History of the neutrino:
parity violation, first neutrino properties, muon neutrino discovery

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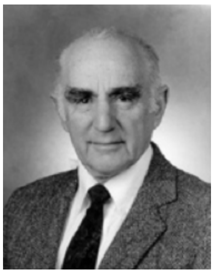

Prior to 1955, the neutrino was a massless particle of spin 1/2 that made up the deficit of energy or momentum or spin that was needed to maintain conservation laws in weak interactions. That view changed dramatically in the years covered by this review. It came from the efforts of individuals and small groups, of theorists and experimentalists. Parity was shown to not be conserved in weak decays; the helicity of the neutrino was measured; a robust theory of weak decays evolved; the first beam of ν_μs was developed to prove that ν_μ and ν_e were separate particles. By 1962, the one-neutrino-fits-all had become independent neutrinos and anti-neutrinos in both beta and muon decay.

1 Introduction

For almost a quarter of a century after its speculative inception, the neutrino was a massless particle of spin 1/2, whose role was to make up the deficits of energy or momentum or spin that were needed to maintain conservation laws in nuclear interactions. That changed between 1955 and 1962. Those were years of dramatic insights into neutrino properties and the nature of weak interactions. The discoveries were made by individuals and small groups, by theorists and experimentalists working together. Several publications introduce this period.

In the early 1950's, Raymond Davis, of Brookhaven National Laboratory (BNL), built the first neutrino detector following the prescription detailed by Bruno Pontecorvo in a 1946 classified document from Chalk River Laboratories[1]. Pontecorvo suggested that neutrinos can be detected by the inverse of the decay of $^{37}_{18}$Ar by K-electron capture, which produces $^{37}_{17}$Cl plus a neutrino. The method was elegant, simple, and convincing. Chlorine, in the form of CCl_4, was cheap; a large mass of detector, required because the neutrino's interaction cross section was so small, was not expensive. ^{37}Ar, the product of the inverse reaction was a radioactive, inert gas with a 35-day half-life. It would not interact with any other elements before being extracted, atom by atom, by boiling the carbon tetrachloride and collecting the ^{37}Ar atoms in a proportional counter. A neutrino event would be unambiguously detected by the 2.8 keV X-ray ejected when the ^{37}Ar decayed back to ^{37}Cl.

Davis placed his first Pontecorvo detector beside the nuclear reactor at Brookhaven National Laboratory and searched, unsuccessfully, for neutrinos events. He persevered with larger and larger detectors near more and more powerful reactors until, in 1955, he reported that Pontecorvo's method was insensitive to neutrinos emitted from reactors, i.e. produced in (Z-1 $\rightarrow$ Z) decays. But it did detect the Sun's neutrinos, which come dominantly from (Z+1 $\rightarrow$ Z) decays. In 1955, Davis, concluded, with high confidence, that the neutrino emitted in electron beta decay is a different particle than the neutrino emitted in positron decay [2].

In 1954, William Chinowsky and Jack Steinberger reported their experimental proof that the parity of the π^- was negative[3], and reported in 1955 that the parity of the π^0 was also negative[4]. Both experiments, which were parts of Chinowsky's PhD thesis work at Columbia University, based their conclusion on measurements of the properties of the neutrons produced by pions that stopped and were captured from the K shell of π-deuteron:

$$\pi^- \text{ (spin 0)} + {}_1\text{H}^2 \text{ (spin 1)} \rightarrow \text{n} + \text{n}.$$

Neither experiment elicited much attention, probably because the results only strengthened already formed wisdom. But the results may have helped focus the discussions on the compelling $\tau - \theta$ puzzle whose solution had stumped physicists for several years.

2 Parity Violation

In the years leading up to 1955, cosmic ray physicists, using cloud chambers or stacks of emulsions, were finding new fundamental particles. New accelerators capable of providing beams of BeV protons or electrons came on line to more effectively study this frontier. And keeping pace was the development of large volume detectors capable of studying their properties.


