Neutrino Physics

- Need of neutrino
- Types of neutrino
- Mass of neutrino

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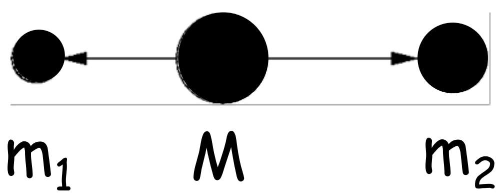
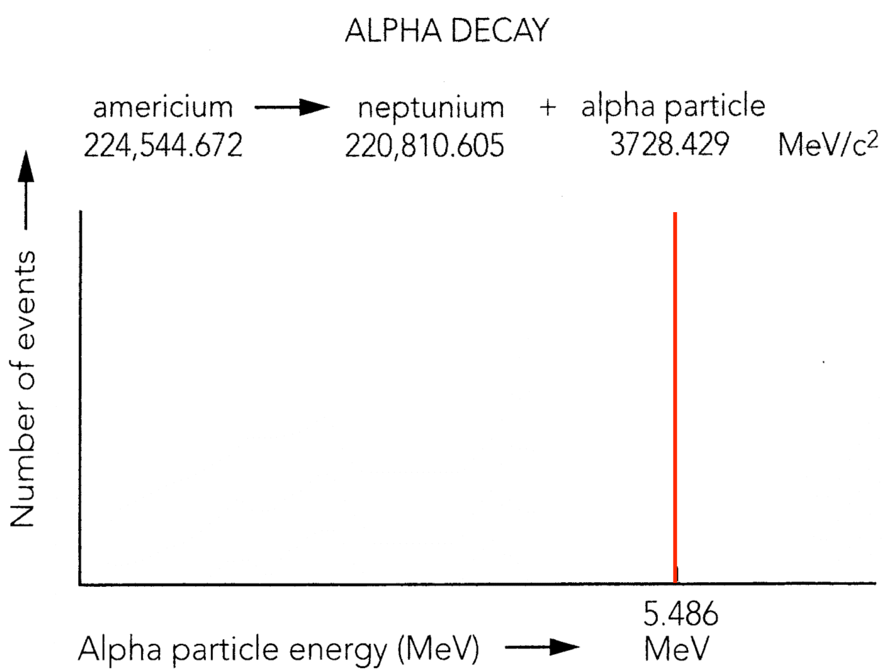
Alpha Decay

$$ {}^{A}_{Z}N \rightarrow {}^{A-4}_{Z-2}N + \alpha \ ; \ \alpha = {}^{4}_{2}He $$

It is a two-body decay:

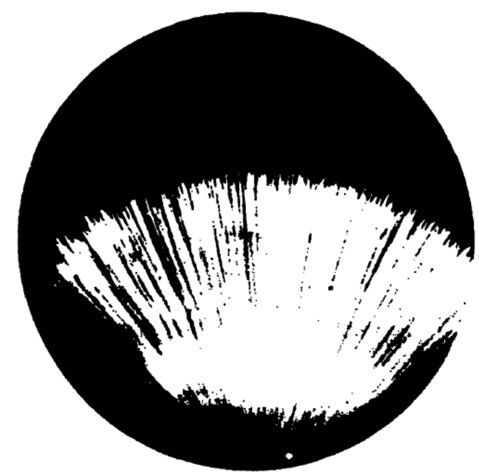




Energy-momentum conservation:

$$ E_2 = \sqrt{m_2^2 + p^2} = \frac{M^2 + m_2^2 - m_1^2}{2M} $$

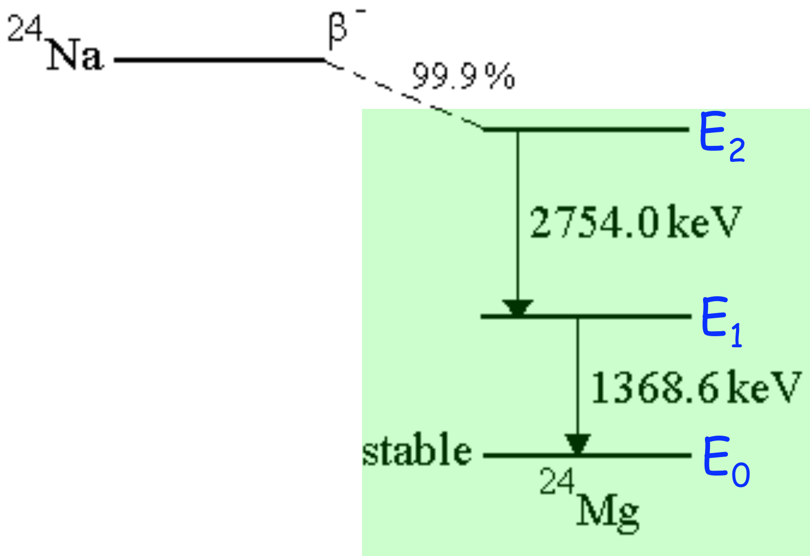
Energy of the decay products always the same



$^{212}Po \rightarrow {}^{208}Pb + \alpha(8.95\ \text{MeV})$

Gamma Decay

$$ {}^{A}_{Z}N^{*} \rightarrow {}^{A}_{Z}N + \gamma $$



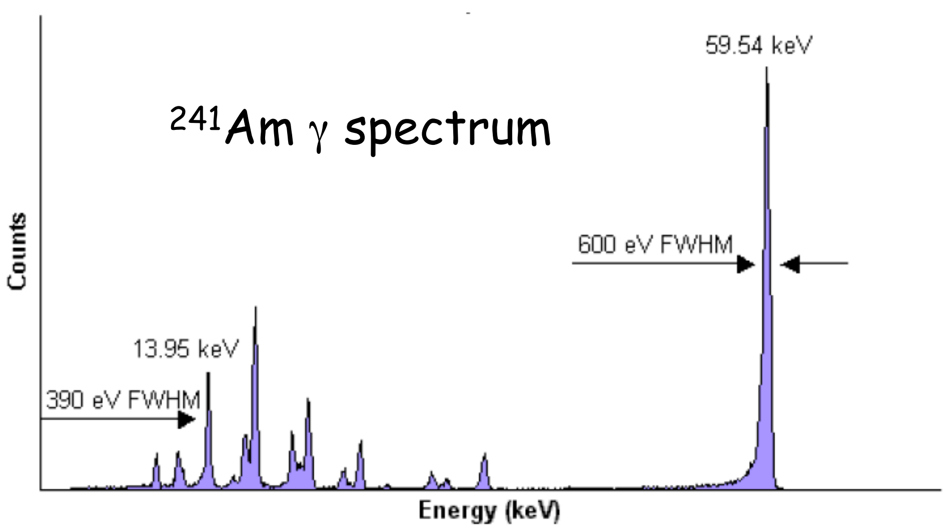
Energy of the emitted gamma ray:

$$E_\gamma = E_i - E_f$$

For ^{24}Mg,

$$E_{\gamma 1} = E_2 - E_1 = 2754.0 \text{ keV}$$

$$E_{\gamma 2} = E_1 - E_0 = 1368.6 \text{ keV}$$



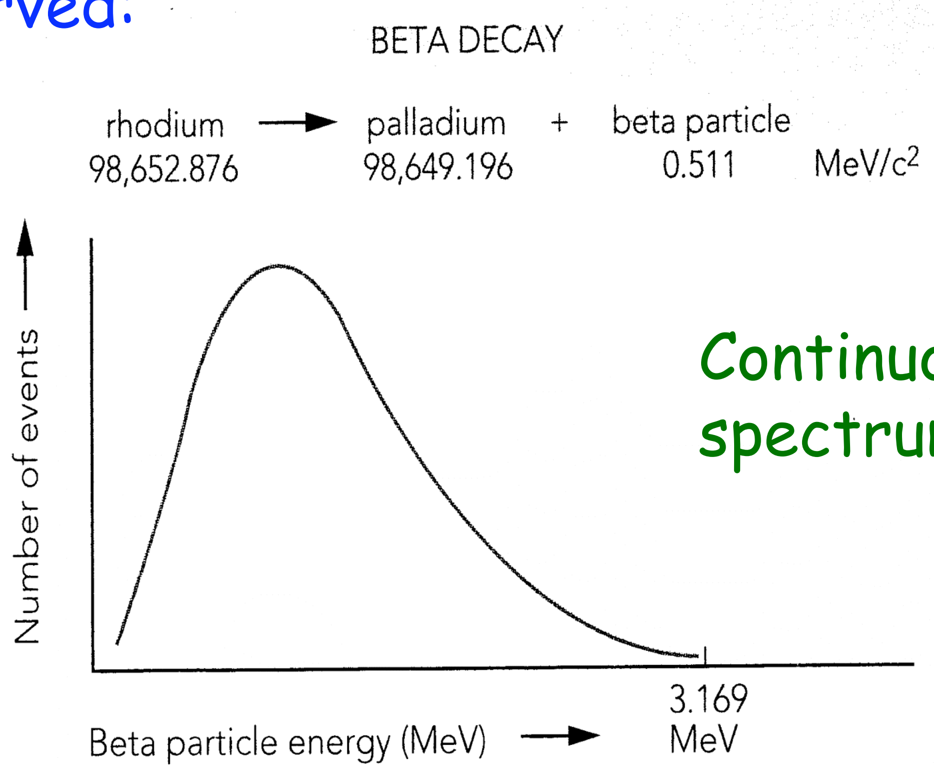
Again, the energy of the decay products is always the same.

Beta Decay Prior 1930

Assumed:

$$ {}^{A}_{Z}N \rightarrow {}^{A}_{Z+1}N + \beta $$

But observed:



Continuous energy spectrum for β particles

Is Energy not conserved ?

Bohr: gave up conservation of energy

Pauli's Desperate Remedy

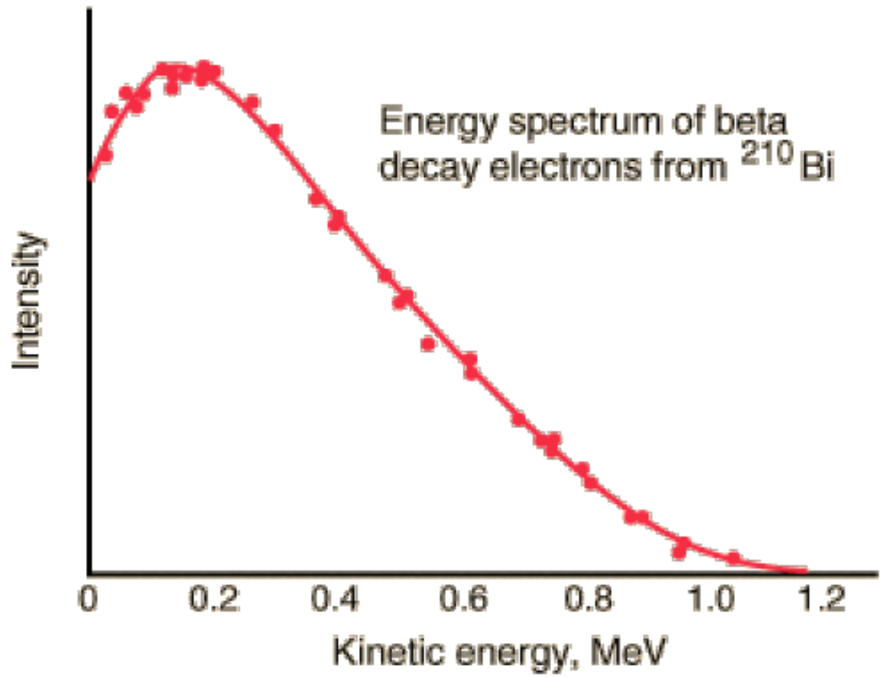
4th December 1930

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li^6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...

neutrino named by Fermi

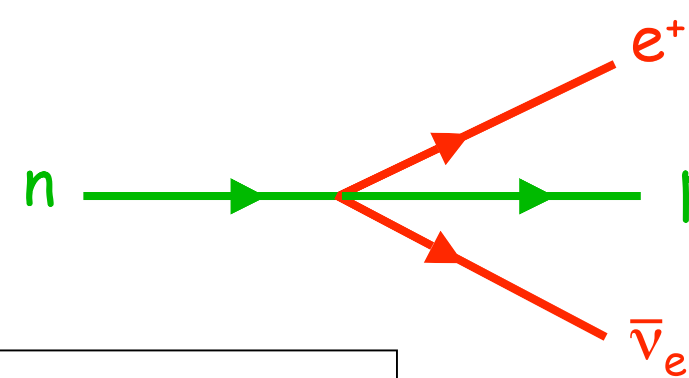
Fermi's Great Idea



$$^{210}Bi_{83} \rightarrow {}^{210}Po_{84} + e^- + \bar{\nu}_e$$

Beta decay is actually due to the decay of a neutron:

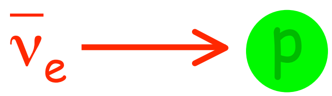
$$n \rightarrow p + e^- + \bar{\nu}_e$$



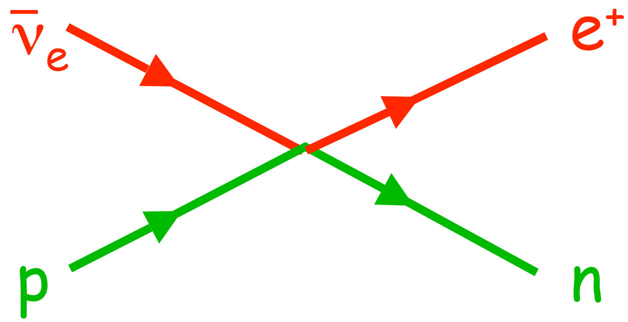
$$^{A}_{Z}N \rightarrow {}^{A}_{Z+1}N + \beta + \bar{\nu}_e$$

Neutrino Is Like A Ghost

- Bethe applied Fermi's theory of weak interaction to



Lab frame



Center-of-mass frame

Inverse beta decay:

$\bar{\nu}_e + p \rightarrow e^+ + n$

the cross section is:

$\sigma_{\nu p} \sim 10^{-44}\ cm^2/MeV$

- The number of collisions with N_p protons and N_ν $\bar{\nu}_e$s is:

$$N_c \propto N_p N_\nu \quad \Rightarrow \quad N_c = \sigma\, N_p N_\nu$$

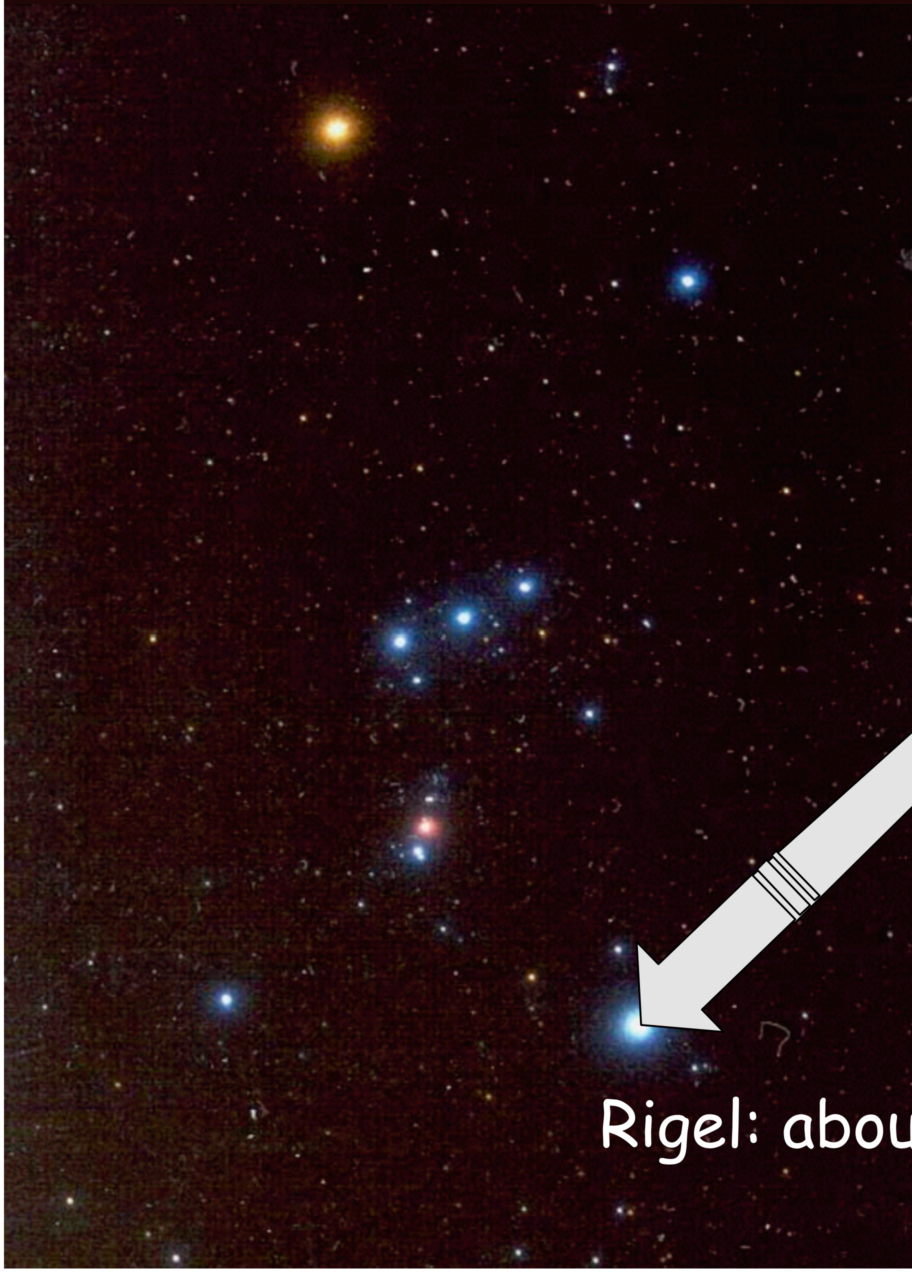
- In 1 cm^3 of water, the number of protons is

$$N_p \sim 7 \times 10^{22}$$

For **a 1-MeV $\bar{\nu}_e$**, the probability of having an inverse beta-decay reaction is

$$\text{Prob} = E_\nu \cdot N_p \cdot \sigma_{\nu p} \sim 7 \times 10^{-22}/cm$$

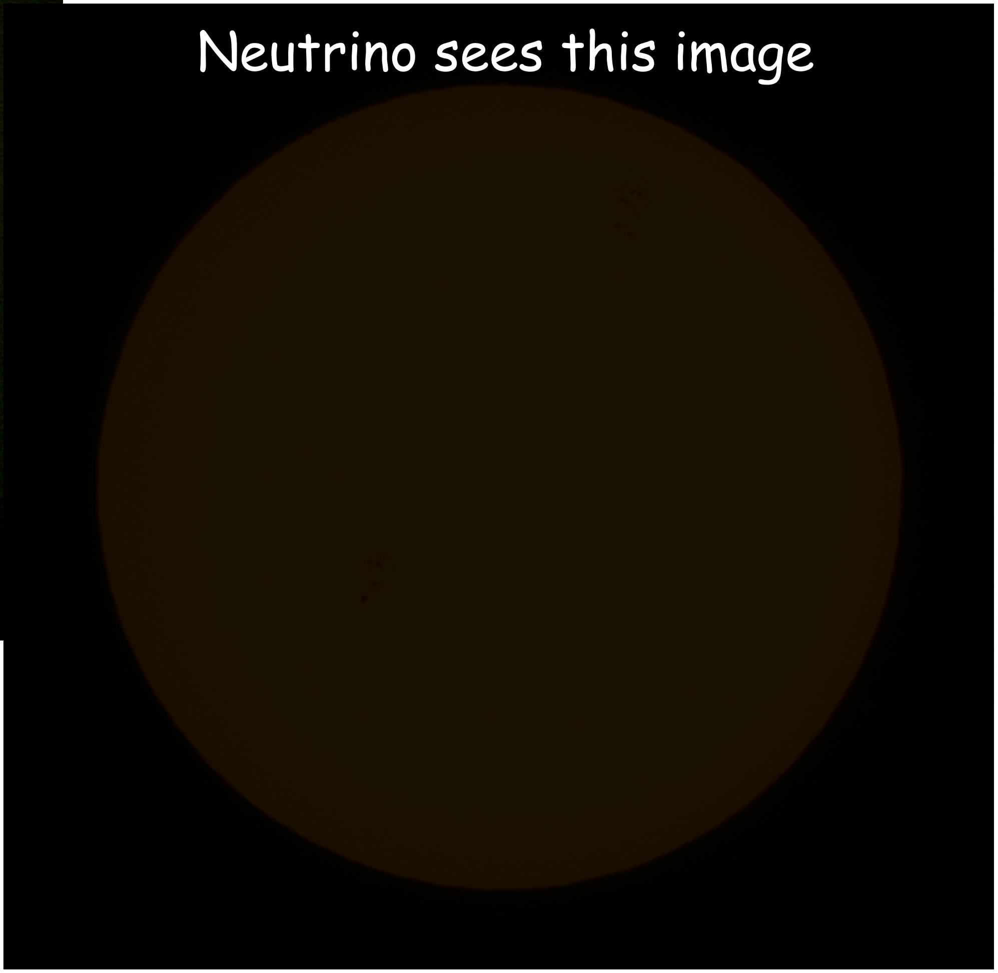
Fill the space with black ink:



A 1 MeV neutrino, on the average, will collide with a water molecule by the time it gets to Regel

