PHY-302

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Lecture 12 - Symmetry and CPT

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- In 1956 (anti)-neutrino was experimentally detected directly by Reines & Cowan
- Nuclear reactor used as source of anti-neutrinos
- Fission products undergo negative beta decay - provide neutrino source
- Use liquid scintillator - rich in 'free' protons
- Scintillator doped with Cadmium - large neutron capture cross section

$$\bar{\nu}_e + p \rightarrow n + e^+$$

positron annihilates with scintillator electrons - 2 photons emitted $e^+ + e^- \rightarrow 2\gamma \quad 0.511 \text{ MeV}$

neutron slowed by many collisions - captured by ^{114}Cd

$$^{114}Cd + n \rightarrow \ ^{115}Cd^*$$

$$^{115}Cd^* \rightarrow \ ^{115}Cd + \gamma \quad 9.1 \text{ MeV}$$

Signal is 9.1 MeV photon and two 0.511 MeV photons

Later, same team demonstrated anti-neutrino capture by neutrons is not possible

$$\bar{\nu}_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^- \qquad \text{i.e. look for } \bar{\nu}_e + n \rightarrow p + e^-$$

They exposed a tank of very pure CCl_4 with anti-neutrinos from fission reactor

Periodically purged tank and tested for presence of ^{37}Ar

No ^{37}Ar was found

In other words anti-neutrino interacts with p^+ but not n^0

Implication is neutrino is different from anti-neutrino - but how....?

$$h = \frac{\mathbf{s} \cdot \mathbf{p}}{|\mathbf{s} \cdot \mathbf{p}|}$$

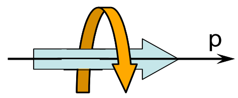
helicity is spin projected onto direction of momentum

For neutrinos h>0

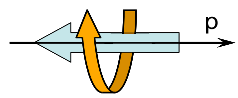
For anti-neutrinos h<0

strictly only true for massless particles

Right handed



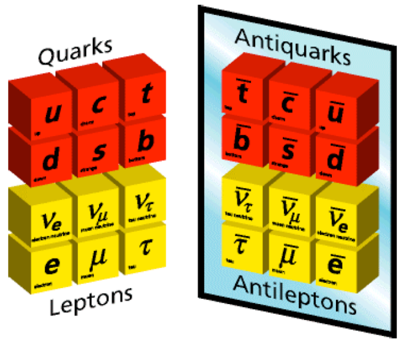
Left handed



Neutrinos still play a fundamental role in understanding phenomena

Meet them in our later discussion of:

- Solar fusion - solar neutrino flux problem
- nucleosynthesis in stars
- supernovae
- matter & anti-matter in early universe



All matter is comprised of quarks & leptons
They all have anti-particles
Only first generation is required to account for all visible matter
Higher generations only seen in particle colliders

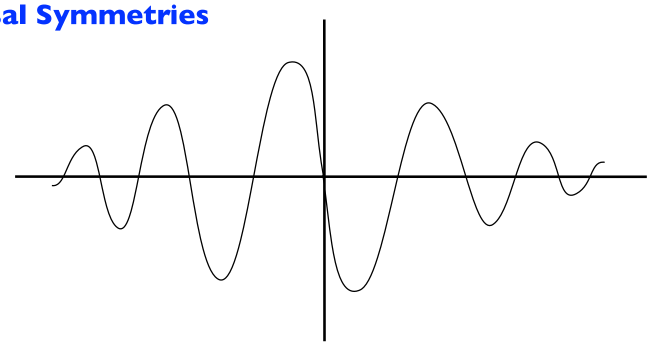
Particle	Baryon Number	Lepton Number
proton	1	0
neutron	1	0
electron	0	1
positron	0	-1
neutrino	0	1
anti-neutrino	0	-1

Baryon and lepton number are conserved

Universal Symmetries

Consider this function f(x):
exact functional form is unknown

What do we know about it?
it is odd i.e. f(-x) = -f(x)
Fourier transform will have no cos terms
integral from -n to +n is 0



So symmetries can provide useful information
Particularly dynamical symmetries of motion
Greeks believed stars moved in circles since they were most symmetrical orbits
Newton realised fundamental symmetries revealed **not** in motions of individual objects...
...but in **set of all possible motions**
Symmetries are manifest in equations of motion - not particular solutions to those equations
Gravity is spherically symmetric, but planets have elliptical orbits
In 1917 role of symmetries in physics was understood: Emmy Noether's Theorem:

Every symmetry of nature yields a conservation law (and vice versa!)

