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Eingang: 26.08.05
an PAC:

Mainz Microtron MAMI

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

Update of Proposal for an Experiment

"Test of Chiral Perturbation Theory and C and CP Invariance in Eta Meson Decay"

Collaborators :

CrystalBall@MAMI collaboration

Spokespersons for the Experiment :
A. Starostin - UCLA,
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and R. Beck - Bonn University

Abstract of Physics :
We propose to investigate six neutral decay modes of the eta meson; all are measured simultaneously. This is the second phase of the experiment. The first stage was successfully completed in 2004. Our priority is the measurement of the Dalitz plot and decay spectrum of $\eta \to \pi^0\gamma\gamma$. The decay amplitude is determined by the third-order term in the momentum expansion; the first term is zero and the second is small. Thus, $\eta \to \pi^0\gamma\gamma$ provides a unique, sensitive test of Chiral Perturbation Theory (χPT). Furthermore we will measure the speculated quadratic parameter for the slope in $\eta \to 3\pi^0$. We will also improve by a factor of $10 - 20$ three tests of charge conjugation invariance, namely $\eta \not\to 2\pi^0\gamma$, $\eta \not\to 3\pi^0\gamma$, and $\eta \not\to 3\gamma$, and improve on a unique test of CP invariance, namely $\eta \not\to 4\pi^0$. Etas are photoproduced in the reaction $\gamma p \to \eta p$ with tagged photons of 720 to 900 MeV.

Abstract of Equipment :
We require a beam of tagged photons incident on a liquid-hydrogen target. The detector is the 4π Crystal Ball photon spectrometer in combination with TAPS as forward wall, the outer chamber of the DAPHNE tracker and a scintillator PID. The Glasgow-Edinburgh-Mainz tagging system will provide the intense photon beam.

MAMI–Specifications :

beam energy	980 MeV
beam current	< 100 nA
time structure	cw
polarization	unpolarized

Experiment–Specifications :

experimental hall/beam	A2
detector	Crystal Ball, TAPS, MWPC, PID
target material	5 cm liquid hydrogen

Beam Time Request :

set–up/tests with beam	50 hours (parallel with proposal A2/ ???)
data taking	900 hours (parallel with proposal A2/ ???)

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1 Introduction

The η is a unique meson because it provides a very sensitive test of chiral perturbation theory, χPT. The decay rate and the Dalitz plot of $\eta \to \pi^0\gamma\gamma$ are determined by the third order term of χPT. Another test of χPT is provided by the slope parameter of $\eta \to 3\pi^0$. Selected eta decays such as $\eta \to 3\gamma$, $\eta \to 2\pi^0\gamma$, and $\eta \to 3\pi^0\gamma$ are forbidden to occur by charge conjugation invariance of the flavor conserving electro-strong interaction. A sensitive search for those forbidden η decays gives important new limits on C-invariance. Finally, the decay mode $\eta \to 4\pi^0$ is forbidden by CP-invariance.
In the CB experiment at the AGS the above six eta decays together with several others were successfully studied [1, 2, 3, 4, 5]. They were investigated simultaneously which resulted in a substantial savings in running and analyzing time.
The importance of the six η decays was discussed in details in our 2003 MAMI-B proposal [6]. Here we give an update of the experimental situation in η decay physics. A few new experimental results on η decays have been published in the past two years. This includes data from the KLOE collaboration on the $\eta \to \pi^0\gamma\gamma$ and $\eta \to 3\pi^0$ decays. There are also four new upper limits on C, and one on CP forbidden η decay published by the Crystal Ball at AGS (CB@AGS).
In a 300 hour eta run in 2004 at MAMI-B we collected about 3×10^6 $\eta \to 3\pi^0$ decays which corresponds to about 3×10^7 η's produced on target. The preliminary results of the test run will be shown in the third chapter. We will provide the updated η rate at MAMI-C. 71.6% of all η decays result in neutral particles — photons and π^0's. The neutral decay modes are listed in Table 1, which also shows the physics theories and symmetries which can be investigated with each mode.

