VI. Probing the weak interaction

1. Phenomenology of weak decays
2. Parity violation and neutrino helicity
3. V-A theory
4. Structure of neutral currents

The weak interaction was and is a topic with a lot of surprises:

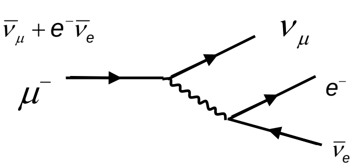
Past: Flavor violation, P and CP violation.
Today: Weak decays used as probes for new physics

1. Phenomenology of weak decays

All particles (except photons and gluons) participate in the weak interaction. At small q^2 weak interaction is shadowed by strong and electro-magnetic effects.

• Observation of weak effects only possible if strong/electro-magnetic processes are forbidden by conservation laws:

$\mu^- \rightarrow \bar{\nu}_\mu + e^- \bar{\nu}_e$



$\tau = 2.6 \cdot 10^{-6}\,\mathrm{s}$

Electromagnetic decay $\mu^- \rightarrow e^- \gamma$ forbidden by lepton number conservation

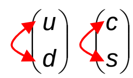
•In addition the observation of interference effects is possible (e.g. atomic parity violation: γ/Z interference).

1.1 Weak hadronic decays

a) Dominant decay modes (quark level)

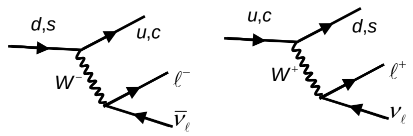
$d \to u\, \ell^- \bar{\nu}_\ell \qquad u \to d\, \ell^+ \nu_\ell$

$s \to c\, \ell^- \bar{\nu}_\ell \qquad c \to s\, \ell^+ \nu_\ell$



$M^2 \sim \cos^2\theta_c \sim 0.95$

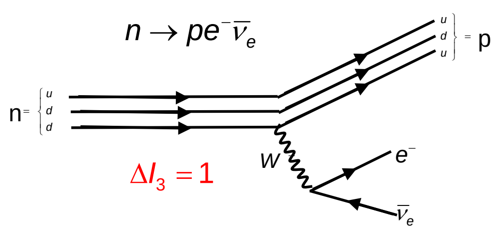
Cabibbo angle: $\theta_c \approx 0.22$



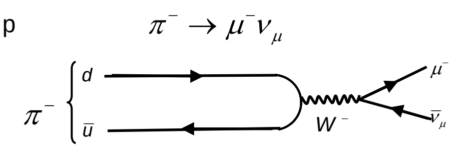
If q^2 is large enough the W can also decay to (u, $\bar{d}$) or ($\bar{u}$ d) quark pairs

Using the the "quark level" decay one can describe weak hadron decays (treating the not weakly interacting quarks as spectators)

$n \to p e^- \bar{\nu}_e$ $\qquad$ $\pi^- \to \mu^- \nu_\mu$



$\Delta I_3 = 1$

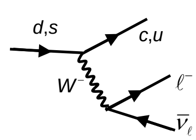


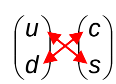
$\Delta I = 1 \quad \Delta I_3 = 1$

b) suppressed decay modes

$d \to c\, \ell^- \bar{\nu}_\ell \qquad u \to s\, \ell^+ \nu_\ell$

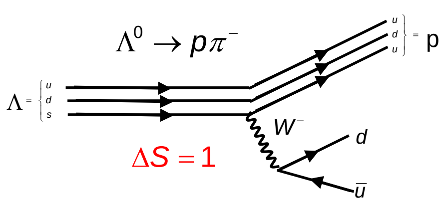
$s \to u\, \ell^- \bar{\nu}_\ell \qquad c \to d\, \ell^+ \nu_\ell$