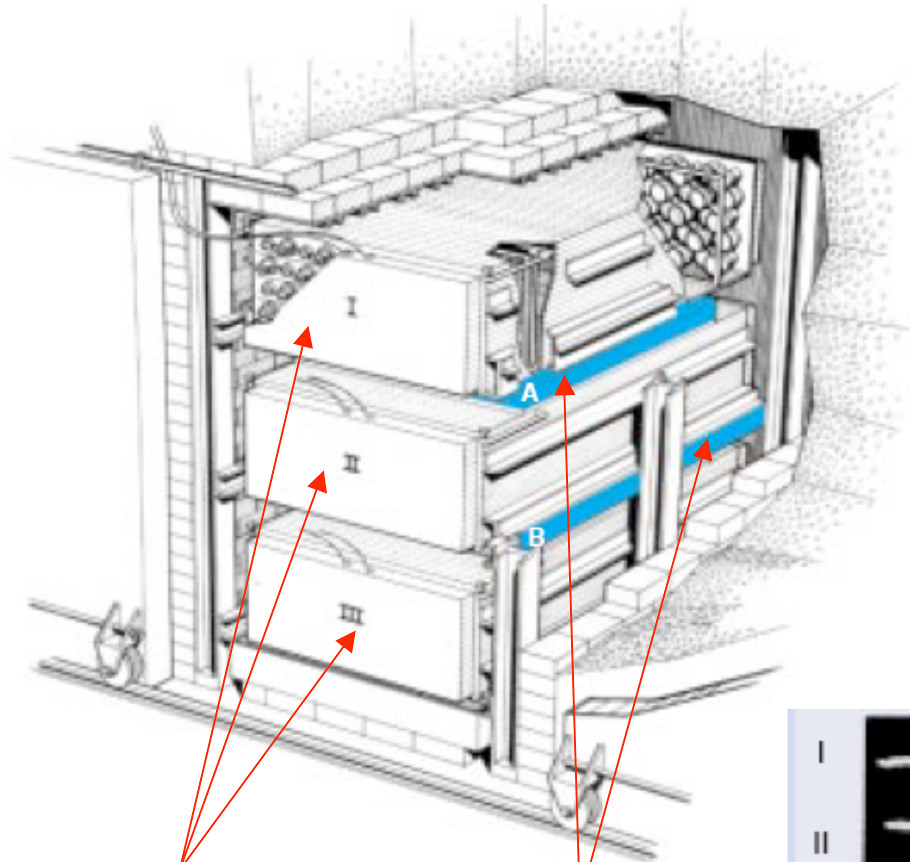
Rigel: about 1000 light years away

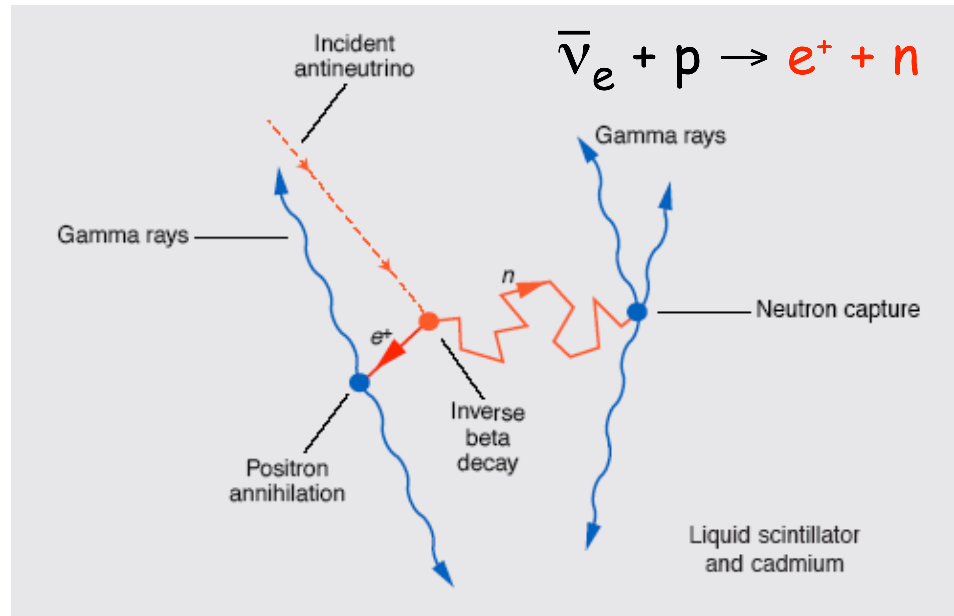
How Does Neutrino See The Sun?



Catching The Poltergeist

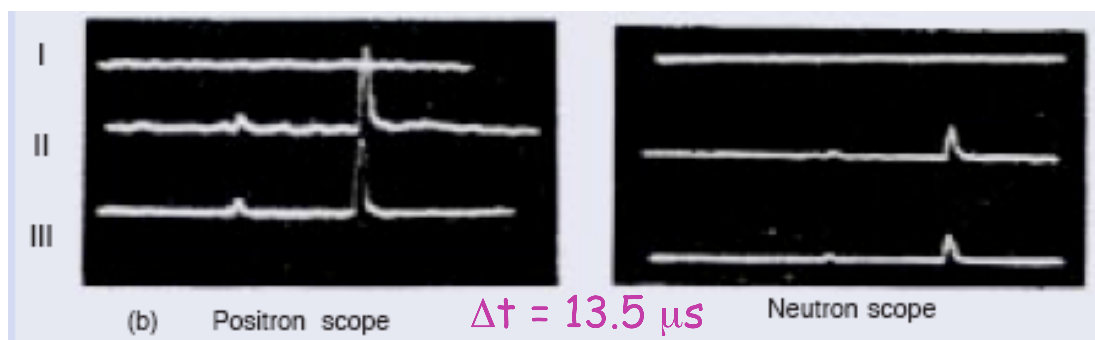
Reines-Cowan Experiment with reactor $\bar{\nu}_e$ at Savannah River (1953-1956)
1995 Nobel prize





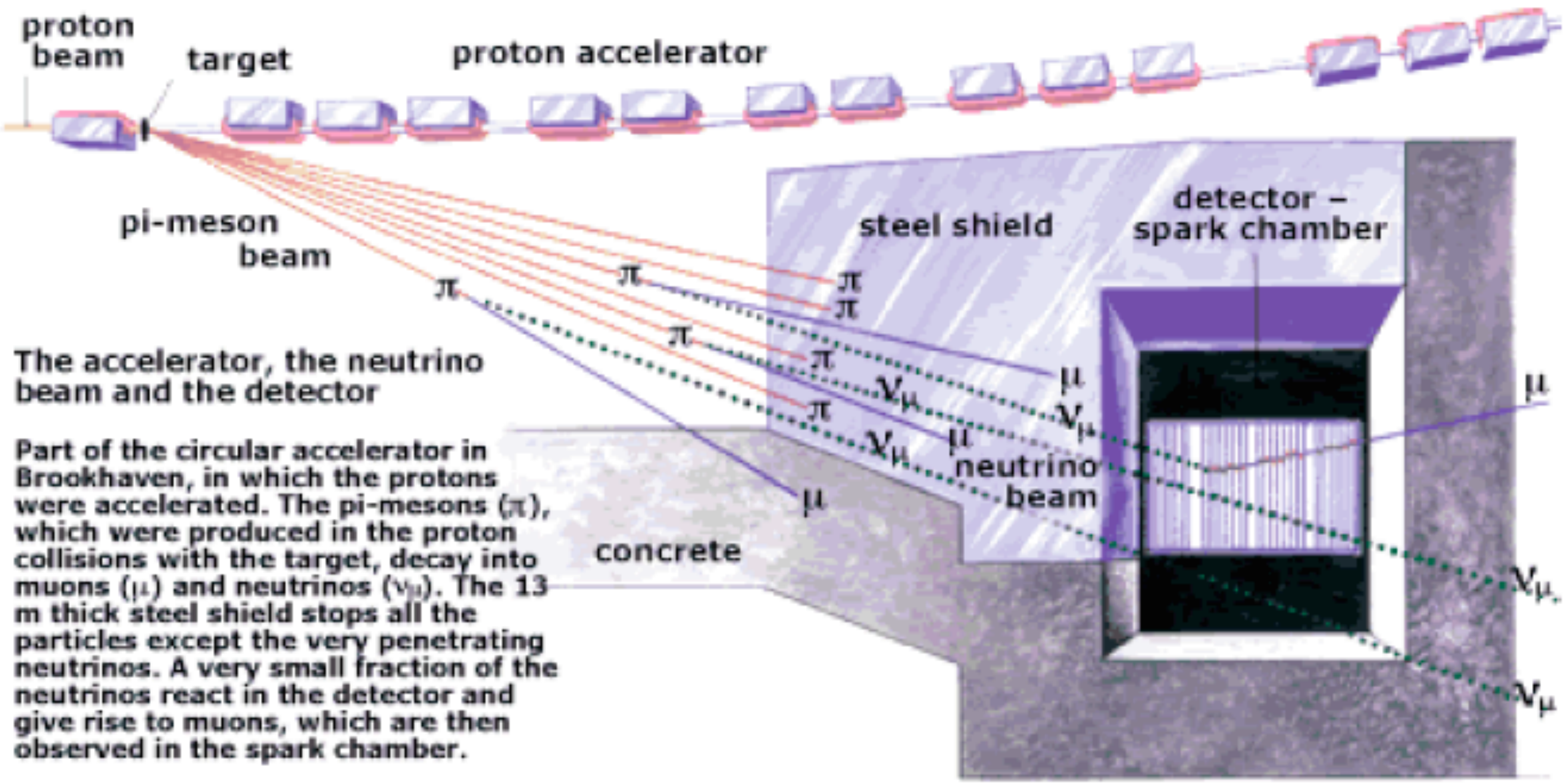
Each with 1000 l of liquid scintillator viewed with PMTs

Each with 200 l of water with $CdCl_2$



$\bar{\nu}_e$ is seen !

