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# Nuclear Emulsion Evidence for Parity Nonconservation in the Decay Chain $\pi^+ \rightarrow \mu^+ \rightarrow e^+$*

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Following a suggestion of Lee and Yang, the correlation between the initial direction of motion of the muon and the direction of emission of the positron in the decay chain $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ was investigated in nuclear emulsion to detect a possible parity nonconservation in both decay interactions. Positive pions from the University of Chicago synchrocyclotron were brought to rest in emulsion carefully shielded from magnetic fields, and 2000 complete decay events were measured. A correlation $W(\theta)=1+a\cos\theta$ was found, with $a=-0.174\pm0.038$, clearly indicating a backward-forward asymmetry, i.e., a violation of parity conservation in both decay processes. Actually, following an argument of Lee, Oehme, and Yang, this asymmetry implies a noninvariance of either interaction with respect to both space inversion and charge conjugation, taken separately.

A detailed discussion of a depolarization process specific to $\mu^+$ mesons, i.e., the possible formation of "muonium," $(\mu^+e^-)$, is given. The results of this and similar experiments are compared with those obtained with muons originating from $\pi^+$ decays in flight, and the implications of such a comparison are discussed.

## I. INTRODUCTION

In a recent brief communication,[1] we presented the preliminary results of a nuclear emulsion experiment conducted in principle along the lines originally suggested by Lee and Yang[2] to test the conservation of parity in the decay chain $\pi^+ \rightarrow \mu^+ \rightarrow e^+$. These results, obtained on the basis of 1300 complete decay events, indicated to a high confidence level (95%) a preference for the backward emission of the decay position with respect to the initial direction of motion of the $\mu^+$ meson. They clearly implied that space inversion (and also[3] charge conjugation) invariance does *not* hold in *either* of the decay processes involved in this chain. Similar results in nuclear emulsion were obtained independently at Columbia University by electronic techniques by Garwin, Lederman, and Weinrich,[4] who used $\mu^+$ mesons originating from pions decaying in flight. The Columbia workers showed in addition that this forward-backward asymmetry in $\mu^+$ decay arises also in a number of other stopping media, though its magnitude appears to vary from material to material. Additional evidence for the same angular asymmetry has been presented by Rau *et al.*[5] on the basis of 1000 $\pi$-$\mu$-$e$ decays from positive pions coming to rest in hydrogen.

The purpose of the present paper is to present data derived from a total of 2000 measured decay events. These data bear out our initial conclusions fully and at a much higher confidence level. We wish also to give a fuller discussion of the experimental techniques and statistical procedures than contained in reference 1, and to discuss the bearing of experiments of this type on data obtained with muons that originate from pions not decaying at rest. For this reason we include a detailed account of the role of "muonium" formation as a possible depolarization mechanism in nuclear emulsion.

## II. EXPERIMENTAL PROCEDURE

### A. Exposure and Development

Stacks of 1000 μ G5 unsupported emulsion were exposed to a 40-Mev $\pi^+$ beam from the University of Chicago synchrocyclotron.[6] The emulsion received about $1.5\times10^4$ pions/cm$^2$ which is considered an optimum exposure as it produces a high density of events without obscuration.

In view of the fact[1] that the precession frequency of a Dirac muon is $(2.8/207)\times10^6$ sec$^{-1}$/gauss and the "muonium," i.e., $(\mu^+e^-)$, could be formed and precess in its $^3S_1$ state at a hundred times greater frequency/gauss (see Sec. IV), the emulsion was shielded during the exposure from stray magnetic fields such as occur near a cyclotron. This was accomplished by placing the emulsion within the innermost of three concentric tubular magnetic shields. Each shield consisted of two layers: the outer layer was a medium permeability, high saturation steel, and the inner layer was a high permeability alloy. The magnetic field in the experimental area was of the order of 10 gauss; however, the emulsion in the shields was subject to less than $4\times10^{-3}$ gauss, as measured with a calibrated flip coil.

To insure most uniform development, the emulsion was processed unsupported and later glued to glass. Special attention was given to producing a reasonably high density for minimum ionization tracks (20 g/100 μ) with a low background grain density in order to facilitate the locating of electrons.

