Search for the CP Forbidden Decay $\eta \to 4\pi^0$

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We report the first determination of the upper limit for the branching ratio of the CP forbidden decay $\eta \to 4\pi^0$. No events were observed in a sample of 3.0×10^7 η decays. The experiment was performed with the Crystal Ball multiphoton spectrometer installed in a separated π^- beam at the AGS (Alternating Gradient Synchrotron). At the 90% confidence limit, $\mathcal{B}(\eta \to 4\pi^0) \leq 6.9 \times 10^{-7}$.

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The origin of the CP violation that is seen in the decay of the neutral K meson is not determined. This void in our knowledge exists in spite of major experimental and theoretical efforts which have been made since the surprise discovery of the decay $K_L \to \pi^+\pi^-$ in 1964. The best insight we have at present on the origin of CP violation lies in the standard model (SM) where CP violation comes from a phase angle in the Cabibbo-Kobayashi-Maskawa matrix due to the existence of a third family of quarks. In this scenario, all quark-family-conserving interactions have only an extremely small CP violation [1]. For example, the calculation by Cho [2] yields the upper limit: $\mathcal{B}(\eta \to \pi^+\pi^-) \leq 10^{-17}$. The very distinct feature of the SM that all CP violations are extremely small, except in family-changing weak interactions, has hardly been tested experimentally.

Assuming CPT invariance, the different possible violations of C, P, and T invariance can be arranged into the four classes listed in Table I. At low and medium energies, P violating effects are now routinely measured at the level of 10^{-6}. These effects come from the interference of a small, P violating, weak-interaction amplitude with the P conserving one. The magnitude of P violation in electroweak interactions is energy dependent; it becomes quite large in the vicinity of the Z-boson pole. The existing experimental limit on the electric dipole moment (EDM) of the neutron gives an important limit on the strength of possible P violations. It is a test of class 3 from Table I because an EDM requires a violation of both P and T while preserving C. Not much is experimentally known about the validity of C and T invariance [1].

In order to test CP invariance one desires a system which is an eigenstate of the CP operator. For reactions involving quarks which belong to the same family, the traditional probes, K and B mesons, are excluded. One of the few remaining particles that is a CP eigenstate and can also be produced in large quantities is the η meson. It is sufficiently massive to allow the occurrence of hadronic and electromagnetic (EM) decay modes that are useful as

TABLE I. The four classes of C, P, T violation assuming CPT invariance.

Class	Violated	Valid
1	C, P, CT, PT	T, CP
2	C, T, CP, PT	P, CT
3	P, T, CP, CT	C, PT
4	C, P, T, CP, CT, PT	

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a test of CP. The width of the η, $\Gamma = 1.18$ keV, is small because the major decay mode $\eta \to 3\pi$ is forbidden in first order by conservation of G parity. However, this decay does occur as a result of the difference in the up and down quark masses. The partial width of the $\eta \to 2\gamma$ EM decay mode is just 0.5 keV because it is a second order transition. Before considering phase space factors, we have $\approx 10^5$ advantage in sensitivity for any η decay relative to a comparable decay of most other mesons, for example, the $\rho(770)$ which has a width of 150 MeV$/c^2$. The actual sensitivity is dependent on the kinematical phase space of the particular decay mode. The phase space for the $\eta \to 4\pi^0$ decay mode is small, but it still allows one to make a definitive measurement as discussed below. The advantage of this decay mode is that it is essentially background free.

The $\eta \to 4\pi^0$ decay tests CP violation for classes 3 and 4. When the rate of a CP violating η decay mode is smaller than 10^{-4} eV, which corresponds to an η branching ratio less than 10^{-7}, the decay of the η may result from a weak interaction that violates P and/or C, corresponding to classes 3 and 4 of Table I. If a forbidden decay is observed at a rate higher than this value, then the CP violation is associated with the strong and/or EM interactions.

