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Mainz Microtron MAMI

Collaboration A2: "Real Photons"
Spokesperson: A. Thomas

Proposal for an Experiment

"Testing Chiral Perturbation Theory and C Invariance in η' Decays"

Collaborators :

CrystalBall@MAMI collaboration

Spokespersons for the Experiment :
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Abstract of Physics :

We propose to make a new high–statistics measurement of several neutral η' decays. The principal ones $\eta' \to \eta\pi^0\pi^0$, and $\eta' \to 3\pi^0$ are tests of ChPT. The ratio of those two η' decays is a direct determination of the up–down quark mass difference by induced $\pi^0 - \eta$ mixing. The Dalitz plots of both η' decays provide information on the $\pi\pi$, and $\pi\eta$ scattering lengths. The expected statistics is about 10^5 $\eta' \to \eta\pi^0\pi^0$ events in 500 hours. That is an order of magnitude more than the existing world data sample. We will test C–invariance improving by a factor of 100 the upper limits of the $\eta' \to \pi^0 e^+e^-$, $\eta' \to \eta e^+e^-$, and $\eta' \to 3\gamma$ C–forbidden decays. We will test CP–invariance searching for $\eta' \to 4\pi^0$. All neutral η' decays will be measured simultaneously.

Abstract of Equipment :

The experiment will use the high intensity MAMI-C photon beam $E^{\gamma}_{max} = 1.5$ GeV incident on a liquid-hydrogen target. The 4π experimental setup consists of the self–triggering Crystal Ball multiphoton spectrometer equipped with TAPS as a forward wall, and a scintillator PID.

MAMI–Specifications :

beam energy	1500 MeV
beam current	< 100nA
time structure	cw
polarization	unpolarized photons

Experiment–Specifications :

experimental hall/beam	A2
detector	Crystal Ball, TAPS, MWPC, PID
target material	liquid hydrogen

Beam Time Request :

set–up without beam	—
set–up/tests with beam	100 hours (parallel with proposal A2/ ???)
data taking	600 hours (parallel with proposal A2/ ???)

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1 Introduction

The η and η' mesons have the same quantum numbers. Both mesons can be used to test chiral perturbation theory as well as many models and theories of hadron interaction. One can also look for violation of lepton–family number, and place limits on the masses and couplings of many proposed lepto–quark families, see Refs [1, 2, 3, 4, 5] for example. They are suitable also to search for violation of C, CP, and even CPT invariance [6]. The later can be tested, for example, in the decay $\eta' \to \pi^0\mu^+\mu^-$.
The η has been the subject of several high quality experiments involving many millions of eta decays. The η' decays have hardly been explored; the samples used are a few thousand decays only.
We propose to make a new high–statistics measurement of several neutral η' decays. The principal ones are

$$\eta' \to \eta\pi^0\pi^0 \tag{1}$$

$$\eta' \to 3\pi^0 \tag{2}$$

The ratio of those two η' decays is a direct determination of the up–down quark mass difference [7] by induced $\pi^0-\eta$ mixing. The Dalitz plots of both η' decays provide information on the $\pi\pi$, and $\pi\eta$ scattering lengths. We also plan to measure the branching ratio, BR, for

$$\eta' \to \gamma\gamma. \tag{3}$$

This ratio, in conjunction with $BR(\eta \to \gamma\gamma)$, allows to investigate the $SU(3)$ singlet–octet mixing angle. We can also improve on the upper limit for the decays

$$\eta' \to \eta e^+e^-, \tag{4}$$

$$\eta' \to \pi^0 e^+e^-, \tag{5}$$

which are forbidden by C–invariance in first order, but allowed in second. We can improve on the upper limit for

$$\eta' \to 3\gamma, \tag{6}$$

which is another test of C invariance. We can even make an interesting test of CP invariance by a search for the CP forbidden decay

$$\eta' \to 4\pi^0. \tag{7}$$

The proposed experiment uses the unique properties of the Crystal Ball (preferable with TAPS as a forward wall) multiphoton spectrometer, which has near–4π acceptance, excellent energy and angle resolution and which is self–triggering. The later property we have found to be indispensable in our extensive measurements of various η decays carried out with the Crystal Ball at the AGS. We plan to use the nontagged real photons from the end point of the bremsstrahlung spectrum produced by the 1.5 GeV electron beam from MAMI-C.

2 η, and η' quark structure

The nonet of pseudoscalar mesons P can be described in terms of the $SU(3)$ octet and singlet matrices [8]:

$$P_8 = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta_8}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta_8}{\sqrt{6}} & K^0 \\ K^0 & \bar{K}^0 & -\frac{\sqrt{2}}{\sqrt{6}}\eta_8 \end{pmatrix} \tag{8}$$

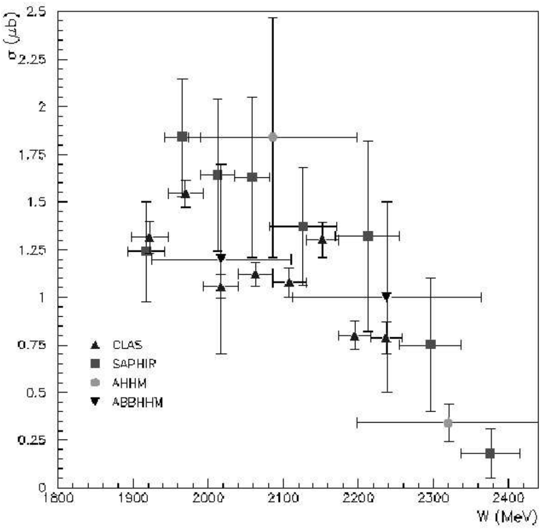

Figure 1: Total cross section for η' photoproduction.

