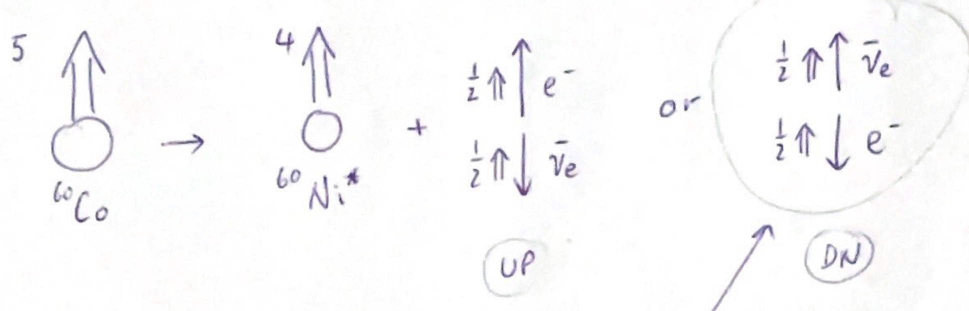
WU → PARITY VIOLATED IN WEAK INT.
(1956)

→ CROSS SECTIONS CAN DEPEND ON $\vec{\sigma} \cdot \vec{p}$



WU says this one is favored

in UP :

e^- : $\vec{\sigma} \Rightarrow$, $\vec{p} \rightarrow$ $\quad h = +1$

$\bar{\nu}_e$: $\vec{\sigma} \Leftarrow$, $\vec{p} \rightarrow$ $\quad h = -1$

in DN :

e^- : $\vec{\sigma} \Leftarrow$, $\vec{p} \rightarrow$ $\quad h = -1$

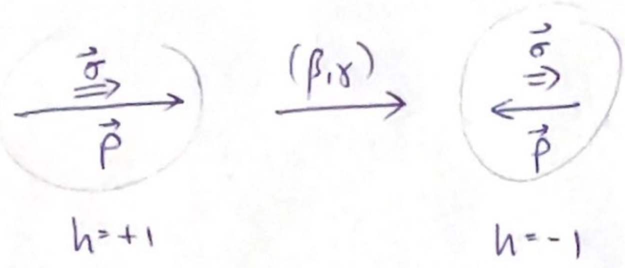
$\bar{\nu}_e$: $\vec{\sigma} \Rightarrow$, $\vec{p} \rightarrow$ $\quad h = +1$

let's define helicity. $h := \dfrac{\vec{\sigma} \cdot \vec{p}}{|\vec{\sigma}| \cdot |\vec{p}|}$

IN GENERAL h is <u>NOT</u> an invariant

→ depends on frame

$\Leftrightarrow$ $\exists$ boost (β, γ) that flips $\vec{p}$ so



HOWEVER in SM $m_\nu = 0$ $\Rightarrow$ $v = c$

$\Rightarrow$ $\nexists$ boost that flips its $\vec{p}$

$\Rightarrow$ h of neutrinos is invariant

I.E. if a neutrino is produced with $h = -1$

$\Rightarrow$ it will have $h = -1$ forever

NOW weak int. can distinguish between the two

if parity is <u>maximally</u> violated

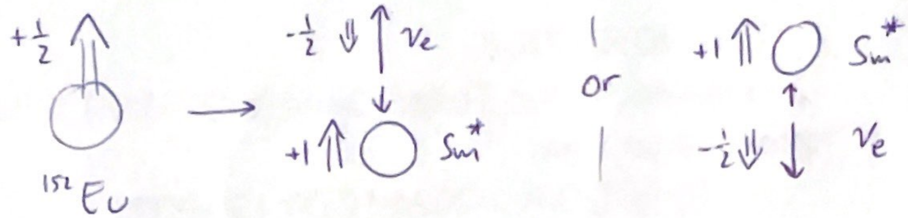
$\Rightarrow$ weak force will interact with ONLY ONE $h = \pm 1$

GOLDHABER EXPERIMENT (1957)