Not Just One, But Two types !



The accelerator, the neutrino beam and the detector

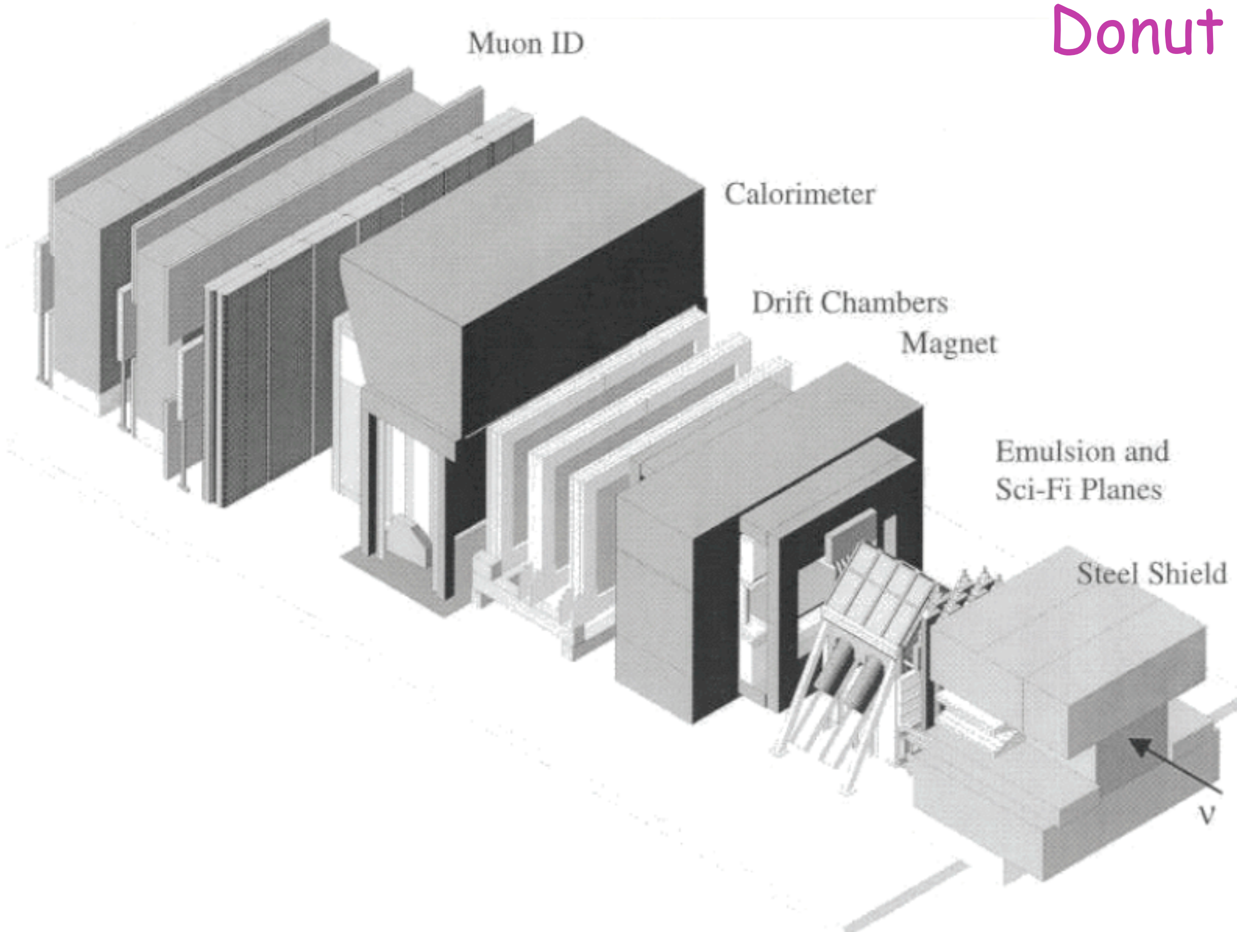
Part of the circular accelerator in Brookhaven, in which the protons were accelerated. The pi-mesons (π), which were produced in the proton collisions with the target, decay into muons (μ) and neutrinos (ν_μ). The 13 m thick steel shield stops all the particles except the very penetrating neutrinos. A very small fraction of the neutrinos react in the detector and give rise to muons, which are then observed in the spark chamber.

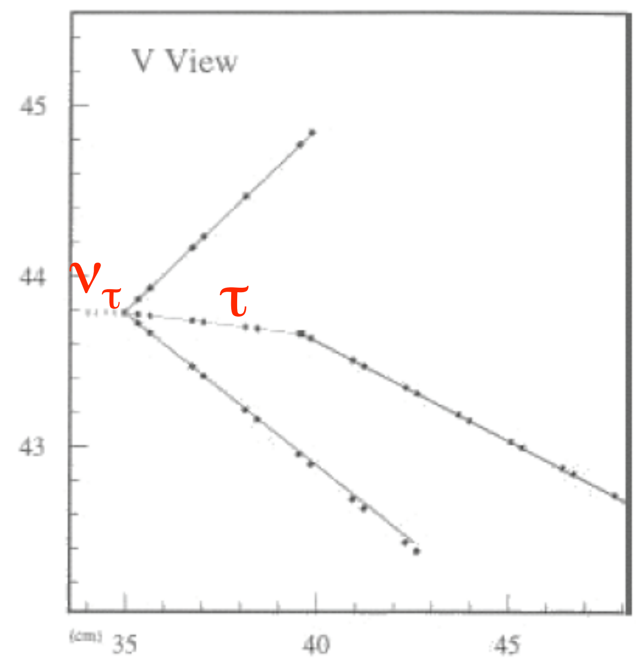
Based on a drawing in Scientific American, March 1963.

1988 Nobel prize

Wait, History Repeats Itself !