$$P_0 = \frac{1}{\sqrt{3}}\eta_0 I. \tag{9}$$

The physical η and η' are not a pure SU(3)–octet and SU(3)–singlet. The $\eta - \eta'$ mixing is usually formulated in terms of the mixing angle θ, or $\phi = \theta + \arctan(\sqrt{2})$. Θ refers to the octet–singlet, and ϕ to the nonstrange–strange basis:

$$\eta = \cos\theta\eta_8 - \sin\theta\eta_0 = \cos\phi(u\bar{u} + d\bar{d})/\sqrt{2} - \sin\phi s\bar{s} \tag{10}$$

$$\eta' = \sin\theta\eta_8 + \cos\theta\eta_0 = \sin\phi(u\bar{u} + d\bar{d})/\sqrt{2} + \cos\phi s\bar{s} \tag{11}$$

The value for θ is $(20 \pm 2)^\circ$. If we choose $\theta = 19.5^\circ$, the physical η can be parameterized as:

$$|\eta\rangle = \frac{1}{3}\sqrt{3}|\overline{u}u + \overline{d}d - \overline{s}s\rangle,$$

which means that the η is an eigenstate of the I, U, and V operators of SU(3) [9]. One also has $|\eta'\rangle = \sin\theta|\eta_8\rangle + \cos\theta|\eta_0\rangle = \frac{1}{6}\sqrt{6}|\overline{u}u + \overline{d}d + 2\overline{s}s\rangle$. The η' has twice the s–quark content of the η.

The existing experimental data on η' photoproduction are rather scarce. The total cross sections of the $\gamma p \rightarrow \eta' p$ in the vicinity of the η' threshold can be estimated from SAPHIR results at ELSA [10] and results from Jefferson Lab [11], see Fig. 1. The average total cross section of $\gamma p \rightarrow \eta' p$ from threshold to the maximum photon energy avaliable at MAMI-C is about 1 μb.

3 The decays of $\eta'(958)$ into three pseudoscaler mesons

The dominant η' neutral decay $\eta' \rightarrow \eta\pi^0\pi^0$ (21 %), takes place by strong interaction. In contrast the similar decay $\eta' \rightarrow 3\pi^0$, which has a larger phasespace, is G–parity forbidden. It still occurs, but as a consequence of the G–violating mass term of the QCD Lagrangian,

$$\mathcal{L}_m = -\sum_q m_q \overline{\psi}_q^i \psi_{q_i}, \tag{12}$$

so it is small (1.5 %). Equation 12 implies that the decay width, $\Gamma(\eta' \to 3\pi^0)$, depends directly of the mass difference of the up and down quarks. Naively, one may consider the decay $\eta' \to 3\pi^0$ to occur first as a $\eta' \to \eta\pi^0\pi^0$ transition, followed by $\eta - \pi^0$ mixing. As shown by Gross, Treiman and Wilczek [7], it provides the basis for the relation

$$R^2 = \Phi \times \frac{\Gamma(\eta' \to \eta\pi^0\pi^0)}{\Gamma(\eta' \to 3\pi^0)}, \tag{13}$$

where

$$R = \frac{m_s - \hat{m}}{m_d - m_u}. \tag{14}$$

In the equation above $\hat{m} = 1/2(m_u + m_d)$, and Φ is a combination of a phase–space factor and Clebsch–Gordan coefficients. The current masses of the quarks are input to QCD. The quark masses cannot be determined directly because they are not free particles. A program has been launched for the determination of the measurable quark mass differences in many different experiments [12]. One of the objectives of the η and η' decay program is to extract better values for R including the ratio of the η' decays of Eq. 13.

Another objective of our η, η' program is to investigate the $\pi\pi$ and $\pi\eta$ scattering phases. At low energy $\pi\pi$ and $\pi\eta$ scattering are relatively small and appear not to vary much. The modest energy dependence of $\pi\pi$ and $\pi\eta$ scattering gives rise to a small variation in the density of the Dalitz plots which shows up in the pion slope parameter.

Because the energy release in the $\eta' \to \eta\pi^0\pi^0$ decay is small, only 141 MeV, the matrix element for the $\eta' \to \eta\pi^0\pi^0$ can be described by the following:

$$|M|^2 \sim |1 + \alpha y|^2 + cx^2, \tag{15}$$

where x and y are the Dalitz variables

$$y = \frac{(2 + m_\eta/m_\pi) \times T_\eta}{Q} - 1 \tag{16}$$

$$x = \frac{\sqrt{3} \times (T_1 - T_2)}{Q}. \tag{17}$$

In the equations above T_1, T_2, and T_η are the kinetic energies of the two π^0 and the η in the η' rest frame; $Q = m'_\eta - m_\eta - 2m_\pi \approx 141$ MeV.

The current data are limited to a single experiment performed by the GAMS-2000 collaboration [13]. They used about 5400 $\eta' \to \eta\pi^0\pi^0$ decays and obtained $Re(\alpha) = -0.058 \pm 0.013$, $Im(\alpha) = 0.0 \pm 0.13$, and $c = 0.00 \pm 0.03$. Thus the matrix element is well described by a linear function with slope $\alpha = -0.058 \pm 0.013$.

For the decay $\eta' \to 3\pi^0$ the slope parameter is quoted as $\beta = -0.1 \pm 0.3$ by the GAMS-2000 group [14].They used a sample of about 100 $\eta' \to 3\pi^0$ events.

The CLEO collaboration has looked at a sizable sample of η' decays obtained in e^+e^- collisions with the Cornell Electron Storage Ring, CESR, using $\Upsilon(4S)$ and $B\bar{B}$ decays. CLEO has investigated the spectrum of $\eta' \to \eta\pi^+\pi^-$ and quoted $Re(\alpha) = -0.021 \pm 0.025$ [15], see Fig. 2. Unfortunately the signal–to–background ratio of their η' sample is less than one. We prefer the η' decays to neutral π^0's because one avoids having to make Coulomb corrections.

