Newton Day 2025:
Crib notes for the 1957 Goldhaber, Grodzins, Sunyar neutrino helicity experiment

by Peter H. Mao for Margaret and Owen

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Abstract

For Sir Isaac Newton's 383rd birthday, I pay homage to Lee Grodzins, one of my physics heroes, who passed away in March.

> *...it's a part of our responsibility as artists to take the baton, and you learn a lot, and you grow a lot, and it's a part of the tradition, the lineage, to be around the elders... It's like the tribal wisdom of the Griots... You just sit, and you absorb, and it's intangible. It's not like they give you a lesson. It's just something that's transferred.*
>
> –Jon Batiste on collaborating with his musical heroes[11]

1 Introduction

Most classes at MIT are referred to by number only (e.g., 2.70, 5.11, 6.001, 8.01, 18.01), but a select few, which tend to be very memorable to those who take them, go by names – "Unified" in Aero/Astro and "Project Lab" in Biology come to mind. In Physics, that class is "Junior Lab," the required lab class that is normally taken, as the name suggests, in one's junior year. I took it in my senior year because I was late in coming to Physics, having veered from my original plan of doubling in Chemistry and Chemical Engineering in October of my junior year. When I took "Junior Lab" in the fall term of my senior year, Lee Grodzins taught the course; that was my first contact with him. My short term life plan at the time was to apply to graduate school in physics and defer admission for a year to let the tendinitis in my hands heal. By spring-time, I had settled on going to Caltech, but I had no real plans for the interim. I went to Lee for advice, asking him, "What does someone with an SB in physics do?" Appalled at my fecklessness, he arranged for me to work at his company, Niton, during my gap year.

When Jon Batiste talked about working with Stevie Wonder and Randy Newman, I thought about my own experience with Lee Grodzins. Lee impressed on me the societal benefits of pursuing a career in *experimental* physics. He did it in words once, on that first drive from MIT to Niton in Bedford, but mostly in the example of the work he took on and the ideas he had (home radon detection kits, lead paint detection and mitigation are top-of-mind for me, but he had countless other ideas and inventions). Lee was very much an optimist and saw the best in everyone. I recall a political discussion with him that year, in which he pointed out that everyone *thinks* they're doing the right thing – very few people are actually evil. And he showed me, in that intangible way that Batiste talks about, holistically, how to be an experimental physicist.

Lee passed away in March at the age of 98. The last time I saw him was in August of 2024 when I was in the Boston area to drop off Maggie for her freshman year at Wellesley. Due to Covid-19, six years had passed since our previous meeting, so I made a point of telling him how much it meant to me to have learned physics from him at MIT and at Niton, and the joy of catching up with him periodically over the years in between. The night before his memorial service, for which I had volunteered to speak, I realized how short my interaction time with him had actually been. I was going to be the person there with the shortest "working" time with him (one semester + one year); yet it would have been unthinkable *not* to speak, given his outsized influence on me.

After the memorial service, some people mentioned that they had hoped that someone would explain the neutrino helicity experiment to a non-technical audience. Clash Bowley, one of my colleagues from my year at Niton "volunteered" me to do it for Newton Day this year. That was my going-in plan this year, but it turns out that Lee already did 99% of the work in a conference proceedings paper from 2018 (published in 2019)[9]:

Grodzins, Lee (2019). "History of the neutrino: parity violation, first neutrino properties, muon neutrino discovery". In Cribier, Michel; Dumarchez, Jacques; Vignaud, Daniel (eds.). Proceedings of the International Conference on History of the Neutrino: 1930-2018: Paris, France. September 5-7, 2018.

As the title suggests, the paper contains the entire historical context of neutrino physics up to the helicity experiment along with some later developments. For context here, I will give a shorter, less complete accounting of that history, and then provide the (high school level) classical physics derivations for the equations that appear in the paper.

2 Technical/historical context of the neutrino helicity experiment

The Goldhaber, Grodzins, Sunyar neutrino helicity experiment (GGS1958)[5] found that all electron neutrinos, those coming from electron capture ($p+e^- \rightarrow n+\nu_e$) or positron emission ($p \rightarrow n + e^+ + \nu_e$) reactions, are left-handed ("negative helicity") – their momentum and angular momentum point in opposite directions. This is a result that is cited in particle physics text books, and it has some penetration into our broader culture. For example, long before I met Lee, I had read that this was the way to tell aliens across the galaxy how we defined left- and right-handedness. Prior to 1956, there was no reason to pursue an experiment of this type – neutrinos had never been directly detected, and there was no reason to go looking for a correlation between their momentum and angular momentum.

