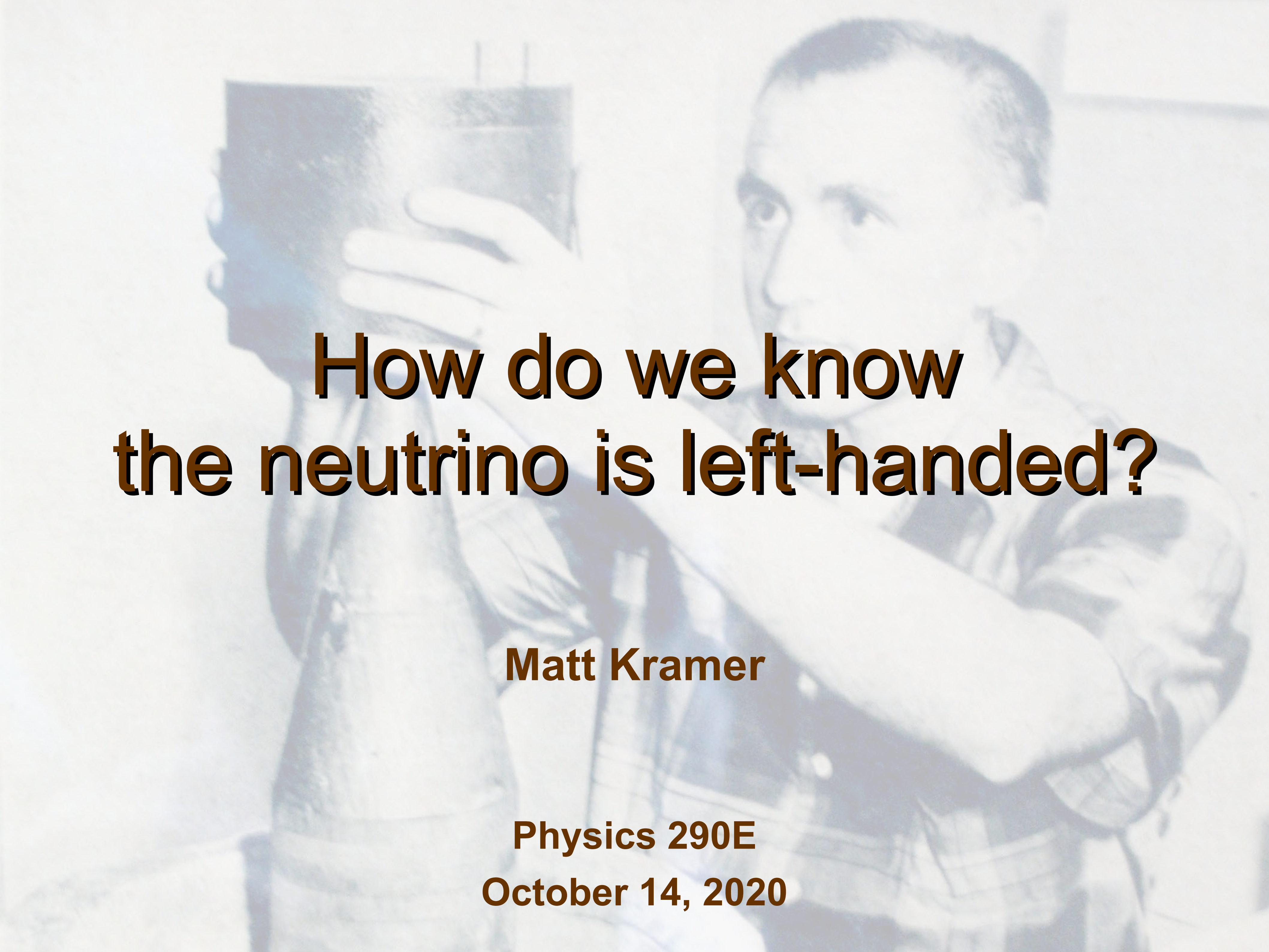

How do we know the neutrino is left-handed?

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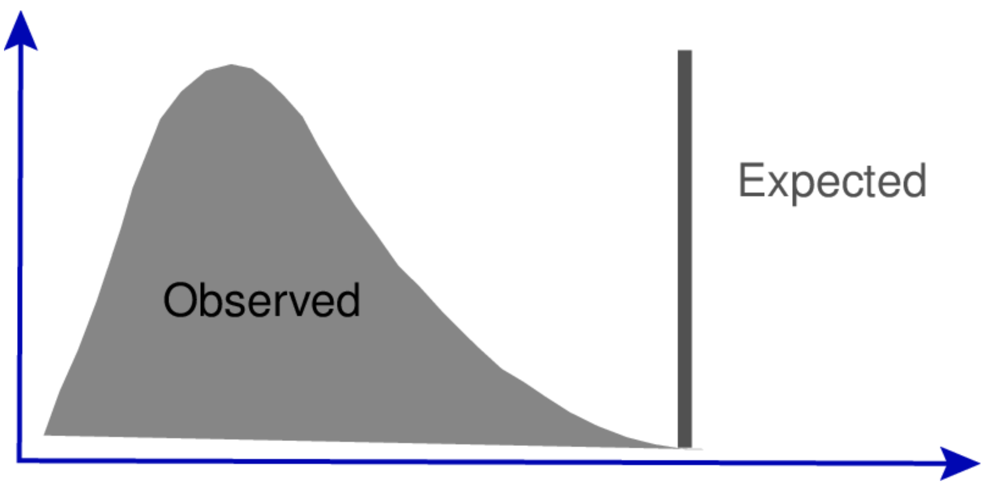
Physics 290E

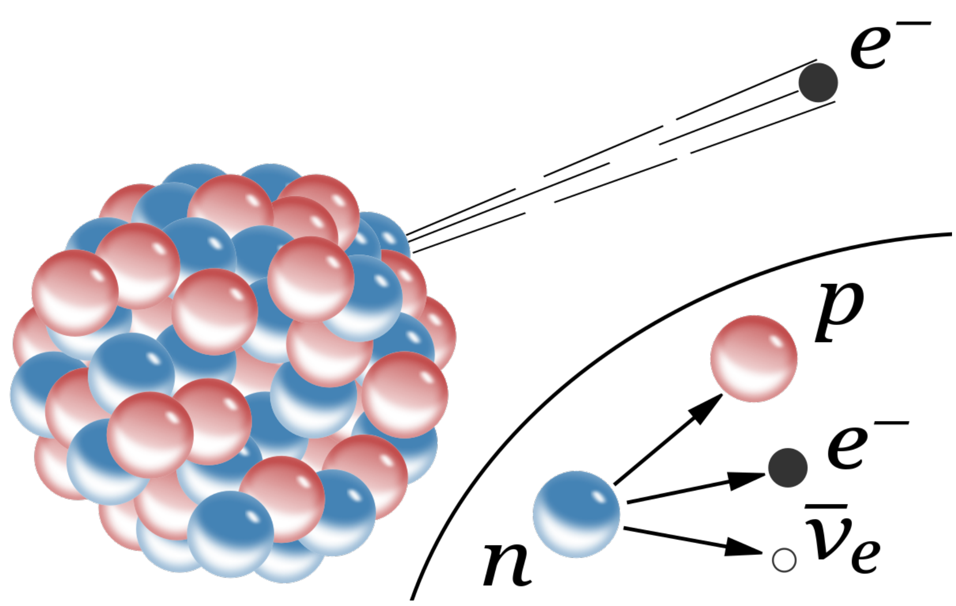
October 14, 2020

Part 1: Some history

β decay and the neutrino

- 1896: Radioactivity! (Becquerel)
- 1914: Chadwick observes continuous spectrum. Violation of energy conservation?
  - Angular momentum too, after discovery of spin
- Various crazy ideas: Statistical energy conservation (Bohr)?
- 1930: Pauli proposes the neutrino to rescue the conservation laws





Early theory of weak interactions

- 1933: Fermi theory (based on Pauli's neutrino)

$$\frac{G_F}{\sqrt{2}} \left(\widetilde{p}(x)\gamma_\mu n(x)\right) \left(\widetilde{e}(x)\gamma^\mu \nu(x)\right)$$

- Late 1940s: Universal Fermi interaction?
  - Beta decay, muon decay, muon capture:
    All seem to be governed by the same coupling constant
- 1949: Intermediate vector bosons?
- By mid-1950s: Data seemed to indicate a confusing mix of scalar, vector, tensor, axial interactions. No universal Fermi interaction?

