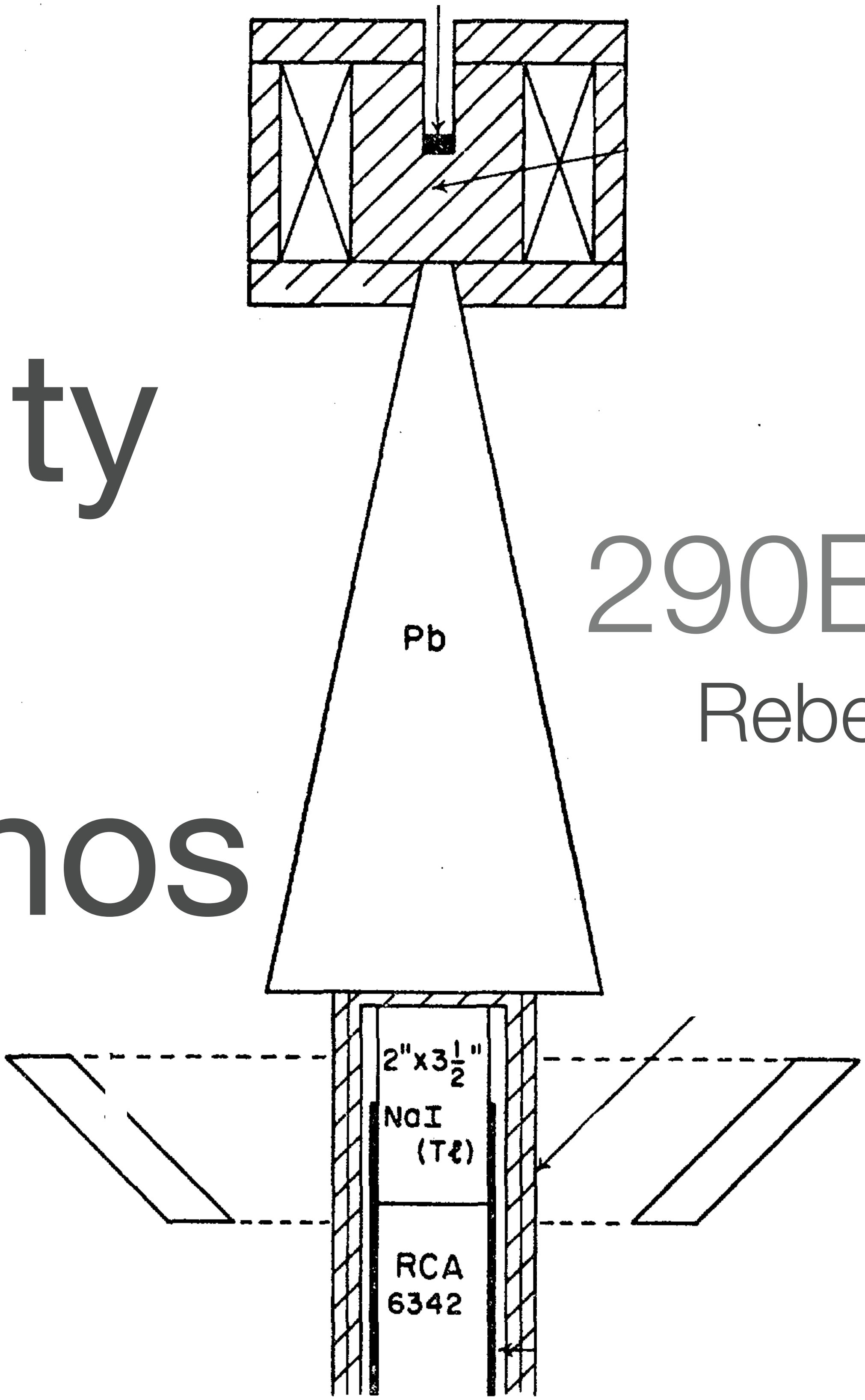
Why this experiment?

It was the right time

In a lab investigating the right techniques

With a touch of ingenuity
to put them all together



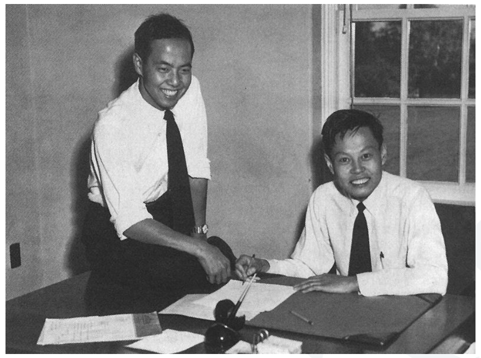
Helicity of Neutrinos

290E seminar

Rebecca Carney

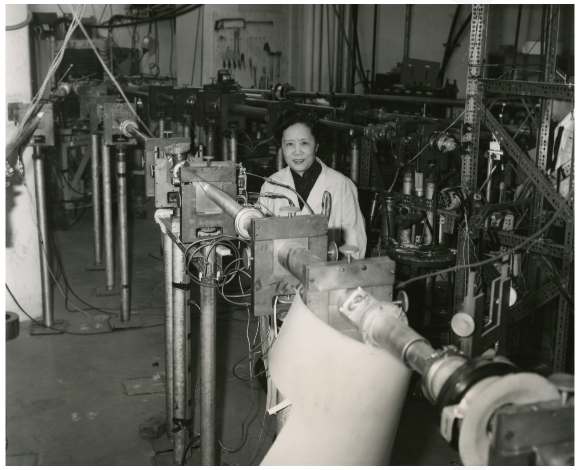
Setting the scene

June 1956



- Yang and Lee demonstrated there was no evidence that parity was conserved in weak interactions.
- So, between 1957-1960, many groups devised experiments to find the smoking gun.

January 15th-17th 1957



- Wu's team showed an asymmetrical angular distribution of electrons from the Beta decay of polarized nuclei: this was the first documented proof of parity violation in weak interactions.
- Also on the **15th**, Garwin, and **2 days later** Friedman, separately, show polarization in a muon from pion decay.

March 1st 1957

- Then, on March 1st, the polarization of the electron in beta decay, from non-polarized nuclei, was measured by Fraunfelder's team.

The state of the **lepton current**

How did the weak interaction transform under parity?

- But these experiments only narrowed down the problem. In what way did the weak interaction couple to leptons? This could be quantified by how the lepton current transformed under parity in beta decay.

ruled out by observations of nuclear spin not being conserved in beta decay e.g. He->Li Gamow-Teller transition

Type	Form	Components	"Boson Spin"
~~♦ SCALAR~~	~~$\overline{\psi}\phi$~~	~~1~~	~~0~~
♦ PSEUDOSCALAR	$\overline{\psi}\gamma^5\phi$	1	0
♦ VECTOR	$\overline{\psi}\gamma^\mu\phi$	4	1
♦ AXIAL VECTOR	$\overline{\psi}\gamma^\mu\gamma^5\phi$	4	1
♦ TENSOR	$\overline{\psi}(\gamma^\mu\gamma^\nu - \gamma^\nu\gamma^\mu)\phi$	6	2

Start off with the scalar current in expanded form: $\bar{\psi}\phi = \psi^\dagger\gamma^0\psi$

Which under parity becomes: $(\gamma^0\psi)^\dagger\gamma^0(\gamma^0\psi)$ because: $\psi \xrightarrow{P} \gamma^0\psi$

Simplify: $\psi^\dagger(\gamma^0)^\dagger\gamma^0(\gamma^0\psi),\ \gamma^0\gamma^0 = I,\ (\gamma^0)^\dagger = \gamma^0$

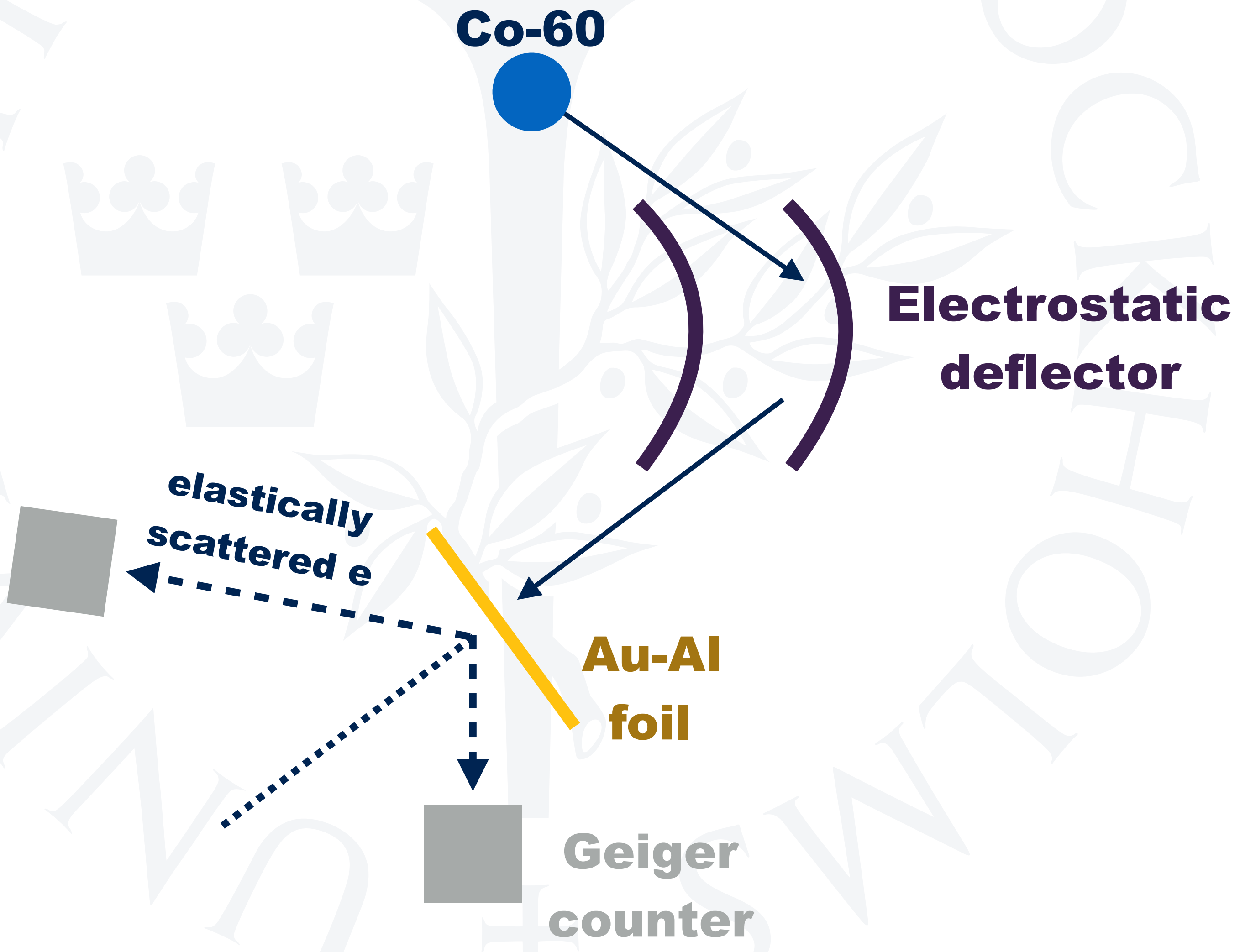
Finally: $\psi^\dagger\gamma^0\psi = \bar{\psi}\phi \qquad \therefore \bar{\psi}\phi \xrightarrow{P} \bar{\psi}\phi$

