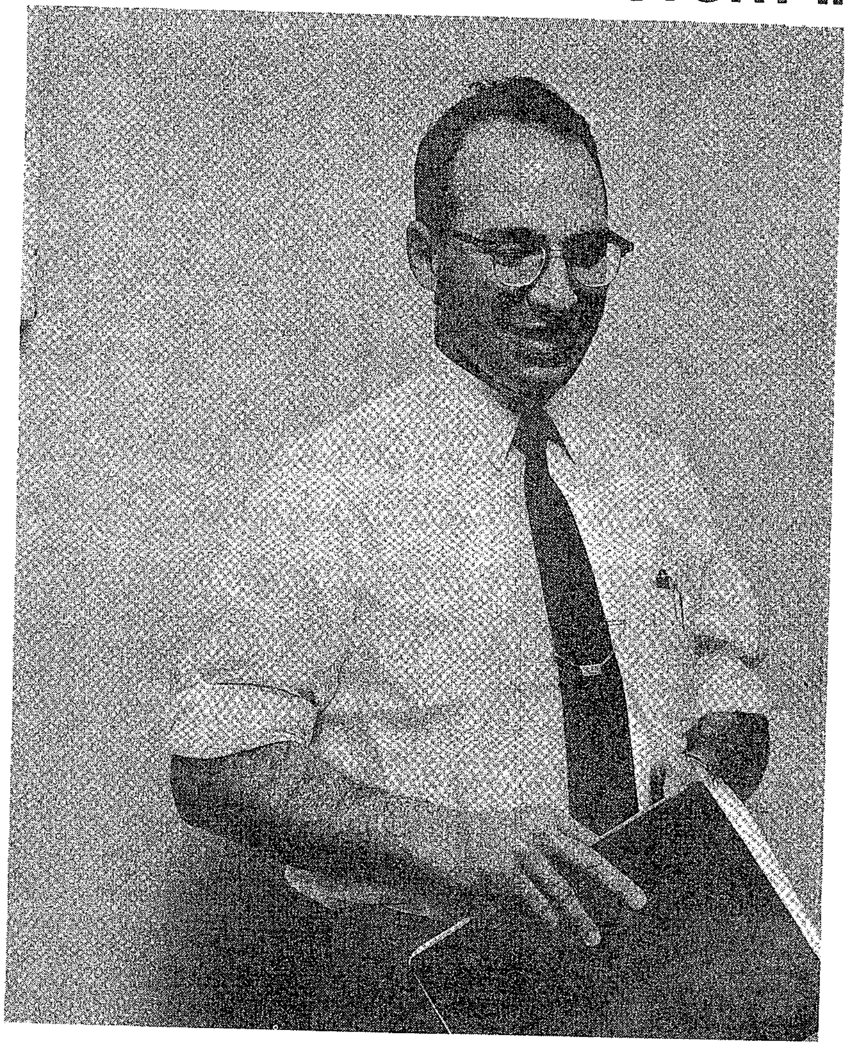
DISCOVERY STORY II



Richard L. Garwin, August, 1961

One Researcher's Personal Account

by Richard Garwin

MUCH of the physics and direct communication in the Physics Department at Columbia takes place around the lunch table of a Chinese restaurant on Fridays. It was at such a luncheon, toward the end of December 1956, that we learned of the positive results indicating nonconservation of parity in the cobalt-60 experiment of Professor Wu. Ideas of parity violation in decays involving the μ-meson, however, centered on studying the π - μ - e decay chain in photographic emulsion—or else working with the submillimeter range of the μ-meson to separate the μ's from the π's—since it was also predicted, under certain assumptions, that the μ would be polarized along its direction of emission from a pion at rest.

On Friday, January 4, I had been at Poughkeepsie and missed our weekly luncheon. Shortly after I returned home around 8 o'clock, I received a phone call from Leon Lederman. He quickly

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told me that he had thought of a way to obtain a beam of polarized muons by taking advantage of the well-known fact that muons emitted forward from a beam of pions in flight have higher energy and range than those emitted backwards. In fact, for many years, counting experiments had been done at Nevis* using such beams of separated muons produced in the fringe field of the cyclotron by the forward decay of pions in flight. Thus there was the possibility, if parity was really not conserved, that these muons in our standard beams were already polarized! Leon continued by saying that if we could think of a reliable way to measure the asymmetry of the emitted electrons from these muons, then we could actually *do* the experiment! I suggested that we meet at the cyclotron in fifteen minutes, and Leon quickly agreed.