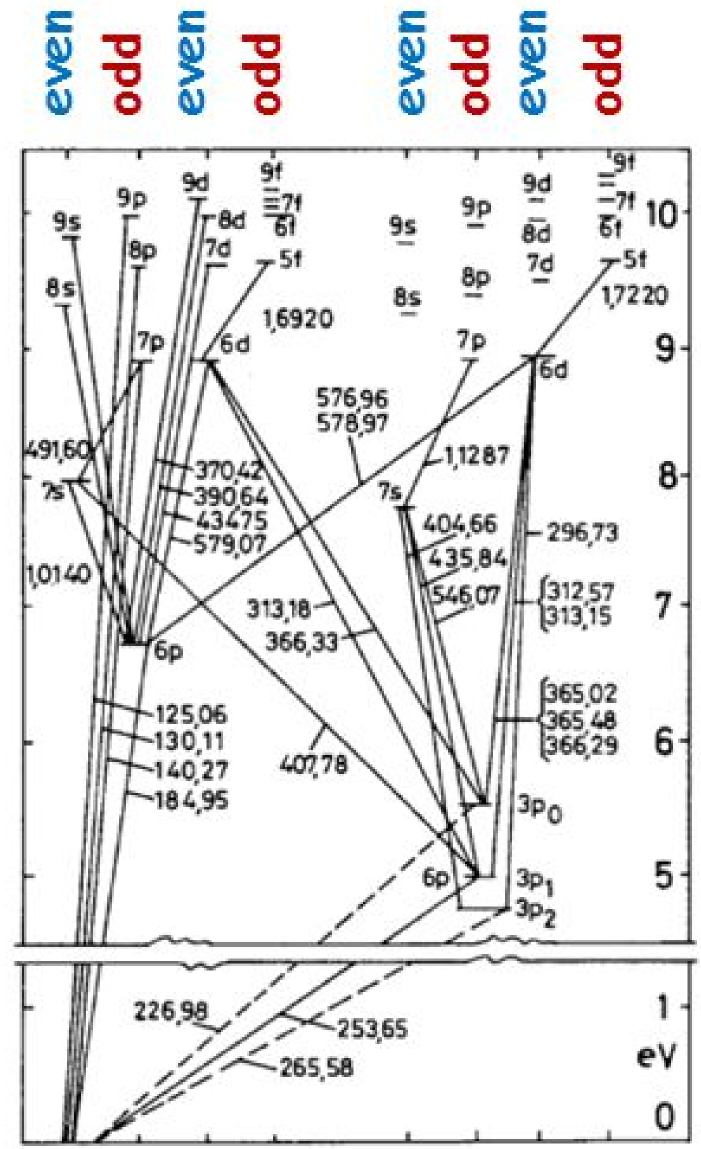
Back to 1924: A curious pattern

even → odd
odd → even
OK

even $\not\to$ even
odd $\not\to$ odd
not allowed

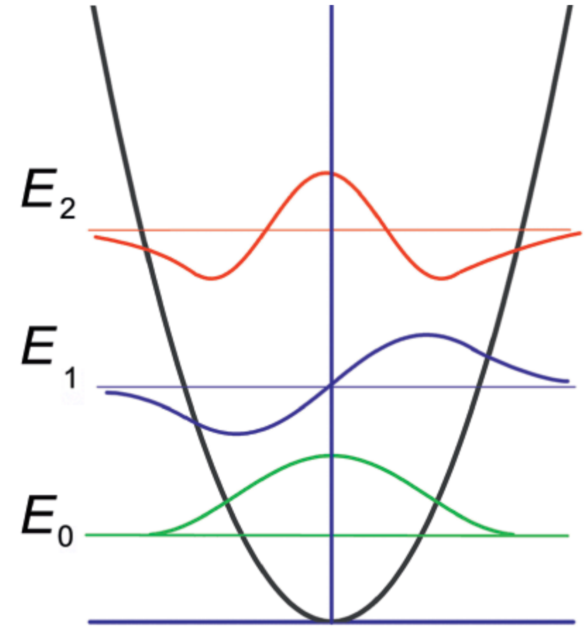
Otto Laporte, in studying the energy levels of iron, finds that they lie in two groups, “even” and “odd.”

Single photon transitions are always *between*, never *within*, the two groups. What’s going on?



1927: Parity

$$\mathbf{P}: \begin{pmatrix} x \\ y \\ z \end{pmatrix} \mapsto \begin{pmatrix} -x \\ -y \\ -z \end{pmatrix}$$



Eugene Wigner defines the *parity* operator: $P\psi(\mathbf{x}) = \psi(-\mathbf{x})$.

Each atomic level has *P* eigenvalue of 1 or -1 (even or odd).

Assuming *P* conservation, and assuming photon has negative parity (provable in QED), the Laporte rule is explained!

Parity conservation remained a "sacred cow" of physics for the next 3 decades...

A zoo of mesons

- 1947: C.F. Powell discovers the pion in emulsions exposed in the Alps and Andes
- Also 1947: Heavier mesons discovered in cloud chambers by Manchester group
  - 1955: Gell-Mann introduces concept of strangeness
- From these “strange” particles, a new mystery arose...

Mid 1950s: The θ-τ puzzle

$$\theta^{\pm} \longrightarrow \pi^{\pm}\,\pi^{0}$$
$$\tau^{\pm} \longrightarrow \pi^{\pm}\,\pi^{+}\,\pi^{-}$$

Two "strange" mesons that appeared to have the **exact same masses and lifetimes,** yet (assuming *P* conservation), **opposite parities!**

Spoiler: We now know that θ and τ are the same particle, the **charged Kaon,** and that the decay pattern results from parity violation. But back then, parity violation was sacrilege!

1956: The 6th Rochester Conference

T. D. Lee and C. N. Yang propose *parity doubling*: Strange particles appear in pairs of opposite parity.

- Doesn't work for other particles
- Doesn't explain equal lifetimes

Feynman (on behalf of experimentalist roommate **Martin Block**): *"What if parity is not conserved?"*

Lee, of Lee and Yang, answered something complicated, and as usual I didn't understand very well. At the end of the meeting Block asked me what he said, and I said I did not know, but as far as I could tell, it was still open — there was still a possibility. I didn't think it was likely, but I thought it was possible…

Lee-Yang, 1956

Question of Parity Conservation in Weak Interactions*

T. D. Lee, *Columbia University, New York, New York*

AND

C. N. Yang,† *Brookhaven National Laboratory, Upton, New York*

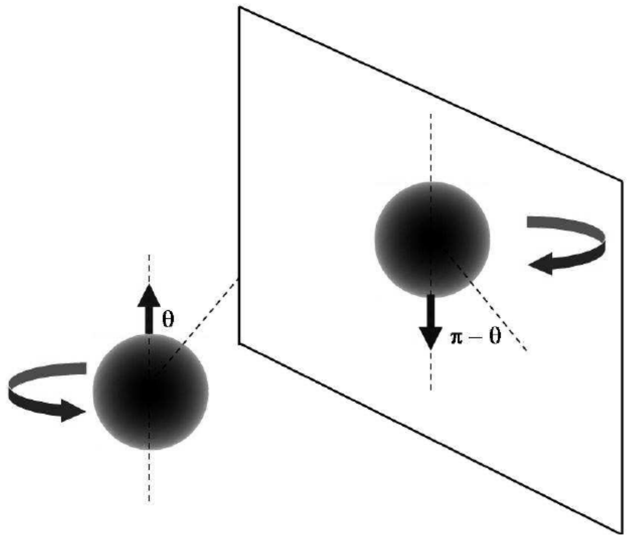
(Received June 22, 1956)