- A scalar form is invariant under parity, but linear combinations with other forms might not be.

Electron helicity

If the neutrino had a single-handedness the correct combination could be narrowed down.
In beta decay, the electron polarization was only part of the puzzle. So it an experiment was formed to measure the helicity of the neutrino.

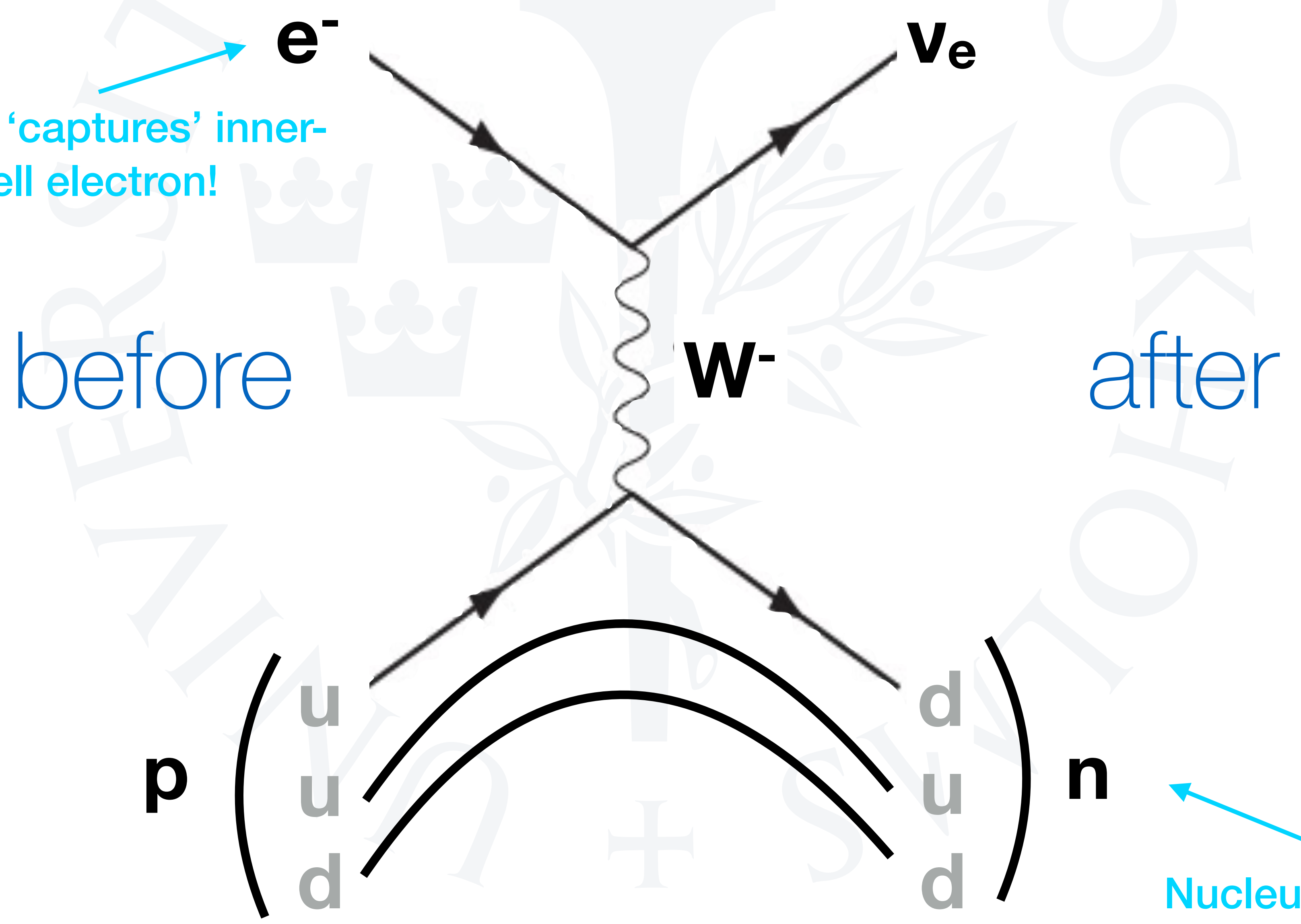
How had the helicity of the electron been measured?



But a pure scattering-counting experiment wouldn’t work for the neutrino since it interacts so infrequently (and… has no charge).

Electron capture

Instead, consider how angular momentum is conserved across a different type of weak interaction: electron capture.



Nucleus 'captures' inner-shell electron!

Nucleus left in excited state (maybe/ sometimes?)

Electron capture in **Europium**

Unstable element (stable mass is 153)

K-shell capture most common

Excited Samarium

$$\mathrm{Eu}^{152}_{63} + e^- \rightarrow \mathrm{Sm}^{152*}_{62} + \nu_{\mathrm{e}}$$

$$0^- \pm \frac{1}{2} \rightarrow \pm 1^- \mp \frac{1}{2}$$

Ground state, spin 0

K-shell, i.e. "s"-orbital defined as having no angular momentum

Both of the final states are polarized.

As both final states are polarized, they must have opposite spins to conserve angular momentum.

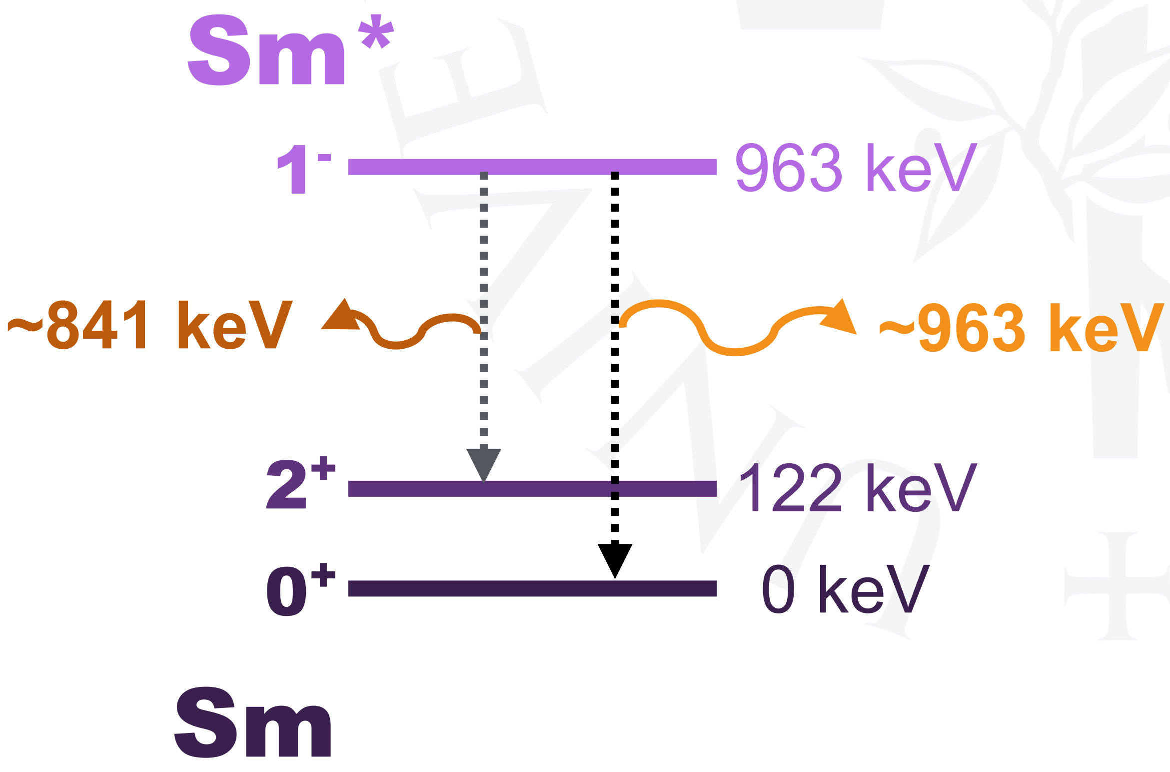
De-excitation of **Samarium**

The neutrino has disappeared, that's the last we'll hear from it in this experiment.

