Charge Asymmetry in the Decay $\eta \to \pi^+\pi^-\gamma$†

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We have measured the charge asymmetry in the decay $\eta\to\pi^+\pi^-\gamma$. η mesons were produced in the reaction $\pi^-p\to\eta n$ at 730 and 810 MeV/c incident pion momentum. The asymmetry is 0.005 ± 0.006 for 36155 events. We see no evidence for C-invariance violation in this decay.

We have carried out an experiment at the Princeton-Pennsylvania Accelerator (PPA) to investigate the charged decay modes of the η. This Letter deals with the decay $\eta\to\pi^+\pi^-\gamma$; in the following Letter we report on the decay $\eta\to\pi^+\pi^-\pi^0$. The purpose of the experiment was to determine if there exists a difference between the π^+ and π^- energy spectra in these decays. The detection of such a difference would be sufficient proof of the existence of a C-noninvariant interaction of the hadrons.[1] Specifically we have measured the asymmetry parameter A, where $A=(N_+-N_-)\times(N_++N_-)^{-1}$ and N_+ is the number of events for which the π^+ energy is greater than the π^-, and N_- is the number for which the π^- energy is greater in the η rest system.

η's were produced in the reaction $\pi^-p\to\eta n$. The π's were produced by the interactions of slowly extracted 3-GeV protons with a Be target $\frac{1}{4}$ in. in diameter and 4 in. long. The π^- beam was a 0° secondary beam, doubly focused, with a momentum spread of $\pm\frac{1}{2}$%.

Figure 1(a) shows the arrangment of the experimental apparatus. The π^-'s passed through a hole in the center of the upstream pole piece of the PPA spark-chamber magnet. The pole-tip diameter and the gap were both 36 in. A conical veto counter lining the hole eliminated particles scattering off the iron. With this geometry, the incident beam was not deflected in the 9-kG magnetic field. The beam telescope shown in Fig. 1(b) indicated the passage of a π through the hydrogen target, $1\frac{1}{2}$ in. in diameter and 24 in. long. The counter B_5, in anticoincidence, signaled an interaction in the target.

A large opening in the downstream pole piece allowed noninteracting pions and produced neutrons to leave the target region. The neutrons were then detected and their time of flight measured by an array of liquid-scintillator detectors placed 30 ft from the center of the hydrogen target, as shown in Fig. 1(a). The array consisted of 12 detectors 2 ft square, arranged in four rows of three each. An additional neutron coun-

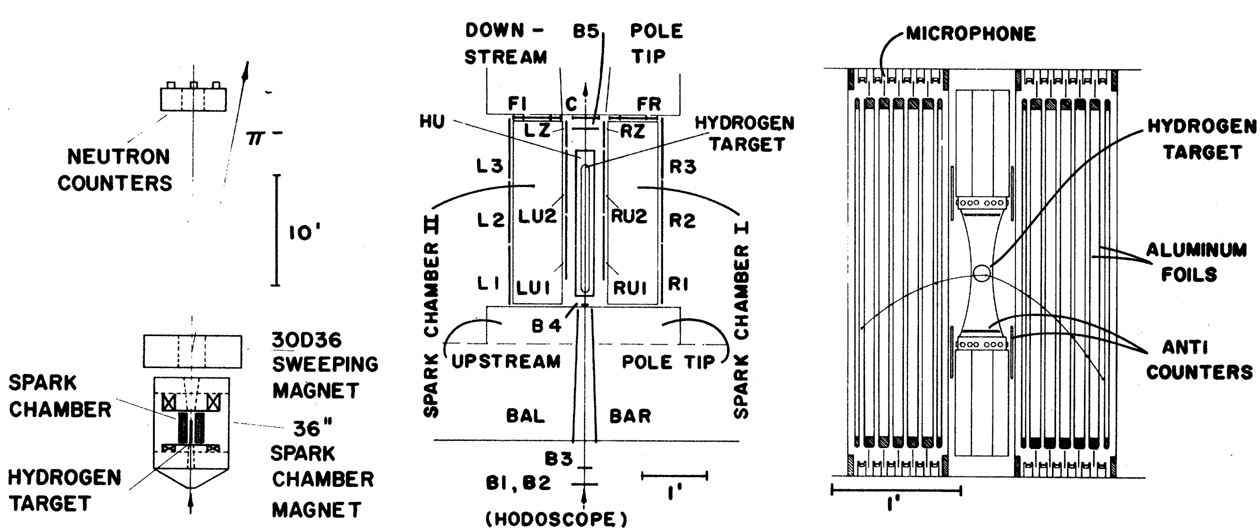

FIG. 1. (a) Layout of the experiment, viewed from the top. (b) Enlarged view of target and spark chambers showing locations of beam and trigger counters and anticounters. (c) Sonic spark chambers viewed along the beam line.

ter of plastic scintillator, 5 in. in diameter and 11 in. long, was placed at the center of the array, along the beam line. Charged particles were swept away from the neutron detectors by a large aperture magnet following the 36-in. magnet.