Review of experimental results: Parity *is* conserved in strong and EM interactions, but the results on weak interactions are completely inconclusive

Propose multiple methods to search for parity violation:

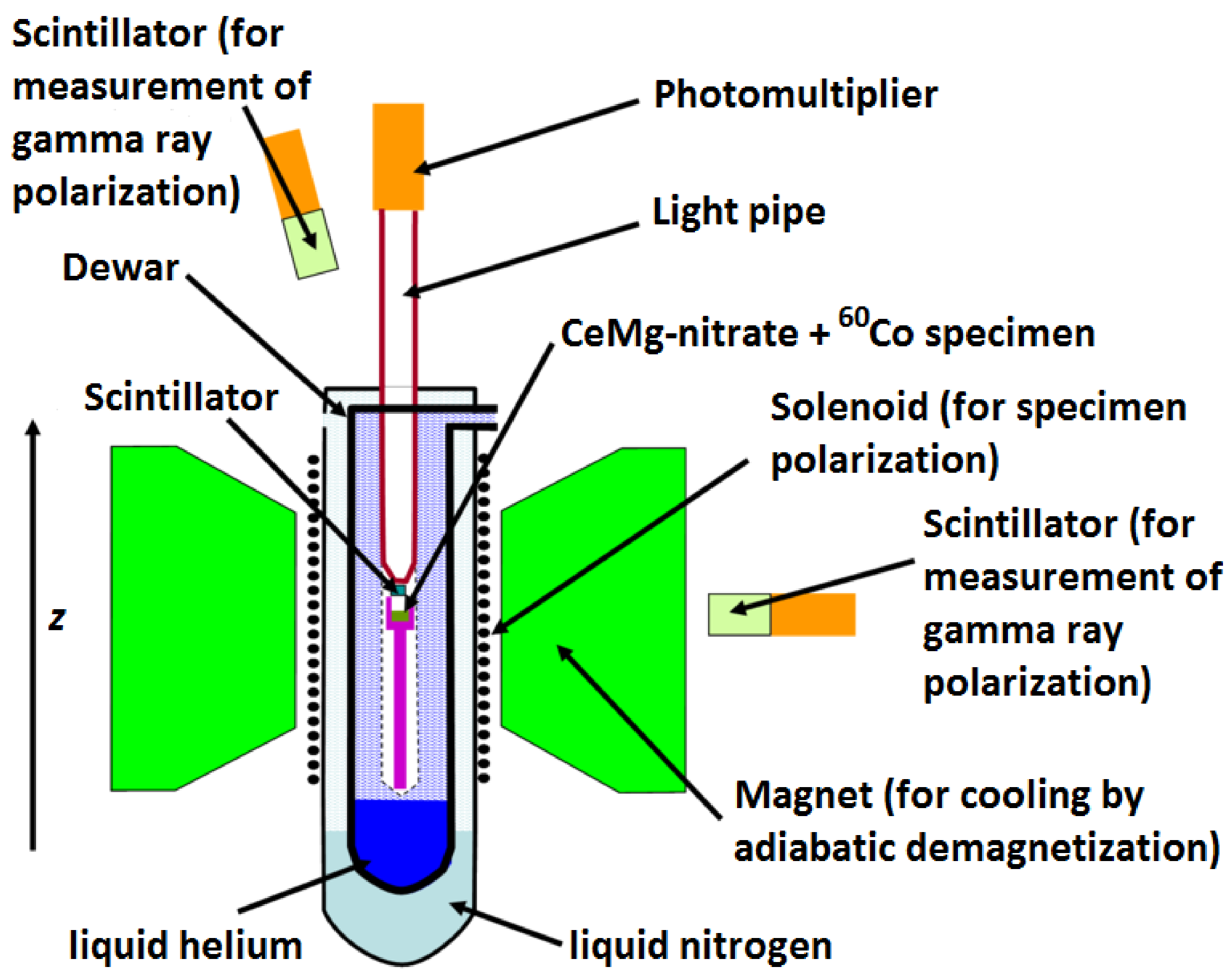
- β decay of polarized nuclei

- π → μ → e decay



Wu experiment (1956-7)

- Look for up-down asymmetry in β decay of polarized ^{60}Co nuclei
- Many challenges; six months of hard work:
  - Need strong magnetic fields. Only internal atomic fields strong enough; need a paramagnetic salt.
  - Need 0.01 K temp. to maintain polarization → adiabatic demagnetization
  - Short range of betas → need very thin layer of ^{60}Co, with scintillator in cryostat.
  - PMT operates at room temp → need to get scint. light out of cryostat
  - PMT gain can vary w/ **B** direction, biasing the results