The existence of the neutrino was first proposed by Wolfgang Pauli in 1930 in order to satisfy conservation of linear momentum, angular momentum, and energy in β-decay, but there was no direct detection of a neutrino until 1956[1]. To give a sense of how hard they are to detect, Ray Davis's Homestake Mine experiment,[6] which used a 380,000 liter tank of perchloroethylene (C_2Cl_4) to measure the solar neutrino fluence from 1970 to 1994, detected about 3 neutrinos per week (making the detection rate on the order of 1 per millimole). In contrast to direct-detection experiments, GGS1958 was a table-top experiment that inferred the helicity of the neutrinos from the helicity of γ-rays emitted further down the decay chain.

As to why this became a measurement to pursue, we have to understand a little bit about parity nonconservation. In physics (which, of course, means in all of real life), a conserved quantity is one that doesn't change. Some examples are the total linear momentum, angular momentum and energy of a closed system. The simplest example of parity is the image in a mirror reflection. If something looks the same in the mirror as it does on our side of the mirror, it has positive parity (e.g., the letters Y,T and O in most fonts); if it looks different (e.g., F or Q), then it has negative parity. Parity conservation would mean that in any physical process, the parity of the thing we start with (e.g, a neutron) is the same as the collective parity of the things we end with (the resulting proton, electron and electron antineutrino).

In the early 1950's, physicists began to suspect that dispensing with parity conservation would allow them to understand the nature of some particle decays (the $\tau - \theta$ problem). In 1956, Tsung-Dao Lee and Chen-Ning Yang "critically surveyed the experimental information concerning this question and reached the conclusion that there is no existing evidence either to support or to refute parity conservation in weak interactions."[3] Lee and Yang proposed several experiments that could expose parity nonconservation;[2] Chien-Shiung Wu took up the challenge with ^{60}Co β-decay, and, in a brilliant experiment, which you can read about in Grodzins' 2019 paper and elsewhere, she and her team definitively observed spatial asymmetry in the β emission from polarized ^{60}Co, showing that parity was not conserved in the weak decay. Infamously, C.S. Wu was not awarded a share of the 1957 Nobel Prize in Physics, which went to T.D Lee and C.N Yang.

With parity violation an established fact from the Wu experiment, Lee and Yang hypothesized that neutrinos have only one spin state, that they are all either left-handed or right handed.[4] As Grodzins recounts in his paper, when Goldhaber returned from the 1957 Rehovoth Conference on Nuclear Structure, he laid out how they could combine the experimental techniques that Grodzins and Andrew Sunyar had been perfecting for other studies over the past two years. Before the end of 1957, they had determined, to an uncertainty of 10%, that all neutrinos are left-handed.

3 The neutrino helicity experiment in a nutshell

GGS1958 depended on two things:

1. A way to measure the polarization of γ-rays.
2. A way to ensure that the γ-ray encodes the helicity of the neutrino.

Measurement of the polarization of γ-rays was an established technique at the time. Compton scattering was known to be sensitive to the polarization of the electron spin. Sending the γ-rays through the iron core of an electromagnet, they were able to suppress or enhance Compton scattering in the forward direction by aligning the magnetic field with or against the direction of photon travel. I leave it to the reader to figure out which field direction suppresses transmission through the iron electromagnet core.

Ensuring that the γ-ray encodes the helicity of the neutrino is the magic of this experiment. Experimentally, one has no control over the direction of the emitted neutrino or that of the γ-ray from the daughter nucleus. If the γ-ray is emitted in-line with the neutrino, then

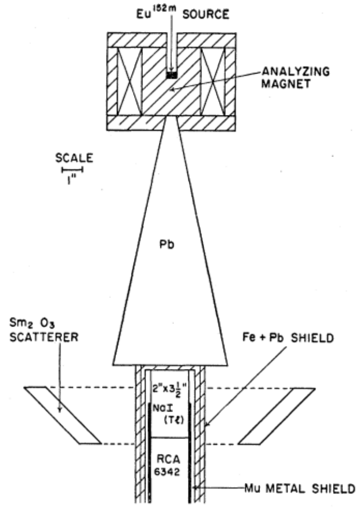

FIG. 1. Experimental arrangement for analyzing circular polarization of resonant scattered γ-rays. Weight of Sm_2O_3 scatterer: 1850 grams.