C.N. Yang

Understanding these heavy mesons and hyperons was the focus of three of the sections of The Sixth Annual Rochester Conference on High Energy Nuclear Physics, which took place from April 3 to 7, 1956. Session VIII, "Interpretation of New Particles", presided over by J.R. Oppenheimer, focused on the K mesons with their similar masses and lifetimes. C.N. Yang summarized the primary issue: "There are 5 different K mesons, differentiated by subscripts, $K_{\pi 3}$, $K_{\pi 2}$, $K_{\mu 2}$, $K_{\mu 3}$, and K_{e3}. Their measured masses are all close to half that of a nucleon, and their measured lifetimes are also nearly identical, around 10^{-10} s. One tries to discover whether in fact one is dealing with five, four, three, two or one particle" [5].

The most transparent problem was posed by the $K_{\mu 3}$ and $K_{\pi 2}$ mesons, whose common names were τ^+ and θ^+. The τ^+ meson decays to 3 pions. The θ^+ decays into 2 pions. Their masses were known to be equal to within a few percent. But they could not be the same meson because Chinowsky and Steinberger had proven that the pion had negative parity.


Richard Feynman

Yang, R.E. Marshak, R. Dalitz, M. Gell-Mann and others spoke directly to this problem. None had an acceptable answer. No one voiced a promising new direction to explore. Indeed, Yang "cautioned that as long as we understand so little about the degeneracy it may perhaps be best to keep an open mind." Richard Feynman, pursuing the open mind approach, asked the question posed to him by Marty Block, an experimentalist: "Could it be that the θ^+ and τ^+ are different parity states of the same particle, which has no definite parity; i.e., that parity is not conserved in the K decays". Feynman then rephrased the question at a more philosophical level: "Does nature have a way of defining right- or left-handedness uniquely?" Yang stated that he and T. D. Lee had "looked into this matter" without arriving at any definite conclusion.

T.D. Lee

Lee and Yang may not have arrived at a definite conclusion, but they were becoming convinced that parity violation must be tested. After several months of intensive study, they concluded that there was no experimental evidence that parity was conserved in weak interactions and suggested experimental tests for both beta decay and muon decay. They submitted their paper to the Physical Review on June 22, 1956; it was published in October 22 [6]. It would win them the Nobel Prize in Physics in 1957.

Yang's statement that he and Lee had "looked into this matter" downplayed what was, in fact, their total concentration on the question of parity conservation in weak decays. They were becoming convinced that parity was not be conserved there. C.S. Wu makes that clear in her personal account of her own involvement [a]:

C.S. Wu

"In the early spring of 1956 [i.e., even before the Rochester Conference and well before the submission of their Nobel Prize paper to the Physical Review], Professor T.D. Lee came to my little office on the thirteenth floor of Pupin Physical Laboratories. He asked me a series of questions concerning the status of the experimental knowledge of beta decay." Lee told her about the τ-θ puzzle, which could be resolved by measuring the spatial distribution of electrons from a polarized beta-decaying nucleus. Wu had no experience in low-temperature measurements or in polarizing radioactive sources, but she "was captivated". She not only wanted to do this fundamental experiment but was "challenged by two things which had never been tried before and were difficult. One was to put a working electron detector inside a cryostat at a liquid helium temperature. The other was to have a β source located in a thin surface layer and polarized for a time-period long enough to obtain sufficient statistics."

3 Parity Violation in Beta Electron Decay

Wu began her concentrated focus on this experiment in May 1956, as soon as the spring semester ended. A world expert on beta decay, she was sure she could handle the nuclear physics aspects but had never done experiments at liquid helium temperatures. For that she needed the right collaborator. On June 4 (three weeks before the Lee and Yang paper was submitted), she called Ernest Ambler of the National Bureau of Standards (NBS; now N.I.S.T), a pioneer in the nuclear orientation field, and "asked whether he would be interested. He accepted enthusiastically."

Ambler, together with the NBS group that he would assemble to help her, would not begin working on the cryogenics until September. During that interim, Wu, together with her graduate student, Marion Biavati, solved the detector problems, grew their own single crystals necessary for polarizing the layer of ^{60}Co placed on the crystal surface, and determined the percentage of ^{60}Co beta rays that would backscatter, reducing the sought-for angular asymmetry. Ambler and the NBS group that joined him, provided both the cryostat and the electronics needed to measure the ^{60}Co beta rays in coincidence with the ^{60}Co gamma rays, whose anisotropy measured the degree of nuclear polarization. Figure 1 shows the key elements of her experiment: the thin source of ^{60}Co is on a single large crystal of polarizable CMN, which is in a cup

