnitude smaller than a typical strong decay, such as the ρ and ω mesons. This feature makes η decay proportionally more sensitive than the ρ and ω decays at a comparable branching ratios for testing symmetries of QCD.

The $\eta \to \gamma\gamma$ decay is directly associated with the chiral anomaly. This is one of the most profound symmetry aspects in QCD, namely, the explicit breaking of a classical symmetry by the quantum fluctuations of the quark fields when they couple to a gauge fields. This phenomenon is of a pure quantum mechanical origin and can be calculated exactly at all orders in the chiral limit. In QCD there are several observable phenomena that originate from anomalies. One connected to the couplings of the quarks to the gluons is responsible for the non-zero mass of the η' at the chiral limit. The axial anomaly related to the η two-photon decay involves the corresponding coupling of the quarks to photons. In the chiral and large N_c limits the two-photon decay of the η can be predicted. The relatively straightforward situation of the chiral limit becomes more complex in the case in which the quark masses are non-vanishing. These masses make the η massive, while SU(3) and isospin breaking by the unequal quark masses induce mixings among the π^0, η and η' mesons. The $SU(3)$ breaking is primarily manifested by η mixing with the η' meson, which contributes significantly in the next-to-leading order term in Chiral Perturbation Theory (ChPT) calculations.

Using the best fit to the current widths as provided by PDG (average of the Cornell Primakoff and the e+e- collider results) one obtains θ = -10.6±2.0deg. The error in η decay width gives an uncertainty in θ which can be estimated by $\delta\theta \sim -\frac{\delta\Gamma_{\eta\to\gamma\gamma}}{\Gamma_{\eta\to\gamma\gamma}} \times 15$ deg. Thus a 3% precision in proposed measurement of the $\eta \to \gamma\gamma$ decay width would yield a factor of four improvement in determination of mixing angle ($\delta\theta$=0.45°) as it shown in Figure 1.

Proposed high precision measurement of the η radiative decay width will have a broad impact to all other partial widths of the η decays in PDG listing, as they are determined by using the $\eta \to \gamma\gamma$ decay width and their corresponding experimental branching ratios. One of the prominent examples is the $\eta \to 3\pi$ decays. These decays can only proceed through the isospin symmetry breaking by the quark mass difference. Therefore, the decay amplitude is

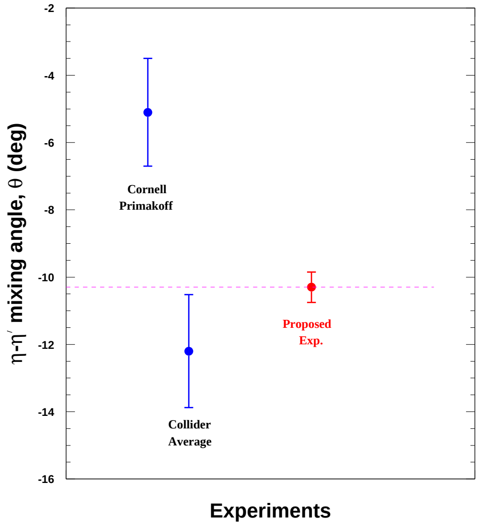

Figure 1: The mixing angles extracted from different experiments. The first left two points are mixing angles calculated using the Cornell Primakoff and average from the e+e- collider experiments.The expected result from the proposed experiment is arbitrarily projected to the average value from existing experiments.

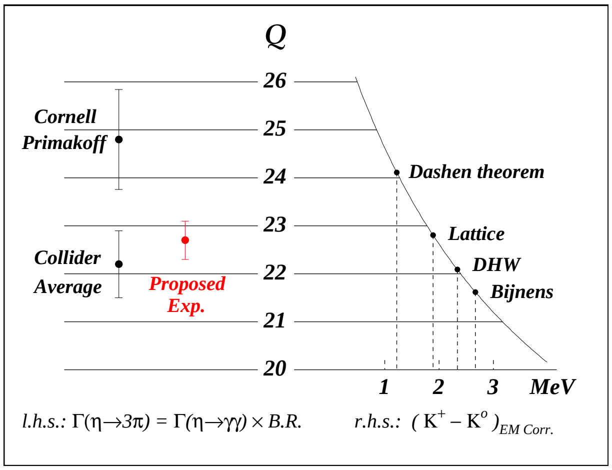

Figure 2: Light quark mass ratio determined by two different methods: the left side is from the η decay width, the right side is from the meson mass difference (see text and the Proposal for more detail explanations).