So what is left? An excited nucleus…

$$\mathrm{Sm}^{152*}_{93} \rightarrow \mathrm{Sm}^{152}_{93} + \gamma$$

$$1^- \rightarrow 0^+ + 1^-$$

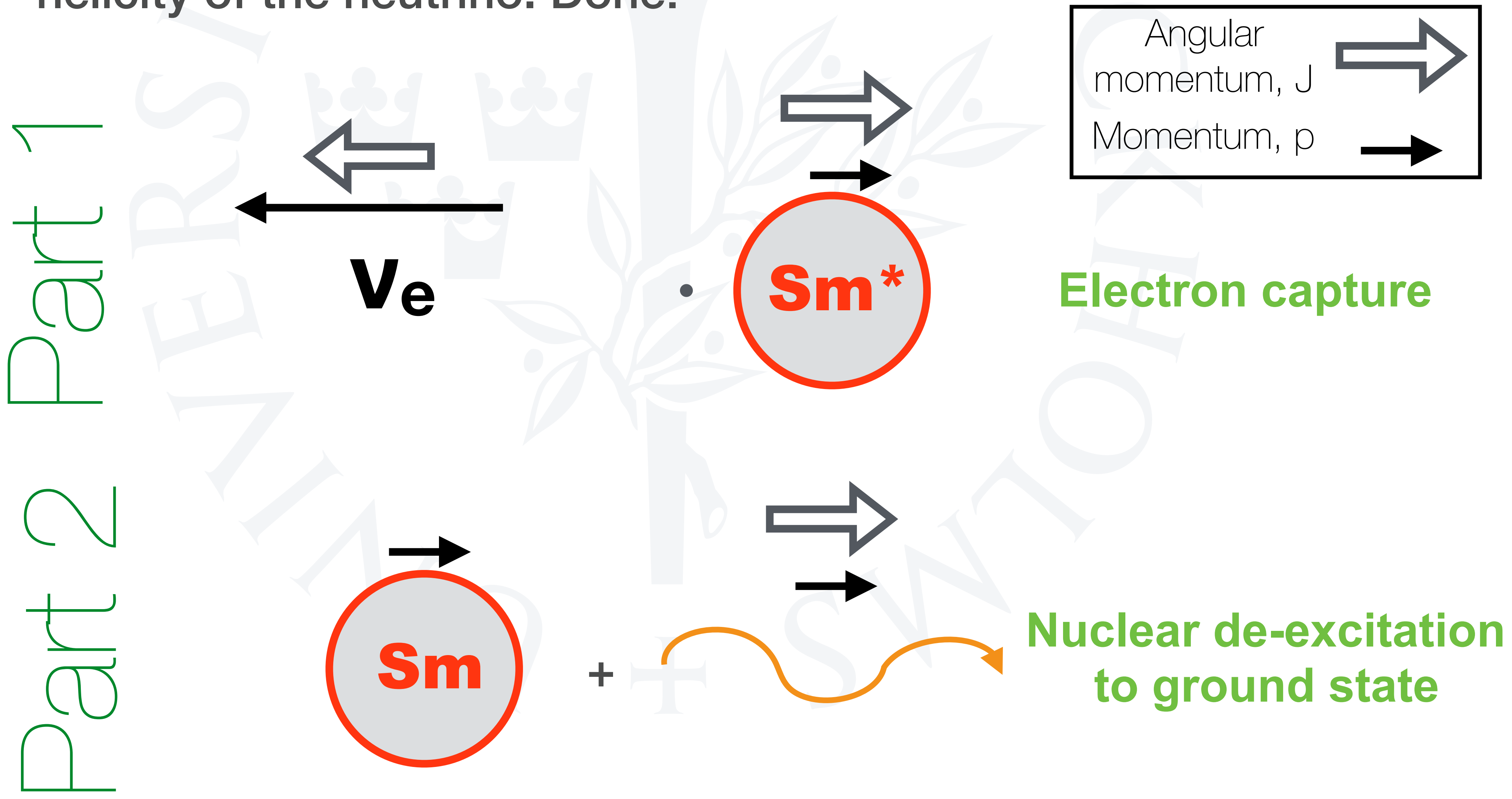


- A non-exhaustive diagram of excited states of the Sm nucleus.
- From the excited 1^- state, the nucleus can de-excite in two ways.
- Only the transition to ground state will carry away the nuclear spin.
- In 1957, only the BNL team knew the decay scheme of Sm-152!

What were we measuring again?

How does this help us?
If we know that the photon was emitted back-to-back with the neutrino, i.e. same direction as nucleus then it has the same helicity as the neutrino.

And so, measuring the helicity of the photon tells us the helicity of the neutrino. Done!



Angular momentum, J

Momentum, p

Part 1

ν_e

Sm*

Electron capture

Part 2

Sm

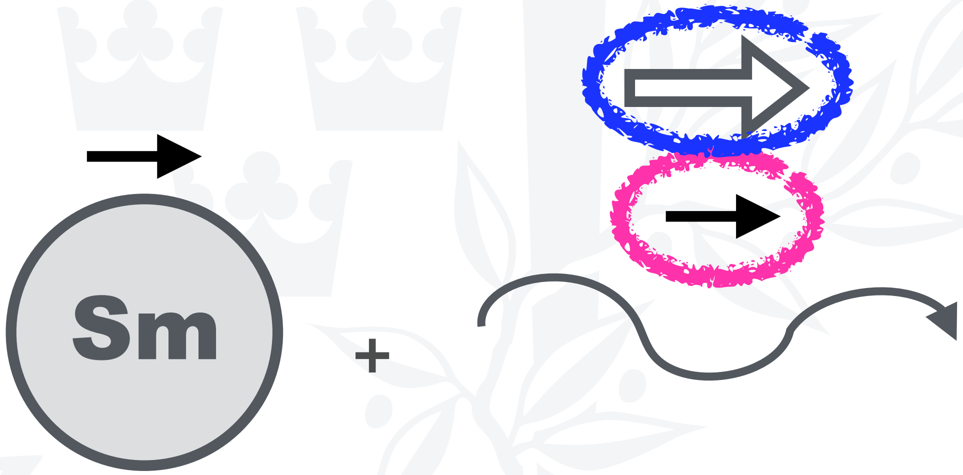
+

Nuclear de-excitation to ground state

There were some **assumptions**

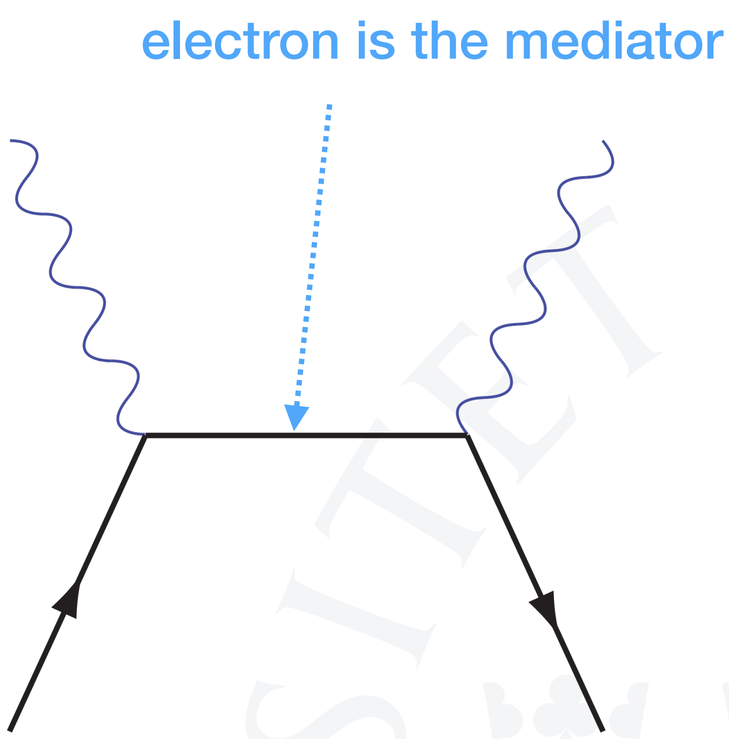
But there are various complications with this.

1. How do you measure the helicity (polarization) of the photon?
2. How do ensure the photon was emitted anti-parallel to the neutrino?



The answers to these questions are what makes this experiment so unique.

