

## Lecture 26

### Parity Violation

This is an example of a little detail that did not look as expected and lead down a rabbit hole (only really resolved at the LHC)

#### 1950s

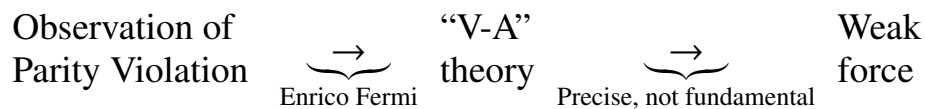
Parity conservation is the idea that physics is unchanged if L and R are reversed.

(eg: cant tell if your looking in a mirror or not)

What was found in the 50s was that some particle interactions distinguished L and R.

**SHOCKING** could never happen in Gravity / EM or the strong force. (Was not tested in the weak interaction, b/c its weak its hard to study, but parity was assumed to hold there)

The weak interaction completely changed our ideas about what a force could be.



Next few lecture we will explore this new force, lead us down a path with surprise after surprise, ultimately to the Higgs boson which provides a framework on which all of this sits.

---

## Discrete Lorentz Transformations

Early in the course we discussed LT.

Focus was on continuous LT.

Also discrete transformations that leave  $t^2 - x^2$  invariant.

## Parity

$$\mathcal{P}\vec{x} = -\vec{x}$$

Can be thought of as viewing something in the mirror.

Vectors, like position and velocity are flipped by  $\mathcal{P}$ .

$$\mathcal{P}\vec{v} = -\vec{v}$$

$$\mathcal{P}\left(\frac{dx}{dt}\right) = \frac{-1}{+1}$$

Other mathematical objects that transform as vectors under continuous LTs, but do not pick up a “-” sign under  $\mathcal{P}$ .

“Pseudo-vectors” (vampire vectors)

(Tend to arise from cross products.)

Example Angular Momentum (torque and B-fields are others)

$$\vec{L} = \vec{x} \times \vec{p}$$

$$\begin{aligned}\mathcal{P}(\vec{L}) &= \mathcal{P}(\vec{x}) \times \mathcal{P}(\vec{p}) \\ &= -\vec{x} \times -\vec{p} = \vec{L}\end{aligned}$$

Aside Also notion of Scalars and Pseudo-scalars

$$\mathcal{P}n = +n \text{ (scalars) or } -n \text{ (pseudo-scalars)}$$

Maxwell's equations are invariant under  $\mathcal{P}$  (Homework)

QCD and Gravity are also invariant.

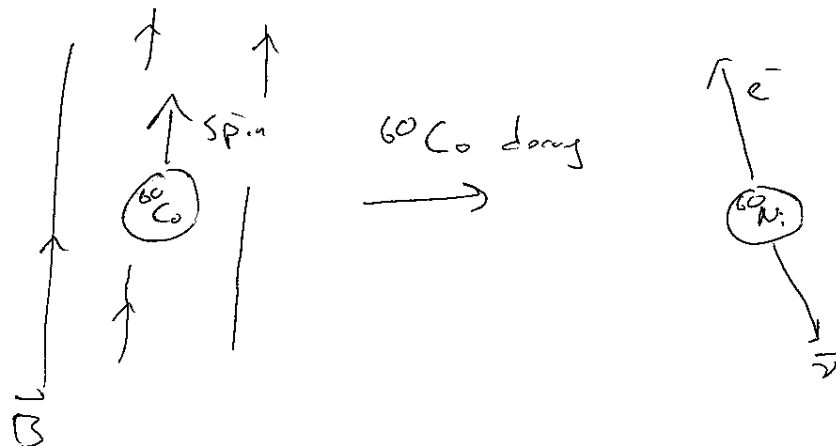
### Other discrete Lorentz Transforms

- $\mathcal{T}$  - time reversal  $\mathcal{T}t = -t$
- $\mathcal{C}$  - charge conjugation  $\mathcal{C}q = -q$

Maxwell's equations invariant under  $\mathcal{C}$  and  $\mathcal{T}$  (also in HW)

Turns out that  $\mathcal{T}$  needs to be defined as  $\mathcal{T}i = -i$  to leave the Schrodinger equation invariant (more HW)

### Parity Violation



Initial State: Invariant under  $\mathcal{P}$

Final State:

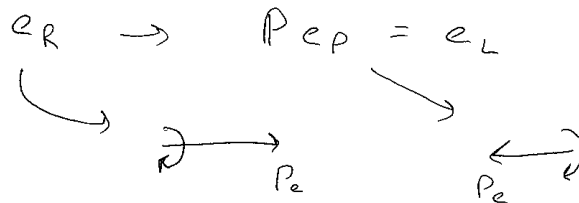


So under  $\mathcal{P}$  the experimental setup is unchanged but the final configuration is flipped. So if  $\mathcal{P}$  is conserved, you should see both final configurations with equal probabilities.

