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RADIATIVE WIDTHS OF LIGHT PSEUDOSCALAR MESONS AT 11 GeV VIA THE PRIMAKOFF EFFECT

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The spontaneous breaking of chiral symmetry and the chiral anomalies in low-energy QCD are manifested in their most unambiguous form in the light pseudoscalar mesons sector. Understanding the electromagnetic properties of these mesons are, therefore, crucial for probing QCD at the confinement scale. The study of two-photon decay widths of the π^0, η, and η' are of fundamental importance in determining mixing effects among the mesons and in obtaining the light-quark mass ratios. The *PrimEx* collaboration at Jefferson Lab has a comprehensive program to perform a high precision measurement of the $\pi^0 \to \gamma\gamma$ decay width via the Primakoff effect. With the planned 11 GeV upgrade of CEBAF, the current program will be extended to include the η and η' mesons.

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1. Introduction

In the limit of massless u, d, and s quarks, the classical QCD Lagrangian exhibits a $SU(3)_{\mathrm{L}} \times SU(3)_{\mathrm{R}} \times U(1)_{\mathrm{A}}$ symmetry. In full quantum theory, the $U(1)_{\mathrm{A}}$ symmetry is explicitly broken, leading to chiral anomaly in QCD [1]. On the other hand, the $SU(3)_{\mathrm{L}} \times SU(3)_{\mathrm{R}}$ symmetry is spontaneously broken, giving rise to eight massless pseudoscalar Goldstone bosons. The effects of $SU(3)$ and isospin breaking by the u, d and s quark mass differences lead to important mixing effects among the light pseudoscalar mesons. Understanding the electromagnetic properties of these mesons is, therefore, fundamentally important in probing QCD at the confinement scale. One of the most interesting systems in low-energy QCD is represented by the three neutral light pseudoscalar mesons, π^0, η, and η', the first two being Goldstone bosons. The study of two-photon partial decay widths of π^0, η, and η' are of fundamental importance in determining the mixing angle of the η–η' system, and the light quark mass ratios [2]. These studies will provide a test of the low-energy limit of QCD in a relatively clean setting, and help us better understand the origin and dynamics of chiral symmetry breaking.

The *PrimEx* collaboration at Jefferson Lab has a comprehensive program to perform a high precision ($\sim$1.5%) measurement of the neutral pion lifetime using the small angle coherent photoproduction of π^0's in the Coulomb field of a nucleus, i.e., the Primakoff effect [3]. The proposed measurement will fill an important gap between theoretical prediction and the experimental value of the π^0 lifetime. The primary experimental equipment for this measurement includes a high-resolution electromagnetic hybrid calorimeter (HYCAL), with Pb-glass modules and a central insertion of high resolution $PbWO_4$ crystals, together with the Hall B photon tagger, and a pair production luminosity monitor.

With the planned upgrade of the CEBAF beam energy to 11 GeV, the current development of the high precision measurement of the $\pi^0 \to \gamma\gamma$ decay width will be extended to include the $\eta \to \gamma\gamma$ and the $\eta' \to \gamma\gamma$ channels [4]. These measurements of the radiative decay widths will provide important and fundamental tests of both QCD and QCD inspired models.

2. Radiative widths of pseudoscalar mesons

The production of mesons in the Coulomb field of a nucleus by real photons is essentially the inverse of the decay $\eta, \eta' \to \gamma\gamma$, and the cross section for this process thus provides a measure of the η, η' two-photon decay widths. For unpolarized photons, the Primakoff cross section is given by [5]

$$\frac{\mathrm{d}\sigma_{\mathrm{P}}}{\mathrm{d}\Omega} = \Gamma_{\gamma\gamma} \frac{8\alpha Z^2}{m^3} \frac{\beta^3 E^4}{Q^4} |F_{\mathrm{e.m.}}(Q)|^2 \sin^2\theta_{\mathrm{m}} \,, \tag{1}$$

where $\Gamma_{\gamma\gamma}$ is the decay width of the η or η', Z is the atomic number, m, β, θ_{m} are the mass, velocity, and production angle of the mesons, E is the energy of the incoming photon, Q is the momentum transferred to the nucleus, and $F_{\mathrm{e.m.}}(Q)$ is the nuclear electromagnetic form factor, corrected for final-state interactions of the outgoing mesons. However, in addition to the contribution from the Primakoff effect, there are other competing hadronic mechanisms for meson photoproduction at high energies. The separation of the Primakoff effect from other contributing processes is realized by measuring $\mathrm{d}\sigma/\mathrm{d}\Omega$ at forward angles.