Measuring **photon polarization**

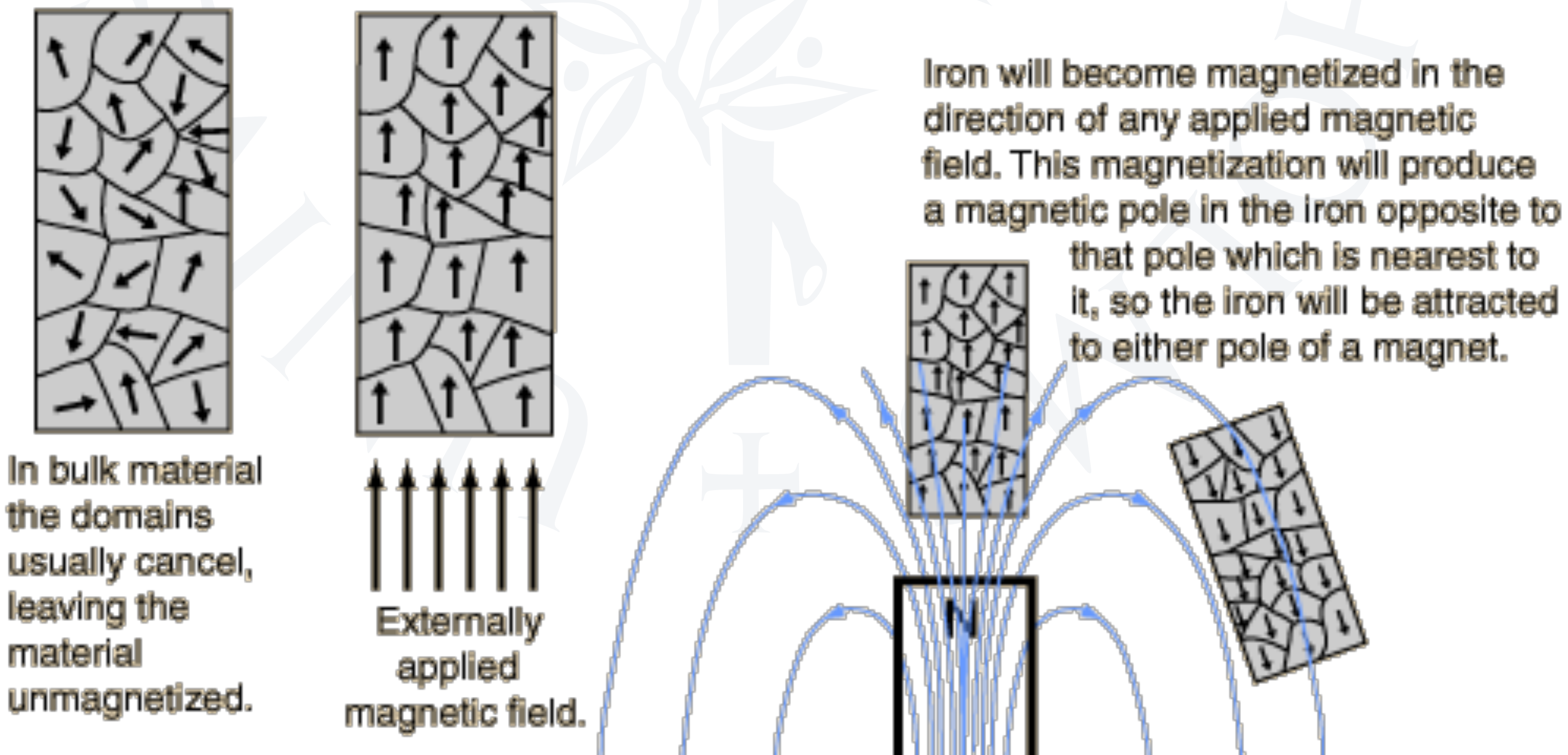


Q: How do you measure the helicity (polarization) of the photon?

A: Filters made with wave-plates are most commonly used. Disadvantages both for experiment design & b/c gamma rays

However

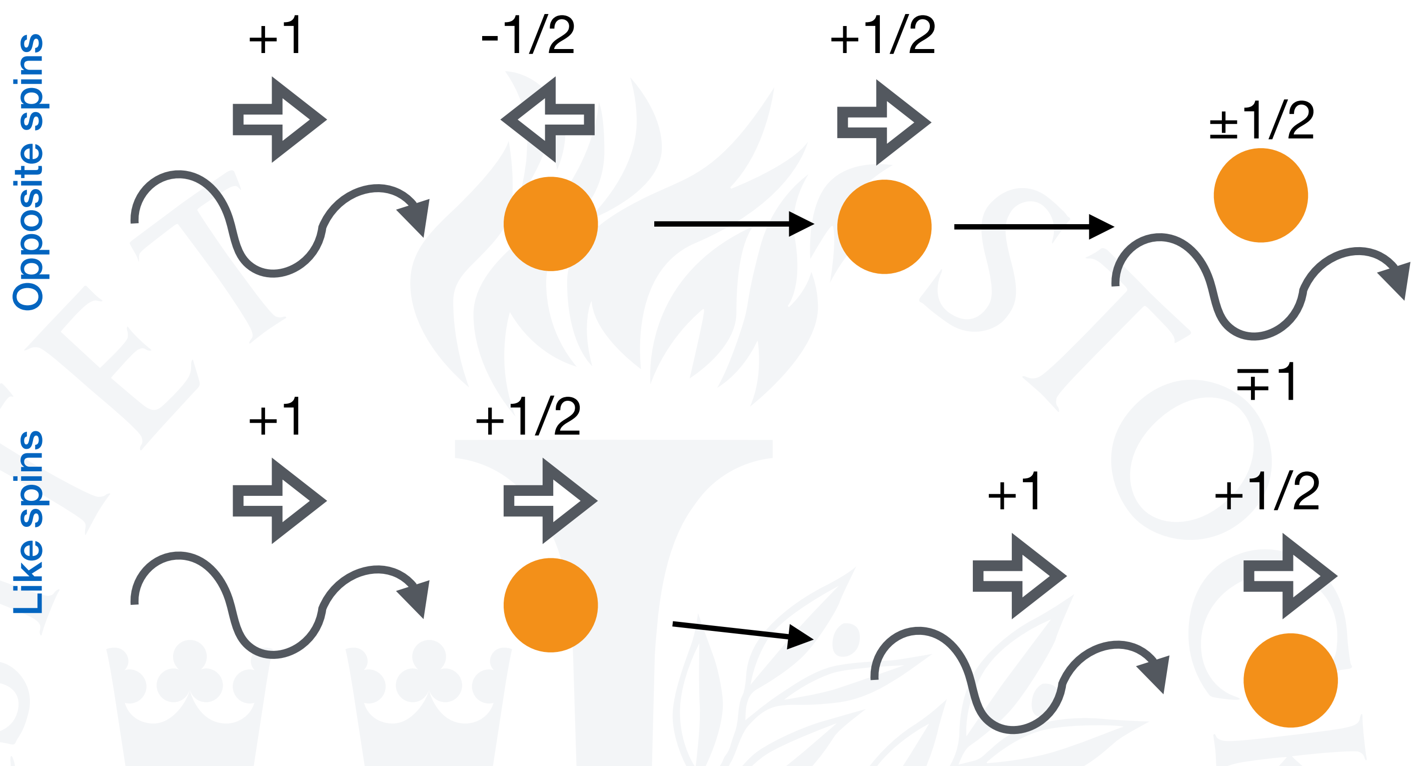
There is a spin dependence of Compton scattering off atomic electrons


In bulk material the domains usually cancel, leaving the material unmagnetized.

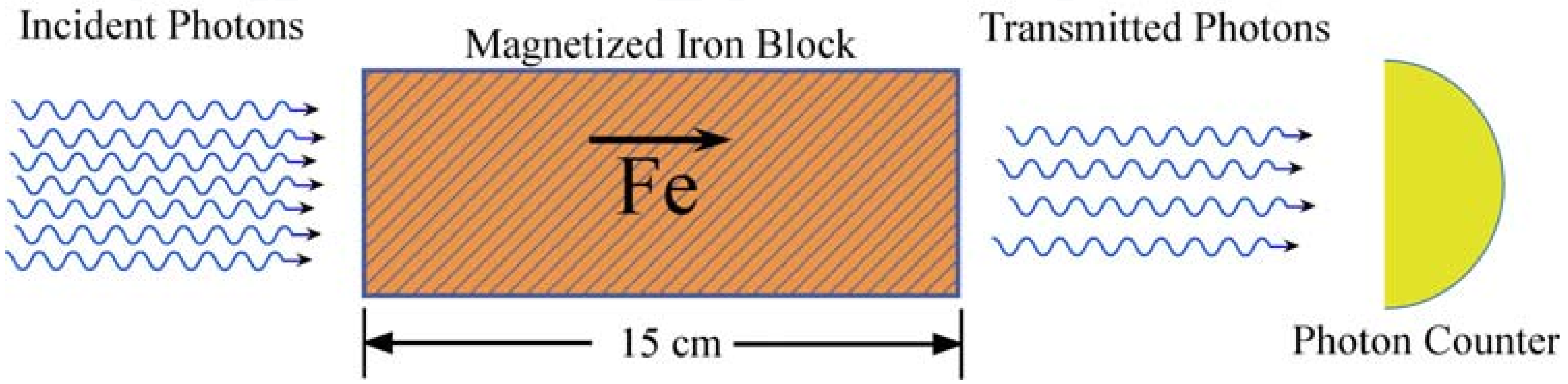
Externally applied magnetic field.

Iron will become magnetized in the direction of any applied magnetic field. This magnetization will produce a magnetic pole in the iron opposite to that pole which is nearest to it, so the iron will be attracted to either pole of a magnet.