proportional to $m_d - m_u$, alternatively, to the quark mass double ratio, $\mathcal{Q}$ The $\mathcal{Q}$ can be determined by comparing the theoretical amplitude with the η decay width measurement as it shown in Figure 2. Due to chiral symmetry, the electromagnetic effects on this decay channel have been known to be small and most model independent. Therefore, it is widely recognized as an unique path to an accurate determination of quark mass ratios (see the Proposal for more detail explanations). An alternative approach to obtain the quark mass ratio is through the measured kaon mass differences, shown on the right side of Figure 2. Major drawback of the second approach, however, arises from the theoretical uncertainties of the electromagnetic contributions (also shown in Figure 2). More detail discussion on the quark mass ratio can be found in the original Proposal [1]. This proposed experiment (PR12-10-011) was submitted to PAC35 in January, 2010 and have been approved to run in Hall D using the standard GlueX experimental setup. The upper 10% energy range (10.5–11.7 GeV) of the photon tagger will be used to produce η mesons off 30 cm length of liquid hydrogen and ^{4}He targets. The two decay photons from the η will be detected by the forward electromagnetic calorimeter (FCAL), located $\sim$ 5.6 m downstream of the targets. The only addition to the standard GlueX setup was the proposed small (32.8×32.8 cm^2) PbWO$_4$ crystal calorimeter (CompCal), located $\sim$ 4 m downstream of FCAL, which was also approved together with the proposal by PAC35. Two major difficulties of η decay width precision extraction are: (1) measurement of the differential cross sections at forward angles (measurement of absolute values of photon flux, number of nuclei in target, detection efficiencies, acceptances, etc...); (2) extraction of the coherent amplitudes, both for Primakoff and nuclear processes. For the second part, we propose to use the lightest possible targets, proton and ^{4}He. The proton will sidestep many of the complications that accompany complex nuclear targets. On the other hand, the ^{4}He will have larger Primakoff cross section (Z^2 effect) vs. nuclear coherent process, while it remains as the simplest compact nuclear target with the best known charge form factor. The photon flux will be measured by periodically measuring the absolute photon tagging efficiency with a total absorption counter at low beam intensities and monitoring the relative tagging efficiency with the pair spectrometer (PS) during the production runs at high beam intensity. To make the tagging efficiency more stable and controllable on the 1% level, we propose to use a 5 mm diameter collimator vs. the GlueX standard smaller 3.4 mm collimator. The 5 mm diameter collimator is in the standard design package of hall D beam line. Since the Compton scattering process in many ways kinematically similar to the proposed experiment and its cross sections are known with better than 1% accuracy, we proposed to measure the Compton cross sections, parallel to the experiment, by detecting the recoiled electrons (and part of the scattered photons) in the CompCal. This will provide a unique opportunity to control and verify all systematic uncertainties in the experiment.

More detail explanations and descriptions of the proposed experiment and setup can be found in the original Proposal [1].

2 Recent Theoretical Development

Uncertainties in the previous measurements of the η radiative decay width are typically large and they are ranging from 8 to 25%, which in part defines the level of requested accuracy in the theoretical simulations. Our proposed experiment, with its 3and simulation accuracies based on those models. Firstly, this applies to new developments in the theoretical treatments of the η meson propagation through the nuclear matter, for the accurate extraction of the coherent Primakoff amplitude from the measured differential cross sections. Secondly, the expected new precision in the radiative decay width requires development of new theoretical methods, approaches and simulations for the better extraction of the mixing angle and light quark mass ratios from the upcoming decay width measurement. Stimulated by this proposed experiment, an analytical calculation in the frame work of the ChPT was carried out in the past year by J. Bijnens and K. Kampf [3]. They considered next-to-next-to-leading order of the chiral expansion and computed all the one-loop and two-loop diagrams which contribute to the decay amplitude at this order in the SU(3) limit. The authors are also stating in their article that independent new calculations with the physical masses have been in progress for the past few years, they will be published soon.

