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THE TABLETOP MEASUREMENT OF THE HELICITY OF THE NEUTRINO

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This paper is dedicated to Maurice Goldhaber[2]

Fifty-two years ago, Maurice Goldhaber, Lee Grodzins and Andrew Sunyar experimentally determined that the spin of the neutrino is antiparallel to its momentum. The ingenious experiment was done in a few weeks, for a few thousand dollars, using equipment that fit on a small table. Here is the story of the two years of seemingly unrelated ideas and experiments that came to a focus during those few weeks.

Figure 1 shows a photograph of the Goldhaber, Grodzins and Sunyar (GGS) experiment that established that the neutrino's helicity is negative. The result proved that beta decay proceeds via the axial vector and vector modes.

Figure 1 shows the main components on a stool. An electromagnet polarimeter, with a radioactive source of europium-152 centered in a hole on top, sat on a conical lead absorber that prevented direct radiation from entering the NaI(Tl) gamma-ray detector below. The detector, in an iron and mu-metal shield, was surrounded by a hollow, truncated cone filled with samarium. The ^{152}Sm in the samarium only "saw" ^{152}Eu gamma rays that had passed through the magnet. The detector only "saw" fluoresced gamma rays from the truncated cone. The helicity of the neutrinos was determined by measuring the change in the count rate as the magnetic field in the iron flipped from pointing up to pointing down. The method was ingenious, the results unambiguous. The intense weeks to completion were in fact the culmination of two years of seemingly unrelated ideas and experiments. Here is my recollection of those two years, written without my lab notebooks and with the obligatory cautions about fallible memory of events that took place long ago.

From my point of view, the thread that weaves through this story begins in the1930's when Wen Yu Zhang came from China to the Cavendish Laboratory to study with Earnest Rutherford. When Rutherford died in 1937, Zhang became James Chadwick's student. In practice, however, he was mentored by Maurice Goldhaber. Maurice, a year younger than Zhang and still a graduate student, was working with James Chadwick, the discoverer of the neutron. Maurice was a star pupil having conceived of the photodisintegration of the deuteron, which Chadwick verified experimentally.

Fig. 1 Set-up of the GGS tabletop experiment.

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[2] Now 99 years old.

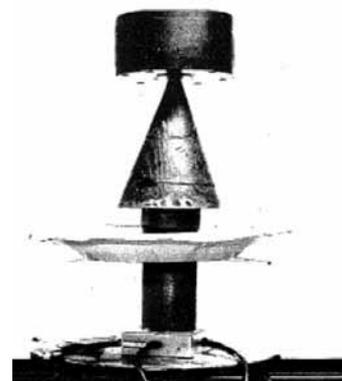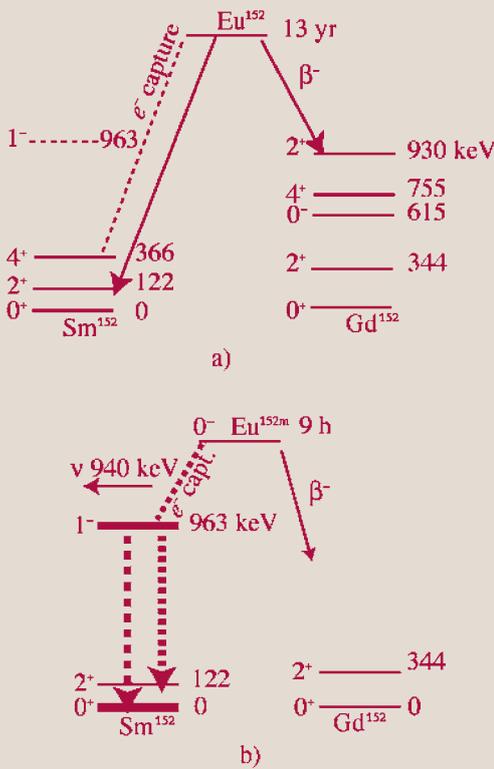Fig. 2 The levels scheme of ^{152}Sm and ^{152}Gd emphasizing the relevant transitions.

