η and η' Physics with the Crystal Ball

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A sample of 3×10^7 η's collected with the Crystal Ball spectrometer at the AGS (BNL) was used to calculate a new precise values of the π^0 slope parameter of the $\eta \to 3\pi^0$ Dalitz plot, and a new branching ratio for $\eta \to \pi^0\gamma\gamma$. For the first time the upper limit for the CP violating $\eta \to 4\pi^0$ decay was obtained as well as upper limits for the C violating decays $\eta \to \gamma\pi^0$, $\eta \to \gamma\pi^0\pi^0$, $\eta \to \gamma\pi^0\pi^0\pi^0$, and $\eta \to 3\gamma$. A new Crystal Ball program has started at the Mainz Microtron. Among other experiments the program includes a study of neutral and charged decays of η and η'. The first data set of about 3×10^7 η's was obtained in 2004.

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A sample of 3×10^7 η's was collected with the Crystal Ball spectrometer at the AGS (BNL) in 1998. The eta's were produced in the reaction $\pi^- p \to \eta n$ at the π^- beam momentum of 720 MeV/c. All neutral final states were detected simultaneously using an open trigger. The trigger signal required: i) the π^- passing through the 10 cm liquid hydrogen target, ii) "all neutral" final state, and iii) the total energy deposited in the Crystal Ball be higher than 350 MeV. About 15% of all recorded events came from various neutral η decays. Other reactions contributing to the neutral events were $\pi^- p \to \pi^0 n$, $\pi^- p \to 2\pi^0 n$, and a very limited number of $\pi^- p \to 3\pi^0 n$ events produced via sequential decays of resonances (not from $\eta \to 3\pi^0$). The rate was about 10^5 η's per hour.

The Dalitz plot of the $\eta \to 3\pi^0$ decay is uniform is first order because of the three indistinguishable particles in the final state [1]. A structure on the Dalitz plot is due to the energy dependent $\pi - \pi$ interaction, which can be calculated in χPT. The Dalitz plot is usually parameterized by variable z:

$$z = 6\sum_{i=1}^{3}(E_i - m_\eta/3)^2/(m_\eta - m_{\pi^0})^2 = \rho^2/\rho^2_{max},$$

where E_i is the energy of the $i^{\rm th}$ pion in the η rest frame, and ρ is the distance from the center of the Dalitz plot. The variable z varies from $z = 0$ (all three π^0's have the same energy of $m_\eta/3$), to $z = 1$ (one π^0 is at rest). The matrix element of the decay can be written as $|M^2| \sim 1 - 2\alpha z$.

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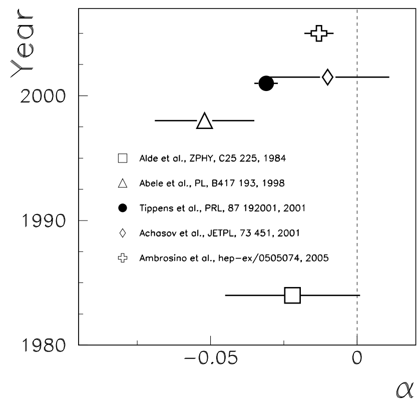

Fig. 1. Recent experimental results for the π^0 slope in $\eta \to 3\pi^0$.

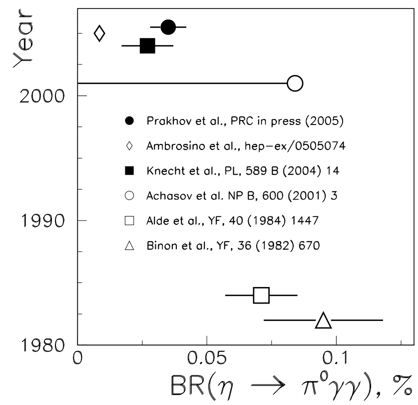

Fig. 2. Recent experimental results for the branching ratio of $\eta \to \pi^0\gamma\gamma$.