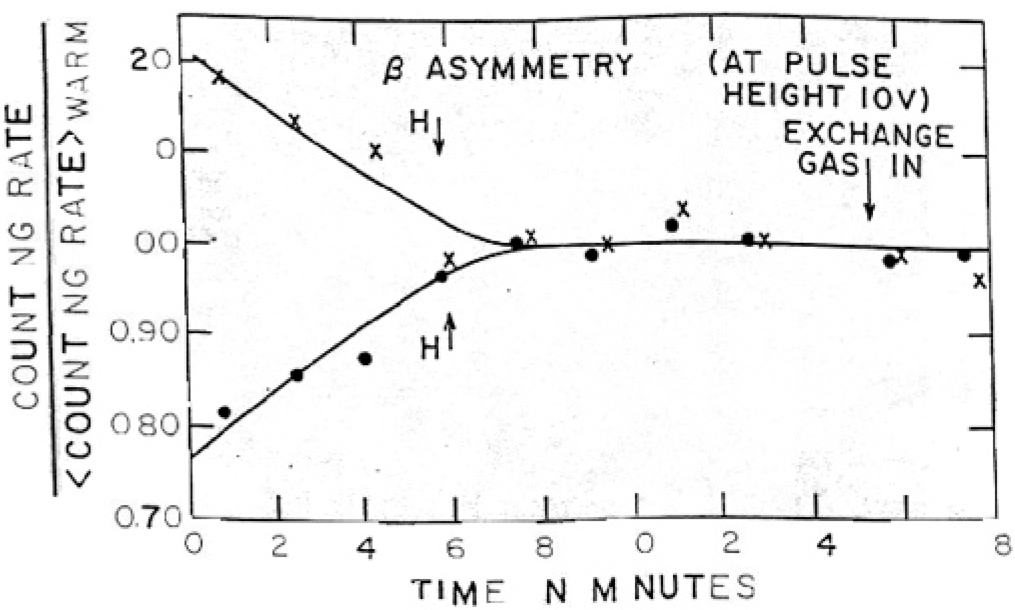


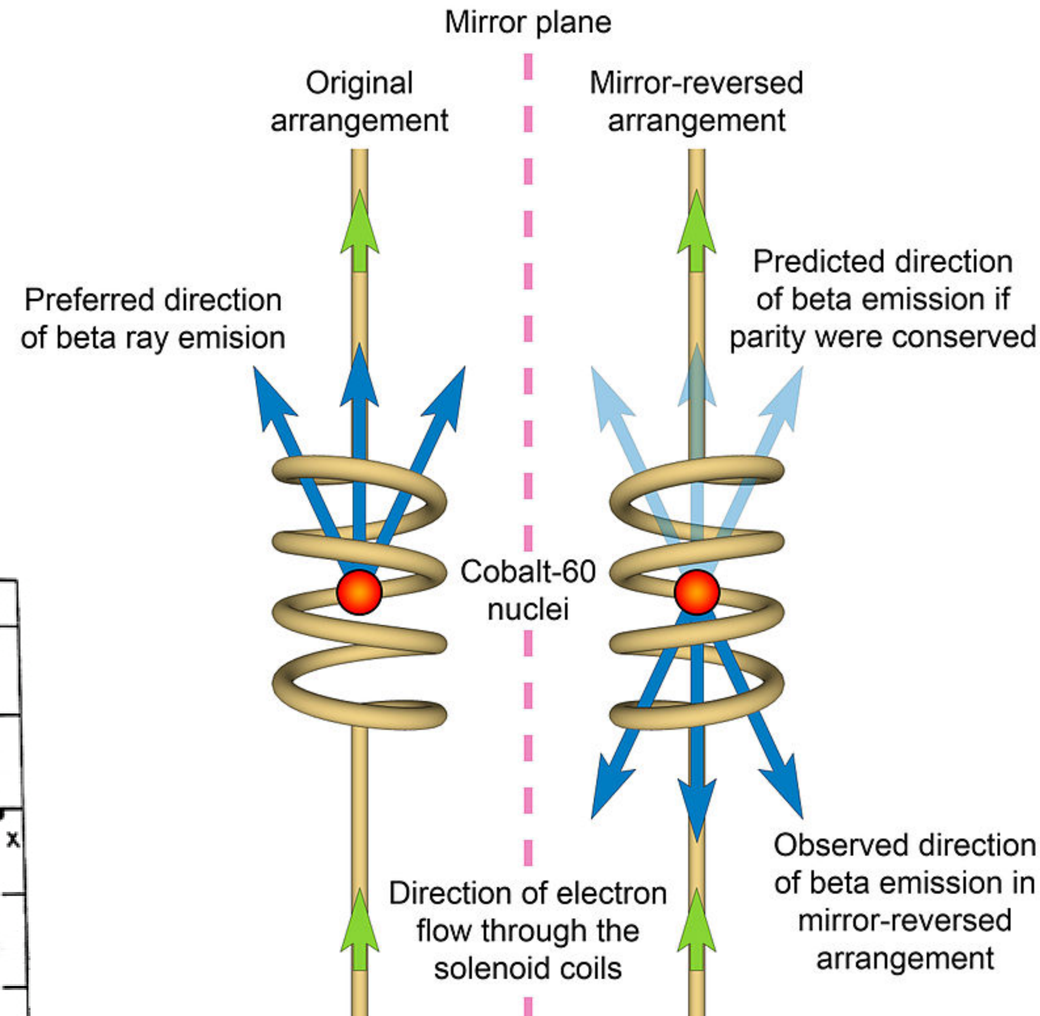
Wu's results

Initial results (Dec 27, 1956) supported parity violation, but were difficult to reproduce.

Finally, after achieving consistent results, they popped a bottle of champagne at 2 AM on Jan 9, 1957, toasting the downfall of parity

$\Delta J = -1$ + preferred e- direction →
β is left-handed



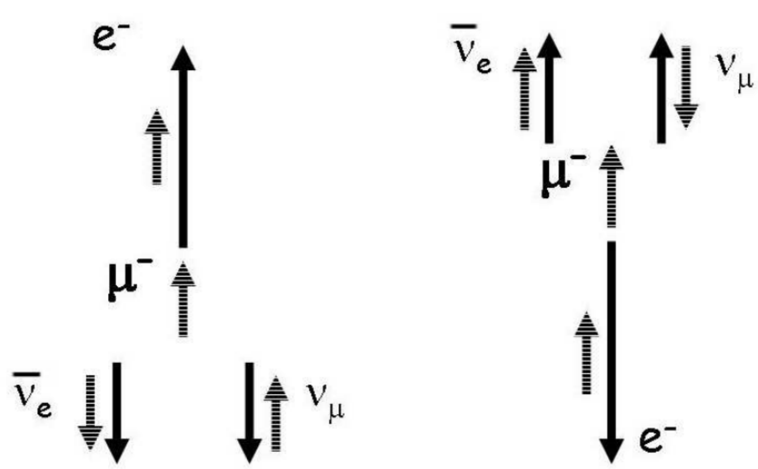


Lederman experiment (1957)

Jan 4, 1957: Lederman hears about Wu's results, realizes that Lee-Yang's proposed study of π/μ decay can be done with Columbia's cyclotron

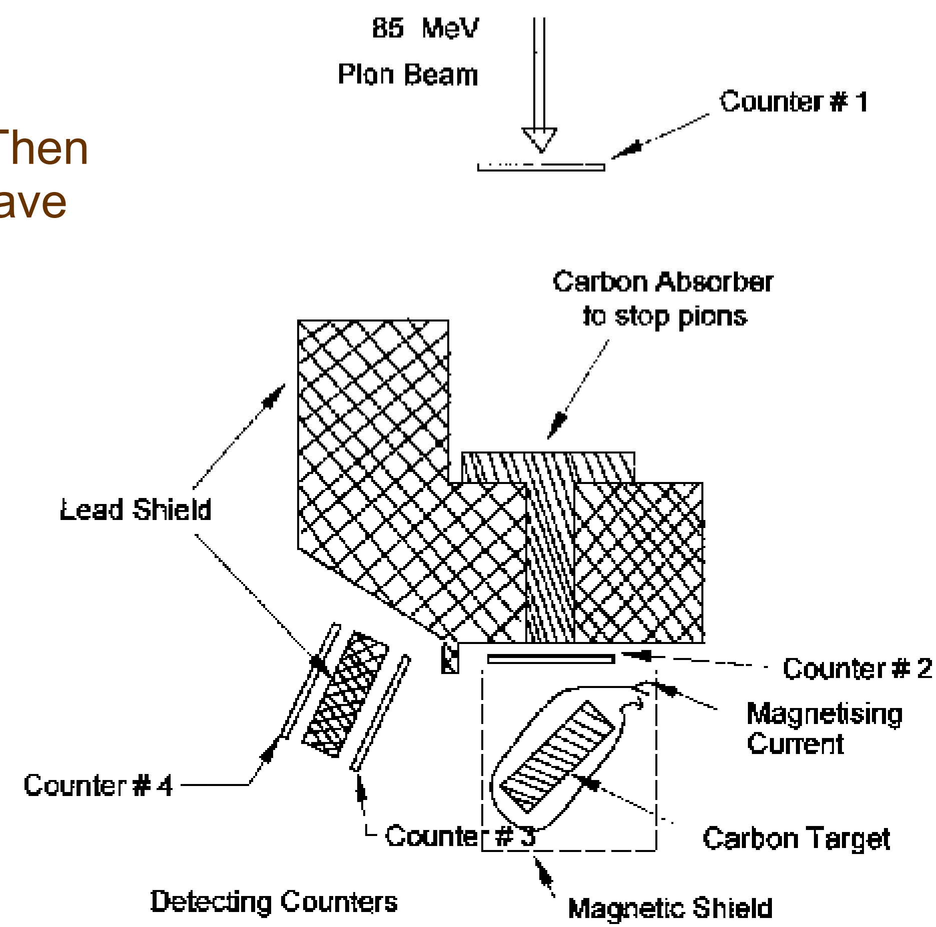
Idea: If π decay violates P, μ will be polarized. Then if μ decay violates P, the Michel electrons will have asymmetric distribution.

With Garwin and Weinrich, got results within 48 hours!



