PARITY OF THE NEUTRAL PION*

R. Plano, A. Prodell,† N. Samios,† M. Schwartz, and J. Steinberger‡
Columbia University, New York, New York
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The parity of the pion relative to the nucleon is essential to the understanding of the strong interactions. Our most direct knowledge, to date, comes from the observation of the capture reaction $\pi^- + d \rightarrow 2n$.[1] It can be shown that this capture proceeds from the s atomic state,[2] and for scalar pions s-state capture would be forbidden. The neutral pion parity can then be inferred either from the mounting evidence on the validity of charge independence, or perhaps more directly from the forbiddenness of the reaction $\pi^- + d \rightarrow \pi^0 + 2n$.[3]

The possibility of a direct determination of the neutral pion parity, using the decay $\pi^0 \rightarrow 2\gamma$, was pointed out by Yang quite some time ago.[4] Yang demonstrated that angular momentum and parity conservation require parallel and perpendicular correlation of the polarizations of the two photons, for scalar and pseudoscalar pions, respectively. The experiment has not been carried out so far, however, because no one has solved the problem of the measurement of the relative polarizations of gamma rays of this energy (70 Mev).

Here we present a preliminary report of a study of certain angular correlations in the decay $\pi^0 \rightarrow e^+ + e^- + e^+ + e^-$. This decay is expected theoretically, and is calculable on the basis of quantum electrodynamics. It is the internal conversion of the two photons of the normal decay. The planes of the pairs "remember" the polarization of the virtual intermediate photons; the correlation of these planes reflects then the polarization correlation of Yang. The correlation of the planes in double internal conversion has been calculated by Kroll and Wada.[5]

Since the parity is not inferred from the observed correlations on the basis of invariance arguments alone, but is linked to them through the dynamical theory of internal conversion, it is important that the theory be thoroughly reliable. To this end we point out, that in addition to the success of quantum electrodynamics in previous applications, it has now been tested in the details of both single and double internal pair creation of π^0 decay (absolute rates, energy, and angular distributions)[6] and has been confirmed in every instance within experimental limits.

The experimental difficulty is due to the rarity of the decay (1/30 000) in combination with the necessity of establishing at least the relative orientation of the planes of the two pairs. In this experiment, the π^0's are produced in the capture reaction $\pi^- + p \rightarrow \pi^0 + n$. About 60% of the negative pions coming to rest in hydrogen undergo this reaction, emitting 4-Mev π^0 mesons. A liquid hydrogen bubble chamber, 30 cm diam, 15 cm deep, in a field of 5500 gauss, is exposed to a stopping π^- beam. 700 000 pictures have been taken, and there are ~15 stopping mesons per picture. We expect therefore that ~200 events will be found eventually. We report here an analysis of the first 103 events, since we believe that this already permits a convincing conclusion.[7] Figure 1 exhibits a photograph of a typical double internal conversion.

In each event the momenta and directions of the 4 tracks were measured, and transformed to the center-of-mass system of the decaying π^0. Nine of the events were not measurable. In addition, 15 events in which the measured angle between any pair was less than 3 degrees were excluded, on the grounds that the plane normal was inadequately measured. The remaining 79 events should now be analyzed with the help of the theoretical result of Rockmore.[8] We hope to do this eventually, but it encounters some technical difficulties which we are still fighting. Here we make the analysis with the help of the theory

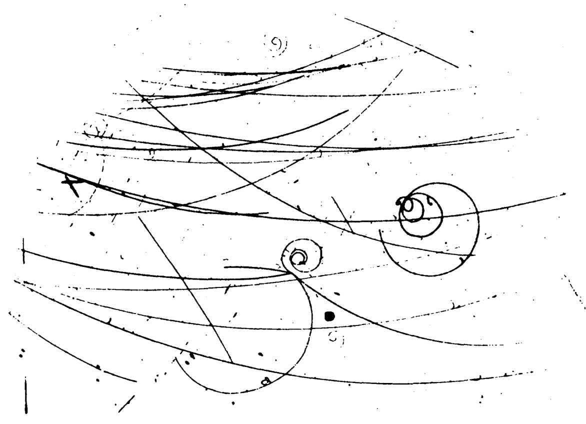

FIG. 1. A photograph of a typical double internal conversion.

