EXPERIMENTAL TEST OF C INVARIANCE IN $\eta\to\pi^+\pi^-\gamma$ *

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We report an asymmetry of $2.4\pm1.4\%$ based on 6710 events of $\eta\to\pi^+\pi^-\gamma$.

We have carried out an experiment to determine whether any difference exists between the π^+ and π^- energy spectra in the decay $\eta\to\pi^+\pi^-\gamma$.[1] The detection of such a difference would be sufficient proof of the existence of a C-noninvariant electromagnetic interaction of the hadrons.[2] Such an interaction was proposed to explain the small CP nonconservation observed in the decay $K_2\to\pi^+\pi^-$.[3]

The simplest characterization of a C violation in this decay is the asymmetry A which is defined as follows: Let N^+ be the number of events for which the π^+ energy is greater than the π^-, and N^- be the number of events for which the π^- is greater than the π^+. A is then the ratio of the difference to the sum:

$$A=(N^+-N^-)/(N^++N^-).$$

Eta mesons were produced in the reaction $\pi^-p\to n\eta$ in the 10° beam from the G-10 target at the Brookhaven National Laboratory alternating-gradient synchrotron (AGS). The incident π^- beam had a momentum of 720 MeV/c with a spread of $\pm\frac{3}{4}\%$. The neutron momentum was measured by time of flight, and the momenta of the charged pions from the decay of the η were measured by a set of sonic spark chambers in a magnetic field. The neutron detector consisted of nine tanks of liquid scintillator each of which was viewed by a single XP1040 photomultiplier tube. Each counter defined the neutron angle to $\pm2°$ and had a time resolution of ±1 nsec. The nine counters were arranged in a 1.8-m×1.8-m array, 9.2 m downstream from the liquid-H_2 target along the beam direction as shown in Fig. 1(a). The target and spark chambers were placed inside a 4.4-kG magnetic field as shown in Fig. 1(b). The beam entered the target through a hole in the upstream magnet pole piece, and the uninteracted beam and forward-going reaction products left the magnet through a conical hole in the downstream pole piece. Reversing the magnetic field polarity did not affect beam position in the target. A second magnet swept the incident beam away from the neutron detectors.

The spark-chamber planes were parallel to the incident beam. Each set of three chambers covered one quadrant in the azimuthal direction as shown in Figs. 1(b) and 1(c). The geometric efficiency for detecting both pions in the η decay was approximately 3 %. The positions of the sparks within a chamber were computed from the transit times of the sound associated with the spark to a set of four microphones mounted within the chamber. Assuming all three chambers in a quadrant had equal spark-position resolutions, we infer an rms resolution of ±0.4 mm in each chamber. The liquid-hydrogen target was 30 cm long and 3.8 cm in diameter. Decay pions on the average went through 2.5 cm of liquid hydrogen to get into the spark chambers. This represented a very large fraction of the material that the pions passed through prior to detection.

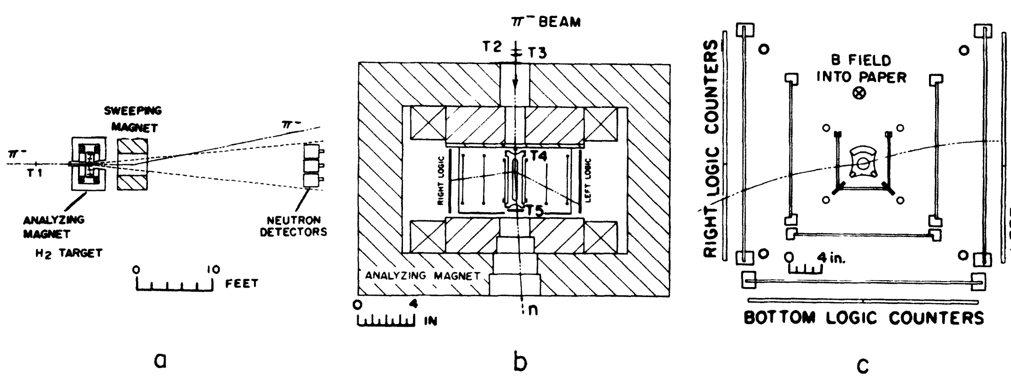

FIG. 1. (a) Layout of the experiment viewed from the top. (b) Enlarged view of the spark chambers viewed from the top. (c) Enlarged view of spark chambers viewed along the beam line.