As with the π^0, the $\eta \to \gamma\gamma$ and the $\eta' \to \gamma\gamma$ are also dominated by the chiral anomaly. In addition, there is also the effect of $SU(3)$ breaking which causes π, η, η' mixing. The precise experimental determination of $\Gamma_{\eta\to\gamma\gamma}$ and $\Gamma_{\eta'\to\gamma\gamma}$ radiative widths will lead to a good determination of the η–η' mixing angle. Also, the $\eta \to \gamma\gamma$ will significantly improve the $\eta \to \pi\pi\pi$ decay width, leading to a determination of the light-quark mass ratios.

2.1. Previous measurements of $\Gamma_{\eta\to\gamma\gamma}$ and $\Gamma_{\eta'\to\gamma\gamma}$

The present experimental status of the $\Gamma_{\eta\to\gamma\gamma}$ partial decay width for the η is shown in Fig. 1, along with the projected measurement which would be possible

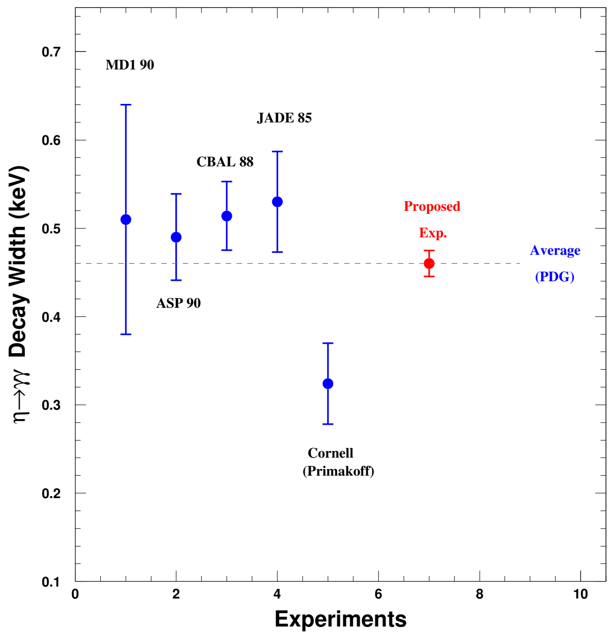

Fig. 1. Two-photon decay width of the η meson. Numbering from left to right, points 1 through 4 are the results of e^+e^- *collision experiments (for references, see Ref. [6]), point 5 is the result of the Primakoff experiment [7]. The dashed line is the Particle Data Group [6] average based on the first five points. Point 7 is the expected error for the future* PrimEx *experiment, arbitrarily plotted to agree with the Particle Data Group average value.*

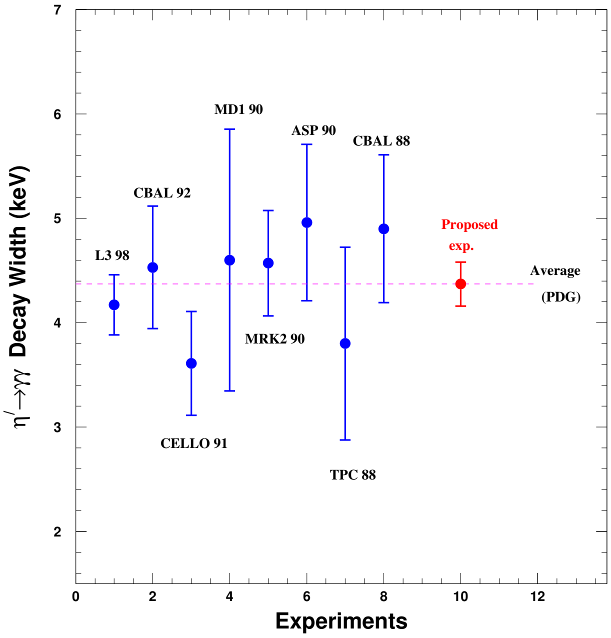

Fig. 2. Two-photon decay width of the η' meson. Numbering from left to right, points 1 through 8 are the results of e^+e^- *collision experiments (for references, see Ref. [6]). The dashed line is the Particle Data Group [6] average based on the points 2-8. The last point is the expected error for the future* PrimEx *experiment, arbitrarily plotted to agree with the Particle Data Group average value.*

with the upgraded 11 GeV beam at Jefferson Lab. Most of the measurements in the figure have been performed using two photon interactions in e^+e^- collisions, except the Cornell measurement [7] which was done via the Primakoff effect. This gives a two-photon decay width for the η which is significantly lower than those from e^+e^- collision experiments. A re-measurement of the η decay width using state-of-the-art experimental techniques, as proposed for the future *PrimEx* experiment, will resolve this discrepancy.

