EXPERIMENTAL EVIDENCE CONCERNING CHARGE-CONJUGATION NONINVARIANCE IN THE DECAY OF THE η MESON*

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It has been recently pointed out[1] in connection with the experimental detection[2] of the process $K_{\rm long}^0 \to \pi^+ + \pi^-$ that the apparent CP-invariance violation necessary to explain the above decay might be due to violation of charge-conjugation invariance at a much higher level than the weak interactions through higher order processes. The strength of such a C-nonconserving interaction can be estimated to be of the order of 10^{-2} to 10^{-3} with respect to the strong interactions.[3] Throughout the paper, C will be taken to be the particle-antiparticle conjugation operator as determined by the usual strong interactions. The C invariance of the usual strong interactions has been tested to an accuracy of about one part in 100.[4]

The decay of the η meson cannot proceed through the usual strong interactions, while it can proceed via the electromagnetic interactions. If the above C-noninvariant interaction were to contribute to the η-meson decay, then one might expect sizable C-noninvariant effects.[5] In particular, in the decay

$$\eta^0 \to \pi^+ + \pi^- + \pi^0, \qquad (1)$$

the energy spectrum of the positive pion could be different from that of the negative pion. The observation of such a difference would be an unequivocal proof of C noninvariance.[6]

We report in the following on our observation that in the rest system of the η^0 meson the positive pion is on the average slightly more energetic than the negative pion in the decay $\eta^0 \to \pi^+ + \pi^- + \pi^0$. More quantitatively, define N^+ to be the number of events for which the π^+ is more energetic than the π^-, and N^- the corresponding number for which the π^- is more energetic. The result of our experiment can be expressed in terms of the asymmetry $A = (N^+ - N^-)/(N^+ + N^-)$. In a sample of 1441 η-meson decays into $\pi^+ + \pi^- + \pi^0$, we observe

$$A = 0.072 \pm 0.028.$$

The distribution of the decays in the sextants of the η-meson-decay Dalitz plot is shown in Fig. 1.

Indications of the same effect have been previously obtained in a compilation[7] of 1300 η-meson decays yielding $A = 0.058 \pm 0.034$, and in an experiment of Fowler[8] whose result was $A = 0.087 \pm 0.053$.

On the basis of our result we conclude that C invariance is violated in η-meson decay into three pions. This conclusion is further strengthened by the two other results quoted above.

It has been pointed out[6] that even if the violation of C invariance is due to an interaction comparable in strength to the electromagnetic interaction, the asymmetry A observable in the decay (1) should be relatively small, possibly of the order of 5%. The relative smallness of this effect is mainly due to centrifugal barriers in the $C = -1$ states of three pions.

It has also been proposed[9] that the electromagnetic interaction of the hadrons strongly violates C invariance, and that C noninvariance arises from the second-order interference effect of the C-noninvariant and the C-invari-

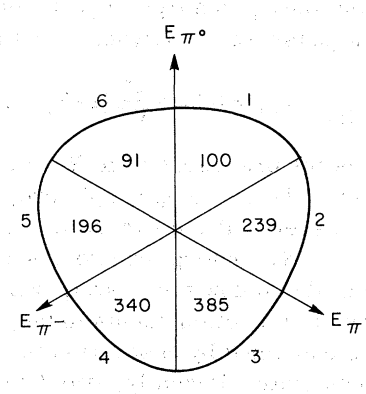

FIG. 1. Distribution of the events $\eta^0 \to \pi^+ + \pi^- + \pi^0$ in the sextants of the η-meson Dalitz plot. E_{π^+}, E_{π^-}, E_{π^0} are the total energies of the π^+, π^-, π^0, respectively, in the η^0 rest frame. The numbers on the outside of the boundary are the sextant numbers referred to in the text.

ant parts of the electromagnetic interaction. While our result is consistent with a maximal C-invariance violation in the hadronic electromagnetic interaction, we cannot distinguish whether the observed C nonconservation is of electromagnetic origin or not, since there is no real photon involved in the process we observed.