To measure helicity of neutrinos

Based on $\;{}^{152}Eu\,(+e^-) \rightarrow \nu_e + {}^{152}Sm^*$ ← electron capture

$$(p + e^- \rightarrow \nu_e + n)$$



$h(\nu) = -1$ $\qquad\qquad$ $h(\nu) = +1$

$h(Sm^*) = -1$ $\qquad\qquad$ $h(Sm^*) = +1$

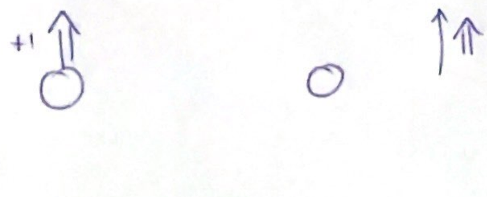
$$\Rightarrow \quad h(\nu) = h(Sm^*) \;!$$

then: EM decay of Sm^*

$$\tau(Sm^*) \sim 10^{-14}\,s$$

$${}^{152}Sm^* \rightarrow {}^{152}Sm + \gamma$$

SPIN: $\quad +1 \rightarrow 0 + 1$



So $\underline{\underline{\text{if}}}$ γ emitted in direction of flight

$h = +1$ $\quad \overset{\Rightarrow}{\underset{Sm^*}{\longrightarrow}} \qquad \underset{Sm}{\bullet} \quad \overset{\Rightarrow}{\underset{\gamma}{\longrightarrow}} \qquad h(\gamma) = h(Sm^*) \; (= h(\nu))$

$h = -1$ $\quad \overset{\Leftarrow}{\underset{Sm^*}{\longrightarrow}} \qquad \underset{Sm}{\bullet} \quad \overset{\Leftarrow}{\underset{\gamma}{\longrightarrow}} \qquad h(\gamma) = h(Sm^*) \; (= h(\nu))$

TRANSFERING THE HELICITY

from ν to Sm^* to γ

NOW $\quad Sm^* \longrightarrow Sm + \gamma$

$E(\gamma) = 961$ keV

Sm^*

$\Delta E = 961$ keV

Sm

line width $\sim 10^{-2}$ eV

if this γ encounters another Sm it will $\underline{\text{NOT}}$ be reabsorbed by

$$\gamma + Sm \to Sm^*$$

why? Because part of the energy $(\sim 3.2 \text{ eV})$ is lost to give it to recoiling Sm

LAB FRAME

s.i.

Sm^*

AT REST

s.f.

Sm γ

$\Rightarrow$ in LAB frame $E(\gamma) < 961$ keV $= \Delta E(Sm, Sm^*)$

HOWEVER

Eu

ν

Sm^* ← Sm^* produced with boost in the $-z$ direction

$-z$

LAB

Sm^*

CdM

Sm^*

so if γ emitted in $-z$

$\Rightarrow$ it will get a boost in $-z$

$\Rightarrow$ E increases

$\Rightarrow$ goes back to resonant 961 keV

IT JUST HAPPENS to regain exactly the energy it needs

THIS ONLY HAPPENS WHEN γ emitted in direction of Sm^*

RECAP: Selecting γ that are emitted in direction of Sm^* flight:

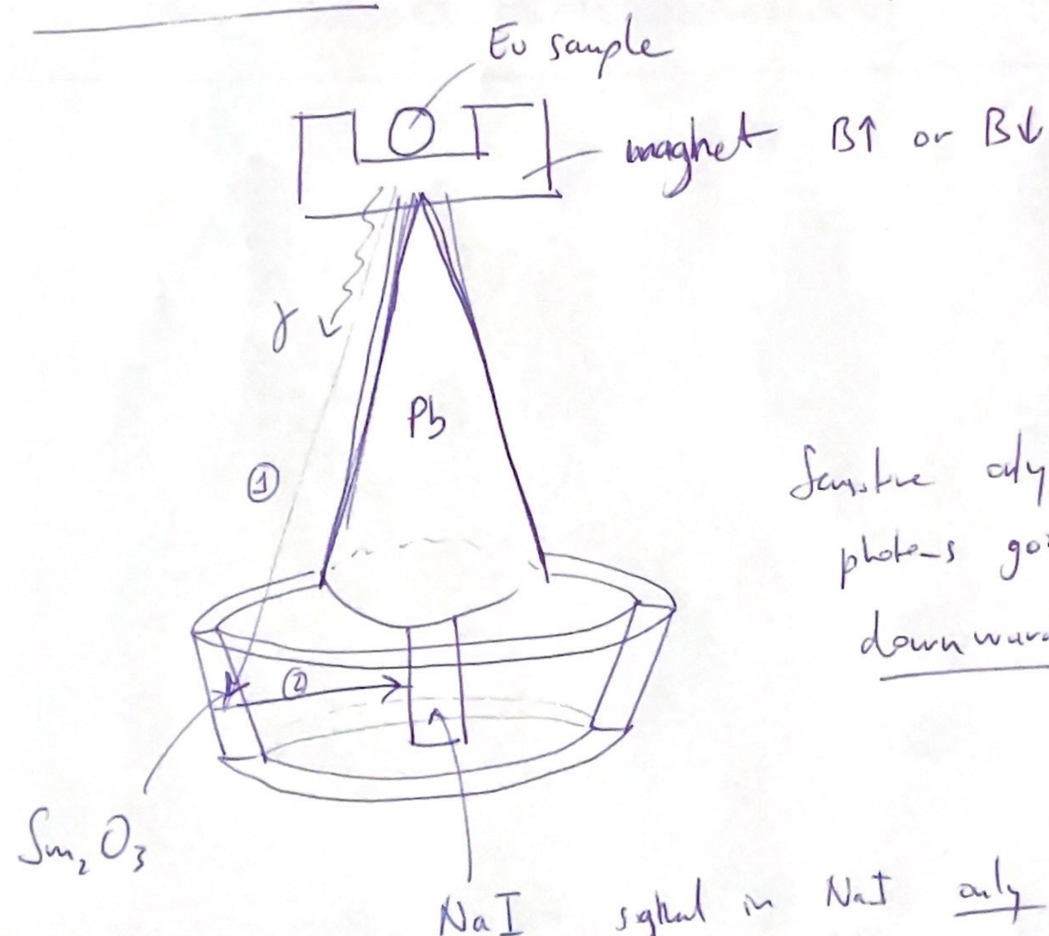
$\Rightarrow$ ① they have same k as neutrino