Fig. 3 A schematic of the $\beta\gamma$ coincidence measurement and electromagnetic polarimeter.

In 1950, Maurice Goldhaber left his Professorship at the University of Illinois to take a position at Brookhaven National Laboratories. At about the same time, Zhang joined the physics Department of Purdue University where I was a graduate student. When I finished my PhD under Zhang's supervision, he recommended me to Goldhaber.

Goldhaber replied positively to my application but regretted that he would not have an open position for another year. Zhang's admiration for Goldhaber must have been very persuasive for I stayed at Purdue as an Instructor until the position opened up.

I arrived at Brookhaven in January, 1955. Goldhaber, a good-idea-every-day scientist (sometimes two), suggested that I compare the nuclear spectroscopy of nuclei with 88 neutrons to those with 90 neutrons. We now know that isotopes with an even number of protons and 88 neutrons, such as $^{88}_{62}$Sm and $^{88}_{64}$Gd, have spherical ground shapes, while those with 90 neutrons, such as $^{90}_{62}$Sm and $^{90}_{64}$Gd have spheroidal ground shapes, and we know why. In 1955, the evidence was sparse, the understanding primitive. $^{152}_{63}$Eu was an ideal candidate for this study since it was easily produced in a reactor and decayed by electron beta decay to $^{88}_{64}$Gd, with 88 neutrons, and by positron emission or electron capture to $^{90}_{62}$Sm with 90 neutrons. The lowest-lying excited states of $^{152}_{64}$Gd were known to have spins and energies appropriate to the vibrations of a spherical shape while the lowest-lying excited states of $^{152}_{62}$Sm were more appropriately described as rotations of an ellipsoidal shape. It was an ideal problem for a neophyte nuclear spectroscopist.

Figure 2a shows the two types of states exhibited in $^{152}_{62}$Sm and $^{152}_{64}$Gd. The lower states of $^{152}_{62}$Sm exhibit the classic rotational structure of an ellipsoidal shape with energies approximately proportional to $I(I+1)$, where I is the spin of the state. The lowest states of $^{152}_{64}$Gd, on the other hand, exhibit the classic vibrational structure of a spheroidal shape with a triplet of states (0^+, 2^+, 4^+) centered at roughly twice the energy of the first 2^+ vibrational state at 344 keV. Determining the spins, parities, and lifetime of the states was an excellent problem for a postdoc who knew next to nothing about nuclear spectroscopy.

My initial studies had little relevance to the measurement of the helicity of the neutrino. It did, however, set me on the path to measuring properties of the centerpiece of this paper, the 963 keV state of ^{152}Sm, which is only populated by the 9 hour isomer, ^{152m}Eu, fig. 2b. With the mentoring of Andy Sunyar, a well-established, gifted experimental physicist, I mastered the techniques of nuclear spectroscopy, and had a ball.

1 1956: Parity violation

Prior to 1956, it was "self-evident" that the results of an experiment could not depend on the coordinate system used to describe it. An experiment done by a physicist standing in front of a mirror would give the same result as the experiment done by the physicist's image. That changed in 1956 after T. D. Lee and C. N. Yang submitted a paper to "Physical Review" proposing that parity might not be conserved in weak interactions [1]. They proposed measurements of pseudoscalar quantities, which depend on the chosen coordinate system. They called special attention to the angular distribution of electrons emitted in the decay of polarized nuclei, which should be isotropic if parity is conserved, and
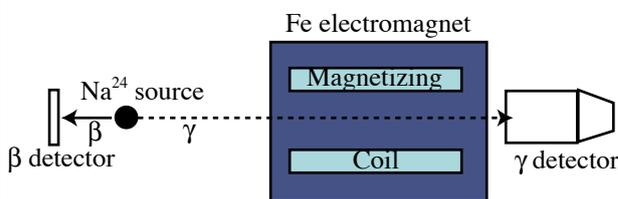
anisotropic if parity is not.

