<u>Parity Violation</u> (this is example of a little detail that did not look as expected and the field down a rabbit hole that was only resolved @ the LHC)

<u>1950s</u>

Parity ~~is~~ conservation is the idea that physics is unchanged if L + R are reversed (Eg ~~physics is the same~~ can't tell if your looking in mirror or not.

What was found in 50's was that some particle interaction distinguished L + R. <u>Shocking</u> could never happen in Gravity / EM or Strong force

New force (weak interaction) completely changed our ideas about what a force could be.

<u>effective</u> theory

<u>Observation of Parity violation</u> $\longrightarrow$ "V-A" theory $\longrightarrow$ Weak force

Enrico Fermi

V-A precise, but not a satisfactory fundamental theory.

Next few lectures we will explore this new force, lead us down a path w/ surprise after surprise ultimately to Higgs boson which provides a framework on which all this sits.

Discrete Lorentz Transformations

Early in course we discussed LT. focus was on continous LT. Also discreet transformations that leave $t^2 - x^2$ invariant.

Parity $\quad \mathbb{P}\vec{x} = -\vec{x}$ $\quad$ Can be thought of as act of viewing something through mirror.

Vectors, like position & velocity are flipped by $\mathbb{P}$.

$$\mathbb{P}\vec{v} = -\vec{v} \qquad \left(\mathbb{P}\left(\frac{dx}{dt}\right)\right)$$

Other mathematical objects that transform as vectors under continous LT, but do not pick up "−" sign under $\mathbb{P}$

"Pseudo vectors" (vampire vectors)

Example Angular Momentum $\quad$ Tend to arise from cross products.

$$\vec{L} = \vec{x} \times \vec{p} \qquad \mathbb{P}(\vec{L}) = \mathbb{P}(\vec{x}) \times \mathbb{P}(\vec{p})$$

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

{ torque
{ B-field

> **Asside** Also notion of Scalars & Pseudo Scalars
>
> $$\mathbb{P}n = \pm n$$
>
> ($+$ ← Scalar; $-$ ← Pseudo scalar)

Maxwells equations, invariant to $\mathbb{P}$ ← Hw

$\mathcal{L}$ QCD & G.R. are also invariant.

Other Discrete L.T.s

$\mathbb{T}$ - time Reversal $\qquad \mathbb{T}\, t = -t$

$\mathbb{C}$ - Charge Conjugation $\qquad \mathbb{C}\, q = -q$

Maxwells equations invariant under $\mathbb{C}\,\mathbb{T}$. ← Hw

$\mathbb{T}$ needs to be defined $\mathbb{T}\, i = -i$ to leave the Schrodinger eq invariant. ← Hw

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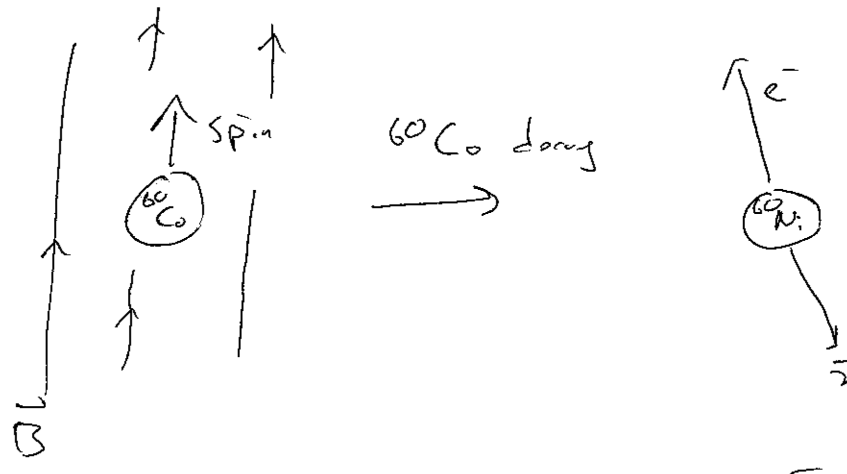
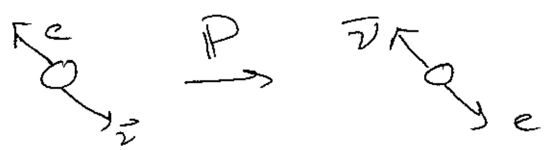