② they have $E = \Delta E(Sm, Sm^*)$

resonance

$\Rightarrow$ can be reabsorbed by Sm

EXPERIMENTAL SETUP

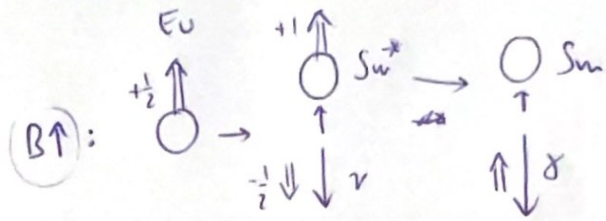


Sensitive only to photons going <u>downwards</u>

signal in NaI <u>only</u> if γ emitted downwards and with right energy

CASES

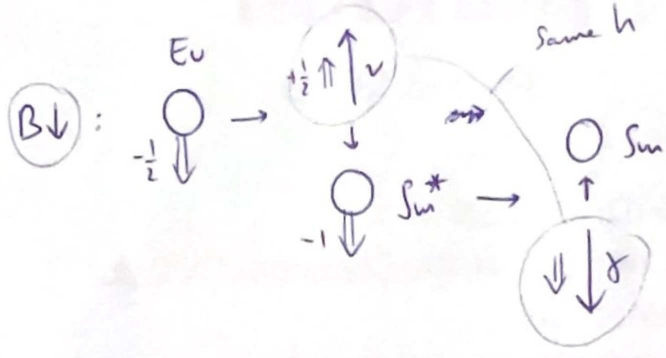
if $h(\nu) = +1$



NO BOOST

$E_\gamma < \Delta E$

NO COUNTS

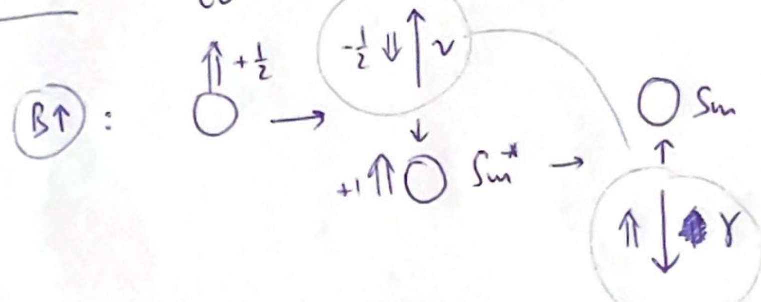


YES BOOST

$E_\gamma = \Delta E$

YES COUNTS

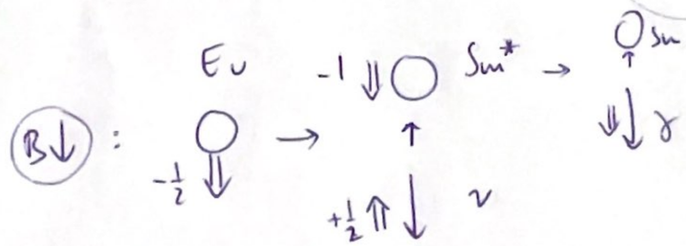
if $h(\nu) = -1$



YES BOOST

$E_\gamma = \Delta E$

YES COUNTS



NO BOOST

NO COUNTS

SO

	$h_\nu = +1$	$h_\nu = -1$
B↑	NO COUNTS	YES COUNTS
B↓	YES COUNTS	NO COUNTS

DATA compatible with <u>only</u> $h_\nu = -1$

$\Rightarrow$ WEAK INTERACTIONS only see

NEUTRINOS with $h=-1$

(and antineutrinos with $h=+1$)

WHAT ABOUT NEUTRINOS with $h=+1$?