2 New experimental results on η decays

2.1 The $\eta \to \pi^0\gamma\gamma$ decay

The detection of $\eta \to \pi^0\gamma\gamma$ is a very challenging experimental task. The most serious problems are the large $\eta \to 3\pi^0$ background and background from $\pi^0\pi^0$ production. A highly segmented 4π photon detector is needed for a reliable identification of the $\eta \to \pi^0\gamma\gamma$ events. Figure 1 shows all recent measurement of the $\eta \to \pi^0\gamma\gamma$ branching ratio. Until 1980, there were 13 experiments with contradictory and unconvincing results because of huge neutral backgrounds coming from $\eta \to 3\pi^0$ and other processes. In 1982, the first major high-energy detector used for η-decay studies, GAMS-2000, yielded $BR(\eta \to \pi^0\gamma\gamma) = (9.5 \pm 2.3) \times 10^{-4}$ [7]. The data were later reanalyzed, and a new result for the BR of $(7.1 \pm 1.4) \times 10^{-4}$ was reported in 1984 [8], based on a sample of 40 events. It implies that $\Gamma(\eta \to \pi^0\gamma\gamma) = 0.84 \pm 0.17$ eV. This width is double the χPTh evaluation of 0.42 ± 0.20 eV [9] and of most other predictions (see Ref. [10, 11, 12, 13, 14, 15, 16]). The recent work of the SND collaboration at VEPP-2M gave a 90% CL upper limit on the $BR(\eta \to \pi^0\gamma\gamma)$ of 8.4×10^{-4} [17]. Note that if the GAMS-2000 result were to be confirmed, it would be the first real failure of χPTh and give a major setback to non-perturbative QCD.
The discrepancy between theory and experiment was resolved only recently when the Crystal Ball data became avaliable [4]. The final result of the Crystal Ball experiment at the AGS $BR(\eta \to \pi^0\gamma\gamma) = (3.5 \pm 0.7_{\text{stat}} \pm 0.6_{\text{syst}}) \times 10^{-4}$ is in agreement with calculations of chiral perturbation theory to third-order. The result is based on more than one thousand $\eta \to \pi^0\gamma\gamma$ events.
Meanwhile new preliminary data from KLOE have been published [18]. One of the results is $BR(\eta \to \pi^0\gamma\gamma) = (8.4 \pm 2.7_{\text{stat}} \pm 1.4_{\text{syst}}) \times 10^{-5}$ shown in Fig. 1 as the open diamond. This value is about 2.5 standard deviation lower than the one by the Crystal Ball.

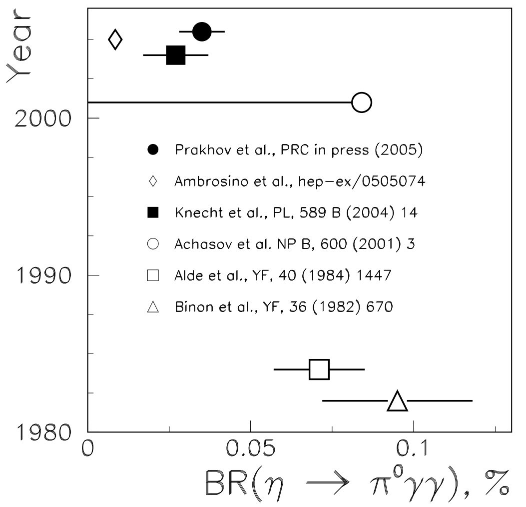

Figure 1: Recent experimental results for the branching ratio of $\eta \to \pi^0\gamma\gamma$.

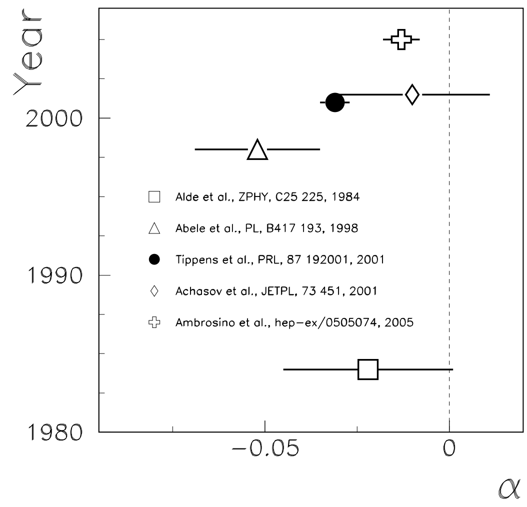

Figure 2: Recent experimental results for the π^0 slope in $\eta \to 3\pi^0$.