The η' two-photon decay width, in contrast to the η, has been measured only in collider-type experiments which have provided an internally consistent data set. In view of the inconsistency between the Primakoff and the collision methods for the η, *PrimEx* also plans to measure the η' width via the Primakoff technique. In Fig. 2, the current status [6] of the η' decay width is shown, with the last point being the projected measurement at Jefferson Lab.

2.2. Impact of precise determination of $\Gamma_{\gamma\gamma}$ for η and η'

One of the impacts of a more precise measurement of the two-photon partial widths would be in the corresponding improvement in the determination of the rest of the partial widths, as these are determined using the two-photon widths and the corresponding branching ratios. This would therefore have a wide ranging impact. One decay that is of particular importance is the decay $\eta \to \pi\pi\pi$ which is driven by isospin breaking, and thus gives access to the quark mass ratio $(m_\mathrm{u} - m_\mathrm{d})/m_\mathrm{s}$. Leutwyler [2] in a very elegant analysis constructed a relation, now called Leutwyler's ellipse, given by

$$\left(\frac{m_\mathrm{u}}{m_\mathrm{d}}\right)^2 + \frac{1}{\mathcal{Q}^2}\left(\frac{m_\mathrm{s}}{m_\mathrm{d}}\right)^2 = 1\,, \tag{2}$$

where the semi-major axis $\mathcal{Q}$ is given by the ratio

$$\mathcal{Q}^2 = \frac{m_\mathrm{s}^2 - \hat{m}^2}{m_\mathrm{d}^2 - m_\mathrm{u}^2}\,, \tag{3}$$

with $\hat{m} = (m_\mathrm{u} + m_\mathrm{d})/2$.

One way to determine $\mathcal{Q}$ is given by a ratio of meson masses

$$\mathcal{Q}^2 = \frac{M_\mathrm{K}^2}{M_\pi^2}\frac{M_\mathrm{K}^2 - M_\pi^2}{(M_{\mathrm{K}^0}^2 - M_{\mathrm{K}^+}^2)_\mathrm{QCD}}\{1 + \mathcal{O}(m_\mathrm{quark}^2)\} \tag{4}$$

The main problem in extracting $\mathcal{Q}$ from this relation arises from the uncertainties in the electromagnetic contributions to the $\mathrm{K}^0 - \mathrm{K}^+$ mass difference. Another way to extract $\mathcal{Q}$ is by means of $\eta \to \pi\pi\pi$ decay that has negligibly small electromagnetic corrections due to chiral symmetry. The second approach thus represents a more sensitive probe of the symmetry breaking generated by $(m_\mathrm{d} - m_\mathrm{u})$ [8]. As emphasized by Leutwyler [9], the main errors in determining $\mathcal{Q}$ using $\eta \to \pi\pi\pi$ decays are due to the experimental uncertainties in the partial width $\Gamma_{\eta\to\pi\pi\pi}$ that are determined by the two-photon width $\Gamma_{\eta\to\gamma\gamma}$ and branching ratio. The significant improvement that an η photoproduction experiment via the Primakoff effect at Jefferson Lab would have over previous measurements is shown in Fig. 3. This is one important example of the impact that a more precise measurement of the η and η' two-photon widths would have for determining fundamental parameters of QCD.