In the present experiment the η mesons were produced in the reaction

$$\pi^+ + d \rightarrow p + p + \eta^0 \qquad (2)$$

in the 30-inch Columbia-Brookhaven National Laboratory bubble chamber filled with liquid deuterium at the Brookhaven alternating-gradient synchrotron. The laboratory momentum of the incident π^+ was 820 ± 5 MeV at the center of the chamber. The exposure consisted of approximately 435 000 pictures corresponding to some 1.6×10^7 pions through the chamber. In the subsequent analysis only those events were used in which both protons were visible. (In ~60% of the cases the range of the spectator proton is too short for the proton to be visible.) The topology of Reaction (2) followed by the decay of the η^0 mesons into charged pions is a positive incident track, and three positive and one negative outgoing tracks. Both protons in Reaction (2) had bubble densities twice maximum or larger; this fact was used to make the scanning easier and more reliable. We note that any selection criteria based on the properties of the two protons does not distort in any way the η-decay distributions. The film was scanned twice for these events with a combined scanning efficiency estimated to be better than 90%. Events within a clearly visible fiducial region of the chamber were measured and those which failed in the geometric reconstruction programs were remeasured. This procedure yielded 54 000 events which are estimated to be 90% of the total of such events in the entire exposure.

After geometric reconstruction, 12 000 events were rejected for one of two reasons: (a) One of the protons scattered in the deuterium within 15 cm of the interaction vertex; (b) the event had two nonstopping protons, one of which was shorter than 15 cm. Elimination of these events improved the resolution in the η^0 mass without indroducing any biases in the η-decay products.

The remaining 42 000 events were subjected to kinematic fitting to the following hypotheses:

$$\pi^+ + d \rightarrow p + p + \pi^+ + \pi^-, \qquad (3a)$$

$$\rightarrow p + p + \pi^+ + \pi^- + \pi^0, \qquad (3b)$$

$$\rightarrow p + p + \pi^+ + \pi^- + \gamma, \qquad (3c)$$

$$\rightarrow p + \pi^+ + \pi^+ + \pi^- + n. \qquad (3d)$$

There were 32 000 events which fitted Reaction (3a) with a χ^2 less than 20. Since this is a four-constraint fit, the probability that events of Reaction (3b) will simulate the kinematics of (3a) is small. This loss of events from Reaction (3b) has been estimated to be ~4% using a Monte Carlo calculation. This calculation also indicates that the lost events are not biased with respect to the energy asymmetry of the pions.

Events which made fits to Reaction (3b) or (3c), or for which the mass x^0 in the reaction $\pi^+ + d \rightarrow p + p + x^0$ was within 50 MeV of the η^0 mass, were remeasured in order to improve the rejection of events of Reaction (3a). It is estimated that about 200 events of Reaction (3a) still failed to fit the proper hypothesis after two measurements. Monte Carlo studies indicate that less than ~10 of these events could simulate a fit to Reaction (3b). A total of 460 events made a fit to Reaction (3d) with a $\chi^2 < 1.0$. These events were dropped from the sample. From the Monte Carlo studies it is expected that approximately 20 events of Reaction (3b) made a fit to Reaction (3d) with $\chi^2 < 1.0$. Experimentally no η peak was visible in the rejected events.

There remained 3331 events which fit Reaction (3b) or (3c). The presence of the η^0 meson in Reaction (3b) is evident from the distributions of the missing mass squared, Fig. 2, and of the $\pi^+\pi^-\pi^0$ effective mass, shown in Fig. 3. These events were further fitted to the chain of production and decay hypotheses:

$$\pi^+ + d \rightarrow p + p + \eta^0, \quad \eta^0 \rightarrow \pi^+ + \pi^- + \pi^0, \qquad (4a)$$

$$\pi^+ + d \rightarrow p + p + \eta^0, \quad \eta^0 \rightarrow \pi^+ + \pi^- + \gamma. \qquad (4b)$$