The KLOE detector is a nearly 4π acceptance spectrometer designed to measure momentum and directions of charged particles as well as energy and direction of 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 uses the DAPHNE e^+e^- collider tuned for maximum ϕ–meson production. The radiative photons from the $\phi \to \eta\gamma$ decays are used to tag η's. Compared to the Crystal Ball, the KLOE electromagnetic calorimeter has relatively poor energy and space resolution for photons. Combined with the poor segmentation of the KLOE photon detector it may result in a significant combinatorial background. Beside that, there are a few sources of physical backgrounds such as $e^+e^- \to \phi \to \omega\pi^0$, $e^+e^- \to \phi \to \rho\gamma$, $e^+e^- \to \phi \to K_L^0 K_S^0$, *etc*, which do not exist in the Crystal Ball experiment. The KLOE sample of $\eta \to \pi^0\gamma\gamma$ events is less than 100 out of about 1.7×10^7 η's produced in the experiment. The corresponding Crystal Ball number is over one thousand $\eta \to \pi^0\gamma\gamma$ events from 3×10^7 η sample. All this shows a superiority of the Crystal Ball experiment over the KLOE measurement. However, the inconsistency of the two experimental results cannot be ignored.
A new experiment is needed to arbitrate. The proposed high statistic experiment will measure the decay spectrum and the Dalitz plot as well as the branching ratio of the decay. The spectral shape is of course needed for a good determination of the branching ratio. Incidentally, the spectral shape of $\eta \to \pi^0\gamma\gamma$ is given by another third-order χPT calculation as illustrated in Fig. 3 and thus provides a test of χPT.

2.2 π^0 slope parameter in $\eta \to 3\pi^0$ decay

The slope in the Dalitz plot of $\eta \to 3\pi^0$ decay appears as a result of the energy dependence of the $\pi - \pi$ interaction in the final state. Figure 2 shows all avaliable experimental results on the slope parameter. The Crystal Ball result published in 2001 [1] was the first statistically significant measurement of this important quantity. The parameter $\alpha = -0.031 \pm 0.004$ was measured using about one million reconstructed $\eta \to 3\pi^0$ events. The Crystal Ball event sample is about 98% clean. A systematical uncertainty introduced by 2% background from the

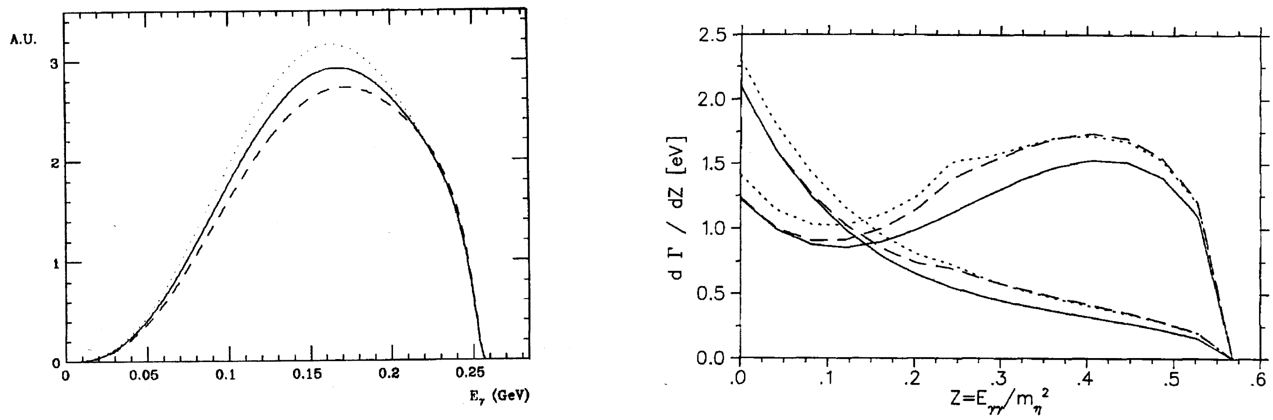

Figure 3: Examples of theoretical predictions for the $\eta \to \pi^0\gamma\gamma$ spectrum. Left figure is the single photon spactrum from Ref. [9] and right figure is the π^0 spectrum from Ref. [15].