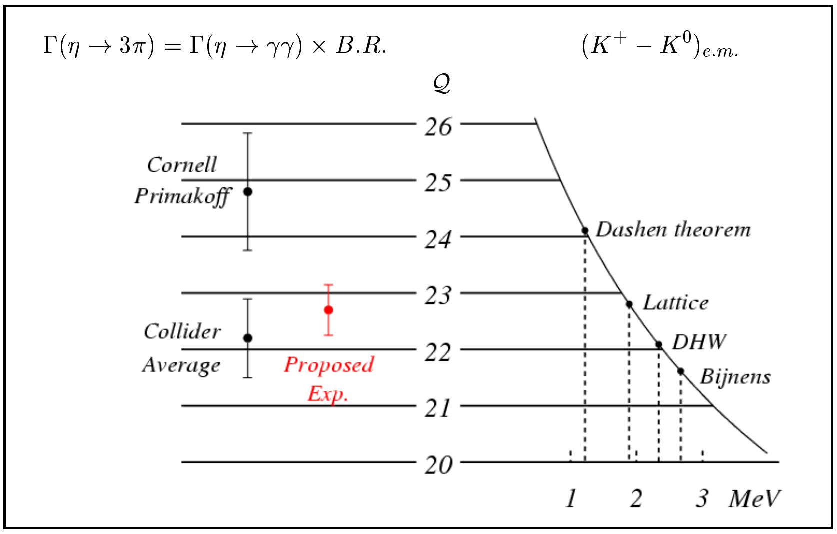

Fig. 3. The importance of $\Gamma_{\eta\to\gamma\gamma}$ in the measurement of $\mathcal{Q}$. The l.h.s. indicates the values of $\mathcal{Q}$ corresponding to the Primakoff and collider experimental results for the $\Gamma_{\eta\to\gamma\gamma}$, as well as what could be obtained with 11 GeV at Jefferson Lab. The r.h.s. shows the results for $\mathcal{Q}$ obtained with four different theoretical estimates for the electromagnetic self energies of the kaons [2].

The non-zero quark masses in the real world make the relatively straightforward situation of the chiral limit much more complex. The current quark masses make the π^0 and the η massive and shift the mass of the η' due to explicit breaking of chiral symmetry, while $SU(3)$ isospin breaking induce mixings among the three mesons. The mixings are expressed in terms of three mixing angles [10]. Writing the eigenstates in the chiral limit on the left, they are expressed in terms of the physical states by

$$\begin{aligned} \pi_8^0 &= \pi^0 - \epsilon\eta - \epsilon'\eta' \\ \eta_8 &= \cos\theta\,(\eta + \epsilon\pi^0) + \sin\theta\,(\eta' + \epsilon'\pi^0) \\ \eta_0 &= -\sin\theta\,(\eta + \epsilon\pi^0) + \cos\theta\,(\eta' + \epsilon'\pi^0) \end{aligned} \tag{5}$$

A recent global analysis [10] has been performed that uses as input the two-photon decay widths of the η and η' and includes next to leading order chiral corrections as well as $1/N_c$ corrections. The angles ϵ and ϵ' play an important role in the lifetime of the π^0, decreasing it by approximately 4% [10, 11].

The mixing angle, θ, based on the Cornell Primakoff measurement and the collider experiments, is shown in Fig. 4, as calculated in the three mixing angle scenario of Ref. [10]. The rightmost point in the figure shows the expected precision which could be obtained at 11 GeV at Jefferson Lab.

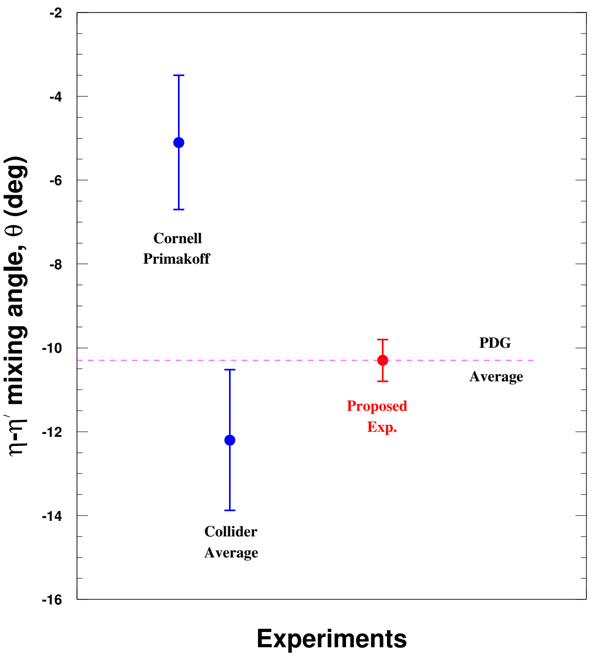

Fig. 4. The $\eta - \eta'$ mixing angle as determined by a previous Primakoff measurement, $\gamma - \gamma$ collisions, and the projected results from the future PrimEx *experiment, arbitrarily plotted to agree with the Particle Data Group [6] average value (dashed line).*

3. Experimental setup for decay width measurements

The *PrimEx* collaboration proposes to use a tagged photon beam obtained from the 11 GeV electrons to produce the η/η' via the Primakoff effect in which pseudoscalar mesons are produced by the interaction of a real photon with the quasi-real photon from the Coulomb field of the nucleus. The primary targets that will be studied are liquid hydrogen (LH2) and helium-4 (LHe4). The multi-photon final states of the decayed mesons will be detected in a calorimeter. In addition to the planned upgraded 11 GeV beam of CEBAF, such measurements would require (1) a high-energy photon tagging system, and (2) a multichannel calorimeter consisting of high resolution lead tungstate scintillating crystals.