Figure 2 shows the distribution of the square of the mass of x^0, computed from the measured variables, in $\pi^+ + d \rightarrow p + p + \pi^+ + \pi^- + x^0$, for events which fit either Reaction (4a) or (4b). Events were selected as η^0 decays into $\pi^+ + \pi^- + \pi^0$ if (a) they fit Reaction (4a) but not (4b), or (b) if they fit both Reactions (4a) and (4b) but have $m_{x^0}{}^2 > 0.007$ BeV^2. There was a total of 1515 such events. From a fit of the experimental

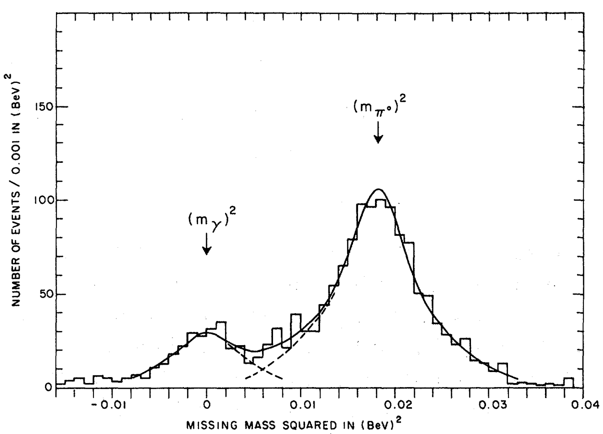

FIG. 2. Distribution of the square of the mass of x^0 in $\pi^+ + d \to p + p + \pi^+ + \pi^- + x^0$. The solid curve fitted to the distribution is consistent with our experimental resolution function.

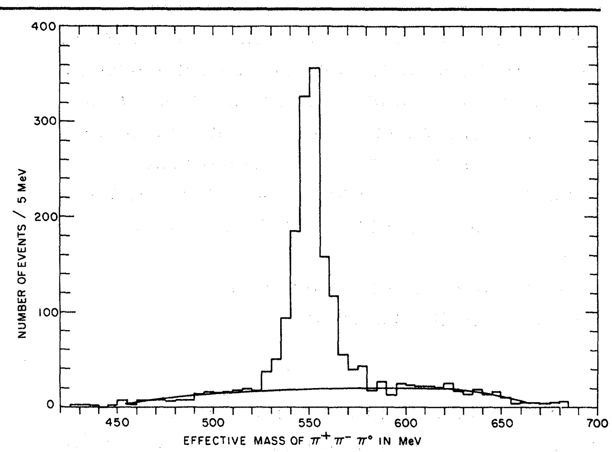

FIG. 3. Distribution of the effective mass of $\pi^+\pi^-\pi^0$ in the reaction $\pi^+ + d \to p + p + \pi^+ + \pi^- + \pi^0$. The solid curve represents a polynomial fit to the background below 520 MeV and above 580 MeV.

resolution function, as obtained by Monte Carlo methods, to the distribution of Fig. 2, it is estimated that ~20 events of Reaction (4a) have $m_{\chi^0}^2$ below 0.007 and were lost because of the selection criteria, and ~20 events of Reaction (4b) have $m_{\chi^0}^2$ over 0.007 and are included in the sample of $\eta^0 \to \pi^+ + \pi^- + \pi^0$.

The number of true decays $\eta^0 \to \pi^+ + \pi^- + \pi^0$ lost in the entire kinematic fitting and selection process was checked by generating a large sample of Monte Carlo events corresponding to Reaction (4a), using isotropic production of the η^0 in the $\pi + n$ center-of-mass frame[10] and a linear matrix element in the η^0 decay.[11] The generated variables were randomly displaced, according to the estimated measuring resolution in each variable, and the events were put through the identical kinematic fitting and selection procedures as the actual events. It was found that the events lost in this procedure introduced no asymmetry in the pion energies.

