

# Particle Physics WS 2012/13

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# Content of the Lecture

- 1. Introduction
  - 1.1 Natural units ✓
  - 1.2 Standard model basics ✓
  - 1.3 Relativistic kinematics ✓
- 2. Interaction of Particles with Matter ✓
- 3. Detectors for Particle Physics
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- 4. Scattering process and transition amplitudes
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  - 4.3 Decay Width and Lifetime ✓
  - 4.4 Two and Three Bod decay rate, Dalitz plot ✓
  - 4.5 Cross section ✓
- 5. Description of free particles
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- 6. QED
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  - 6.4. Electron Scattering ✓
- 7. Radiativ correction and renormalization ✓

- 8. Elastic and inelastic electron  
Proton scattering and the quark model ✓
- 9. Strong Interaction (QCD)
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  - 9.2. Local gauge invariance ✓
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- 10. Weak Interaction
  - 10.1. Parity, Wu Experiment, Goldhaber Experiment
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- 13. CP Violation
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**weak interaction**

# Content of Today

- Hadronic decays of weak interaction
- Reminder of Parity
- Parity conservation in QED/QCD
- The  $\Theta/\tau$  puzzle
- Discovery of Parity Violation: Wu-Experiment
- Goldhaber-Experiment: Helicity of the Neutrino
- Structure of vertex current weak IA

# Phenomenology of weak IA (charged current)

All particles (except photons and gluons) take part in weak IA.

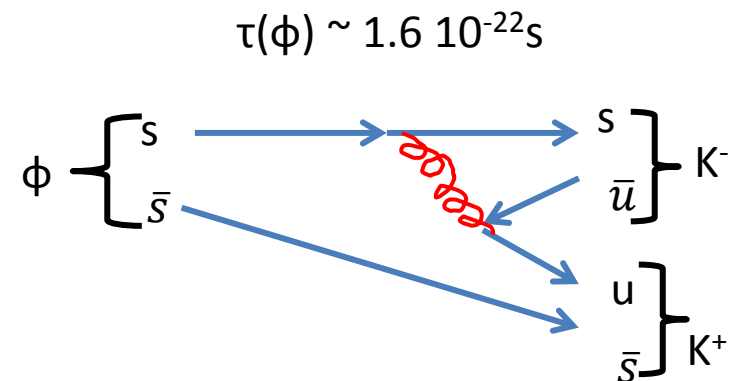
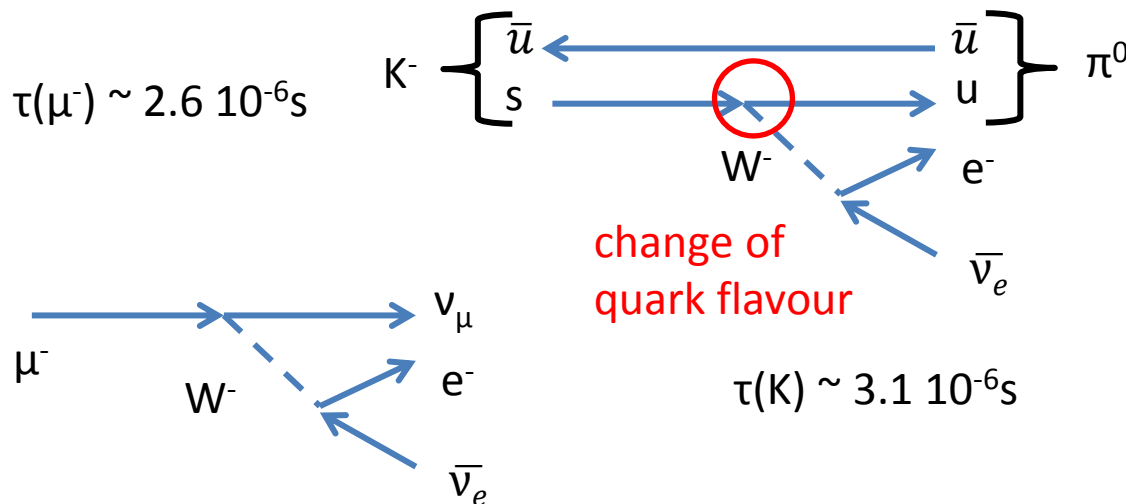
Massive exchange bosons:  $W^\pm$  ( $m=80$  GeV),  $Z^0$  ( $m=91$  GeV)

Propagator term for massive spin=1 particle:  $-i \frac{[g_{\mu\nu} - q_\mu q_\nu / m_W^2]}{q^2 - m_W^2}$

polarization

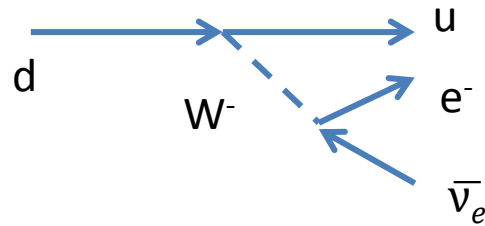
For  $q < m_W/m_Z$  weak IA is negligible small compared to QED/QCD  
(for large  $q$ , weak IA comparable to electromagnetic IA)

➡ Observation of weak IA mainly in decays which are forbidden in strong/elm IA  
Due to conservation and/or which involve neutrinos



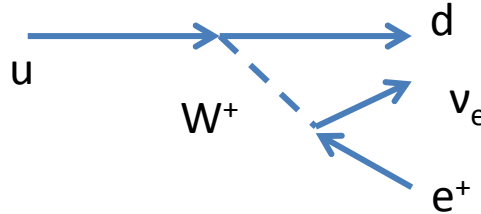
# Weak Hadronic Decays

dominant decay mode at quark level



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

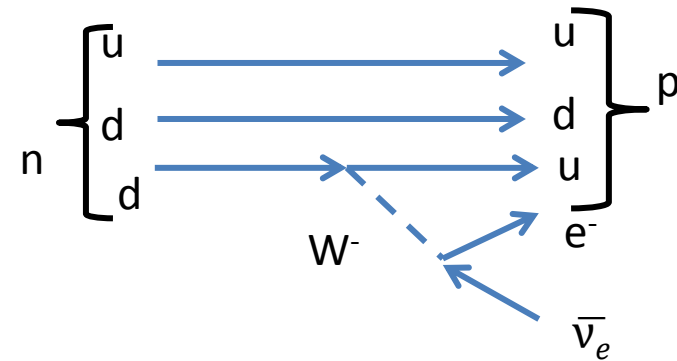
$\Theta_c$  : Cabbibo angle



$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix}$$

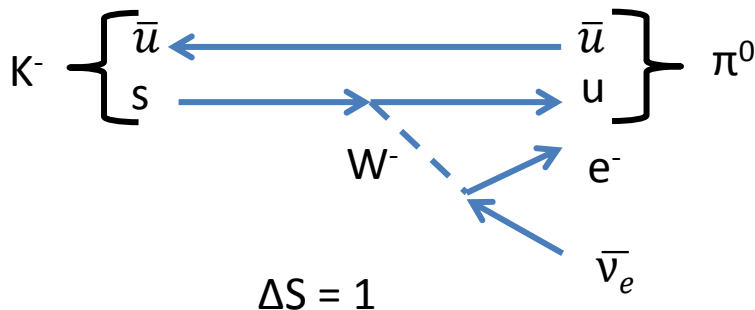
e.g.  $\beta$  decay

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



$$\Delta I_3 = 1$$

subpressed decay modes



$$\Delta S = 1$$

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

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix}$$

Weak IA does not conserve isospin, strangeness or any other **quark flavour** number.

Lepton numbers is however conserved

# Reminder of Parity

particle solution  $\Psi_i = u_i(E, \vec{p}) e^{i(\vec{p}\vec{x} - Et)}$

$$u_1 = \sqrt{E + m} \begin{pmatrix} 1 \\ 0 \\ \frac{p_z}{E+m} \\ \frac{p_x + ip_y}{E+m} \end{pmatrix} \quad u_2 = \sqrt{E + m} \begin{pmatrix} 0 \\ 1 \\ \frac{p_x - ip_y}{E+m} \\ \frac{-p_z}{E+m} \end{pmatrix}$$

antiparticle solution  $\Psi_i = v_i(E, \vec{p}) e^{-i(\vec{p}\vec{x} - Et)}$

$$v_1 = \sqrt{E + m} \begin{pmatrix} \frac{p_x - ip_y}{E+m} \\ \frac{-p_z}{E+m} \\ 1 \\ 0 \end{pmatrix} \quad v_2 = \sqrt{E + m} \begin{pmatrix} \frac{p_z}{E+m} \\ \frac{p_x + ip_y}{E+m} \\ 0 \\ 1 \end{pmatrix}$$

These solutions have positive energies.

Parity operator P:

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

Spin ½ particles AT REST have intrinsic parity P = +1

Spin ½ particles AT REST have intrinsic parity P = -1

# Reminder of Parity

$$P \Psi(\vec{x}, t) = \Psi(-\vec{x}, t) \quad P^2 \Psi(\vec{x}, t) = \Psi(\vec{x}, t)$$

Parity is conserved in strong and electromagnetic IA (to be shown next slide)

Parity and momentum operator do not commute!  $\hat{P}\hat{p} = -\hat{p}\hat{P}$  : „Operator“

Therefore intrinsic parity is (strictly speaking) defined only for particles AT REST.

If a system of two particles has a relative angular momentum L, total parity is given by:

$$P(\mathbf{x}_1 \mathbf{x}_2) = P(\mathbf{x}_1) P(\mathbf{x}_2) (-1)^L \quad (*)$$

Parity of W, Z, photon, gluons:  $P=-1$  (result of gauge theory)

[parity of photon and gluons are not well defined, use definition of fields]

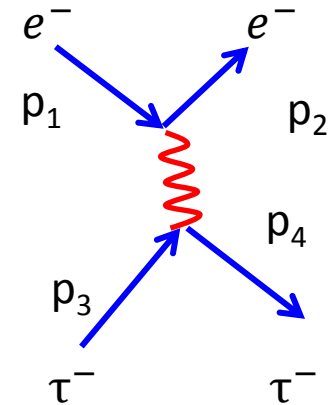
For all other composed and excited particles (e.g. kaon, proton, ion) use rule (\*) and parity conserving IA to determine intrinsic parity.

# Parity Conservation in QED/QCD

$$M = -q_e q_\tau \overline{u_e(p_2)} \gamma^\mu u_e(p_1) \frac{g_{\mu\nu}}{q^2} \overline{u_\tau(p_4)} \gamma^\nu u_\tau(p_3)$$

$$= -\frac{q_e q_\tau}{q^2} j_e^\mu g^{\mu\nu} j_\tau^\nu$$

$$M = -\frac{q_e q_\tau}{q^2} j_e j_\tau$$



$$u \xrightarrow{P} \gamma^0 u$$

$$\bar{u} = u^\dagger \gamma^0 \xrightarrow{P} (Pu)^\dagger \gamma^0 = (\gamma^0 u)^\dagger \gamma^0 = u^\dagger \gamma^{0\dagger} \gamma^0 = u^\dagger \gamma^0 \gamma^0 = \bar{u} \gamma^0$$

$$j = \bar{u} \gamma^\mu u \xrightarrow{P} \bar{u} \gamma^0 \gamma^\mu \gamma^0 u$$

$$j^0 = \bar{u} \gamma^0 u \xrightarrow{P} \bar{u} \gamma^0 \gamma^0 \gamma^0 u = \bar{u} \gamma^0 u = j^0$$

$$j^k = \bar{u} \gamma^k u \xrightarrow{P} j^k = \bar{u} \gamma^0 \gamma^k \gamma^0 u = -\bar{u} \gamma^k \gamma^0 \gamma^0 u = -j^k \quad k = 1, 2, 3$$

$$M = -\frac{q_e q_\tau}{q^2} j_e j_\tau \xrightarrow{P} -\frac{q_e q_\tau}{q^2} (j_e^0 j_\tau^0 - (-j_e^k)(-j_\tau^k)) = -\frac{q_e q_\tau}{q^2} j_e j_\tau$$

➡ **parity conservation!**

# Historical $\theta/\tau$

In 1956, parity conservation as well as T and C symmetry was a “dogma”

→ very little experimental tests done

$\theta/\tau$  puzzle:

$$\theta \rightarrow \pi^+ \pi^0; \quad P(\pi^+ \pi^0) = +1$$

$$\tau \rightarrow \pi^+ \pi^+ \pi^-; \quad P(\pi^+ \pi^+ \pi^-) = -1$$

$$P(q) = 1; P(\bar{q}) = -1;$$

$$P(\text{meson}) = P_q P_{\bar{q}} (-1)^L;$$

lowest energy,  $S = 0$

$$P = -1$$

$\theta, \tau$  have same mass, same lifetime, however different parity ...

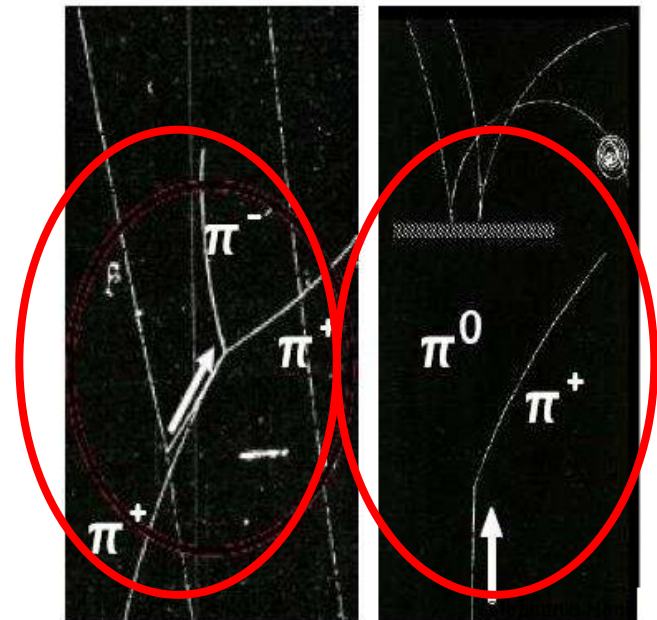
Yang, Lee:

$$\rightarrow \theta = \tau = K^+$$

weak interaction violates parity

proposed a set of measurements which

test parity



# Wu-Experiment

1956: Lee and Yang:

No evidence for parity conservation  
in weak IA, thus proposed set of measurements  
on of them was the Wu-Experiment



Wu-Experiment:

(performed by M<sup>me</sup> Wu and collaborators)

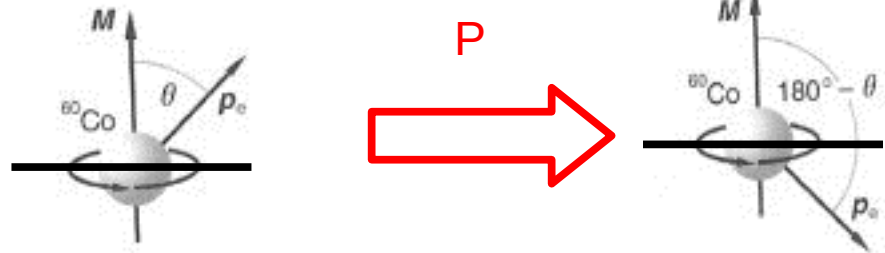
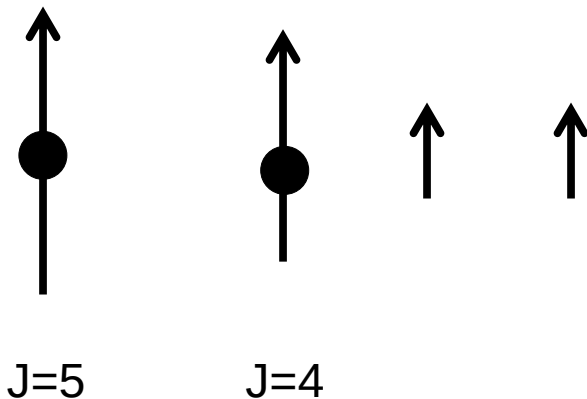
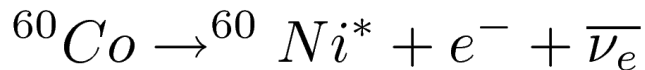


# Wu-Experiment

Partly conservation: physics stays invariant under parity conservation

Idea: Check that number of electrons emitted in direction of spin ( $\vec{J}$ ) of  $^{60}\text{Co}$  and in opposite direction ( $-\vec{J}$ ) are the same.

$$P\vec{J} = P(\vec{r} \times \vec{p}) = (-\vec{r}) \times \vec{p} = -\vec{J}$$



Experiment: Invert polarization of  $^{60}\text{Co}$  and compare electron rate in same angle  $\Theta$

$\text{Ni}^* \rightarrow \text{Ni} + \gamma$  photons are preferentially emitted in direction of spin. Use photon distribution to test polarization of  $^{60}\text{Co}$ . (elm IA conserves parity)

# MAIN CHALLENGE: Polarization of $^{60}\text{Co}$

Spin of  $^{60}\text{Co}$ :  $J=5 \rightarrow M = -5, -4, \dots, 4, 5$

$$M=5 \begin{array}{c} \text{---} \\ \text{---} \\ \text{---} \end{array} \} \Delta E = g \mu_K B$$

$$\mu_K \sim 5.05 \times 10^{-27} \text{ J/T}$$

Population of energy levels follows Boltzmann distribution:

$$e^{-\frac{E}{k_B T}}$$

$$M=-5 \begin{array}{c} \text{---} \\ \text{---} \end{array}$$

for  $\Delta E \gg k_B T$  only lowest energy level is populated, however for given B field in experiment (2.3 T) **very low temperatures** needed

**g factor depends on gitter structure**

Example:  $g = 7.5$  ( $^{60}\text{Co}$ ),  $B = 2.3 \text{ T}$ ,  $T = 0.003 \text{ K}$

$$\frac{P(m=-4)}{P(m=-5)} = e^{-\frac{\Delta E}{k_B T}} = 0.074 \rightarrow 92\% \text{ polarized } ^{60}\text{Co}$$

Solution Part-I: embedding  $^{60}\text{Co}$  in a paramagnetic material ( $B \sim \mu_r$ ;  $\mu_r \sim 3-4$ )  
still temperatures of  $T=0.01\text{K}$  needed

# Adiabatic Colling

1926 von Debye proposed method to create low temperature

Fundamental relation of thermodynamics:

$$dU = T dS - p dV$$

1. Step: **isotherm** magnetisation

- paramagnetic material **in helium gas** is put into magnetic field
- energy levels are split up, only lower once are populated
- entropy gets smaller:  $dS < 0 \rightarrow dU < 0$ , **helium gas absorbes heat**

2. Step: helium gas removed  $\rightarrow$  **thermal isolation** of nitrit

3. Step: adiabatic cooling

- **magnetic field is slowly switched off**
- split off of energy levels get smaller
- system likes to polpulate higher states, however  $dU = \text{const}$  due to **isolation**
- $dS$  gets larger thus **T gets smaller**



Caveat: need magnetic field to get polarized  $^{60}\text{Co}$

# How to combine Cooling and Polarization?

Two competing effects needed in the nitrite-crystal to get high degree of polarization

- 1) Need high B field and low temperature to get polarization
- 2) Switch off B field to lower temperature via adiabatical cooling  
B field on  $\rightarrow$  warm up, B field off  $\rightarrow$  cool down

## How does this work?

Solution: Some paramagnetic material have large anisotropic distribution of g-factors (artefact of crystal structure, different binding mechanisms)

B field for adiabatic cooling in direction with high g-factor

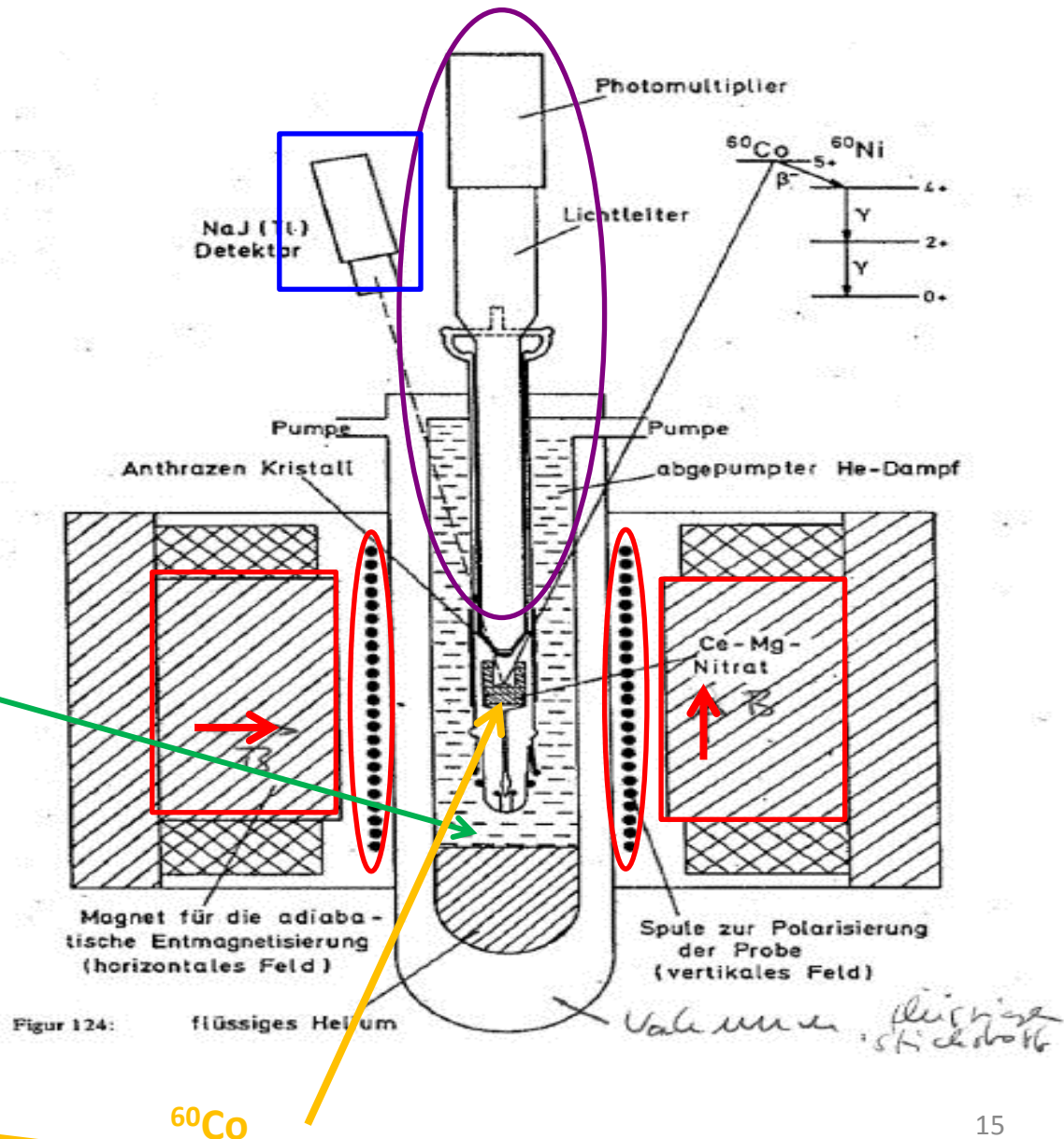
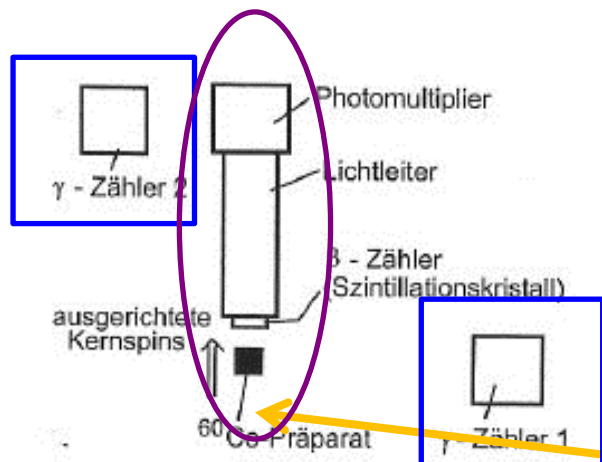
Thus large split up of energy levels, thus large cooling effect

B field for polarization in direction of low g-factor, thus only little warm up

# Wu-Experiment

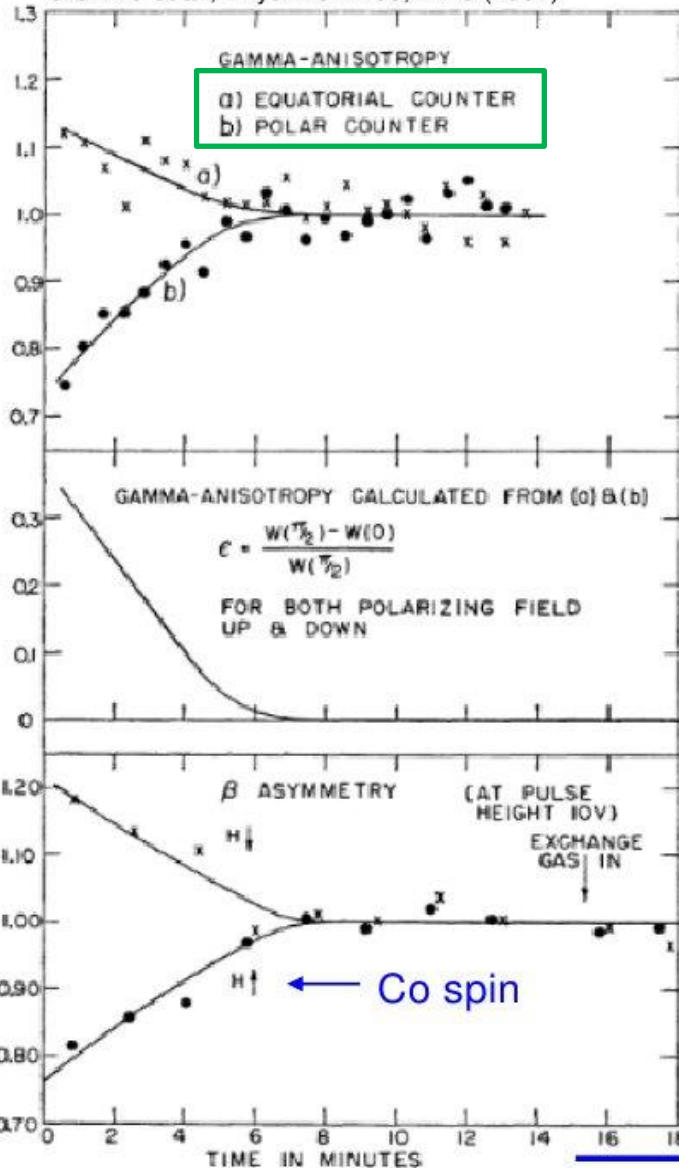
## Requirements:

- 2 B fields in orthogonal directions
- detection of emitted electron  
(cover a small opening angle  $\Theta$ )
- detection of emitted gamma  
(to test polarization of  $^{60}\text{Co}$ )
- crystal needs to be located in helium bath first than in vacuum



# Wu-Experiment: Results

C.S. Wu et al., Phys. Rev. 105, 1413 (1957)



measure photon anisotropy, to determine degree of polarization

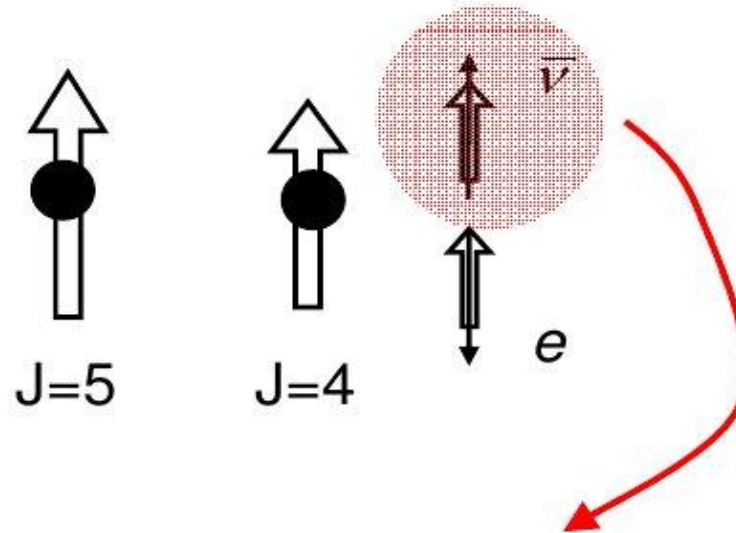
electron rates are different depending on the polarization!

warm up with time

→ parity violation

counting rate relative to warm (unpolarized) rate

# Qualitative Explanation



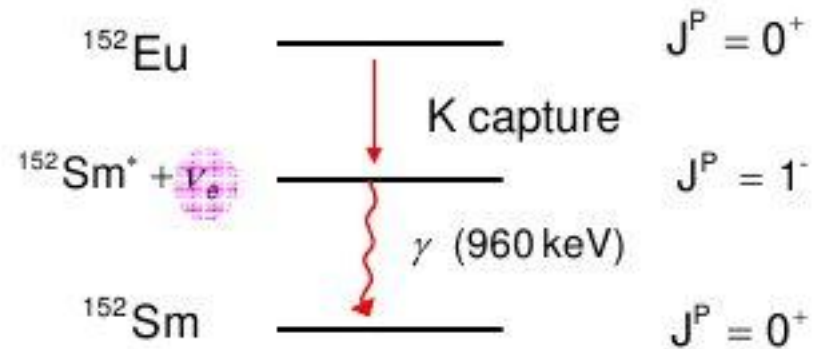
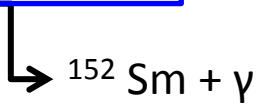
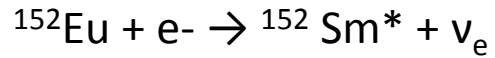
Consequence of existence of only left-handed (LH) neutrinos (RH anti-neutrinos)

Wu experiment established CP violation!

It was however not precise enough to measure helicity of neutrino  
 $H \sim 0.7 \pm \text{large uncertainties}$

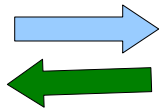
 Goldhaber experiment

# Goldhaber Experiment



Light blue and green arrows indicate possible spin configurations

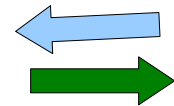
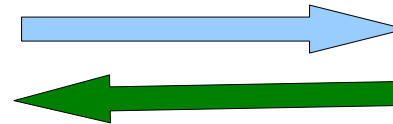
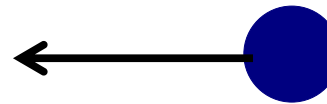
$^{152}\text{Eu}, J = 0; + e^-$



$^{152}\text{Sm}^*, J = 1$

+

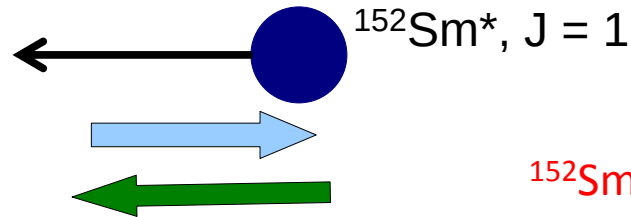
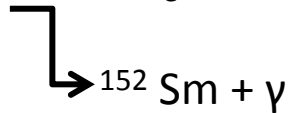
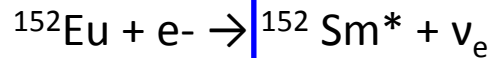
$\nu_e$



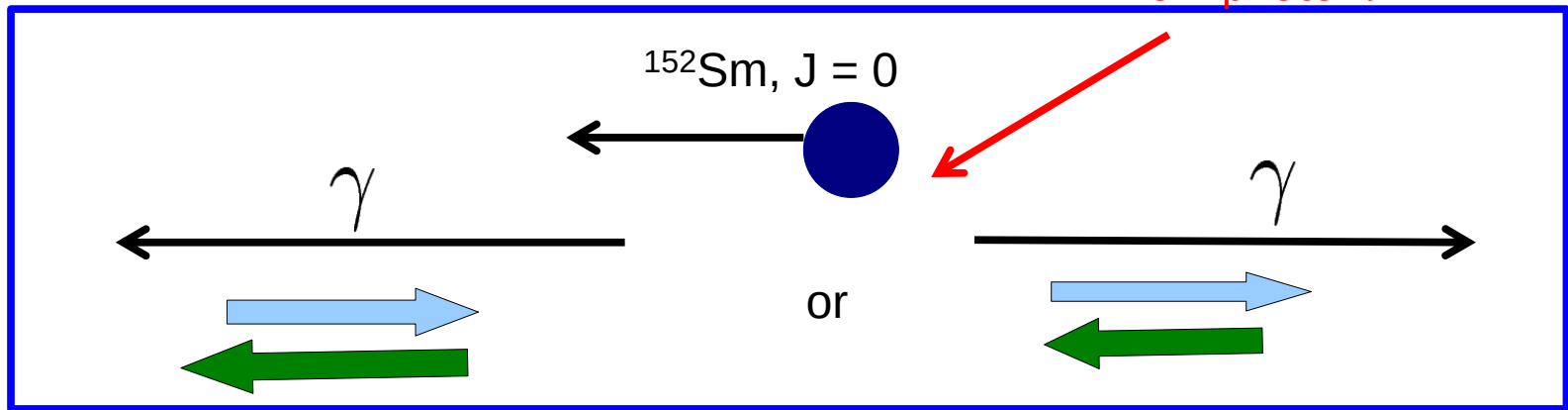
center of mass system

spin of neutrino is in **opposite direction** than the one of  $^{152}\text{Sm}^*$ ,  
momentum of is **in opposite direction** than the one of  $^{152}\text{Sm}^*$

# Goldhaber Experiment



$^{152}\text{Sm}$  gets small recoil from photon!



direction of spin of photon is opposite of neutrino

emitted in direction of  $\text{Sm}^*$

$$h(\gamma) = h(\nu_e)$$

emitted in opposite direction of  $\text{Sm}^*$

$$h(\gamma) = -h(\nu_e)$$

Two open question: 1) What is the direction of emission of the photon?

2) What is the polarization of the photon?

# 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  $\text{Eu} \rightarrow \text{Sm}$  recoil (Doppler-effect).



Resonant scattering only possible for "forward" emitted photons, which carry the polarization of the  $\text{Sm}^*$  and thus the polarization of the neutrinos.

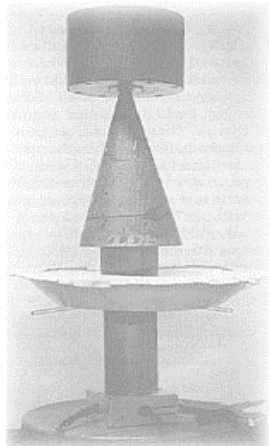


foto of exeperiment

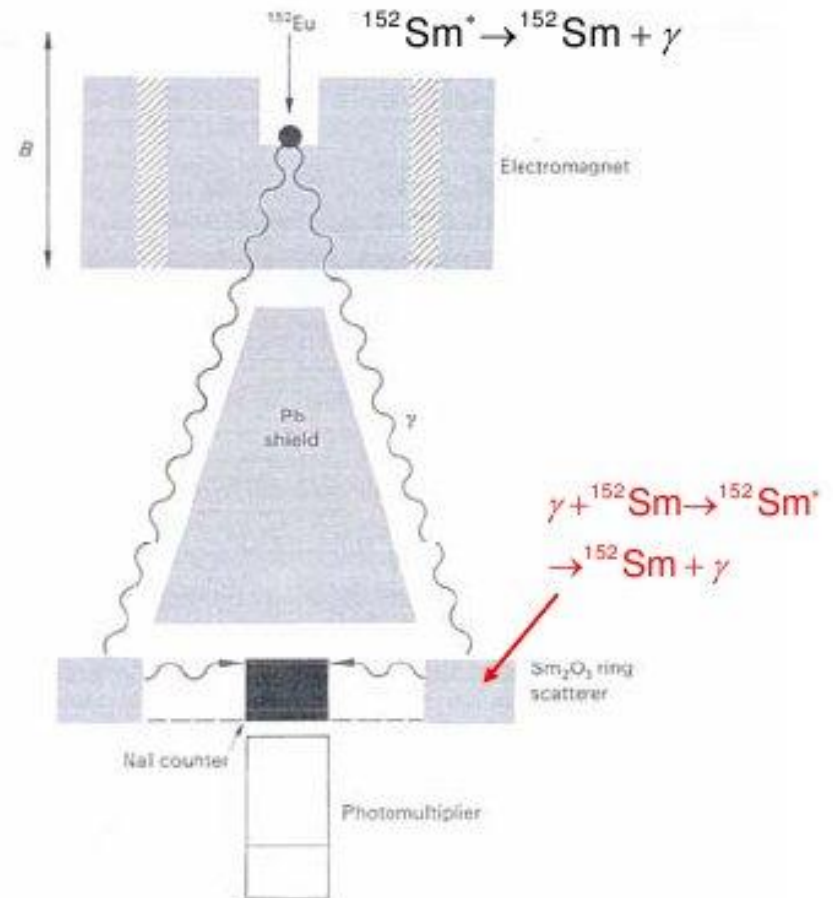
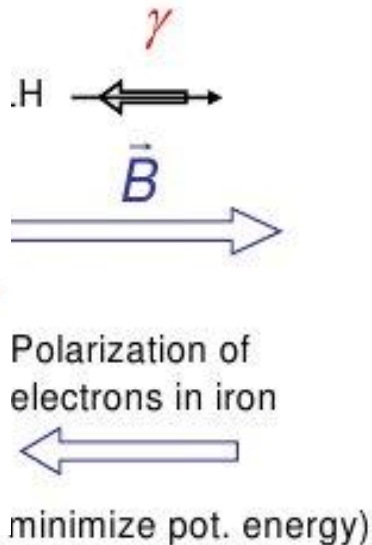
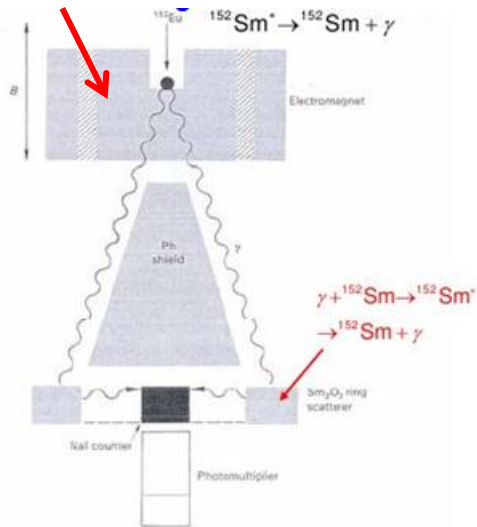


Fig. 7.8. Schematic diagram of the apparatus used by Goldhaber *et al.*, in which  $\gamma$ -rays from the decay of  $^{152}\text{Sm}^*$ , produced following K-capture in  $^{152}\text{Eu}$ , undergo resonance scattering in  $\text{Sm}_2\text{O}_3$  and are recorded by a sodium iodide scintillator and photomultiplier. The transmission of photons through the iron surrounding the source depends on their helicity and the direction of the magnetic field  $\mathbf{B}$ .

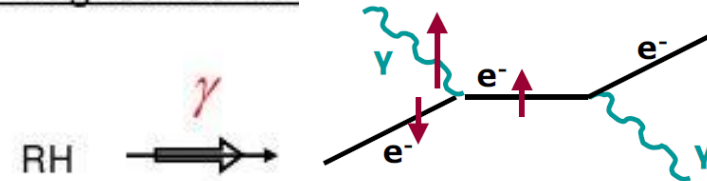
# Measurement of Polarization of Photon

Exploit that the transmission index through magnetized iron is polarization dependent: Compton scattering in magnetized iron

iron in B field



LH photons cannot be absorbed:  
Good transmission



RH photons undergo Compton scattering: Bad transmission

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

# Goldhaber Experiment: Result

- Due to geometry of experiment, only resonant scattered photons are detected  
**Helicity of detected photons identical to helicity of neutrino.**
- Detect photons which pass through magnetized iron.

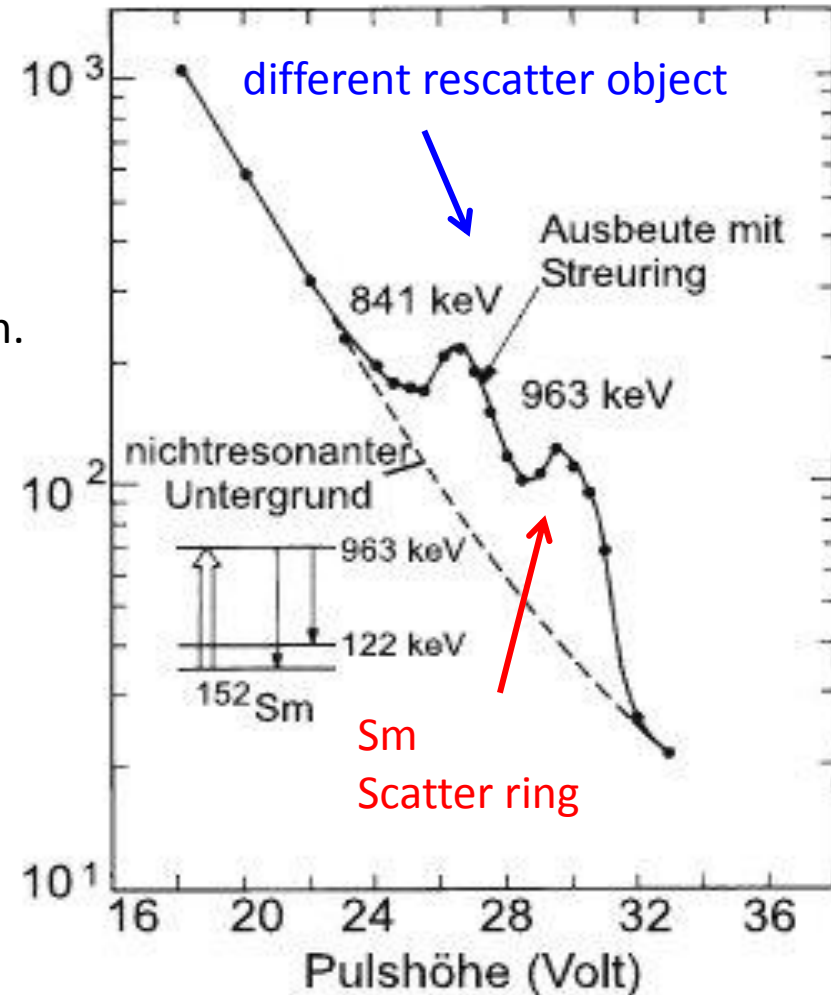
B field points in flight direction of photons  
→ measure fraction of (mainly) LH photons

B field points in opposite direction  
→ measure fraction of (mainly) RH photons

$$\delta = \frac{N_- - N_+}{0.5(N_- + N_+)} = 0.017 \pm 0.003$$

$N_-$  : counting rate with magnetic field down

$N_+$  : counting rate with magnetic field up



# Goldhaber-Experiment: Result

**Result:  $\delta = +0.017 \pm 0.003$**

Theoretical expectation (for 100% polarized photons)

$$\delta = \pm 0.025 \quad \left\{ \begin{array}{ll} \text{„-“} & \text{for } h > 0 \\ \text{„+“} & \text{for } h < 0 \end{array} \right.$$

Only 5-8% of electrons in iron are polarized, thus asymmetry of scattering for LH and RH photons is very small, thus heavily wash out the asymmetry.

Due to background effects (thermal movements inside the source, polarisation can depend on angle, ...) expect for pure LH neutrinos 75% polarized photons

Measured photo polarisation:  $66 \pm 15\%$ , consistent with 75%



**Neutrino are left handed particles**

# Structure of Current of Weak IA

Vertex current of QCD/QED:  $j = \bar{\Psi} \gamma^\mu \Psi \Rightarrow M \sim j_1 j_2$  conserves parity!

How do potential vertex currents can look like?

In order to have a Lorentz invariant representation of the matrix element, vertex currents are restricted to be of the form:

$\bar{\Psi} (4 \times 4) \Psi$ , where the 4x4 matrix is a product of  $\gamma$  matrices

|               |                                       | nb of components | „Boson Spin“ |
|---------------|---------------------------------------|------------------|--------------|
| scalar        | $\bar{\Psi} \Psi$                     | 1                | 0            |
| vector        | $\bar{\Psi} \gamma^\mu \Psi$          | 4                | 1            |
| tensor        | $\bar{\Psi} \sigma^{\mu\nu} \Psi$     | 4x4              | 2            |
| axial vector  | $\bar{\Psi} \gamma^\mu \gamma^5 \Psi$ | 4                | 1            |
| pseudo scalar | $\bar{\Psi} \gamma^5 \Psi$            | 1                | 0            |

Lorentz invariant bilinears  
≡  
bilinear covariants

$$\sigma^{\mu\nu} = i/2(\gamma^\mu \gamma^\nu - \gamma^\nu \gamma^\mu)$$

# Axial Vector Current

Test parity of  $M \sim j_{A1} j_{A2}$        $j_A^\mu = \bar{u} \gamma^\mu \gamma^5 u$

$$j_A^0 = \bar{u} \gamma^0 \gamma^5 u \xrightarrow{P} \bar{u} \gamma^0 \gamma^0 \gamma^5 \gamma^0 u = -\bar{u} \gamma^0 \gamma^0 \gamma^0 \gamma^5 u = -\bar{u} \gamma^0 \gamma^5 u = -j_A^0$$

$$j_A^k = \bar{u} \gamma^k \gamma^5 u \xrightarrow{P} \bar{u} \gamma^0 \gamma^k \gamma^5 \gamma^0 u = \bar{u} \gamma^0 \gamma^0 \gamma^k \gamma^5 u = \bar{u} \gamma^k \gamma^5 u = j_A^k$$

$$M \sim j_{A,1} j_{A,2} = j_{A,1}^0 j_{A,2}^0 - j_{A,1}^k j_{A,2}^k \xrightarrow{P} (-j_{A,1}^0) (-j_{A,2}^0) - j_{A,1}^k j_{A,2}^k = j_{A,1} j_{A,2}$$

→ parity conservation!

Axial vector currents conserve as well parity

→ Weak IA must be linear combination of axial and vector coupling

$$j_1 = \bar{u} (g_V \gamma^\mu + g_A \gamma^\mu \gamma^5) u = g_V j_{V,1} + g_A j_{A,1} \qquad j_2 = g_V j_{V,2} + g_A j_{A,2}$$

$$M \sim j_1 j_2 = g_V^2 j_{V,1} j_{V,2} + g_A^2 j_{A,1} j_{A,2} + g_V g_A (j_{V,1} j_{A,2} + j_{A,1} j_{V,2})$$

$$g_V^2 j_{V,1} j_{V,2} + g_A^2 j_{A,1} j_{A,2} - g_V g_A (j_{V,1} j_{A,2} + j_{A,1} j_{V,2}) \neq M \rightarrow \text{parity violation}$$

relative strength of parity violation:  $\frac{g_V g_A}{g_V^2 + g_A^2}$       maximal violation for V-A, V+A coupling

# V-A Coupling of Weak IA

The coefficients  $g_A$ ,  $g_V$  must be determined from data. For the Charge current interaction (W exchange) the parity violation is maximal:

$$\text{weak current: } J = \underbrace{-i \frac{g_W}{\sqrt{2}} \frac{1}{2}}_{\text{coupling}} \bar{\Psi} \underbrace{\gamma^\mu (1 - \gamma^5)}_{\text{V-A structure}} \Psi$$

[V+A coupling would result in only right handed neutrinos exist/take part in IA, in contradiction to Goldhaber experiment]

Projection operator on right and left handed chirality states:

$$P_R = \frac{1}{2}(1 + \gamma^5) \quad P_L = \frac{1}{2}(1 - \gamma^5)$$

$$\Psi = \Psi_R + \Psi_L = \frac{1}{2}(1 + \gamma^5)\Psi + \frac{1}{2}(1 - \gamma^5)\Psi$$

$$\begin{aligned} \text{Remember: QED/QCD vertex: } \bar{\Psi} \gamma^\mu \varphi &= (\bar{\Psi}_R + \bar{\Psi}_L) \gamma^\mu (\varphi_R + \varphi_L) \\ &= \bar{\Psi}_R \gamma^\mu \varphi_R + \cancel{\bar{\Psi}_R \gamma^\mu \varphi_L} + \cancel{\bar{\Psi}_L \gamma^\mu \varphi_R} + \bar{\Psi}_L \gamma^\mu \varphi_L \end{aligned}$$

$$\Rightarrow \bar{\Psi} \gamma^\mu (1 - \gamma^5) \varphi = \bar{\Psi}_L \gamma^\mu \varphi_L$$

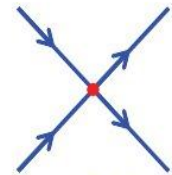
Only left handed chirality particles and right handed chirality anti-particles take part in **charged current IA**

# Connection to Fermi-Theory

- ★ In 1934, before the discovery of parity violation, Fermi proposed, in analogy with QED, that the invariant matrix element for  $\beta$ -decay was of the form:

$$M_{fi} = G_F g_{\mu\nu} [\bar{\psi} \gamma^\mu \psi] [\bar{\psi} \gamma^\nu \psi]$$

where  $G_F = 1.166 \times 10^{-5} \text{ GeV}^{-2}$



- Note the absence of a propagator : i.e. this represents an interaction at a point
- ★ After the discovery of parity violation in 1957 this was modified to

$$M_{fi} = \frac{G_F}{\sqrt{2}} g_{\mu\nu} [\bar{\psi} \gamma^\mu (1 - \gamma^5) \psi] [\bar{\psi} \gamma^\nu (1 - \gamma^5) \psi]$$

(the factor of  $\sqrt{2}$  was included so the numerical value of  $G_F$  did not need to be changed)

- ★ Compare to the prediction for W-boson exchange

$$M_{fi} = \left[ \frac{g_W}{\sqrt{2}} \bar{\psi} \frac{1}{2} \gamma^\mu (1 - \gamma^5) \psi \right] \frac{g_{\mu\nu} - q_\mu q_\nu / m_W^2}{q^2 - m_W^2} \left[ \frac{g_W}{\sqrt{2}} \bar{\psi} \frac{1}{2} \gamma^\nu (1 - \gamma^5) \psi \right]$$

which for  $q^2 \ll m_W^2$  becomes:

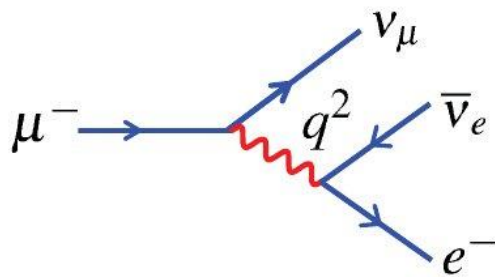
$$M_{fi} = \frac{g_W^2}{8m_W^2} g_{\mu\nu} [\bar{\psi} \gamma^\mu (1 - \gamma^5) \psi] [\bar{\psi} \gamma^\nu (1 - \gamma^5) \psi]$$

→  $\boxed{\frac{G_F}{\sqrt{2}} = \frac{g_W^2}{8m_W^2}}$

Still usually use  $G_F$  to express strength of weak interaction as this is the quantity that is precisely determined in muon decay

# Strength of Weak Interaction

- ★ Strength of weak interaction most precisely measured in muon decay



- Here  $q^2 < m_\mu$  (0.106 GeV)
- To a very good approximation the W-boson propagator can be written

$$\frac{-i [g_{\mu\nu} - q_\mu q_\nu / m_W^2]}{q^2 - m_W^2} \approx \frac{ig_{\mu\nu}}{m_W^2}$$

- In muon decay measure  $g_W^2 / m_W^2$

- Muon decay  $\rightarrow G_F = 1.16639(1) \times 10^{-5} \text{ GeV}^{-2}$

$$\frac{G_F}{\sqrt{2}} = \frac{g_W^2}{8m_W^2}$$

- ★ To obtain the intrinsic strength of weak interaction need to know mass of W-boson:  $m_W = 80.403 \pm 0.029 \text{ GeV}$

$$\rightarrow \alpha_W = \frac{g_W^2}{4\pi} = \frac{8m_W^2 G_F}{4\sqrt{2}\pi} = \frac{1}{30}$$

★ The intrinsic strength of the weak interaction is similar to, but greater than, the EM interaction ! It is the massive W-boson in the propagator which makes it appear weak. For  $q^2 \gg m_W^2$  weak interactions are more likely than EM.