Lecture 26

Parity Violation

This is an examples of a little detail that did not look as expected and lead down a rabbit hole that was really only 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.

$$\begin{array}{l}\text{Observation of}\\ \text{Parity Violation}\end{array} \underbrace{\rightarrow}_{\text{Enrico Fermi}} \begin{array}{l}\text{“V-A”}\\ \text{theory}\end{array} \underbrace{\rightarrow}_{\text{Precise, not fundamental}} \begin{array}{l}\text{Weak}\\ \text{force}\end{array}$$

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 (scalars) or -n (pseudo-scalars)

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

QCD and Gravity are also invariant.

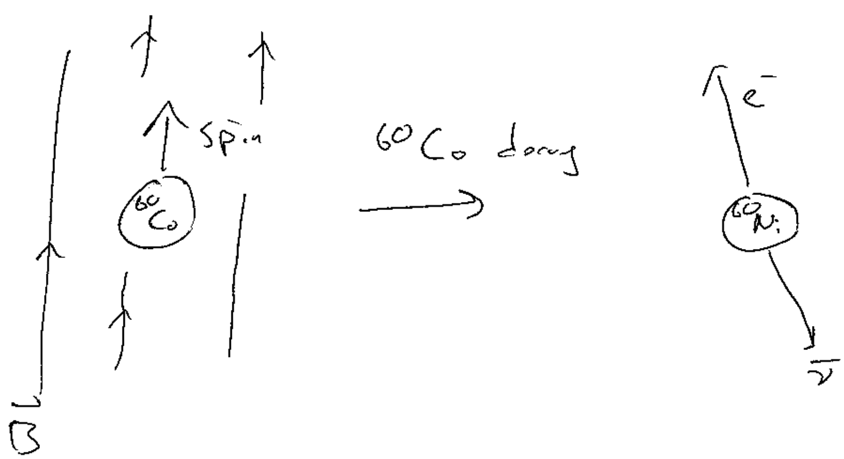
Other discrete Lorentz Transforms

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

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

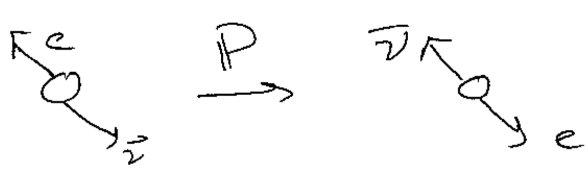
Turns out that $\mathcal{T}$ needs to be defined as $\mathcal{T}i = -i$ to leave the Schrodinger equation invariant (more HW)

Parity Violation



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

Final State:



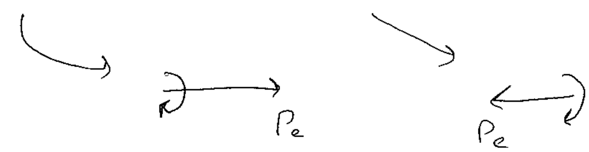
So under $\mathcal{P}$ the experimental setup is unchanged but the final configuration is flipped. So if $\mathcal{P}$ is conserved, you should see both final configurations with equal probabilities.

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

$$e_R \to \mathcal{P} e \mathcal{P} = e_L$$



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

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

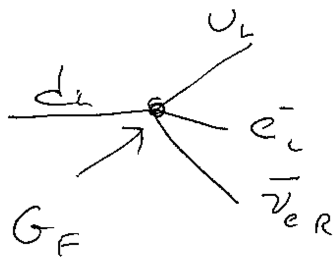
Weird and unexpected. eg. we know from study of $e^+e^- \to \mu^+\mu^-$ that e's and μ's can be left or right-handed. (leads to the observed $(1 + \cos^2\theta)$ cross section.)

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

or even more fundamental:

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

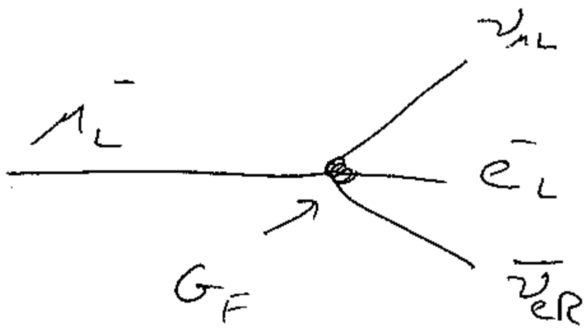
$$d \to u + e_L^- + \bar{\nu}_{eR}$$



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

↳ fermi constant units GeV^{-2}

Also describes the decay of μs (easier to measure, cleaner to calculate)



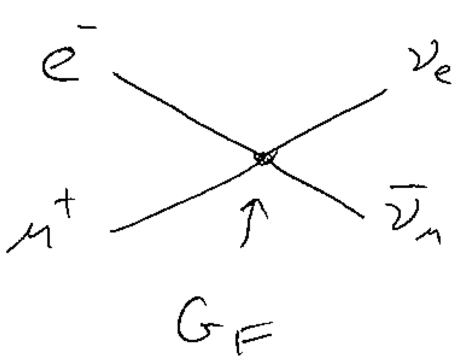
Can apply Feynman rule to Fermi theory and you would get

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

which is in very good agreement with observations.

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

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



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

σ needs units of Area $\sim \text{GeV}^{-2}$
$$\Rightarrow \sigma \sim G_F^2 E_{CM}^2$$

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

Doesn't make physical sense (e and μ wavelengths shrink with E)

σ should get <u>smaller</u>!

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

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

<u>Force Carriers</u>

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.

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

m_F - "Fermi Mass"

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

Leads to Crisis in the field.