FINAL EXAM...

MONDAY,
DECEMBER 11...   12:45 – 2:45 pm

BPS 1415

Problems possibly from
Chapters:

- 2 Relativity
- 3 Expt. Basis Quantum Theory
- 4 Structure of Atom
- 5 Wave Properties of Matter
- 6 Quantum Mechanics
- 7 Hydrogen Atom
- 12 Atomic Nucleus
- 13 Nuclear Reactions

THERMODYNAMICS

"Questions" => famous people & what they did
famous experiments.

Chapters 2, 3, 4, 5, 6, 7, 12, 13, 14

CHAPTER ~~13~~ 14! ELEMENTARY PARTICLE PHYSICS

AKA: "High Energy Physics"

Nuclear physics branched in the 1950's

1950's nuclear physics

→ more and more energies ⇒ probing smaller & smaller distances

→ more and more complexity
- rare isotopes
- complicated higher excited st.
- high densities from heavy ion collisions (NSCL, RHIC)

Both became reliant on artificial beams

— but important early discoveries came from imaging cosmic rays

When we last left our story so far... ~1935

electrons

photons

protons

neutrons

discovered, used as probes

neutrinos

pions

predicted

electromagnetic force: electrons, protons (charged)

photons (uncharged)

strong force: protons, neutrons, pions

"weak force": neutrons, neutrinos

then, it got weird.

Paul Dirac _.

young British theorist.

- 1st showed that Schrödinger's & Heisenberg's quantum mechanics were equivalent.
- worried about Relativistic Quantum mechanics.

remember operators:

$$P_x \longrightarrow -i\hbar \frac{\partial}{\partial x}$$

$$E \longrightarrow i\hbar \frac{\partial}{\partial t}$$

so,

$$E = \frac{p^2}{2m} + V \longrightarrow i\hbar \frac{\partial}{\partial t}\psi = -\frac{\hbar^2}{2m}\psi + V\psi$$

But, what about relativity?

$$E^2 = p^2c^2 + m^2c^4$$

$$E = \pm\sqrt{p^2c^2 + m^2c^4} \xrightarrow{?} \text{huh?}$$

$E = \pm$ what?

negative energy?

negative probability!!

Schrödinger's Equation is 2nd order in space.

& ψ is 2-valued $\psi_{+,-}$

for 2 spin components

with ad hoc suggestion

by Pauli

In general: $\psi = \begin{pmatrix} \psi_\uparrow \\ \psi_\downarrow \end{pmatrix}$

a matrix in "spin space"

So, a general solution which picks out a spin state — like a magnetic field

$$S\psi \to \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}\psi = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}\begin{pmatrix} \psi_\uparrow \\ \psi_\downarrow \end{pmatrix} = \begin{pmatrix} \psi_\uparrow \\ 0 \end{pmatrix}$$

all of this built-in to Schrödinger's scheme

- could solve everything
- a cludge

Dirac found he could get around the negative probability problem with a 1st order differential equation

$$\frac{\partial}{\partial t}$$

$$\frac{\partial}{\partial p_x}, \frac{\partial}{\partial p_y}, \& \frac{\partial}{\partial p_z}$$

at the price of $\quad \psi = \begin{pmatrix} \psi^+_\uparrow \\ \psi^+_\downarrow \\ \psi^-_\uparrow \\ \psi^-_\downarrow \end{pmatrix}$ } positive energies, e^- ; } NEGATIVE ENERGIES, X^+

↗ 4 component wave function - a "spinor"

what was X ?

→ at first, he guessed "proton"

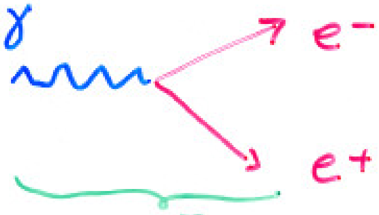
but $m_X \equiv m_e$ so $X \neq$ proton

→ had to be a positive electron

an anti-electron.

1928

His interpretation was... controversial.



← "Dirac Equation" describes this and requires this, and this

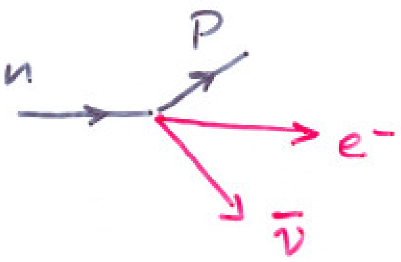
suggesting

a multi-particle quantum mechanics

&

creation of particles

Fermi used this idea in 1934 for his theory of beta-decay



} an antineutrino, actually.