Absorbent photon polarimeter



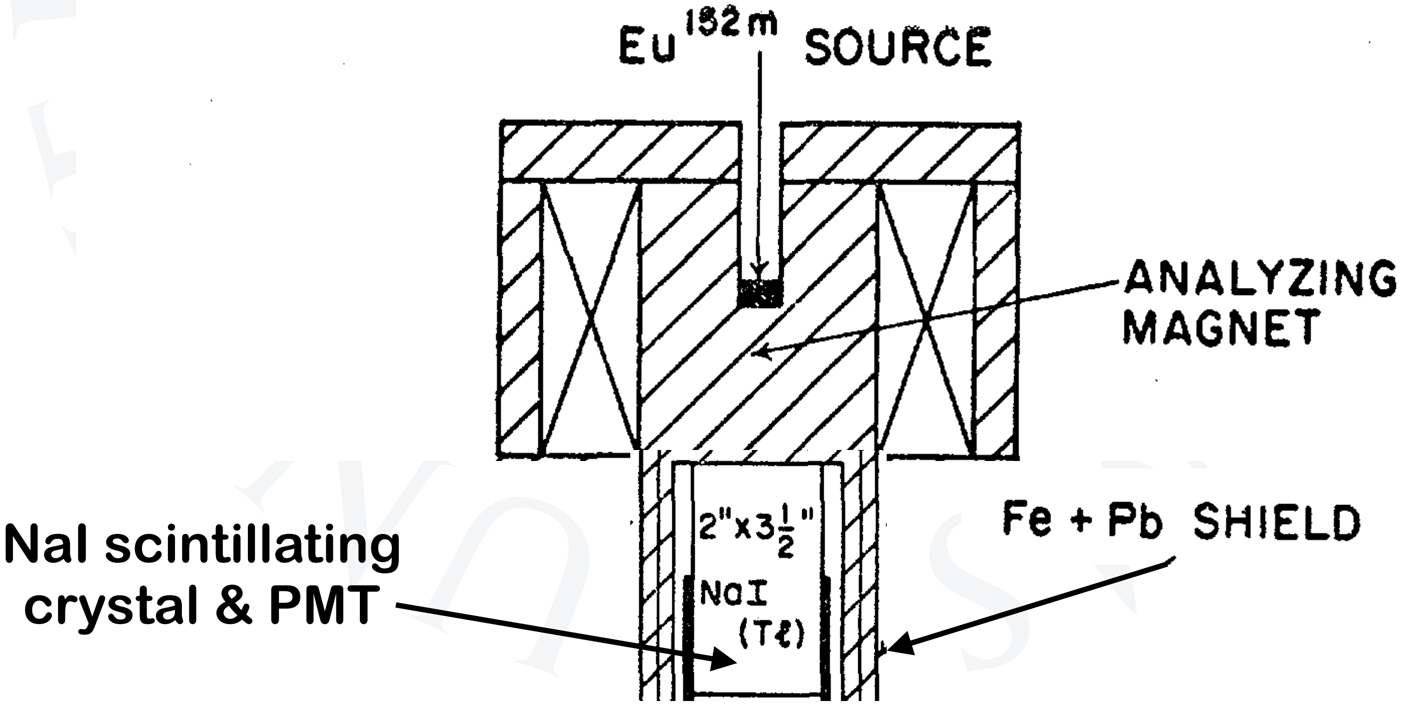
- If an electron in Fe has opposite spin to the photon: it can absorb the ang. mom. by spin-flip (top row).
- If spin is parallel, it cannot (bottom row).
- If polarized photons travel through enough magnetized Fe, more of one polarization will pass than the other.



Measurable quantity

- Measure the transmission of unscattered photons through a thick, magnetized iron absorber.
  Those with aligned spins will transmit through the absorber at a greater rate. So if there is a discrepancy in the amount produced it will be seen.

- This, then, is your measurement: a simple counting experiment looking for a discrepancy in the number of LHP vs. RHP photons.

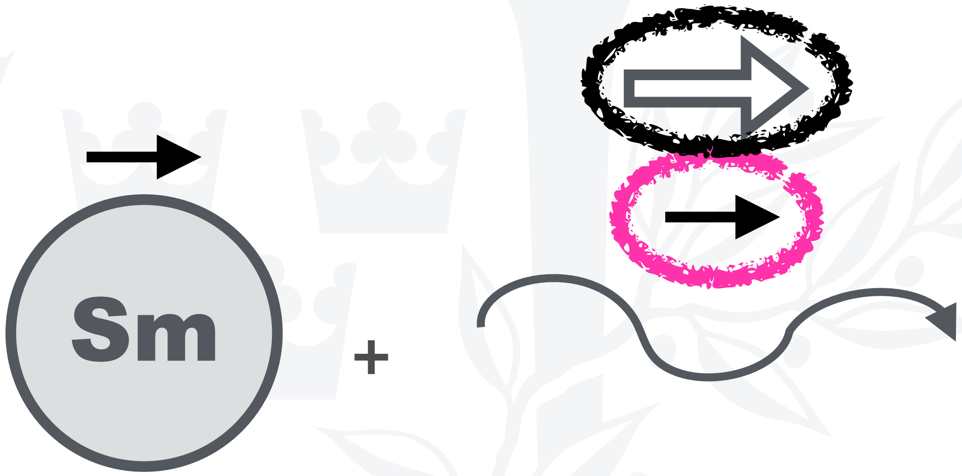


NaI scintillating crystal & PMT

Halfway there

But there are various complications with this.

1. How do you measure the helicity (polarization) of the photon?
2. How do ensure the photon was emitted anti-parallel to the neutrino?



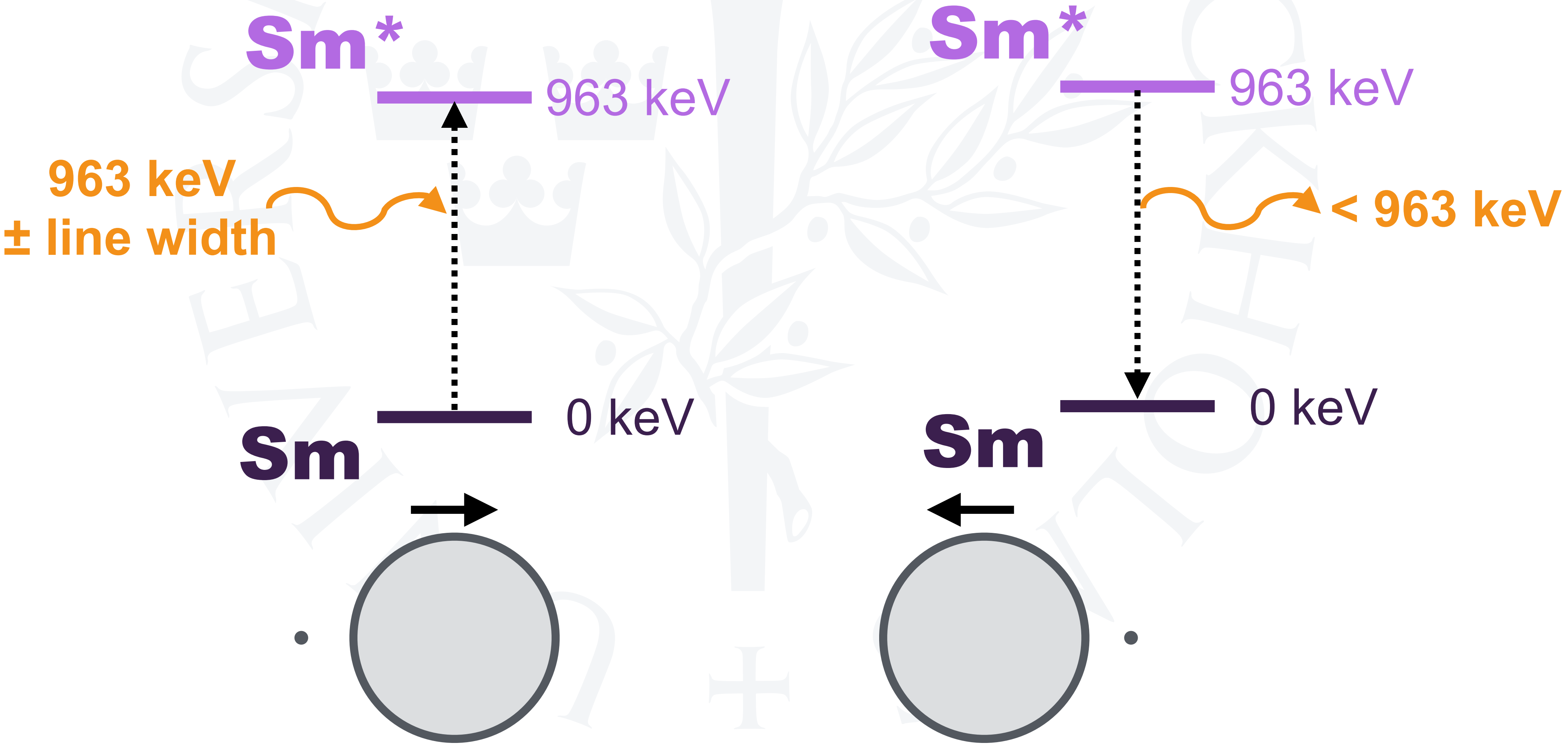
But what about the momentum vector? We still don’t know if the photon was produced back-to-back or not.

The solution in how to get around this is two-fold. First, resonant fluorescence.

Induced phosphorescence

1. Photon promotes nucleus to excited state.
2. Nucleus will then emit the photon to de-excite.

But some energy is lost by conservation of momentum: the nucleus recoils on absorption and emission (Mössbauer effect).