I $\qquad\qquad$ F

Invariant under $\mathbb{P}$ $\qquad$ under



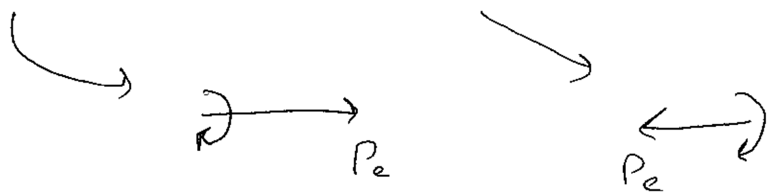
So under $\mathbb{P}$ the experimental setup is unchanged by the final configuration is flipped. So if $\mathbb{P}$ conserved you should see both final configuration w/ equal prob

Shocking Result $\boxed{\text{C. S. Wu}}$ more electrons emitted opposite to the direction of the spin.

Force that governs nuclear decays violates parity

<u>Now</u>

$e_R \rightarrow \mathbb{P}\, e_R = e_L$



If parity violated by weak interaction, we would expect different numbers of e_R & e_L produced in the ^{60}Co decays.

In fact experiments showed that the produced electrons are <u>Always</u> left-handed.

$\mathbb{P}$ not just violated, but <u>maximally</u> violated.

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

ν's only interact w/ weak interaction. These interactions only involve ν_L & $\bar{\nu}_R$ Suggests that only one helicity of ν's exist.

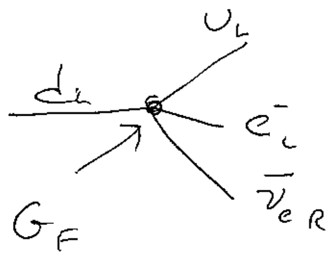
Weird & unexpected. eg we know from study of $e^+e^- \rightarrow \mu^+\mu^-$ scattering that e's & μ's can be L or R leads to observed $1+\cos^2\theta$ cross section

Fundamental Process in $^{60}Co \to {}^{60}Ni$: is $n \to p$

or

$$d \to u + e^-_L + \bar{\nu}_{e_R}$$

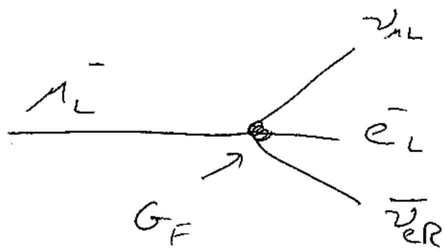
"V - A" theory "Fermi" Theory was invented to describe this



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

$\hookrightarrow$ fermi Constant Units GeV^{-2}

Also describes the decay of μ's (easier to measure
cleaner to calculate)



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

Can apply feynman rules to ~~QFA~~ fermi theory get Γ

which is in very good agreement with observations.

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

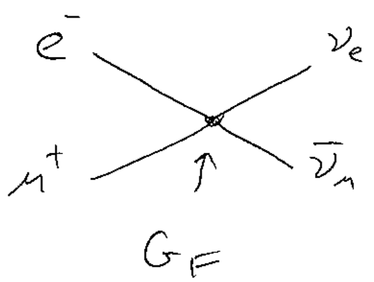
-) Postulate about 4-fermion interaction
-) In QCD + EM 4-fermion " controlled by Spin-1 Bosons ~~total~~
-) Tip of the ice bergh.

<u>will find</u>

- Structure fermi theory requires massive force carriers
- Seems to violate gauge invariance
- Can Maintain GI by adding new particles

Problems w/ Fermi theory.

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



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

σ needs units of Area $\sim \text{GeV}^{-2}$

$$\Rightarrow \quad \sigma \sim G_F^2 E_{cm}^2$$

↪ Weird cross section diverges w E_{cm}?
Doesn't make physical sense (e & μ wavelengths ~~scales~~ shrink w/ E)
σ should get smaller.

Eg

$$\sigma(ee \to \mu\mu) \sim \frac{1}{E_{cm}^2} \quad \text{As expected}$$

Force Carrier

Assume force carrier associated w/ interaction. Spin 1

G_F arrise from force carrier, more importantly needs right mass dimension $\Rightarrow$ force carriers are massive

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

↪ "Fermi Mass" $\quad \Rightarrow \quad m_F \sim 300$ GeV

Problematic mass terms for force carriers are not gauge invariant $\quad m^2 A^2$

Crisis