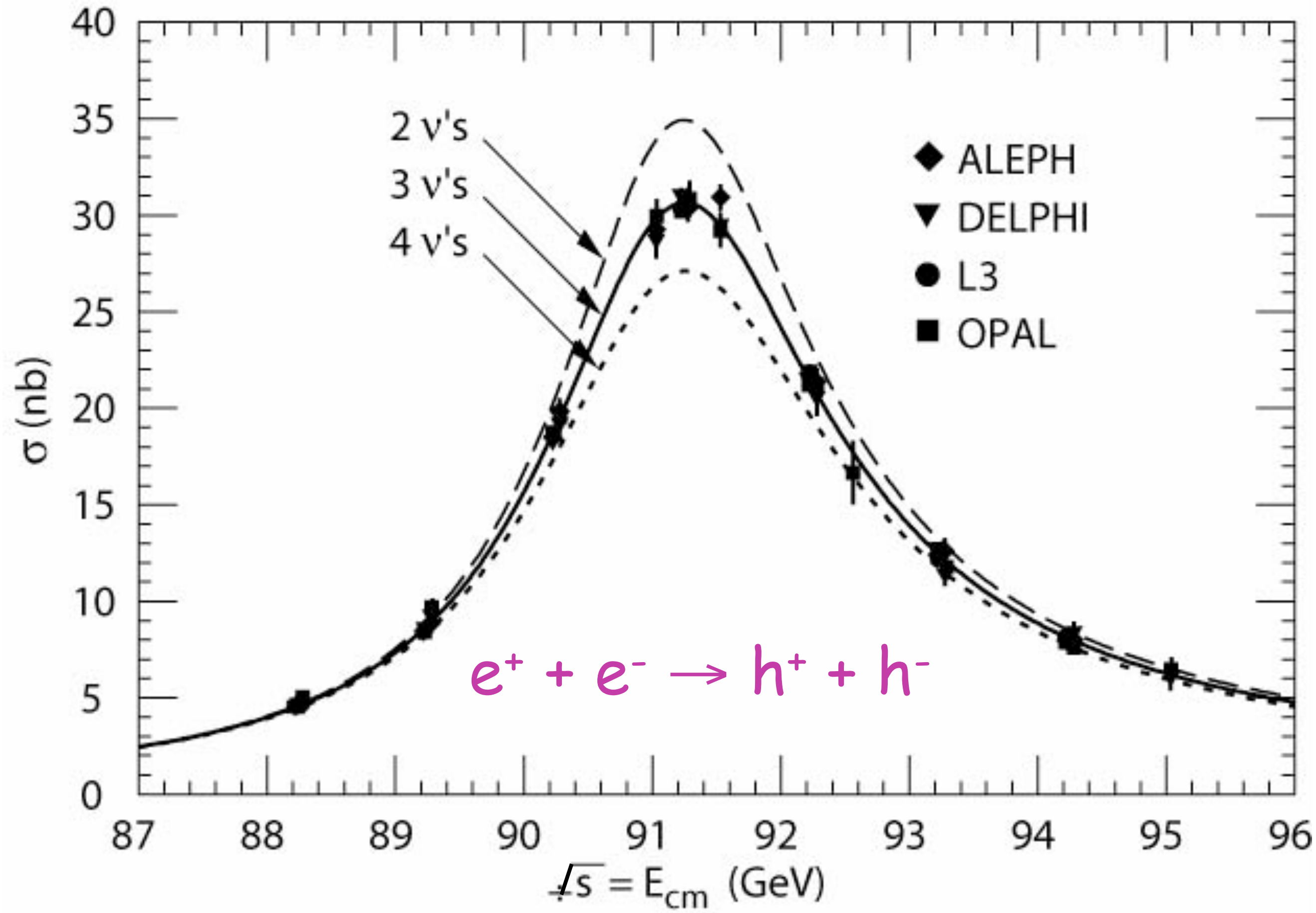
Donut at Fermilab (2000):





$\nu_\tau + N \rightarrow \tau + \text{hadrons}$

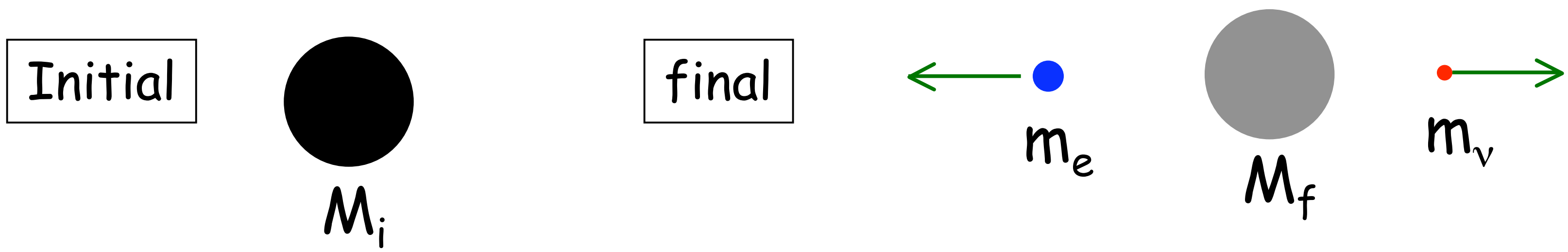
Three and No More



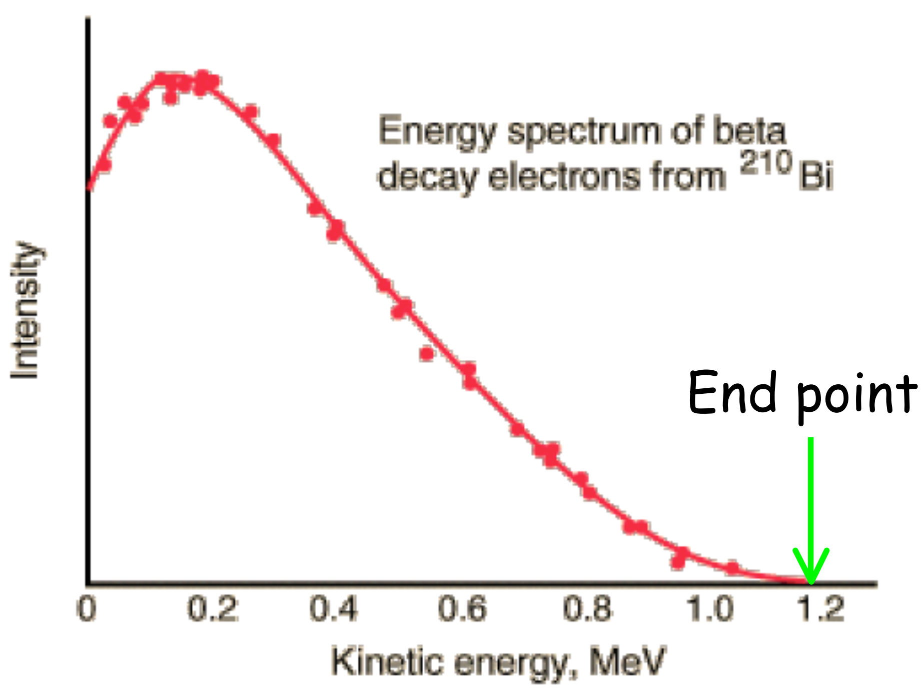
How Massive Is A Neutrino?

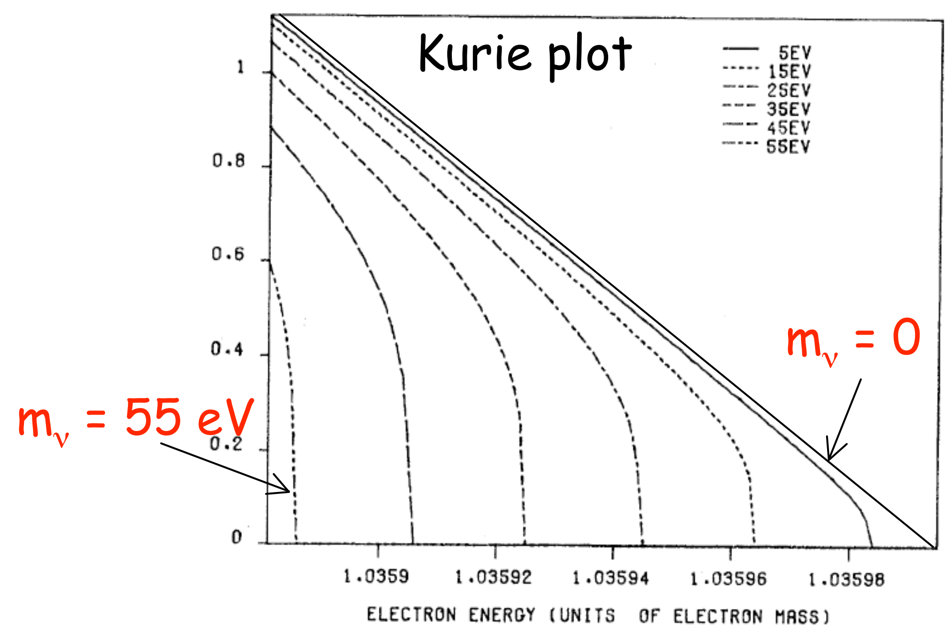
For the electron neutrino, take advantage of beta decay.