which neglects exchange.[5] It is necessary to give a short account of this neglect. If 1, 2 are the positrons, 3, 4 the electrons, two pairings are possible: (13), (24) or (14), (23). The decay rate will then be of the form $\{|M[(13)\ (24)]|^2 + |M[(14)\ (23)]|^2 + 2\ \mathrm{Re}M^*[(13)\ (24)]M[(14)\ (23)]\}$. The formula of Kroll and Wada[5] consists of the first or second term, depending on how the pairing is chosen. Usually the angles of the pairs are quite small (~10°) so that the proper pairing is clear on sight. Theoretically small angles have the consequence that one of the first two terms is much larger than the other. If this pairing is used, then it is clear that the terms neglected in Kroll and Wada are small. We have adopted the criterion $|M[(13)\ (24)]|^2 > 4|M[(14)\ (23)]|^2$ for the applicability of the Kroll-Wada formula. Fifteen events failed to qualify; so that 64 events remain.

Let ϕ be the angle between the planes of the two pairs. The theoretical correlation is then of the form

$$E_s(\phi) = 1 + \alpha(x_1, y_1; x_2, y_2)\cos 2\phi,$$

$$E_{ps}(\phi) = 1 - \alpha(x_1, y_1; x_2, y_2)\cos 2\phi,$$

where the correlation coefficient $\alpha(x_1, y_1; x_2, y_2)$ is the function of the remaining four nontrivial observables, which can be taken to be the angle and energy division within each pair. The parity dependence of F is entirely in the sign. α is calculated for each event. Its square is a measure of the usefulness of the event, and varies widely from event to event.

We have tabulated the results in two ways. In the first case we plot the observed distribution in ϕ, weighting each event with the square of its correlation coefficient α. In this way the graph of Fig. 2 is obtained. It can be analyzed for an effective α, $\bar{\alpha}$. We find $\bar{\alpha}_{\mathrm{exp}} = -0.75 \pm 0.42$. The theoretically expected value for our distribution in $\alpha(x_1, y_1; x_2, y_2)$ is $\alpha_{\mathrm{th}} = \pm 0.48$, where the plus and minus sign refer to even and odd parity, respectively. The alternate method is that of relative likelihood. The relative likelihood $L(ps)/L(s)$ is obtained by finding for each event the relative probability for finding the event on the basis of pseudoscalar versus scalar theory, and forming the product

$$\frac{L(ps)}{L(s)} = \prod_{i=1}^{64} \frac{1-\alpha_i \cos 2\phi_i}{1+\alpha_i \cos 2\phi_i} = 1500.$$

(If the events excluded for the above-stated reasons were included, it would increase the relative likelihood to a figure of about 30 000.) Both types of analysis lead to the conclusion that the neutral pion is pseudoscalar. In each case, the confidence in the conclusion corresponds to about three standard deviations.

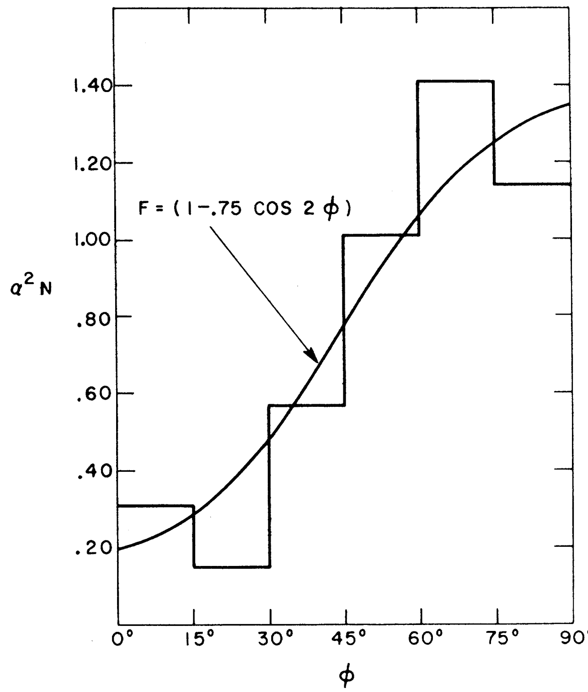

FIG. 2. Plot of weighted frequency distribution of angle between planes of polarization.