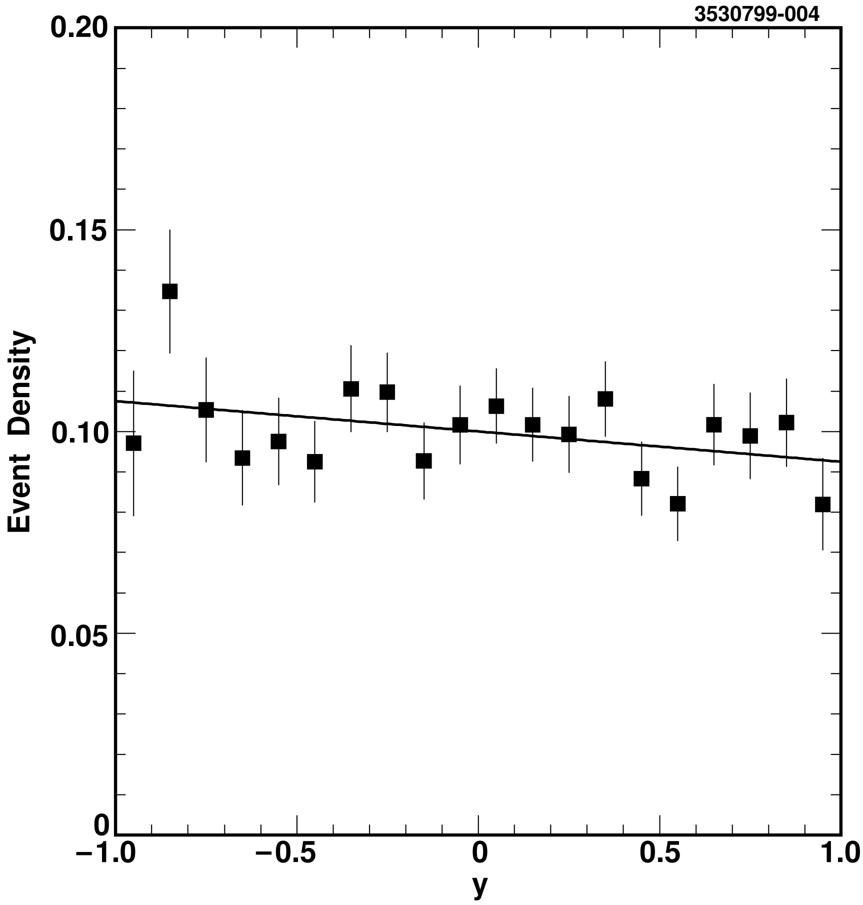

Figure 2: Linear fit to the event density of the $\eta' \to \eta\pi^+\pi^-$ Dalitz plot, projected along the y–axis, with $p_\eta > 0.6$ GeV/c and sidebands defined as 4–6 σ to either side of the mean [15].

4 The Determination of the S–wave $\pi - \pi$ Scattering Length from the dipion invariant mass spectrum.

Pion–pion elastic scattering is an attractive way for testing our understanding of spontaneous as well as explicit chiral symmetry breaking in QCD. The $\pi\pi$ S-wave scattering lengths vanish in the chiral limit since Goldstone bosons can interact only if they carry momentum. In reality, the quarks have masses and this causes a nonzero value for the measured scattering lengths a_0^0 and a_0^2. Hence these quantities represent a sensitive probe of the symmetry breaking generated by the quark masses. Weinberg's low energy theorems [16] state that the values of the a_0's are related to the pion mass, which also represents the symmetry breaking effect:

$$a_0^0 = \frac{7m_\pi^2}{32\pi F_\pi^2} + O(m^2), \tag{18}$$

$$a_0^2 = -\frac{m_\pi^2}{16\pi F_\pi^2} + O(m^2)\ [19]. \tag{19}$$

Chiral perturbation theory (ChPT) makes firm predictions for the S-wave a_0^0 scattering length. The tree level calculation in χPT gives $a_0^0 = 0.16$ (in units of m_π); the one–loop ($a_0^0 = 0.20$) and two–loop calculation ($a_0^0 = 0.217$) show a satisfactory convergence [17]. The most recent calculation matches the known chiral perturbation theory representation of the $\pi\pi$ scattering amplitude to two loops [17] with a phenomenological description that relies on the Roy equations [18], resulting in the prediction $a_0^0 = 0.220 \pm 0.005$ [19]. Practically, the $\pi\pi$ scattering length can be extracted from dipion phase shift δ_0^0. The phase shift as a function of $M(\pi\pi)$ can be obtained experimentally. The phase shift then can be related to the scattering lengths using various parameterizations [20]. For example in the energy range of K_{e4}- decay the relation between δ and a_0^0 can be approximated by the following expansion [21]:

$$\sin 2\delta = 2\left(\frac{s_\pi - 4m_\pi^2}{s_\pi}\right)^{1/2}(a_0^0 + bq^2/m_\pi^2), \tag{20}$$

where $b = b_0^0 - a_1^1$, i.e, the difference between the S–wave slope and the P–wave scattering length. According to Ref. [22] b and a_0^0 are related by the expression $b = 0.19 - (a_0^0 - 0.15)^2$ with a theoretical uncertainty of ± 0.04 on b.

Currently there are two significant measurements of the a_0^0 scattering length; both experiments used $K^+ \to \pi^+\pi^-e^+\nu$ decay, see Refs. [21, 23]. The lastest value for the S–wave $\pi\pi$ scattering length is $[a_0^0 = 0.216 \pm 0.013(\text{stat}) \pm 0.004(\text{syst}) \pm 0.005(\text{theor})]$ [23].

The $\eta' \to \eta\pi\pi$ decay provides an alternative way of measuring the S–wave scattering length. Assuming that the $(\pi\pi)$ pair is predominantly in $I = J = 0$ state and reasonably small $\pi\eta$ interaction, the shape of the $\pi\pi$ invariant mass distribution depends on $\sin^2 \delta_0^0$.