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[1] J. I. Friedman and V. L. Telegdi, Phys. Rev. **105**, 1681 (1957).

[2] T. D. Lee and C. N. Yang, Phys. Rev. **104**, 254 (1956).

[3] Lee, Oehme, and Yang, Phys. Rev. **106**, 340 (1957).

[4] Garwin, Lederman, and Weinrich, Post-deadline paper at the New York Meeting of the American Physical Society, January, 1957; Phys. Rev. **105**, 1415 (1957).

[5] A. Abaskiars *et al.*, Post-deadline paper at the New York Meeting of the American Physical Society, January, 1957; Phys. Rev. **105**, 1927 (1957).

[6] Pellicles of this thickness were chosen so that a large fraction of the stopping pions would produce usable decays.

### B. Detection and Measurement of Events

Events were detected by area-scanning under oil with a total magnification of 330. Under this magnification about two $\pi$-$\mu$ decays were found per field of view (about 500 $\mu$ in diameter) in the region of the pellicle where pions were coming to rest.

In order to insure that the detection efficiency be completely independent of the direction of the positron from the decay of the muon, the observers were instructed to measure only those events that were detected by first seeing the $\pi$-$\mu$ decay. All events so found were used in the analysis except those in which the muon decays occurred within 50 $\mu$ of either surface.

When a $\pi$-$\mu$ decay was found, the scanner followed the muon to the end of its range and searched for the positron. A considerable effort was made to detect all positrons because it was felt that the loss of positrons could be a source of bias. In only about 1% of muon decays could the positron not be found. For each positron found, a check was made to make sure that it indeed originated at the end of the muon track.

For each $\pi$-$\mu$-$e$ decay found, the space angle $\theta$ between the initial direction of motion of the muon and that of the positron was measured. This was done to eliminate the effects of multiple scattering which change the momentum but not the spin orientation of the muon. The angles were measured with an accuracy of about $\pm 2°$. The lateral and vertical shrinkage factors were accurately determined for subsequent calculation of the space angles ($\theta$).

## III. RESULTS[7]

2000 complete $\pi$-$\mu$-$e$ decays were analyzed (see Fig. 1) and the space angle $\theta$ defined above was calculated for each. For 60% of all events, chosen at random, this angle was recalculated independently; no appreciable discrepancies were revealed. From these data we find for a distribution function $W(\theta)$ of the decay positron

$$\epsilon=(B-F)/(B+F)$$

$$=\left[\int_{90°}^{180°}|W(\theta)|d\Omega-\int_{0}^{90°}|W(\theta)|d\Omega\right]\Big/\int_{0}^{180°}W(\theta)d\Omega$$

$$=0.091\pm0.022, \qquad (1)$$

i.e., a preference for backward emission with respect to the direction of motion of the muon. The events in the backward and forward hemispheres are statistically uncorrelated; the error is thus given by

$$\sigma_\epsilon=(1-\epsilon^2)^{\frac{1}{2}}/N^{\frac{1}{2}},$$

where $N$ is the total number of events used. $\sigma_\epsilon$ is the estimated error indicated above. This estimate does not make any allowance for errors of systematic nature, such as those introduced by possible local variations in shrinkage, etc. An estimate of the latter effects shows them to be small and of such a nature as to only decrease the experimentally observed value of $\epsilon$.

The nonconservation of parity will assure the presence of odd powers of $\cos\theta$ in $W(\theta)$ but *per se* imposes no limitation on the number of even powers present. Such a limitation, however, is effectively provided by the fact that the highest even power, say $2n$, must satisfy the inequality $n\leqslant s$ where $s$ is the spin of the muon. Lacking *a priori* information as to the latter, we first performed an analysis[8] of $W(\theta)$ into suitable orthogonal polynomials in $\cos\theta$. These are the Tchebysheff polynomials, differing from Legendre polynomials in that they are defined over discrete intervals. This analysis showed that the best fit is obtained with a constant and a linear term only, the parameter $S$ defined in reference 8 increasing with the addition of higher terms.