$q=0 \Rightarrow$ no EM interaction

color $=0 \rightarrow$ ~~…~~ no strong

$m=0 \Rightarrow$ no gravity (and no Higgs)

$h=+1 \Rightarrow$ no weak

$\Rightarrow$ neutrinos with $h=+1$ DO NOT EXIST IN SM

(may have been produced at big bang
but then unable to interact with anything
else $\rightarrow$ so they have remained untouched)

BUT AS SAID HELICITY IS NOT INVARIANT

So if weak int. really "saw" only $h=-1$

$\Rightarrow$ weak int are not invariant

$\rightarrow$ ~~not~~ a good physical theory!

WHAT MATTERS IS CHIRALITY

$$\psi(x) = \underbrace{\tfrac{1}{2}(1+\gamma^5)}_{P_R}\psi + \underbrace{\tfrac{1}{2}(1-\gamma^5)}_{P_L}\psi$$

$$\equiv \underset{\text{"RIGHT"}}{\psi_R(x)} + \underset{\text{"LEFT"}}{\psi_L(x)}$$

INVARIANT

→ WEAK INTERACTIONS ONLY COUPLE TO LEFT FIELDS

NOW, for massless particles : HELICITY = CHIRALITY

$\Rightarrow$ $h = -1 \iff$ LEFT

$h = +1 \iff$ RIGHT

invariant

FOR MASSIVE PARTICLES HELICITY $\neq$ CHIRALITY

depends on frame,
on β of particle in given frame

let's take electron with β

if $h(e) = -1$ helicity $= -1$

$\Rightarrow$ this state has both e_L and e_R components

$\Leftrightarrow$ $h_e = -1 \neq \psi = e_L$

there is $e_R \neq 0$ but suppressed by $(1-\beta)$

that is why $\pi^\pm \to \mu^\pm \nu_\mu$

$\pi^- \to \mu^- \bar{\nu}_\mu$

$\pi^- \to e^- \bar{\nu}_e$

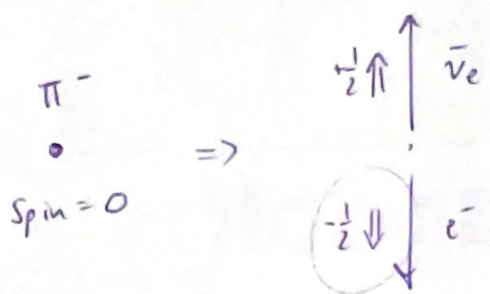
$m(\pi^-) \sim 140$ MeV

$m(\mu^-) \sim 106$ MeV

$m(e^-) \sim 0.5$ MeV

$\Rightarrow$ $\pi^- \to e^- \bar{\nu}_e$ is favored by phase space

BUT in π^- rest frame



massless $\Rightarrow$ can only $\exists$ with $h = +1$

$\Rightarrow$ to conserve spin $\underline{\underline{h(e^-) = +1}}$

only the <u>LEFT</u> part of this electron is involved in WEAK int

for particles:

$h = -1$

$\xrightarrow{\Leftarrow}$ has $\psi_L \sim \frac{1}{2}(1+\beta)$

$\psi_R \sim \frac{1}{2}(1-\beta)$

$h = +1$

$\xrightarrow{\Rightarrow}$ has $\psi_R \sim \frac{1}{2}(1+\beta)$

$\psi_L \sim \frac{1}{2}(1-\beta)$

(OPPOSITE FOR ANTIPARTICLES)

in $\pi^- \to e^- \bar{\nu}_e$

$$\beta_e = 0.99997 \quad (ex) \quad \text{and} \quad h = +1$$

$\Rightarrow$ ψ_L is heavily suppressed

for $\pi^- \to \mu^- \bar{\nu}_\mu$

$$\beta_\mu = 0.27$$

THIS IS WHY $R_\pi = \dfrac{\pi \to e\nu}{\pi \to \mu\nu} \sim 10^{-4}$

WEAK FORCE INTERACTS

ONLY WITH $\psi_L(x) \leftarrow$ PARTICLES

$\psi_R(x) \leftarrow$ ANTIPARTICLES

$\Leftrightarrow$ ONLY LEFT (RIGHT) COMPONENT OF $\psi(x)$ PARTICIPATES ~~TO~~ WEAK INTERACTIONS FOR PARTICLES (ANTIPARTICLES)