Universal Symmetries

Translation in time: → Energy conservation
Translation in space: → Momentum conservation
Rotations: → Angular Momentum conservation
Gauge Transformation: → Charge conservation

Laws of physics are symmetric with respect to translations in time:
they are the same today as they were yesterday

Analysing the set of transformations of a system uses Group Theory

Imagine swapping all numbers +ve and -ve e.g. my bank account
doing this does not break the laws of mathematics
I suddenly become very rich indeed...
If the entire world did this simultaneously we would notice no difference at all!
The banking world is symmetric under sign inversion of real numbers
⇔ total amount of money is conserved !!

Universal Symmetries

In forming theories physicists look for symmetries to help explain phenomena
In particle physics such symmetries tell us of the nature of space-time & particles themselves
Consider charge symmetry: replace all particles with anti-particles

Our universe is composed of matter
We **happen** to call it "matter"
We **could** have called it "anti-matter"
But, we **do know** that we are made of the same type (either all matter or not)
Fundamental laws of nature do not tell us if we are made of matter or anti-matter
There is no difference!

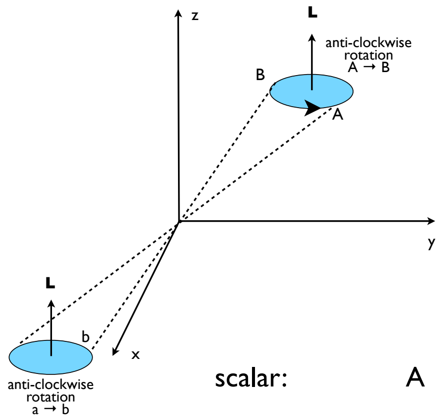
Same is true of parity inversion:

Parity inversion turns left-handed co-ordinate system into a right-handed one
There is no fundamental distinction between "left" and "right"
OK, humans have hearts on left side of body...
But we concern ourselves with laws of nature, not accidental arrangement of objects

Similarly for time reversal symmetry:

If we replace t with -t in all equations
If we did turn time backwards - laws of physics are expected to be the same
In this universe time does run forwards...
...if we changed this, we don't expect Newton's laws to fail

At least, we expect universe to behave this way...

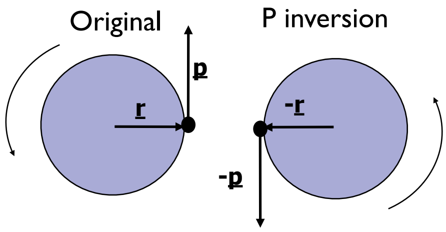


- Parity transformation is reflection about a given axis
- In 3D: reflection about all three axes
- original particle travels A to B to C
- reflection travels from A' to B' to C'
- Note some quantities do not change under inversion
  - vector **r** changes sign (**r'** = **-r**)
  - these are vector quantities
- Others do not:
  - angular momentum / spin does not change sign
  - (use right-hand rule to define direction)
  - these are axial-vector quantities

scalar:	A → A
pseudo-scalar:	S → −S
vector:	$\underline{V}$ → −$\underline{V}$
axial-vector:	$\underline{P}$ → $\underline{P}$

Consider vector definition of angular momentum:

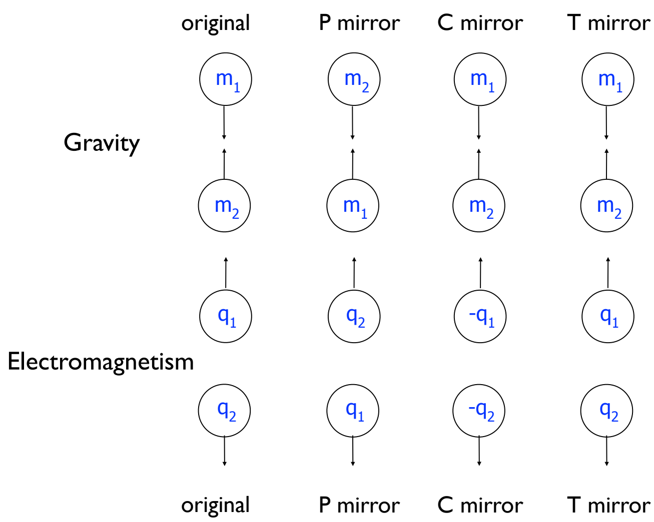
$\underline{\mathbf{L}} = \underline{\mathbf{r}} \times \underline{\mathbf{p}}$ and $\underline{\mathbf{L}}' = \underline{\mathbf{r}}' \times \underline{\mathbf{p}}' = \underline{-\mathbf{r}} \times \underline{-\mathbf{p}} = \underline{\mathbf{L}}$!!!