The preprint of their paper inspired Sergio De Benedetti, a BNL summer visitor from Carnegie Mellon University, to propose a test of parity conservation by measuring the circular polarization of gamma rays with respect to the momentum of a preceding beta particle. With Goldhaber's acquiescence, though without his usual enthusiasm, Sergio, Andy, Richard Madey (another summer visitor) and I did the experiment. Maurice made the prescient comment that the predicted effect would be small and would not be considered a credible proof of so revolutionary an idea.

Techniques for measuring the circular polarization of gamma rays make use of the spin dependence of Compton scattering [2, 3], which depends on the handedness of the polarization with respect to the longitudinal polarization of the scattering electrons. Fully magnetized iron gets its internal magnetic field from the two polarized electrons per iron atom. We constructed an appropriate electromagnet for the chosen source and measured the coincident rate of beta rays with the follow-on gamma rays that had traversed about three mean free paths of magnetized iron. Figure 3 shows the essential components.

The coincidence count rate difference on field reversal was about 0.5%; a correct result for the spins involved in the decay chain. But it was not convincing enough to shed doubt on parity conservation. A paper was never submitted for publication. The work had no consequence other than our learning how to measure circular polarization of gamma rays.

In December, C. S. Wu, E. Ambler and coworkers did the definitive experiment by measuring the angular anisotropy of beta particles from polarized ^{60}Co nuclei. Their results, consistent with total violation of parity in beta decay, were published on February 15, 1957 [4]. The direction of the anisotropy of the electron distribution with respect to the polarization of the ^{60}Co showed that the helicity of the beta decay electron is negative, *i.e.* its spin is opposite to its emission direction.

2 1957: Goldhaber's parity experiment

Studies of parity violation dominated the nuclear and particle physics of the year. One of the confirming experiments was a new test proposed by Goldhaber. He argued that conservation of angular momentum, indicated by the open arrows in fig. 4, dictates that the helicity of a beta-particle should be transferred to the bremsstrahlung it produces in the forward direction.

Most theorists whom Maurice queried over a period of several weeks were reluctant to give an opinion. But Freeman Dyson, who was visiting BNL, thought it was not a difficult theoretical problem and volunteered to calculate that afternoon. He came to the lab, sat at the desk with a few sheets of paper and shortly announced that Maurice was right: bremsstrahlung in the forward direction should retain the helicity of the beta-particle [5].

We took the magnet out of storage, placed a collimated source of high-energy betas from a ^{90}Sr source on top, and a well-shielded gamma-ray detector below. Figure 5 shows the set-up. Figure 6 shows the results of the count rate difference on magnetic field reversal as a function of the gamma-ray energy.

The experiment [6], published in the spring of 1957, was one of many that confirmed that parity was not conserved in weak interactions.
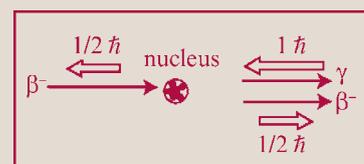

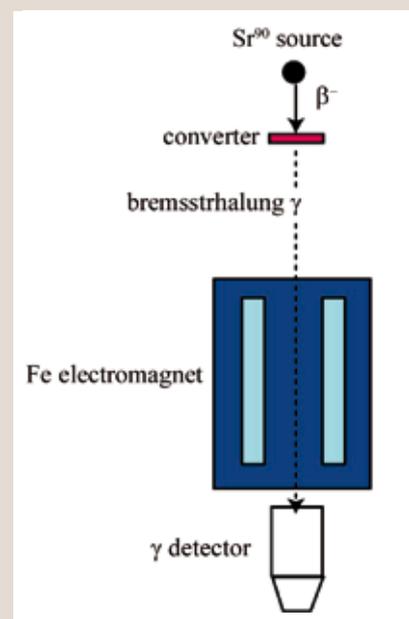Fig. 4 Scheme of the Goldhaber idea that the helicity of the electron is transferred to a forward bremsstrahlung γ.