Detailed calculations of the electromagnetic corrections were made as early as 1997 by U. Meissner *et al.* [24, 25]. Recently N. Cabibbo [26] presented a specific calculation of the $\pi - \pi$ scattering length combination $a_0 - a_2$ based on a study of the $\pi^0\pi^0$ invariant mass spectrum in $K^+ \to \pi^0\pi^0\pi^+$ in the vicinity of the $\pi^+\pi^-$ threshold. He noted the applicability of this method to $K_L \to 3\pi^0$ with less sensitivity as well as to $\eta \to 3\pi^0$, also with less sensitivity. C. W. Wong [27] has worked out the specifics. He found that the effect which is small in $\eta \to 3\pi^0$, is much larger in $\eta' \to \eta\pi^0\pi^0$. The consequence of the scattering $\pi^-\pi^+ \to \pi^0\pi^0$ is to induce a cusp at the opening of the $\pi^-\pi^+ \to \pi^0\pi^0$ channel. This cusp is about 1% in $\eta \to 3\pi^0$, which is hard to measure at present. For $\eta' \to \eta\pi^0\pi^0$ the situation is much better: the cusp has a 13% effect. We belief that a preliminary determination of the Dalitz plot should be made before considering an actual measurement of this cusp. The basic physics to be learned in certainly worth the efforts to investigate the feasibility of a detailed study of the shape of the $\eta' \to \eta\pi^0\pi^0$ Dalitz plot.

5 Other decays of the η'

C invariance, or charge conjugation symmetry, is the invariance of a system to the interchange of the colored quarks with their antiquarks of anticolor, the charged leptons with their antileptons, the left(right)-handed neutrinos with the left(right)-handed antineutrinos, and vice versa. According to QED and QCD, C invariance holds for all purely electromagnetic and all strong interactions, but the experimental limits are not impressive. The Review of Particle Physics [28] lists "all weak and electromagnetic decays whose observation would violate conservation laws." Seventeen tests of C invariance are listed: eight involve decays of the η, six of the η', two of the ω and one of the π^0. Only the two new tests given in Ref. [29] have a significant limit. Because the width of η' is broader than η, the η' decays are less sensitive to a C violation than corresponding η decays.

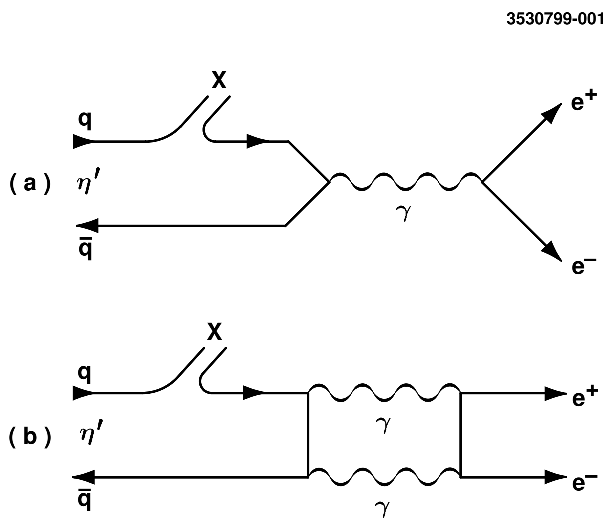

Figure 3: (a) C-violating ($BR \sim \alpha^2$) and (b) C-conserving ($BR \sim \alpha^4$) contributions to the decay $\eta' \to e^+e^-X$, where X is an η or π^0 [15].

The η', η, and π^0 are even eigenstates of C, while a photon is C–odd; thus the one–photon process will be C–violating and the two–photon process C–conserving. The decays $\eta' \to \eta e^+e^-$ and $\eta' \to \pi^0 e^+e^-$ can occur with one (C–violating) or two (C–conserving) intermediate virtual photons, as shown in Fig. 3 [15]. Cheng has estimated the relative rate for the C–conserving part of the amplitude for the similar decay $\eta \to \pi^0 e^+e^-$: $BR(\eta \to \pi^0 e^+e^-)/BR(\eta \to \pi^0\gamma\gamma) \approx 10^{-5}$ [30]. The branching ration of $\eta' \to \pi^0\gamma\gamma$ is $< 8 \times 10^{-4}$. Assuming a similar ratio for the η' decays, a signal at the 10^{-9} level or larger would signify a large C-violating contribution or other new physics. The current 90% confidence upper limits for these decays are $BR(\eta' \to \eta e^+e^-) < 2.4 \times 10^{-3}$ and $BR(\eta' \to \pi^0 e^+e^-) < 1.4 \times 10^{-3}$ [15].
The decay of η' into three photons is rigorously forbidden by C-invariance. The 3γ decay should be small as it is a third order electromagnetic interaction and $\alpha^3 = 4 \times 10^{-7}$. The rate is further suppressed by substantial factors coming from phase space and angular momentum barrier considerations. [31]. The decay $\eta' \to 3\gamma$ can be isoscalar or isovector and even the hypothetical isotensor interaction. The Particle Data Group [28] lists the upper limit for the $\eta' \to 3\gamma$ branching ratio as 1×10^{-4}. We can improve the upper limit substantially.
The decay $\eta' \to e\mu$ with no accompanying neutrinos is an example of lepton number violation. The theoretical upper bound for this decay is on the order of 10^{-11}, calculated from the experimental limit on $\mu^- \to e^-$ conversion in heavy nuclei [32]. The current upper limit for this decay is $B(\eta' \to e\mu) < 4.7 \times 10^{-4}$ [15].