Figure 1 shows all avaliable experimental results on the slope parameter α. The Crystal Ball result published in 2001 [2] was the first statistically significant measurement of this important quantity. The value of $\alpha = -0.031 \pm 0.004$ 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 direct $3\pi^0$ production and the $\eta \to \pi^0\pi^0\gamma\gamma$ decay is small [3, 4]. All other possible sources of systematical uncertainty, including combinatorial background, were carefully studied.

There are 15 possible ways of combining the 6 photons in three π^0. We have fitted all 15 combinations with the $\eta \to 3\pi^0 \to 6\gamma$ hypothesis. A χ^2 value was calculated for each combination. A combination was accepted for further analysis if it satisfied the hypothesis with a probability greater than 2%, i.e. a 2% confidence level. About 80% of our $\eta \to 3\pi^0$ events were reconstructed from a "unique" combination of photons, meaning that only one combination from the 15 has passed the probability test. For the remaining 20% of events, a multiple (in most cases two) combinations survived. In such cases the combination with the minimum χ^2, or "best" combination was used. Within our statistical uncertainty we found no dependance of the slope on the events with the best combination [2]. However, the effect of the combinatorial background on the slope can be very significant. To investigate the effect, we have calculated the slope using the "second best" combination of photons for the events with two or more combinations. This sample contains about 50% of events reconstructed from a wrong combination. We used the Monte Carlo data with the initial slope $2\alpha = -0.12$ for the exercise. Figure 3(a) shows the result for our usual analysis with 80% of unique events and 20% of best events. The calculated slope $2\alpha = -0.11$ is in agreement with the initially simulated value. Figure 3(b) shows the z distribution calculated for the second best combination. The distribution is badly distorted. The value of the slope parameter is very far from the initial, and in fact has an opposite sign.

Recently the KLOE collaboration has published their preliminary result for the slope: $\alpha = -0.013 \pm 0.005_{\rm stat} \pm 0.004_{\rm syst}$ [5]. The value is more than 2σ lower than the one from the Crystal

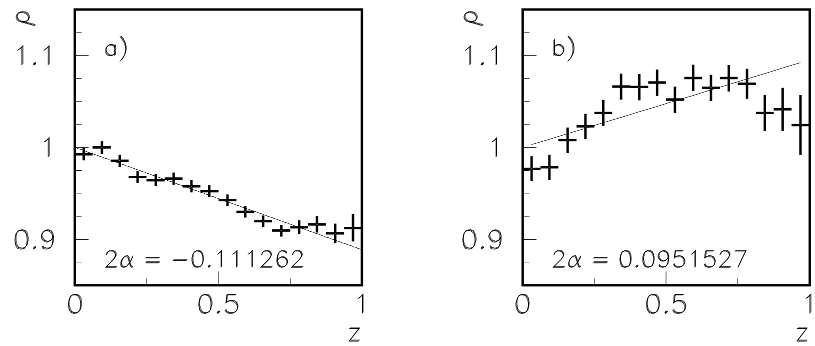

Fig. 3. Results for the Monte Carlo simulation with the initial slope $2\alpha = -0.12$. a) The slope is obtained using 80% of events with "unique", and 20% of events with "best" combination. b) The result is obtained using the "second best" combination for the 20% of events. The estimated combinatorial background in this sample is about 50%.

Ball. The energy and angular resolution of the KLOE detector for photons is poor compared to the ones for the Crystal Ball. One may expect a significant combinatorial background in the KLOE event sample. In fact, the KLOE acceptance for the fully reconstructed $\eta \rightarrow 3\pi^0$ events is about 4.5% [5]. This is about factor of four less than the corresponding Crystal Ball acceptance. The geometrical acceptances for both detectors is roughly the same, and the difference is mainly due to the procedure applied by KLOE to suppress the combinatorial background. The procedure removes from the analysis all events when the χ^2 for the best and for the second best combination are close. For the remaining events the best combination was used to reconstruct the η. The fraction of events with the unique combination is not specified in the publication.