Our interpretation comes from Feynman.

Dirac's Theory –

all spin ½ particles – Fermions –

have antiparticle cousins with

same mass

opposite electric charge

e^-	e^+	$(\bar{e})$
p (+)	$\bar{p}$	(−)
n	$\bar{n}$	

it is also true for integer spin particles

π^+ π^- for example

Recall the time dependence of wave functions:

$$\psi^+ \sim e^{-iEt}$$ ⇒ moving forward in time

Formally the "electron current" is "like"...

$$j^+ \propto Q \frac{\partial}{\partial t} \psi^+ = Q \frac{\partial}{\partial t} e^{-iEt}$$

$$j^+ \propto Q(-iE)\, e^{-iEt}$$

for negative energy...

$$j^- \propto Q \frac{\partial}{\partial t} e^{-i(-E)t}$$

$$= Q(-i)(-E)\, e^{+iEt}$$

$$= -Q(-iE)\, e^{iEt}$$

sorta like j^+ but moving wrong way...

instead write

$$\psi^- \propto e^{-i(-E)(-t)}$$

$$j^- \propto Q \frac{\partial}{\partial t} e^{-i(-E)(-t)} = Q(-i)(-E)\, e^{-iEt}$$

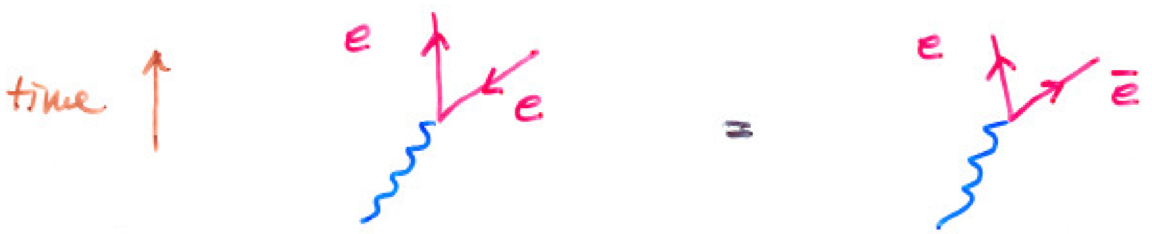
$$j^- = -Q(-iE)\, e^{-iEt}$$

j^- like j^+ except for $-Q$...

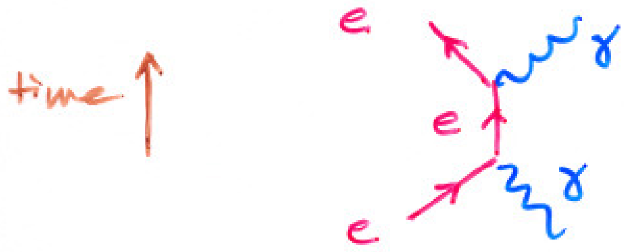
Feynman's interpretation:

we can treat negative energy particles going backwards in time

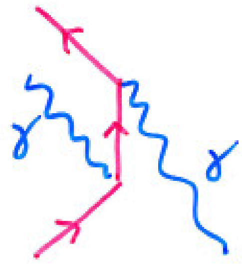
as positive energy antiparticles going forwards in time



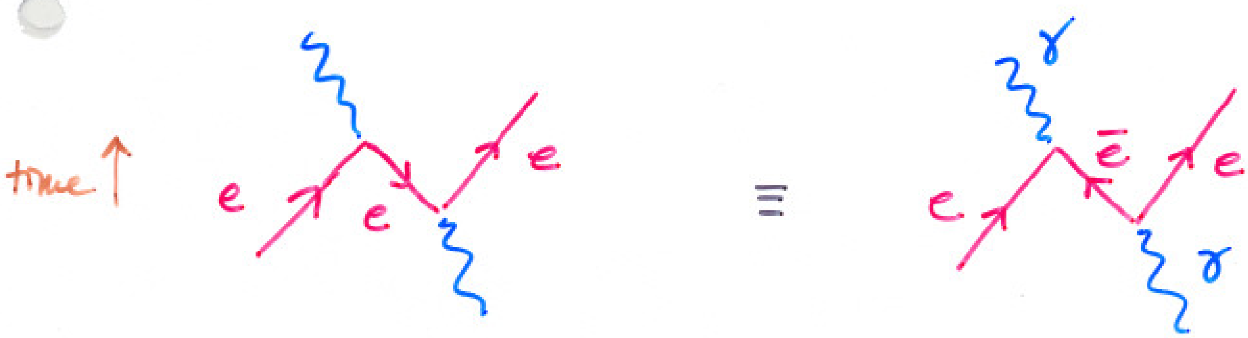
Now... say... Compton scattering:



also:



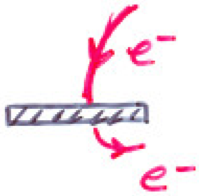
which <u>includes</u>



Goofy, right?

so... right on time in 1934, the positron shows up.

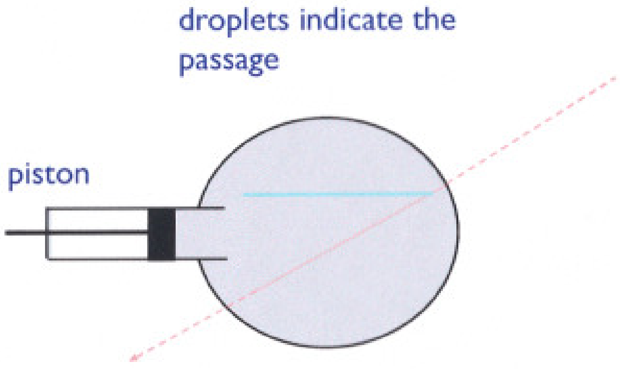
further, they put a plate of lead inside to slow down particles

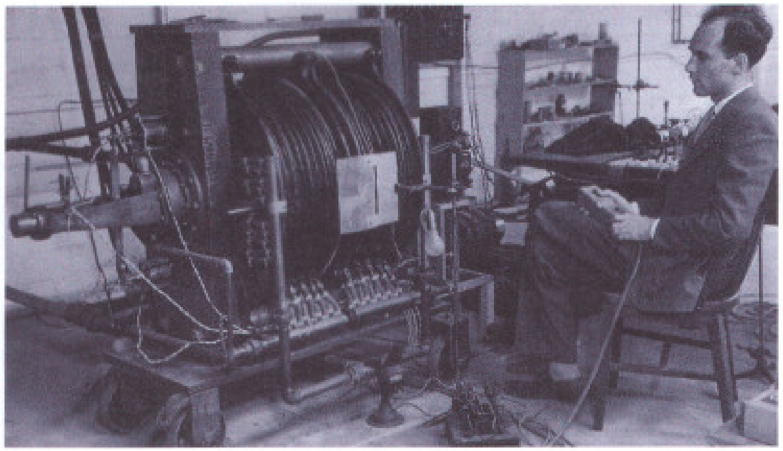


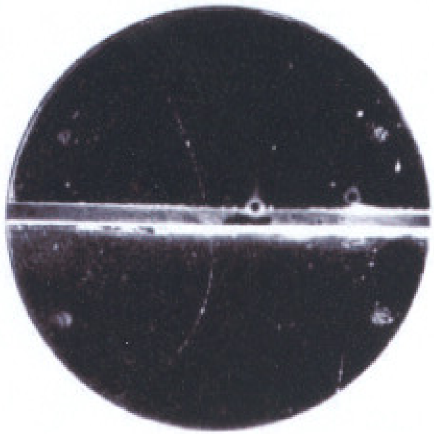
⇒ can tell downward from upward particles

Carl Anderson's graduate school research.

Positrons exist -- all features of electrons, but + charge.

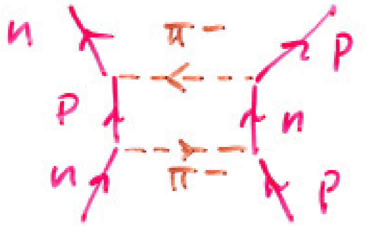

droplets indicate the
passage
piston





Remember Yukawa's particle .. 1934

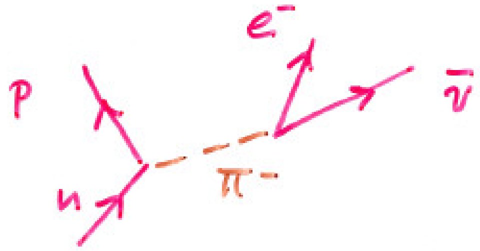
"Y" now, "π"