6 Experiment

The upgraded MAMI-C machine is anticipated to provide a high quality electron beam with maximum energy of $E_e = 1.5$ GeV, i. e. maximum energy of the bremsstrahlung photons will be also 1.5 GeV. The maximum energy of the tagged photon spectrum is about 92% of the maximum electron energy, that is about $E_\gamma = 1.4$ GeV. The threshold for $\gamma p \to \eta' p$ is $E_\gamma^{thresh} = 1.447$ GeV. Therefore the η' can be produced by the MAMI-C photon beam

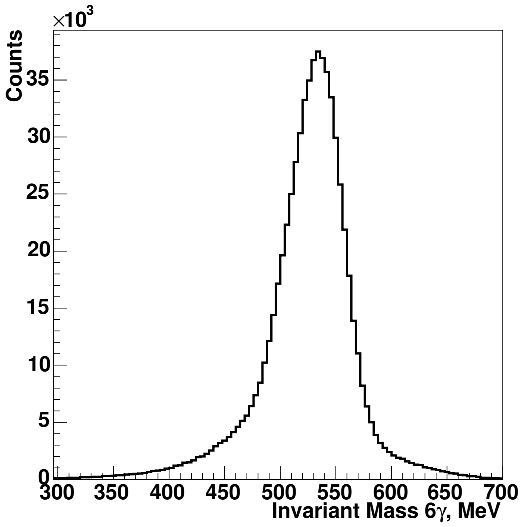

Figure 4: Experimentally measured invariant mass spectrum of six photons produced in reaction $\gamma p \to 6\gamma p$.

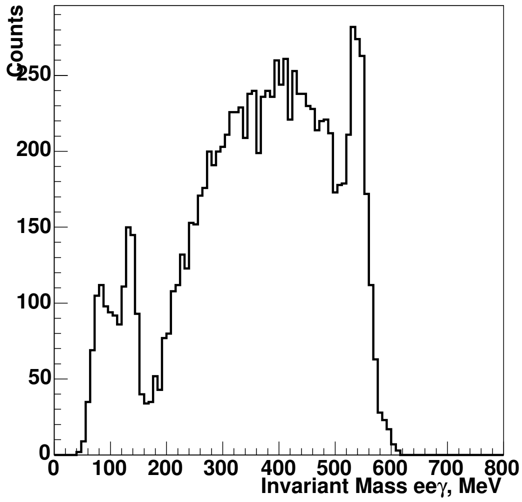

Figure 5: Spectrum of $e^+e^-\gamma$ invariant mass measured with the Crystal Ball detector at MAMI-B.

by the untagged part of the photon spectrum. We still have a constraint on the energy of the incident photon beam ($\Delta E_\gamma = 53$ MeV from the threshold to $E_\gamma = 1.5$ GeV), but with a resolution of ± 26 MeV. This is worse compared to the energy resolution of the tagged photon beam, however the average beam energy can be used to calculate the missing mass of η' with an accuracy of about 30 MeV/c^2.

Because of the limitation of the photon tagging system, we should relay on tagging the η''s by using the recoil proton from $\gamma p \to \eta' p$, and use the internal reaction constraints to clean up the event sample. There are four internal constraints in the decay chain $\eta' \to \eta\pi^0\pi^0$ followed by the $\eta \to \gamma\gamma$ ($\eta(2\gamma)2\pi^0$) decay, namely the masses of the two π^0, η and the η'. Three more constraints can be used in case the $\eta' \to \eta\pi^0\pi^0$ decay is followed by $\eta \to 3\pi^0$ ($\eta(3\pi^0)2\pi^0$). This makes an events with seven internal constraints! Of course, there is a problem of combinatorial background to deal with, but the Crystal Ball is known for its ability to handle multiphoton final states [34].

6.1 Experimental Setup

The proposed detector for a high quality measurement of the η' decays is the Crystal Ball multiphoton spectrometer at MAMI-C. The CB is augmented with TAPS as a forward detector, with a charged particle tracker which consists of two DAPHNE coaxial cylindrical multiwire proportional chambers (MWPC) and with a particle identification detector (PID) which is a cylinder made of 24 scintillator strips 2 mm thick located around the liquid H_2 target, see Ref. [35] for details on the experimental setup. The experimental apparatus provides close to 4π sr coverage for outgoing photons. Protons are detected by the TAPS forward wall for $\Theta_{lab} < 21°$, and by the MWPC plus PID for other angles. The Crystal Ball has new electronics with a TDC and a flash ADC for every crystal. The use of the flash ADC's minimizes the effects of old tracks on the event efficiency and improves the photon energy resolution because the "afterglow" in the NaI is corrected for. The experimental readout electronics will be upgraded for the MAMI-C stage of the program. The anticipated

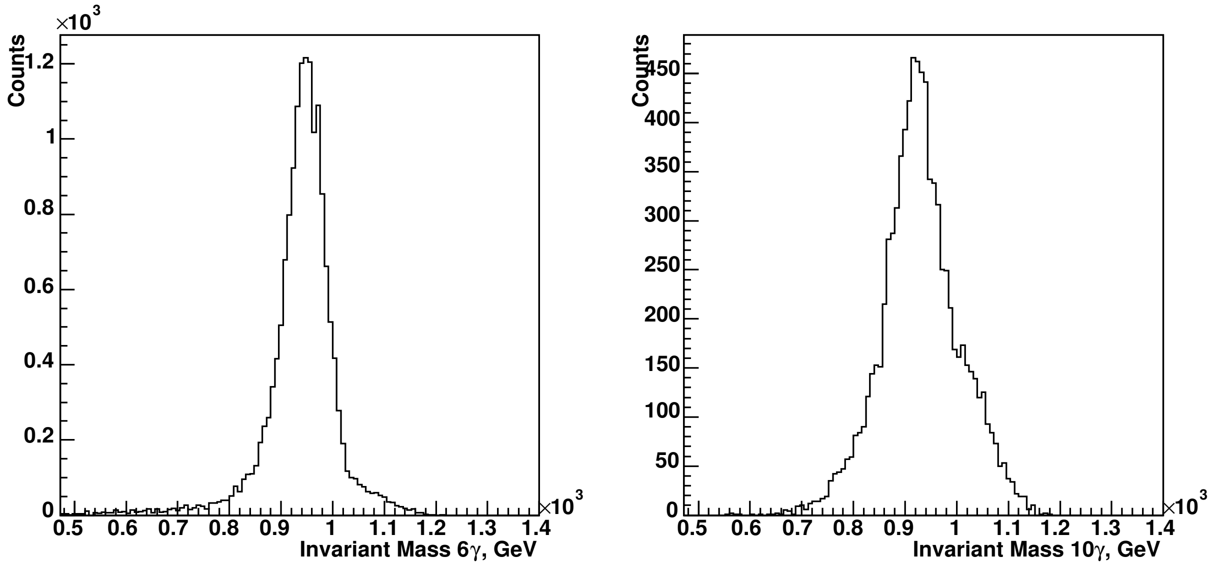

Figure 6: Monte Carlo simulation of $\gamma p \to \eta' p$ followed by $\eta' \to \eta\pi^0\pi^0$ for two η decay modes. Left figure shown the invariant mass of six photons for the η' decay followed by $\eta \to \gamma\gamma$. Right figure shows invariant mass of 10 photons for the $\eta' \to \eta\pi^0\pi^0$ decay followed by $\eta \to 3\pi^0$ decay.