Figure 1: Experimental setup for the neutrino helicity measurement. Neutrinos are produced by the decay of ^{152}Eu into an excited state of ^{152}Sm. γ-rays are produced by the relaxation of the daughter ^{152}Sm, some of which resonantly scatter off the conical Sm_2O_3 dish into the NaI detector. The magnet analyzes the polarization of the of the γ-rays, and the magic of the decay chain ensures that only γ-rays carrying the neutrino helicity resonantly scatter into the detector. (From Goldhaber, Grodzins, Sunyar *Phys. Rev.* 1958)

it will encode the helicity of the neutrino – the same helicity if it is emitted in the opposite direction and the opposite helicity if it emitted in the same direction. As the relative angle between the two approach orthogonality, the helicity encoding is lost.

The experiment used nuclear resonance scattering (absorption and re-emission of a photon by the same type of nucleus as the emitter) to ensure that, aside from the usual Compton scattering background, it would only see γ-rays that were emitted in nearly the opposite direction relative to the neutrino. In the simplest picture of emission and absorption, an excited nucleus emits a photon which carries all of the energy from that transition. An identical nucleus in the ground state can absorb that photon and then re-emit it again. In reality, the photon loses a bit of energy upon emission due to recoil and needs twice the energy it lost on emission in order to be absorbed by a stationary nucleus. Luckily, when the neutrino is emitted in the "up" direction, the recoil it imparts on the daughter nucleus is almost sufficient to allow the emitted γ to be absorbed in the Sm_2O_3 resonance scattering dish. The remainder of the energy is provided by Doppler shifts due to thermal motions of the atoms, so the experiment is only sensitive to γ-rays that encode the helicity of the neutrino!

4 Applications of (mostly) classical physics in the GGS1958

Lee's 2019 paper contains four equations on pages 6 and 7 that can be easily derived from classical physics: the energy lost or needed by the photon on emission or absorption, respectively; the recoil velocity equation; the neutrino-induced Doppler shift; and the thermal Doppler shift.

4.1 Recoil

The "energy lost to recoil" equation shows up at both the bottom of page 6 and the top of page 7:

$$\Delta E(963\ \mathrm{keV}) = -E_\gamma^2/(2M_{152}c^2). \tag{4.1}$$

When two objects separate without outside influence, there is some internal potential energy that is converted to kinetic energy. In the case of a nucleus, we can assume that the internal energy is vibrational or rotational. Momentum conservation governs the partitioning of energy between the two objects.

To warm up, let's first get a sense of what happens when two objects, like a bowling ball of mass M and a small rubber "superball" of mass m, are initially compressed together and stationary, then allowed to separate. I'll label the compression energy of the superball K and assume that all of that energy goes into the kinetic energies of the bowling ball and the superball. Momentum conservation tells us that

$$MV = mv,$$

where V and v are the respective speeds of the two balls. As velocities, we know that they point in opposite directions, but that doesn't come into play in this derivation, so we don't need the additional notational cruft. Notice that if $M \gg m$, then $V \ll v$. The superball gets most of the velocity, so we think of it as the "ejected" object and the bowling ball takes up the "recoil" from the ejection of the superball.

Energy conservation tells us that

$$K = \frac{1}{2}MV^2 + \frac{1}{2}mv^2.$$

Since we're interested in the recoil energy in terms of known quantities, we want to isolate $MV^2/2$ and eliminate v. The momentum equation can help us eliminate v, but first we rewrite the second term on the right, multiplying it by $1 = m/m$:

$$K = \frac{1}{2}MV^2 + \frac{1}{2}(mv)^2/m.$$

Using the momentum equation to replace mv with MV, and factoring, we have:

$$\begin{aligned} K &= \frac{1}{2}MV^2(1 + M/m) \\ &= \frac{1}{2}MV^2\frac{m+M}{m}. \end{aligned}$$