The experimental limits on CP invariance in a quark-family-conserving interaction are few [1] and, for the reasons stated above, are primarily η decays: $\mathcal{B}(\eta \to \pi^+\pi^-) < 9 \times 10^{-4}$ and $\mathcal{B}(\eta \to \pi^0\pi^0) \leq 2.8 \times 10^{-2}$. The first test is limited by the radiative decay $\eta \to \pi^+\pi^-\gamma$, which has a branching ratio of 5%, and by $\pi^+\pi^-$ production from background reactions. The second test also suffers from direct $2\pi^0$ background production. Decays of the η' meson are 2 orders of magnitude less sensitive than η decays for testing CP invariance because the η' mean life is 160 times smaller than that of the η. There are two upper limits: $\mathcal{B}(\eta' \to \pi^+\pi^-) \leq 2 \times 10^{-2}$ and $\mathcal{B}(\eta' \to 2\pi^0) \leq 9 \times 10^{-4}$.

We report here the first search for the P and CP violating decay $\eta \to 4\pi^0$. Any evidence for this decay mode in our sample would signal a violation of CP invariance outside the SM. This test was proposed in Ref. [3], because the η mesons can be produced close to threshold in the process $\pi^- p \to \eta n$ where there is no known reaction which gives a $4\pi^0$ final state. The final-state requirement of four π^0's which together have the invariant mass of the η enables us to eliminate the expected background from the $\eta \to 3\pi^0$ decay due to photons producing multiple shower clusters. Note that a potential background reaction, the radiative decay $\eta \to 3\pi^0\gamma$, is forbidden by C invariance.

The data were taken during two weeks of running with the Crystal Ball (CB) detector, which was recently installed in the Alternating Gradient Synchrotron (AGS) C-6 beam line at BNL. This beam line provides electrostatically separated π and K beams up to 0.760 GeV$/c$ momentum. The CB detector was built at SLAC in the mid-1970s by a SLAC-Caltech-Harvard-Princeton-Stanford Collaboration [4]. It is a multiphoton spectrometer with nearly 4π geometric acceptance. EM showers are measured with an energy resolution $\sigma_E/E = 3.0E^{-1/4}\%$ with E given in GeV. Photon shower angular resolutions for energies in the range 0.05–0.5 GeV are $\sigma_\theta = 2°$–$3°$ for the polar angle and $\sigma_\phi = \sigma_\theta/\sin\theta$ for the azimuthal angle.

A 10-cm-long, 10-cm-diameter liquid hydrogen target was installed in the center of the CB. The target was housed in a 2.2-mm-thick aluminum vacuum pipe which extended through both tunnel regions of the CB. Four 120-cm-long, 5-mm-thick scintillation counters were mounted on this pipe and surrounded the target to provide a charged-particle veto. The primary neutral trigger was a coincidence between a beam trigger, which required a vanishing beam particle and a total energy signal from the NaI counters of the CB. An anticoincidence was made with the charged-particle veto counters. The data acquisition system could handle up to 1200 events per second, depending on the various triggers. Beam rates were limited to $\approx 0.5M$ pions per second since the NaI crystals have a relatively long signal decay time of ≈ 1 μs. Time-to-digital converters (TDC) were put on the CB so that a time coincidence window of typically 40 ns could be applied to each photon cluster. A photon cluster consists of 13 neighboring crystals in the CB where at least 15 MeV is deposited in the central crystal and the TDC associated with the cluster is within the 40-ns coincidence window. This TDC requirement enabled us to remove spurious clusters in the analysis not associated with the trigger event, and substantially reduced the effect of accidentals, beam halo, AGS background, and residual energy in the NaI crystals. The resulting centroid of the η invariant mass varied by less than 1 MeV for different beam intensities. We recorded the energy deposited in all crystals but in the analysis we required a minimum of 1 MeV before including a crystal in the event. The CB along with the veto barrel and target were fully simulated with GEANT 3.21 Monte Carlo (MC) tracking software. Both real and simulated data were passed through the same analyzer to determine backgrounds and acceptances.