Charge, Parity & Time are 3 fundamental symmetries:

C	Charge conjugation	swap all particles with anti-particles
P	Parity inversion	reflect system about origin: Pψ(r) = ψ(-r)
T	Time reversal	time is reversed in direction: Tψ(t) = ψ(-t)

Gravity, & electromagnetism are both invariant to C, P and T inversions



Time reversal:
Planetary orbits are reversed
Masses decelerate as they move apart
Force between masses remains same

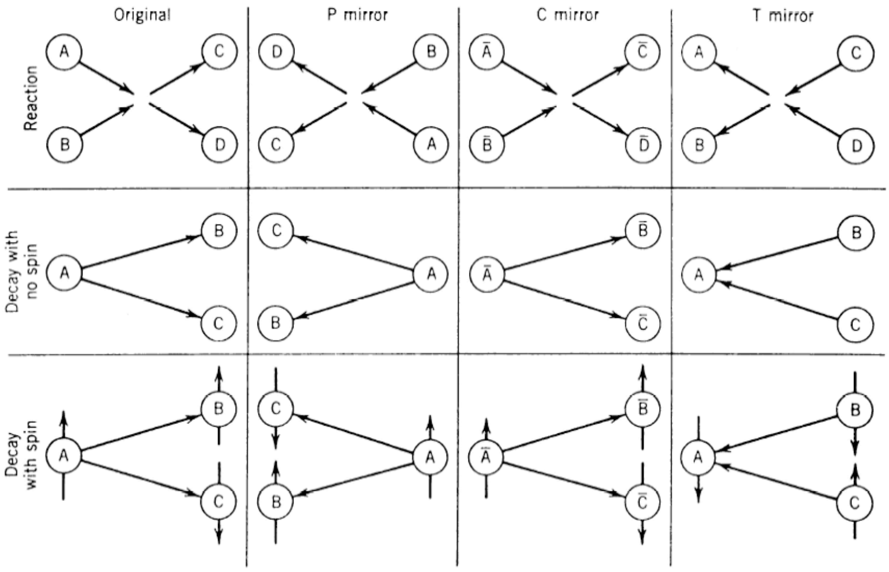
Time reversal:
Charges decelerate as they move together
Force between charges remains same

Can test C, P, and T symmetries in a series of experiments: A+B → C+D

Test P: swap positions of A and B (i.e. projectile A and target B, instead of vice versa)

Test C: exchange A and B for anti-particles

Test T: collide C and D to produce A and B



- Physicists assumed parity to be a conserved symmetry
- Natural to assume any experiment gives same result as mirror image
- Quantum physics is never so accommodating!
- Particle physicists observed two particles: θ and τ
- Both had same spin, mass, charge, lifetime
- Suggests they are same particle
- But, decayed to different final states with different parities
- Decay process similar to nuclear beta decay
- In 1956 Lee & Yang proposed they are same particle, but parity is violated
- Dec 1956 Wu et.al. measured beta decay of ^{60}Co nuclei confirming parity violation

Wolfgang Pauli wrote: *"I do not believe that the Lord is a weak left-hander, and I am ready to bet a very large sum that the experiments will give symmetric results"*

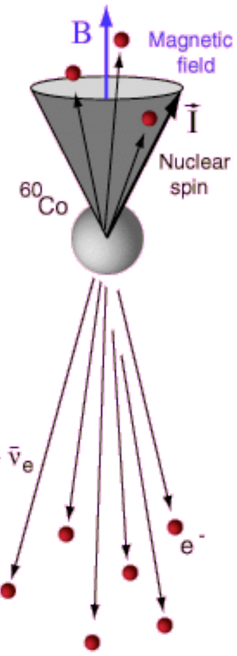
Richard Feynman bet $50 that Wu's experiment would confirm parity as a valid symmetry

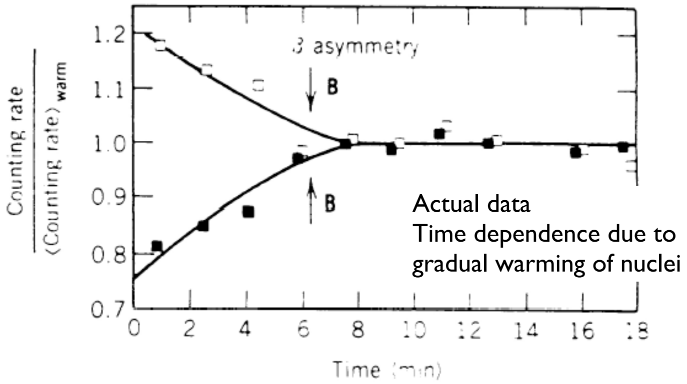
- First define axis about which to measure parity transf.
- Use magnetic moment of ^{60}Co to align spins in B field
- Need very low T to avoid thermal disruption: 0.01K
- Compare no. e^- emitted along field and opposite field dir^n.