3.1. High-energy photon tagging system

The proposed program requires a high-intensity, high-precision 11 GeV photon tagging system. The existing Hall B photon tagging facility is designed for a maximum of 6 GeV and currently there are no plans for upgrading this to tag higher energy photons. The *PrimEx* collaboration is proposing the construction of a high-energy photon tagging system based on a new approach involving parallel transport of both the photon and primary electron beams through the beamline up to the beam dump. The beamline setup will consist of two identical 'C-type' dipoles, the second one of which will displace the incident electron beam and make it parallel to the photon beam produced in the bremsstrahlung radiator placed just upstream of the first dipole. Figure 5 shows a schematic layout of the proposed high-energy tagging system. The post-bremsstrahlung electrons will be deflected in the first C-dipole and detected by the tagger focal plane detectors. The primary targets will be placed downstream of the second dipole.

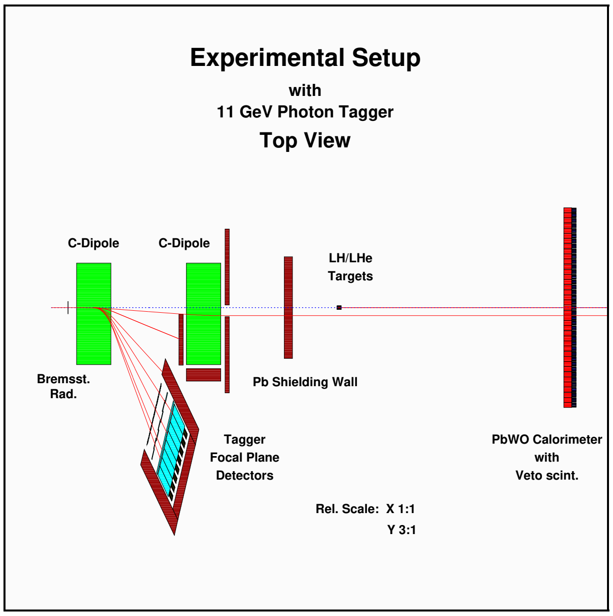

Fig. 5. Top view of the experimental setup for $\Gamma_{\eta\to\gamma\gamma}$ and $\Gamma_{\eta'\to\gamma\gamma}$ measurements. It includes (1) a photon tagging system, and (2) a $1.5\,\mathrm{m} \times 1.5\,\mathrm{m}$ *multichannel calorimeter.*

3.2. The electromagnetic calorimeter

The photons resulting from the decay of the forward produced η and the η' will be detected in a high-resolution electromagnetic calorimeter. For this purpose, the current hybrid shower calorimeter (HYCAL) that is being constructed by the *PrimEx* collaboration for the π^0 lifetime measurement in Hall B, will be upgraded such that it is composed entirely of $PbWO_4$ modules with a total overall size of $1.5\,\mathrm{m} \times 1.5\,\mathrm{m}$. Therefore, the calorimeter is designed for high-precision measurements of both the position and the energy of the electromagnetic showers. The calorimeter will be placed at a variable distance downstream of the production targets to provide optimal acceptance for photon detection.

4. *Summary*

The *PrimEx* collaboration has proposed a comprehensive program to measure the two-photon decay widths of the light pseudoscalar mesons (π^0, η, η') which would be possible with the planned 11 GeV upgrade of the CEBAF beam energy. The radiative-width measurements will have a significant impact on the experimental determination of fundamental parameters of QCD, namely the ratio of light quark masses ($m_\mathrm{u}, m_\mathrm{d}, m_\mathrm{s}$) and on the magnitude of the $\eta - \eta'$ mixing.

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MJERENJE RADIJATIVNE ŠIRINE LAKIH PSEUDOSKALARNIH MEZONA NA 11 GeV PROMAKOFFOVIM EFEKTOM

Spontano kršenje kiralne simetrije i kiralne anomalije u niskoenergijskoj QCD očituju se najnedvosmislenije za lake pseudoskalarne mezone. Dakle, razumijevanje elektromagnetskih svojstava tih mezona je ključno za provjeru QCD u sektoru sužanjstva. Proučavanje širina dvofotonskog raspada π^0, η i η' ima temeljnu važnost za određivanje efekata miješanja među tim mezonima i za dobivanje omjera masa lakih kvarkova. Suradnja *PrimEx* ima opsežan program za precizna mjerenja širina raspada $\pi^0 \to \gamma\gamma$ putem Primakoffovog efekta. Planirano povećanje energije CEBAF na 11 GeV omogućit će proširenje na η i η' mezone.