DAQ speed is a few kHz.

All major components of the proposed experimental setup were successfully used with the MAMI-B [35] tagged photon beam in 2004-2005. The 2004-2005 experimental run included the experiment on η production, which is similar to the one described in this proposal. The primary goal of the η experiment was a new high precision measurement of $\eta \to \pi^0\gamma\gamma$ decay as well as improving upper limits on a few CP and C violating decays, including $\eta \to 3\gamma$ [36]. During about 300 hours of data taking we collected $\sim 3 \times 10^6$ $\eta \to 3\pi^0$ decays this corresponds to $\sim 3 \times 10^7$ η's produced. Figure 4 shows the preliminary results for the invariant mass spectrum of six photons produced in reaction $\gamma p \to 6\gamma p$. One can see a dominant peak from the $\eta \to 3\pi^0$ events measured with good resolution and very little background. Most of the background under the peak comes from the direct three π^0 production in $\gamma p \to 3\pi^0 p$ via sequential decay of resonances [37]. A small part of the background is due to $\gamma - p$ misidentification in the analysis. Figure 5 shows a preliminary invariant mass spectrum for η decay into $e^+e^-\gamma$. The branching ratio for this η Dalitz decay is $BR(\eta \to e^+e^-\gamma) < (6.0 \pm 0.8) \times 10^{-3}$. A little peak from the $\pi^0 \to e^+e^-\gamma$ Dalitz decay is also see in Fig. 5. The peak from the π^0, however, is suppressed by our trigger conditions.

The acceptance calculated for the $\eta' \to \eta(\gamma\gamma)\pi^0\pi^0$ is about 30% when all six photon are detected, see Fig. 6. The acceptance for the $\eta' \to \eta\pi^0\pi^0$ decay followed by $\eta \to 3\pi^0$ is about 15%. The later decay can be used to check systematic uncertainties of the measurement, for example combinatorial background.

6.2 Trigger conditions

The trigger will be optimized to insure the high η' relative production rate. The following trigger conditions will be applied:

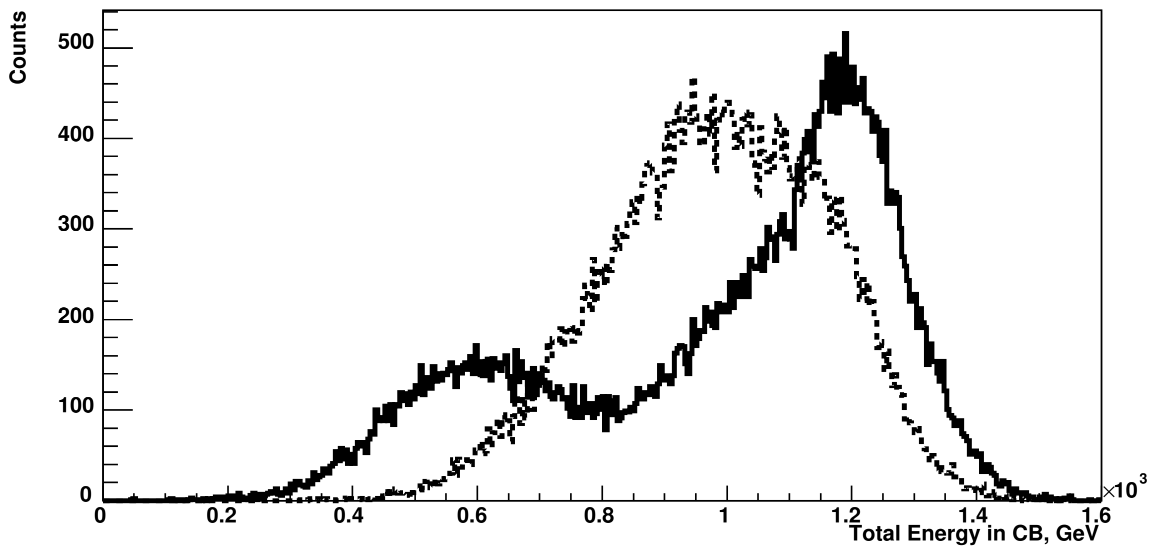

Figure 7: Monte Carlo simulation for $\gamma p \rightarrow \eta' p$ followed by the decay $\eta' \rightarrow \eta\pi^0\pi^0$. The figure shows the total energy in the Crystal Ball for two η decay modes. The solid line is for $\eta \rightarrow \gamma\gamma$, the dased line in for $\eta \rightarrow 3\pi^0$ decay.

i. The threshold on total energy in the Crystal Ball is 400 MeV.

ii. The TAPS forward wall is excluded from the trigger.

iii. The number of blocks fired in the Ball is five or more.

Similar conditions were used in the high intensity η production run. This type trigger allowed us to achieve the total photon flux of 10^5 [1/MeV] [1/sec] for photons above the η threshold. The distribution of the trigger energy in the Crystal Ball for the decays $\eta' \rightarrow \eta(2\gamma)2\pi^0$ and $\eta' \rightarrow \eta(3\pi^0)2\pi^0$ are shown in Fig. 7.
The rather open trigger conditions allow the simultaneous measurement of all the neutral decay modes of the η'. Beside the dramatic decrease in the time needed for the measurement, is improves considerably on systematic uncertainly of the experiment allowing cross checks between the different decay modes.