On the other hand, the progress achieved in the numerical simulation of QCD on a lattice has made it possible to reach sufficiently light quark region. The π^0 to off-shell photon transition form factor is calculated by JLQCD collaboration [4]. After extrapolating to the chiral and the vanishing photon momentum limit with a fit function based on the vector meson dominance (VMD) model, the Adler-Bell-Jackiw anomaly is correctly reproduced in this work. Recently the Jlab lattice QCD group fully demonstrated their capability to access the light meson two-photon decays on lattice by applying the Lehmann-Symanzik-Zimmermann reduction formula [5]. These new developments give a realistic expectation that in the near future, the lattice calculation will be able to determine the η decay widths from the first QCD principles. Newly planned precision experiments, such as the proposed experiment PR12-10-011, will provide a critical information to test the fast upcoming lattice results, which are highly expected by the nuclear/particle community for this energy range. Inspired by the future availability of precise experimental data on the η decay width, in the past year, there has been significant activities to improve the theoretical uncertainty in the $\eta \to 3\pi$ amplitude simulation. A comprehensive analysis of this decay is under active development [2][7] One of the very recent results is based on the dispersive analysis method [7]. An excellent overview on the current status of the light quark mass ratio using the $\eta \to 3\pi$ decay process as an input is given by H.Leutwyler and G.Colangelo in [2] and [7]. As it demonstrated by G. Colangelo, *et al.* (Figure 3 in [7]) the quark mass ratio determined by different independent calculations [2][7][**?**][**?**] using the $\eta \to 3\pi$ process are all converging and they well agree with the lattice QCD result[8] within their error bars. These recent intensive theoretical activities, in return, show the urgency to perform a new high precision measurement on the $\eta \to \gamma\gamma$ decay width.

The elementary amplitudes of forward η-photoproduction on proton and neutron are required to describe and separate the coherent and incoherent hadronic processes from the Primakoff amplitude which defines the η radiative decay width. Up to now, these amplitudes are not known experimentally for the forward angles and at this energy range. Inspired by the PrimEx-12GeV physics program, developed in the past several years, J.M. Laget published his work “The Primakoff Effect on a Proton Target” [9]. This article provides a theoretical guidance to handle the hadronic processes on the proton target based on Regge model. A new and more comprehensive approach is developed in the recent article by A. Sibirtsev *et al.* “Primakoff Effect in η-photonproduction off Protons”[10] published in this year. The authors demonstrated the feasibility of obtaining an accurate extraction of the η decay width by analyzing the available data from DESY, Cornell and SLAC on η-photoproduction off a proton target for relatively small angles (which are still not covering the Primakoff forward peak region). In their analysis the hadronic amplitudes are strongly constrained by a global fit to a wide range of available data set for differential cross sections and polarization observables on $\gamma p \to p\eta$ process in the frame of Regge model. Based on their comprehensive evaluation on the existing world data of the $\eta \to \gamma\gamma$ decay width, including the collider and Cornell results, shown in Figure 5 of [10], the authors are making a strong call for a new precision measurement via the Primakoff effect.

In the past few years, inspired by the PrimEx project, the subject of the light pseudoscalar meson photoproduction in the electromagnetic and strong fields of the light and heavy nuclei have been revisited and a comprehensive theoretical treatment based on the Glauber theory of multiple scattering has been developed and published [11][12]. The effects of final state interactions, corrections for light nuclei, contributions from nuclear collective excitations, and photon shadowing effects in nuclei have been correctly incorporated. These recent theoretical developments provide a solid physical foundation to extract the $\eta \rightarrow \gamma\gamma$ decay width from the measured differential cross sections on both proton and ^{4}He targets via the Primakoff effect with a negligible model error.

In summary, the theoretical activities in this field for the past one year, inspired by this proposed experiment, are a clear proof for the importance of a new high precision measurement of the $\eta \rightarrow \gamma\gamma$ decay width. η-photoproduction experiments on nucleon and nuclei.