Suppressed configuration

Preferred configuration



Theoretical picture by 1958

- The most general parity-violating interaction has ten parameters (using example of β decay):

$$\sum_{i=S,V,T,A,P} (\widetilde{p}(x)\, O_i\, n(x))\, (\widetilde{e}(x)\, O^i\, (C_i + C_i'\gamma_5)\, \nu(x)) + h.c.\ ,$$

$$O_S = 1\!\!1\ ,\ O_V = \gamma_\mu\ ,\ O_T = \sigma_{\mu\nu}\ ,\ O_A = \gamma_\mu\gamma_5\ ,\ O_P = \gamma_5\ ,$$

- The V-A hypothesis: For all particles, only the left-handed component interacts weakly

$$\frac{G}{\sqrt{2}} (\widetilde{\psi}_4(x)\, \gamma_\mu \Pi_L\, \psi_3(x))\, (\widetilde{\psi}_2(x)\, \gamma^\mu \Pi_L\, \psi_1(x)) + h.c.$$

$$C_i = C_i' = 0\ ,\quad i = S, T, P, \qquad C_V = C_V' = C_A = C_A' \equiv \frac{G}{4\sqrt{2}}$$

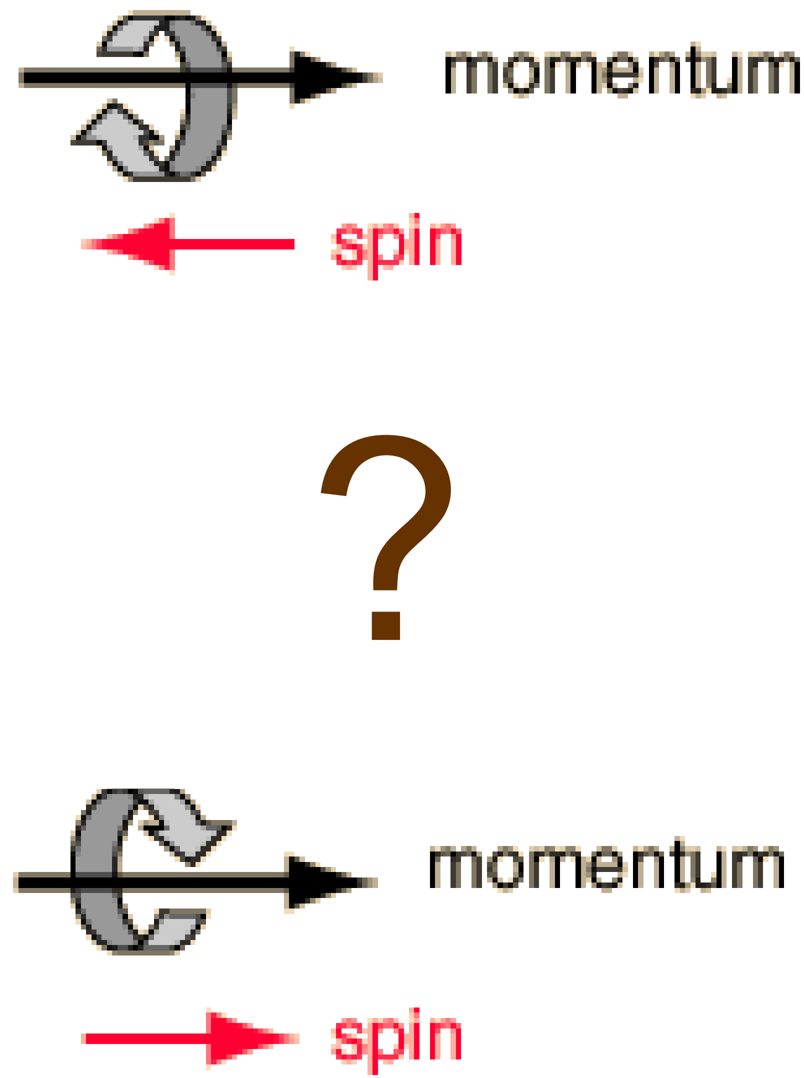
- V-A very elegant, but tension with some data on β decay
  - Marshak and Sudarshan: Those experiments should be redone!

Part 2:

The Goldhaber-Grodzins-Sunyar experiment

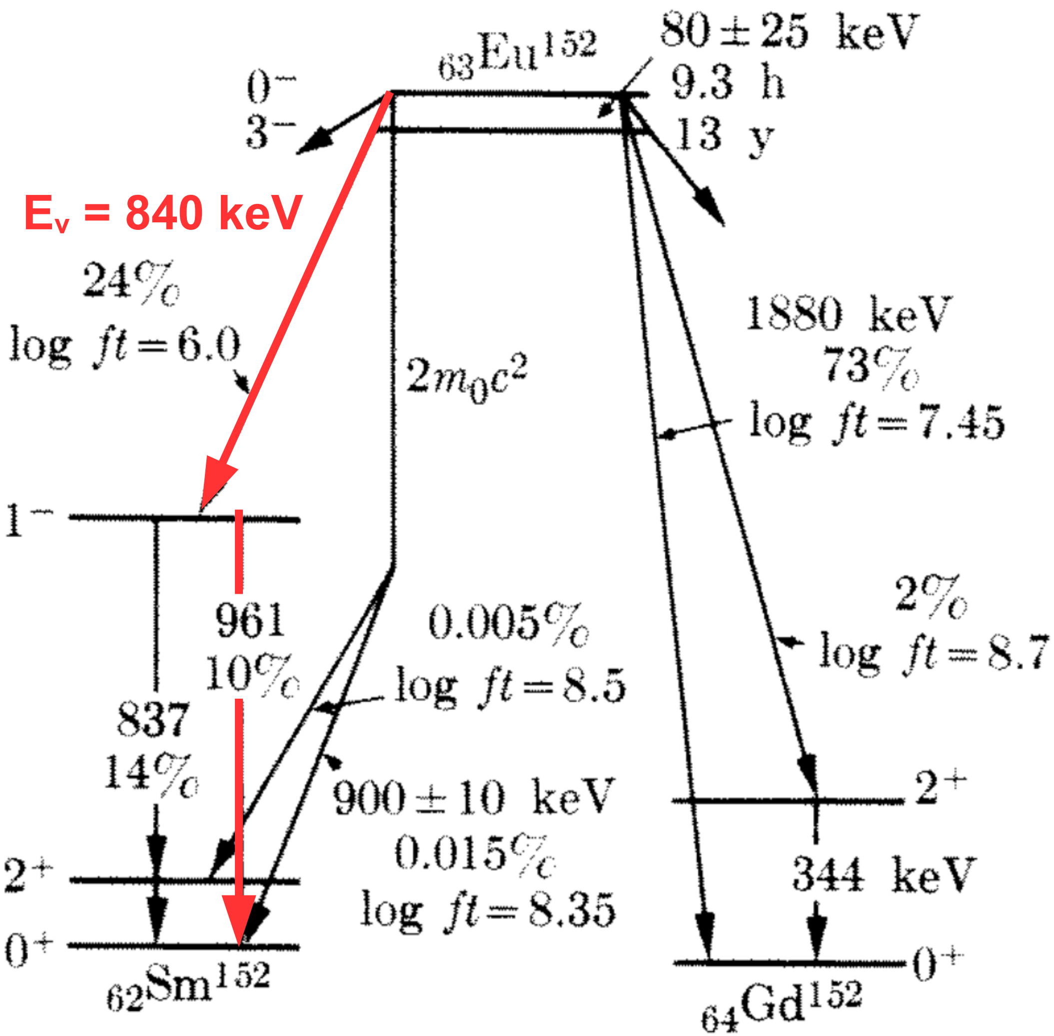
Neutrino helicity?