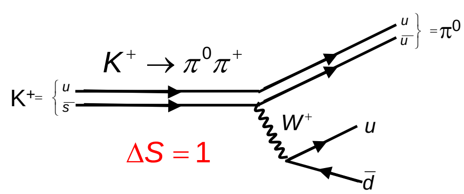


$M^2 \sim \sin^2\theta_c \sim 0.05$

$\Lambda^0 \to p \pi^-$ $\qquad$ $K^+ \to \pi^0 \pi^+$



$\Delta S = 1$

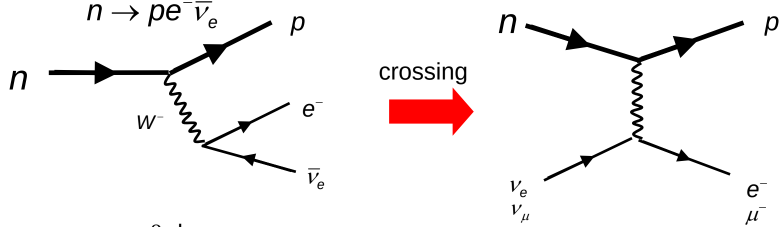


$\Delta S = 1$

Weak interaction does not conserve strong isospin, strangeness or other quark flavor numbers. Lepton number is conserved.

1.2 Neutrino interactions

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



β decay

Neutrino-nucleon scattering

Very small cross section for νN scattering: $\sigma(\nu N) \approx E_\nu[\text{GeV}]\text{x}10^{-38}\ \text{cm}^2$
$= E_\nu[\text{GeV}]\text{x}10\ \text{fb}$

- intense neutrino beams
- large instrumented targets

(see also DIS neutrino nucleon scattering)

2. Parity violation

Reminder: Parity transformations (**P**) = space inversion

$$P\psi(t,\vec{x}) = \psi'(t,\vec{x}) = \psi(t,-\vec{x})$$

⇔ mirroring at plane + rotation around axis perpendicular to plane

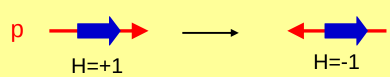
⇒ To test P symmetry it is sufficient to study the process in the "mirrored system": physics invariant under rotation

P transformation properties:

$$P: \quad \vec{r} \to -\vec{r}$$
$$t \to t$$
$$\vec{p} \to -\vec{p}$$
$$\vec{\ell} = \vec{r} \times \vec{p} \to \vec{\ell} \quad \text{Axial/pseudo vector}$$

e.g.: Helicity operator

$$H = \frac{\vec{s}\cdot\vec{p}}{|\vec{s}||\vec{p}|} \xrightarrow{P} -\frac{\vec{s}\cdot\vec{p}}{|\vec{s}||\vec{p}|} \quad \text{(pseudo-scalar)}$$



2.1 Historical θ/τ puzzle (1956)

Until 1956 parity conservation as well as T and C symmetry was a “dogma”:
→ very little experimental tests done

In 1956 Lee and Yang proposed parity violation in weak processes.

<u>Starting point:</u> Observation of two particles θ^+ and τ^+ with exactly equal mass, charge and strangeness **but** with different parity:

$$\theta^+ \to \pi^+\pi^0 \quad w/ \quad P(\theta^+) = P(\pi)^2(-1)^\ell \to J^P(\theta^+) = 0^+, 1^-$$
$$\tau^+ \to \pi^+\pi^+\pi^- \quad\quad P(\tau^+) = P(\pi)^3(-1)^{2\ell} \to J^P(\tau^+) = 0^-, 2^-$$

Lee + Yang: θ^+ and τ^+ same particle, but decay violates parity

⇒ particle is K^+:

$$K^+(0^-) \to \pi^+\pi^0 \qquad \text{P is violated}$$
$$K^+(0^-) \to \pi^+\pi^+\pi^- \qquad \text{P is conserved}$$

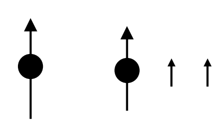
To search for possible P violation, a number of experimental tests of parity conservation in weak decays has been proposed:

1957 Observation of P violation in nuclear β decays by Wu et al.

2.2 Observation of parity violation, Wu et al. 1957

Idea: Measurement of the angular distribution of the emitted e^- in the decay of polarized ^{60}Co nuclei

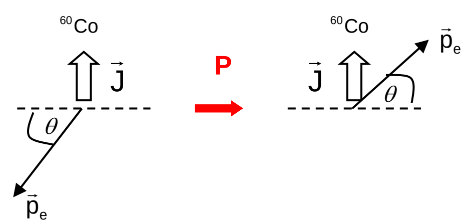
$$^{60}\text{Co} \to {}^{60}\text{Ni}^* + e^- + \bar{\nu}_e$$



$$\underbrace{J=5 \qquad J=4}$$

Gamov-Teller Transition ΔJ=1

(see section 3.1)



Observable: $\vec{J}\cdot\vec{p}_e$ → $-\vec{J}\cdot\vec{p}_e$

If P is conserved, the angular distribution must be symmetric in θ (symmetric to dashed line): transition rates for $\vec{J}\cdot\vec{p}_e$ and $-\vec{J}\cdot\vec{p}_e$ are identical.