The η mesons were produced in the reaction $\pi^- p \to \eta n$ at a beam momentum of 0.720 GeV$/c$. This momentum is a good compromise between having a large production cross section and remaining close enough to threshold so that all the η's move in the forward direction with about the same total energy of 0.6 GeV. The associated neutrons also move forward, exiting the CB through the downstream tunnel without interacting in the CB. This arrangement is important for further reducing background. The two-body production kinematics greatly facilitate the search for rare decay modes by constraining the η's energy and direction. The η production cross section rises rapidly above threshold and it is large, nearly 2 mb at 0.720 GeV$/c$, which allowed us to use a relatively low incident pion beam intensity to reduce accidentals. The number of η's produced in our data sample was determined to be $(2.97 \pm 0.03) \times 10^7$, based on the $\eta \rightarrow 2\gamma$ decay mode with the known branching ratio of $(39.2 \pm 0.3)\%$.

The first step in the analysis was the energy calibration of the 672 NaI crystals. The individual phototube gains were adjusted based on the 662-keV photon from a ^{137}Cs source. Then the software gains were adjusted to reproduce the correct invariant mass for the π^0 and η mesons from their 2γ decay modes. This calibration was independently verified with the 129.4-MeV monoenergetic photons from the reaction $\pi^- p \rightarrow \gamma n$ at rest. The $\eta \rightarrow 2\gamma$ and $\pi^0 \rightarrow 2\gamma$ events in the CB are recorded simultaneously with other data during all runs, thus providing us with a continuous monitor of the gain.

The η-meson decays are cleanly identified by the invariant mass of the decay photons, as illustrated in Fig. 1(a) for the $\eta \rightarrow 3\pi^0$ decay mode. The spectrum consists of those events which, as a result of a kinematical fit, exceeded a 2% probability in a χ^2 test for satisfying the hypothesis $\pi^- p \rightarrow \eta n \rightarrow 6\gamma n$, referred to as a 2% confidence level. The good agreement with the MC simulation indicates we have a good understanding of the overall response of the CB detector. We have determined the contribution of direct $3\pi^0$ production to be less than 2% of our η sample, which contributes to the slight disagreement of the MC with the data in the wings of the distribution.

Figure 1(b) shows the improvement of the resolution after passing the events through a kinematical fit in which the photon cluster energy and angle values are adjusted within the resolution limits of the CB to satisfy the $\pi^- p \rightarrow 3\pi^0 n \rightarrow 6\gamma n$ hypothesis. This hypothesis constrained the invariant mass of the three π^0's, but not the invariant mass of the η. The value of the χ^2 test was again chosen to yield a 2% confidence level. As a result, the resolution of the η invariant mass was improved from 4.3% to 0.9%.

The reaction $\pi^- p \rightarrow \eta n \rightarrow 4\pi^0 n$ must produce eight-photon clusters in the CB. Our sample of 2.97×10^7 η mesons yielded 44 289 neutral, eight-cluster events. The eight-photon invariant mass spectrum is shown in Fig. 2(a). The major source of eight-cluster events is from $\eta \rightarrow 3\pi^0$ decay in association with two random clusters in the CB which pass the TDC requirement. Candidate events were subjected to a kinematical fit for the hypothesis $\pi^- p \rightarrow \eta n \rightarrow 4\pi^0 n \rightarrow 8\gamma n$. This fit procedure is similar to that above for the $3\pi^0$ decay but with an additional constraint on the η invariant mass. After applying a χ^2 test on the kinematical fit at the 0.5% confidence level, no candidates remained from the real data sample. The overall combined acceptance for the analysis of $\eta \rightarrow 4\pi^0$ events was determined by MC to be 12.0%. Approximately 84% of the events were lost due to photon conversion in the vacuum pipe and veto counters, failing to detect all eight photons, or the total energy deposited in the CB being less than the hardware threshold. The remaining 4% of events were lost due to failure of the χ^2 test on the kinematical fit. Applying the same analysis to the $\eta \rightarrow 3\pi^0$ and $\eta \rightarrow 2\gamma$ decay modes, including the constraint on the η mass, yields a ratio for the two decay rates in agreement with the value reported in Ref. [1]. We varied the analysis parameters and found the ratio stable within 1%. Allowing for the two extra photons in the $\eta \rightarrow 4\pi^0$ decay, we estimate a 2% overall systematic error for determining the upper limit for the $\eta \rightarrow 4\pi^0$ branching ratio, which is small enough to be ignored in determining the final value.