- To support V-A, need to confirm that neutrino is left-handed. **How to do this?**
- Can't detect neutrinos *at all* from a tabletop experiment...
- *Can* detect neutrinos from reactor/beam/sky. Polarized target might be sensitive to helicity, but need to assume a form for the interaction... circular reasoning! Never mind!
- **What if a nuclear decay were to give us something "easy" to measure (like a gamma ray) whose helicity is correlated with a neutrino's?**

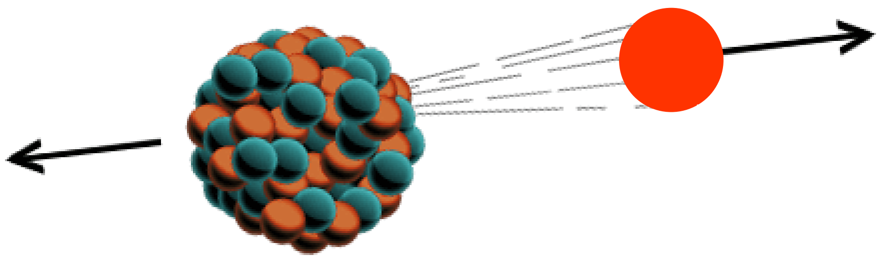


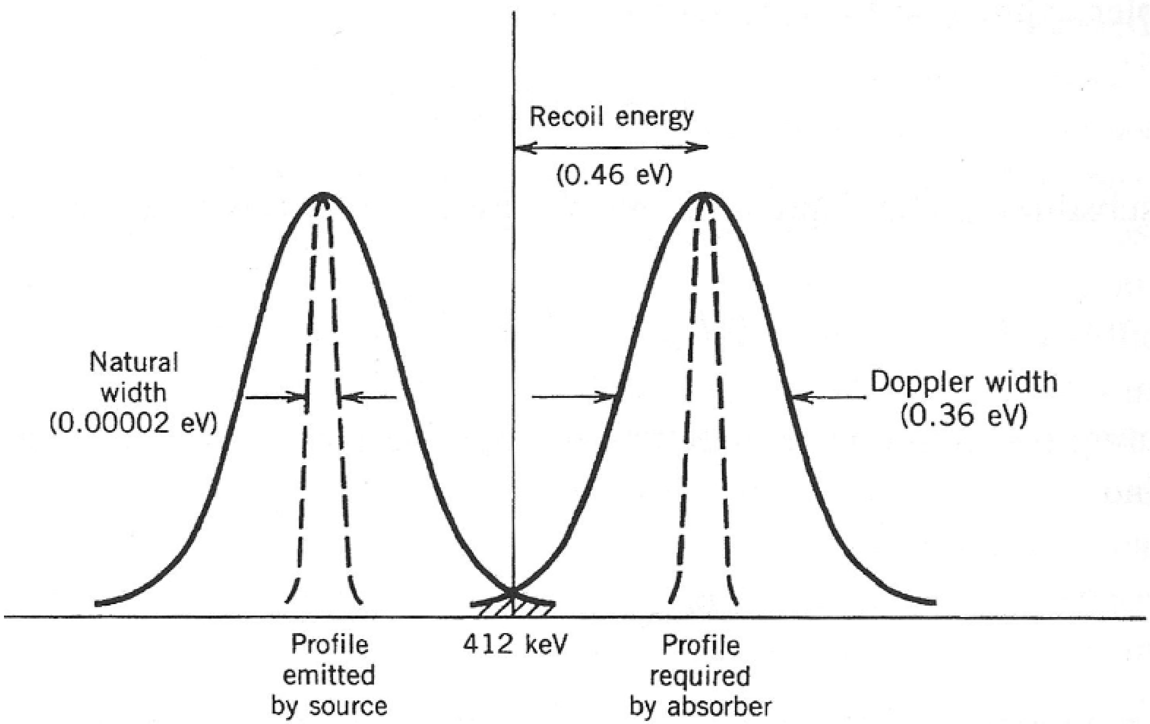
A special nucleus

- The 0^- excited state of ^{152}Eu decays via e^- capture (emitting a 840 keV neutrino) to the 1^- state of ^{152}Sm
- This 1^- state of ^{152}Sm then decays to the ground state via emission of a 961 keV gamma
- So what? The key point, as we'll see, is that **840 ≈ 961**



Nuclear recoil and Doppler shift

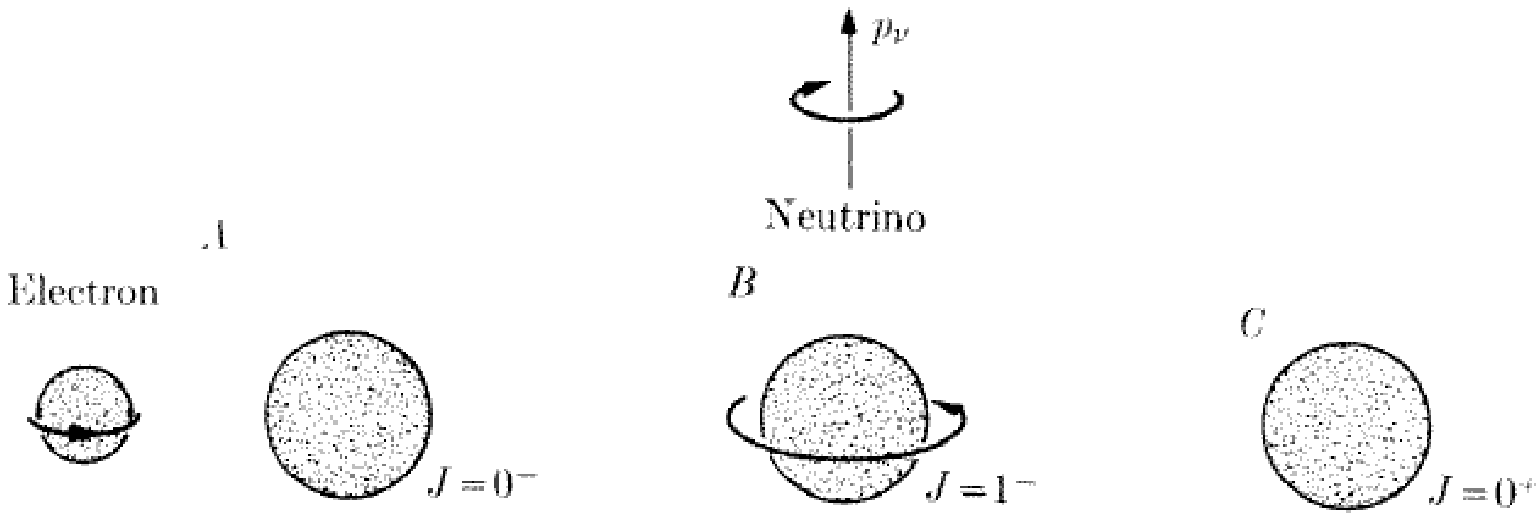




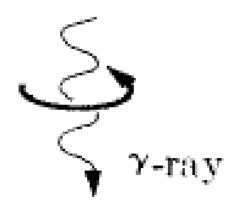
- Nuclear recoil leads to offset (Doppler shift) between gamma emission and absorption peaks, suppressing reabsorption (i.e. resonant scattering) in general
- However, when $^{152}Eu^{m}$ decays, the neutrino provides an initial recoil to $^{152}Sm^{*}$. If the gamma is emitted opposite to the neutrino, the two recoils nearly cancel
- Therefore, **a sample of ^{152}Sm will only scatter those ~961 keV gammas emitted opposite to the neutrino!**

Putting it all together

As this cartoon shows, angular momentum conservation implies that, when the gamma is emitted in the opposite direction to the neutrino’s, it must have the **same** handedness. We thus have our correlation!