Experiment: Invert Co polarization and compare the rates at the same position θ.

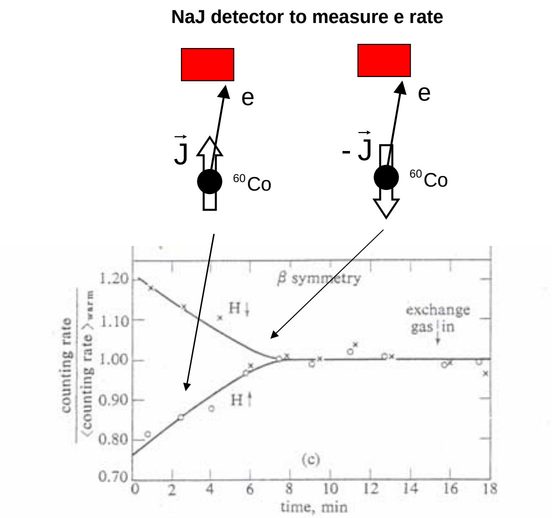
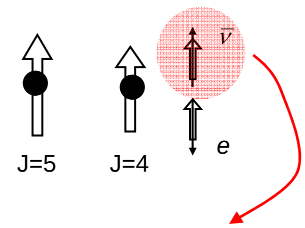


Figure 9-12 Gamma anisotropy (as determined from the two NaI counters) and beta asymmetry for the polarizing field pointing up and down as a function of time. The times for disappearance of the beta and gamma asymmetry coincide; this is the warm-up time. The warm-up time for the sample is approximately 6 min and the counting rates for the warm unpolarized sample are independent of the field direction. [From C. S. Wu, E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson, *Phys. Rev.*, **105**, 1413 (1957).]

Result:

Electron rate opposite to Co polarization is higher than along the ^{60}Co polarization:
parity violation

Qualitative explanation:



Consequence of existence of only left-handed (LH) neutrinos (RH anti-neutrinos)

Electron polarization in β decays

$$\boxed{H_{e^-} = -\frac{v}{c}}$$

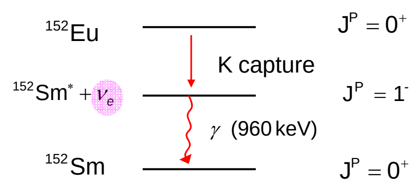
2.3 Determination of the neutrino helicity

Goldhaber et al., 1958

Indirect measurement of the neutrino helicity in a K capture reaction:

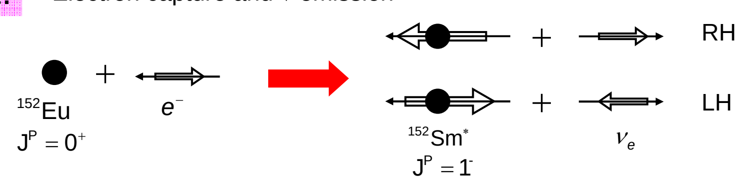
$$^{152}\mathrm{Eu} + e^- \rightarrow {}^{152}\mathrm{Sm}^* + \nu_e$$

$$E_\nu \approx 950\,\mathrm{KeV}$$



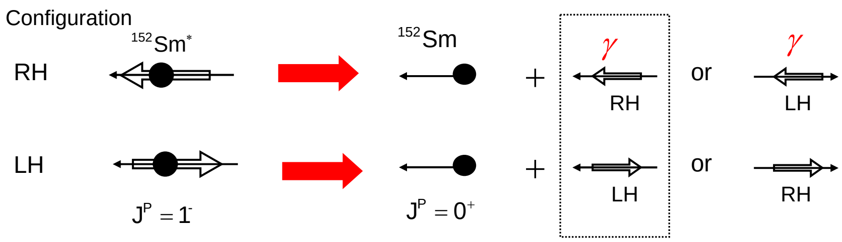
Idea of the experiment:

1. Electron capture and ν emission



Sm undergoes is small **recoil (p_{recoil} =950 KeV)**. Because of angular momentum conservation Spin J=1 of Sm* is opposite to neutrino spin.
Important: **neutrino helicity is transferred to the Sm nucleous.**

2. γ emission: ${}^{152}\text{Sm}^*(J^P = 1^-) \to {}^{152}\text{Sm}(J^P = 0^+) + \gamma$



Photons along the Sm recoil direction carry the polarization of the Sm* nucleus

- How to select photons along the recoil direction ? $\Rightarrow$ 3
- How to determine the polarization of these photons ? $\Rightarrow$ 4

3. Resonant photon scattering: $\gamma + {}^{152}\text{Sm} \to {}^{152}\text{Sm}^* \to {}^{152}\text{Sm} + \gamma$

Resonant scattering:

To compensate the nuclear recoil, the photon energy must be slightly larger than 960 keV.

This is the case for photons which have been emitted in the direction of the Eu$\to$Sm recoil (Doppler-effect).

Resonant scattering only possible for “forward” emitted photons, which carry the polarization of the Sm* and thus the polarization of the neutrinos.

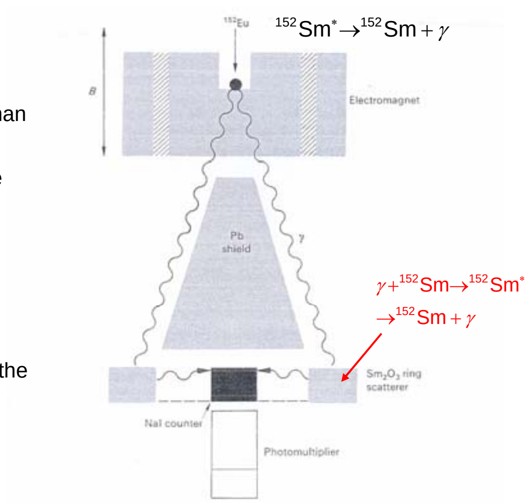


Fig. 7.8. Schematic diagram of the apparatus used by Goldhaber *et al.*, in which γ-rays from the decay of ^{152}Sm*, produced following K-capture in ^{152}Eu, undergo resonance scattering in Sm_2O_3 and are recorded by a sodium iodide scintillator and photomultiplier. The transmission of photons through the iron surrounding the source depends on their helicity and the direction of the magnetic field **B**.

4. Determination of the photon polarization

Exploit that the transmission index through magnetized iron is polarization dependent: <u>Compton scattering in magnetized iron</u>

γ

LH

$\vec{B}$

Polarization of electrons in iron

(to minimize pot. energy)

LH photons cannot be absorbed:

Good transmission

γ

RH

$\vec{B}$

Polarization of electrons in iron

Absorption leads to spin flip

RH photons undergo Compton scattering: Bad transmission

Photons w/ polarization anti-parallel to magnetization undergo less absorption

Experiment

Sm* emitted photons pass through the magnetized iron. Resonant scattering allows the photon detection by a NaJ scintillation counter. The counting rate difference for the two possible magnetizations measure the polarization of the photons and thus the helicity of the neutrinos.

<u>Results:</u> $P_\gamma = -0.66 \pm 0.14$

→ photons from Sm* are left-handed. The measured photon polarization is compatible with a neutrino polarization of H=–1.

From a calculation with 100% photon polarization one expects a measurable value $P_\gamma \sim 0.75$. Reason is the finite angular acceptance.
→ Also not exactly forward-going γ's can lead to resonant scattering.