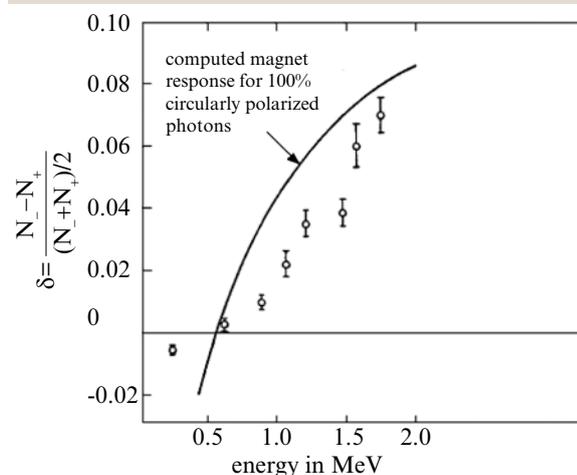Fig. 5 Set-up for helicity transfer from β electron to a forward bremsstrahlung γ.

Fig. 6 Asymmetry in the counting rate with up-down magnetic field as a function of γ-ray energy from [6] with the set-up of fig. 5.

Theoretical advances were rapid and Goldhaber was now thinking constantly about experimental tests. Andy returned to the study of the lifetimes of nuclear states by electronic means. I turned to the study of the states populated by the nine-hour isomer ^{152m}Eu.

3 Resonance fluorescence

The two lowest states in ^{152}Sm, at 122 keV and 366 keV, (fig. 2b) have spins, parities and energy ratios expected for a rotational band of an ellipsoidal nucleus. The 963 keV state, with readily deduced spin-parity of 1⁻, was a plausible candidate to be the lowest member of an odd-parity collective band built on that collective ground state. Measuring its lifetime would test this hypothesis but the expected value of about 10^{-14} s was far too short for electronic methods. In principle, such lifetimes can be determined by measuring the cross-section for the width of the resonance fluorescence of the state. Resonance fluorescence is a well-known and readily observed optical phenomenon, but its application to nuclear states is generally difficult to achieve [7]. That was not the case here.

Figure 7 illustrates the essentials of resonance fluorescence as applied to the 963 keV transition. The 963 keV gamma ray emitted from the radioactive ^{152m}Eu excites the 963 keV state in a nearby stable nucleus of ^{152}Sm. The excitation can only occur if the energy of the fluorescing gamma ray coincides with the energy of the state being fluoresced. The fluorescence is measured by detecting the decay of the fluoresced state by a detector that is shielded from radiation from the ^{152m}Eu.

The energy of the emitting 963 keV state is divided between the gamma-ray energy and the nuclear recoil energy. The momenta of the two are the same, so the energy of the recoil, in both emission and absorption, is

$$(1) \qquad E_{\text{recoil}} = \frac{E_\gamma}{2 M_{152} c^2} \approx 3\,\text{eV}\ .$$

The total decrement is about 6 eV. Six electronvolts is five orders of magnitude less than the gamma-ray energy, but it is two orders of magnitude larger than the 0.01 eV natural line width of a state whose mean life τ is 10^{-14} s.

Resonance can only be achieved if the 963 keV gamma ray can be Doppler-shifted by at least 6 eV. Two sources of Doppler shift are necessary, one from the ambient temperature that is directly related to the mean velocity of the atoms, the other from the neutrino recoil.

The ambient temperature was about 300 K. The mean thermal energies of both the emitting and stimulated nuclei is kT, where k is Boltzman's constant. Both the emitting and the absorbing gamma rays are therefore Doppler-shifted, on average, by

$$(2) \qquad \Delta E_\gamma = E_\gamma^0 \frac{v}{c} \cos\theta = E_\gamma^0 \left(\frac{2kT}{M_{152} c^2} \right)^5 \cos\theta \cong 0.5 \cos\theta\,\text{eV}\ ,$$

where θ is the angle between the photon direction and the nucleus direction and v is its velocity. The thermal Doppler broadening is almost two orders of magnitude greater than the expected natural line width but it is still far from the 6 eV needed for resonance. That requires the Doppler shift from the ^{152*}Sm that is recoiling from the emitted neutrino.