[a] I have made use of personal essays by C.S. Wu and R. Garwin in *Adventures in Experimental Physics, Vol.* γ (1973), and have been informed by L. Lederman's Nobel Prize Lecture, "Observations in Particle Physics from Two Neutrinos to the Standard Model" (1988), and his book, written with D. Teresi, *The God Particle: If the Universe Is the Answer, What Was the Question?* (Boston: Houghton, Mifflin, 1993).

in the center of the long solenoid magnet. An anthracene crystal, sitting a few centimeters above the source, is connected by a long light-pipe to a room temperature PMT. The carefully polished and contoured light-pipe carries the beta decay signal from the anthracene crystal to a room-temperature PMT that is well above the Dewar. Two gamma ray detectors, positioned 90°apart, measure the polarization of the source from the gamma ray anisotropy of the 1.17 MeV and 1.33 MeV cascade from ^{60}Co.

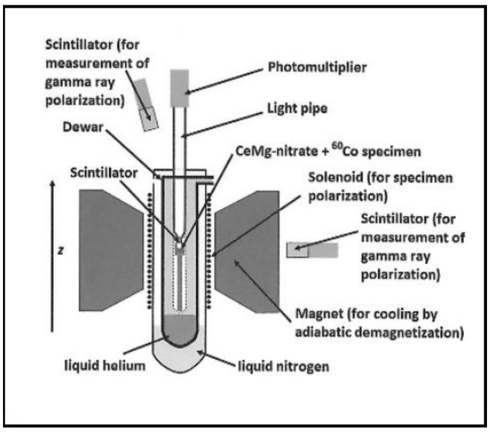

Figure 1 – Parity Experimental Arrangement.

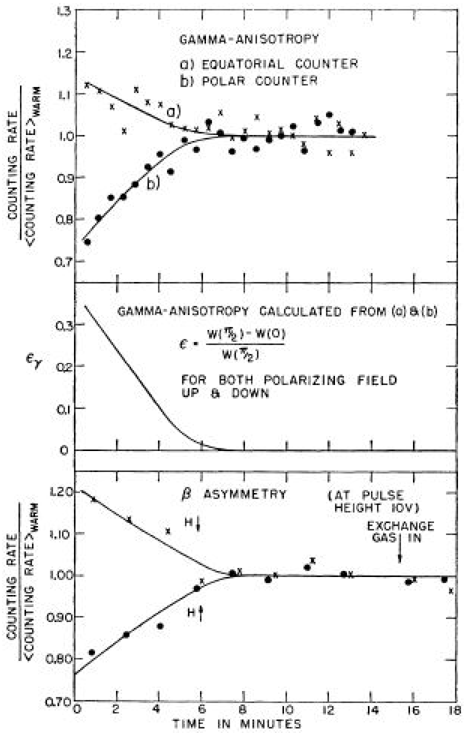

Figure 2 – Parity Results.

Figure 2 shows the results as a function of time for one of her runs. The upper graphs show the polarization of the source, the lowest graph displays the detected anisotropy of the beta-ray anisotropy. The anisotropy of the beta rays, and its tracking with the source polarization, is clear and compelling[7]. Just before Christmas, after eight months of focused effort, Wu informed Lee and Yang that she could claim with high confidence that her results were consistent with total violation of parity in beta decay.

4 Parity Violation in Muon Decay

Wu reported her results to her Columbia colleagues at a weekly Friday luncheon held at a Chinese restaurant. Present was Leon Lederman, a leading figure in pion and muon experiments using the 400 MeV Cyclotron at Columbia's Nevis Laboratory.

The previous summer, Lederman had considered the Lee and Yang challenge to search for parity violation in the π - μ - ν chain but had concluded that the anisotropy would be small and difficult to measure. As he drove home that Friday, he realized that Wu's results implied a fully polarized muon beam that would produce a substantial anisotropy of the distributions of the decay electrons. He could measure that anisotropy by measuring the intensity of the electrons emitted at several angles with respect to the pion beam. It would be a straightforward experiment. By his own account, he thought, "Fame and fortune!"