6.3 Event Rates

The proposed experiment will use the non–tagged A2 photon beam produced by the upgraded MAMI-C facility. We plan to increase the photon flux by using a thicker radiator to produce the bremsstrahlung photons. The parameters entering the count rate estimate and resulting beam time request are:

- Incoming electron beam energy: $E_0 = 1500$ MeV.
- Photon energy range: $E_\gamma = 1450 - 1500$ MeV, thus $\Delta E_\gamma = 50$ MeV.
- Photon flux: $N_\gamma = 10^5 \frac{1}{s}\frac{1}{MeV}$.

- Number of protons in a 5 cm long LH_2 target: $N_t = 2.15 \times 10^{23} \frac{1}{cm^2}$.
- η' photoproduction cross section: $\sigma_t(\gamma p \to \eta' p) \approx 1 \mu b$

The resulting number of events expected per hour is

$$N_{\eta'} = N_\gamma \times \Delta E_\gamma \times \sigma_t \times N_t \times 3600 \approx 4 \times 10^3. \quad (21)$$

The beam time requested for the data taking is 500 hours, plus 100 hours for the engineering run plus 100 hours for empty target and background measurements. This will provide about 2×10^6 η' events integrated over the 50 MeV region between threshold and 1500 MeV for the incident photons.
With a detection efficiency for the $\eta' \to \eta\pi^0\pi^0$ decay conservatively taken to be 30%, a data acquisition system livetime of 80%, and $BR(\eta' \to \eta\pi^0\pi^0) = (20.7 \pm 1.3)\%$, we expect about 200 good $\eta' \to \eta\pi^0\pi^0$ events each hour. In 500 hours, we will get 10^5 events what is one order of magnitude more than the existing world data sample. We will collect about 1000 $\eta' \to \pi^0\pi^0\pi^0$ events assuming $BR(\eta' \to \pi^0\pi^0\pi^0) = (1.54 \pm 0.26)^{-3}$ and acceptance of 40%. This is also an order of magnitude more than the previous experiment which was used to calculate the slope of the $\eta' \to 3\pi^0$ Dalitz plot. Finally we expect to improve by two orders of magnitude the upper limits of the $\eta' \to \pi^0\gamma\gamma$, $\eta' \to \eta\gamma\gamma$, $\eta' \to 4\pi^0$, $\eta' \to 3\gamma$. The total beam time requested for this experiment is

700 Hours.

A Competition in η' physics.

The η' meson is a unique laboratory allowing the study of fundamental physics problems such as the $\pi - \pi$ and $\pi - \eta$ interaction, C, and CP invariance, test chiral perturbation theory, *etc*. The existing world data on the η' decays is very limited. There are, however several groups who have recently joined the η and η' community. No less then 11 institutions are presently actively engaged, or planning, η/η' research. They are MAMI, ELSA, COSY, GRAAL, Spring8, JLab, DAPHNE, SLAC(BaBar), Belle, VEPP-2M and CESR. Here we comment on efforts of some research groups which could be consider as a competitors to the MAMI-C η' program.

A.1 KLOE at DAPHNE

The experiment KLOE in Frascati uses the DAPHNE e^+e^- collider. The collider consists of a separate e^+ and e^- ring with ~ 25 mrad crossing angle at the interaction point. DAPHNE is tuned for maximum ϕ–meson production. The total cross section for ϕ production at the DAPHNE c. m. energy of $\sqrt{s} = 1.05$ GeV is about 3.3 μb [38].
The KLOE detector is a nearly 4π acceptance spectrometer designed to measure the momentum and directions of charged particles as well as the energy and direction of the photons. It consists of a multilayer drift chamber placed in a magnetic field, and a sandwich–type electromagnetic calorimeter made of layers of scintillating fiber and lead converter. The calorimeter is segmented along the azimuthal angle. The polar angle of a hit is determined using the time–of–flight information from opposite sides of the scintillating fiber. The typical energy resolution of the calorimeter is $\sigma_E/E = 5.7\%/\sqrt{E(GeV)}$. The Θ resolution is determined by the TOF resolution which is typically $\sigma_t = 54(\text{ps})\sqrt{E(GeV)}$.
KLOE is expected to discontinue its operation permanently by the end of 2005. By that time they expect to collect about 2 fb^{-1} of ϕ decays that corresponds to about 8.6×10^7 $\phi \to \eta\gamma$ and about 4.1×10^5 $\phi \to \eta'\gamma$ [39].
The KLOE method of η and η' tagging is based on the detection of the radiative photon from the ϕ decay. This recipe works rather well for the cases then the radiative photon can be reliably separated from other decay particles. For example, in the case of $\phi \to \eta\gamma \to \pi^0\pi^0\pi^0\gamma$ decay the energy of the radiative photon is about 363 MeV, and an average energy of the photons from the η decays is around 100 MeV. However, in the case of $\phi \to \eta'\gamma$ decay the radiative photon is about 60 MeV. Therefore it can be easily misidentified with other photons from the $\eta' \to \eta\pi^0\pi^0$, or $\eta' \to \pi^0\pi^0\pi^0$ decays. Thereafter, consider the relatively poor energy and space resolution of the KLOE electromagnetic spectrometer for photons, it becomes even more difficult to find a proper combination of the photons needed to reconstruct the π^0's and η from η' decay. Such reconstruction will be the key to obtaining an accurate results for the Dalitz plots of the $\eta' \to \eta\pi^0\pi^0$, and $\eta' \to \pi^0\pi^0\pi^0$ decays. KLOE's combinatorial background for such seven photon events most likely are an unsolvable problem.
Consider those arguments, we conclude that despite the fact that the KLOE has a relatively large η' sample in hand, they cannot be seen as a real competitor the the Crystal Ball in experiments with muliphoton η' decays.