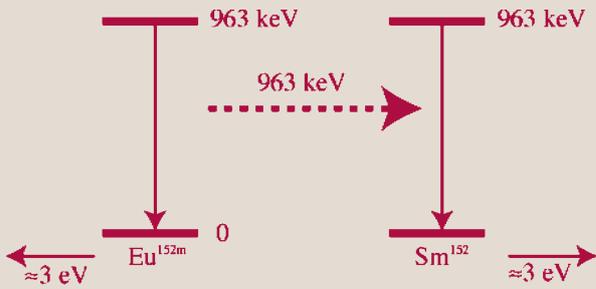K-electron capture results in a two-body final state so the neutrino and

Fig. 7 Illustration of the effect of the recoils, to be considered in the resonance conditions. The dashed line represents the 963 keV γ-ray emitted when a 963 keV level, ^{152*}Sm, decays to the ground state. If ^{152*}Sm decays from rest the emission results in ^{152}Sm recoiling with 3 eV kinetic energy. Moreover, when the emitted 963 keV γ hits a stationary target ^{152}Sm it gives it its momentum, corresponding also to 3 eV recoil kinetic energy. The missing 6 eV can only be made up by the Doppler shift when the 963 keV γ is emitted from a moving ^{152*}Sm.
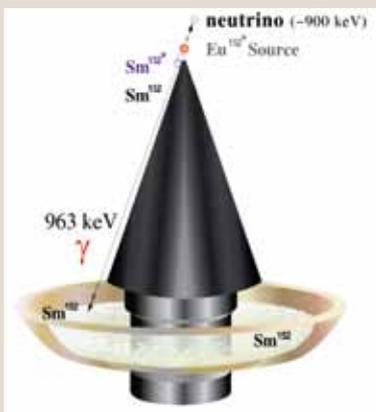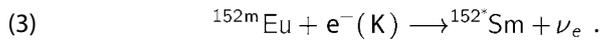

Fig. 8 Cartoon of the arrangement of the GGS neutrino helicity experiment. The γ is emitted opposite to the ν direction. In the depicted case the γ points to the Sm ring and may induce fluorescence.

the recoiling ^{152*}Sm share the total energy of about 940 keV.

(3)
$$^{152m}\mathrm{Eu} + \mathrm{e}^-(\mathrm{K}) \longrightarrow {}^{152*}\mathrm{Sm} + \nu_e \ .$$

Conservation of momentum dictates that the velocity of the ^{152*}Sm is simply $E_\nu/(M_{152}c)$ so that the 963 keV gamma ray, emitted in flight, is Doppler-shifted by

(4)
$$\Delta E_\gamma = \frac{E_\nu E_\gamma}{M_{152}c^2}\cos\theta \cong 5.4\cos\theta \ \mathrm{eV} \ ,$$

where θ is the angle between the direction of the gamma ray and the recoiling ^{152}Sm. When the 963 keV gamma ray is emitted opposite to the direction of the 940 keV neutrino, almost 95% of the shortfall has been eliminated. The sum of the Doppler shifts from temperature and neutrino recoil, when occurring in the vicinity of their appropriate maxima, produces resonance fluorescence.

The one remaining condition for resonance to occur in a solid target (the only practical medium) is that the 963 keV gamma ray must be emitted in flight, a condition that was fulfilled for lifetimes below about 10^{-13} s.

Figure 8 is a cartoon of the experimental arrangement. The 9 hr ^{152m}Eu source was placed at the apex of a truncated cone of lead, which itself sat on top of a NaI(Tl) gamma-ray detector. Surrounding the detector was approximately two pounds of natural samarium (26.7% ^{152}Sm) placed inside a truncated conical shell made of cardboard and duck tape.

The emission of the neutrino tagged the direction of the recoiling nucleus. (The energy of the neutrino in fig. 8 was believed at the time of the experiment to be about 900 keV.) The recoiling ^{152*}Sm promptly emitted either a 963 keV or an 841 keV gamma ray (see fig. 2b); the latter being of no consequence. The 963 keV gamma, emitted in the direction of the stable ^{152}Sm was Doppler-shifted by energies ranging between about −6 eV and +6 eV, depending on the direction of emission of the neutrino.