Richard Garwin

That evening he called his friend Richard Garwin to tell him Wu's results and to explain his plans to measure the electron anisotropy at several angles. Garwin suggested that they meet that same evening at the Nevis Cyclotron. At the meeting, Garwin proposed that a better arrangement would be to keep the counter at a fixed angle with respect to the pion beam and rotate the presumed polarized magnetic moment of the muon with a magnetic field created by Helmholtz coils.

The superiority of his suggestion was both evident and easy to implement, in part because they appropriated the scattering chamber, as well as the electron detector, of Lederman's graduate student, Marcel Weinrich. In the next few hours, Garwin made the carbon target to stop the muon and wound the magnet coil to rotate its assumed magnetic moment. With the makeshift apparatus, they made their first run that same Friday evening. The results were inconclusive but encouraging. The cyclotron was shut down over the weekend, which was enough time to make the stable setup shown in Figure 3. The experimental arrangement and methodology were simple and robust.

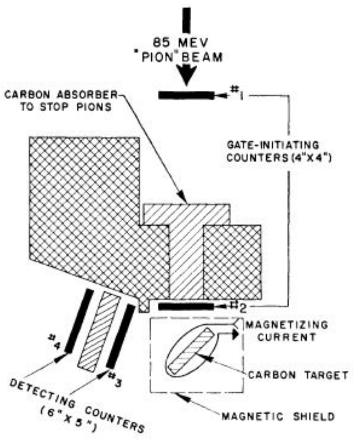

Figure 3 – Muon polarization experimental arrangement.

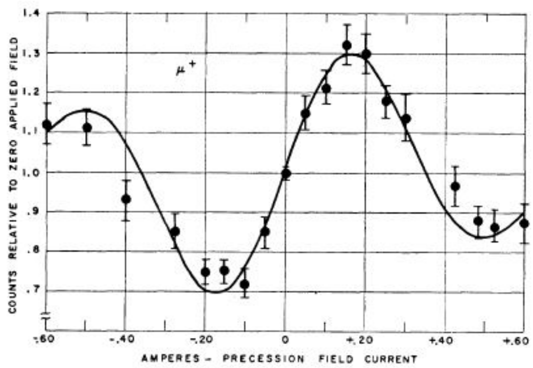

Figure 4 – Muon polarization experimental results.

The 85 MeV pions trigger counter #1 and are stopped in the carbon block. The produced muons trigger counter #2 and stop in a fixed carbon target that is inside the uniform magnetic field created by a pair of Helmholtz coils. The emitted electrons from the muon decay are counted in the 90° detectors 3 and 4. An event is a coincidence between counters 1, 2 and 3 not 4. Events are collected as a function of the strength of the current in the Helmholtz coils. The 22 standard deviation result from one of the runs is shown in Figure 4 [8] [a]. The result was as convincing as Wu's result for β decay. Parity was violated in the weak decays:

$$\pi^+ \to \mu^- + \nu \text{ and } \mu^- \to e^+ + 2\nu$$

5 Helicity of the Neutrino

The theory of weak-interaction decays was now a two-component theory. Still uncertain, however, was whether the linearly polarized neutrino, emitted in the beta decay of Z → (Z-1) was ν_{left} or ν_{right}; i.e. whether Gamow-Teller decays were axial-vector or tensor-scalar. The sum of existing experiments, each with large uncertainty, favored the latter; theory favored the former.

[a] The precession of the intrinsically polarized muon produced the first measurement of the g factor of the free muon, obtaining a value of g = -2.00 ± 0.10. The present value, made with many refinements of the Columbia technique, is -2.0023318418. The uncertainty is in the last place.

The question was decided in the fall of 1957 by the measurement of the helicity of the 940 keV neutrino emitted in the K-electron capture, of the 9-hour Eu^{152m}, a radioactive nucleus with spin-parity 0 . The relevant decay path through the 963 keV state is shown in Figure 5.

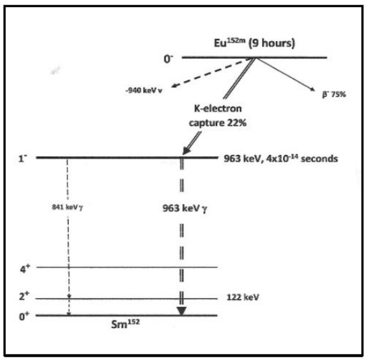

Figure 5 – Helicity experiment decay scheme.