With no events found and the selection of 2.44 events as the upper bound at the 90% confidence limit [1], the upper limit becomes $\mathcal{B}(\eta \rightarrow 4\pi^0) \leq 6.9 \times 10^{-7}$. Equivalently, this upper limit can be expressed as $\Gamma(\eta \rightarrow 4\pi^0) \leq 8.3 \times 10^{-4}$ eV. For comparison, note that the major $3\pi^0$ decay mode has a width $\Gamma(\eta \rightarrow 3\pi^0) = 360$ eV. The existing upper limit for the best known test of CP is $\Gamma(\eta \rightarrow 2\pi^0) \leq 1.1$ eV; however, $\eta \rightarrow 2\pi^0$ has a larger phase space than $\eta \rightarrow 4\pi^0$.

The main limitation on the sensitivity of the $4\pi^0$ decay mode is its small phase space. The maximum π^0 momentum in $\eta \rightarrow 4\pi^0$ is only 39 MeV$/c$, as compared to 238 MeV$/c$ for the π^0 in $\eta \rightarrow 2\pi^0$. The difference in sensitivity between $\eta \rightarrow 2\pi^0$ and $\eta \rightarrow 4\pi^0$ may be discussed by using the ratio $R = \Gamma_4(\eta \rightarrow 4\pi^0)/\Gamma_2(\eta \rightarrow 2\pi^0)$. When M_n is the Lorentz invariant n-body decay

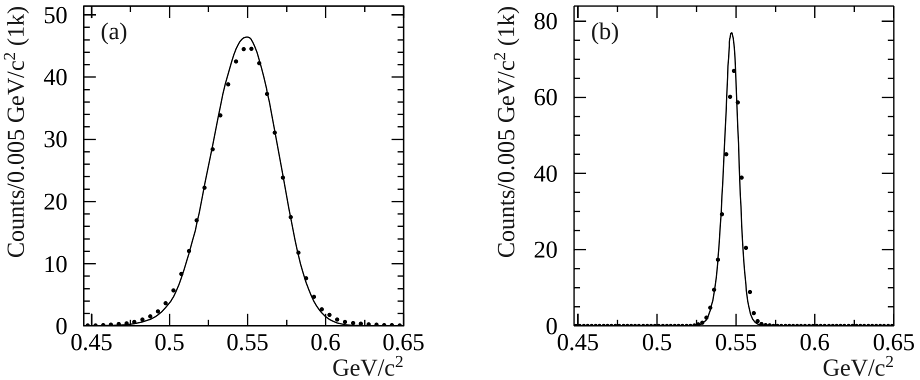

FIG. 1. (a) Invariant mass spectrum for data (●) and Monte Carlo (—) satisfying a χ^2 test for the reaction $\pi^- p \rightarrow \eta n \rightarrow 6\gamma n$. (b) Improved resolution of (a) due to requiring a kinematical fit to the reaction $\pi^- p \rightarrow 3\pi^0 n$.