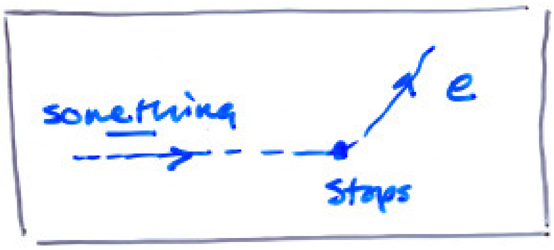
predicted, roughly:

$m_\pi \sim 200\ MeV/c^2$

Also, he thought, an explanation for β decay:



1937... right on schedule, Y turns up...

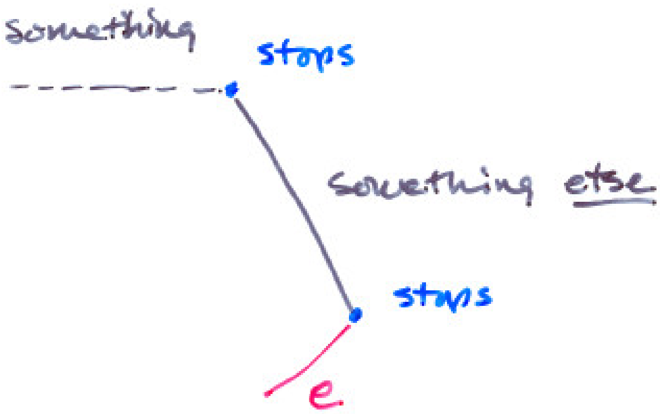


the "something" had mass ~ $200\ MeV/c^2$

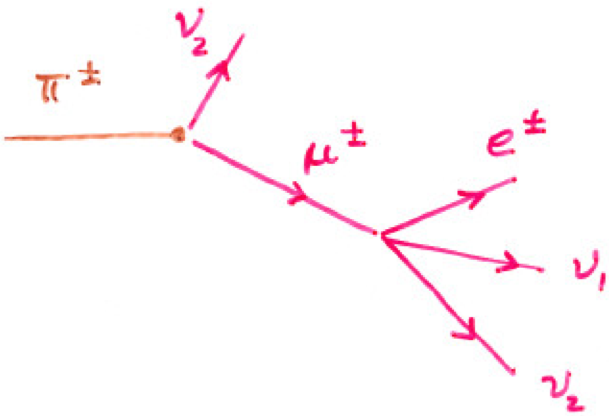
But: $\tau \sim 2 \times 10^{-6}$ s too long to be π

After WW II -- 1947 sophisticated measurements

showed more going on:



A chain:



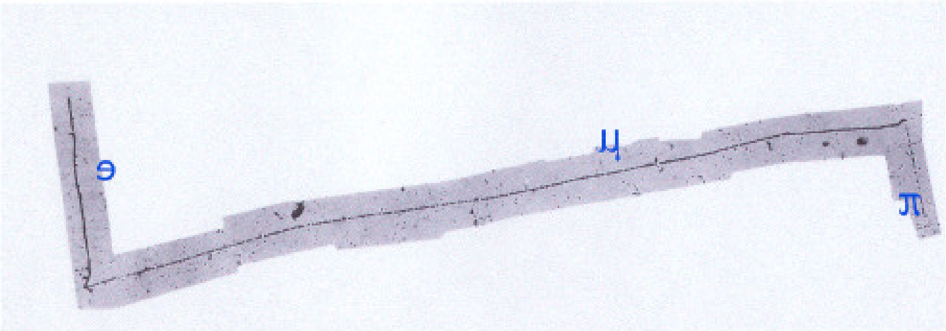
the muon. μ

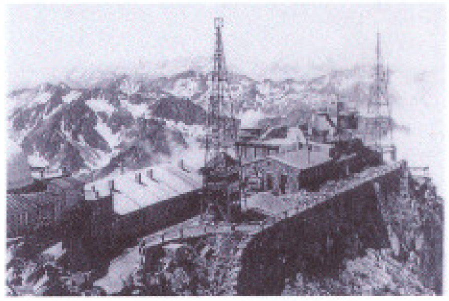
"Who ordered that?"
I.I. Rabi

$m(\pi) = 140\ \text{MeV}/c^2$ -- spin = 0

$m(\mu) = 106\ \text{MeV}/c^2$ -- spin = $1/2$

μ like e -- just heavier!