The experiment was reported in consecutive *Physical Review Letters*[9,10]. The first Letter, by me, describes the resonance fluorescence of the 963 keV state in Sm^{152}, which is initiated by the neutrino's momentum. Those 963 *keV* gamma rays that have been Doppler shifted with enough energy to enable fluorescence, have been emitted forward of the recoiling target Sm^{152}; i.e., opposite to the momentum of the neutrinos.

The second Letter, by Maurice Goldhaber, Lee Grodzins, and Andrew Sunyar, describes the measurement of the circular polarization direction of those fluorescing gamma rays with their known momentum direction.

I have been asked many times how I found that "perfect" decay path? I did not search for it. The decay path found me as I was investigating the properties of the nuclear states populated in the decays of Eu^{152} and Eu^{152m}.

In early 1955, I became a postdoc in Maurice Goldhaber's nuclear spectroscopy group at Brookhaven National Laboratory. Goldhaber, knowing that I had little experience in nuclear spectroscopy, suggested that I investigate the nuclear decays of the long-lived $_{63}Eu^{152}$ and the 9-hour isomer $_{63}Eu^{152}$. Both decayed by electron emission to states in $_{64}Gd^{152}$ and by positron emission or K-capture to states in $_{62}Sm^{152}$. Atomic studies suggested that the shape of nuclei with 88 neutrons, such as $_{64}Gd_{88}$, is spherical, while the shape of nuclei with 90 neutrons, such as $_{62}Sm_{90}$, is oblate. Investigating the nuclear spectroscopy of the isotopes might illuminate the origin of the unexpected shape change.


Maurice Goldhaber

I had a wonderful time learning the techniques and measuring the properties of the states and transitions. The lowest eigenstates of Sm^{152} did indeed have the energies and quantum numbers of a rotational band, while the lowest eigenstates of Gd^{152} did not. The 963 keV state of Sm^{152} almost certainly had spin-parity 1^-, and we speculated that it was the lowest odd spin of the rotational band. If so, it should have a lifetime shorter than 10^{-13} second. Measuring that short a lifetime could only be done by resonance fluorescence.

Nuclear resonance fluorescence requires that the energy of the fluorescing gamma ray match the energy of the fluoresced state. Such studies are rare because the energy losses, intrinsic to the method, are much greater than the width of the involved nuclear state, and canceling the deficit generally requires a mechanically produced Doppler shift[11]. The neutrino helicity experiment remains the only nuclear resonance fluorescent induced by a neutrino's momentum.

The energy changes in the sequence of steps for resonance fluorescence of the 963 keV state reveal the uniqueness of the decay chain. The relevant decay path of Eu^{152m}, shown in Figure 5, begins with the emission of the neutrino with an energy, $E_\nu = 940 \pm 20$ keV. The $Sm^{152,963}$ recoils with an energy of 3 eV and a velocity of $\sim 10^4$ cm/sec.

$$E(Sm^{152,963}) = E^2/(2Mc^2) = 3\,eV$$

$$v = (E/Mc^2)c = 9.4 \times 10^3 \text{ cm/sec}$$

The energy of the 963 keV gamma is decreased on emission because it shares the state's energy with the recoil energy of the Sm^{152}, now in its ground state.

$$\Delta E \text{ (963 keV)} = -E\gamma^2/(2M_{152}c^2) = -3\,\text{eV}$$

The gamma ray energy is lowered another 3 eV when it fluoresces the 963 keV state in the Sm^{152} in a target of Sm_2O_3. The total decrement is only 6 eV; 5 orders of magnitude less than the 963 keV gamma ray. But 6 eV is 600 times the natural width of 0.01 eV for a state with an expected lifetime of 10^{-14} second.

The decrement is cancelled by the gains in energy produced by Doppler shifts. The principal shift originates from the momentum of the neutrino, which has been transferred to the $Sm^{152,963}$. When that state decays in flight, the energy of the 963 keV gamma ray is changed by:

$$\Delta\ E_\gamma = (E_\gamma\ E_\nu\ /Mc^2)\ \cos\theta = 6\ \cos\theta\ \ \text{eV},$$

where θ is the angle of emission with respect to the Sm^{152} moving away from the neutrino.