The 1515 events selected as $\eta^0 \to \pi^+ + \pi^- + \pi^0$ still contained some small background of Reaction (3b) without η^0 production, and possibly some amount of Reactions (3a) and (3d). In order to reduce this background, the additional criterion that the effective mass of the $\pi^+\pi^-\pi^0$, as computed from the fit to Reaction (3b), lie between 520 and 580 MeV, was imposed in selecting events as $\eta^0 \to \pi^+ + \pi^- + \pi^0$ decays. A sample of 1441 events remained after this final selection. The amount of background was estimated to be ~90 ± 10 events, or 7% of the sample, by a polynomial fit to the background outside of the η^0 mass region in the distribution of the effective mass of the $\pi^+\pi^-\pi^0$ in all events that fit Reaction (3b), shown in Fig. 3.[12] The effect of the background on the asymmetry A in the η^0 decays was evaluated by studying the asymmetry in the background (Fig. 3) with $m(\pi^+\pi^-\pi^0)$ below 520 MeV and above 580 MeV. The asymmetry in the background events is $A = 0.08 \pm 0.06$.

The distribution of the 1441 events in the sextants of the η^0-decay Dalitz plot is 117, 254, 402, 354, 209, and 105 in sextants 1 to 6, respectively. The distribution of the background events in the sextants of the Dalitz plot was taken to be the same as the distribution of the background events below 520 MeV and above 580 MeV, normalized to 90 events. After subtracting out the background, the distribution of the $\eta^0 \to \pi^+ + \pi^- + \pi^0$ events in the sextants was 100, 239, 385, 340, 196, and 91 (Fig. 1). The asymmetry A, corrected for the background, is

$$A = 0.072 \pm 0.028,$$

where the errors due to the background corrections have been taken into account. The probability of obtaining a result $|A| \geq 0.072$ because of random fluctuations in the data in this experiment, if there were no violation of C-invariance, is 1.08×10^{-2}. Combining our data with the data of Refs. 7 and 8, we obtain

$$A = 0.068 \pm 0.020.$$

The probability,[13] in the same sense as before, of obtaining this result, there being no C-invariance violation, is 8×10^{-4}.

A general objection to the statement that a nonzero asymmetry in η-meson decay is a proof of C noninvariance is that the η^0 meson does not decay in vacuum but in an environment which is not an eigenstate of C. Because of this it might be possible to observe an energy asymmetry which is not due to a violation of C invariance. We believe that in our experiment these effects are negligible.

We can divide the sources of asymmetry into external and internal sources. The first type is concerned with the behavior of the positive and negative pions while traveling in the liquid D_2 in which the kinematic measurements are made. The two processes that can distinguish between oppositely charged pions are nuclear scattering and electromagnetic effects (energy loss and multiple scattering). Since only ~10% of the pions interact in the liquid, and the isotopic spin of the deuteron is zero, nuclear scattering can at most introduce an asymmetry of the order of 10^{-3}. In our experiment the fractional energy loss is about 8%, and the ratio of the rms deflections due to multiple scattering to deflections due to the chamber magnetic field is about 2%. Again, we conclude that Coulomb effects could at most introduce an asymmetry smaller than 10^{-3}. Finally we consider effects due to the fact that the η^0 meson decays in the presence of two protons which might interact differently with the positive and negative pions. The η^0 is known to decay into two photons; therefore its width is smaller than a few keV. In this case the effect of the final-state interactions on the energy distribution of the pions is totally negligible. From our experiment we can set an upper limit of ~4 MeV for the width of the $\pi^+\pi^-\pi^0$ decay of an η^0 by a comparison of our data, Fig. 3, with our experimental resolution. Even if one makes the unlikely assumption that the particle we observe is not the same as the one which decays into two photons, the above limit on the width is such that only a few percent of the η^0 decays will occur within one pion Compton wavelength of the η-meson production. It is quite unlikely that this effect will produce an asymmetry in all of the η^0 decays larger than a fraction of a percent.