The spark chambers were triggered when the following conditions were met:

(a) A beam pion detected in counters $T1$, $T2$, $T3$, and $T4$ interacted in the target, and did not count in $T5$ [Figs. 1(a) and 1(b)].

(2) A neutron was detected in a 12-nsec wide time interval which was centered at the time corresponding to the velocity of neutrons from η production.

(3) Coincident with $T3$, two charged particles were detected by the logic counters placed behind the outermost chamber in any two of the three quadrants as shown in Fig. 1(c).

After each event, data were transferred to the memory of an IBM 360/30, and after each AGS pulse it was written onto magnetic tape for subsequent analysis. Neutron time of flight, the transit times of sound from sparks, the neutron counter pulse height, and the logic counter pulse heights were measured and recorded. Neutron time of flight and pulse height were also measured and recorded on tape for neutral final states. For these events neutrons were accepted in a wider time interval that covered both charge exchange and η production. These events were used to calibrate the time-of-flight measurement.

Every two hours we changed the polarity of the analyzing magnet, and every four hours we reversed polarities of the clearing field voltage and spark-chamber high voltage. Every 12 hours we turned the analyzing magnet off for two hours to calibrate the sonic chambers with straight tracks.

During the experiment the spark chambers were triggered 2.5×10^6 times. Since the momentum of each track was determined by constructing a helix that passed through the position of the three sparks, it was necessary to have a spark in each of the three chambers in a quadrant. Moreover, before analyzing an event, we required that in each of two quadrants, three sparks must have been associated with a logic counter count from the same quadrant. Also, the reconstructed spark positions were required to lie within the foil areas. About 1.0×10^6 events were rejected for these reasons. They resulted from a variety of causes: particles scattered by the magnet or the spark-chamber supports into a logic counter bypassing some chambers; γ rays which converted in the target supports or other obstructions; accidental counter triggers; and inefficiency of the chambers.

The events which could be analyzed were assumed to have come from one of the following reactions:

$$\pi^- p \to \pi^+ \pi^- n, \tag{1}$$

$$\pi^- p \to \pi^+ \pi^- \gamma n, \tag{2}$$

$$\pi^- p \to \pi^+ \pi^- \pi^0 n. \tag{3}$$

Because more than 90% of the events originated from Reaction (1), we first eliminated all events which clearly conserved momentum and energy assuming this reaction. We eliminated events which conserved three components of momentum to within 1.5 rms of the Reaction (1) missing-momentum distribution and also conserved energy to within 30 MeV, which is 1.2 rms of the missing-energy distributions. There were 685 000 events remaining. The following cuts were applied to these events:

(1) The redundancy in reconstructing spark positions from four microphones allowed us to calculate two constraint quantities. Acceptable values of these quantities were determined from histograms and used in cutting out events with apparently ambiguous spark positions. The approximately 182 000 events cut in this fashion were studied separately with results reported in the following paper. We attribute these events to multiple sparking and poor transducer pickup of marginal sparks.

(2) There were 54 000 events in which both tracks appeared to have the same charge. These events were eliminated.

(3) There were 23 000 events which struck spark-chamber supporting posts. These events were eliminated.

(4) The pitch of the helix was determined from the first two chambers encountered by the pion. The helix was projected into the third chamber, and the difference between the projected position and the measured position, $\Delta\zeta$, was used to eliminate pions which scattered or decayed. The $\Delta\zeta$ distribution widths are momentum dependent because of Coulomb scattering in the neon and spark-chamber foils. Our $\Delta\zeta$ cut reflected this momentum dependence and increased with decreasing momentum being 3 mm in the high-momentum limit. There were 88 000 events rejected by this cut.