For those neutrinos that were emitted away from the target ^{152}Sm, the Doppler shift of the 963 keV gamma ray was positive. Some fraction of those gamma rays resonantly excited the ^{152}Sm to the 963 keV level. The excited states decayed by emitting either a 963 keV or an 841 keV gamma ray. A fraction of them, depending on geometry and the angular correlation of the electric dipole excitation and decay, are detected in the NaI(Tl) detector.

Figure 9, shows the gamma-ray spectra obtained in the NaI(Tl) detector [8].

The resonant signature of the 963 keV and 841 keV gamma rays appeared quickly, well above the background of Compton scattered radiation. I had demonstrated one of the clearest "observations" of the neutrino's momentum. And I was paid to do that experiment!

The experimental data had been collected but the analysis was unfinished when Maurice and his wife Trudy left for Israel to attend the Rehovoth Conference on Nuclear Structure, a conference dominated by papers and discussions of parity violation. They may have been still abroad when Lee and Yang accepted the Nobel Prize.

Upon Maurice's return to Brookhaven Labs, he called me into his office. What I recall is intense fascination as he described the method for measuring the helicity of the neutrino. The concepts were clear
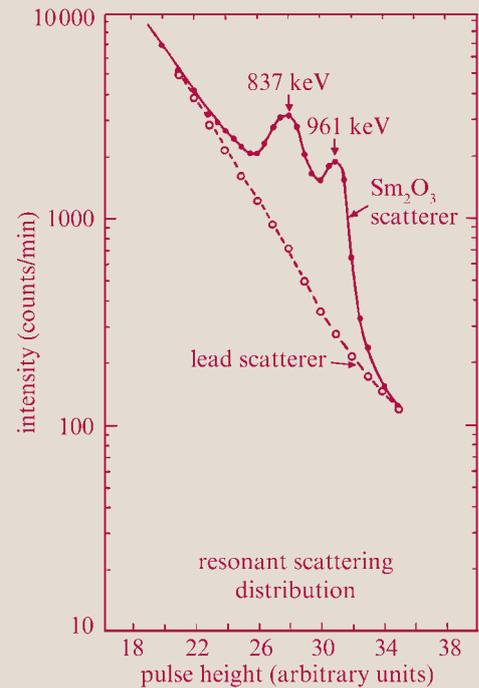

Fig. 9 Gamma-ray spectra obtained in the NaI(Tl) detector.
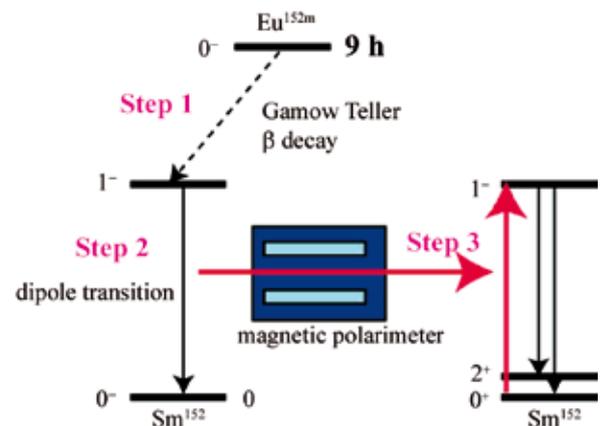

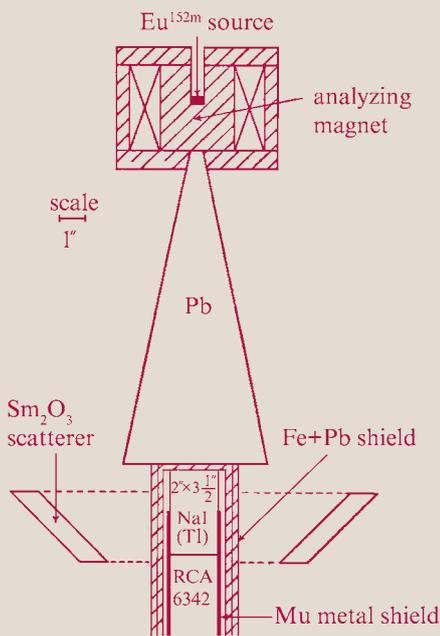Fig. 10 The basic spin-parity levels of the neutrino helicity experiment.

