[4] Their arguments are as follows: From the He[6] recoil experiment and from Eq. (A-4) of reference 1 one concludes that $(|C_A|^2+|C_A'|^2)/(|C_T|^2+|C_T'|^2) \lesssim \frac{1}{3}$. Hence, by comparing Eq. (16) of reference 3 [see also Eq. (A-6) of reference 1], one concludes that the present large asymmetry is possible only if both conservation of parity and invariance under charge conjugation are violated.

Observations of the Failure of Conservation of Parity and Charge Conjugation in Meson Decays: the Magnetic Moment of the Free Muon*

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L EE and Yang[1-3] have proposed that the long held space-time principles of invariance under charge conjugation, time reversal, and space reflection (parity) are violated by the "weak" interactions responsible for decay of nuclei, mesons, and strange particles. Their hypothesis, born out of the $\tau-\theta$ puzzle,[4] was accompanied by the suggestion that confirmation should be sought (among other places) in the study of the successive reactions

$$\pi^+ \rightarrow \mu^+ + \nu, \tag{1}$$

$$\mu^+ \rightarrow e^+ + 2\nu. \tag{2}$$

They have pointed out that parity nonconservation implies a polarization of the spin of the muon emitted from stopped pions in (1) along the direction of motion and that furthermore, the angular distribution of electrons in (2) should serve as an analyzer for the muon polarization. They also point out that the longitudinal polarization of the muons offers a natural way of determining the magnetic moment.[5] Confirmation of this proposal in the form of preliminary results on β decay of oriented nuclei by Wu et al. reached us before this experiment was begun.[6]

By stopping, in carbon, the μ^+ beam formed by forward decay in flight of π^+ mesons inside the cyclotron, we have performed the meson experiment, which establishes the following facts:

I. A large asymmetry is found for the electrons in (2), establishing that our μ^+ beam is strongly polarized.

II. The angular distribution of the electrons is given by $1+a \cos\theta$, where θ is measured from the velocity vector of the incident μ's. We find $a = -\frac{1}{3}$ with an estimated error of 10%.

III. In reactions (1) and (2), parity is not conserved.

IV. By a theorem of Lee, Oehne, and Yang,[2] the observed asymmetry proves that invariance under charge conjugation is violated.

V. The g value (ratio of magnetic moment to spin) for the (free) μ^+ particle is found to be $+2.00\pm0.10$.

VI. The measured g value and the angular distribution in (2) lead to the very strong probability that the spin of the μ^+ is $\frac{1}{2}$.[7]

VII. The energy dependence of the observed asymmetry is not strong.

VIII. Negative muons stopped in carbon show an asymmetry (also leaked backwards) of $a \sim -1/20$, i.e., about 15% of that for μ^+.

IX. The magnetic moment of the μ^-, bound in carbon, is found to be negative and agrees within limited accuracy with that of the μ^+.[8]

X. Large asymmetries are found for the e^+ from polarized μ^+ beams stopped in polyethylene and calcium. Nuclear emulsion (as a target in Fig. 1) yields an asymmetry of about half that observed in carbon.
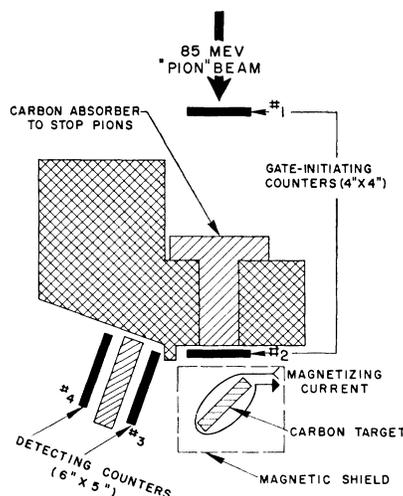

FIG. 1. Experimental arrangement. The magnetizing coil was close wound directly on the carbon to provide a uniform vertical field of 79 gauss per ampere.

