III Lepton - Sektor

1. Neutrinos

1.1 Postulation and discovery

a) Nuclear β-decay

After the observation of discrete energy lines in α and γ decays the continuous spectrum for β-decays was surprising. To explain the spectrum Pauli proposed a new undetectable light neutral spin-$\frac{1}{2}$ particle (he called it neutron) - later called neutrino by E. Fermi which carries away spin, momentum and energy. (1930)

In the 1930's Fermi developed the first Theory of Neutrino and the β-decay:

After the postulation of the neutrino in 1930 by Pauli (Hypothesis was presented only in 1933 during 17th Solvay Conf. in Brussels) it took until 1956 before the neutrino was discovered by Cowan & Reines (Nobelpreis Reines 1995): They used (anti)-neutrinos from a nuclear reactor and detected the neutrino via the inverse neutron decay:

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

Experiment: Water tank w/ $CdCl_2$ and 2 liquid scintillators to detect the 2γ from the e^+e^- annihilation as well as the γ from the neutron capture reaction: $^{113}Cd\,(n,\gamma)\,^{114}Cd$

Finally they observed neutrino induced reactions with an average cross section of:

$$\bar{\sigma} = (11.0 \pm 2.6) \cdot 10^{-44}\,cm^2$$

→ Figure of Experiment

b.) Neutrino and Anti-Neutrino

If neutrinos ν_e and anti-neutrinos $\bar{\nu}_e$ were the same particle the reaction

$$\bar{\nu}_e + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$$

should be possible with Reactor neutrinos ($\bar{\nu}_e$, anti-neutrinos). (This experiment goes back to an idea of Bruno Pontecorvo 1946 - at that time ν and $\bar{\nu}$ were thought to be the same particle).

R. Davis (Nobelprize 2002 for the detection of ν with the same Method) excluded the reaction for reactor neutrinos with a cross section limit:

$$\sigma < 0.9 \cdot 10^{-45}\ cm$$

(theoretical estimation $\gtrsim 2.6 \cdot 10^{-45}$)

This detection technique was later used to measure the neutrino flux from the sun!

c) Helicity of the neutrino (M. Goldhaber, 1957)

With his ingenious experiment M. Goldhaber was able to measure the neutrino helicity:

Goldhaber Exp: EC: $^{152}Eu + e^- \longrightarrow {}^{152}Sm^* + \nu_e + 950\,keV$

$^{152}Sm^* \longrightarrow {}^{152}Sm + \gamma + 961\,keV$

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

$-\vec{p}_\nu = \vec{p}_{Sm}$ Rückstoß $= \vec{p}_\gamma = \vec{p}_{Sm^*} - \vec{p}_\gamma$

Only the γ in the direction of the Sm* recoil will undergo resonant scattering:
- Momentum of these Photons // ν
- Spins of ν and γ must be opposite → Helicity the same $\mathcal{H}(\nu) = \mathcal{H}(\gamma)$

→ Measurement of the photon polarisation via compton scattering in magnetized iron.

→ $\mathcal{H}(\nu) = -1$; i.e. neutrinos are LH particles

Together with the observation of the helicity of the electron in β-decays this observation led to the (V−A)-theory of charged-current interaction.

d) <u>Difference between ν_e and ν_μ:</u>

(Lederman, Schwartz, Steinberger et. al., 1962)
= Nobelpreis, 1988 =

Use ν's from π decay at Brookhaven AGS:

$$\pi^\pm \to \mu^\pm + \overset{(-)}{\nu}$$

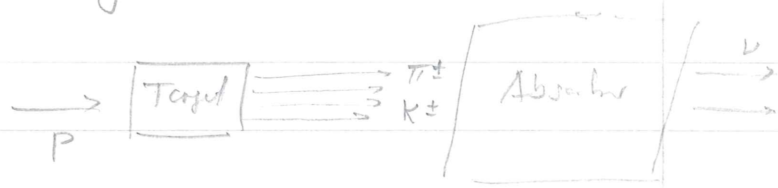
→ these neutrinos in the interaction with matter

$$\nu + n \to \ell^- + p$$
$$\bar{\nu} + p \to \ell^+ + n$$

produce only μ's and are therefore different from the neutrinos involved in β-decays/nuclear reactors.

→ the observed production rate of muon-like events is what one expects from Fermi-Theory assuming $\nu_e \neq \nu_\mu$. No indication for e-like events.

Fig. from Zuber:



<u>Discovery of the τ-Neutrino</u> (Donut Exp, 2000)

<u>Dir</u>ect <u>Obs</u>ervation of <u>Nu</u> <u>Tau</u>

800 GeV p beam from Tevatron on Beam-Dump;
(8×10^{12} p/20s ≙ 20 kW beam power)

97% ν are ν_e, ν_μ from π, K decay

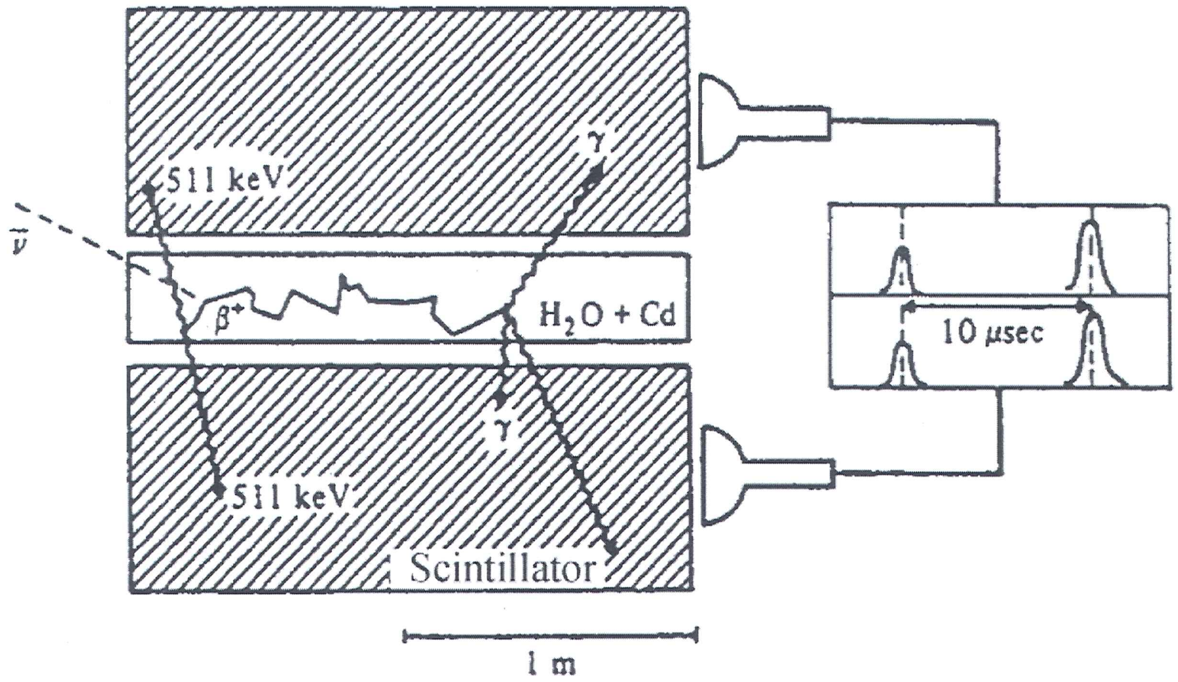
3% ν_τ mostly from $D_s \to \nu_\tau \tau$

← Emulsion Target for excellent vertex resolution

→ 9 τ events observed.

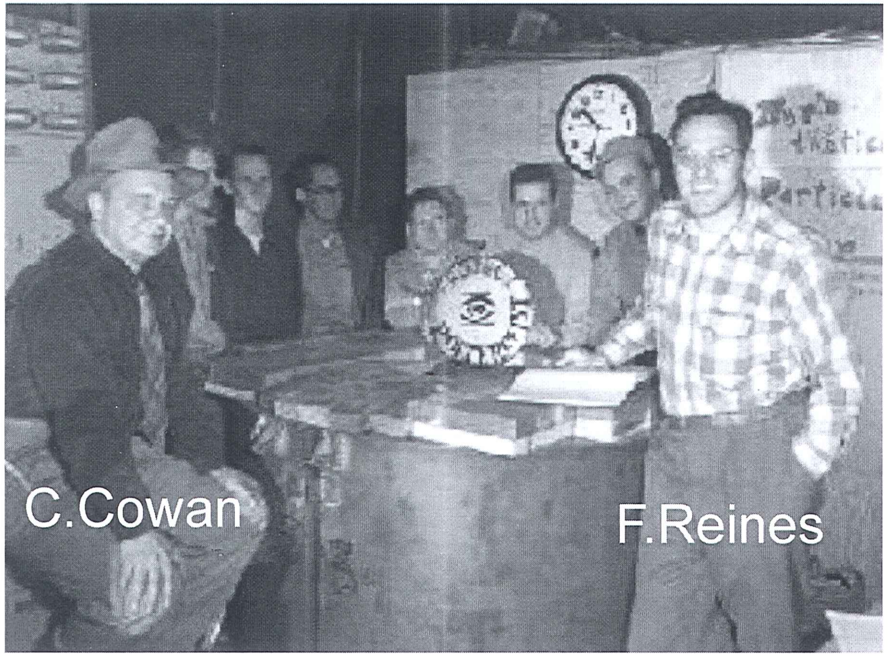
Neutrino Discovery

Cowan & Reines, 1956 (Nobel prize 1995)

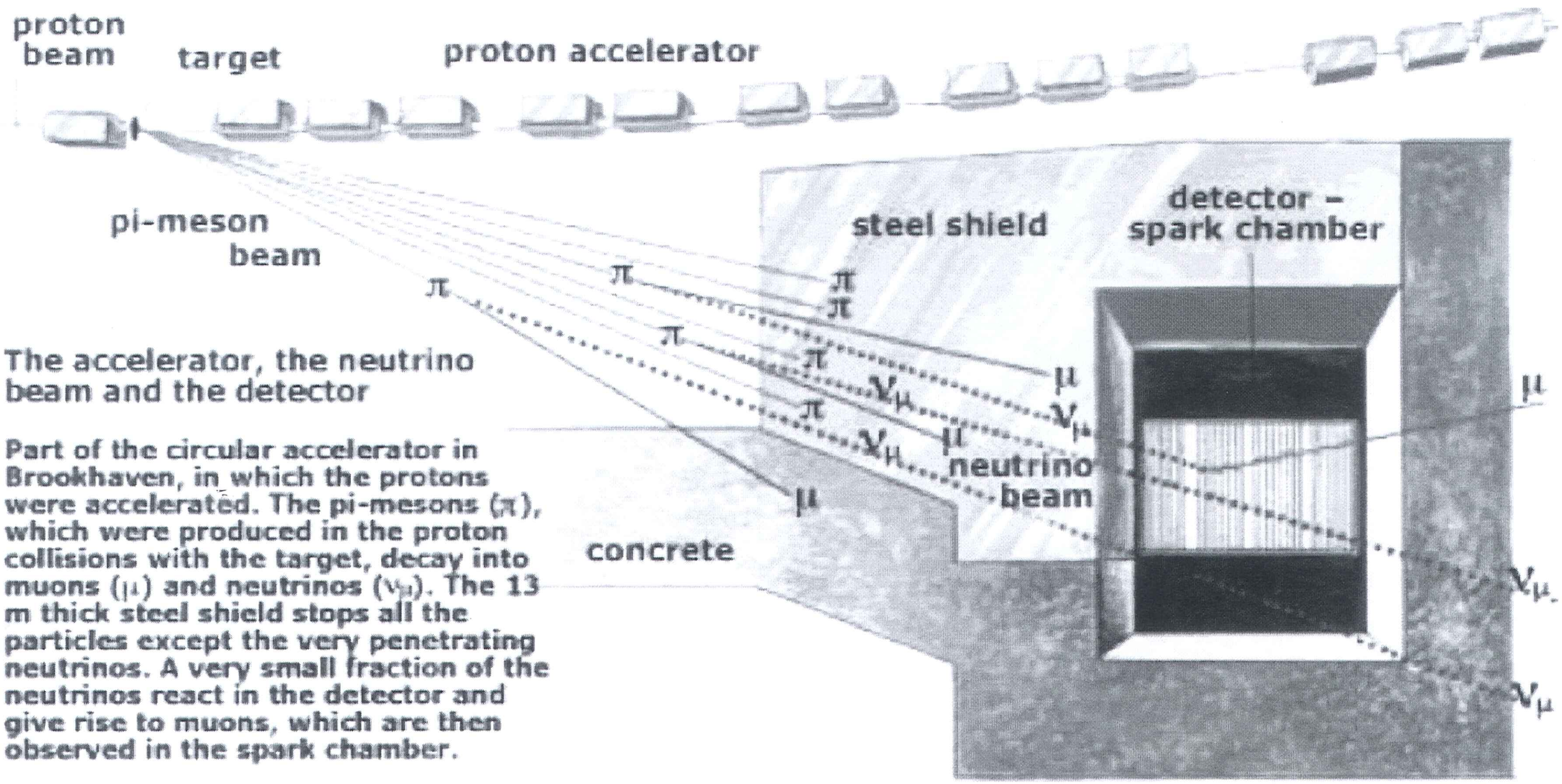


$$\bar{\nu}_e + p \rightarrow e^+ + n \qquad {}^{113}\text{Cd}(n,\gamma)^{114}\text{Cd}$$

Project Poltergeist & Herr Auge



Electron and Muon Neutrino



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.

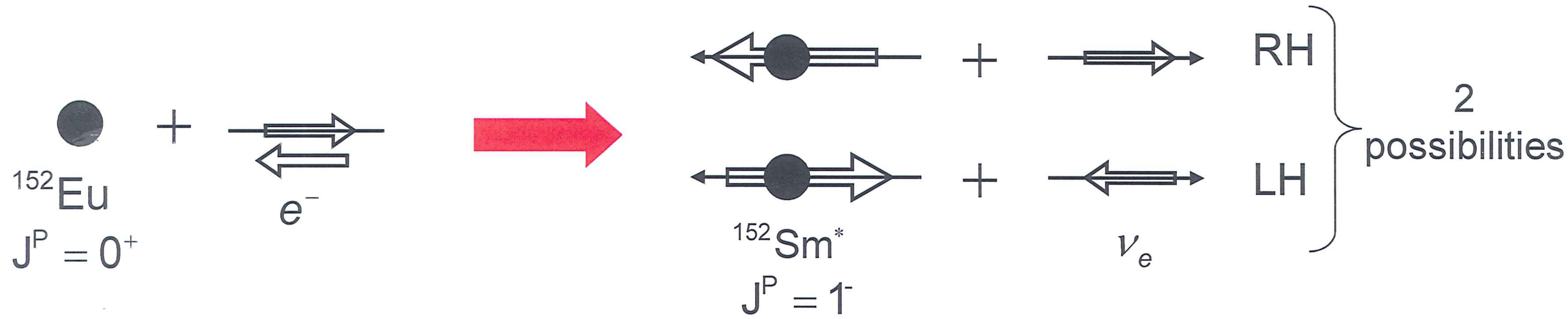
Neutrino Helicity

M.Goldhaber (1957)

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

$$E_\nu \approx 950 KeV$$

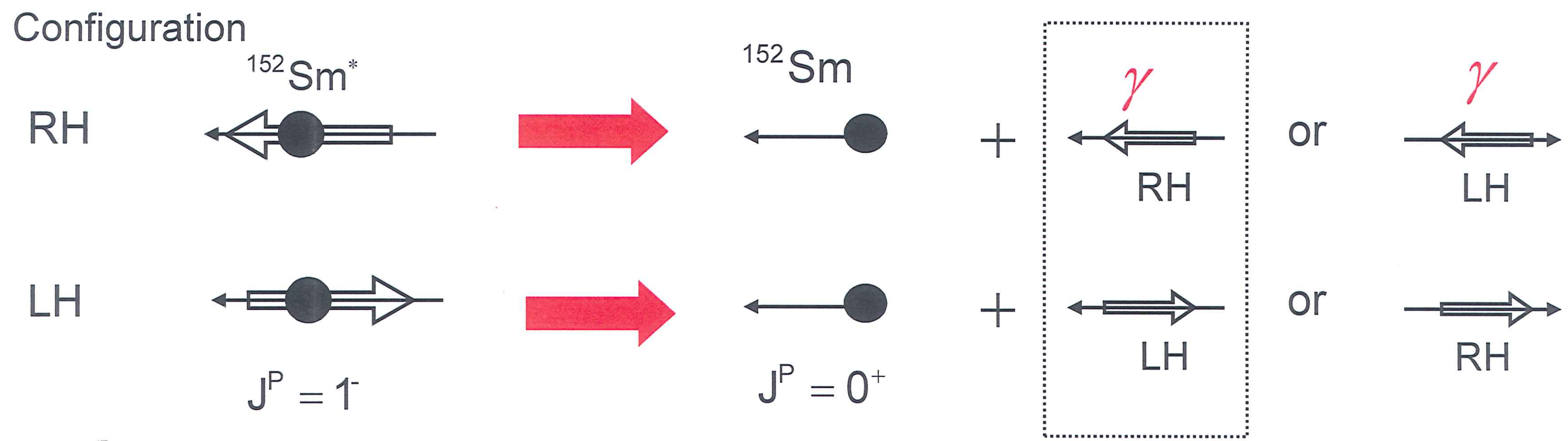
1.



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.**

Neutrino Helicity

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

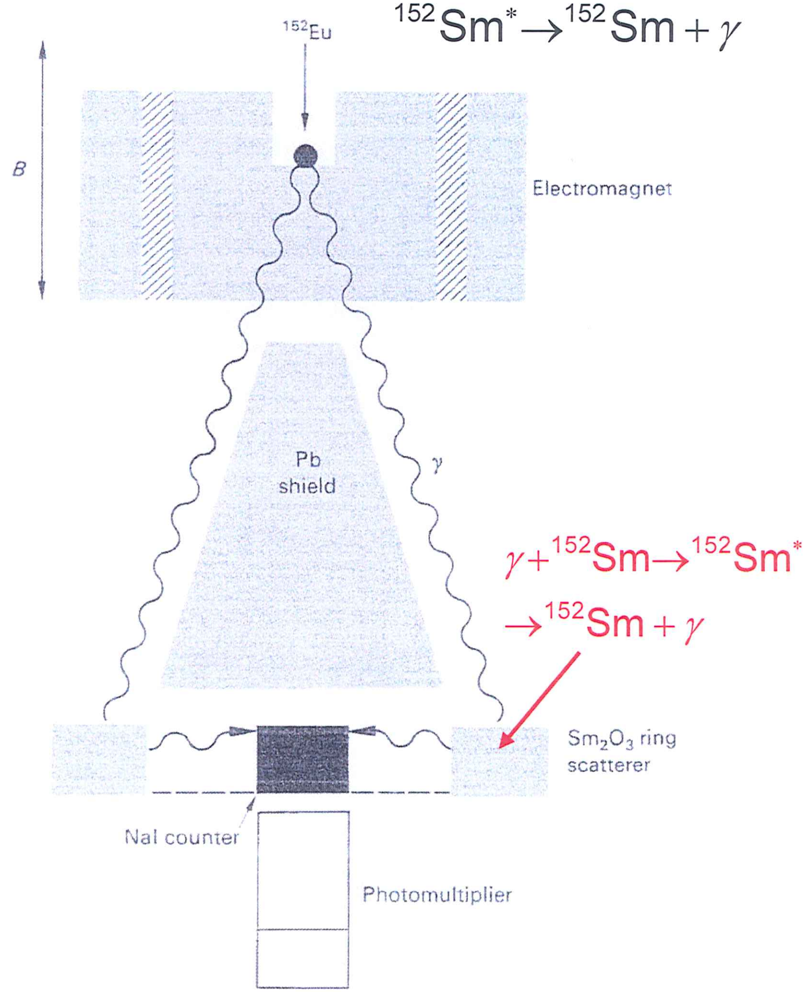


Photons along the Sm recoil direction carry the polarization of the Sm* nucleus

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

Neutrino Helicity

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



4.

Determination of the photon polarization

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

$P_\gamma = -0.66 \pm 0.14$ (expect. 0.75)