At the end point:



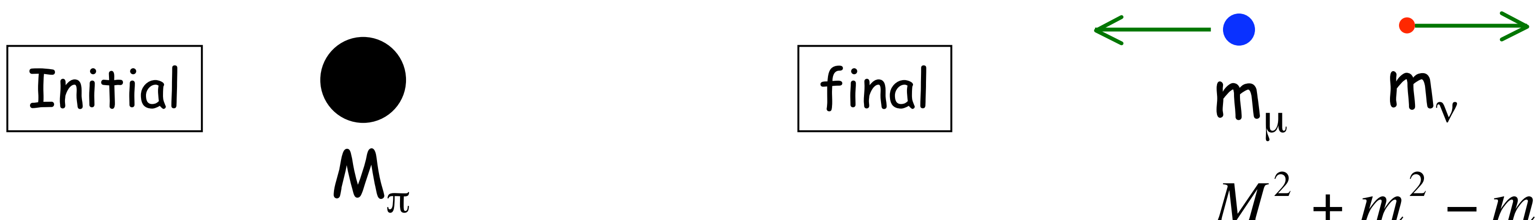
$$E_e = \frac{M_i^2 + m_e^2 - (M_f + m_\nu)^2}{2M_i}$$





Mass of A Neutrino (Cont.)

- For the muon neutrino, study $\pi^+ \to \mu^+ + \nu_\mu$ decay.



$$E_\mu = \frac{M_\pi^2 + m_\mu^2 - m_\nu^2}{2M_\pi}$$

- For the tau neutrino, study $\tau^+ \to \nu_\tau$ + many hadrons decay.

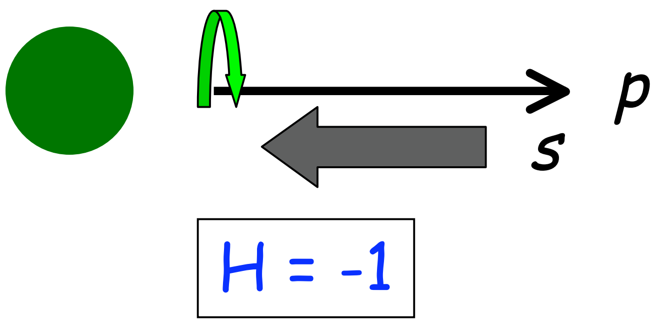
- Currently, from direct measurements:

ν_e : $m < 2$ eV
ν_μ : $m < 190$ keV
ν_τ : $m < 18$ MeV

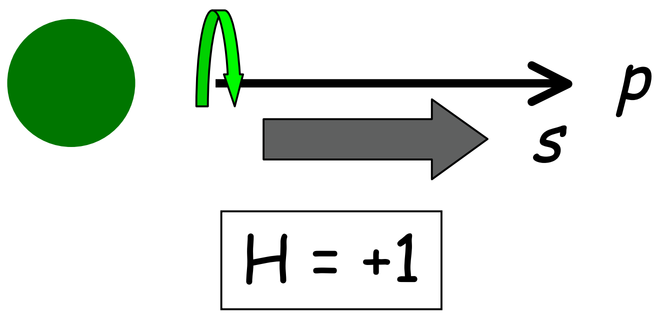
Helicity

$$Helicity,\ H = \frac{\vec{s}\cdot\vec{p}}{|\vec{s}\cdot\vec{p}|}$$

spin momentum



Left-handed state



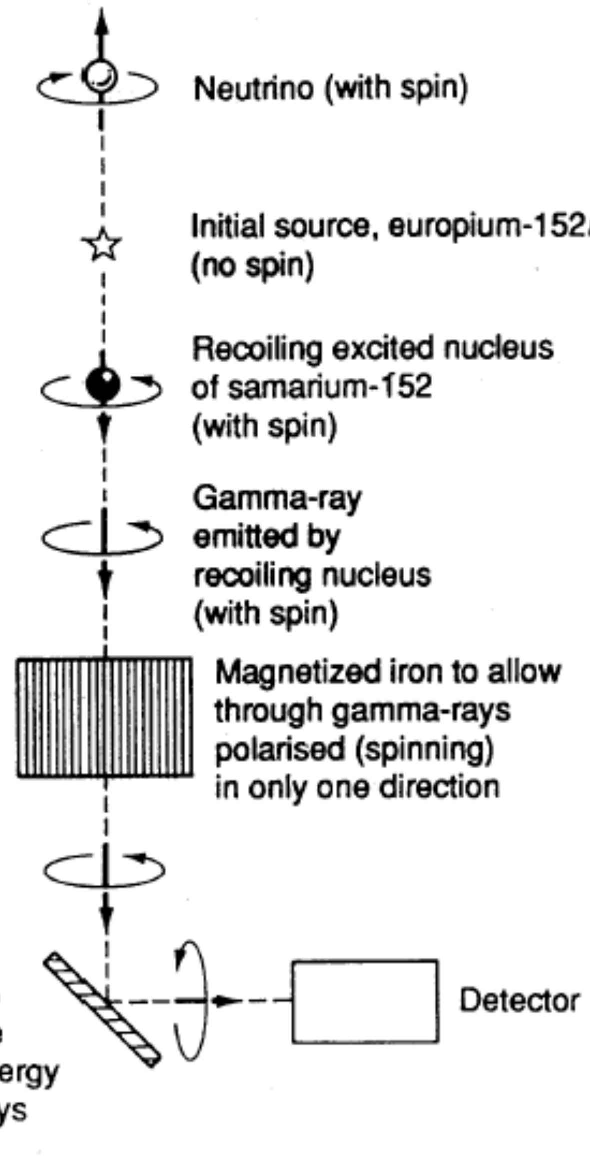
Right-handed state

Neutrinos Are Left-handed

Helicity of Neutrinos*

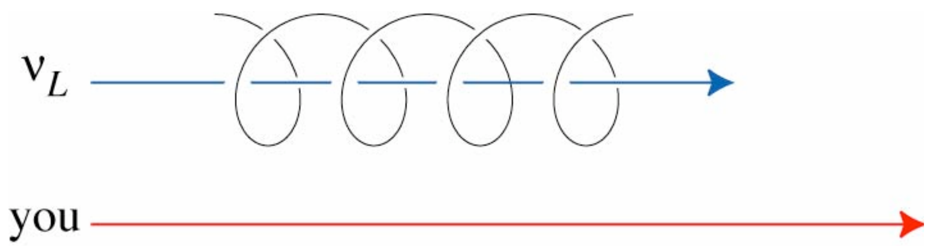
M. GOLDHABER, L. GRODZINS, AND A. W. SUNYAR
Brookhaven National Laboratory, Upton, New York
(Received December 11, 1957)

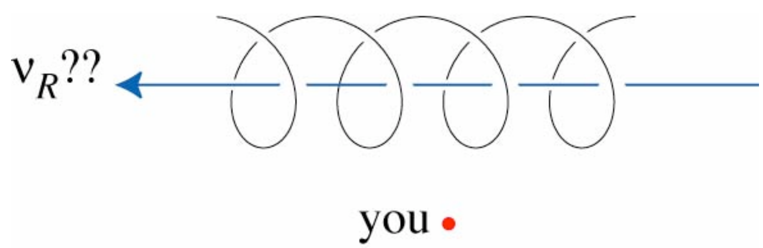
A COMBINED analysis of circular polarization and resonant scattering of γ rays following orbital electron capture measures the helicity of the neutrino. We have carried out such a measurement with Eu^{152m}, which decays by orbital electron capture. If we assume the most plausible spin-parity assignment for this isomer compatible with its decay scheme,[1] 0−, we find that the neutrino is "left-handed," i.e., $\boldsymbol{\sigma}_\nu \cdot \hat{\boldsymbol{p}}_\nu = -1$ (negative helicity).