The experimental arrangement is shown in Fig. 1. The meson beam is extracted from the Nevis cyclotron in the conventional manner, undergoing about 120° of magnetic deflection in the cyclotron fringing field and about −30° of deflection and mild focusing upon emerging from the 8-ft shielding wall. The positive beam contains about 10% of muons which originate principally in the vicinity of the cyclotron target by pion decay-in-flight. Eight inches of carbon are used in the entrance telescope to separate the muons, the mean range of the "85-"Mev pions being ∼5 in. of carbon. This arrangement brings a maximum number of muons to rest in the carbon target. The stopping of a muon is signalled by a fast 1-2 coincidence count. The subsequent beta decay of the muon is detected by the electron telescope 3-4 which normally requires a particle of range >8 g/cm²(∼25-Mev electrons) to register. This arrangement has been used to measure the lifetimes of μ^+ and μ^- mesons in a vast number of elements.[9] Counting rates are normally ∼20 electrons/

min in the μ^+ beam and $\sim$150 electrons/min in the μ^- beam with background of the order of 1 count/min.

In the present investigation, the 1–2 pulse initiates a gate of duration $T=1.25$ μsec. This gate is delayed by $t_1=0.75$ μsec and placed in coincidence with the electron detector. Thus the system counts electrons of energy >25 Mev which are born between 0.75 and 2.0 μsec after the muon has come to rest in carbon. Consider now the possibility that the muons are created in reaction (1) with large polarization in the direction of motion. If the gyromagnetic ratio is 2.0, these will maintain their polarization throughout the trajectory. Assume now that the processes of slowing down, stopping, and the microsecond of waiting do not depolarize the muons. In this case, the electrons emitted from the target may have an angular asymmetry about the polarization direction, e.g., for spin $\frac{1}{2}$ of the form $1+a\cos\theta$. In the absence of any vertical magnetic field, the counter system will sample this distribution at $\theta=100°$. We now apply a small vertical field in the magnetically shielded enclosure about the target, which causes the muons to precess at a rate of $(\mu/s\hbar)H$ radians per sec. The probability distribution in angle is carried around with the μ-spin. In this manner we can, with a fixed counter system, sample the entire distribution by plotting counts as a function of magnetizing current for a given time delay. A typical run is shown in Fig. 2. As an example of a systematic check, we have
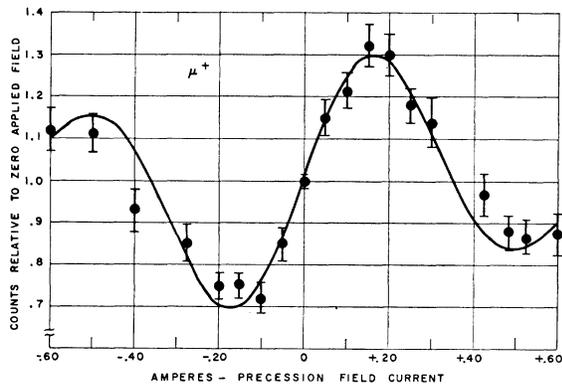

FIG. 2. Variation of gated 3–4 counting rate with magnetizing current. The solid curve is computed from an assumed electron angular distribution $1-\frac{1}{3}\cos\theta$, with counter and gate-width resolution folded in.

reduced the absorber in the telescope to 5 in. so that the end-of-range of the main pion beam occurred at the carbon target. The electron rate rose accordingly by a factor of 10, indicating that now electrons were arising from muons isotropically emitted by pions at rest in the carbon. No variation in counting rate with magnetizing current was then observed, the ratio of the rate for $I=+0.170$ amp to that for $I=-0.150$ amp, for example, being 0.989 ± 0.028. The highest field produced at the target was $\sim$50 gauss which generates a stray field outside of the magnetic shield of $<\frac{1}{10}$ the

cyclotron fringing field of 20 gauss. The only conceivable effect of the magnetizing current is the precession of muon spins and we are, therefore, led to conclusions I–IV as necessary consequences of these observations.

The solid curve in Fig. 2 is a theoretical fit to a distribution $1-\frac{1}{3}\cos\theta$, where

(1) the gyromagnetic ratio is taken to be $+2.00$;[10]

(2) the angular breadth of the electron telescope and the gate-width smearing are folded in, as well as (to first order) the exponential decay rate of muons within the gate;

(3) the small residual cyclotron stray field (up for Fig. 2, the positive magnetizing current producing a $down$ field) is included. This has the accidental effect of converting the 100° initial angle ($H=0$) to 89° as in Fig. 2. We note that this experiment establishes only a lower limit to the magnitude of a, since the percent polarization at the time of decay is not known. If polarization is complete, $a=-0.33\pm0.03$.