Recoils on absorption

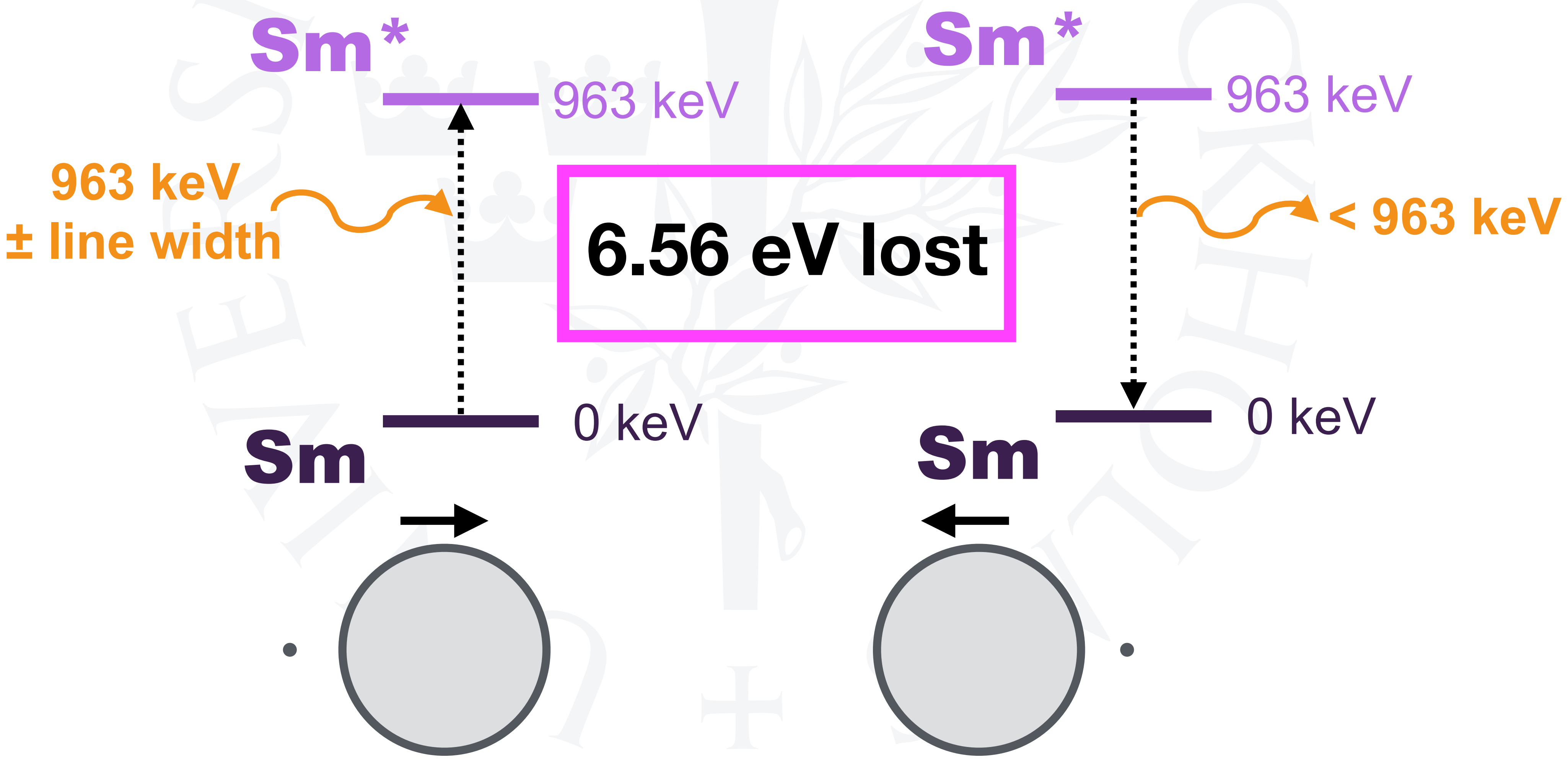
Recoils on emission

Induced phosphorescence

How much energy is lost?

$$\Delta E = \frac{E_0^2}{2Mc^2} = \frac{(963 \times 10^3)^2}{2 \cdot 141.51 \times 10^9} \approx 3.28 \text{ eV}$$

$$M_{152} = 151.92 \text{ [g mol}^{-1}] \times 931.49 \text{ [MeV}/c^2] = 141.51 \text{ [GeV}/c^2]$$



6.56 eV lost

Recoils on absorption

Recoils on emission

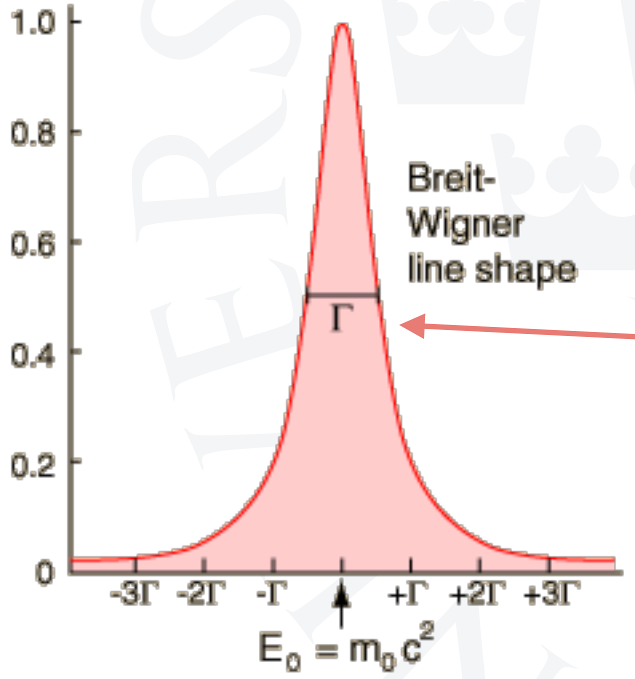
Induced phosphorescence

Why does this (relative to the excitation gap) tiny difference matter?

$$6.56\ [\mathrm{eV}] \ll 963\ [\mathrm{keV}],\ (\sim 1 \times 10^5)$$

Because it's not that small compared to the natural line-width

$$6.56\ [\mathrm{eV}] > 0.01\ [\mathrm{eV}],\ (\sim 1 \times 10^2)$$



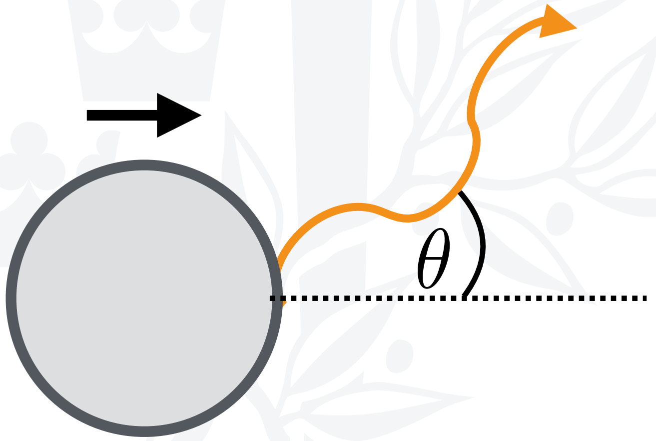
natural line-width of this this state (from the uncertainty principle, each excited state has an associated lifetime)

So, imagine you wanted to induce fluorescence from a photon emitted from a different nucleus of the same type: you'd have to give additional energy to the photon.

Thermal doppler shift

How about temperature? Doppler shifting photon according to mean thermal energy:

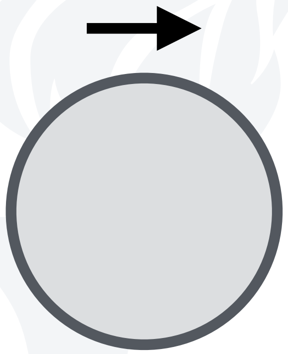
$$\Delta E_\gamma = E_\gamma^0 \beta \cos(\theta) = E_\gamma^0 \left(\frac{2kT}{Mc^2} \right)^5 \cos(\theta) \approx 0.5 \cos(\theta) \ [\mathrm{eV}]$$



Even though thermal doppler shift is > 10x natural line-width it’s still <10x what is needed to compensate for the 6.56 eV loss from the Mössbauer effect.

Another doppler shift

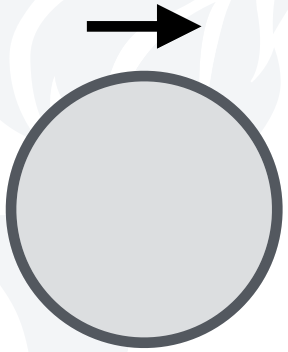
But what about a different type of Doppler shift?



Let's take another look at that Sm-152 961 keV level..

Another doppler shift

But what about a different type of Doppler shift?

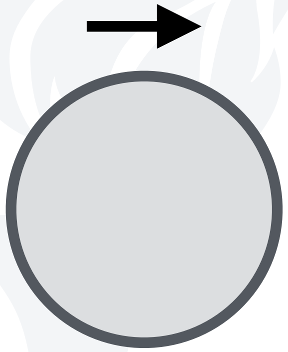


Let's take another look at that Sm-152 961 keV level..

$$\text{Mean lifetime} = (3.5 \pm 1) \times 10^{-2}\ [\text{ps}]$$

Another doppler shift

But what about a different type of Doppler shift?



Let’s take another look at that Sm-152 961 keV level..

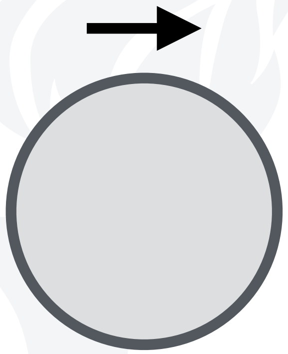
$$\text{Mean lifetime} = (3.5 \pm 1) \times 10^{-2}\ [\text{ps}]$$

Stopping time of Sm-152 following electron capture:

rcarney@lbl.gov

Another doppler shift

But what about a different type of Doppler shift?