The total deficit is almost completely cancelled for 963 keV gamma rays moving exactly opposite to the neutrino direction. But that is a small subset of the emitted 963 keV gamma rays. The thermal Doppler shift, from the velocity distribution of the involved nuclei at a room temperature of 300 K, opens the window of angles that produce fluorescence.
The thermal Doppler broadening of the 963 keV state in both the source and scatterer is given by:

$$\Delta\ E_\gamma = E_\gamma\ (2KT/(M_{152}c^2))^5\ \ \cos\theta \approxeq 0.5\ \ \cos\theta\ \text{eV}.$$

The effective net broadening is about 0.7 cosθ, which effectively allows resonance to occur for 963 keV gamma rays that are emitted in a cone with a half-angle of $\sim 30°$ centered on the recoil direction.

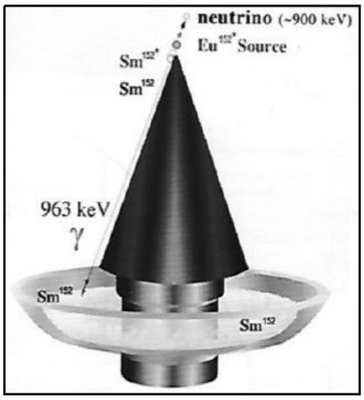

Figure 6 – Resonance fluorescence experiment.

The geometry of the experiment is shown in the pictorial of Figure 6. A 100 mCi source of Eu^{152m} was placed above the apex of the cone of lead that shielded the NaI(Tl) gamma ray detector from the source. Doppler-shifted gamma rays fluoresced the Sm^{152} in the truncated conical container of Sm_2O_3. The fluorescence spectrum, shown in Figure 7, appeared immediately.

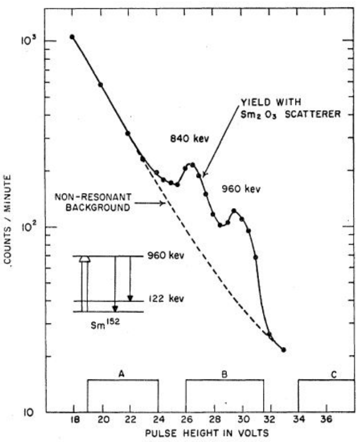

Figure 7 – Resonant scattering energy spectrum.

I measured the lifetime of the 963 keV state to be $4\ \pm 1 \times 10^{-14}$ s. The state was indeed the lowest odd spin state of the rotational band.

Turning on the multichannel analyzer and watching the 963 keV and 861 keV peaks rise decisively above the background has been one of the most memorable experiences of my life [b].

Maurice Goldhaber, a constant source of ideas and advice during both the construction and data-taking phases of my research, shared my pleasure in making such a vivid demonstration of the neutrino's momentum. But he never took an active role in the experiment, contenting himself with frequent discussions in his office. That was not the case with the helicity experiment

[b] The energy of the neutrino is now known to be 955 ± 5 keV; i.e. within 1% of the 963 keV gamma ray. See Table of Isotopes, Seventh Edition, M. Lederer and V. Shirley, eds. (New York: Wiley, 1978).

carried out a few months later.

In September 1957, Goldhaber attended the Rehovoth Conference on Nuclear Structure, which was dominated by papers on parity violation. The day he returned to Brookhaven he called me into his office and explained how we could use the resonance fluorescence to measure the helicity of the neutrino. I vividly recall my intense fascination as he went through the steps.

Step 1. The decay transfers the helicity of the neutrino to the helicity of the recoiling nucleus.

$$\begin{array}{lccccccccc} & Eu^{152m} & + & e^- & \rightarrow & \nu & + & Sm^{152*} \\ \text{Spin}-\text{parities}: & 0^- & + & \frac{1}{2} & = & \frac{1}{2} & + & 1^- \end{array}$$

For angular momentum to be conserved, the 1^- state in Sm^{152}, which has opposite momentum to that of the neutrino, must have opposite polarization. Therefore, the helicity of the recoiling $Sm^{152\ (963)}$ must be the same as that of the neutrino.