Fig. 11 Schematic arrangement of the neutrino helicity experiment. (From Goldhaber *et al*. [9])

Fig. 12 Distribution of the resonant scattered γ-rays of ^{152m}Eu [9]. Taken with the arrangement of fig. 11.

and inevitable. The resonant fluorescence determined the momentum direction of the neutrino. If we measured the helicity of the fluorescing gamma rays then the conservation of angular momentum would determine the helicity of the neutrino.

Goldhaber's idea has four sequential steps (see fig. 10).

Step 1. The helicity of the neutrino is transferred to the helicity of the recoiling nucleus.

The first line of eq. (5) gives the reaction, the second one the angular-momentum conservation:

(5)
$$^{152m}_{93}\text{Eu} + \text{e}^-(\text{K}) \longrightarrow \nu + {}^{152*}_{93}\text{Sm},$$
$$0^- + \tfrac{1}{2} = \tfrac{1}{2} + 1^-.$$

About 20% of the beta decays of $^{152m}_{63}$Eu (spin 0) take place by capturing one of its K-electrons, which has no orbital angular momentum. The initial state has a total spin of ½. The final state is a polarized 940 keV neutrino, spin ½, and a polarized $^{152*}_{62}$Sm in a 1^- state. The samarium and the neutrino must have opposite momenta and must have opposite spin directions. They therefore have the same sign of helicity.

Step 2. The helicity of the recoil is transferred to the helicity of the gamma ray.

(6)
$$^{152*}_{92}\text{Sm} \longrightarrow {}^{152}_{92}\text{Sm} + \gamma\,(963\,\text{keV})$$
$$1^- = 0^+ + 1^-$$

The 1^- state of ^{152*}Sm decays in less than 10^{-13} s by emitting a 963 keV electric dipole gamma ray to the 0^+ ground state, or an 841 keV electric dipole gamma ray to the 2^+ first excited state. Only the former, which connects the 963 keV state to the ground state, is of interest. Those 963 keV gamma rays carry away the spin of the ^{152*}Sm. If they are emitted in the same direction as the still recoiling ^{152*}Sm then they must retain the helicity of the recoil.

Step 3. The momentum and polarization conditions are satisfied.
The 963 keV gamma rays that strike the ^{152}Sm nuclei in the SmO_2 target have traversed the core of the magnet polarimeter. A fraction of them were emitted opposite to the direction of the emitted neutrino in Step 1. Only that fraction resonantly excites the 963 state of ^{152}Sm. In sum: the only gamma rays that can resonantly excite the ^{152}Sm are those that carry the signature of the neutrino helicity and have traversed the magnetic polarimeter. It should be noted that the fluorescing 963 keV gamma rays are not expected to be fully circularly polarized since they are not emitted exactly 180° from the neutrino. (The gamma rays emitted at 90° from the recoil direction are transversely polarized.)

Step 4. The signature is detected. The fluoresced state de-excites by emitting either a 963 keV or an 841 keV gamma ray, which are detected in an energy-dispersing counter that is shielded from the primary source. The helicity of the neutrino is determined from their count rate as a function of magnetic field direction.