Let's take another look at that Sm-152 961 keV level..

$$\text{Mean lifetime} = (3.5 \pm 1) \times 10^{-2}\ [\text{ps}]$$

Stopping time of Sm-152 following electron capture:

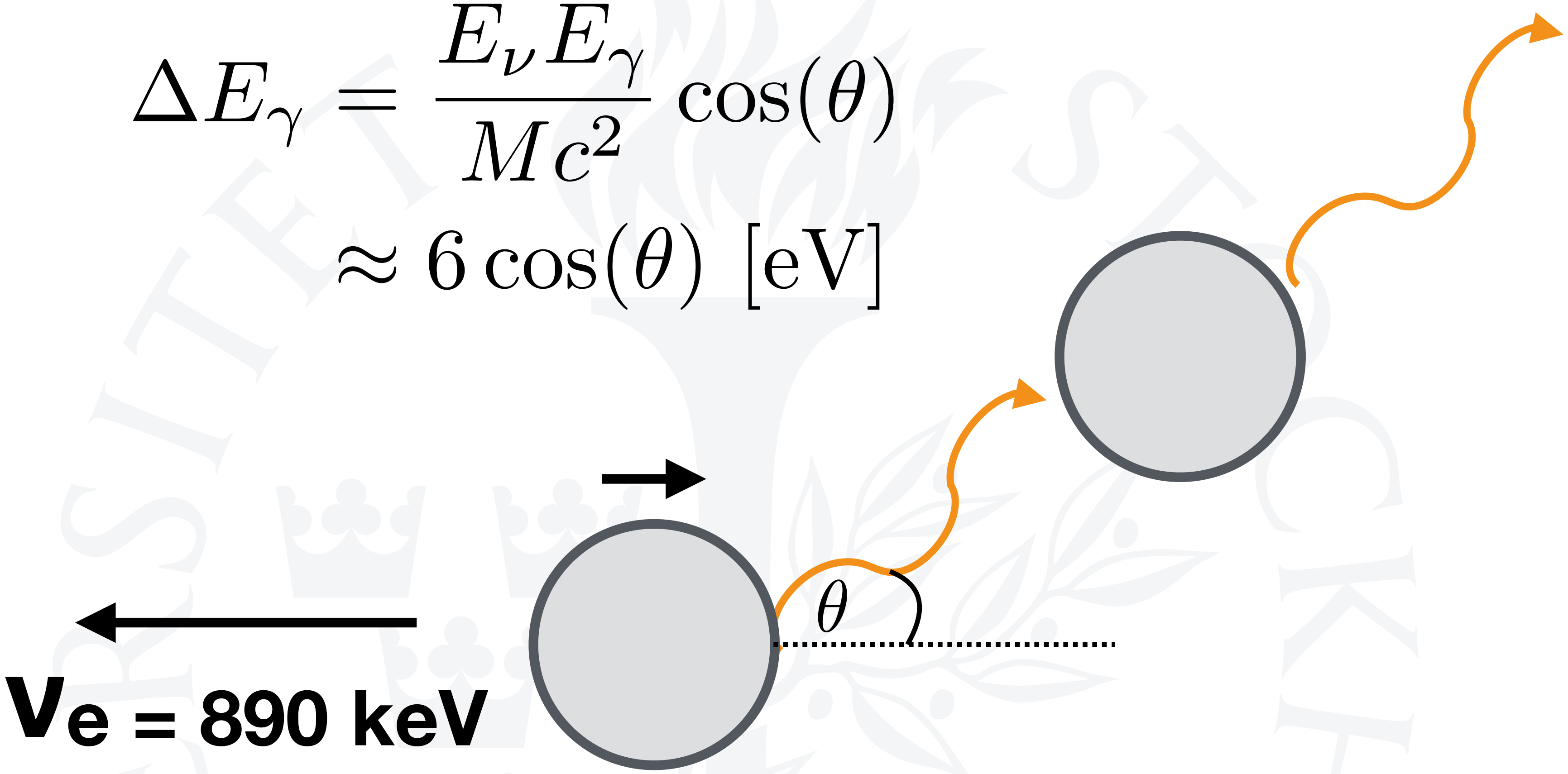
$$\text{Stopping time} \approx 1\ [\text{ps}]$$

Sm-152 will de-excite whilst still recoiling from electron-capture. The photon it emits will be doppler shifted.

Induced phosphorescence

Making up that 6 eV

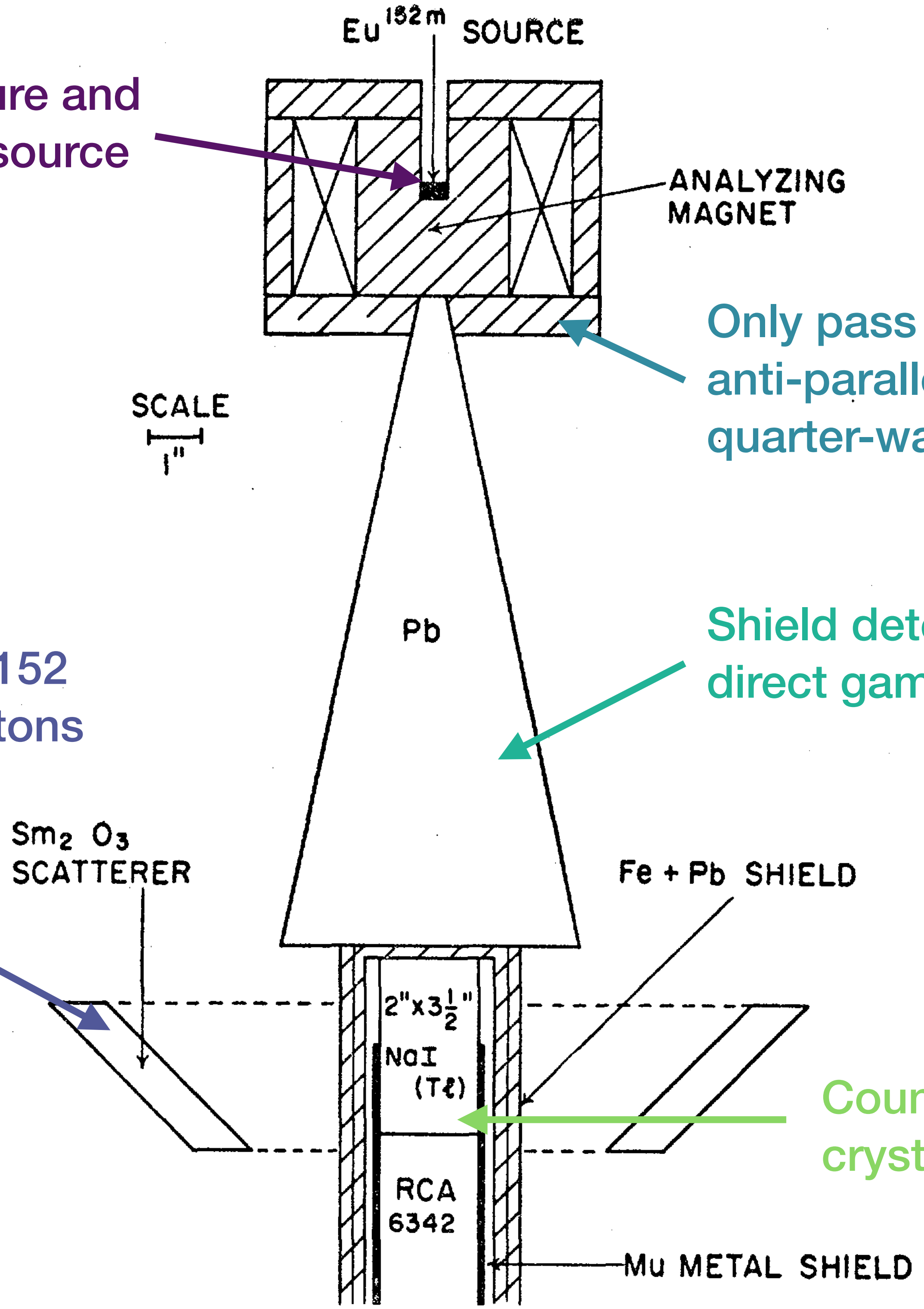
$$\Delta E_\gamma = \frac{E_\nu E_\gamma}{Mc^2}\cos(\theta)$$
$$\approx 6\cos(\theta)\ \ [\text{eV}]$$



So, to put that in perspective, sent into a bath of Sm-152, the only gamma rays that will undergo resonant fluorescence are those that have undergone maximal doppler shift from the nuclear recoil: i.e. only those that are back-to-back with the neutrino.