Once at the cyclotron, we mulled over the possibility of stopping the muons and worried that either the muon spin would not retain its initial direction during the stopping process, or that the muons might be depolarized in the microsecond or two before decay. There was also the problem of detecting an electron asymmetry which might be small even in the case of *fully* polarized muons. What made matters worse was the fact that we had no guarantee that our muon beam was anywhere near fully polarized.

Marcel Weinrich had been doing his thesis with Leon Lederman. His work involved the stopping of positive or negative muons in various materials and the determination of the rate of emission of electrons as a function of delay time (with a view to measuring the lifetime of the negative muon). It was therefore natural that we first considered physically swinging a counter around a block in which the muons were to be stopped. But we immediately noted that false front-to-back asymmetries would be introduced by a nonsymmetrical stopping distribution of muons, by the fringe field of the cyclotron modifying the gain of the photomultiplier tubes, etc.

Since about 1953**, I had been working in nuclear magnetic resonance on He^3 liquid, so that I was quite familiar with the extent to which one could rely completely on classical concepts in dealing with nuclear spins and their interactions with magnetic fields. It therefore occurred to me that the best arrangement by far would be to leave the counters fixed and to move the spins (if, indeed, there was a magnetic moment associated with the muon spin, the magnitude of the muon spin, itself, being uncertain at that time). This would sweep any electron decay asymmetry past a fixed counter telescope.

Our problems were to choose a stopping material which would not depolarize the muons in the slowing-down period of about two microseconds, and to produce a uniform magnetic field throughout the stopping material. The system also had to be compatible with the detection of electrons by an electron telescope.

The machine shop at Nevis was locked by that time on Friday

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*** Before joining IBM in New York in 1952, Dick Garwin worked at the University of Chicago in beta-gamma angular correlation and on some cyclotron experiments. He developed first a twofold, and then a multiple-input coincidence-anticoincidence analyzer[1] and subsequently arranged for IBM to purchase one of the latter instruments from the University of Chicago that he had made there. This instrument and similar devices, which had been built at Nevis, were major components of the equipment used in 1957 for the $\pi - \mu - e$ experiment.*

In 1950, a flexible coincidence-anticoincidence set of 10^{-8} sec resolution and good stability was a major advance, and the Garwin coincidence circuit was in standard use for over a decade.

[1] *Rev. Sci. Instr.*, **24**, 618 (1953).

night, so, using what was on hand, I selected a standard one-inch carbon block for the stopping material. A lathe served to trim a hollow cylindrical lucite shell and to wind upon it a uniform solenoid which we could connect to some nominal counter signal leads in order to control a precession field from the counting room, as well as being able to leave the experiment unattended on the counting floor.

The Appearance and Disappearance of the Effect

As I remember now, the cyclotron closed Saturday morning for the weekend, but by approximately 6 A.M. we had observed a substantial influence of solenoid current on the electron counting rate—a significant effect. Such an effect could only mean that the muon beam was strongly polarized and that the electron asymmetry about the muon spin direction was large. Furthermore, we had selected the magnitude of solenoid current to give the largest effect if the muon spin was one half, and the muon g-value was 2.

There was no initial basis for assurance regarding any of these assumptions, so our experiment required a small amount of hunting for the best g-value, and thus the best magnetic field to produce the largest amplitude of precession curve. As our counting rate was quite low, the counts during alternate 20-minute cycles were recorded manually and differenced to give an indication of the asymmetry. Unfortunately, by 9 A.M., when the cyclotron shut down for the weekend, our effect seemed to have vanished. We verified the connections and the counter calibration. Finding nothing amiss, we went down to the experimental area to turn off the power supplies to the counters. Here, unhappily, we noticed that the lucite coil form had overheated and that the copper wire was lying at the base of the form, instead of being wrapped around its surface.

Over the weekend, we considered better ways to produce the magnetic field, and finally decided to uniformly wind wire in the form of a solenoid of rectangular cross section directly onto the carbon stopping block and to provide a ferromagnetic return path which would not interfere with either the incident beam or the electron telescope.

A 22 Standard Deviation Effect

Monday was maintenance day, consequently the cyclotron did not come on until evening. We set up the new apparatus, checked counters, and about midnight began taking data. At around 3 A.M. when Leon went home, it was still not certain that there was any effect. I continued the run. Three hours later I was on the phone to tell him that the effect was now 22 standard deviations and that there was absolutely no doubt that we had established the nonconservation of parity and charge conjugation in the case of the π - μ decay and the subsequent μ - e decay! Leon returned immediately, inspected the data, and recorded a few more points. Shortly thereafter, we called T. D. Lee and gave him the good news.