direct $3\pi^0$ production and the $\eta \to \pi^0\pi^0\gamma\gamma$ decay is small [5, 19]. All other possible sources of systematical uncertainty were carefully studied.
In May of 2005 the KLOE collaboration published their preliminary result for the slope. The KLOE value for the parameter α is $-0.013 \pm 0.005_{\text{stat}} \pm 0.004_{\text{syst}}$ [18]. Presently we have not sufficient information to judge about the quality of the KLOE event sample. However, Ref. [18] states that the KLOE acceptance for the fully reconstructed $\eta \to 3\pi^0$ events is about 4.5%. This is a roughly a factor of four less than the corresponding Crystal Ball acceptance. Since the geometrical acceptance for both detectors is very similar, the difference could suggest that the KLOE combinatorial background is significantly larger then the one for the Crystal Ball.
The proposed new high statistics measurement of the α slope parameter will help to resolve the experimental discrepancy. The sample of $\eta \to 3\pi^0$ events which we propose to collect in this experiment is 10–20 times larger than the AGS experiment and it is of better quality than the one from the CB@AGS experiment. It will allow a more careful investigation of the slope. In particular, for the first time we will obtain the second order term of the slope.

2.3 CP and C forbidden η decays

The CB@AGS has produced the first upper limit for the CP–forbidden $\eta \to 4\pi^0$ decay [2]:

$$BR(\eta \to 4\pi^0) < 6.9 \times 10^{-7}. \tag{1}$$

Combined with $\Gamma(\eta \to \text{all}) = 1.29 \pm 0.07\,\text{eV}$, this gives $\Gamma(\eta \to 4\pi^0) < 8.9 \times 10^{-4}$ eV. No events were found in a sample of 3×10^7 η decays produced near threshold in $\pi^- p \to \eta n$ close to threshold. To evaluate the sensitivity of this test, note that the η meson is an eigenstate of the CP operator. This allows for a comparison with a related but CP-allowed decay. The decay of a hypothetical η meson, the η_{hyp}, with $J^{PC} = 0^{++}$ into $4\pi^0$ is allowed. As η_{hyp} does not exist, we use instead $f_0(1500) \to 4\pi^0$. The f_0 has the same quantum numbers as the η except for its positive parity. The experimental value for the partial width is $\Gamma(f_0 \to 4\pi^0) = 33$ MeV. The ratio of the phase space is $\Phi(\eta \to 4\pi^0)/\Phi(f_0 \to 4\pi^0) = 4.7 \times 10^{-8}$ [20], so we might expect $\Gamma(\eta_{hyp} \to 4\pi^0) \simeq 1.6\,\text{eV}$. Thus, the CP-violating amplitude for $\eta \to 4\pi^0$ compared to a comparable, allowed decay is

$$A_{\not{c}\not{p}}/A_{cp} < \left[\frac{8.9 \times 10^{-4}\,\text{eV}}{1.6\,\text{eV}}\right]^{\frac{1}{2}} = 2.3 \times 10^{-2} \tag{2}$$

at 90% CL.

Table 1: The Neutral η Decays.

Decay Mode	Branching Ratio	Physics highlight
All Neutrals	$(71.6 \pm 0.4)\%$	
2γ	$(39.3 \pm 0.3)\%$	$SU(3)$ octet-singlet mixing
$3\pi^0$	$(32.2 \pm 0.3)\%$	χPTh; $m_u - m_d$
$\pi^0\gamma\gamma$	$(3.2 \pm 0.9) \times 10^{-4}$	χPTh, $O(p^6)$
$2\pi^0$	$< 4.3 \times 10^{-4}$	P and CP invariance
$4\pi^0$	$< 6.9 \times 10^{-7}$	P and CP invariance
$\pi^0\pi^0\gamma$	$< 5 \times 10^{-4}$	C (isoscalar) invariance
$\pi^0\pi^0\pi^0\gamma$	$< 4.7 \times 10^{-5}$	C (isovector) invariance
3γ	$< 4.5 \times 10^{-5}$	C (isovector, isoscalar)
4γ	$< 2.8\%$	
$\pi^0\pi^0\gamma\gamma$	$< 3.1 \times 10^{-3}$	χPTh, New Physics
$\nu_e\bar{\nu}_e$	$< 2.8\%$	New Physics (leptoquarks)
$\nu_e\bar{\nu}_\mu$	$< 2.8\%$	New Physics (leptoquarks)
$\nu_e\nu_e$	$< 2.8\%$	New Physics (leptoquarks)
$\gamma\nu\nu$	$< 2.8\%$	New Physics (leptoquarks)
$\pi^0\nu\bar{\nu}$	$< 2.8\%$	New Physics (leptoquarks)

The η has the charge–conjugation eigenvalue $C = +1$, and the $\pi^0\pi^0\gamma$ system with $J^P = 0^-$ has $C = -1$. Thus, the decay $\eta \to \pi^0\pi^0\gamma$ is strictly forbidden by C invariance. This decay would be an isoscalar electromagnetic interaction of hadrons. It has been suggested that there may exist an isotensor electromagnetic interaction with a C-violating component [21, 22]. The decay $\eta \to \pi^0\pi^0\gamma$ provides an opportunity to search for such an exotic interaction; it would be a clear signal for New Physics.