With this information at hand, we determined $W(\theta)$ by a least-squares fit to a linear form in $\cos\theta$. This yields

$$W(\theta)=1-(0.174\pm0.038)\cos\theta, \qquad (2)$$

where the error indicated is derived from the $e^{-\frac{1}{2}}$ width of the likelihood function of $\chi^2$. This latter function is quite symmetric; if we identify the indicated error as a standard deviation, Eq. (2) implies that the asymmetry observed is real to an extremely high confidence level.

It is worth pointing out that the individual $\epsilon$ values computed from the data supplied by each of three scanners were all statistically consistent with the mean. In fact, the three individual values were $0.06\pm0.035$, $0.11\pm0.036$, and $0.13\pm0.045$.

As an additional check of possible bias, an analogous determination of the distribution of the muon direction of emission with respect to the direction of incidence of the pion beam was carried out. This distribution was found to be isotropic, within statistics, as would be expected. In notation analogous to that of Eq. (1), we find

$$\epsilon=-0.026\pm0.029.$$

## IV. INTERPRETATION OF RESULTS

Solely from the existence of an asymmetry such as displayed in (2), one can conclude that both interactions responsible for the transitions in the decay chain $\pi^+\rightarrow\mu^+\rightarrow e^+$ are not invariant under either space inversion or charge conjugation.

The sign and magnitude of the coefficient $a$ of the $\cos\theta$ term in (2) could in principle be predicted if the interaction responsible for the process $\mu^+\rightarrow e^+ + 2\nu$ were completely specified and the state of polarization of the $\mu^+$ known. This polarization in turn could be derived for any specific interaction operating in the $\pi$-$\mu$ decay process. At present, however, neither of these two interactions is *a priori* known, and the coefficient $a$ could

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[7] These results were presented as a post-deadline paper at the New York meeting of the American Physical Society, January, 1957.

[8] Anderson and Bancroft, *Statistical Theory in Research* (McGraw-Hill Book Company, Inc., New York, 1952), pp. 207 ff.

in principle be used to restrict possible choices. In particular, the experimental value for $a$ might be used to test a particularly parameter-free type of interaction, involving so-called two-component neutrinos.[9]

Unfortunately, the experimental value of $a$ is only indirectly related to the asymmetry coefficient predicted by theory. Muons can be depolarized by various causes during their lifetime, and the observed value of $a$ represents only a lower limit. The experimentally observed dependence of $a$ on the material in which the muons are brought to rest clearly points to the existence of efficient depolarization (or relaxation) mechanisms; in graphite, for instance, about twice as large an asymmetry as reported here has been found.[4,10] We wish to discuss here only one possible depolarization mechanism, *viz.*, the formation of "muonium," because it is peculiar to the $\mu^+$ meson and leads with certainty, if it operates at all, to a very short relaxation time.[1]

A $\mu^+$ can towards the end of its range easily capture an electron, leading to a "muonium" atom, $(\mu^+e^-)$.[11] Such an atom, essentially of the same size as $(\mathrm{H}^+e^-)$, could of course lose its electron again in further collisions, and indeed go through several "charge exchange" cycles. Such cycles would in fact be likely to occur in gases,[12] and could perhaps also take place in condensed media where the mobility of muonium is much more limited. We shall, however, first assume that muonium, once formed, does not further undergo collisions in, say, nuclear emulsion.†

Muonium will have a ${}^1S_0$ ground state and ${}^3S_1$ first excited state, separated by the hyperfine splitting $[\hbar\times(3\times10^{10}\ \mathrm{sec}^{-1})]$ from it.[13] If the $\mu^+$ is initially in a completely polarized state, say $\alpha(\mu)$, while the electrons of the medium are, of course, unpolarized $[\alpha(e)$ and $\beta(e)]$, two "muonium" states can be formed, $\alpha(\mu)\alpha(e)$ and $\alpha(\mu)\beta(e)$. The first of these is an exact eigenstate of muonium $({}^3S_1,\ m=1)$, while the latter is not, corresponding to a coherent superposition of ${}^1S_0$ and ${}^3S_1$ states with $m=0$. As the capture process is no doubt to high order of purely electric character, $\alpha(\mu)\alpha(e)$ and $\alpha(\mu)\beta(e)$ will be formed in equal amounts, leading to a net time-dependent expectation value of the muon spin $z$ component after capture given by $\langle S_z(t)\rangle=\frac{1}{4}(1+\cos\omega t)$, where $\omega\cong3\times10^{10}\ \mathrm{sec}^{-1}$. Thus 50% of the muons captured into muonium will be effectively depolarized in a time short compared to their mean life for decay $(2\times10^{-6}\ \mathrm{sec})$. Hence if $x$ is the fraction of muons forming muonium, a theoretical asymmetry coefficient $a$ will be reduced to $a(1-x/2)$, if no further depolarization mechanisms are at work.

