PROCEEDINGS OF SCIENCE

PoS(CD12)117

Precision Measurement of $\eta \to \gamma\gamma$ Decay Width via the Primakoff Effect

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Liping Gan[*][†]
University of North Carolina Wilmington, NC, USA
E-mail: `ganl@uncw.edu`

A precision measurement of the $\eta \to \gamma\gamma$ decay width via the Primakoff effect is underway in Hall D at Jefferson Lab. The decay width will be extracted from measured differential cross sections at forward angles on two light targets, liquid hydrogen and ^{4}He, using a 11.5 GeV tagged photon beam. Results of this experiment will not only potentially resolve a long standing discrepancy between the Primakoff and the collider measurements, but will also reduce the experimental uncertainty by a factor of two on the average value of previous experimental results listed by the Particle Data Group(PDG) [1]. It will directly improve all other η partial decay widths which rely on the accuracy of the η radiative decay width. The projected 3% precision on the $\Gamma(\eta \to \gamma\gamma)$ measurement will have a significant impact on the experimental determination of the fundamental parameters in QCD, such as the ratio of light quark masses (m_u, m_d, m_s) and the $\eta - \eta^{'}$ mixing angle. It will be a sensitive probe for understanding QCD symmetries and the origin and the dynamics of QCD symmetry breaking.

The 7th International Workshop on Chiral Dynamics,
August 6 -10, 2012
Jefferson Lab, Newport News, Virginia, USA

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[*] Speaker.
[†] This project is supported by US NSF grant PHY-0855578 and PHY-1206043.

1. Introduction

The availability of a high quality, high duty factor 12 GeV electron beam at Jefferson Lab (Jlab) will offer a new opportunity to perform precision measurements on the electromagnetic properties of light pseudoscalar mesons. A comprehensive Primakoff experimental program has been developed in the last decade at Jlab to study the two photon decay widths, $\Gamma_{\gamma\gamma}$, and the transition form factors, $F_{\gamma\gamma^*}$, of π^0, η, and η' [2][3]. An approved experiment to measure $\Gamma(\eta \to \gamma\gamma)$ is the first project among a series of other experiments planned in the Primakoff 12 GeV program [3]. The goal of this experiment is to measure the η radiative decay width at the 3% level via the Primakoff effect using the newly developed GlueX apparatus in Hall D.

2. Physics Motivation

Our present experimental knowledge of the η radiative decay width is presented in Fig. 1, along with the projected result which could be obtained by the proposed experiment at Jlab. Uncertainties in the previous measurements (left five black points in Fig. 1) are typically large and range between 8-25%. The first four data points were performed using two photon interaction in e^+e^- collisions [1], and the fifth point was done by the Cornell collaboration via the Primakoff effect [4] in 1974. Clearly, the existing Primakoff result is significantly lower (at the 3σ level) than those from e^+e^- collisions. The planned new experiment at Jlab with a 3% precision will potentially resolve this long standing discrepancy, as well as reduce the overall experimental uncertainty.

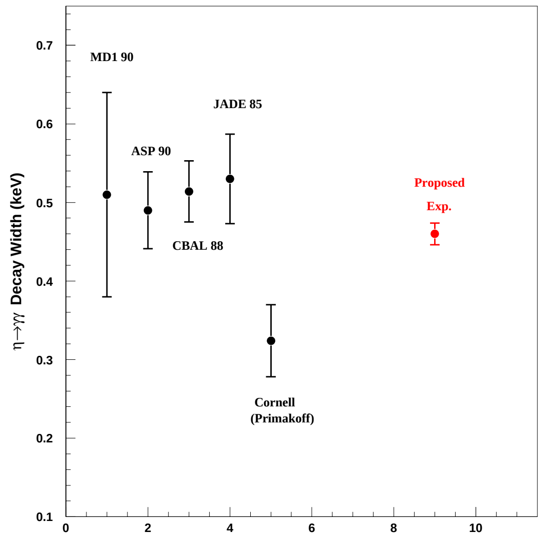

Figure 1: Two-photon decay width of η. Points 1 through 4, are the results from e^+e^- collisions [1], point 5 is the result from the Primakoff experiment [4]. Point 6 is a projected result for the proposed experiment (in red) with a 3% total uncertainty, arbitrarily plotted to agree with the average value of the previous five measurements.

The η meson is of great importance for understanding fundamental QCD symmetries. 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 eight spontaneously broken symmetry generators. These states are identified to be the octet pseudoscalar mesons (π^0, $\pi^\pm$, $K^\pm$, 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 GBs. As the heaviest member in the octet, η is more sensitive to the effects caused by the quark masses. It has an interesting feature that the lowest orders of its strong and electromagnetic decays are filtered out by conserved symmetries. The width of the η is about five orders of magnitude smaller than a typical strong decay. This feature makes η decays a sensitive probe to test high order Chiral Perturbation Theory (ChPT) predictions, and to search for new physics beyond the standard model.