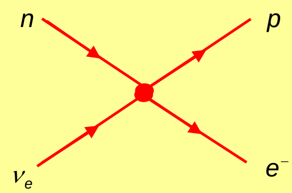
Summary: Lepton polarization in β decays

	e^-	e^+	ν	$\bar{\nu}$
H	-v/c	+v/c	-1	+1

3. "V-A Theory" for charged current weak interactions

3.1 Nuclear β decay

Fermi's original ansatz for $n \to p\, e^- \, \bar{\nu}_e$



4-fermion "point" interaction of fermion vector currents:

$$M = \frac{G_F}{\sqrt{2}} \cdot J_{N,\mu} \cdot J_e^{\mu +} = \frac{G_F}{\sqrt{2}} \cdot \left(\bar{u}_p \gamma_\mu u_n\right) \cdot \left(\bar{u}_e \gamma_\mu v_\nu\right)$$

Fermi coupling constant

Problem: ansatz cannot explain parity violation

More general ansatz by Gamov & Teller: (Lorentz invariant current current form)

$$M = \sum_i C_i \left(\bar{u}_p \Gamma_i u_n\right) \cdot \left(\bar{u}_e \Gamma_i v_\nu\right)$$

$$i = \mathrm{S, P, V, A, T}$$

$\bar{u}_p \Gamma_i u_n$

S: $\bar{u}_p u_n$

P: $\bar{u}_p \gamma^5 u_n$

V: $\bar{u}_p \gamma^\mu u_n$

A: $\bar{u}_p \gamma^5 \gamma^\mu u_n$

T: $\bar{u}_p \sigma^{\mu\nu} u_n$

Nuclear transitions in non-relativistic limit:

S:	$\bar{u}_p u_n \to u_p^+ u_n$			No spin change
P:	$\bar{u}_p \gamma^5 u_n \to 0$			
V:	$\bar{u}_p \gamma^\mu u_n \to u_p^+ u_n$	if μ=0, else =0		No spin change
A:	$\bar{u}_p \gamma^5 \gamma^\mu u_n \to u_p^+ \sigma^i u_n$	If μ=i=1,..,3, else =0		spin change
T:	$\bar{u}_p \sigma^{\mu\nu} u_n \to u_p^+ \sigma^i u_n$	If μ=j ν=k j,k=1,..,3, and i,j,k cyclic, else =0		spin change

Fermi-Transitions: e.g. $^{14}O \rightarrow {}^{14*}N + e^{+} + \nu \; (0^{+} \rightarrow 0^{+})$

$\Rightarrow$ S or V

Gamov-Teller - Transitions: e.g. $^{6}He \rightarrow {}^{6}Li + e^{-} + \overline{\nu} \; (0^{+} \rightarrow 1^{+})$

$\Rightarrow$ A or T

+ Parity violation

+ neutrino helicity

+ muon decay properties together with universality

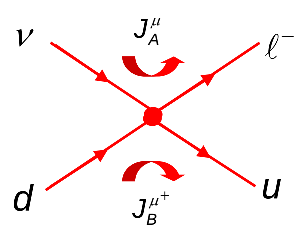
$\Rightarrow$ V – A Theory

$$M = \frac{G_F}{\sqrt{2}} \left(\overline{u}_p \gamma^{\mu} (\overbrace{c_V - c_A \gamma^5}^{V\;-\;A}) u_n \right) \cdot \left(\overline{u}_e \gamma^{\mu} (\overbrace{1 - \gamma^5}^{V-A}) v_{\nu} \right)$$

c_V, c_A vector and axial-vector couplings of nucleons:

$$c_A / c_V = 1.262 \pm 0.005$$

3.2 V-A ansatz for fundamental fermions



J_A and J_B are lepton and quark currents

$$J_{\ell}^{\mu} = \overline{u}_{\ell} \gamma^{\mu} (1 - \gamma^5) u_{\nu}$$

$$J_{q}^{\mu} = \overline{u}_{u} \gamma^{\mu} (1 - \gamma^5) u_{d}$$

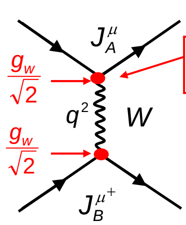
$$M = \frac{G_F}{\sqrt{2}} \cdot J_{A,\mu} \cdot J_B^{\mu +}$$

