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:

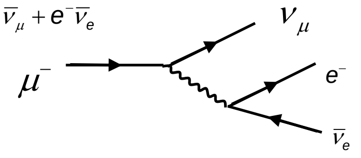
Past: Flavor violation, P and CP violation.
Today: Weak decays used as probes for new physics

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:

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



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

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

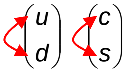
- In addition the observation of interference effects is possible (e.g. atomic parity violation: γ/Z interference).

1.1 Weak hadronic decays

a) Dominant decay modes (quark level)

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

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

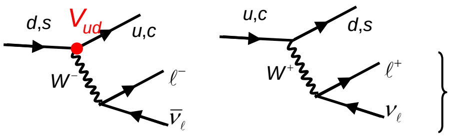


Historically

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

Cabibbo angle: $\theta_c \approx 0.22$

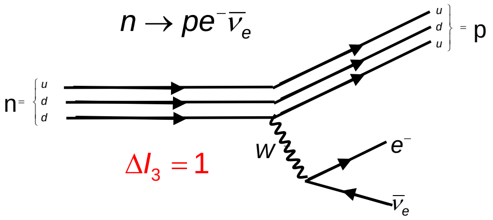
Today: CKM Matrix



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

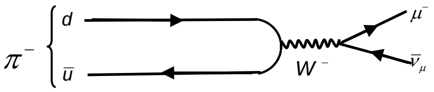
Using the the "quark level" decay one can describe weak hadron decays (treating the quarks which are not weakly interacting as spectators)

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



$\Delta I_3 = 1$

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

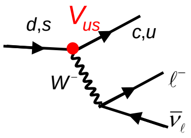


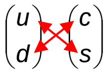
$\Delta I = 1 \quad \Delta I_3 = 1$

b) suppressed decay modes

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

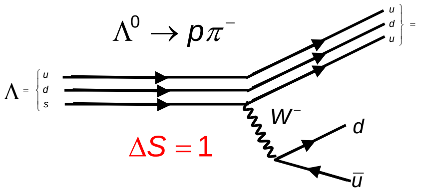
$s \to u\,\ell^-\bar{\nu}_\ell$ $\quad c \to d\,\ell^+\nu_\ell$





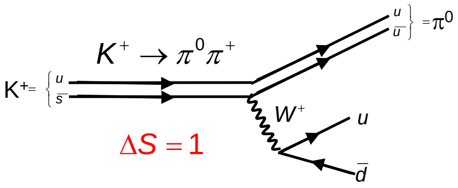
$M^2 \sim \sin^2\theta_c \sim 0.05$

$\Lambda^0 \to p\pi^-$



$\Delta S = 1$

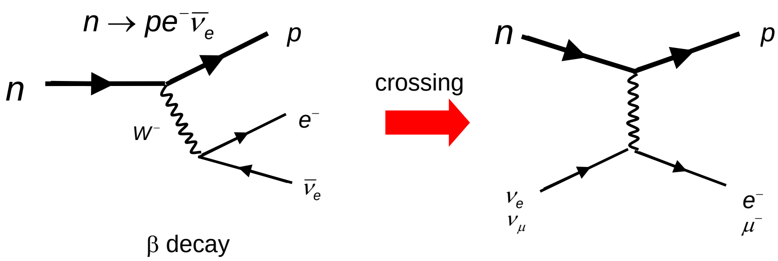
$K^+ \to \pi^0\pi^+$



$\Delta S = 1$

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

1.2 Neutrino interactions



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

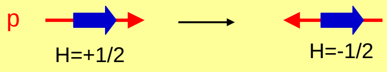
⇒ To test P symmetry it is sufficient to study the process in the "mirrored system": physics invariant under rotation

P transformation properties:

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

e.g.: Helicity operator

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



2.1 Historical θ/τ puzzle (1956)

P violation in pion decay:
Heintze vs. Jensen

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.

Starting point: Observation of two particles $\overbrace{\theta^+ \text{ and } \tau^+}^{\text{Historical names}}$ with exactly equal mass, charge and strangeness **but** with different parity:

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

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

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

⇒ particle is K⁺:

$K^+(0^-) \to \pi^+\pi^0$ P is violated

$K^+(0^-) \to \pi^+\pi^+\pi^-$ P is conserved

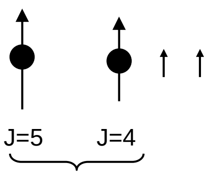
To search for possible P violation, a number of experimental tests of parity conservation in weak decays has been proposed:

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

2.2 Observation of parity violation, C.S. Wu et al. 1957

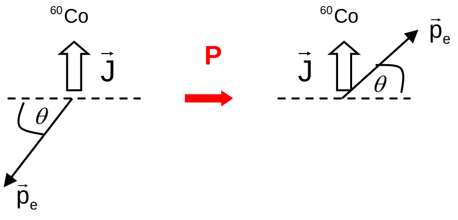
Idea: Measurement of the angular distribution of the emitted e^- in the decay of polarized ^{60}Co nuclei

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



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.

NaJ detector to measure e rate

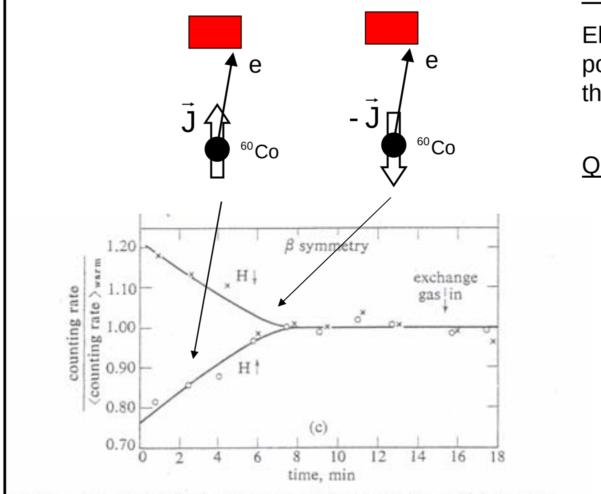
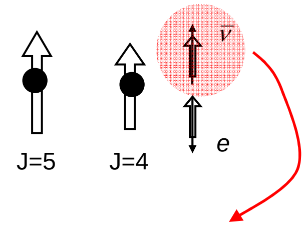


Figure 9-12 Gamma anisotropy (as determined from the two NaI counters) and beta asymmetry for the polarizing field pointing up and down as a function of time. The times for disappearance of the beta and gamma asymmetry coincide; this is the warm-up time. The warm-up time for the sample is approximately 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

$$\boxed{H_{e^-} = -\frac{1}{2}\frac{v}{c}}$$

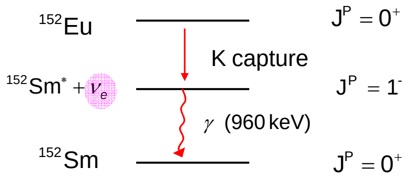
2.3 Determination of the neutrino helicity

Goldhaber et al., 1958

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

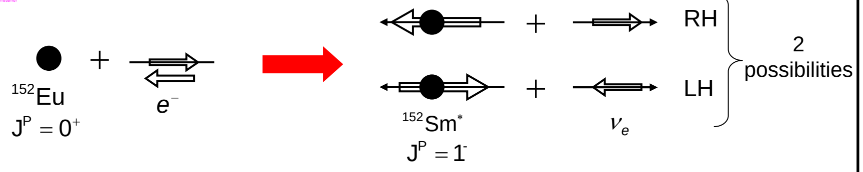
$$^{152}\mathrm{Eu} + e^- \rightarrow {}^{152}\mathrm{Sm}^* + \nu_e$$

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



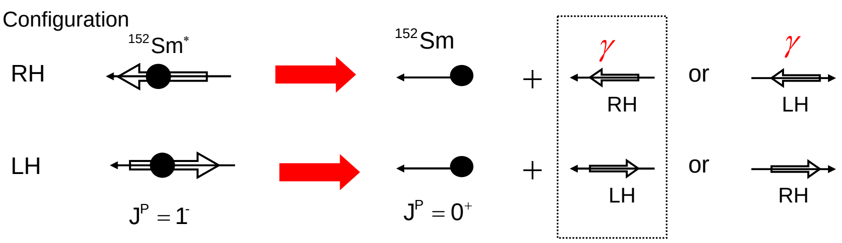
Idea of the experiment:

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: ${}^{152}\mathrm{Sm}^*(J^P=1^-)\rightarrow{}^{152}\mathrm{Sm}(J^P=0^+)+\gamma$



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

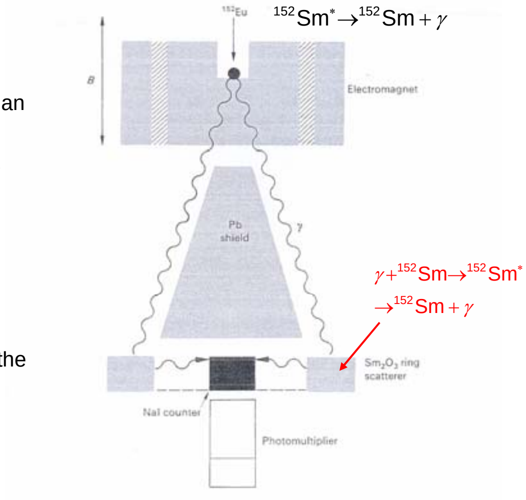
3. Resonant photon scattering: $\gamma+{}^{152}\mathrm{Sm}\rightarrow{}^{152}\mathrm{Sm}^*\rightarrow{}^{152}\mathrm{Sm}+\gamma$

<u>Resonant scattering:</u>

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→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.



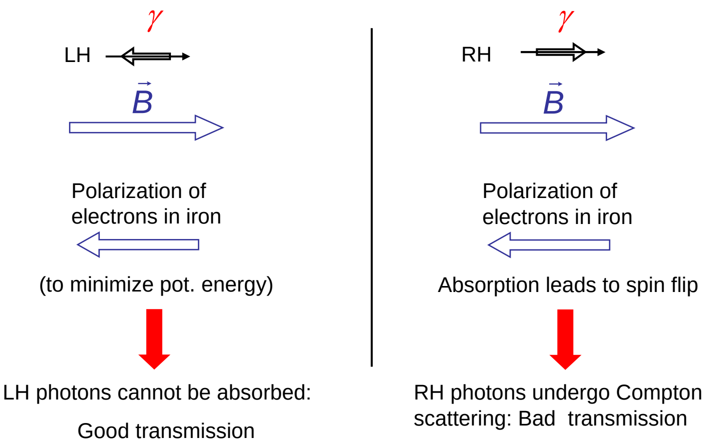
${}^{152}\mathrm{Sm}^*\rightarrow{}^{152}\mathrm{Sm}+\gamma$

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

Fig. 7.8. Schematic diagram of the apparatus used by Goldhaber *et al.*, in which γ-rays from the decay of $^{152}\mathrm{Sm}^*$, produced following K-capture in $^{152}\mathrm{Eu}$, undergo resonance scattering in $\mathrm{Sm_2O_3}$ 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>



LH γ

$\vec{B}$

Polarization of electrons in iron

(to minimize pot. energy)

LH photons cannot be absorbed:

Good transmission

RH γ

$\vec{B}$

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 helicity of H=–1/2.

From a calculation with 100% photon polarization one expects a measurable value P_γ~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

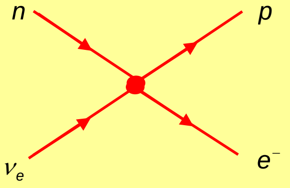
	e^-	e^+	ν	$\bar{\nu}$
$H=\frac{1}{2}\cdot$	-v/c	+v/c	-1	+1

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

What is the Lorentz structure of the weak currents ?

3.1 Nuclear β decay – Historical approach

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)

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

$$\underbrace{i = \mathrm{S, P, V, A, T}}_{\text{Assume most general Lorentz structure}}$$

$\bar{u}_p \Gamma_i u_n$

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. $^{14}O \rightarrow {}^{14*}N + e^{+} + \nu \; (0^{+} \rightarrow 0^{+})$

⇨ S or V

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

⇨ A or T

+ Parity violation

+ neutrino helicity

+ muon decay properties together with universality

⇨ V – A Theory

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

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

$c_A / c_V = 1.2695 \pm 0.0029$ PDG 2004