Step 2. The polarization of the 963 keV state is transferred to the 963 keV electric-dipole gamma ray.

$$\begin{array}{lccccccc} & Sm^{152*(963\ keV)} & \rightarrow & Sm^{152} & + & 963\,\text{keV}\ \gamma \\ \text{Spin}-\text{parities}: & 1^- & = & 0^+ & + & 1^- \end{array}$$

Those gamma rays that can produce the resonance fluorescence have the same helicity as the neutrinos and are their surrogates.

To measure the helicity of the neutrino, we measured the longitudinal polarization of the 963 keV gamma emitted from the source. Goldhaber did not have to remind Andrew Sunyar and me that we had measured such polarizations a year earlier, when we investigated the polarization of bremsstrahlung produced by beta-decay electrons from Sr^{90}.

With Goldhaber now a dominant, commanding presence in the laboratory, we placed the polarizable iron core magnet used in that experiment on top of the conical lead shield (Figures 6 and 9); surrounded the NaI(Tl) detector with magnetic shielding; placed a 100 mCi Eu^{152m} source on the top of the magnet and took data as a function of the direction of the internal longitudinal magnetic field of the electromagnet. The fluorescent spectrum we obtained was the same as shown in Figure 7. Only the intensity in region B in the figure changed when switching the magnetic field direction. Figure 8 shows the measured helicity results of nine runs. The average helicity was found to be -.67 with an uncertainty of about 15 %.

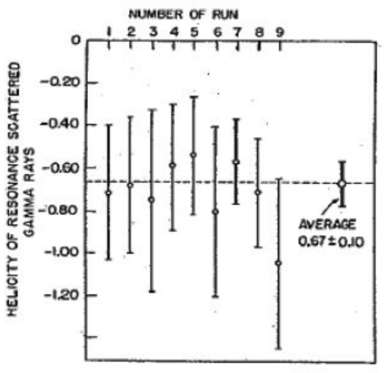

Figure 8 – Helicity values of 9 runs.

Figure 9 – Lee Grodzins with helicity apparatus.

The helicity of the neutrino is negative; i.e., anti-parallel to its direction. Positron beta decay proceeds through vector and axial vector modes.

The experiment, which took about two weeks, was done on a tabletop. Figure 9, taken by a newspaper photographer, is the only photograph of the experimental apparatus.

6 Neutrino Beams

In the 1950's, it was accepted that the mu neutrino and the electron neutrino were the same particle. There was no compelling experiment that proved otherwise. That would change in 1960, with the first experiment that used the first beam of accelerator-produced neutrinos. The story is as interesting as any from the previous decade.

Melvin Schwartz

In late 1959, Melvin Schwarz, an Alfred P. Sloan Research Fellow at Columbia University, attended a coffee-hour talk by T. D. Lee, who discussed potential investigations of weak interactions at high energy. Schwarz writes in his Nobel Lecture that the key ideas of making a beam of neutrinos came to him that evening [12].

His idea, shown in Figure 9, was elegantly straightforward. High energy ν_μs, which are produced in the target from pion production by high energy protons, will tend to go in the pion direction. They will create a beam of pions and ν_μs. Surround the detector with shielding that only the ν_μ can penetrate. Place the shielded target of the neutrinos at least 10 meters from the proton target to give the pion sufficient time for at least 10 % of them to decay.

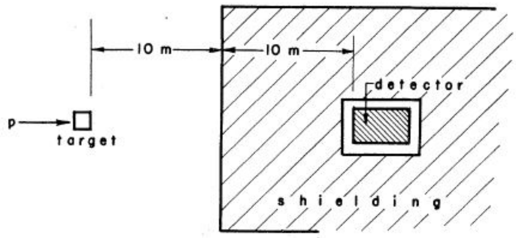

Figure 10 – Experimental arrangement for a neutrino beam

Schwartz estimated a count rate of 1 event per hour; too few to be practical. But he noted that proton accelerators were coming on line or being planned would meet the requirements.