In a given external magnetic field, ${}^3S_1$ muonium would precess at an about one hundred times faster rate $(1.4\times10^6\ \mathrm{sec}^{-1}/\mathrm{gauss})$ than the free muon. This was the reason for our elaborate shielding precautions.

Conversely some depolarization mechanisms too slow to affect appreciably the spin of a free positive muon during its lifetime could relax the total spin of ${}^3S_1$ muonium quite effectively during the same time. If such mechanisms were in action, an asymmetry coefficient $a(1-x)$ would be observed even in perfectly shielded emulsion. It is clear that a succession of several "charge exchange" processes would lead to about the same reduction in asymmetry.

In comparing our results with those obtained in experiments[4,10] in which the muon spin is made to precess by the application of an external field, the preceding remarks have to be borne in mind. These external fields would necessarily wash out contributions to the asymmetry from muons bound in ${}^3S_1$ muonium, just like the hypothetical relaxation mechanisms mentioned above. Thus, if such microscopic relaxations were not operative, the asymmetry observed by our method in nuclear emulsion would differ for a given original muon polarization by a factor $(1-x)/(1-x/2)$ from the electronically obtained value.

The longitudinal polarization of muons emitted by pions in motion will in general be reduced by relativistic kinematics with respect to pion rest frame value. Aside from depolarization effects, experiments of our type[14] should hence lead to maximal asymmetry. If one assumes that decays at rest lead to *complete* polarization, the results of such experiments can conversely be used to determine the polarization of muons originating from pions in flight, provided these are brought to rest in the same medium. Comparison of our $a$ value with the one

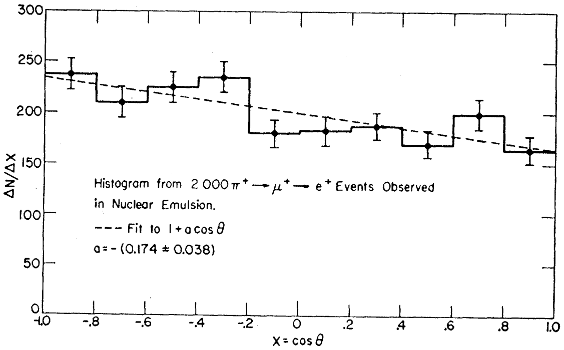

FIG. 1. Histogram from 2000 $\pi^+\to\mu^+\to e^+$ events observed in nuclear emulsion. Dashed curve is least-squares fit to $1+a\cos\theta$; $a=-(0.174\pm0.038)$. Indicated errors are statistical standard deviations.

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[9] Abdus Salam, Nuovo cimento **5**, 299 (1957); L. D. Landau, Nuclear Physics **3**, 127 (1957); T. D. Lee and C. N. Yang, Phys. Rev. **105**, 1671 (1957).

[10] Swanson, Campbell, Garwin, Sens, Telegdi, Wright, and Yovanovitch, Bull. Am. Phys. Soc. Ser. II, **2**, 205 (1957).

[11] L. D. Landau (reference 7) has independently pointed out that such an atom (which he calls "mesonium") could be a source of depolarization.

[12] S. K. Allison and S. D. Warshaw, Revs. Modern Phys. **25**, 779 (1953).

[13] In all that follows, we shall assume the muon to be essentially a heavy Dirac electron.

† See note added in proof at end of paper.

