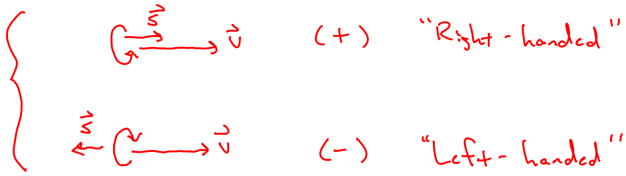
Tuesday, February 28, 2012
11:49 AM

Parity violation is actuall much more common. Recall the notion of helicity.

$$\text{Helicity} \equiv \text{sign}(\underbrace{\vec{s}}_{\text{spin}} \cdot \underbrace{\vec{v}}_{\text{velocity}})$$



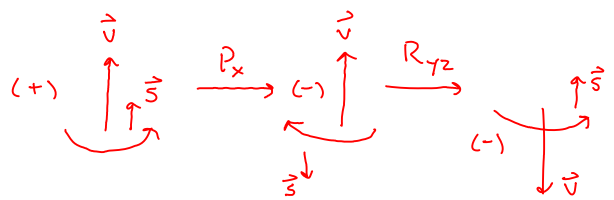
Recall:
If we start with a particle at rest then its helicity is undefined (since $\vec{v}=0$) but its spin $\vec{s}$ is still well defined. We can then get $\pm$ helicity states by boosting to a frame S' moving along or against the particles spin.

So the helicity of a particle can be changed simply by switching reference frames. This is in contrast to the more useful invariant particle properties like charge, mass, spin, etc.

Unless... the particle is never at rest!

For massless particles (neutrinos, photons, gluons) the helicity is an unchanging property of the particle. For example if a left-handed neutrino is created in a process, then it will be left-handed to all observers.

What does this have to do with parity?



So parity interchanges left ⟷ right handed helicity states.

If P was a good symmetry of the SM, then we would expect about 50/50 mixture of left and right handed neutrinos.

What do we see? All neutrinos are left-handed!!!

This can be seen in: $\overset{\vec{p}}{\pi^+} \longrightarrow \overset{\leftarrow}{\mu^+} + \overset{\longrightarrow}{\nu_\mu}$ (the helicity of μ^+ is easy to detect and
$\quad\;\; 0 \qquad\quad \text{left} \quad \text{left}$ it is always − in this configuration)

Note: Be careful and don't assume too much. The process above might lead you to think that μ^+ always has − helicity. But μ^+ is massive so this doesn't really mean anything.

Tuesday, February 28, 2012
12:11 PM

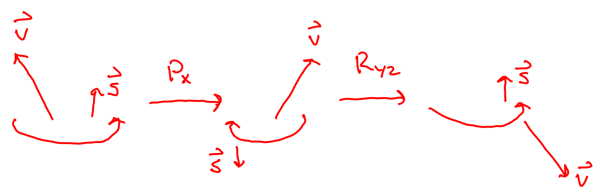
Do you notice a theme in P-violation? It always seems to involve the neutrinos.
But these only come about from weak interactions.
Turns out that while the strong and electromagnetic interactions are actually parity symmetric, the weak interactions maximally violate parity.

Okay so let's see if we can see parity violation in terms of <u>non-conservation</u> of parity in a process.

First of all, how do we assign a P-value?

$\underbrace{\hat{P}^2 = +1}_{\mathbb{Z}_2} \Rightarrow \hat{P}\psi = \pm\psi$

So particles can have parity eigenvalues of ± 1. Which one?



Clearly: $\boxed{\begin{array}{ll} \hat{P}\vec{v} = -\vec{v} & \text{vectors} \\ \hat{P}\vec{s} = +\vec{s} & \text{pseudo-vectors} \end{array}}$

$\vec{L} = \vec{r}\times\vec{p} \Rightarrow \hat{P}\vec{L} = -\vec{r}\times(-\vec{p}) = \vec{L}$

What about scalars? Our usual idea of a scalar is $\boxed{\begin{array}{ll} \hat{P}s = +s & \text{scalars} \\ \hat{P}p = -p & \text{pseudo-scalars} \end{array}}$
but we can introduce

Note the "pseudo" is opposite between vectors and scalars!