Proof of the 2π symmetry of the distribution and the sign of the moment was obtained by shifting the electron counters to 65° with respect to the incident muon direction. The repetition of a magnetizing run yielded a curve as in Fig. 2 but shifted to the right by 0.075 ampere (5.9 gauss) corresponding to a precession angle of 37°, in agreement with the spatial rotation of the counter system. Thus we are led to conclusions V and VI.

A specific model, the two-component neutrino theory, has been proposed by Lee and Yang[3] in an attempt to introduce parity nonconservation naturally into elementary particle theory. This theory predicts, for our experimental arrangement and on the basis of 1.86 for the integrated spectrum (Fig. 2), a ratio of the order of 2.5 for energies greater than 35 Mev. We have increased the amount of absorber in the electron telescope to exclude electrons of less than $\sim$35 Mev. The resulting peak-to-valley ratio was then observed to be 1.92 ± 0.19.[11]

We have also detected asymmetry in negative muon decay and have verified that the moment is negative and roughly equal to that of the positive muon.[7] The asymmetry in this case is also peaked backwards.

Various other materials were investigated for μ^+ mesons. Nuclear emulsion as a target was found to have a significantly weaker asymmetry (peak-to-valley ratio of 1.40 ± 0.07) and it is interesting to note that this did not increase with reduced delay and gate width. Neither was there any evidence for an altered moment. It seems possible that polarized positive and negative muons will become a powerful tool for exploring magnetic fields in nuclei (even in Pb, 2% of the μ^- decay into electrons[9]), atoms, and interatomic regions.

The authors wish to acknowledge the essential role of Professor Tsung-Dao Lee in clarifying for us the papers of Lee and Yang. We are also indebted to Professor C. S. Wu[6] for reports of her preliminary results in the Co^{60} experiment which played a crucial part in the

Columbia discussions immediately preceding this experiment.

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

[2] Lee, Oehme, and Yang, Phys. Rev. (to be published).

[3] T. D. Lee and C. N. Yang, Phys. Rev. (to be published).

[4] R. Dalitz, Phil. Mag. 44, 1068 (1953).

[5] T. D. Lee and C. N. Yang (private communication).

[6] Wu, Ambler, Hudson, Hoppes, and Hayward, Phys. Rev. 105, 1413 (1957), preceding Letter.

[7] The Fierz-Pauli theory for spin $\frac{3}{2}$ particles predicts a g value of $\frac{2}{3}$. See F. J. Belinfante, Phys. Rev. 92, 997 (1953).

[8] V. Fitch and J. Rainwater, Phys. Rev. 92, 789 (1953).

[9] M. Weinrich and L. M. Lederman, Proceedings of the CERN Symposium, Geneva, 1956 (European Organization of Nuclear Research, Geneva, 1956).

[10] The field interval, ΔH, between peak and valley in Fig. 2 gives the magnetic moment directly by $(\mu \Delta H/s\hbar)(t_1 + \frac{1}{2}T)\delta = \pi$, where $\delta = 1.06$ is a first-order resolution correction which takes into account the finite gate width and muon lifetime. The 5% uncertainty comes principally from lack of knowledge of the magnetic field in carbon. Independent evidence that $g = 2$ (to $\sim 10\%$) comes from the coincidence of the polarization axis with the velocity vector of the stopped μ's. This implies that the spin precession frequency is identical to the μ cyclotron frequency during the 90° net magnetic deflection of the muon beam in transit from the cyclotron to the 1–2 telescope. We have designed a magnetic resonance experiment to determine the magnetic moment to $\sim 0.03\%$.

[11] Note added in proof.—We have now observed an energy dependence of a in the $1 + a \cos\theta$ distribution which is somewhat less steep but in rough qualitative agreement with that predicted by the two-component neutrino theory ($\mu \rightarrow e + \nu + \bar{\nu}$) without derivative coupling. The peak-to-valley ratios for electrons traversing 9.3 g/cm², 15.6 g/cm², and 19.8 g/cm² of graphite are observed to be 1.80±0.07, 1.84±0.11, and 2.20±0.10, respectively.

