VI. Probing the weak interaction

1. Phenomenology of weak hadronic decays
2. Neutrino interactions
3. Parity violation
4. V-A theory
5. 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

Remark:

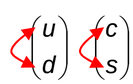
All particles (except photons and gluons) participate in the weak interaction. At small q^2 interaction is shadowed by strong and electro-magnetic effects.

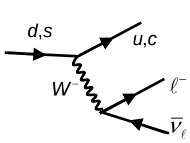
- Observation of weak effects only possible if strong/electro-magnetic processes are forbidden by conservation laws.
- In addition the observation of interference effects is possible (e.g. atomic parity violation).

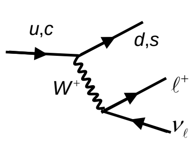
Weak hadronic decays

a) Dominant decay modes (quark level) $\rightarrow$ $M^2 \sim \cos^2\theta_c \sim 0.95$

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



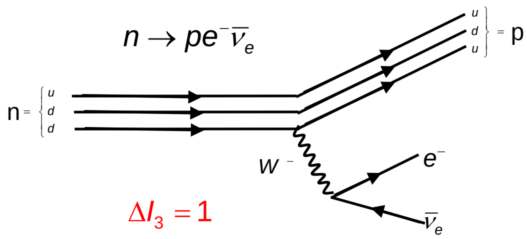




If q^2 is large enough the W can also decay to (u, $\bar{d}$) or ($\bar{u}$ d) quark pairs

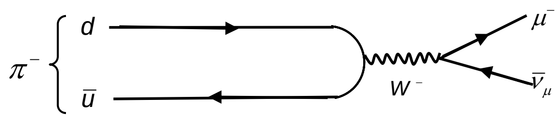
Using the the “quark level” decay one can describe weak hadron decays (treating the not weakly interacting quarks as spectators)

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



$\Delta I_3 = 1$

$\pi^- \to \mu^- \nu_\mu$

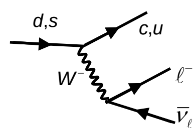


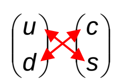
$\Delta I_3 = 1$

b) suppressed decay modes $\rightarrow$ $M^2 \sim \sin^2\theta_c \sim 0.05$

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

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





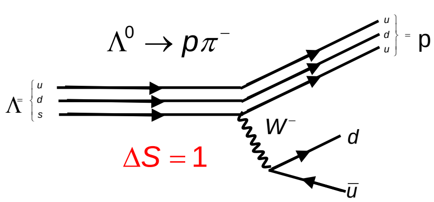
Cabibbo Angle $\theta_c \approx 0.22$ is introduced as a measure of the relative strength of d→u and s→u transitions, e.g. decay rate difference between:

(ignoring phase space):

$\Lambda \to p e^- \bar{\nu}_e \sim \sin^2\theta_c$

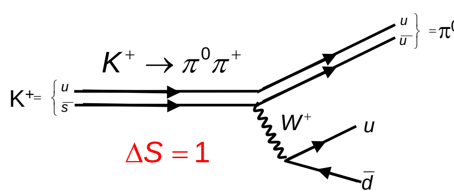
$n \to p e^- \bar{\nu}_e \sim \cos^2\theta_c$

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



$\Delta S = 1$

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



$\Delta S = 1$

c) Selection rules

Quark model allows to deduce selection rules for weak hadronic decays

i. $\Delta S=\pm1$ ($\Delta C=\pm1$) rule

There are no weak decays observed with $\Delta S=2$.

Example: $\Xi \to p\pi$ with $\Delta S=2$ $\to$ BR < 4×10^{-5}

ii. $\Delta S= \Delta Q$ rule

In decays with changes of the strangeness number S, the change ΔS is equal to the change of the charge ΔQ.

allowed

$$\Sigma^- \to n\ e^-\bar{\nu}_e \qquad \Delta S\ \ \Delta Q$$
$$|dds\rangle \quad |ddu\rangle \qquad +1\ \ +1$$

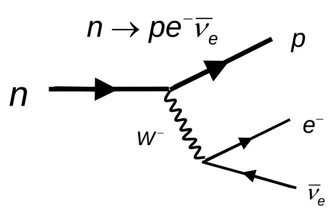
$$\bar{K}^0 \to \pi^-\ e^+\nu_e \qquad \Delta S\ \ \Delta Q$$
$$|d\bar{s}\rangle \quad |d\bar{u}\rangle \qquad -1\ \ -1$$

forbidden

$$\Sigma^+ \to n\ e^+\nu_e \qquad \Delta S\ \ \Delta Q$$
$$|dds\rangle \quad |udd\rangle \qquad +1\ \ -1$$

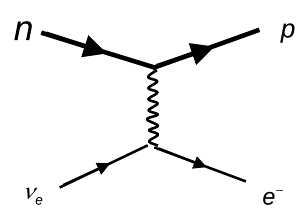
$$\bar{K}^0 \to \pi^+\ e^-\bar{\nu}_e \qquad \Delta S\ \ \Delta Q$$
$$|d\bar{s}\rangle \quad |u\bar{d}\rangle \qquad -1\ \ +1$$

2. Neutrino interactions with hadrons



β decay

crossing



Neutrino-nucleon scattering

Very small cross section for νN scattering: $\sigma(\nu N) \approx E_\nu[\text{GeV}]\times10^{-38}\ \text{cm}^2$
$= E_\nu[\text{GeV}]\times10\ \text{fb}$

→

- intense neutrino beams
- large instrumented targets

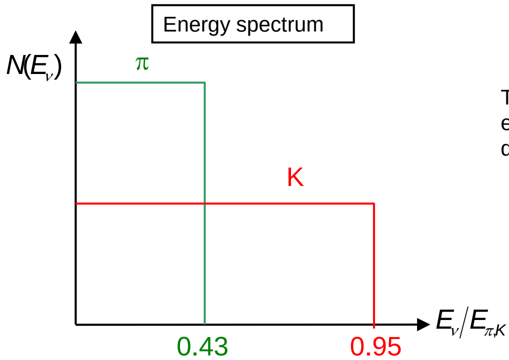
2.1 Neutrino beams

Sources of intense neutrino beams are 2-body decays of intense hadron beams

$$\pi^{\pm} \rightarrow \mu^{\pm} \nu_{\mu} (\overline{\nu}_{\mu}) \qquad K^{\pm} \rightarrow \mu^{\pm} \nu_{\mu} (\overline{\nu}_{\mu})$$

where the pions/kaons are generated in proton-nucleon interactions: p+N→π, K

Energy spectrum

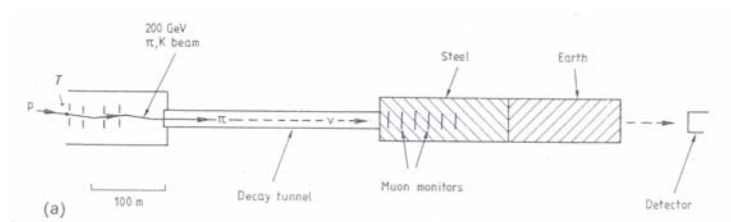


The Lorentz boost transforms the mono-energetic neutrino of the two-body decay into a flat energy spectrum:

$$0 < \frac{E_{\nu}}{E_{\pi,K}} < 1 - \frac{m_{\mu}^2}{m_{\pi,K}^2}$$

Beams contain small admixture (0.5%) of electron neutrinos !

a) Generation of neutrino beams

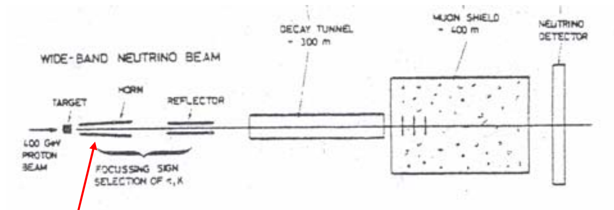


1. ~400 GeV proton beam on a (Be) target: secondary hadrons π, K
2. Possibly: Momentum and charge selection of π's and K's using a focusing system
3. Selected π's and K's enter a decay tunnel: $\pi^{\pm}, K^{\pm} \rightarrow \mu^{\pm} \nu_{\mu} (\overline{\nu}_{\mu})$
4. Remaining hadrons and decay muons are filtered by a massive absorber (~400 m iron, concrete, earth): only neutrinos after absorber

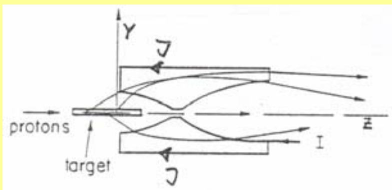
There exist 2 different focusing systems for the selection of π's and K's:

the two systems lead to neutrino beams with much different energy spectra and fluxes.

Wide-band neutrino beam: Magnetic Horn



Magnetic Horn (S. van der Meer)

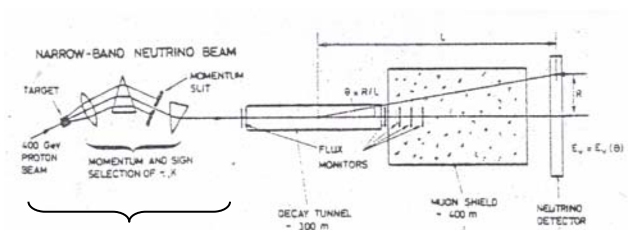


Horn formed from thin aluminum skin

- Short current pulses of 100 to 180 kA
  → large short-time magnetic field perpendicular to particle direction

  → magnetic deflection similar to a paraboloid for hadrons of one charge
- Advantages: use all $\pi^+/K^+ \rightarrow$ **large ν flux**
- Disadvantage: large background of wrong "sign" ν's

Narrow-band neutrino beam:

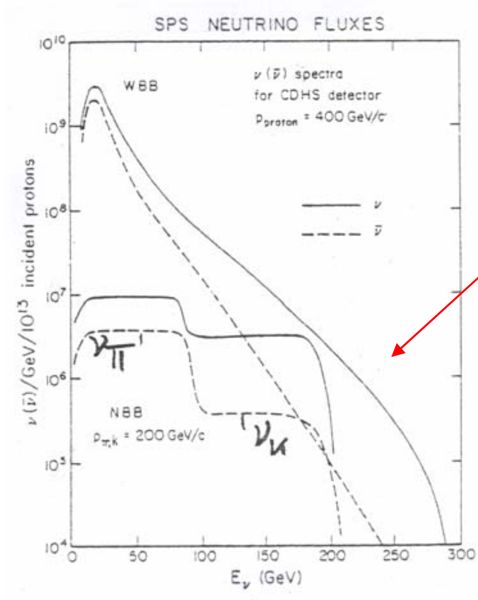


Deflection and focusing magnets to select and focus hadrons (one charge) of a narrow momentum range

➡ $\frac{\Delta p_{K,\pi}}{p_{K,\pi}} \approx 7\%$ (at SPS $p_{K,\pi}$ ~ 200 GeV)

➡ One gets a neutrino beam with a 2-component spectrum

Narrow-band neutrino beam used if one needs to know the exact neutrino flux and wants to achieve max. neutrino energies



At high energies, there are much more ν than $\bar{\nu}$?

Reason:

•High energy neutrinos are produced from K decays:

$pN \to \Lambda \quad K^+$ with $K^+ \to \mu^+ \nu_\mu$

$|uds\rangle |u\bar{s}\rangle$

(associated strange baryon production: no anti-baryon production !!)

2.2 Neutrino detectors

Two detector detector types have been used at neutrino beams:

- Big bubble chambers:

  filled with Ne, freon, lq. H_2, lq. D_2. Max. volumes up to 18 m^3 : BEBC; target mass < 20 tons
- Counter experiments:

  Target material = instrumented iron, marble, concrete with target masses up to 800 tons

Blasenkammer	Zählerexperiment
elementare Targets: freie Protonen und Neutronen	nur komplexe Kerne mit N ≈ Z
Targetmassen : ca. 20 to Neon ca. 1 to H ca. 2.2 to ^2_1D	 ca. 800 to Fe (CDHS, CFRR) ca. 100 to Marmor (CHARM)
misst einzelne Hadronen exklusive Endzustände (s. Abb. S. 64 a)	misst nur Gesamtenergie der Hadronen
mäßige Müonidentifizierung (durch externe Zähler → Abb. 4.9)	sehr gute Müonidentifizierung
sehr gute Elektronidentifizierung	"mäßige" Elektronsignatur nur für leichte Materialien (nicht Fe)

(F.Eisele)

Bubble chamber: BEBC (CERN)

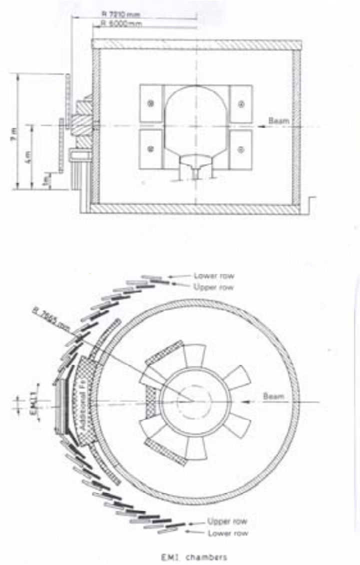
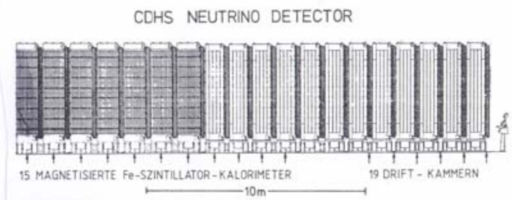


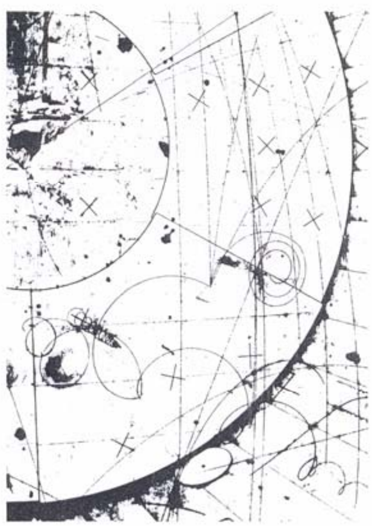
Figure 2.14 Elevation and plan views of the 3.7-m-diameter bubble chamber (BEBC) at CERN. The chamber is filled with liquid hydrogen, deuterium, or neon-hydrogen mixture and is equipped for neutrino experiments with an external muon identifier. This consists of 150 m² of multiwire proportional chambers placed outside the magnet yoke.

Counter experiment: CDHS (CERN)



Wegen des sehr kleinen totalen Wirkungsquerschnitts von Neutrinos mit Nukleonen, der bei 150 GeV Neutrinoenergie nur 10^{-36} cm^2 beträgt, müssen Neutrino-Detektoren massiv sein. Bei dem in Fig. 8.13 abgebildeten Detektor der CERN-Dortmund-Heidelberg-Saclay Kollaboration [HO 78a] dient die Targetmasse von 1500 t Stahl ausserdem drei Zwecken: a) die Eisenplatten mit 3.75 m Durchmesser sind in einer Dicke von 75 cm jeweils durch eine Spule zu einem toroidalen Magneten zusammengefaßt; b) zwischen je zwei Eisenplatten der Dicke 5 cm (für 7 Magnete) bzw. 15 cm (für 8 Magnete) wird durch acht Plastikszintillatoren und 16 Photomultiplier die Ionisationsenergie hadronischer Schauer gemessen; c) Teilchen, die mehr als 2 m Stahl durchqueren, werden als Myonen identifiziert, und ihr

Neutrino event in bubble chamber: BEBC (CERN)



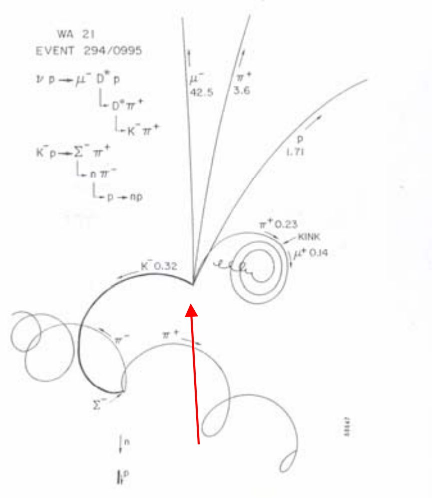


Figure 2.15 Example of charmed-particle production and decay in the hydrogen bubble chamber BEBC exposed to a neutrino beam at the CERN SPS. (Courtesy CERN.)

Muon and electron neutrino induced charged current events:

$$\nu_\mu + n \rightarrow p + \mu^-$$

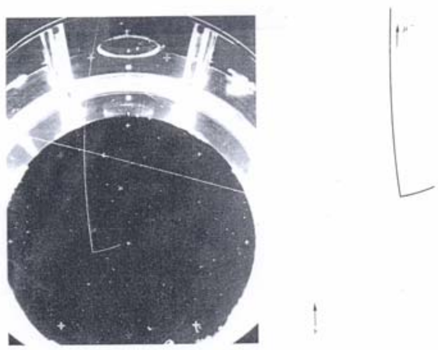


Fig. 6.16 Event attributed to an "elastic" neutrino interaction $\nu_\mu + n \rightarrow p + \mu^-$ in the CERN heavy-liquid bubble chamber, filled with freon (CF_3Br). The negatively charged particle passes out of the chamber without interaction; it was identified as a muon because, in many events of this type, the observed interaction length of the negative particles was very much larger than for strongly interacting particles. The original interaction takes place in a heavy nucleus, and one observes a proton plus a short nuclear fragment.

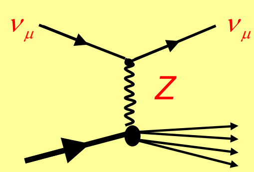
$$\nu_e + n \rightarrow p + e^-$$

Fig. 6.17 Event produced by interaction of an electron-neutrino ν_e: $\nu_e + n \rightarrow p + e^-$. The incident beam consists mostly of muon-neutrinos ν_μ, with a very small admixture of ν_e ($\sim \frac{1}{2}\%$) from the 3-body decays in flight, $K^+ \rightarrow \pi^0 + e^+ + \nu_e$. The high-energy electron secondary is recognized by the characteristic shower it produces by the processes of bremsstrahlung and pair production. The chamber diameter is 1.1 m, and the radiation length in CF_3Br is 0.11 m. The relative numbers of events giving electron and muon secondaries are consistent with the calculated fluxes of ν_e and ν_μ in the beam, and thus confirms conservation of muon number. (Courtesy CERN.)

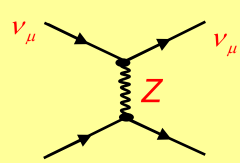
2.3 Discovery of neutral current events

In 1973 the bubble chamber "Gargamelle" has detected neutrino induced reactions without a final state lepton:

$$\nu_\mu + N \rightarrow \nu_\mu + Hadrons$$



$$\nu_\mu + e^- \rightarrow \nu_\mu + e^-$$



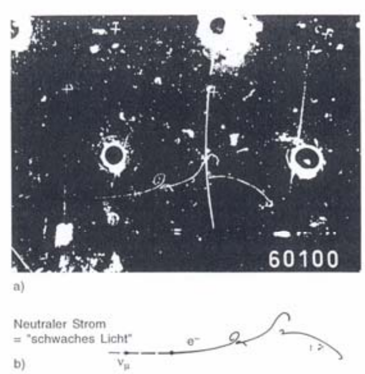


Abb. 9. Dieses erste Ereignis mit einem neutralen schwachen Strom wurde in Aachen entdeckt. Ein Neutrino dringt von links in die Blasenkammer ein (auf dem Bild nicht sichtbar) und wird elastisch an einem Elektron gestreut. Das Elektron ist als rechte Spurkaskade (Bremsstrahlung) zu erkennen. Dieses Bild ist in die Geschichte des CERN eingegangen

One out of three νe→ νe events

"Neutral current events"

For the ratio R

$$R = \frac{\sigma_{NC}(\nu N \to \nu X)}{\sigma_{CC}(\nu N \to \mu X)}$$

Gargamelle measured for neutrino energies larger than $E_\nu \approx 5$ GeV

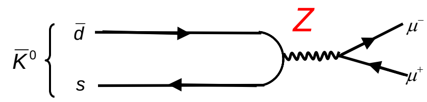
$$R_\nu = 0.307 \pm 0.008$$
$$R_{\bar{\nu}} = 0.370 \pm 0.025$$

i.e. in 1/3 of the cases, neutrinos interaction proceeds via neutral currents.

Flavor changing neutral currents (FCNC) ?

$$\bar{K}^0 \to \mu^+ \mu^-$$

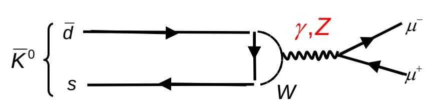
Do flavor changing neutral current reactions of the following type exist ?



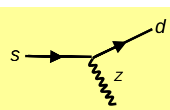
Experimental limit

$$\frac{K_L \to \mu^+\mu^-}{K_L \to all} = (7.2 \pm 0.5) \cdot 10^{-9}$$

Compatible with Standard Model prediction for:



No flavor changing neutral current transitions of the type



3. 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

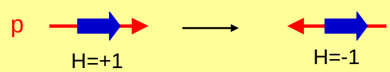
⇒ To test P symmetry it is sufficient to study the process in the "mirrored system": physics invariant under rotation

P transformation properties:

$$P: \quad \vec{r} \to -\vec{r}$$
$$t \to t$$
$$\vec{p} \to -\vec{p}$$
$$E \to E$$
$$\vec{\ell} = \vec{r} \times \vec{p} \to \vec{\ell} \quad \text{(pseudo-vector)}$$

e.g.: Helicity operator

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



3.1 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.

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

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

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

Today: particle is called K^+:

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

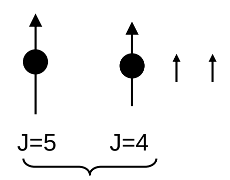
To search for possible P violation a sequence of experimental tests of parity conservation in weak decays have been proposed:

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

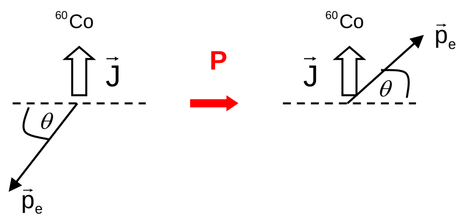
3.2 Observation of parity violation, Wu et al. 1957

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

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



Gamov Teller Transition $\Delta J=1$



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

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

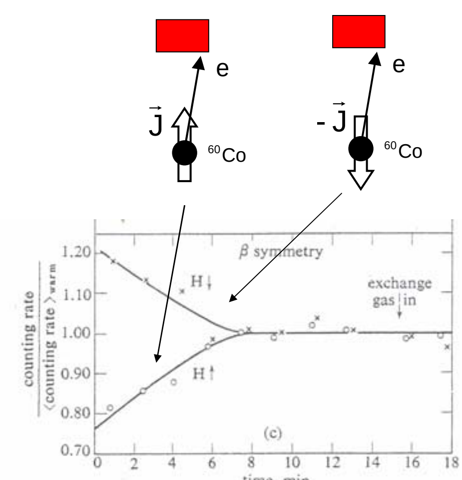
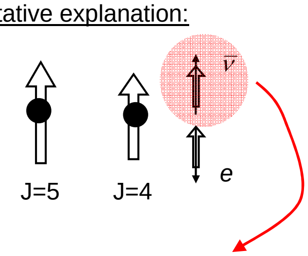


Figure 9-12 Gamma anisotropy (as determined from the two NaI counters) and beta asymmetry for the polarizing field pointing up and down as a function of time. The times for disappearance of the beta and gamma asymmetry coincide; this is the warm-up time. The warm-up time for the sample is approximately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

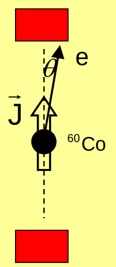
Electron rate opposite to Co polarization is higher than along the ^{60}Co polarization:
parity violation

Qualitative explanation:



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

Electron helicity in nuclear β decays



Because of angular momentum conservation one expects for an electron helicity H the angular distribution I(θ):

$$I(\theta) \sim (1 + H\cos\theta) \qquad H = \frac{\Rightarrow}{\Leftarrow} = \begin{cases} \pm 1 & m = 0 \\ \pm v/c = \pm\beta & m \neq 0 \end{cases}$$

$$\Rightarrow \quad H = P \equiv \frac{I(0) - I(\pi)}{I(0) + I(\pi)}$$

Electron helicity in β decays

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

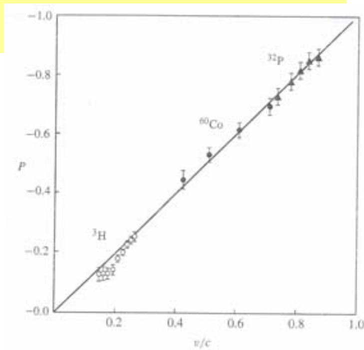


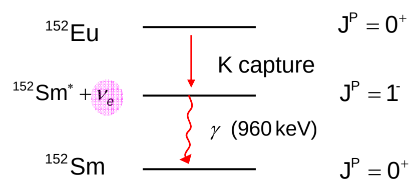
Fig. 7.6. The polarisation P of electrons emitted in nuclear β-decay, plotted as a function of electron velocity. The results demonstrate that $P = -v/c$, as in (7.16). After Koks and Van Klinken (1976).

3.3 Determination of the neutrino helicity

Goldhaber et al., 1958

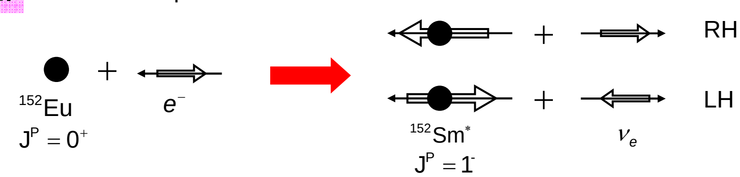
Indirect measurement of the neutrino helicity in the K capture reaction:

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



Idea of the experiment:

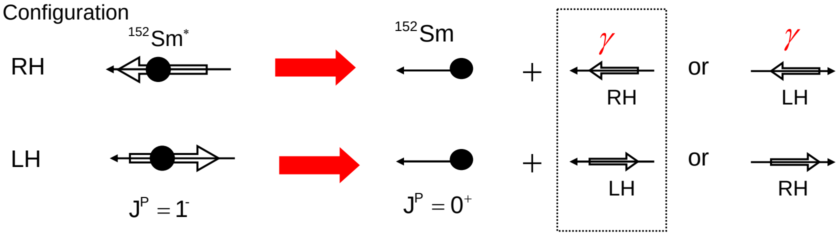
1. Electron capture and ν emission



Sm undergoes is small **recoil**. 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: ${}^{152}Sm^*(J^P = 1^-) \rightarrow {}^{152}Sm(J^P = 0^+) + \gamma$

Configuration



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

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

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

<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.

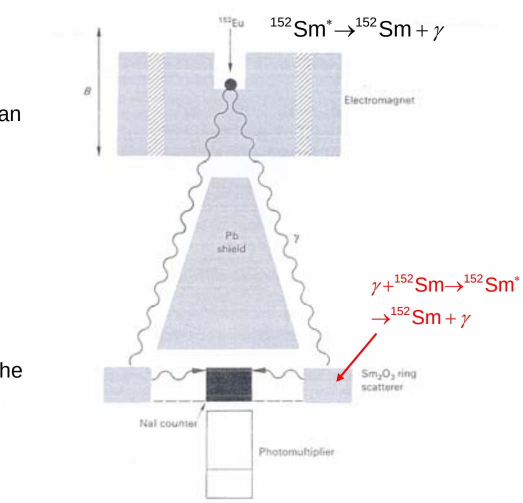
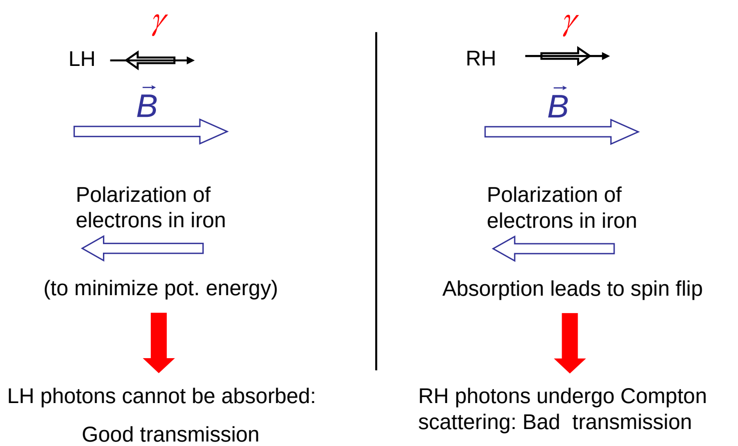


Fig. 7.8. Schematic diagram of the apparatus used by Goldhaber *et al.*, in which γ-rays from the decay of ${}^{152}Sm^*$, produced following K-capture in ${}^{152}Eu$, undergo resonance scattering in Sm_2O_3 and are recorded by a sodium iodide scintillator and photomultiplier. The transmission of photons 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: Compton scattering in magnetized iron



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.

Results: $P_\gamma = -0.66 \pm 0.14$

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

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 helicity in β decays

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