A.2 Crystal Barrel at ELSA

The *Electronen Stretcher Anlage* (ELSA) accelerator and storage facility at Bonn University provides a beam of polarized, or unpolarized electrons with energy up to 3.2 GeV. The electron beam is used to produce a tagged bremsstrahlung beam with the photon energy in the range from 25 to 98% of the electron beam energy. The ELSA beam energy is high enough to cover the entire maximum of the $\gamma p \to \eta' p$ total cross section shown in Fig. 1.
In the past few years the ELSA photon beam has been used together with the CERN Crystal Barrel detector. The Crystal Barrel has a design concept similar to one of the Crystal Ball. The detector material is CsI and it has a nearly 4π sr geometric acceptance. It provides a high detection efficiency for photons, good energy and angular resolution for an electromagnetic shower. Potentially the Crystal Barrel at ELSA can be used to study η'.
There are a few problems that make a high statistics measurement of η' decays at ELSA rather difficult. First of all, the intensity of the ELSA photon beam is estimated to be about $3 \times 10^3 \frac{1}{sec}\frac{1}{MeV}$ in the region between 1.5 to 2.5 GeV [40]. The photon flux is limited by the intensity of the external electron beam which can be extracted from ELSA. The ELSA photon beam intensity is at least one order of magnitude lower than the one we plan to use for our measurement at MAMI-C. Note, that the MAMI-C beam intensity used in this proposal is far below the maximum photon beam flux achievable from the machine.
The CsI crystals of the Crystal Barrel detector are equipped with photodiodes (in contrast to the Crystal Ball which is equipped with photomultipliers). The slow, low–amplitude photodiode pulse with poor time resolution cannot be used to form a signal proportional to the total energy deposited in the detector. It was proven by the Crystal Ball that such a signal is extremely useful for efficient and selective triggering of the setup. The total energy sum is particularly useful for events with large energy deposition in the detector, such as η and η' neutral decay events. The trigger solutions used for the Crystal Barrel experiment relies on the TAPS forward detector, and/or Forward Plug detector, which is a forward wall made of a limited number of CsI crystals equipped with PMT's. Such triggering method limits the apparatus acceptance to about 10 % [40]. Assuming 50% life time for the CB@ELSA data acquisition system and 5 cm liquid hydrogen target, the estimated rate of the $\eta' \to \eta\pi^0\pi^0$ events detected in the Crystal Barrel is about 25 $\frac{1}{h}$. This rate is about factor of 8 less than the estimated η' flux for the Crystal Ball experiment at MAMI-C.

A.3 Other experimental facilities producing η'

Next year the WASA detector is scheduled to start commissioning at the COSY proton ring. A significant part of the new WASA@COSY experimental program is dedicated to η and η' decay studies. The calculated η' production rate at COSY in proton–proton collisions is about 30 η' per second. The WASA detector is well suited to detect energy and directions of photons as well as momentum and directions of charged particles. However, feasibility of the η' program at COSY still need to be proven. The similar WASA experiment at CELSIUS proton machine at Upsalla suffered from serious complications such as stability of the pellet target, very large hadronic background, beam associated backgrounds, *etc.* Those issues were never fully resolved at CELSIUS and now the COSY team will face similar problems. One may think that is will take at least a few years before the proposed η' rate is achieved. The WASA detector is equipped with the high resolution central magnetic spectrometer. This device makes WASA a unique setup to study charged decays of η and η'. At the other hand, the central tracker introduces about 0.2 of the radiation length worth of material between

the target and the WASA electromagnetic calorimeter. For multi–photon final states, such as $\eta' \to \eta\pi^0\pi^0$ for example, the probability to loose one of the six photons due to photon conversion in the material is about 50%. For this reason, the Crystal Ball detector is a superior device to deal with multi–photon η and η' decays.
The GRAAL and Spring8 machines provide photon beams with energy above the η' production threshold. Both machines use laser backscattering technique to produce the photons. The typical intensity of the beam produced by this method is about two orders of magnitude lower than the intensity of a photon beam produced by bremsstrahlung. Therefore the GRAAL and Spring8 machines will not be able to compite with the Crystal Ball at MAMI-C in η and η' production rates.
Jefferson Laboratory provides a high energy, high intensity photon beam which is ideal for an η' production program. Currently JLab does not have a 4π photon detector to implement such program.
The main objective of the BaBar experiment at SLAC and the Belle experiment at KEK is charm physics. Though the both experiments produce the η' via $B \to \eta' X$ decays, we are not aware about plans to convert the facilities to η' factories.
The CLEO collaboration at CESR has recently published new results on the slope parameter of the $\eta' \to \pi^+\pi^-\eta$ decay as well as the new upper limits on the C–forbidden $\eta' \to e^+e^-\pi^0$ and $\eta' \to e^+e^-\eta$ decays. The experiment used 3.11 fb^{-1} at the $\Upsilon(4S)$ resonance, 10.58 GeV, and 1.69 fb^{-1} at 10.52 GeV. Approximately $(15 \pm 3)\%$ of their η' sample came from $B\bar{B}$ decays. Charged particle momenta are measured in a 67-layer tracking system immersed in a 1.5 T solenoidal magnetic field. The main drift chamber also determines a tracks specific ionization (dE/dx), which aids in particle identification. A 7800-crystal CsI calorimeter detects photons and is the primary tool for electron identification [15]. The total number of detected $\eta' \to \pi^+\pi^-\eta$ decays was about 6700 with about 3% acceptance. The invariant mass distribution of the $\pi^+\pi^-\eta$ event shows a significant (about 50%) background under the η' peak.
The SND experiment at VEPP-2M e^+e^- collider in Novosibirsk uses a method of η and η' production similar to the one used by KLOE. The SND detector is a spherical multilayer CsI calorimeter made to detect multiphoton final states. Recently SND published a few high quality results on η decays, including $\eta \to e^+e^-\gamma$ and $\eta \to \pi^0\gamma\gamma$. Unfortunately our information on the current status of the SND experiment and their plans for future studies is very limited.

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