The amplitude of the $\eta \rightarrow \pi^0\gamma\gamma$ decay is absent in the first and very small in the second orders of the χPT momentum expansion. Only the third and higher orders contribute to the decay amplitude. Therefore, the $\eta \rightarrow \pi^0\gamma\gamma$ branching ratio is a unique test of the higher orders of χPT. The detection of $\eta \rightarrow \pi^0\gamma\gamma$ is a very challenging experimental task. The most serious problems are the large $\eta \rightarrow 3\pi^0$ background and the background from the $\pi^0\pi^0$. A highly segmented 4π photon detector is needed for a reliable identification of the $\eta \rightarrow \pi^0\gamma\gamma$ events. Figure 2 shows all recent measurements of the $\eta \rightarrow \pi^0\gamma\gamma$ branching ratio. Until 1980, there were 13 experiments with contradictory and unconvincing results because of huge neutral backgrounds coming from $\eta \rightarrow 3\pi^0$ and other processes. In 1982, the first major high-energy detector used for η-decay studies, GAMS-2000, yielded $BR(\eta \rightarrow \pi^0\gamma\gamma) = (9.5 \pm 2.3) \times 10^{-4}$ [6]. 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 [7], based on a sample of 40 events. It implies that $\Gamma(\eta \rightarrow \pi^0\gamma\gamma) = 0.84 \pm 0.17$ eV. This width is double the χPTh evaluation of 0.42 ± 0.20 eV [8] and of most other predictions, see for example [9, 10]. 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 [11]. The final result of the Crystal Ball experiment at the AGS $BR(\eta \to \pi^0\gamma\gamma) = (3.5 \pm 0.7_{\rm stat} \pm 0.6_{\rm syst}) \times 10^{-4}$ 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 the new preliminary data from KLOE have been published [5]. One of the results is $BR(\eta \to \pi^0\gamma\gamma) = (8.4 \pm 2.7_{\rm stat} \pm 1.4_{\rm syst}) \times 10^{-5}$, which is shown in Fig. 2 by an open diamond. The KLOE result is based on 68 good $\phi \to \eta(\pi^0\gamma\gamma)\gamma$ events. KLOE uses e^+e^- collisions at $\sqrt{s} = 1.02$ GeV to produce η's. The background situation in this case is much more complicated than is the case of the Crystal Ball. There are many sources of background, such as various ϕ decays (for example $\phi \to f^0(\pi^0\pi^0)\gamma$, $\phi \to \rho^0(\eta\gamma)\pi^0$, and $\phi \to a^0(\eta\pi^0)\gamma$) as well as reactions like $e^+e^- \to \omega(\pi^0\gamma)\pi^0$. The backgrounds were simulated and subtracted from the final sample of the $\eta \to \pi^0\gamma\gamma$ events, but the reliability of such simulation is questionable.

The CB@AGS has produced the first upper limit for the CP forbidden $\eta \to 4\pi^0$ decay [12]: $BR(\eta \to 4\pi^0) < 6.9 \times 10^{-7}$. Combined with $\Gamma(\eta \to {\rm all}) = 1.29 \pm 0.07\,{\rm eV}$, this gives $\Gamma(\eta \to 4\pi^0) < 8.9 \times 10^{-4}$ eV. No events were found in the sample of 3×10^7 η decays. The sensitivity of this test at 90% CL was also evaluated by comparison with an allowed $4\pi^0$ decay of another meson [12]:

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

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.

The first search for $\eta \to \pi^0\pi^0\gamma$ was reported recently by the CB@AGS [13]. 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 $BR(\eta \to \pi^0\pi^0\gamma) < 5 \times 10^{-4}$ at the 90% C.L. This corresponds to $\Gamma(\eta \to \pi^0\pi^0\gamma) < 0.6\,{\rm eV}$. The sensitivity of the result was evaluated using the allowed $\rho \to \pi^+\pi^-\gamma$ decay, which has a width of 1.5 MeV. The sensitivity of the search for $\eta \to \pi^0\pi^0\gamma$ is

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

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. A first ever upper limit for the decay was also reported by the CB@AGS [13]: $BR(\eta \to \pi^0\pi^0\pi^0\gamma) < 6 \times 10^{-5}$. This is a test of an isovector electromagnetic interaction of hadrons. To evaluate the sensitivity of this test a strong, allowed $\omega \to \pi^+\pi^-\pi^0$ decay was used. The sensitivity is