Results from an Enriched Negative K-Meson Beam*

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WE have recently obtained a K^--meson beam from the Bevatron in which the intensity was greatly enhanced by selection of particles emitted in the forward direction. We further improved the usefulness of the beam incident on our emulsion stacks by causing the magnetically analyzed particles of 435 Mev/c to traverse a polystyrene degrader of 18.36 g/cm² and undergo a second bending of 180°, thus discarding the pion component of the beam. The remaining background tracks are chiefly muons and electrons. A small emulsion stack exposed in order to evaluate the beam has already yielded useful information. Although much more work is planned on this and a larger stack, some of the data now in hand are of sufficient interest and reliability for a preliminary report. In order to make quantitative measurements the emulsion density was carefully determined, and we employed our new range-

TABLE I. Measurements obtained from the interaction and decay of negative K mesons in emulsion.

K^- mean life	$(1.46_{-0.31}^{+0.38}) \times 10^{-8}$ sec
K^--proton elastic scattering cross section	$(52_{-21}^{+31}) \times 10^{-27}$ cm²
K^- free path for inelastic collisions in emulsion	27.2 ± 2.3 cm
Σ^+ mass (from $\Sigma^+ \rightarrow$ proton decay)	$(2327.8 \pm 0.7) m_e$
Σ^- mass (from $\Sigma^- - \Sigma^+$ mass difference)	$(2341.5 \pm 2.3) m_e$
K^- mass (from $K^- + p \rightarrow \Sigma^+ + \pi^-$ at rest)	$(965.3 \pm 1.5) m_e$
K^- mass (from $K^- + p \rightarrow \Sigma^- + \pi^+$ in flight)	$(961.4 \pm 3.3) m_e$
K^- mass (from $K^- + p$ elastic collisions)	$(978 \pm 25) m_e$
Binding of Λ^0 in $_\Lambda\text{He}^5$	3.0 ± 0.6 Mev
Binding of Λ^0 in $_\Lambda\text{He}^4$	1.2 ± 1.0 Mev
Binding of Λ^0 in $_\Lambda\text{Li}^9$	3.8 ± 3.0 Mev
Decay branching ratio $(\Sigma^+ \rightarrow p + \pi^0)/(\Sigma^+ \rightarrow n + \pi^+)$	13/13
Frequency distribution of prongs from K^- stars at rest	
Prongs 0: 1: 2: 3: 4: 5:6:7:8:9	
Distrib. 36:43:63:30:28:20:9:2:2:1	
Frequency distribution of prongs from K^- stars in flight	
Prongs 0: 1: 2: 3: 4: 5:6:7:8:9:10:11:12	
Distrib. 16:22:46:34:31:14:8:4:0:1: 1: 0: 1	
Frequency distribution of prongs from K^- stars that emit hyperfragments	
Prongs 1:2: 3: 4:5:6:7:8	
Distrib. 1:3:11:12:6:3:2:3:1	
Frequency distribution of hyperfragment prongs	
Prongs 1: 2: 3:4:5:6:7	
Distrib. 4:11:15:5:3:1:1	
Frequency of hyperfragment emission from K^- stars	28/1152
Ratio of mesonic to nonmesonic decay of hyperfragments	9/42

energy curve.[1] The numbers in Table I were derived from along-the-track scanning of 1224 K mesons. Of these, 21 decayed in flight, 182 interacted inelastically in flight with emulsion nuclei, 6 scattered elastically from free protons in the emulsion, 2 interacted in flight with free protons to produce negative hyperons, and only 2 interacted at rest with free protons to produce charged hyperons (the two had opposite signs). The K-meson energy interval for which the interaction cross sections were calculated was 30 to 90 Mev. Analysis of hyperfragments and their parent stars was carried out on an IBM 650 digital computer using a program kindly supplied by Dr. C. Violet. We are greatly indebted to Ernestine Beleal, Anna-Mary Bush, Thoma Davis, John Dyer, Renée Feldman, Hester Lowe, Lynn Reynolds, and Toni Woodford for their conscientious scanning work.

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[1] Barkas, Barrett, Cüer, Heckman, Smith, and Ticho, Phys. Rev. 102, 583 (1956); 100, 1797 (1955); and Bull. Am. Phys. Soc. Ser. II, 1, 184 (1956).

Energy of Interacting Fermi Systems

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THE purpose of this note is to make known a number of investigations concerning the energy of interacting Fermi systems. All of these investigations