(5) Each track was traced back into the H_2 target, and the distance of closest approach of the two tracks was calculated. Each component of this distance was required to be less than 4 mm. The vertex was also required to be within the

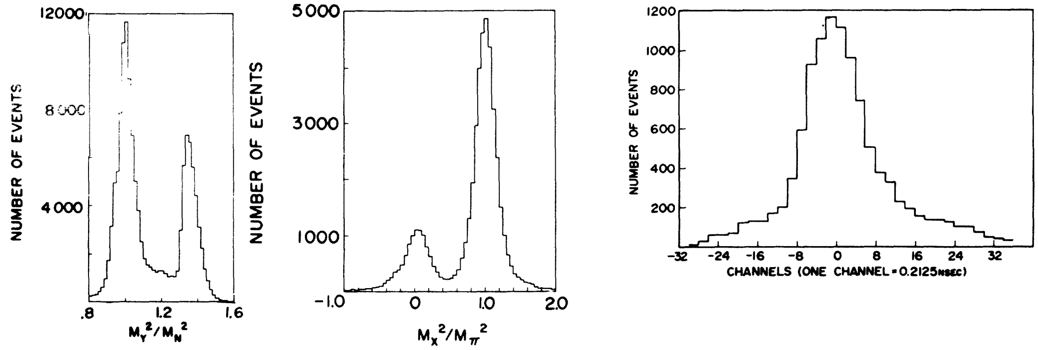

FIG. 2. (a) The missing-mass M_Y^2 distribution. Y is defined as the missing neutral in $\pi^-p \rightarrow \pi^+\pi^-Y$ of events within ±12 channels of the η peak. (b) The missing-mass M_X^2 distribution. X is defined as the missing neutral in $\pi^-p \rightarrow \pi^+\pi^-nX$ for events with $M_Y^2 \geq 1.15M_n^2$ and within ±12 channels of the η peak. (c) Neutron time-of-flight histogram for events with $M_Y^2 \geq 1.15M_n^2$ and $-0.35M_{\pi^0}^2 \leq M_X^2 \leq 0.45M_{\pi^0}^2$. Requirements on T_γ are described in the text.

target volume. There were 54 000 events rejected by this cut.

After the cuts, 284 000 events remained. Among these remained some Reaction (1) events in the tails of the momentum-resolution distributions. To separate events further, we used the missing-mass distribution of all outgoing neutrals, M_Y^2. The M_Y^2 distribution is shown in Fig. 2(a). Events for which $M_Y^2 \geq 1.15M_n^2$ were assumed to be candidates for Reactions (2) and (3). The missing mass M_X^2, where X is defined as the missing neutral in $\pi^-p \rightarrow \pi^+\pi^-nX$, is plotted in Fig. 2(b). There are two well-resolved peaks corresponding to Reactions (2) and (3). Events which were assigned to Reaction (2) were required to have $-0.35M_{\pi_0}^2 \leq M_X^2 \leq 0.45M_{\pi_0}^2$.[4] Reaction (3) will be discussed in the following paper.

This sample still contains some $\pi^+\pi^-n$ events which were removed by requiring the γ-ray laboratory energy to be greater than 75 MeV for $M_Y^2 > 1.2M_n^2$ and greater than 110 MeV for $1.2M_n^2 \geq M_Y^2 \geq 1.15M_n^2$. The time-of-flight spectrum for the remaining 9888 events is shown in Fig. 2(c). The width of the η peak was ±5.5 channels. Most of the η's are within ±12 channels of the η peak. The time-of-flight regions −24 to −12 channels and +12 to +24 channels contain background events and some η's. We believe that most background events are due to accidental triggers. The asymmetry A in the $\pi\pi\gamma$ rest system for the three different time-of-flight regions is given in Table I. After a tentative background subtraction, we obtained an asymmetry of 2.4 ± 1.4 % based on 6710 events.

We have studied the asymmety as a function of Dalitz coordinates x and y of events within ±12 channels of the η peak. The theoretical energy

Table I. Asymmetry for three different neutron time-of-flight regions (upper section) and four different running conditions (lower section).

Neutron time of flight (channel)	$\pi\pi\gamma$ mass (MeV)	Number of events	A (c.m.) (%)
$-24 < \text{TOF} < -12$	$519 < M < 537$	649	−0.5 ±3.9
$-12 < \text{TOF} < 12$	$537 < M < 557$	8299	1.9 ± 1.1
$12 < \text{TOF} < 24$	$557 < M < 563$	940	−0.2 ± 3.3

E field	B field	Number of events	A (c.m.) (%)	A (lab) (%)
+	+	2866	3.2 ± 1.9	3.5 ± 1.9
−	+	1291	0.7 ± 2.8	2.7 ± 2.8
+	−	2847	2.6 ± 1.9	2.6 ± 1.9
−	−	1295	−1.5 ± 2.8	−3.9 ± 2.8

distribution of $\eta\to\pi^+\pi^-\gamma$ is given by Bernstein et al.[2] For a given γ energy, the predicted asymmetry is linear in x. Our data are consistent with the hypothesis of an asymmetry increasing linearly with x.