Two sets of six-gap sonic spark chambers were placed in the analyzing magnet, one on each side of the hydrogen target, as shown in Fig. 1(c). The gap width was $\frac{3}{8}$ in., and there were six microphones in each gap. The spark chambers were triggered when the following conditions were met: (a) The beam telescope indicated a π^- interacted in the hydrogen target. (b) A neutron was detected in a 14-nsec-wide time interval which was centered at the time corresponding to a neutron associated with η production. (c) In time with the π^- interaction, at least one particle was detected in trigger counters, L and R in Fig. 1(b), placed behind each spark chamber. The counters LU, RU, LZ, RZ, and C vetoed particles which would not pass through at least three gaps.

For events having neutral final states, i.e., no particle detected in any counter listed in item (c) above, neutrons were accepted in a wider time gate which covered both charge exchange and η production. These events were used to calibrate the time-of-flight measurement. After each event, data were transferred to the on-line PDP-10 computer. After partial reconstruction by the on-line program, the data were written on magnetic tape. The program issued hourly run summaries which enabled us to monitor the stability of the apparatus throughout the running period. The polarity of the analyzing magnet was reversed every 2 h. After 10 h, we turned the magnet off and took straight-line data for $\frac{1}{2}$ h for spark-chamber calibration. During the experiment, the park chambers were triggered approximately 17 000 000 times, at a rate between 5 and 6 triggers per second. About 1.4×10^5 pions/sec were incident on the hydrogen target under normal beam conditions. Data were taken primarily at an incident momentum of 730 MeV/c; about 10% of the data was obtained with incident pions of 810 MeV/c to check the energy dependence of the background.

We first required that there be at least three good sparks in each box, to be able to obtain the momentum for both tracks. The six sonic times provided several constraints which enables us to reject those gaps with more than one spark. The coordinates of the spark positions in each gap were fitted to a helix through the previously mapped magnetic field. The χ^2 calculated for this fit eliminated scattered particles. Each track was projected back to the hydrogen target, and the distance of closest approach between the two tracks was calculated. We required that this distance be less than 15 mm and that the vertex lie within the target volume. There were 5.5×10^6 events that survived this reconstruction. Most of the rejected events were ones having only one track, a consequence of the one-pion trigger.

The remaining events were assumed to have come from one of the following reactions:

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

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

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

To separate events into Reactions (1), (2), and (3), we used the missing-mass distribution of all outgoing neutrals, M_y^2, and of undetected neutrals, M_x^2, where y and x are defined as the missing neutrals in the reactions $\pi^- p \to \pi^+\pi^- y$ and $\pi^- p \to \pi^+\pi^- nx$, respectively.

We also calculated the mass of one pion and the undetected neutral, $M_{z\pm}^2$, defined by the reaction $\pi^- p \to \pi^\pm n z^\mp$. Events of Reaction (1) should have $M_y^2 = M_n^2$, $M_z^2 = M_\pi^2$, $E_x = 0$, and $M_x^2 = 0$. E_x is the energy of the x particle, and M_n and M_π are the neutron and pion mass, respectively. The distribution of M_y^2 is shown in Fig. 2(a). We eliminated all events with $M_y^2 < 1.15 M_n^2$, $E_x < 50$ MeV, and $M_z^2 < 1.8 M_\pi^2$. There were 413 000 events remaining, most of them from Reactions (2) and (3), with a small amount (5%) from Reaction (1).

We then determined the neutron time-of-flight spectrum for $\pi^- p \to \eta n$. Imposing strict require-

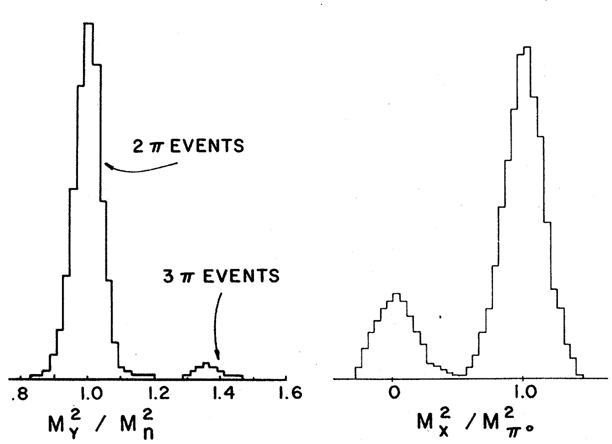

FIG. 2. (a) M_y^2 distribution before kinematic cuts. (b) M_x^2 distribution for one Dalitz-plot bin after background subtraction.