We find that the recoil energy is proportional to the fractional mass of the smaller object:

$$\frac{1}{2}MV^2 = K\frac{m}{m+M}.$$

This looks nothing at all like the equation given by Grodzins because photons are massless and neutrinos are so close to massless that in any reaction, they are relativistic. So I have to bring in a tiny bit of Special Relativity – the relationship between total energy E, rest mass m and momentum p:

$$E^2 = (mc^2)^2 + (pc)^2.$$

In the case of massless or ultra-relativistic particles, the first term on the right disappears or is insignificant, so we can simplify the energy-momentum relation to $E = pc$. The process we are considering now is a nucleus of mass M which releases a photon or a neutrino from a change in internal energy K. Let's call the energy of the emitted photon or neutrino E. From momentum conservation we have

$$MV = E/c,$$

and from energy conservation we have

$$\begin{aligned} K &= \frac{1}{2}MV^2 + E \\ &= \frac{1}{2}MV^2 + MVc \end{aligned}$$

after bringing in the momentum equation as before. We're still after the recoil energy, $\frac{1}{2}MV^2$, but now the equation is quadratic in V. There are many ways to rewrite this equation, but it's nice to see Mc^2 isolated, so let's rearrange the energy equation into

$$\begin{aligned} 0 &= V^2/c^2 + 2V/c - 2K/(Mc^2) \\ &= \beta^2 + 2\beta - 2K/(Mc^2), \end{aligned}$$

where $\beta = V/c$. Solving the above quadratic equation,

$$\begin{aligned} \beta &= \frac{-2 \pm \sqrt{4 - 4\cdot 1\cdot(-2K/Mc^2)}}{2} \\ &= -1 \pm \sqrt{1 + 2K/(Mc^2)} \\ &= \sqrt{1 + 2K/(Mc^2)} - 1. \end{aligned}$$

In the last step above, I have taken the positive root because we are looking for a positive value for β, and the term under the root is greater than 1. The expression for β is still a bit ugly. We can simplify it by using the fact that the internal energy transition K, which is on the order of 1 MeV, is much smaller than the rest mass of the 152 amu nucleus Mc^2, which is around 140 GeV, so $2K/(Mc^2) \approx 10^{-5}$. We can therefore use the Taylor expansion $(1+\epsilon)^n \approx 1 + n\epsilon$ to arrive at

$$\beta = K/Mc^2 = V/c, \tag{4.2}$$

which is the recoil equation at the bottom of page 6.

The recoil energy comes from $E_r = \frac{1}{2}MV^2$. Plugging in β,

$$\begin{aligned} E_r &= \frac{1}{2}M(c\beta)^2 \\ &= \frac{1}{2}Mc^2\beta^2 \\ &= \frac{1}{2}(Mc^2)K^2/(Mc^2)^2 \\ &= \frac{K^2}{2Mc^2}. \end{aligned}$$

Notice that this is experimental physics math, not mathematics math. Since we know that $E_r \ll K$ (by about 5 orders of magnitude), we can freely replace K (the internal transition energy) with E (the emitted energy of the photon or neutrino) to bring it into the form of Equation 4.1.

4.2 Doppler shift

The other two equations on page 7 are Doppler shifts due to the recoil imparted by the neutrino and from thermal motions:

$$\Delta E_\gamma = E_\gamma(E_\nu/Mc^2)$$

$$\Delta E_\gamma = E_\gamma\sqrt{2kT/Mc^2}.$$

Both of these are of the form

$$\Delta E_\gamma = E_\gamma(V/c), \tag{4.3}$$

which is the "experimentalist" form of the Doppler equation. Because $V \ll c$, it doesn't matter which photon energy we use on the right side, the emitted or the observed; at worst they only differ by $\sim$10 ppm. Likewise, we don't need to specify how ΔE_γ is defined – we already know that an approaching velocity corresponds to an increase in energy at the receiving end. Formally, $\Delta E_\gamma = E_{\text{observed}} - E_{\text{emitted}}$ on the left and $E_\gamma = E_{\text{observed}}$ on the right.

The Doppler shift due to the neutrino recoil follows directly by plugging Equation 4.2 into Equation 4.3.