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

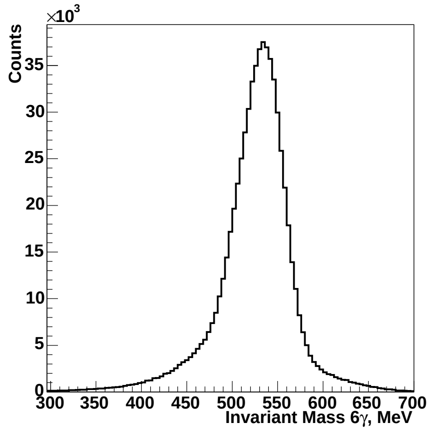

Fig. 4. Invariant mass spectrum of six photons produced in reaction $\gamma p \to 6\gamma p$.

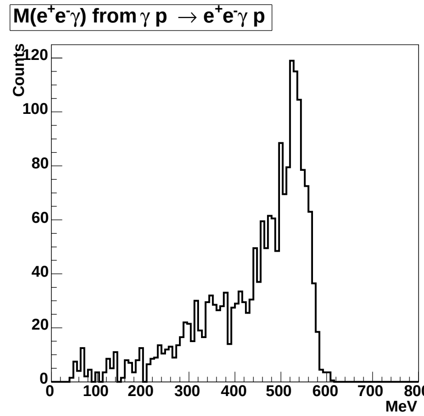

Fig. 5. Spectrum of $e^+e^-\gamma$ invariant mass from $\gamma p \to e^+e^-\gamma p$. The γ, e^+, and e^- are detected in the Crystal Ball in coincidence with the proton detected in TAPS. An additional cut on the missing mass of $e^+e^-\gamma$ is applied. The random background is subtracted.

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 [14]. The CB@AGS has produced a new upper limit for the decay which is [3] $BR(\eta \to 3\gamma) < 4.0 \times 10^{-5}$ 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.

In 2002 the Crystal Ball spectrometer was moved to the Mainz Microtron Facility (MAMI) at the University of Mainz. A large part of the new CB@MAMI program is dedicated to η and η' decays. MAMI currently provides a high intensity photon beam with maximum energy of 880 MeV. The next stage of the microtron, MAMI-C, is under construction. The new machine will be avaliable next year providing high quality photon beam with energy up to 1.5 GeV. The experiment uses the Glasgow–Edinburgh–Mainz photon tagger and consists 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. [15] for details. The experimental apparatus provides close to 4π sr coverage for outgoing photons. Protons are detected by the TAPS forward wall for $\Theta_{lab} < 21^\circ$, and by the MWPC plus PID for other angles.

The experimental apparatus was successfully tested during the 2004 run. Figures 4 and 5 show the quality of the data. The resolution of the new data is typically 10-15% better than the CB@AGS experiment due to the new flash ADC with the dynamic pedestal subtraction and better quality of the beam. The acceptance of the apparatus for the $\eta \to 3\pi^0$ decay is about twice as large as the AGS experiment because of the TAPS forward wall. The MAMI experiment can detect both neutral and charged decays of the eta. Figure 5 shows the invariant mass of $e^+e^-\gamma$ from the $\gamma p \to e^+e^-\gamma p$. The e^+, e^-, and the photon were detected in the Crystal Ball in coincidence with the proton detected in TAPS. The data analysis includes cut on the $e^+e^-\gamma$ missing mass around the mass of the proton. The narrow peak from the $\eta \to e^+e^-\gamma$ events has very little background and is well separated from the main background reaction $\eta \to \pi^+\pi^-\gamma$.

One of the first experiments with the new 1.5 GeV MAMI-C beam will be a new high–statistics measurement of several η' decays. The principal decay is $\eta' \to \eta\pi^0\pi^0$. The Dalitz plot of the decay provides information on the $\pi\pi$ and the $\pi\eta$ scattering length. A sample of about 2×10^6 η' is expected. The sample will also be used to improve the upper limits for the decays $\eta' \to \eta e^+e^-$ and $\eta' \to \pi^0 e^+e^-$, which are forbidden by C–invariance in first order, but allowed in second. We will also make a new test of CP invariance by a search for the CP forbidden decays $\eta' \to 4\pi^0$.

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