The most striking characteristic of the experiment was that our analysis and intuition had succeeded in persuading us of the feasibility of performing such an experiment in the face of three major unknowns: the polarization of the muon beam; the magnitude of the electron decay asymmetry; and the preservation of the muon spin direction in slowing down and stopping before its decay. But the sinusoidal curve of our results left us with no doubts as to the reality and interpretation of the effect. It was exciting to have such a prompt and unambiguous result which at once confirmed all three working hypotheses. We were ready to publish by Tuesday afternoon, by which time I had worked out the theoretical curve for the experimental results and had also found a way of obtaining from the experimental curve the g-value as corrected for the decay of the μ-meson, the angular breadth of the electron telescope, and the effect of the gate width in smearing the curve. It would not, however, have been appropriate for our results to precede in print the work of Professor Wu and her collaborators. There followed intensive exploration of the sensitivity of the asymmetry to both electron energy and stopping material. These results are also reported in our paper (reproduced p. 128).

New Avenue for Adventure Opens

The graphic nature of our muon results left no room for skepticism. As noted in our Letter, we had convincingly demonstrated a tool with applications far beyond the exhibition of nonconservation of parity. Much work followed immediately at Nevis and elsewhere, as energetic and clever physicists raced to exploit this new tool and phenomenon which had been right under our noses for six or seven years. Indeed, nonexponential decays which had sometimes been observed (irreproducibily) for muons stopped in matter had arisen from the precession of polarized muons in the cyclotron fringe field!

As one result of our experiment, sleepy cyclotron laboratories revived; night work became common. Our own work extended to the measurement of some solid state effects, to the precision measurement of the magnetic moment of the muon, and much later to an experiment, in which I participated at CERN, that involved the trapping of polarized muons in a six-meter-long static magnetic field and allowed a direct measurement of the departure of the muon's g-value from 2. Tirelessly, I worked twenty hours a day for weeks, exploring ideas, building multimegawatt rf pulsers, nursing them into operation, and integrating equations of spin motion. All of us were amazed with the amount we could accomplish.☐

New York, January, 1973

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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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LEE 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.

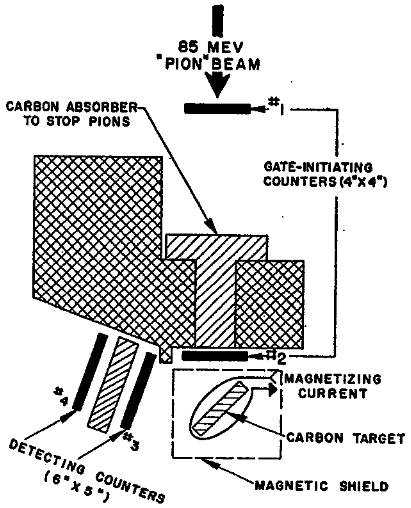

FIG. 1. Experimental arrangement. The magnetizing coil was close wound directly on the carbon to provide a uniform vertical field of 79 gauss per ampere.

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.

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/cm^2($\sim$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 $\sim$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 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.

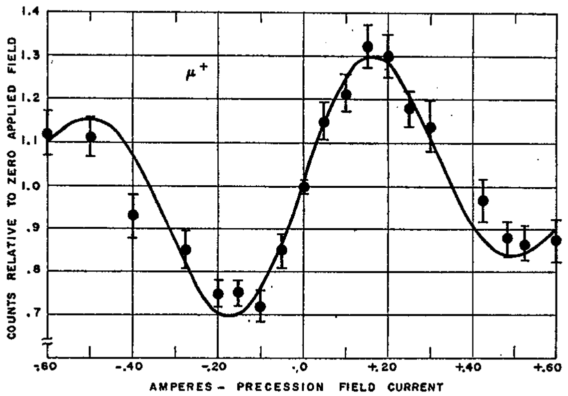

FIG. 2. Variation of gated 3–4 counting rate with magnetizing current. The solid curve is computed from an assumed electron angular distribution $1-\frac{1}{3}\cos\theta$, with counter and gate-width resolution folded in.

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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† Also at International Business Machines, Watson Scientific Laboratories, New York, New York.

[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 ~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 ~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.

The Muon

A muon has all the properties of an electron, except that it is about 210 times heavier and is unstable against decay into an electron and neutrino—antineutrino pair. Its mass, spin, mean life and magnetic moment are compared below to those of the electron. Errors indicated are in the last digits of each value.

	Muon	*Electron*
Mass (in MeV/c²)	105.6595 ± 3	0.5110041 ± 16
Spin	½	½
Mean Life (seconds)	2.1994 x 10^{-6}	stable
Magnetic Moment (in Bohr magnetons $\frac{e\hbar}{2m_i c}$ *	1.00116616 ± 31	1.0011596577 ± 35

** m_i represents the mass of the muon for the muon's magnetic moment; and the mass of the electron for its magnetic moment.*