Schwartz's paper is followed by a four-page Physical Review Letter by Lee and Yang [13] titled "Theoretical Discussions on Possible High-energy Neutrino Experiments." The first of the nine suggestions is a test to determine if ν_μ is the same neutrino as ν_e. More specifically, a neutrino beam made from the decay in flight of very high energy muons, would produce both electrons and positrons if $\nu_\mu \equiv \nu_e$.

$$\nu_\mu + n \rightarrow e^- + p \text{ and } \overline{\nu}_\mu + p \rightarrow e^+ + n$$

Only when Schwartz's paper was in proof did he learn that Pontecorvo had published a paper [14] in the Journal Experimental Theoretical Physics (USSR) in December 1959 (submitted in July 1959) entitled, "Electron and Muon Neutrinos." It presaged the ideas for creating a neutrino beam and using it to determine whether the ν_μ and ν_e were the same or different neutrinos. Pontecorvo also estimated an event rate of one per hour with present accelerates and concluded that "the suggested experiment, although difficult, should be feasible with accelerators capable of producing more intense beams".

Lederman was more optimistic. As he writes in his book *The God Particle*, he estimated that the experiment would be practical using the 30 *GeV* Alternating Gradient Synchrotron, which was nearing completion at Brookhaven National Laboratory. He soon convinced Schwartz and Jack Steinberger. The three of them then added four more members: Jean-Marc Gaillard, a post-doc from France; two doctoral candidates, Dino Goulianos and Nariman Mistry; and one Brookhaven colleague, Gordon Danby.

The choice of detector was critical. It had to be both the target of the neutrinos and the detector of the reaction products. As a target, it had to be massive enough to obtain enough interactions for a conclusive statistical analysis. As a detector, it had to able to unambiguously determine whether each rare high-energy track was created inside the detector and was either an electron or a muon. To meet these requirements, the detector had to be made of multiple units of targets separated by tracking and triggering detectors. The Columbia group soon concluded that the spark chamber being developed for high energy physics by Val Fitch and James Cronin at nearby Princeton University, was what they needed.

Shuji Fukui, in Japan, had invented the spark chamber concept in the early 1950's for cosmic ray studies. He discovered that the passage of an ionizing particle through a parallel-plate capacitor filled with an inert gas would produce a visible spark along the ionized path when, on command that an event occurred, a breakdown voltage was applied across the condenser plates. The tracks through the gap could be photographically recorded [15].

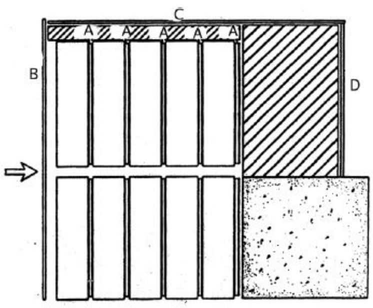

Figure 11 – Spark Chamber.

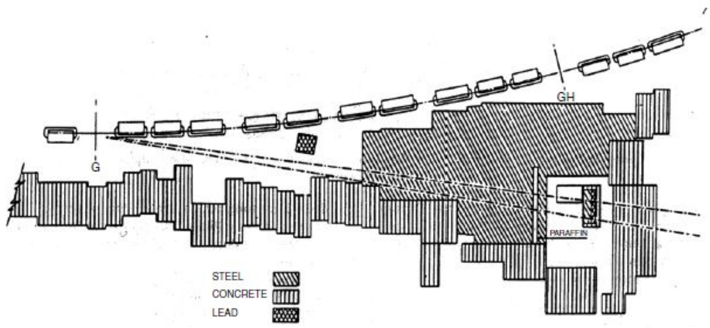

Figure 12 – Neutrinos Beam, Target and Shielding.

Figure 11 sketches the Columbia group's final detector. It consisted of 10 chambers, each made of nine, 112 x 112 cm aluminum plates, 2.5 cm thick. Between and following the spark chambers were scintillator planes for triggering the voltage. Anticoincident detectors surrounded the shielding. The total weight was 10 tons.

Over the course of a year they developed a Schwartz/Pontecorvo neutrino beam that interacted in the spark-chambers, which were surrounded by 13 meters of steel (Figure 12) [16].
In 1962, after several months of running with a proton beam of 15 BeV, they reported on a careful analysis of 113 events that had been culled from an exposure of 3.48×10^{17} protons [17]. They confirmed their selection criteria by exposing the detector to a 250 keV electron beam.

There were no high-energy electrons that met their criteria. The ν_μ was a different particle than the ν_e.

The first chapter of discovery was over. The gates were opened for further discoveries. The neutrinos were now a primary subject for investigation.

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