The first search for $\eta \to \pi^0\pi^0\gamma$ was reported recently by the CB@AGS [3] from a sample of 3.0×10^7 η's. Candidate events in the signal region are predominantly ($\sim 85\%$) due to $\eta \to 3\pi^0$ decay with overlapping photon showers; the rest are due to $2\pi^0$ production with a split-off photon. The net yield is no events resulting in

$$BR(\eta \to \pi^0\pi^0\gamma) < 5 \times 10^{-4} \text{ at the 90\% C.L.} \tag{3}$$

This corresponds to $\Gamma(\eta \to \pi^0\pi^0\gamma) < 0.6\,\text{eV}$. To evaluate the sensitivity of our result, we can compare our upper limit of this decay rate with the measured decay rate of a suitable, C-allowed meson decay. For this purpose, we should not use the otherwise obvious decay mode $\eta \to \pi^+\pi^-\gamma$ because this decay is suppressed by the $U_A(1)$ anomaly [23]. Also, $\rho \to \pi^0\pi^0\gamma$ is not suitable because it is an isovector. The $f_0 \to \pi^0\pi^0\gamma$ decay has not been measured. For our purpose, we can use the $\rho \to \pi^+\pi^-\gamma$ decay, which has a width of 1.5 MeV. This should be adjusted for the difference in phase space [24], Clebsch-Gordan coefficients, and the angular-momentum barrier factor to account for the fact that the $2\pi^0$ system in $\eta \to \pi^0\pi^0\gamma$ decay is in a relative D-state, while the $\pi^+\pi^-$ pair in $\rho \to \pi^+\pi^-\gamma$ is mainly a P-state. The difference for the quadrupole transition involved in $\rho \to \pi^+\pi^-\gamma$ is of order $(kL)^4$, where k is the photon momentum and L is the interaction radius. We estimate that $kL \simeq \frac{1}{2}$ [25]. The decay rate for a C-allowed transition to $\pi^0\pi^0\gamma$ is thus 1.5 MeV. The sensitivity of the search for $\eta \to \pi^0\pi^0\gamma$ is

$$A^S_{\not{c}} / A^S_c \leq \left[\frac{0.64 \text{ eV}}{1.5 \times 10^6 \text{ eV}}\right]^{1/2} = 8 \times 10^{-3} ,$$

where $A^S_{\not{c}}$ is the C-violating, isoscalar, electro-strong *amplitude*, and A^S_c is the C-allowed amplitude. This is the most sensitive limit on an isoscalar C-violating electro-strong reaction.

The radiative decay $\eta \to \pi^0\pi^0\pi^0\gamma$, is strictly forbidden by charge-conjugation invariance. There are seven photons in the final state, which explains the need for a 4π acceptance detector. Recently a first ever upper limit for the decays was also reported by the CB@AGS [3]

$$BR(\eta \to \pi^0\pi^0\pi^0\gamma) < 6 \times 10^{-5}, \tag{4}$$

This is a test of an isovector electromagnetic interaction of hadrons. To evaluate the sensitivity of this test, we proceed as follows. An allowed strong 3π meson decay is $\omega \to \pi^+\pi^-\pi^0$, which has a width of 7.6 MeV. We estimate the radiative decay to be $\alpha = 1/137$ times the corresponding hadron decay width. After adjusting for the spin-statistics and symmetry factor, the C-allowed $3\pi^0\gamma$ decay width is 6.8×10^3 eV. The sensitivity is

$$A^V_{\not{c}} \; / A^V_c \;\leq \left[\frac{7.7 \times 10^{-2}\text{eV}}{6.8 \times 10^3\ \text{eV}}\right]^{1/2} = 3 \times 10^{-3} \ ,$$