The $\eta \to \gamma\gamma$ decay is directly associated with 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 field. This phenomenon is of a pure quantum mechanical origin and can be calculated exactly to all orders in the chiral limit. In the chiral and large N_c (number of QCD colors) 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 η', which contributes significantly in the next-to-leading order term in ChPT calculations. According to a result obtained to next-to-leading order in the chiral expansion[5], the error in $\Gamma_{\eta\to\gamma\gamma}$ gives an uncertainty in the $\eta - \eta'$ mixing angle 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 the 3% precision of the proposed measurement on the $\eta \to \gamma\gamma$ decay width would yield a significant improvement in the determination of the $\eta - \eta'$ mixing angle ($\delta\theta$=0.45°) as shown in Fig. 2.

In addition, the proposed measurement of the η radiative decay width will have a broad impact on all other η partial decay widths in the 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 $\eta \to 3\pi$ decay. This decay can only proceed through isospin symmetry breaking by the quark mass difference. Therefore, the decay amplitude is proportional to $m_d - m_u$, alternatively, to the quark mass double ratio $Q^2 = \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2}$, where $\hat{m} = (m_u + m_d)/2$. The left hand side of Fig. 3 shows the Q determined by the $\eta \to 3\pi$ decay using different experimental results of $\Gamma(\eta \to \gamma\gamma)$ as input. Due to chiral symmetry, the electromagnetic effects on this decay channel are known to be small. Therefore, it is widely recognized as a unique path to an accurate determination of quark mass ratio [6][7]. An alternative approach to obtain the quark mass ratio is through measured kaon mass differences, shown on the right side of Fig. 3. A major drawback of the second approach, however, arises from the theoretical uncertainties of the electromagnetic contributions (also shown in the right hand side of Fig. 3). Clearly, the proposed experiment on the η radiative decay width will open a new possibility to determine the light quark mass ratio in a model independent way.

3. Recent Theoretical Development

There have been several new developments in recent years. Stimulated by the proposed experiment, an analytical calculation of the η radiative decay width in the frame work of ChPT was carried out by J. Bijnens and K. Kampf [8] in 2010. 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. In the meantime, the progress achieved in the

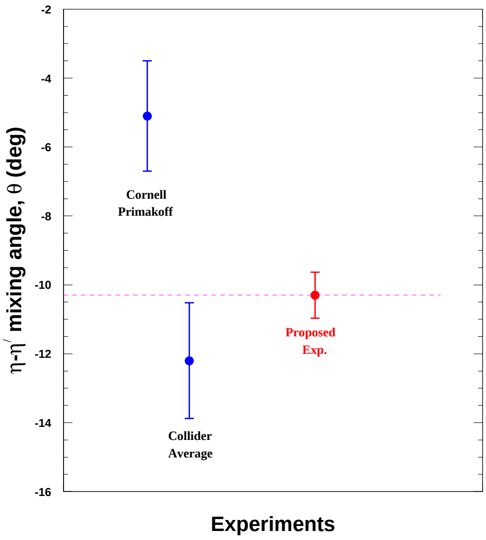

Figure 2: The mixing angles extracted from different experiments. The left two points are the mixing angles calculated using the Cornell Primakoff and average from the e^+e^- collider experiments. The projected result from the proposed experiment is arbitrarily set equal to the average value from the first two points.

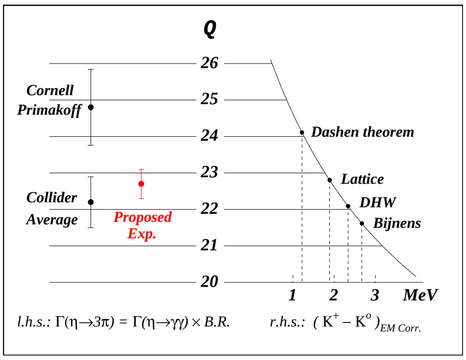

Figure 3: Light quark mass ratio determined by two different methods. The *l.h.s.* indicates the values of Q calculated from the $\eta \to 3\pi$ decay corresponding to the Primakoff and collider experimental results for the $\Gamma_{\eta\to\gamma\gamma}$ as input. The *r.h.s.* shows the results for Q obtained from the kaon mass difference with four different theoretical estimations for the electromagnetic correction. Taken from Ref. [7].

numerical simulation of QCD on a lattice has made it possible to reach a sufficiently light quark mass region. 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 [9]. One of the recent lattice QCD calculations by N.H. Christ *et al.* [10] predicted the $\eta - \eta'$ mixing angle to be $\theta = -14.1 \pm 2.8^{\circ}$. Their extrapolation to the physical light quark mass gives masses of η and η' which are consistent with the physical mass of those mesons. These new developments give a realistic expectation that in the near future, the η decays could be calculated from first QCD principles.