In the table, asymmetries of events within ±12 channels of the η peak are shown for four different running conditions. The + and − indices refer to polarities of the spark-chamber voltage (E) and magnetic field (B). A(c.m.) refers to the asymmetry measured in the rest system of the η, while A(lab) refers to the asymmetry measured in the laboratory. We note that asymmetries in all four running conditions are consistent within errors. Because the momentum spectrum of our event sample for Reaction (2) closely resembles that for Reaction (3), the bias errors for the two reactions arise from similar sources. As discussed in the next paper, we believe the bias error to be negligible compared with the statistical error of 1.4%.

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†National Science Foundation Fellow.

[1]Three previous measurements of the asymmetry in the decay $\eta\to\pi^+\pi^-\gamma$ have been published: F. Crawford and L. Price, Phys. Rev. Letters 16, 333 (1966); R. Bowen et al., Phys. Letters 24B, 206 (1967); P. Litchfield et al., Phys. Letters 24B, 486 (1967).

[2]J. Bernstein, G. Feinberg, and T. D. Lee, Phys. Rev. 139, B1650 (1965); S. Barshay, Phys. Letters 17, 78 (1965).

[3]J. Christenson et al., Phys. Rev. Letters 13, 138 (1964).

[4]This cut is symmetric about the experimentally measured center of the peak.

EXPERIMENTAL TEST OF C INVARIANCE IN $\eta\to\pi^+\pi^-\pi^0$ *

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We report an asymmetry of 1.5 ± 0.5% based on 36 800 events of $\eta\to\pi^+\pi^-\pi^0$.

From an experiment which was designed to detect the charged decay modes of the η, we have obtained a sample of 36 800 η's decaying into $\pi^+\pi^-\pi^0$. The $\pi^+\pi^-\gamma$ decay mode, observed in the same experiment, was reported in the preceding Letter.[1] In that Letter, we discussed the experimental techniques and methods of analysis used in this experiment. In this paper we will report whether there exists a difference between the π^+ and π^- energy spectra in the decay $\eta\to\pi^+\pi^-\pi^0$.[2] The detection of such a difference would be sufficient proof of the existence of a C-noninvariant interaction.[3] Such an interaction has been proposed as one of the means of explaining the small CP nonconservation observed in the decay $K_2\to\pi^+\pi^-$.[4] The origin of this interaction may be either in the electromagnetic interaction of the hadrons[5] or in an entirely new interaction involving the hadrons, the strength of which is weaker than the strong interaction.[6]

In the preceding Letter,[1] we described the requirements imposed on events and how they were momentum analyzed. In the analysis of events we considered three reactions:

$$\pi^- p\to\pi^+\pi^- n, \qquad (1)$$

$$\to\pi^+\pi^-\gamma n, \qquad (2)$$

$$\to\pi^+\pi^-\pi^0 n. \qquad (3)$$

In this paper we consider Reaction (3). Events of this type were required to have $M_Y^2 \geq 1.15 M_\eta^2$, where M_Y is the missing mass of all outgoing neutrals. This criterion also applied to Reaction (2). Reaction (3) was separated from Reaction (2) by requiring that the mass of the missing neutral, M_X, satisfy $0.45 M_{\pi_0}^2 \leq M_X^2 \leq 1.6 M_{\pi_0}^2$.[7] Missing-mass distributions of M_X^2 and M_Y^2 are presented in the previous paper.[1]

There were 41 882 events that satisfied the criteria for $\pi^+\pi^-\pi^0 n$ final states. The distribution of these events by time of flight, which is shown in Fig. 1(a), shows a peak due to the η meson which has a width of ±5.5 channels, where each channel is 0.2125 nsec, corresponding to a full width of 9 MeV.

Most of the η's are within ±12 channels of the center of the η peak. Events outside of this region are contaminated with nonresonant 3π background. The asymmetry A defined in the previous Letter[1] in the 3π rest system for three intervals of time of flight is given in Table I. After