Reminder

$$u_L = \frac{1}{2}(1 - \gamma^5) u$$

$$u_R = \frac{1}{2}(1 + \gamma^5) u$$

According today's understanding of the 4-fermion coupling is the $q^2 \rightarrow 0$ limit of W propagator:



g_w = coupling for weak interaction

$$M = \frac{g_w}{\sqrt{2}} \cdot \frac{1}{2} J_{A,\mu} \underbrace{\frac{\left(g_{\mu\nu} - \frac{q_\mu q_\nu}{M_W^2}\right)}{q^2 - M_W^2}}_{\text{for } q^2 \rightarrow 0: \; = \frac{1}{M_W^2}} \cdot \frac{g_w}{\sqrt{2}} \cdot \frac{1}{2} J_B^{\nu +}$$

$$\frac{G_F}{\sqrt{2}} = \frac{g_w^2}{8 M_W^2}$$

With $G_F \approx 1.16 \times 10^{-5}\,\text{GeV}^{-2}$ follows w $M_W \approx 80\,\text{GeV}$: $g_w \approx 0.65$

3.3 Helicity and chirality

solution spin $\uparrow$

i.e. helicity $\lambda = +\frac{1}{2}$

$$u_1(p) = \sqrt{E+m} \cdot \begin{pmatrix} 1 \\ 0 \\ \frac{p_z}{E+m} \\ \frac{p_x + ip_y}{E+m} \end{pmatrix}$$

$\vec{p}$ along z

$$u_1(p) = \sqrt{E+m} \cdot \begin{pmatrix} 1 \\ 0 \\ p/(E+m) \\ 0 \end{pmatrix}$$

solution spin $\downarrow$

i.e. helicity $\lambda = -\frac{1}{2}$

$$u_2(p) = \sqrt{E+m} \cdot \begin{pmatrix} 0 \\ 1 \\ \frac{p_x - ip_y}{E+m} \\ \frac{-p_z}{E+m} \end{pmatrix}$$

$\vec{p}$ along z

$$u_2(p) = \sqrt{E+m} \cdot \begin{pmatrix} 0 \\ 1 \\ 0 \\ -p/(E+m) \end{pmatrix}$$

Helicity operator $\frac{1}{2}\frac{\vec{\Sigma}\cdot\vec{p}}{|\vec{p}|}$ Measurable quantity !

Chirality operator:

Projection of left- and right-handed components of spinor u

$$\boxed{u_L = \frac{1}{2}(1-\gamma^5)u \qquad u_R = \frac{1}{2}(1+\gamma^5)u}$$

$$\gamma^5 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

Not directly measurable.

$$\frac{1-\gamma^5}{2}u_1 = \frac{1}{2}\sqrt{E+m} \cdot \underbrace{\left(1 - \frac{p}{E+m}\right)}_{\approx 0 \text{ for } E >> m} \cdot \begin{pmatrix} 1 \\ 0 \\ p/(E+m) \\ 0 \end{pmatrix} \rightarrow 0 \quad \text{for } E >> m$$

$$\frac{1-\gamma^5}{2}u_2 = \underbrace{\frac{1}{2}\sqrt{E+m} \cdot \left(1 + \frac{p}{E+m}\right)}_{\approx \sqrt{E} \quad \text{for } E >> m} \cdot \begin{pmatrix} 0 \\ 1 \\ 0 \\ p/(E+m) \end{pmatrix} \rightarrow u_2 \quad \text{for } E >> m$$

In the relativistic limit helicity states are also chirality eigenstates.

Polarization for particles with finite mass

Left handed spinor component $u_L = \frac{1-\gamma^5}{2}(u_1 + u_2)$

$u_1, u_2 \rightarrow u_L, u_R$

$$Pol = \frac{P(\lambda=+1/2) - P(\lambda=-1/2)}{P(\lambda=+1/2) + P(\lambda=-1/2)} = \frac{(1-p/(E+m))^2 - (1+p/(E+m))^2}{(1-p/(E+m))^2 + (1+p/(E+m))^2}$$

$$= -\frac{p}{E} = -\frac{v}{c}$$

i.e. the LH spinor component for a particle with finite mass is not fully in the helicity state “spin down” (λ=-½)

Measurable quantity !

Probability for “wrong” helicity: $= 1 - \frac{v}{c}$