ν_1 & ν_2 ?

There are neutrinos .. one for muon ν_μ

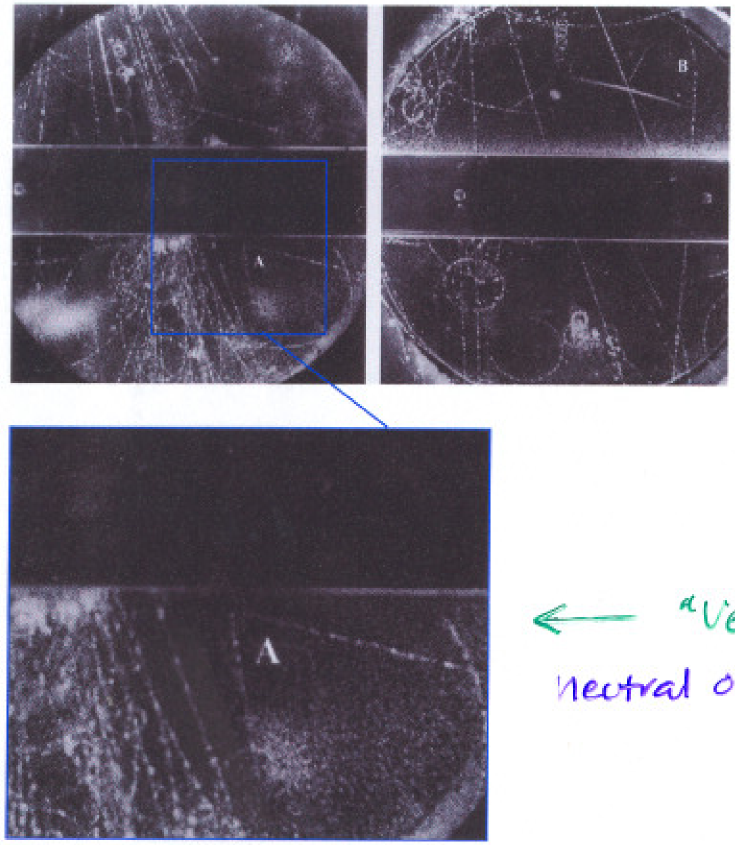
one for electron ν_e

Chay chay.

particle	charge/s	strong	weak	electromagnetic
electron	±1 / ½		✓	✓
proton	±1 / ½	✓	✓	✓
neutron	±1 / ½	✓	✓	
pion	±1 / 0	✓	✓	✓
neutrino	0 / ½		✓	
muon	±1 / ½		✓	✓

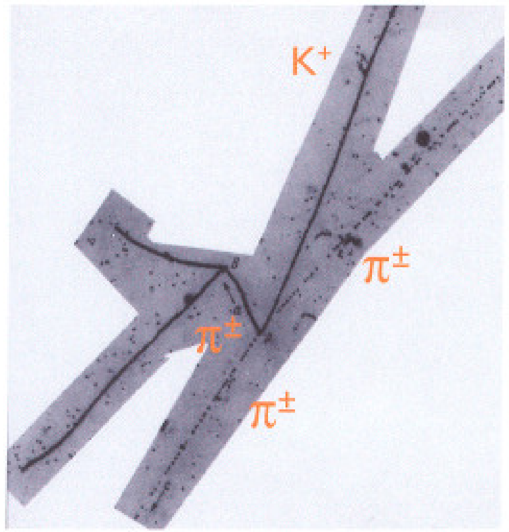
then, it gets weird.

More cosmic ray events



← "Vee's"

neutral objects → $\pi^+\pi^-$



then, more:

this time, charged.

These were strange...

so dubbed "STRANGE PARTICLES"

There were many strange Particles:

$\Lambda \rightarrow p\bar{\pi}$

$\qquad n\bar{\pi}$

$K^{\pm} \rightarrow \mu\nu$

$\qquad e\nu$

$\qquad \pi^{\pm}\pi^{0}$

$\Sigma^{\pm} \rightarrow p\pi^{0}$ $\qquad \Sigma^{0} \rightarrow \Lambda\gamma$

$\qquad n\pi^{+}$

It goes on and on... eventually 100's of "elementary" particles – Fermions and Bosons.

Then it gets weird.