Re-examine the setup

Putting it al together



Electron-capture and de-excitation source

Only pass photons anti-parallel to field: i.e. quarter-wave filter

Shield detector from direct gamma radiation

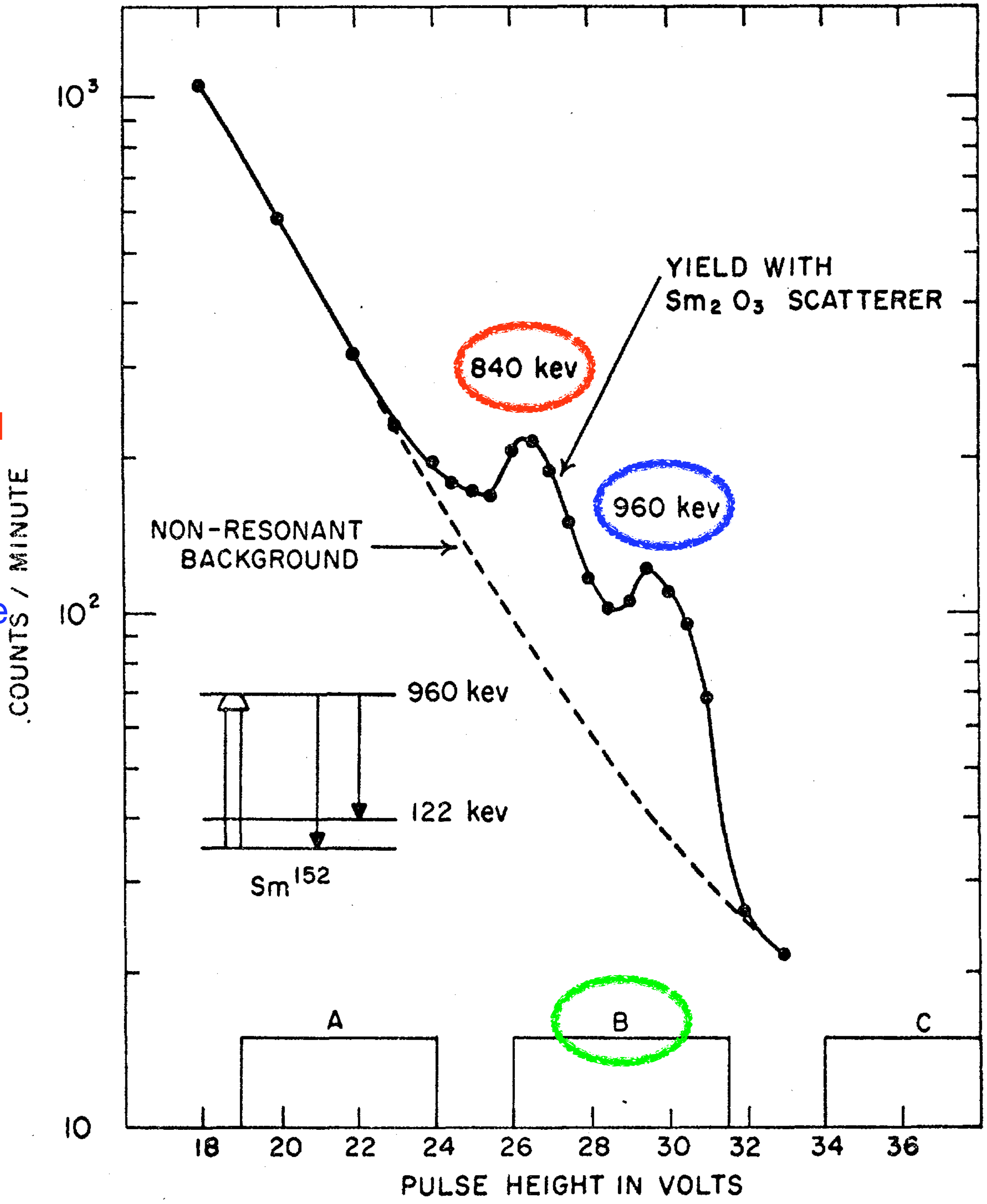
Make a reflecting surface out of Sm-152 to ensure only photons parallel to neutrino reach detector

Count photons with crystal-PMT setup

Procedure: varying magnetic field, measuring count.

Resultant spectrum

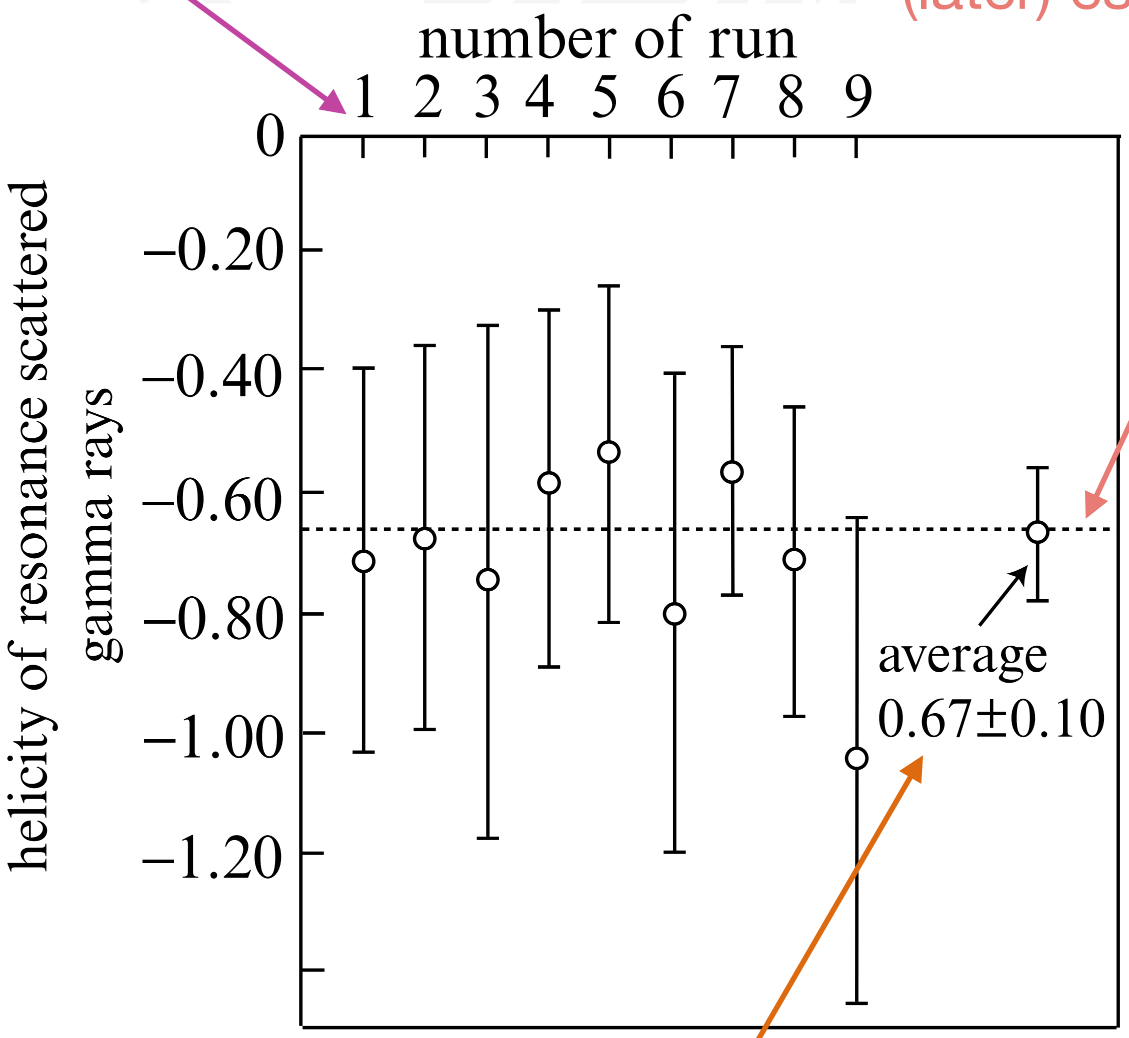
- First, see the non-resonant background from photons that were selected but didn't get re-absorbed and re-emmitted.
- Then, note 2 peaks in the resonant signals!
- The 840 keV is from the second nuclear emission going to the 122 keV state. This is no good as it won't propagate the spin.
- The 960 keV peak is the one we want (NB why 960 and not 963?)
- B - signal region
  - A - compton scattering
  - C - background
- They reversed the magnetic field to check for systematics: the only region that changed was B.



Results

9 independent runs were made. i.e. they replaced their Eu-152 sample 9x

This measurement was an observation of negative helicity, compatible with the (later) established V-A form.



$$\partial = \frac{N_- - N_+}{(N_- + N_+)/2}$$

67% circular polarization was observed. This was consistent with the corrections for non-K shell electron capture, thermal motion, and the 840 keV recoil.

Summary

- The measurement of a net negative helicity in the neutrino confirmed what Wu and others supported: the neutrino produced in weak interactions had negative helicity.
- This did not rule out admixtures of handed-ness, but it did show an asymmetry.
- To date, this remains the most precise direct measurement of the neutrino helicity.
- All it needed was to have a working knowledge of Eu-152 decays, the ingenuity to scope out resonant fluorescence, and the great technique to put them together.

References

Helicity of Neutrinos by M. Goldhaber, L. Grodzins, & A. W. Sunyar
Phys.Rev. 109 (1958) 1015-1017
https://journals.aps.org/pr/pdf/10.1103/PhysRev.109.1015

The Experimental Foundations of Particle Physics by Bob Cahn & Gerson Goldhaber, Chapter 6, 1989
https://www-cambridge-org.ezproxy.cern.ch/core/books/experimental-foundations-of-particle-physics/C874A203ABB6D376ADC7E725C5A32CD2

Helicity of the Neutrino by Amit Roy, Resonance magazine, 2015
https://link.springer.com/content/pdf/10.1007%2Fs12045-015-0227-y.pdf

The Tabletop Measurement of the Helicity of the Neutrino by Lee Grodzins, Italian Institute of Physics Review: Percorsi, Vol. 26, n 5-6, 2010
http://prometeo.sif.it/papers/online/sag/026/05-06/pdf/05-percorsi.pdf

- Eu-152 only decays by electron capture 72% of the time (the review quotes 20%, it is unclear if this is just wrong or if they mean 20% of electron captures come from the K-shell: which would be very odd indeed!)
- The neutrino was emitted with a different momentum to the gamma ray (890 keV vs. 963 keV), which contributes to the polarization being ~84%.
- Electron capture could happen in the L and M shells..
- Replacing the Sm-152 scatterer by a Pb scatterer, allowed to check if resonant scattering was indeed present.
- Only 2% of photons were transmitted through the 3 m.f.p. of Pb: so they understood their systematics to within < 2%!