This to us seems statistically quite convincing. It is fortunate that systematic errors in correlations of the planes would be hard to achieve. We can state with confidence that no such errors, sufficient to influence the result, are present. It can then be concluded that the neutral pion is pseudoscalar. The above-quoted arguments can then be inverted to argue that also the charged pion is pseudoscalar, in agreement with the earlier results.[1]

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†Present address: Brookhaven National Laboratory,

Upton, Long Island, New York.

‡Temporary address: Institute for Advanced Study, Princeton, New Jersey.

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[6]N. Samios (to be published).

[7]Earlier results of this experiment were presented at the Conference on High-Energy Physics, Kiev, 1959 (unpublished). At that time a similar analysis of a single event was presented by Alikhanov.

[8]R. M. Rockmore (private communication). We wish to thank Dr. Rockmore for making his results available to us.

TRANSFORMATION OF MUONS INTO ELECTRONS*

G. Feinberg
Columbia University, New York, New York

P. Kabir
Institute for Nuclear Physics, Calcutta, India

and

S. Weinberg
Lawrence Radiation Laboratory, Berkeley, California

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It is an outstanding puzzle of particle physics that muons do not decay electromagnetically into electrons without the emission of neutrino pairs, even though all quantum numbers of muon and electron are the same.[1] Processes of this sort which could have been observed include $\mu \to e + \gamma$ decay,[2] $\mu \to e$ via absorption of virtual photons in a mesonic atom,[3] $\mu \to 3e$ via internal conversion,[4] muonium decay into photons,[5] etc. The absence of such transformations does not constitute a paradox, there being no compelling reason why muons should transform into electrons, but it seems a mystery that processes which are allowed energetically and in every other known respect do not occur. In this note we shall indicate how for a certain class of interactions which might be expected to induce $\mu - e$ transformations, the similarity of the μ and e actually forbids the transformations.

Let us first consider why $\mu \to e$ transformations do not take place as strong and electromagnetic interactions; for example, why is $\mu \to e + \gamma$ decay not about as fast as $\Sigma^0 \to \Lambda^0 + \gamma$ decay? Let us suppose that the muon and electron are described by a local Lagrangian $\mathcal{L}$ involving only the fields $\psi_e, \psi_\mu, A^\lambda$ where ψ_e and ψ_μ can be chosen to have the same parity. Now, the simplest mechanisms that might yield fast $\mu \to e$ transformations are contact terms in $\mathcal{L}$,

$$\mathcal{L}_1 = -\rho \bar{\psi}_e \psi_\mu - \text{H.c.}; \quad \mathcal{L}_2 = -\xi \bar{\psi}_e \gamma \cdot D \psi_\mu - \text{H.c.}, \qquad (1)$$

where the derivative ∂_λ and the photon field A_λ enter in the gauge-invariant combination, $D_\lambda = \partial_\lambda - ieA_\lambda$. These two interactions exhaust all possible parity-conserving, renormalizable, gauge- and Lorentz-invariant interactions among photons, muons, and electrons that can be added to the usual Dirac Lagrangian in order to generate $\mu \to e$ transformations. Furthermore, because the μ and e appear to differ only in their rest mass, it seems not unreasonable to regard them as "different states of the same particle." In this case, since the bare Lagrangian is known to contain $\bar{\psi}_\mu \psi_\mu$ and $\bar{\psi}_e \psi_e$ terms of the type 1, one might also expect "off-diagonal" $\bar{\psi}_\mu \psi_e$ terms. However, since quantum electrodynamics has been successful without the introduction of nonminimal electromagnetic interactions or other nonrenormalizable interactions, one is also inclined to exclude "off-diagonal" terms of this kind, at least from the fundamental Lagrangian.

Suppose we now attempt to calculate, as an example, the lowest order $\mu - e - \gamma$ vertex. There are five diagrams that add to give a nonvanishing