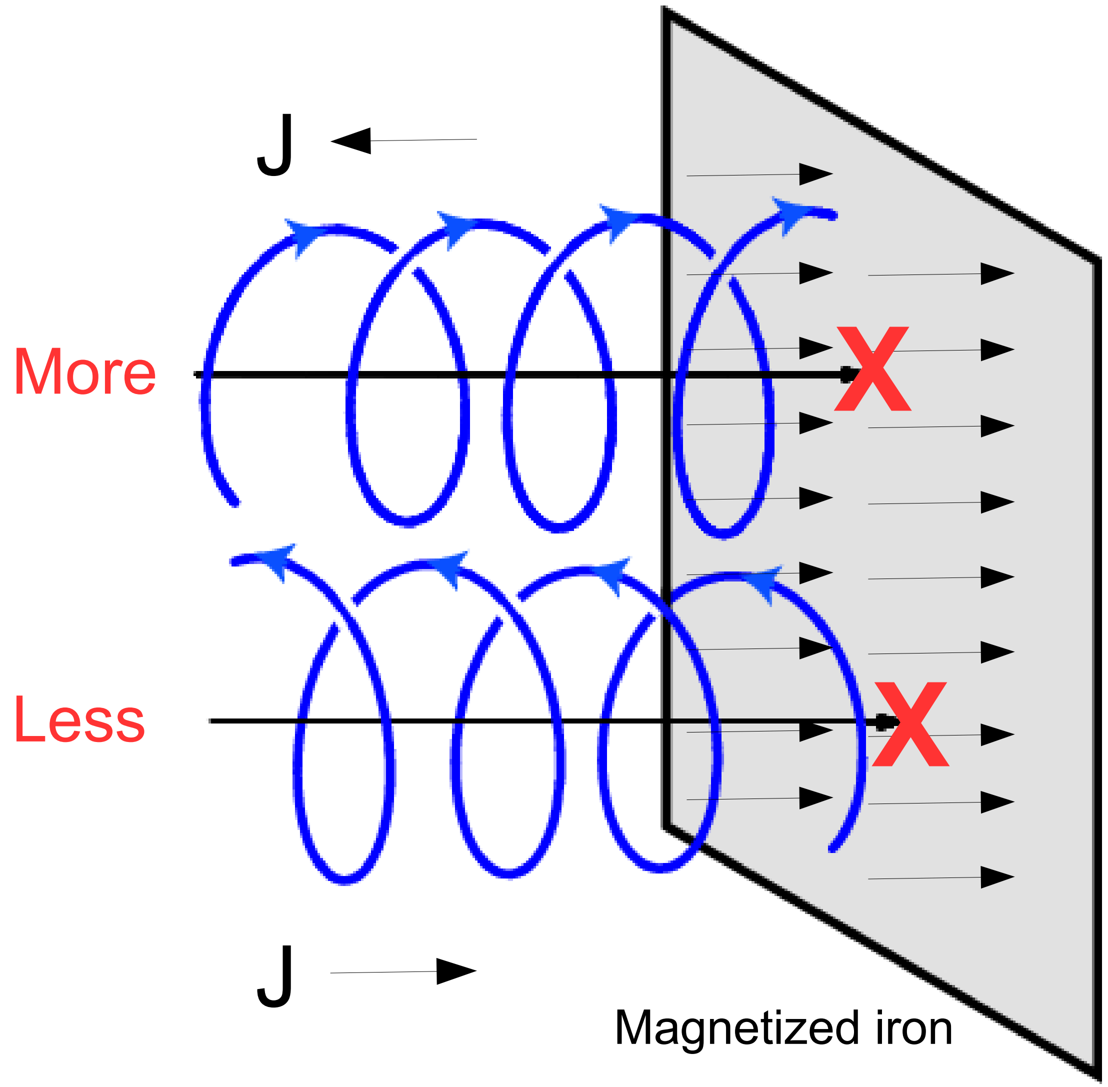
In addition, we have a way to “select” these opposite-direction gammas, since they are the only ones that will scatter in ^{152}Sm (thanks to recoil cancellation).



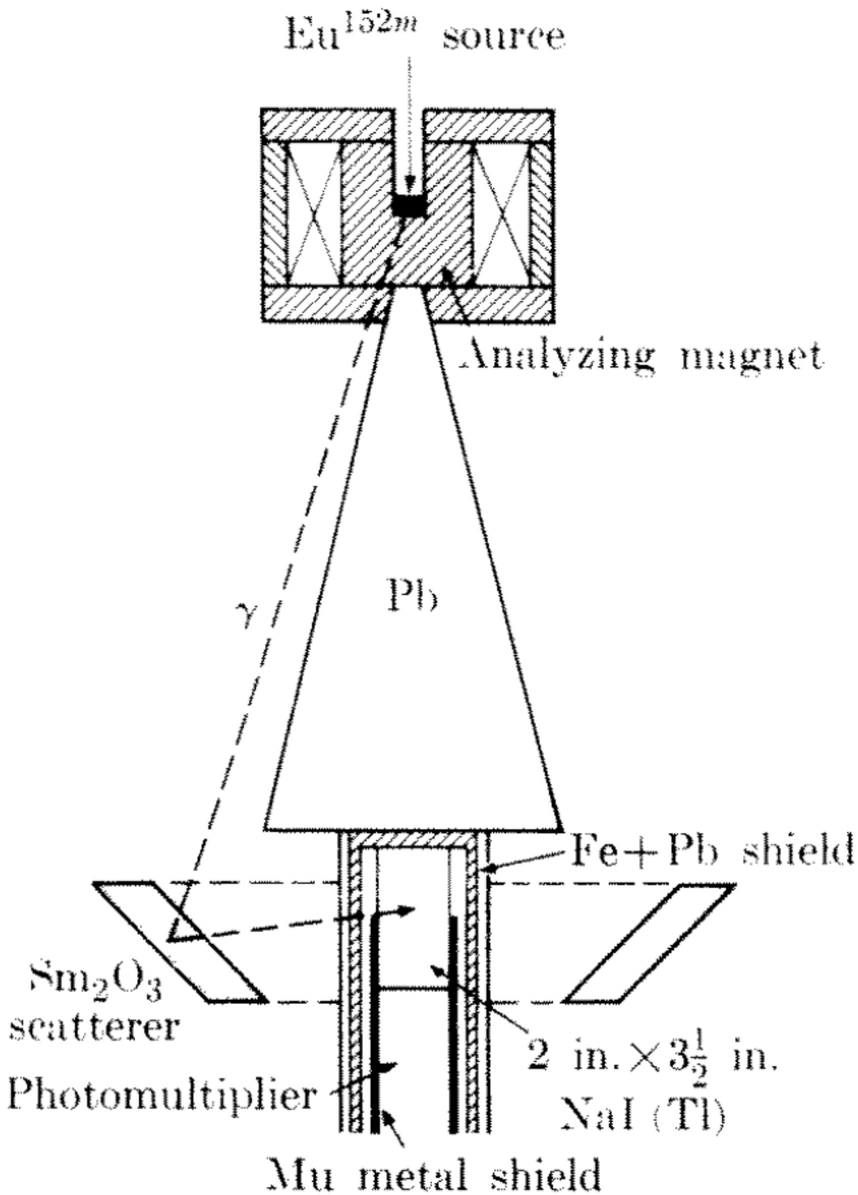
All that remains is to measure the helicity of these gammas...