Andy and I took the magnet out of storage, drilled a hole for the ^{152m}Eu

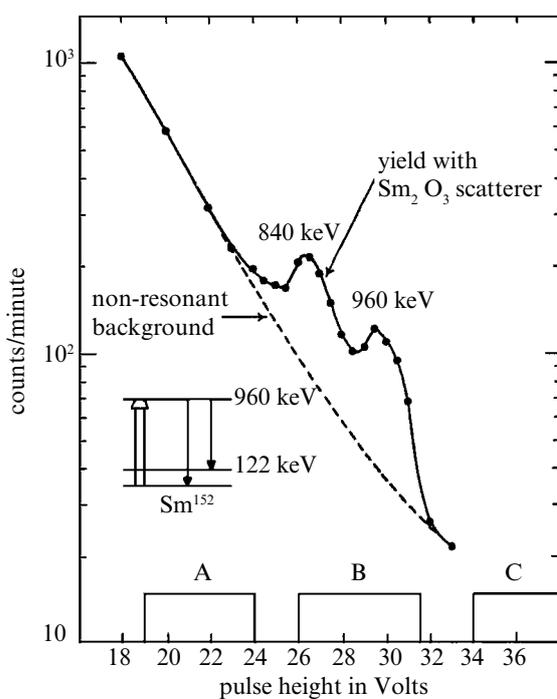source and mounted it on top of the resonance fluorescence apparatus. A schematic of the new configuration is shown in fig. 11. With Maurice fully involved, we obtained the fluorescence spectrum shown in fig. 12, which is essentially identical to that I had obtained without the magnet. Figure 12 adds the regions of interest, A, B, and C, which we used as one of the controls as we switched the direction of the saturated magnetic field in the iron core. Only the intensity in region B changed significantly with field reversal.

My memories of those days are of Maurice in the laboratory insisting on all manners of verification tests. He was particularly concerned that we had correctly correlated the direction of the spin of the polarized electrons with the direction of the magnetic field in the iron and he was not satisfied until all the methods that we could think of gave the same answer.

The change in the net 837 keV/963 keV gamma-ray count rate in region B of fig. 12 is a direct measure of the helicity of the fluorescing 963 keV gamma rays that traversed the magnet polarimeter in fig. 11. The results of 9 independent runs are shown in fig 13. The average helicity was –0.67 with an uncertainty of about 15%.

The 963 keV gamma rays that traversed the magnet had negative helicity; the circular polarization of the gammas was anti-parallel to its momentum.

Therefore, the neutrinos emitted in positron decay or electron capture have negative helicity.

This experiment also settled the controversy of the nature weak-interaction currents. Beta decay proceeds via axial vector and vector modes.

No photograph has been found of Maurice with his experiment. The photo in fig.14 was taken in September, 1958, by a New York Daily News photographer for an article on young scientists. Andy and I cobbled the original parts together. I am holding the magnet in place.
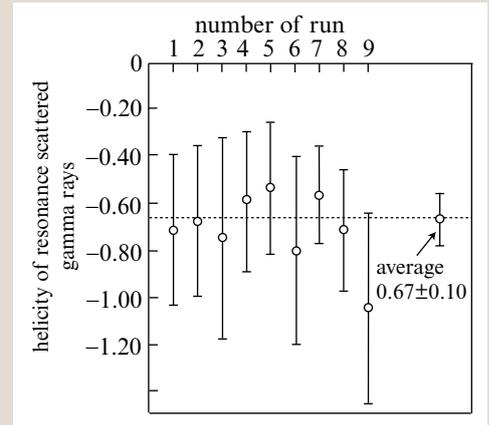
Fig. 13 The helicity of the fluorescing 963 keV gammas deduced from the field reversal measurements.

Fig. 14 Lee Grodzins holding the magnet in September 1958.

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Lee Grodzins
Lee Grodzins, born in 1926, received his Mechanical Engineering degree from the University of New Hampshire and his PhD in Physics from Purdue University. He joined the Physics faculty of MIT in 1959, retiring in 1998 to work in industry, first as VP for Advanced Development at American Science & Engineering, then as VP for R&D for Niton Corporation, a company he founded in 1987, and presently as Senior Fellow at AS&E. He was a Guggenheim Fellow in 1964-65 and in 1971-72; a Senior von Humbolt Fellow in 1980-81; winner, in 1995, 2003 and 2007, of R&D 100 awards given for the 100 best new products in the USA. He has authored more than 150 technical papers and holds more than 40 patents. He is a Fellow of the American Physical Society and the American Academy of Arts and Sciences. He received an honorary Doctor of Science degree from Purdue University in 1998.