The theoretical development on η photo-production off the nucleon or nuclear target has recently reached a new level as well. In order to experimentally extract the Primakoff amplitude from the measured differential cross section of η photo-production, the electromagnetic and hadronic amplitudes of the η production on nucleon in the forward angles are required. These amplitudes, however, are not known experimentally in related kinematic regions. Inspired by the Primakoff 12GeV experimental program at Jlab, J.M. Laget published his work “The Primakoff Effect on a Proton Target” [11]. This article provides theoretical guidance to handle the hadronic processes on the proton target based on the Regge model. Recently, a more comprehensive approach was developed by A. Sibirtsev *et al.* in a work titled “Primakoff Effect in η-photoproduction off Protons”[12]. The authors demonstrated the feasibility of obtaining an accurate extraction of the η radiative decay width by analyzing available η-photoproduction data off a proton target for relatively small angles (but not yet reaching the Primakoff peak region). The light pseudoscalar meson photo-production in the electromagnetic and strong fields of the light and heavy nuclei has been revisited, and a comprehensive theoretical treatment based on the Glauber theory of multiple scattering has been developed [13][14]. The effects of final state interactions, corrections for light nuclei, contributions from nuclear collective excitations, and photon shadowing in nuclei have been correctly incorporated. These recent theoretical developments provide a solid foundation to extract the $\eta \to \gamma\gamma$ decay width from the measured differential cross sections on both proton and light nuclear targets (such as ^{4}He) via the Primakoff effect with negligible model uncertainty.

4. Planed experiment at Jlab

A new precision measurement (at 3% level) of the $\eta \to \gamma\gamma$ decay width via the Primakoff effect will be performed in Hall D with the GlueX experimental setup. The upper 10% energy range (10.5–11.7 GeV) of the tagged photon beam produced by a 12 GeV primary electron beam will be used to produce η's from two 30 cm long liquid targets: hydrogen and ^{4}He. Two decay photons from η will be detected by the forward electromagnetic calorimeter (FCAL), located $\sim$ 5.6 m downstream of the target. The only addition to the standard GlueX apparatus is a small PbWO$_4$ crystal calorimeter (CompCal), located $\sim$ 4 m downstream of FCAL, to measure the Compton cross section in parallel to the η production, in order to verify the systematic uncertainty of the experiment.

The classical method of extracting the Primakoff amplitude from the measured total differential cross section of the η photo-production in the forward direction relies on the different characteristic behaviors of different production mechanisms with respect to the production angles. The Primakoff cross section has a sharp peak at a very small angle, and falls off rapidly at larger angles. It is proportional to Z^2 (the atomic number of target), and its peak value is roughly proportional to E^4 (the beam energy). The nuclear coherent cross section has a broad distribution peaked outside of the Primakoff angular region, and falls off at larger angles. There is an interference term between the Primakoff and nuclear coherent amplitudes, which accounts for a relatively larger background contribution under the Primakoff peak, in addition to the contribution from the extended tail of the nuclear coherent mechanism. The new theoretical developments on the η photo-production off proton and nuclear targets described in the previous section are crucial to achieve the precision projected in this new Primakoff experiment.

Two major experimental challenges in the proposed experiment are: (1) determining the absolute photon flux to obtain the differential cross section, and (2) separating the Primakoff from the hadronic processes. To address the first issue, a high energy tagged photon beam will be used (un-tagged photon beams were used in all previous Primakoff experiments). The photon flux will be determined by periodically measuring the absolute photon tagging efficiency with a total absorption counter (TAC) at low beam intensities, and by monitoring the relative tagging efficiency with a pair spectrometer (PS) to measure the e^+e^- pair production during the production runs at high beam intensities. For the second issue, two light targets, proton and ^{4}He, are proposed. In order to precisely determine the contributions from the hadronic background under the Primakoff peak, a good experimental knowledge of the hadronic amplitude outside of the Primakoff region is necessary. This can be experimentally achieved by using light nuclei as production targets. Since form factors for light nuclei fall slowly with increasing momentum transfer at large angles, such targets are well suited for measuring the nuclear coherent amplitude at large angles, thereby determining the contribution under the Primakoff peak. The proposed proton target will sidestep many of the complications that accompany complex nuclear targets. For examples, it is free of inelastic processes and final state interaction. On the other hand, the ^{4}He target will have a four times larger Primakoff cross section (Z^2 effect), while it remains the simplest compact nuclear target with the best known charge form factor.

5. Summary

The η radiative decay width will be measured via the Primakoff effect at Jlab with a 3% precision. The same experiment will also deliver the first cross section measurement of the $\gamma p \to \eta p$ elementary process on free proton at very forward angles in the 10 GeV energy range. The projected precision on $\Gamma(\eta \to \gamma\gamma)$ will not only potentially resolve a long standing discrepancy between the Primakoff and collider measurements, but will also significantly reduce the overall uncertainty in this important quantity, resulting in a direct improvement in all other partial η decay widths. Results of this experiment will provide an important probe for understanding QCD symmetries and the origin and the dynamics of QCD symmetry breakings.

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