Shocking result (due to C.S. Wu) more electrons emitted opposite to the direction of the spin.

$\Rightarrow$  Force that governs nuclear decays violates parity!

Now electron under parity changes handedness



If parity violated by the nuclear (weak) interaction, we would expect different numbers of  $e_R$  and  $e_L$  produced in the  $^{60}\text{Co}$  decays.

In fact experiments showed that the produced electrons are Always left-handed.

So  $\mathcal{P}$  is not just violated, but maximally violated.

Turns out  $\bar{\nu}$  is always right-handed.

$\nu$ s only interact via the weak interaction. These interactions only involve  $\nu_L$  and  $\bar{\nu}_R$  (Suggests that only one helicity of  $\nu$ 's exist.)

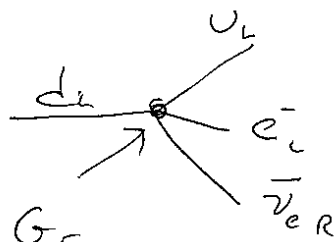
Weird and unexpected. eg. we know from study of  $e^+e^- \rightarrow \mu^+\mu^-$  that  $e$ 's and  $\mu$ 's can be left or right-handed. (leads to the observed  $(1 + \cos^2 \theta)$  cross section.)

Fundamental process in  $^{60}\text{Co} \rightarrow ^{60}\text{Ni}$  is  $n \rightarrow p$

or even more fundamental:

“V-A” theory (aka “Fermi” Theory) was invented to describe this

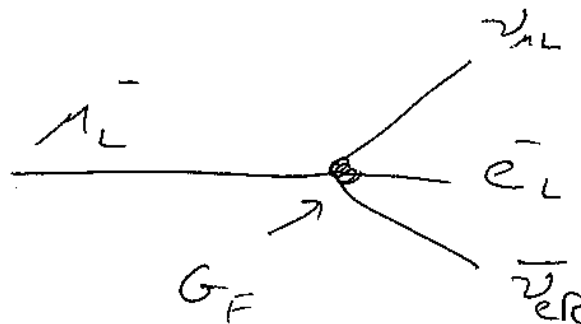
$$d \rightarrow u + e_L^- + \bar{\nu}_{eR}$$



$$L \supset G_F \bar{\nu}_{eR} e_L d_L u_L$$

$\hookrightarrow$  fermi constant units  $\text{GeV}^{-2}$

Also describes the decay of  $\mu s$  (easier to measure, cleaner to calculate)



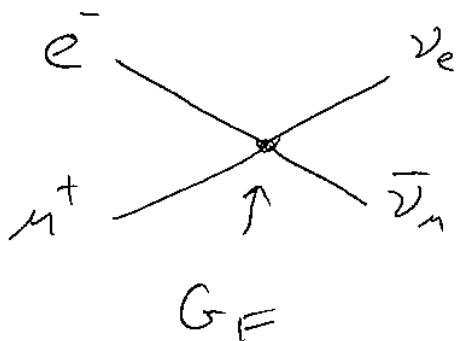
Can apply Feynman rule to Fermi theory and you would get

$$\Gamma = \frac{G_F^2 m_\mu^5}{192\pi^3}$$

which is in very good agreement with observations.

However, there are problems built in to this Fermi theory.

Consider cross section to produce  $\nu_e$  and  $\bar{\nu}_\mu$  from a hypothetical  $e\mu$  collider.



$$\sigma \sim |M|^2 \sim G_F^2$$

$$\begin{aligned} \sigma \text{ needs units of Area } &\sim \text{GeV}^{-2} \\ \Rightarrow \sigma &\sim G_F^2 E_{CM}^2 \end{aligned}$$

This is WEIRD, looks like cross section diverges with  $E_{CM}$ !

Doesn't make physical sense (e and  $\mu$  wavelengths shrink with E)

$\sigma$  should get smaller!

eg: saw exactly this in  $ee \rightarrow \mu\mu$  collisions

$$\sigma(ee \rightarrow \mu\mu) \sim \frac{1}{E_{CM}^2}$$

---

### Force Carriers

In QCD and EM effective 4-fermion interactions are controlled by exchange of Boson force carriers (Spin-1)

Assume force carriers associated with weak interaction also Spin-1.  $G_F$  arises from force carrier exchange, but importantly needs to have the right mass dimension  $\Rightarrow$  force carriers of weak interaction must be massive.

$$G_F = \frac{1}{m_F^2} \quad G_F \sim 10^{-5} \text{ GeV}^2 \Rightarrow m_F \sim 300 \text{ GeV}$$

$m_F$  - "Fermi Mass"

Problematic Mass terms for force carriers are not gauge invariant.  $m^2 A^2$

Leads to Crisis in the field.