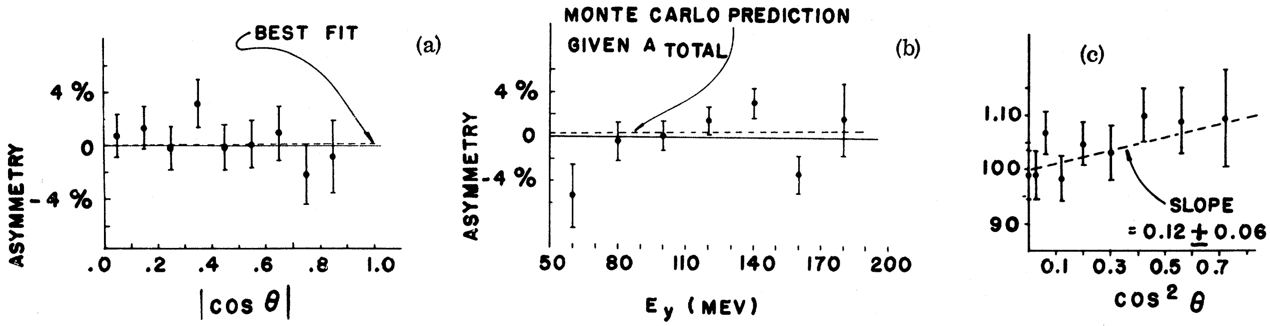

FIG. 3. (a) Asymmetry plotted as a function of $|\cos\theta|$. (b) Asymmetry plotted as a function of the γ-ray energy. E_γ corresponds to k in the text. (c) $(1/\sin^2\theta)dN/d|\cos\theta|$ plotted as a function of $\cos^2\theta$. The data are divided by a distribution generated by a C-conserving Monte Carlo technique.

ments on M_y^2, M_x^2, M_z^2, and E_x, we obtained a pure sample of Reaction (3). Examination of the 3π Dalitz plot showed that in some regions the non-η contamination was less than 1%. This background was then subtracted. This spectrum was used in the subsequent analysis in determining the number of η's in the neutron time-of-flight spectrum of various data blocks.

To eliminate the remainder of Reaction (1), we divided our data into 180 bins, 60 Dalitz-plot bins for each three M_x^2 bins. The neutron time-of-flight spectrum was histogrammed for each bin, and the number of η and background events fitted. We assumed that the non-η events had a linear time-of-flight distribution. Knowing the total amount of background in each bin from this process, we assumed that in each of the 60 Dalitz-plot bins this background depended quadratically on M_x^2, and subtracted the calculated number of events. The resulting M_x^2 distribution for one such Dalitz bin is shown in Fig. 2(b).

Finally, to separate Reactions (2) and (3), we calculated by Monte Carlo technique the expected M_x^2 distribution from Reaction (3) for each Dalitz bin and subtracted this shape from the data, giving the number of events of Reaction (2). From this data, we find an asymmetry of 0.005 ± 0.006 based on 36 155 events. This result is insensitive to various assumptions concerning the shape of the background. Other sources of systematic error, such as measurement error, etc., to be discussed in the following paper,[3] are known to contribute not more than 0.2% to asymmetry.

We have also looked at the dependence of the asymmetry on k and $\cos\theta$, where k is the energy of the γ ray in the η rest system and θ is the angle between the π^+ and the photon in the di-pion center of mass. Then

$$A(k, |\cos\theta|) = \frac{2|a||b| \sin(\delta_p - \delta_d) pk|\cos\theta|}{|a|^2 + |b|^2 p^2 k^2 \cos^2\theta},$$

where p is the momentum of π^+ in the di-pion rest system, δ_p is the phase shift of the two pions in the p state, and δ_d is the phase shift in the d state. Using the expressions for δ_p and δ_d given by Barrett and Truong,[2] we can calculate the asymmetry as a function of k and $|\cos\theta|$. $A(|\cos\theta|)$ is expected to increase linearly as a function of $|\cos\theta|$; the data are shown in Fig. 3(a). $A(k)$ is also expected to increase as k increases; this is shown in Fig. 3(b). In neither case do we see a C-invariance–violating effect.