Beta emission is preferentially in the direction opposite the nuclear spin, in violation of conservation of parity.

Wu, 1957

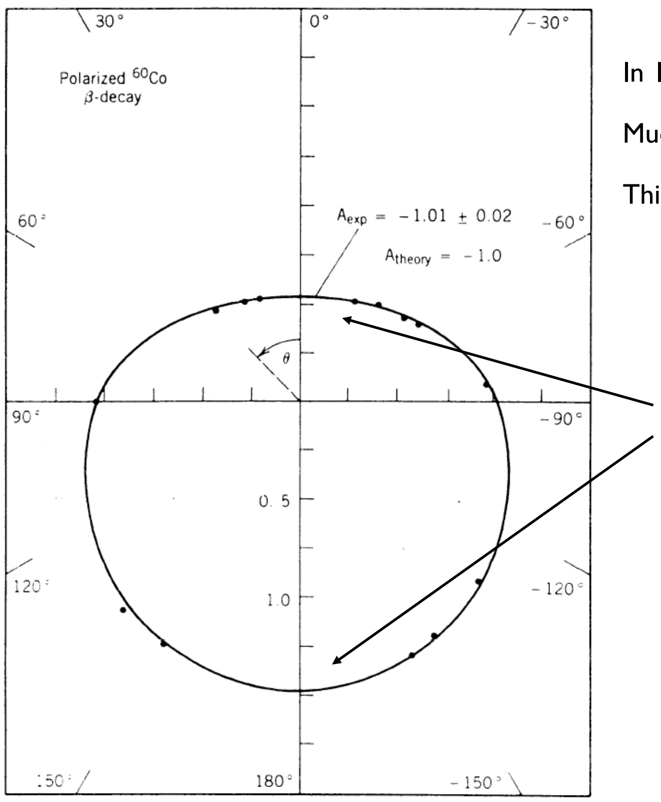
$^{60}Co \rightarrow {}^{60}Ni + e^- + \bar{\nu}_e$





Expect mirror experiment to reverse electron momenta (i.e. mirror electrons emitted parallel to spin)

Experiment showed ~70% electrons are preferentially emitted opposite to spin direction



In 1981 Wu repeated experiment (25 years later)

Much improved experimental apparatus

This time look at angular dependence w.r.t. spin axis

Curve shows expectation of parity violation

Intensity equal at 0° and 180° if parity conserved

Reversing B field achieves parity inversion

Angular mom. is axial-vector quantity
- does not swap sign on parity inversion
electron momenta should be reversed
they are not!

Consider ^{60}Co experiment and its P reflection:

In P reflected expt. e^- emitted along nuclear spin direction

This is not observed in nature: P is not a valid symmetry

Consider ^{60}Co experiment and its C reflection:

B field changes direction

Anti-cobalt emits positrons in direction of opposite to nuclear spin direction

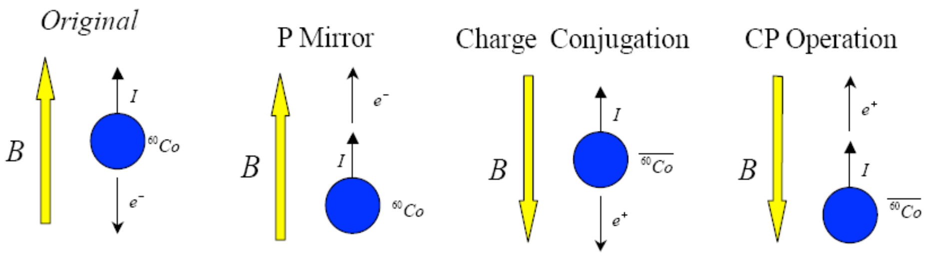
matter & anti-matter behave differently: C is not a valid symmetry

Consider ^{60}Co experiment and its CP reflection:

B field is reversed

anti-cobalt emits positrons in nuclear spin direction

same as original experiment: CP is a valid symmetry



Direction of cobalt spin is the relevant quantity (not B field):

Atom placed in defined B field

Let spins align themselves

Look for direction of emitted electron/positron w.r.t. nuclear spin

- In fact further experiment shows CP is also weakly violated
- But CPT remains absolutely valid as far as has been tested
- If CP is violated & CPT is valid, implies that T is violated
  - Laws of physics are dependent on time running forwards or backwards
  - 'Arrow of Time'
- First direct observation of CP violation made in 2001 Stanford Linear Accelerator - Babar expt
- Effect is ~ $1:10^{12}$ too small to explain observed matter-antimatter asymmetry in universe
- So far only looked at quarks...
- Next generation of experiments will look for CP violation in neutrino sector of Standard Model
- Neutrino only interacts via weak force - CP violation could be much larger!

These effects only appear in Weak interaction