As a direct and independent test of the above conclusion, we have studied the distribution of the invariant mass of the π^+p and π^-p system for the events in the η peak. No significant difference is observed in the two distributions. Especially no difference is found in the mass region corresponding to the $\frac{3}{2}, \frac{3}{2}$ pion-nucleon resonance, where one would expect the difference between positive and negative pions to be most evident.

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[12]Not all the events below the background curve in Fig. 3, between 520 and 580 MeV, are to be counted as background in the $\eta \rightarrow \pi^+ + \pi^- + \pi^0$ sample since about half of them did not make the required fit to the chain (4a).

[13]One might, however, ask a different question, i.e., what is the joint probability that there being no C-invariance violation, the three independent observations should obtain the reported values all with the same sign. This probability is 2.3×10^{-5}.

NEW STRUCTURE IN THE K^--p AND K^--d TOTAL CROSS SECTIONS BETWEEN 1.0 AND 2.45 GeV/c*

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The K^--p and K^--d total cross sections have been measured with increased precision and resolution in the momentum interval 1.0 to 2.45 GeV/c using a partially separated K^- beam at the Brookhaven alternating-gradient synchrotron (AGS). Data were obtained at momentum intervals of 50 MeV/c with $\Delta p/p = \pm 0.01$. The statistical standard deviations are ±0.25% for hydrogen and ±0.13 for deuterium above 1.35 GeV/c, and increase progressively with decreasing momentum. The total cross sections in this energy range show considerable structure. Preliminary analysis indicates two K^--nucleon resonances above Y_0*(1815) in the $I = 0$ state and very likely three in the $I = 1$ state above Y_1*(1765).

The K^- mesons were produced in a 1-mm-diam, 13-mm-long Be-wire target at 10° to the internal proton beam of the AGS. First, the particles were focused with a quadrupole triplet to a beam parallel vertically and slightly converging horizontally, then momentum analyzed. This beam passed through two 15-ft-long electrostatic separators (about 400 kV on a 4-in. gap) and, before being deflected by a 12° angle, was refocused horizontally at a sextupole and vertically onto a mass slit further downstream. Following the mass slit, the beam was recombined in momentum and imaged at the transmission counters. A nuclear fluxmeter was used to calibrate the momentum of the beam at selected values to better than ±0.5%. The flux varied from about 16×10^3 K^- mesons per 10^{12} protons at momenta above 1.8 GeV/c to about 300 K^- mesons per 10^{12} protons at 1 GeV/c.

The K^- mesons were identified by a liquid differential Cherenkov counter with a 3-cm-thick radiator filled with C_6F_{12}. Incorporated into the counter was an anticoincidence arrangement for rejecting fast particles. Thus the contamination of the K^- mesons by other particles was maintained below 0.5% at all momenta. A time-of-flight criterion also had to be imposed to achieve this low contamination at 1.0 and 1.05 GeV/c.

The hydrogen and deuterium targets were identical and were 36 in. long and 5 in. in diameter. Both targets were at a temperature of 20.97°K corresponding to a hydrogen vapor pressure at 18.00 psi. The densities of the liquid hydrogen and liquid deuterium were 0.069 97 g/cm^3 and 0.1691 g/cm^3, respectively. A double-jacketed design provided long-term density stability to better than 0.03%. The cross section at each momentum was determined from the transmission measured successively in the H_2 and D_2 targets and a dummy target. At least two such sequences were repeated and a measurement with a carbon target was also made at each momentum.

The K^--meson telescope consisted of the Cherenkov counter in coincidence with one scintillation counter defining the beam at the exit of the last quadrupole, another behind the Cherenkov counter defining the beam at the entrance to the target. Adjacent to it was a counter with a hole whose signal was in anticoincidence with the telescope. Almost all of the fast particles and nonbeam particles were thus eliminated electronically. Accidental coincidences, primarily due to K^- mesons in the beam, were a negligible effect since the AGS spill was quite uniform over a time interval exceeding 0.4 sec. An artificial dead time of 60 nsec was introduced following each K^- count to eliminate pile-up in the 20-Mc/sec scalers.

The K^- mesons which passed through the tar-