The Doppler shift due to thermal motions comes from the kinetic theory of gases, for which you can find the derivation in any statistical mechanics text. Lee uses $\sqrt{\frac{2kT}{M}}$, the most probable velocity of an ideal gas with particle mass M and temperature T. k is Boltzmann's constant (8.62×10^{-5} eV/K). V/c from this estimate of thermal motion comes out to 6×10^{-7}, roughly a factor of 10 smaller than the neutrino recoil velocity. Is it valid to use an ideal gas model to stand in for the thermal velocity of an atom in a solid or a liquid? Maybe I'll delve into that another year. For now, take it as part of the art of experimental physics.

5 The game

Traditionally, I've come up with some game to go along with Newton Day. Instead, I'll pose a challenge: Find another decay chain in the Chart of the Nuclides which can be used to measure the helicity of a neutrino or anti-neutrino through resonance scattering. Your decay chain needs (at least) the following properties:

- An unstable isotope that decays by electron capture (ε), positron emission (β^+), or beta (electron) emission (β^-) with a half life of (at least) several hours.
- A daughter-product that is in an excited nuclear state with energy above the ground state comparable to the energy of the neutrino produced in the decay.
- The parent must start from a zero-angular momentum state, and the daughter must have angular momentum 1 to ensure that the neutrino angular momentum is encoded in the emitted γ-ray.
- The lifetime of the excited daughter product must be short enough to ensure that it does not undergo any collisions or binding energy effects before emitting the γ-ray (3×10^{-14} s for ^{152}Sm).

Let me know if you find one – Lee mentions in his 2019 paper that at the time of writing, GGS1958 remained the only resonant fluorescence measurement of neutrino helicity!

6 Conclusion

One of the times I saw Lee in the past decade, he remarked that he had lived long enough such that his life “went a good fraction of the way back to Jesus.” About 5%. When I left Niton to continue my formal physics education at Caltech, I had spent about 5% of my time on Earth working with him. In that time, I learned what one does with a degree in Physics – the breadth of possibilities, the opportunity to make the world a better place, the joy of exploration.

For the young ones – I hope that you find a mentor early on who impacts you as Lee impacted me. For the older ones – I hope that you have benefited from the masters of your craft, and that you have let them know how you have benefited from knowing them and learning from them.

Figure 2: Outside the Stata Center at MIT. (January, 2012)

Figure 3: Visiting Lee and Lulu at their home in Lexington, MA. (Photo by Masi Mbiti, July 2018)

Figure 4: My last visit with Lee in Weston, MA. (Photo by Deirdre Scripture-Adams, August 2024)

7 Postscript

Some random tidbits that don't fit into the main narrative:

None of the obituaries that I've seen for Lee mention his academic lineage. Toward the end of my time at Niton, Lee mentioned that his thesis advisor was a student of Ernest Rutherford. The anecdote he told me was that in Rutherford's lab, everyone always went home at 5 PM. None of that "working to all hours of the night" that is common for graduate students here in the US. He pointed out that the flip side of that bargain was that the students were expected to know exactly what needed to be done the next morning!

Lee's thesis advisor at Purdue University was Zhang (Chang) Wen-Yu. In 1956, just two years after Lee received his PhD, Zhang was forced out of this country due to McCarthyism. As with JPL's Qian Xue-Sen, Zhang was instrumental in building up China's technical expertise. In the obituary for his advisor, Lee notes that Zhang did physics research, "with dedication, joy and boundless optimism."[7] Everyone who knew Lee would say the same about him.

In reading up on parity violation, I was struck by how many of the people involved in that research passed away recently. In addition to Lee Grodzins in March, we lost Tsung-Dao Lee in August, 2024, Richard Garwin in May, 2025, and Chen-Ning Yang in October, 2025.

Finally, coming back to Junior lab, my professor for the spring term was Rainer Weiss. Rai and Lee were close friends from the early 1960's when Rai was finishing his PhD at MIT and Lee was a young professor. I was never as close to Rai as I was to Lee, but I received great wisdom from him as well. The last time I saw Rai was at Lee's memorial service in June; I fortunately had the opportunity to let him know how much I had benefited from his instruction. Rai passed away in late August this year.

8 Acknowlegement

Many thanks to Chris Mindas for reading all these papers with me and making himself available to me for discussions over the past few months.

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