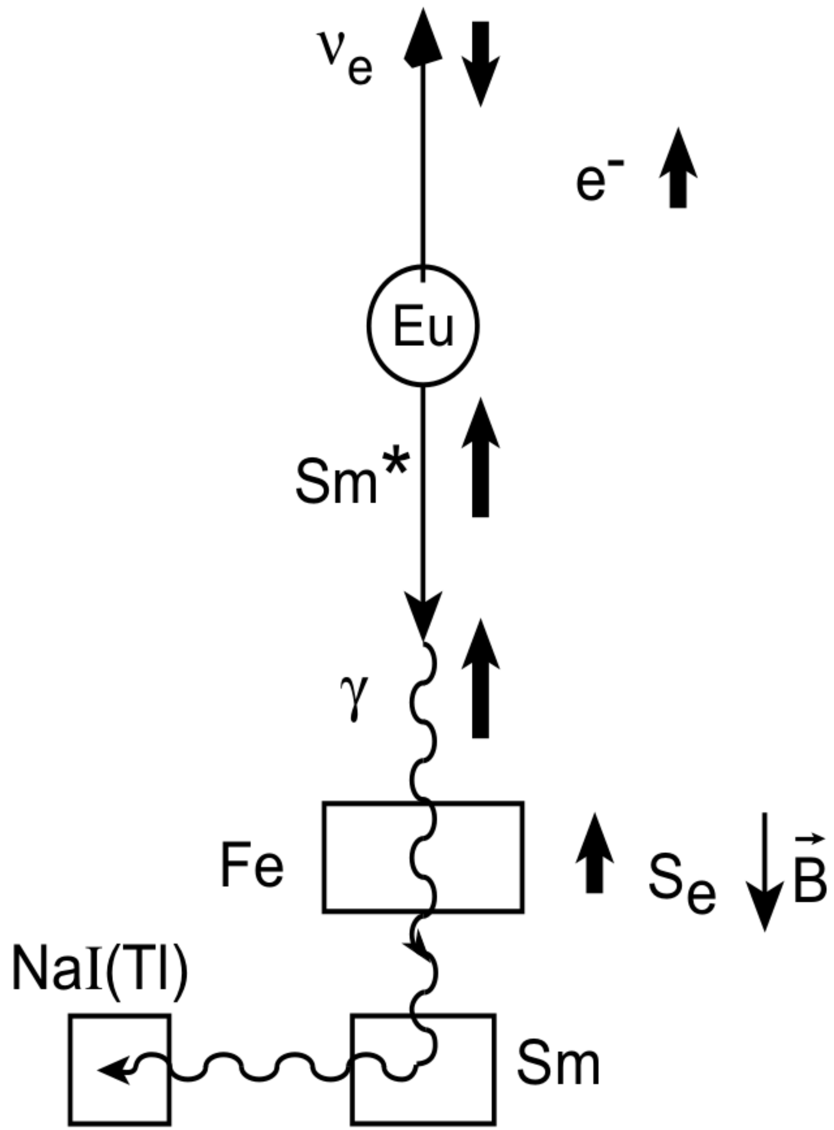
Gamma helicity measurement

- This is the easy part!
- When gammas pass through a magnetized material, those with anti-aligned spin can spin-flip an electron
- Thus the anti-aligned gammas are more likely to be absorbed
- Comparing the event rate before and after flipping **B** will then indicate the gamma helicity

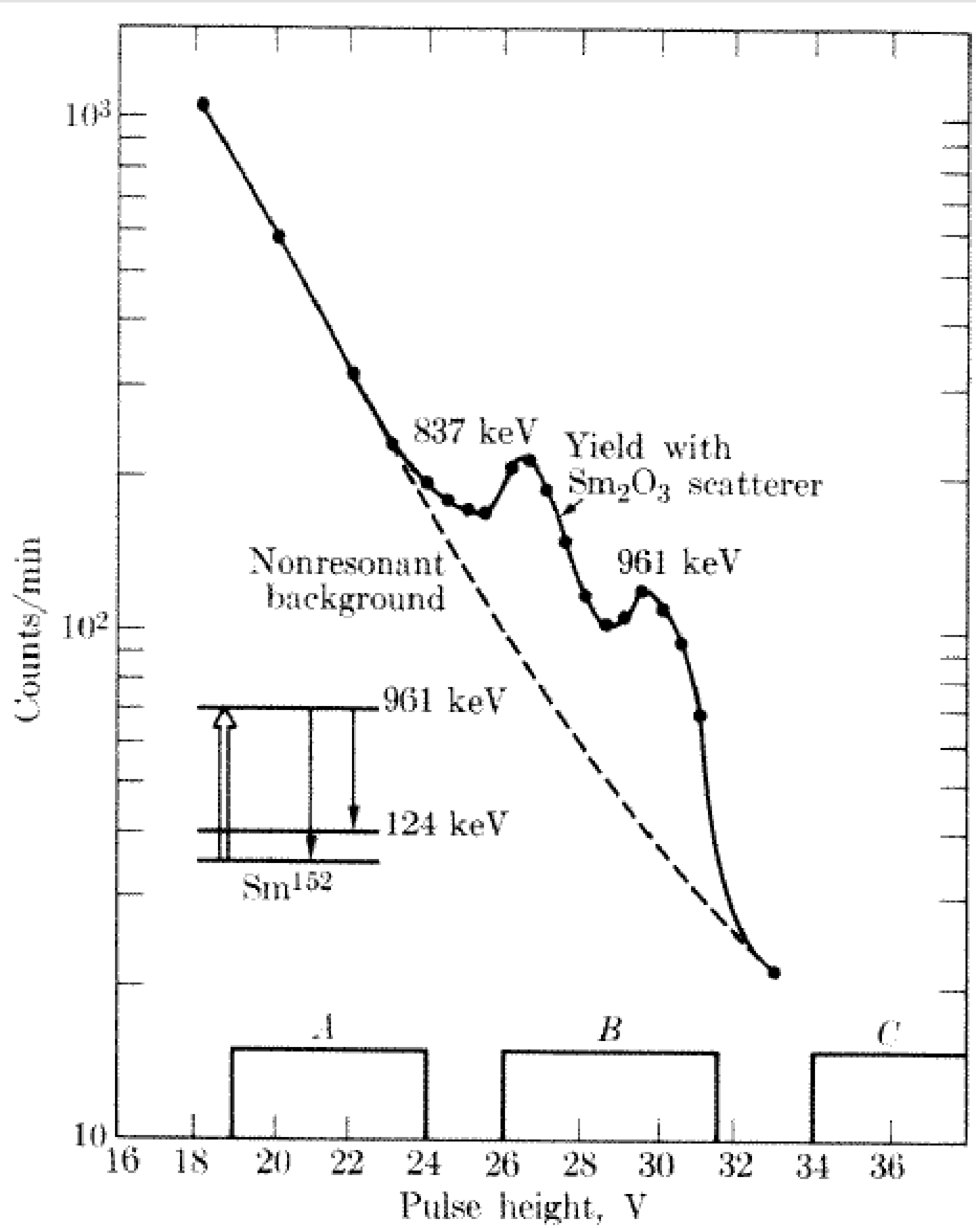


1958: The GGS experiment





GGS results



- GGS divided PMT spectrum into regions A (Compton scattering), **B (resonant scattering),** and C (background)
- They defined the quantity

$$\delta = 2\,(N_- - N_+)\,/\,(N_- + N_+)$$

where N_- and N_+ are the counts in region B for the two magnetic field orientations.

- For 100% polarized gammas, expect δ = 2.1%. Must carefully control systematics!
- They measured δ = 1.7% ± 0.3%, implying (since $\delta > 0$) a **left-handed neutrino!**

Legacy

- The direct measurement of the neutrino's left-handed helicity provided strong support for the V-A theory
- The only remaining evidence against V-A came from a handful of beta decay experiments, which were redone and found to be consistent with V-A
- Although the theory of weak interactions continued to evolve with the addition of intermediate vector bosons, electroweak unification, and the Higgs mechanism, the basic V-A structure remains a cornerstone to this day