It was pointed out by Barret and Truong that the angular distribution may provide a more sensitive test of C-invariance violation than the asymmetry because $\sin(\delta_p - \delta_d)$ is known to be small in this kinematic region. In a folded Dalitz plot, which eliminates left-right asymmetry, we expect the distribution to have the form

$$dN/d|\cos\theta| = A \sin^2\theta\,(1 + \beta \cos^2\theta),$$

where β measures the strength of the d-wave contribution. The existence of d wave implies a C-invariance violation.[4] The experimental distribution is shown in Fig. 3(c). We find that $\beta = 0.12 \pm 0.06$, which is consistent with zero.

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[4]It should be noted that in the absence of an asymmetry, nonzero β does not necessarily imply a C-invariance violation, since the p- and f-wave interference term would also give rise to a $\cos^2\theta$ dependence in the angular distribution.

Measurement of the Charge Asymmetry in the Decay $\eta \to \pi^+\pi^-\pi^0$ †

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We have measured the charge asymmetry in the decay $\eta \to \pi^+\pi^-\pi^0$. η's were produced in the reaction $\pi^-p \to \eta n$ at 730 and 810 MeV/c incident pion momentum. We obtain an asymmetry of -0.0005 ± 0.0022 for 220 659 events. We see no evidence for C-invariance violation in this decay.

We have carried out an experiment at the Princeton-Pennsylvania accelerator to determine if there exists any difference between the π^+ and π^- energy spectra in the decay $\eta \to \pi^+\pi^-\pi^0$.[1] The preceding Letter[2] describes the experimental technique and the methods of analysis employed in the experiment. In this Letter, we discuss our data for the three-pion decay, together with our understanding of the systematic biases which could influence the result.

A number of significant improvements were incorporated into this experiment to reduce biases which could have been present in a previous measurement of the asymmetry.[3] The principal improvements were as follows:

(1) The greatly increased size of the sonic spark chambers, resulting in greater geometrical efficiency, made it feasible to trigger the chambers with a one-pion trigger. This substantially reduced possible trigger biases in the sample and increased the efficiency for detection of low energy pions.

(2) Each of the two spark-chamber arrays employed six gaps. This made the system much less sensitive to gap efficiency ($\geq 97\%$ for each gap), and facilitated the rejection of scattered events.

(3) The high-voltage and clearing fields were oppositely directed in adjacent gaps. This gave rise to an oppositely directed $\vec{E}\times\vec{B}$ for even and odd gaps, and made it possible to measure the drift and correct for it. This is discussed further below.

(4) An additional neutron counter 5 in. in diameter and 11 in. long of solid plastic scintillator was located at the center of the neutron counter array, along the beam line and 30 ft from the hydrogen target. This counter detected axially symmetric events from the reaction $\pi^-p \to \pi^+\pi^-n$. The total transverse momentum of the π^+ and π^- should center at zero for these events. Study of the events obtained from this counter provided a quantitative determination of the measurement bias level of the experiment.

(5) The hydrogen-target assembly was designed in such a way that no supports lay in the path of any particle capable of causing a trigger. This reduced the contribution to the biases of charge-asymmetric scattering in intervening material.

From 17 000 000 spark-chamber triggers, we obtained approximately 5 500 000 reconstructable events. Of these, 85% were from the background reaction $\pi^-p \to \pi^+\pi^-n$. The background reaction was removed by calculating the missing mass M_y^2 of the undetected neutrals, where y is defined by $\pi^-p \to \pi^+\pi^-y$. Discarding events with $M_y^2 < 1.15M_n^2$, where M_n is the neutron mass, removes most of the background reaction and no 3π events. Further cuts were made on the χ^2 from the track reconstruction, and on the event vertex position, requiring that it lay within the hydrogen target volume. There remained 413 000 events, which included the reactions $\eta \to \pi^+\pi^-\pi^0$ and $\eta \to \pi^+\pi^-\gamma$.

The separation of these two reactions was made by considering the x particle in the reaction $\pi^-p \to \pi^+\pi^-nx$. By eliminating events for which the energy of x was less than 115 MeV, we eliminated a large fraction of $\eta \to \pi^+\pi^-\gamma$ events and no $\eta \to \pi^+\pi^-\pi^0$ events. Finally, we eliminated those events for which $M_x^2 < 0.5M_\pi^2$. After these cuts,