Neutrinos Believed To Be Massless

- All neutrinos are left-handed ⇒ massless
- If they have mass, can't go at speed of light:





- Now the neutrino becomes right-handed??
  ⇒ contradiction ⇒ can't be massive

Summary

- There are only three types of neutrino.
- Neutrinos don't like to interact with matter - truly weakly interacting particles
- The neutrino is left-handed.
- The neutrinos are very light; their negative helicity strongly suggests neutrinos are massless.

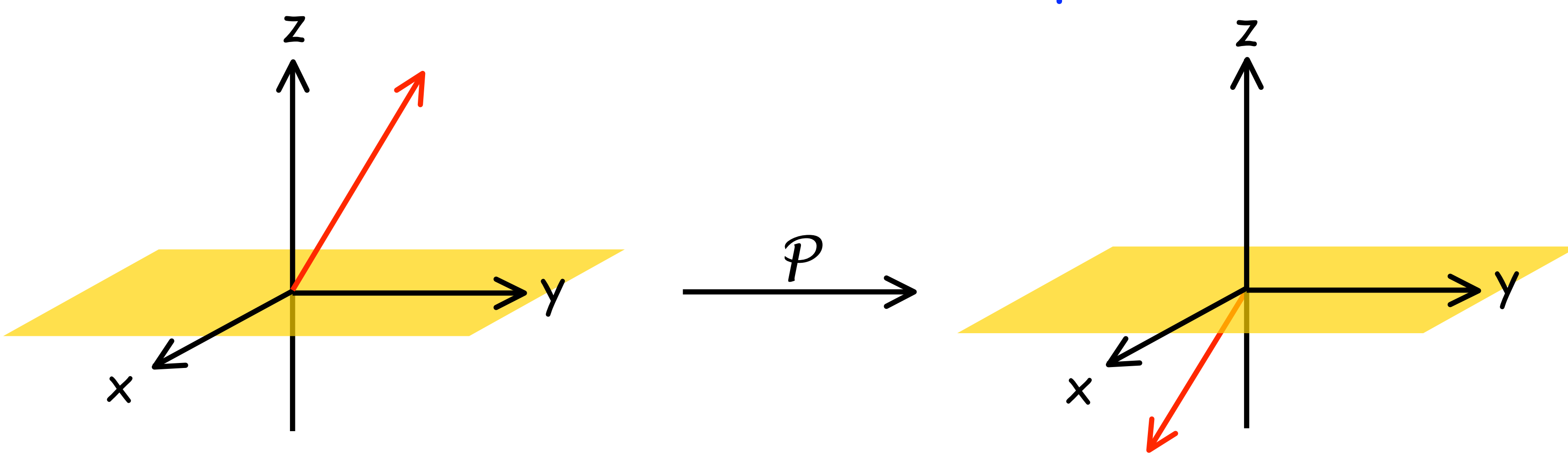
Parity: Left-right Symmetry

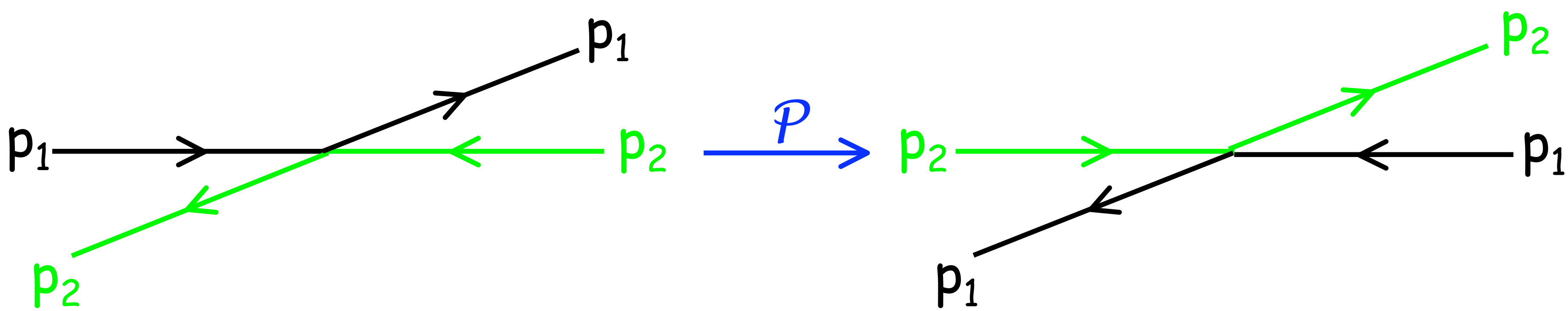
Parity transformation, $\mathcal{P}$:

Displacement: $\mathbf{r} \xrightarrow{\mathcal{P}} -\mathbf{r}$

Momentum: $\mathbf{p} \rightarrow -\mathbf{p}$

Spin: $S \rightarrow S$

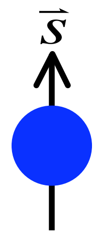




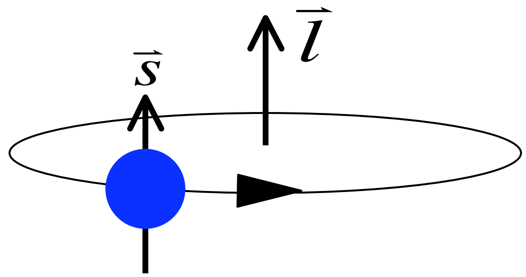
Experience says left and right give the same physics

Quick Review of Angular Momentum

- Spin of a particle (given by Nature), $\vec{s}$



- Orbital angular momentum (due to motion), $\vec{l}$



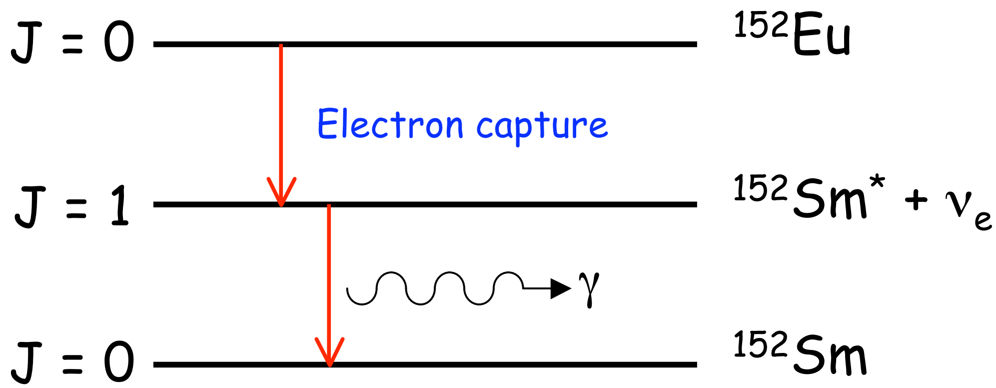
- Total angular momentum, $\vec{J}$

$$\vec{J} = \vec{l} + \vec{s}$$

$$|\vec{J}| \equiv J = |l - s|, \; \ldots \;, \; l + s \qquad \text{(in integral step)}$$

For l = 1, and s = 1/2, the possible values of J are 1/2, 3/2

How To Determine The Spin of Neutrino?



- ^{152}Eu captures a K-shell electron: