Neutrino Physics

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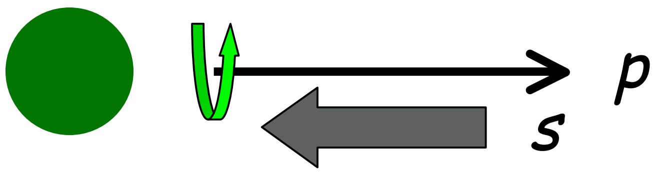
Outline

- Spin of neutrino
- Parity
- Charge conjugation
- Dirac and Majorana neutrino
- Magnetic moment
- Life time

Helicity

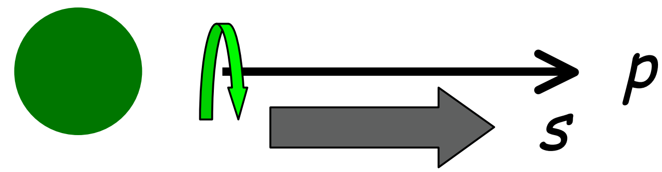
$$\text{Helicity, } H = \frac{\vec{s} \cdot \vec{p}}{\left|\vec{s} \cdot \vec{p}\right|}$$

spin momentum



H = -1

Left-handed state



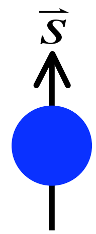
H = +1

Right-handed state

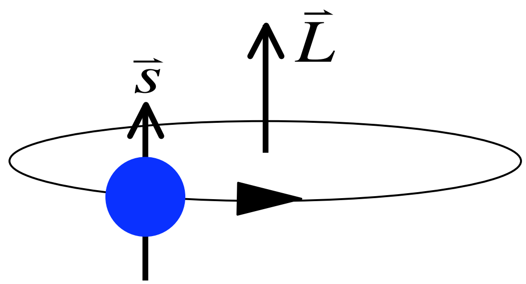
Handedness is referenced to the momentum

Quick Review of Angular Momentum

- Spin of a particle (given by Nature), $\vec{s}$



- Orbital angular momentum (due to motion), $\vec{L}$



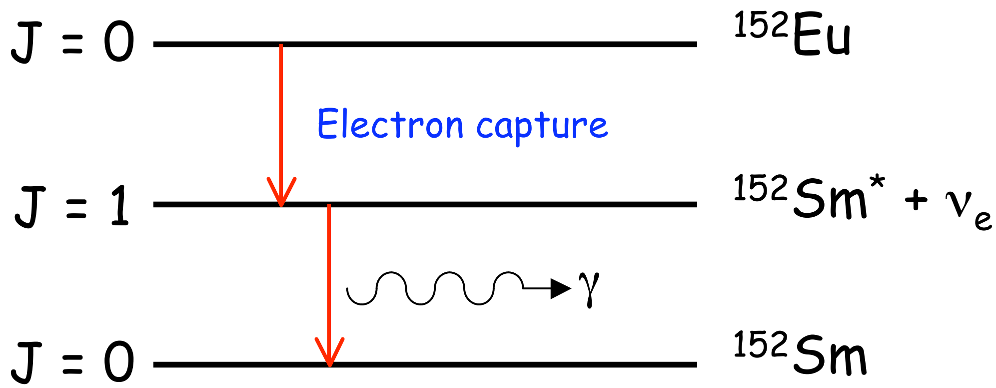
- Total angular momentum, $\vec{J}$

$$\vec{J} = \vec{L} + \vec{S}$$

$$|\vec{J}| \equiv J = |L - S|, \ \ldots\ , \ L + S \quad \text{(in integral step)}$$

For L = 1, and S = 1/2, the possible values of J are 1/2, 3/2

How To Determine The Spin of Neutrino?



- ^{152}Eu captures a K-shell (L=0) electron:

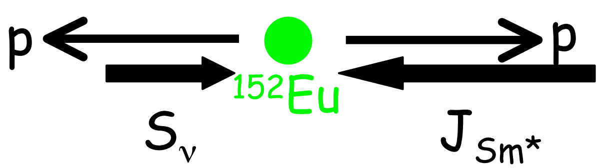
$$J_{tot} = J_{Eu} + J_e = 0 + 1/2 = 1/2$$

- ^{152}Sm* and electron neutrino (L=0):

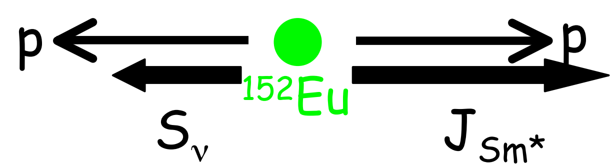
$J_{Sm^*} = 1$, $S_\nu = 1/2$ $\quad J_{tot} = 1/2$ or $3/2$

Conservation of angular momentum requires $J_{tot} = 1/2$

Case 1:



Case 2:



Sm* has the SAME HELICITY as the neutrino

How To Determine The Spin of Neutrino? (cont.)

- ^{152}Sm and gamma ($J_\gamma = 1$):

$$J_{tot} = J_{Sm^*} = J_{Sm} + J_\gamma = 0 + 1 = 1$$

Case 1: Case 2:

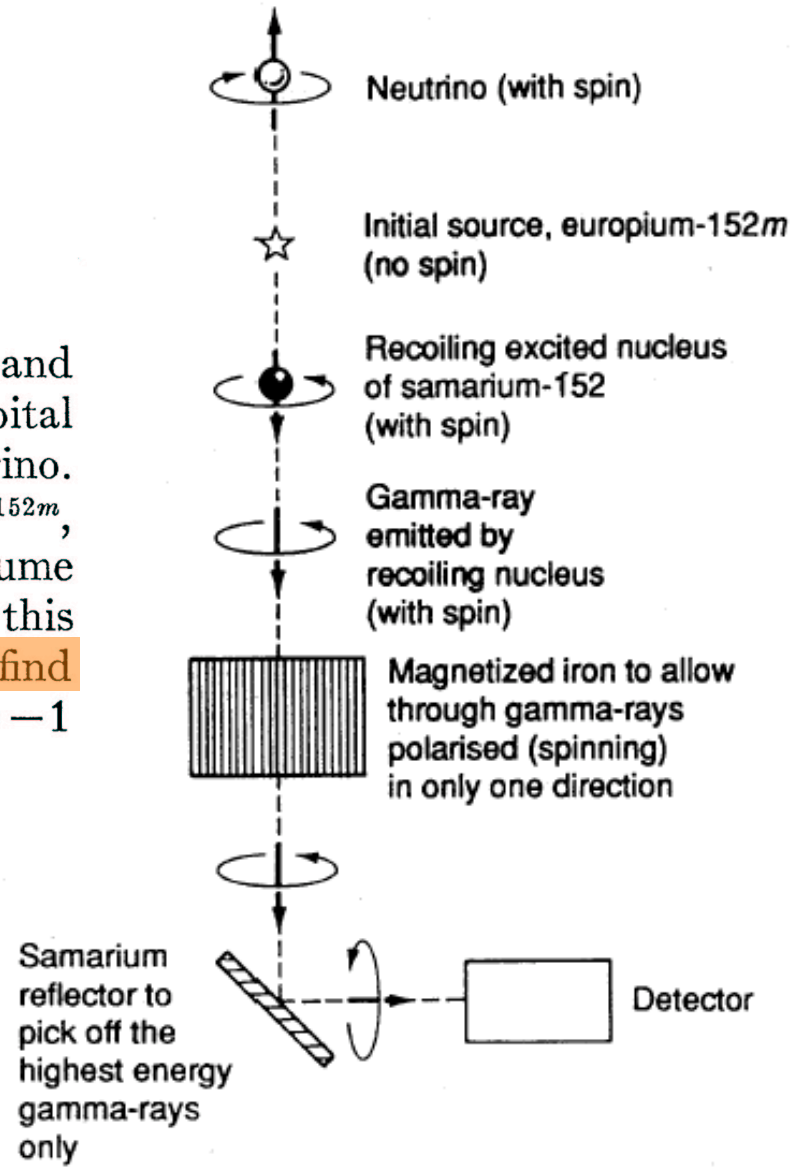
The emitted gamma ray has the SAME HELICITY as the neutrino !!

Neutrinos Are Left-handed

Helicity of Neutrinos*

M. GOLDHABER, L. GRODZINS, AND A. W. SUNYAR
Brookhaven National Laboratory, Upton, New York
(Received December 11, 1957)

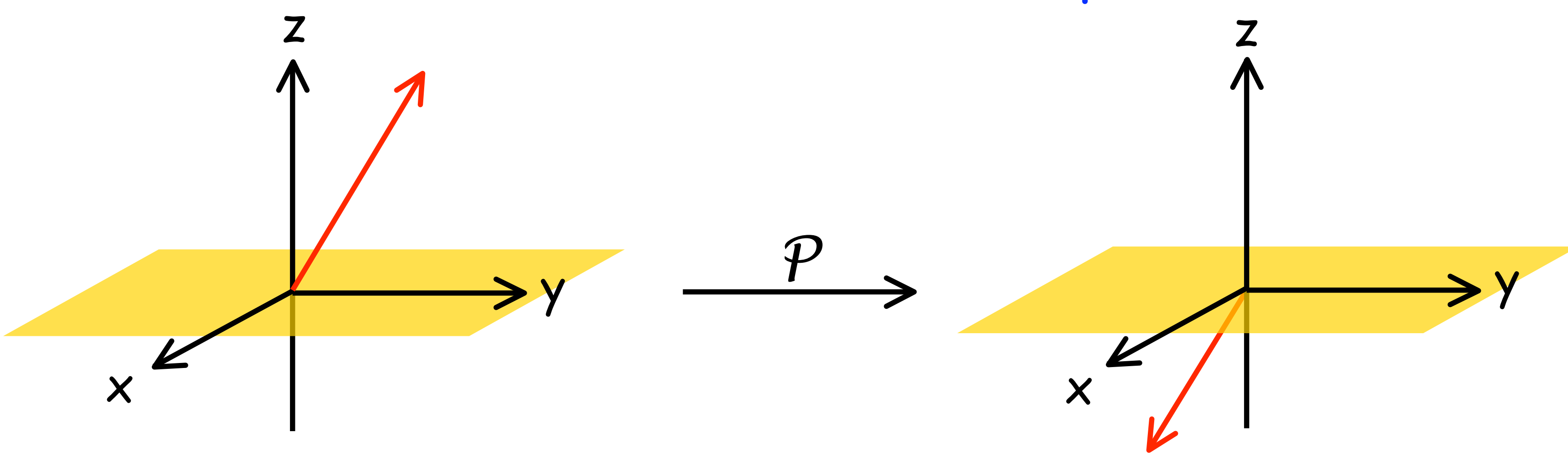
A COMBINED analysis of circular polarization and resonant scattering of γ rays following orbital electron capture measures the helicity of the neutrino. We have carried out such a measurement with Eu^{152m}, which decays by orbital electron capture. If we assume the most plausible spin-parity assignment for this isomer compatible with its decay scheme,[1] 0−, we find that the neutrino is "left-handed," i.e., $\boldsymbol{\sigma}_\nu \cdot \hat{p}_\nu = -1$ (negative helicity).

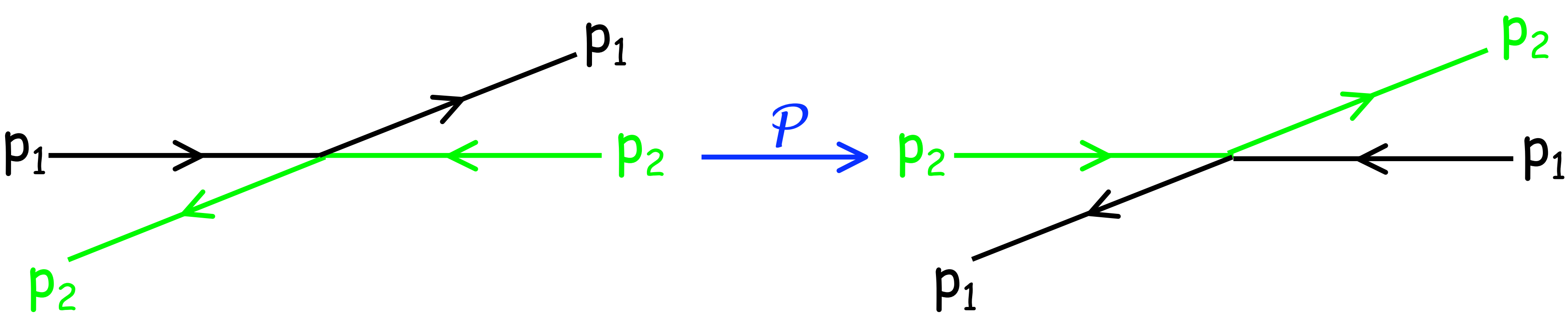


Parity: Left-right Symmetry

Parity transformation, $\mathcal{P}$:

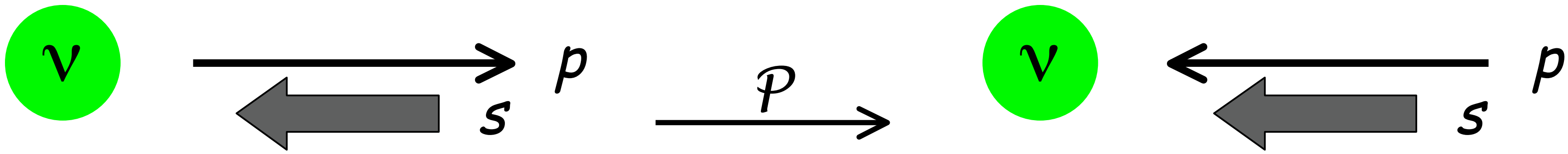
Displacement: $\mathbf{r} \xrightarrow{\mathcal{P}} -\mathbf{r}$
Momentum: $\mathbf{p} \rightarrow -\mathbf{p}$
Spin: $\mathbf{S} \rightarrow \mathbf{S}$





Experience says left and right give the same physics

How Does Neutrino Observe Parity?



Left-handed state Right-handed state

- But no right-handed neutrino is observed
- Parity is violated in any neutrino-related process, i.e. parity is not conserved in weak interaction

Lee-Yang received the Nobel prize in 1957

Parity Nonconservation and a Two-Component Theory of the Neutrino

T. D. Lee, *Columbia University, New York, New York*

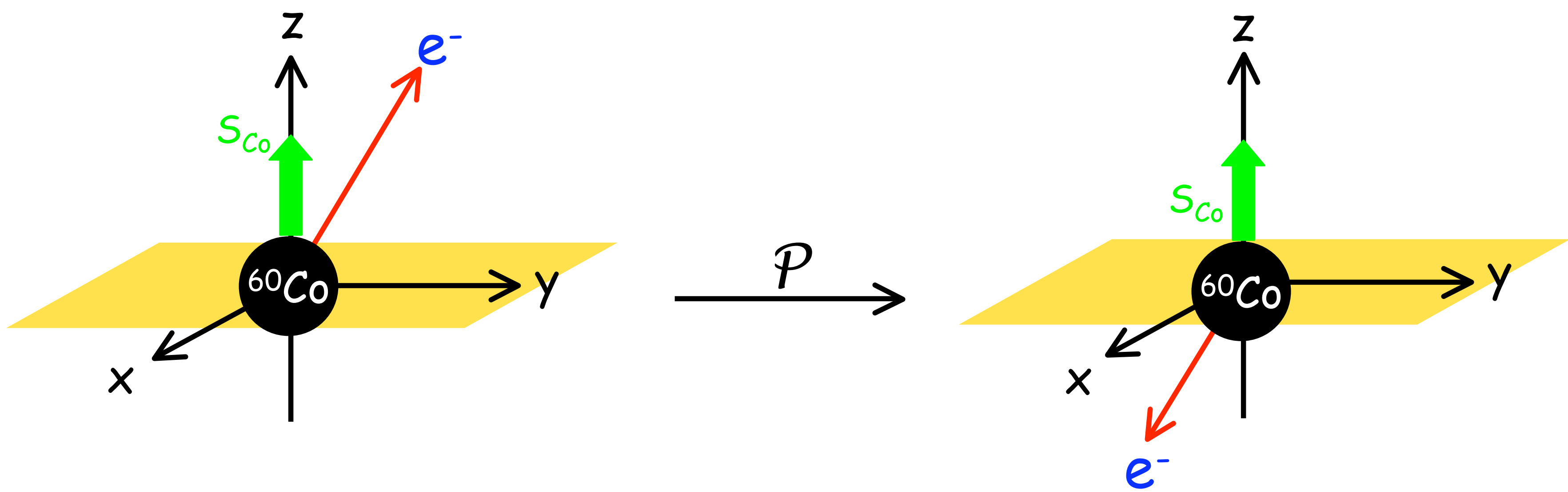
AND

C. N. Yang, *Institute for Advanced Study, Princeton, New Jersey*

(Received January 10, 1957; revised manuscript received January 17, 1957)

In this theory the mass of the neutrino must be zero, and its wave function need only have two components

Observation of Parity Violation



Parity conservation requires the number of electrons in the upper hemisphere equals to the number in the lower hemisphere

Wu et al. (1957) observed asymmetry, proving that parity is not conserved in weak interactions

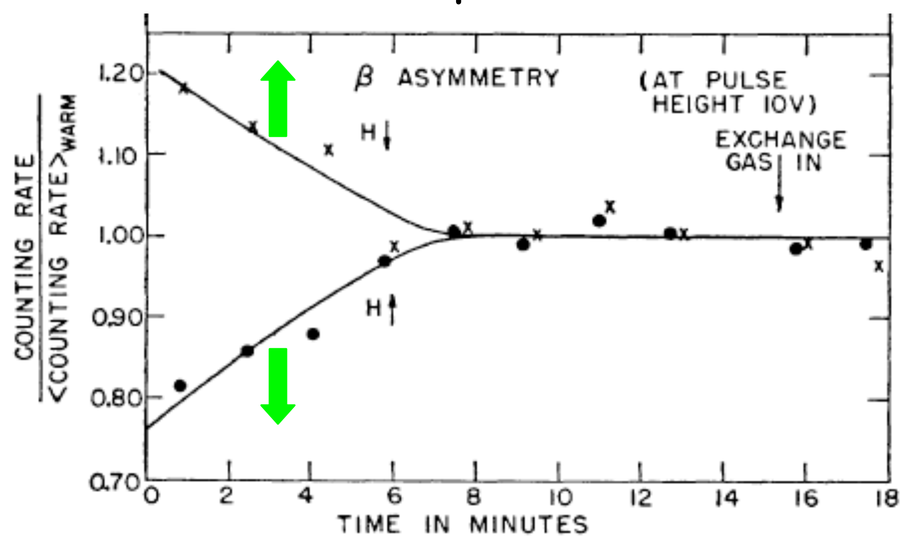


FIG. 2. Gamma anisotropy and beta asymmetry for polarizing field pointing up and pointing down.

Charge Conjugation

An operation that transforms a particle to its antiparticle
And vice versa:

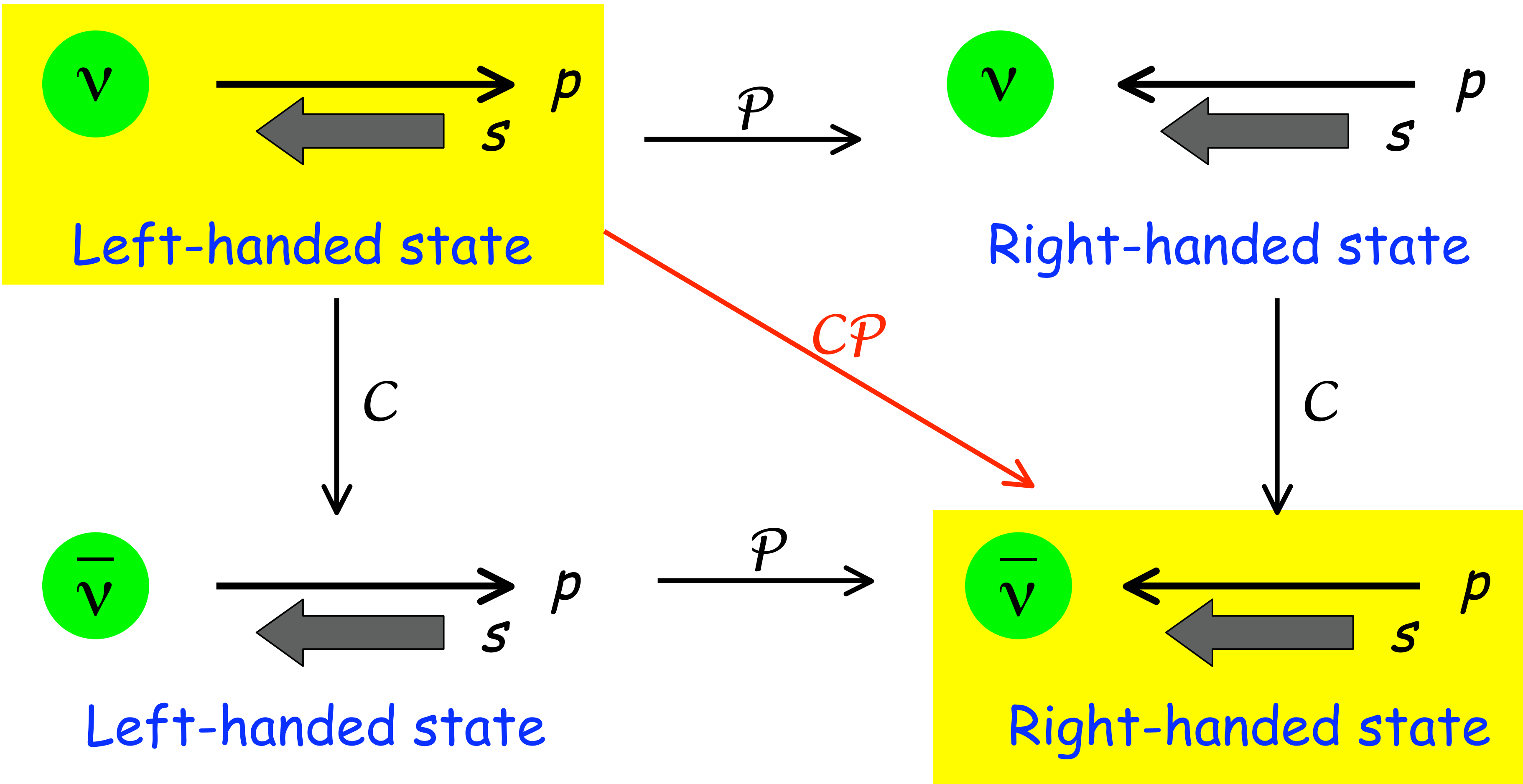
$$\text{particle} \xrightarrow{C} \text{Anti-particle}$$

That is, the electric charge is changed to the opposite.
For example,

$$\mu^- \xrightarrow{C} \mu^+$$

$$n \xrightarrow{C} n$$

CP Transformation



Left-handed neutrino implies right-handed antineutrino

What Is The Nature of Neutrino ?

- Relation between a particle and its antiparticle:

Particle	Antiparticle
Neutron, n	Antineutron, $\bar{n}$
Photon, γ	Photon, γ
π^0	π^0

- Dirac neutrino

  $\nu \neq \bar{\nu}$ (not the same particle)

  conserve lepton number.
- Majorana neutrino

  $\nu = \bar{\nu}$ (same particle)

  in this case, the neutrino must be massive, and violates lepton number.
- Which is the correct description for neutrino?

  Neutrinoless double beta decay can tell.

What Is The Electric Charge of Neutrino?

- From beta decays,

$$ {}^{A}_{Z}N \longrightarrow {}^{A}_{Z+1}N + \beta + \bar{\nu}_e $$

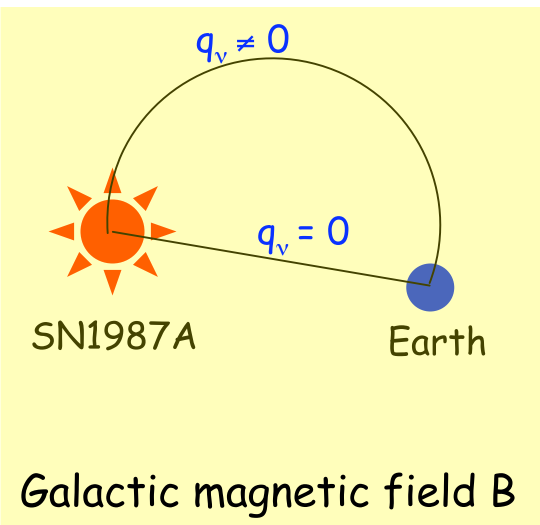
the charge of the neutrino is:

$$ q_\nu = q_{Z+1} + q_\beta - q_Z $$

From experiments,

$$ q_\nu < 8 \times 10^{-15} \, |q_e| $$

- From the detected neutrinos from SN1987A,



The difference in arrival time Δt:

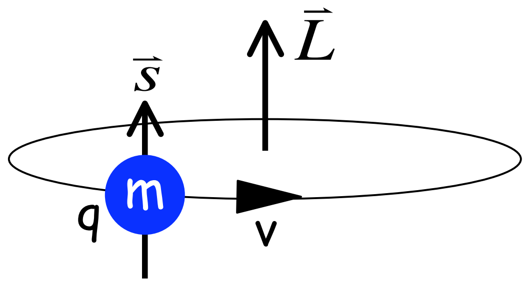
$$ \frac{\Delta t}{t} = \frac{1}{12} \frac{(0.3Bsq)^2}{E^2} \frac{\Delta E}{E} $$

$E \approx 15$ MeV, $\Delta E/E \approx 1/2$ and $\Delta t \lesssim 5$ s.

$$ q_\nu < 10^{-15} \text{ to } 10^{-17} \, |q_e| $$

Magnetic Moment

- Orbital magnetic moment,



μ_L = current x area

$$\mu_L = \left(\frac{q}{2m}\right) L$$

- Intrinsic magnetic moment,

$$\mu = g\left(\frac{q}{2m}\right) S$$

If g = 2, the particle does not have any structure.

For neutron,

$\mu = -1.91\ \mu_N$ where $\mu_N = \frac{e\hbar}{2m_p}$ nuclear magneton

Neutron is not a point particle; it has structure!

- The magnetic moment of neutrino is $\mu < 0.9 \times 10^{-10}\ \mu_B$

Lifetime Of Neutrino

- If neutrino is massive, then

ν_1 (m_1) ————————

ν_2 (m_2) ————————

ν_3 (m_3) ————————

Can decay occur? For example:

$$\nu_1 \rightarrow \nu_2 + \gamma$$

The Standard Model predicts the lifetime of a neutrino is

$$\tau > 10^{22} - 10^{38} \text{ years}$$

- From experiments done at reactors and accelerators:

$$\tau(\nu_e) > 300 \text{ s}$$
$$\tau(\nu_\mu) > 15.4 \text{ s}$$

Summary

- Handedness of neutrinos leads to:
  - neutrinos have no mass
  - parity violation in weak interactions

- We don't know whether
  - neutrinos are Dirac- or Majorana-type
  - neutrinos have any intrinsic magnetic moment
  - neutrinos live forever