3 Response to PAC35 Recommendation

This proposal had been submitted to PAC35 in December, 2009 and it was approved with the following recommendation: *"... The proponents have requested a dedicated run with the solenoidal-detector field turned off. They should consider whether part of their running could be concurrent with GlueX"*. For the past one year we have worked with the GlueX collaboration and with the Hall D management to try to optimize the requested beam time to accomplish the goals of this proposal. One of the largest items in our requested beam time budget is the 30 days for the ^{4}He target run. The ^{4}He currently is not a target for the approved GlueX physics runs. Therefore, we have to leave this part in our requested beam time budget to accomplish the planned measurements. The largest item in the beam time budget is the 40 days of running on the proton target. We have considered all possibilities to perform this part of the experiment parallel with the GlueX run. As described earlier, and in a more detailed way in the original proposal, the high precision differential cross section measurements, required for the η radiative decay width extraction, need a parallel measurement of the Compton cross sections on forward directions with the same incident photon energies. The Compton scattering cross section, as a pure QED process, can be calculated with uncertainty better than 1%, and therefore, can be used for verification and control of all systematic uncertainties in the experiment. This was done in the past during PrimEx-I and PrimEx-II experiments and proven to be a critical tool for the precision cross section measurements. It is also well known that the co-planarity condition between the scattered photon and recoiling electron azimuthal angles is one of the important selection criteria in the effective event selection process. Unfortunately, this information is mostly lost when we require a magnetic field in the solenoid detector (GlueX running condition), is demonstrated in Figs. 3 and 4. We have also considered using the GlueX forward tracking devices to detect and reconstruct the path of the recoiling electron, but due to very small angles (less than 1° at this energy range, shown in Fig. 5), the GlueX apparatus does not have an acceptance for these events. Since the parallel Compton measurement is critical for this proposed experiment, we are required to request a dedicated beam time for the proton target also. The planned 6 days of the empty target runs are designed for the experimental

	PAC35 Request	PAC37 Request
Setup calibration, checkout	8 days	0 days
Tagger efficiency, TAC runs	4 days	1 day
^{4}He target	40 days	40 days
LH$_2$ target	30 days	30 days
Empty target runs	6 days	6 days
Total	88 days	77 days

Table 1: The requested beam time budget (see text for explanations).

background shape determination and, therefore, they are highly sensitive to the experimental setup configuration including the magnetic field value in the solenoid detector. We have to leave this in the requested beam time budget.

However, since we will use the GlueX standard apparatus for the experiment, we can share the setup calibration and checkout time with the GlueX runs. With that, the previously requested 8 days of setup calibration is currently removed from the current beam time budget (shown in Table 1). In addition, we can also share the bigger part of the requested beam time for the tagger efficiency measurements with the GlueX runs, shown in Table 1. With all these, a total of 11 days will be shared with the GlueX runs and they are removed from the updated new beam time request, shown in in Table 1.

4 Summary

We have updated our beam time request and requesting 77 days of beam time to measure the $\Gamma(\eta \rightarrow \gamma\gamma)$ decay width at a precision of 3% using the standard GlueX apparatus in Hall D. This experiment will not only resolve a long standing discrepancy between the Primakoff and collider measurements, but will also significantly reduce the overall uncertainty on this important quantity (individual errors of the existing data listed in PDG [13] are 7.6%–25.5%), which will result a direct improvement on all other partial η decay widths as well. Precise measurement of this quantity will have a significant impact on the experimental determination of fundamental parameters of QCD, such as the ratio of light quark masses (m_u, m_d, m_s), the $\eta - \eta^{'}$ mixing angle and their decay constants. At a more general level, this measurement will provide important test on the chiral anomaly and chiral symmetry breaking in QCD. This experiment will also deliver the first cross section measurement on the $\gamma p \rightarrow \eta p$ elementary process in 10 GeV energy range at the forward angles, which will provide important inputs in the extraction of the η photoproduction amplitude on the nucleon.