where $A^V_{\not{c}}$ is the isovector C-violating amplitude. This is the best available limit on the absence of a C-violating, isovector *amplitude*.
The decay of a neutral, flavorless, $C = +1$, pseudoscalar meson into three photons is forbidden rigorously 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 [25]. The decay $\eta \to 3\gamma$ can be isoscalar or isovector and even the hypothetical isotensor interaction. The Particle Data Group [26] lists the upper limit for the $\eta \to 3\gamma$ branching ratio as 5×10^{-4}.
The CB@AGS has produced a new result which is [5, 27]

$$BR(\eta \to 3\gamma) < 4.0 \times 10^{-5} \tag{5}$$

at the 90% C.L. The largest background in this experiment is from $\eta \to 3\pi^0 \to 6\gamma$ decay, $BR(\eta \to 3\pi^0) = 0.32$, when photon showers overlap in the detector. The background from $\eta \to \pi^0\gamma\gamma$ decay when two photons overlap is insignificant because of the smallness of the branching ratio, $BR(\eta \to \pi^0\gamma\gamma) = 3 \times 10^{-4}$. The background from $\eta \to 2\gamma$ with two split-offs is greatly suppressed in our analysis.
A run of about 750 hours yielding over 3×10^8 η's would improve the current upper limits on the branching ratio listed above by factor of 10.

3 Experimental details

3.1 Experimental apparatus

The proposed measurement will use the existing apparatus located in the real photon beam of MAMI. The experiment uses the Glasgow–Edinburgh–Mainz photon tagger consisting of the Crystal Ball photon spectrometer, TAPS as a forward detector, a charged particle tracker (two DAPHNE coaxial cylindrical multiwire proportional chambers, MWPC) and 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. [28] 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 acceptance calculated for example for the $\eta \to \pi^0\gamma\gamma$ is about 30% when all four photons and the proton are detected. In this experiment we will use only the outer chamber of the DAPHNE.
The experimental apparatus was successfully used for our eta run in 2004 at MAMI-B. Figures 4, 5, and 6 illustrate the quality of the data obtained during the 2004 run. The resolution of

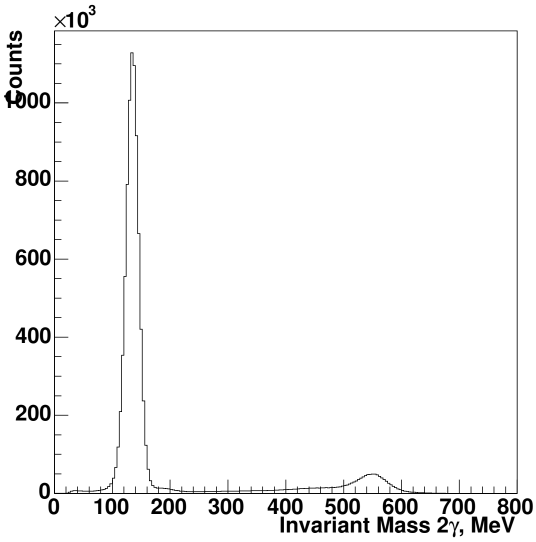

Figure 4: Experimentally measured invariant mass spectrum of two photons produced in reaction $\gamma p \rightarrow \gamma\gamma p$.

the two photon invariant mass detected in the Crystal Ball is typically 10-15% better compared to the CB@AGS experiment. This is due to the new flash ADC with the dynamic pedestal subtraction and better quality of the beam. The acceptance of the apparatus for the $\eta \rightarrow 3\pi^0$ decay is about twice as large as in the AGS experiment because of TAPS which is used as a forward wall.
The MAMI experiment can detect both, neutral as well as charged decays of the eta. Figure 6 shows the invariant mass of $e^+e^-\gamma$ from the $\gamma p \rightarrow e^+e^-\gamma p$. The narrow peak from the $\eta \rightarrow e^+e^-\gamma$ events is clearly seen.