Now if we want to assign parity values to particles, then they must be eigenstates of the parity operator, i.e. $\hat{P}\psi = \pm\psi$
same particle

Unfortunately, for free particles (which can have various values of $\vec{v}$) this is usually quite hard. But a few cases are straightforward.

Now the rules of QFT only dictate that particles and their anti-particles have relative parities according to: bosons - same
fermions - opposite

Quarks: Since quarks are never free we can assign them an intrinsic parity value
<u>Convention</u> : Take all quarks to be even : $\hat{P}q = +q$
then anti-quarks to be odd : $\hat{P}\bar{q} = -\bar{q}$ since quarks are fermions.

Photons: Photons must move at c and are vectors (spin 1) so they have $\hat{P}\gamma = -\gamma$.
Recall that $\bar{\gamma} = \gamma$ so $\hat{P}\bar{\gamma} = -\bar{\gamma}$ which is consistent since they are bosons.

For multi-particle states we <u>multiply</u> the constituent parities. This is forced on us by the requirement that the eigenvalue be ± 1.

Baryons qqq have $P=+1$ $\Rightarrow$ anti-baryons $P=-1$ consistent since fermions
Mesons $q\bar{q}$ have $P=-1$ $\Rightarrow$ anti-mesons $P=-1$ consistent since bosons

Some mesons are vectors $|\uparrow\uparrow\rangle$ and as expected $P=-1$.
But some mesons have spin-0 $\frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$ with $P=-1$ so these are
pseudo-scalars.

We saw experimental verification that parity is not a good symmetry of the SM in the ^{60}Co decay and absence of right-handed neutrinos. But where would we look to find the related non-conservation of parity?

Turns out that this was unknowingly observed early on. The θ^+ and τ^+ particles were completely identical (mass, charge, spin, etc.) except for having different intrinsic parities which was observed through their respective decay modes.

$$\underset{+1}{\theta^+} \rightarrow \overbrace{\underset{-1}{\pi^+} + \underset{-1}{\pi^0}}^{+1}$$

$$\underset{-1}{\tau^+} \rightarrow \underbrace{\overset{-1}{\pi^+} + \overset{-1}{\pi^0} + \overset{-1}{\pi^0}}_{-1}$$

Recall: π's are $q\bar{q}$ and hence have $+1 \cdot -1 = -1$ intrinsic parity.

This seemed odd at the time since no other pair of particles had been found to be identical except for parity.

Of course once parity violation was accepted this situation was given a whole new interpretation. θ^+ and τ^+ were recognized to be the same particle, now called the K^+. What was really happening is that the K^+ with $P = -1$ was occassionally decaying through a parity non-conserving process into 2 π's.

As usual this particular decay is a weak interaction process.

The presence of parity violation in the weak interactions can be incorporated in a so-called V-A interaction term. Here V-vector and A-axial vector where $P(V-A) = -V-A$.

Wednesday, February 29, 2012
11:41 AM

We saw experimental verification that parity is not a good symmetry of the SM in the ^{60}Co decay and absence of right-handed neutrinos. But where would we look to find the <u>related</u> non-conservation of parity?

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The presence of parity violation in the weak interactions can be incorporated in a so-called V-A interaction term. Here V - vector and A - axial vector where $P(V-A) = -V-A$.

We speak of the "intrinsic" parity of particles as the part of their behavior under P aside from how varying velocities change things. For quarks and massless particles the intrinsic parity is really all you have.

In most light hadrons we have $\ell = 0$ for the quarks ($\ell \neq 0$ increases energy, thus mass). If $\ell \neq 0$ then this changes the parity of a state by a factor $(-1)^\ell$.

Finally, you might wonder how P is good for EM w/ $\vec{F} = q(\vec{E} + \underbrace{\vec{v} \times \vec{B}}) $

$$\underbrace{V + A}_{\text{parity violating}}?$$

Actually, $\vec{B}$ itself is axial ($P = +1$)

so $\underset{V}{\vec{v}} \times \underset{A}{\vec{B}} = \underset{V}{\text{vector}}$

Thus $\vec{F} = V + V$ and P is good!