This is the first experiment in a series of measurements planned in our PrimEx-12 GeV program. We believe the results of these future precision experiments will provide a new and powerful experimental window on QCD at JLab in an area where the basic theory has been reasonably well developed.

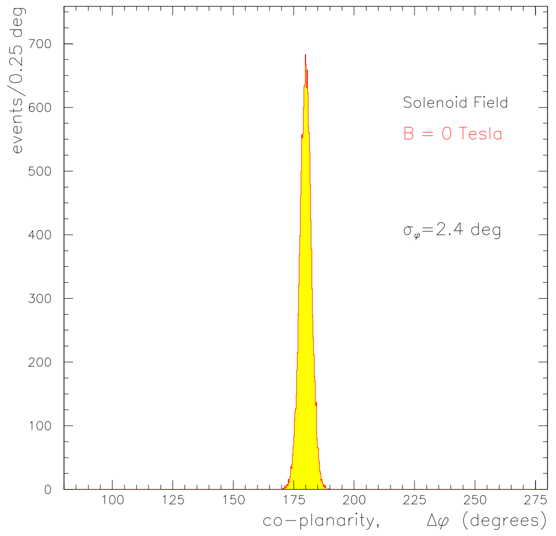

Figure 3: Distribution of the co-planarity angle between scattered photons and electrons from the Compton scattering is peaked at 180^o when the solenoid magnet is off.

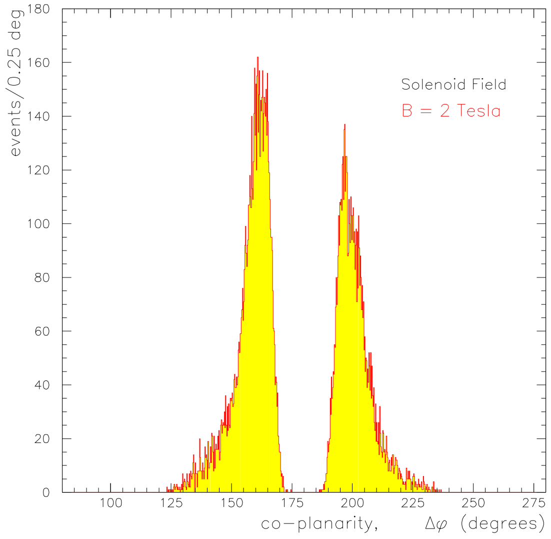

Figure 4: Distribution of the co-planarity angle between scattered photons and electrons from the Compton scattering is destroyed when the solenoid magnet is on.

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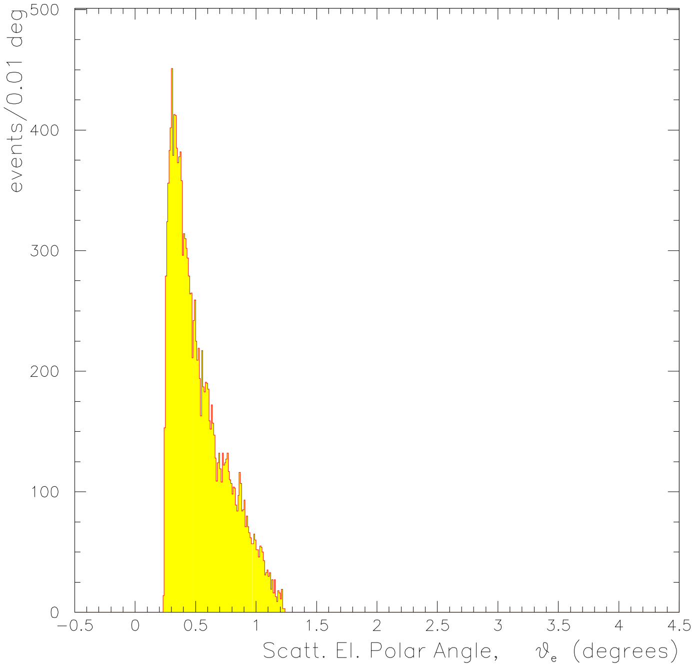

Figure 5: Distribution of the recoiled electron angles from Compton scattering at 11 GeV beam energy.

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