3.2 Event rate

The total photon flux of $10^5 \frac{1}{sec}\frac{1}{MeV}$ was achieved during the MAMI-B run. We plan to increase the flux by factor of 2 using a thicker radiator to produce the bremsstrahlung photons. For the proposed experiment the parameters entering the count rate estimate and the resulting beam time request are:

- Incoming electron beam energy: $E_0 = 980$ MeV.
- Tagged photon energy range: $E^t_\gamma = 720 - 900$ MeV, thus $\Delta E_\gamma = 180$ MeV.
- Electron count rate in the tagger: $N_e = 4 \times 10^5 \frac{1}{s}\frac{1}{MeV}$.
- Tagging efficiency: $\varepsilon_t \approx 50\%$.
- Tagged photon flux: $N_\gamma = 2 \times 10^5 \frac{1}{s}\frac{1}{MeV}$.
- Number of protons in a 5 cm long LH_2 target (modified DAPHNE cryo target): $N_t = 2.15 \times 10^{23} \frac{1}{cm^2}$.
- Eta photoproduction cross section: $\sigma_t(\gamma p \rightarrow \eta p) = 14\mu b$

The number of etas is

$$N_\gamma \Delta E_\gamma \Delta t N_t \sigma_t \approx 4 \times 10^5 \, \eta/h.$$

The total running time of 750 hours allows us to produce about 3×10^8 η's. This eta sample will be the largest in the world. With a detection efficiency for the $\pi^0\gamma\gamma$ channel conservatively taken to be 20%, a data acquisition system livetime of 70%, and $BR(\eta \rightarrow \pi^0\gamma\gamma) = 3 \times 10^{-4}$,

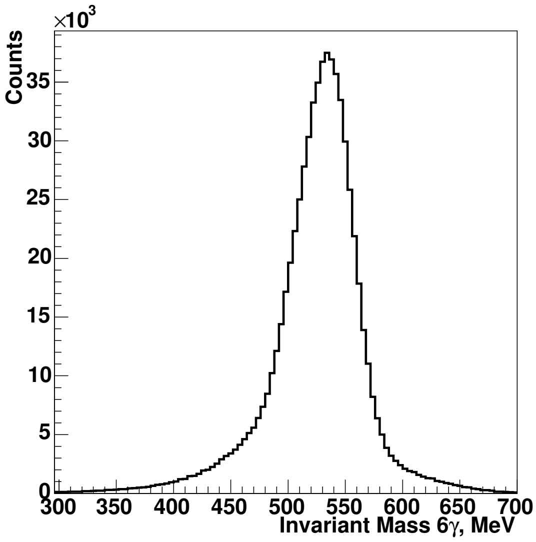

Figure 5: Experimentally measured invariant mass spectrum of six photons produced in reaction $\gamma p \to 6\gamma p$.

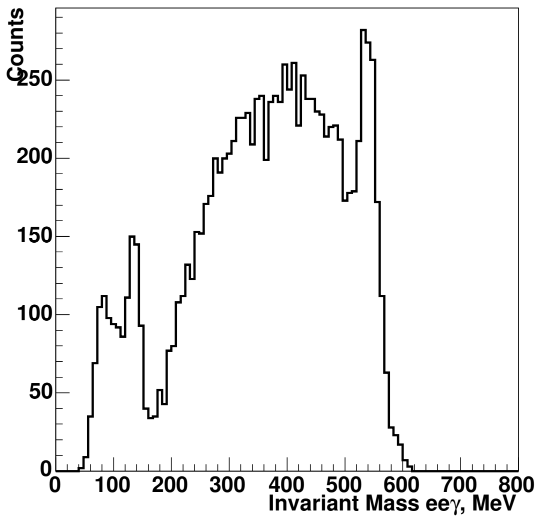

Figure 6: Spectrum of $e^+e^-\gamma$ invariant mass measured with the Crystal Ball detector at MAMI-B.

we expect 12000 good $\eta \to \pi^0\gamma\gamma$ events. We can also can improve by order on magnitude on the upper limits of $\eta \not\to 2\pi^0\gamma$, $\eta \not\to 3\pi^0\gamma$, $\eta \not\to 3\gamma$, and $\eta \not\to 4\pi^0$.
We estimate needing 150 hours of empty target data for background measurements, and 50 hours for trigger studies.

4 Summary

In the preceeding sections we have presented the status of six especially interesting eta meson decays and we have indicated the significance of an eta program with a tenfold increase in sensitivity over CB@AGS. The feasibility of the experiment with the CB as the central detector has been amply demonstrated by the success of the CB@AGS and the 2004 MAMI-B run, see for example Refs. [1, 2, 3, 4, 5]. The added features, new electronics, TAPS, tracker, and PID, help in further suppressing background and increasing efficiency. The total beam time requested for this experiment is

950 Hours.

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