[14] I.e., emulsion and bubble chamber experiments with stopped pions.

obtained at Columbia[4]) by electronic methods for emulsion suggests that the polarization of the $\mu^+$ beam used at Columbia is close to maximal. The two-component theory[9] predicts complete polarization and for it a $|a|$ value of $\leqslant\frac{1}{3}$; $-\frac{1}{3}$ is within the stated errors compatible with Columbia's results for graphite. The statistical accuracy of experiments both with muons from decays in flight and at rest will have to be greatly improved before any firm conclusions can be drawn.

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We also wish to acknowledge illuminating discussions concerning the depolarization problem with Dr. M. Cohen and Dr. F. Reif.

*Note added in proof.*—Detailed electronic experiments at Chicago (reference 10) have shown that even in substances yielding a low $a$ value, $\mu^+$ precess essentially without exhibiting relaxation over a period of 3 $\mu$sec. Hence the depolarization leading to the reduced $a$ value must (1) take place during the slowing down process, presumably when $v_\mu \gtrsim c/137$; (2) act rapidly; (3) affect only a fraction of all muons. These conclusions would appear to support the muonium picture given in the text. At a velocity of the order of $c/137$, however, the muon loses little energy by $e^-$ capture, and muonium (having almost the same velocity) would make $\sim 10^{16}$ collisions/sec in a solid. This may throw some doubt on the literal validity of the picture. On the other hand, the latter is not critically dependent on the assumed *binding* between electron and muon. Conceivably, thermalized muons can sufficiently couple to spins of bound electrons (or nuclei) to depolarize.—These points will be discussed in detail in a future publication.

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# Information Obtainable on Polarization of $\mu^+$ and Asymmetry of $e^+$ in Muonium Experiments*

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The formation of the compound $\mu^+ + e^-$ (muonium) is considered as a tool for gaining information regarding the polarization of the $\mu^+$ before their capture by the $e^-$ and the asymmetry of $e^+$ emission in the disintegration $\mu^+ \rightarrow e^+ + \nu + \nu'$. The detection of asymmetry effects is supposed to take place through the counting of $e^+$. The effect of constant magnetic fields and of microwave-induced transitions among magnetic substates of muonium is calculated, with the conclusion that all of the experiments considered here determine in different ways the same combination of parameters describing the initial muon polarization and the asymmetry of $e^+$ emission in muon decay.

## I. INTRODUCTION AND NOTATION

In order to answer the question of parity conservation raised by Lee and Yang,[1] experiments were performed by Wu, Ambler, Hayward, Hoppes, and Hudson[2] showing that parity is not conserved in beta decay of $\mathrm{Co}^{60}$ giving the first example of lack of conservation of parity in weak interactions. The experiment of Garwin, Lederman, and Weinrich[3] then showed that in the reactions

$$\pi^+ \rightarrow \mu^+ + \nu, \quad \mu^+ \rightarrow e^+ + \nu + \nu',$$

the $\mu^+$ are strongly polarized along the line of motion and that there is a large asymmetry in the angular distribution of the $e^+$ with respect to the spin direction of $\mu^+$. The question arises as to whether the degree of polarization of $\mu^+$ and the asymmetry parameter in the $e^+$ emission, or some parameter connected with both, could be determined by observing the asymmetry of $e^+$ emission from the compound

$$\mu^+ + e^-,$$

the formation of which may be expected to take place at the end of the range of the $\mu^+$ in suitable materials.[4] The present note is concerned with this question.[5] The

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[1] T. D. Lee and C. N. Yang, Phys. Rev. **104**, 254 (1956); T. D. Lee and C. N. Yang, Phys. Rev. **105**, 1671 (1957).

[2] Wu, Ambler, Hayward, Hoppes, and Hudson, Phys. Rev. **105**, 1413 (1957).

[3] Garwin, Lederman, and Weinrich, Phys. Rev. **105**, 1415 (1957).

[4] The possible role of muonium in the Columbia and Chicago experiments has been discussed by J. I. Friedman and V. L. Telegdi, Phys. Rev. **105**, 1681 (1957); estimates of formation may be found in Vernon W. Hughes, Bull. Am. Phys. Soc. Ser. II, **2**, 205 (1957).

[5] After the present work was completed, there arrived a preprint of a paper by Lee, Oehme, and Yang, on "Remarks on