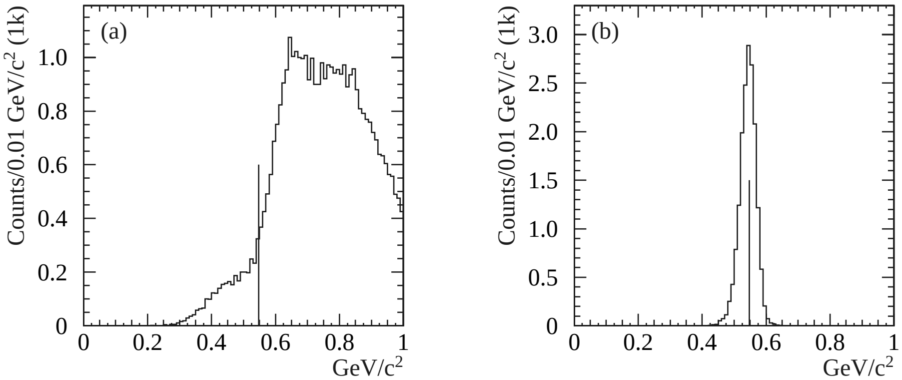

FIG. 2. (a) The 8γ invariant mass spectrum for all 44 289 eight cluster events and (b) the events found in 10^5 $\pi^- p \rightarrow \eta n \rightarrow 4\pi^0 n$ Monte Carlo events. The lines indicate the known value of the η mass.

amplitude and Φ_n is the n-body phase space volume, we have $R = \langle |M_4|^2 \rangle \Phi_4 / \langle |M_2|^2 \rangle \Phi_2$. A numerical evaluation [5] gives $\Phi_4/\Phi_2 = 1.21 \times 10^{-9} m_{\pi^0}^4$ and $\langle |M_4|^2 \rangle / \langle |M_2|^2 \rangle = A/m_{\pi^0}^4$. To determine the factor A, a dynamical model is needed which depends on the origin of CP violation and the decay mechanisms for the 2π and 4π decay modes. To illustrate the latter, we consider the known decay of the $f_0(1500)$. The experimental ratio $\mathcal{B}(f_0 \rightarrow 4\pi^0)/\mathcal{B}(f_0 \rightarrow 2\pi^0) = 3.4 \pm 0.8$ where $\mathcal{B}(f_0 \rightarrow 4\pi^0)$ means 4π decays not proceeding via $\rho\rho$ [6]. The ratio Φ_4/Φ_2 for $f_0(1500)$ decay becomes $2.29 \times 10^{-2} m_\pi^4$ and using $m_\pi = 134.98$ MeV results in a value of $A = 140$.

We can reduce the uncertainty in sensitivity due to differing decay modes by comparing to the allowed $4\pi^0$ decay of a related meson, such as the $f_0(1500) \rightarrow 4\pi^0$. This f_0 has the same quantum numbers as the η except for parity: $I^G(J^{PC}) = 0^+(0^{++})$; the measured decay rate is $\Gamma(f_0 \rightarrow 4\pi^0) = 33$ MeV [6]. The difference in phase space has been calculated to be [5] $\Phi_4(\eta)/\Phi_4(f_0) = 4.7 \times 10^{-8}$. Then, if the decays $\eta \rightarrow 4\pi^0$ and $f_0 \rightarrow 4\pi^0$ have comparable matrix elements, we would expect $\Gamma(\eta \rightarrow 4\pi^0) = 33 \times 4.7 \times 10^{-8}$ MeV $= 1.6$ eV. This is not an unreasonable estimate since it is 0.5% of the rate for the $\eta \rightarrow 3\pi^0$ decay. The limit on the ratio of the CP violating amplitude to this hypothetically allowed amplitude is then $A_{\overline{CP}}/A_{CP} < (8.3 \times 10^{-4}/1.6)^{1/2} < 2.3 \times 10^{-2}$.

In summary, our measurement of the branching ratio for the CP forbidden decay $\eta \rightarrow 4\pi^0$ is the smallest branching ratio yet measured for family conserving decays. Within the applicability of our model, this result is estimated to provide a 2% limit on CP violation in quark-family-conserving interactions.

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