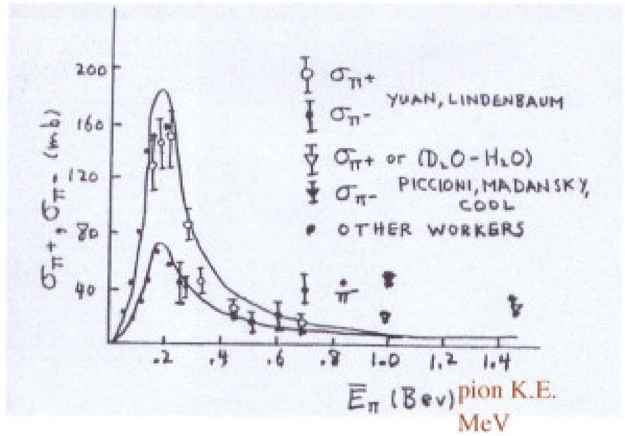
By 1952 Fermi is using artificial π beams and discovering new states

$$\pi + p \to X \to \pi p$$

↑ @ particular energy. corresponding to

$M_X = 1236\ \text{MeV}/c^2$

"Δ" resonance



From a 1954 talk by Luke Yuan

it just gets out of hand from here...

Then it gets weird.

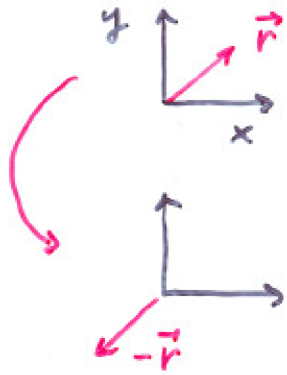
Two kinds of vectors:

polar vectors
axial vectors
} distinguished by how they behave under a Parity Transformation: $\vec{x} \longrightarrow -\vec{x}$

Polar Vectors

$\vec{p} \xrightarrow[\text{transformation}]{\text{parity}} -\vec{p}$

$\vec{r} \longrightarrow -\vec{r}$

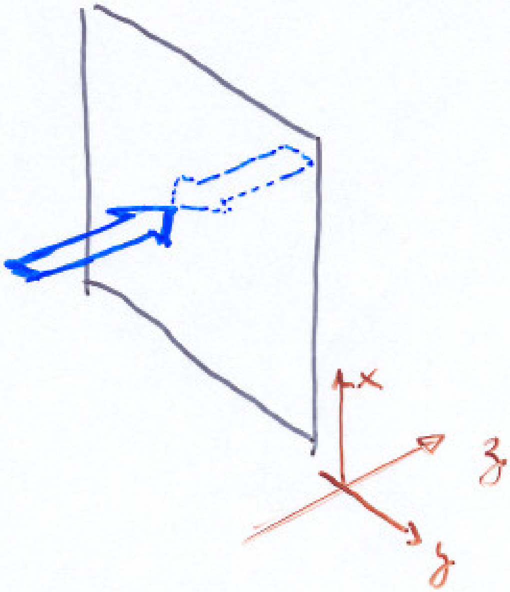


Axial Vectors

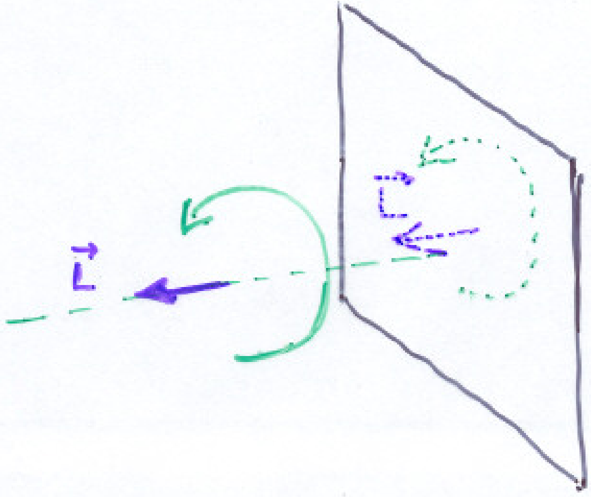
$\vec{L} \longrightarrow +\vec{L}$ -- $\vec{L} = \vec{r} \times \vec{p}$

$\vec{\mu} \longrightarrow +\vec{\mu}$ $\vec{\mu} = -\frac{e}{2m}\vec{L}$

Mirror



arrow goes from +z
to -z
→ polar vector



sense of rotation
doesn't change