$\underline{C}$

Charge conjugation interchanges $\underline{\underline{\text{all}}}$ internal quantum #'s or labels, e.g. electric charge, baryon #, etc.
Effectively it interchanges particles w/ antiparticles.

$C\,|p\rangle = |\bar{p}\rangle$ but also $C\,|udd\rangle = |\bar{u}\bar{d}\bar{d}\rangle$

or   or

$C\,|uud\rangle = |\bar{u}\bar{u}\bar{d}\rangle$ $\underbrace{C\,|n\rangle = |\bar{n}\rangle}_{\text{clearly } C \text{ does more than reverse electric charge}}$

Is C a symmetry of the SM?

a) Look at process and C-conjugated version and compare.
b) Assign C labels and look for non-conservation.

a) We already know: $\pi^+ \longrightarrow \mu^+ + \nu_\mu$ happens in SM

$\vec{p}$: $\bullet$ $\overset{\text{left}}{\longleftarrow}$ $\overset{\text{left}}{\longrightarrow}$

If we C-conjugate: $\pi^- \longrightarrow \mu^- + \bar{\nu}_\mu$

$\vec{p}$: $\bullet$ $\underset{\text{left}}{\longleftarrow}$ $\underset{\text{left}}{\longrightarrow}$

but we know that left-handed $\bar{\nu}_\mu$ do not exist in SM!

So C-conjugation fails (although you may smell a connection to parity).

b) Again we can only assign a "charge" to eigenstates of the C-operator. This is usually difficult for single particles, e.g. $C|p\rangle = \underbrace{|\bar{p}\rangle}_{\text{distinct particle-antiparticle so not an eigenstate of } C}$

We can do this for the photon since $\gamma = \bar{\gamma}$, and mesons of the form $q\bar{q}$ ($u\bar{u}, d\bar{d}$, etc.).
Of course linear combinations can be used, e.g. $C(\pi^+ + \pi^-) = \pi^- + \pi^+$.
In assigning C-values to multi-particle states we need to take orbital and spin angular momentum into account.
For a system of a spin-$\frac{1}{2}$ particle + antiparticle the eigenvalue of C is $(-1)^{l+s}$.
For example: $\pi^0 = \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})$ w/ $l=0, s=0$ has $C = (-1)^0 = +1$
$\pi^+ + \pi^- = u\bar{d} + d\bar{u}$ w/ $l=0, s=0$ has $C = (-1)^0 = +1$
$\rho^0 = \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})$ w/ $l=0, s=1$ has $C = (-1)^1 = -1$

We could try to look for C-nonconservation like we did for P in the K^+ decay, but again with so few eigenstates of C this is difficult. But we will come back to this in a moment.

Monday, March 05, 2012
12:39 PM

CP

If we combine both charge-conjugation and parity reversal, then it looks like we might be getting something that is a good symmetry of the SM:

$$\pi^+ \longrightarrow \underset{\mu^+}{\overset{\text{left}}{\longleftarrow}} + \underset{\nu_\mu}{\overset{\text{left}}{\longrightarrow}}$$

P $$\pi^+ \longrightarrow \underset{\mu^+}{\overset{\text{right}}{\longrightarrow}} + \underset{\nu_\mu}{\overset{\text{right}}{\longleftarrow}} \qquad \times$$

C $$\pi^- \longrightarrow \underset{\mu^-}{\overset{\text{left}}{\longleftarrow}} + \underset{\bar{\nu}_\mu}{\overset{\text{left}}{\longrightarrow}} \qquad \times$$

CP $$\pi^- \longrightarrow \underset{\mu^-}{\overset{\text{right}}{\longrightarrow}} + \underset{\bar{\nu}_\mu}{\overset{\text{right}}{\longleftarrow}} \qquad \checkmark$$

So yeah, it looks like CP is good... well, uhm...