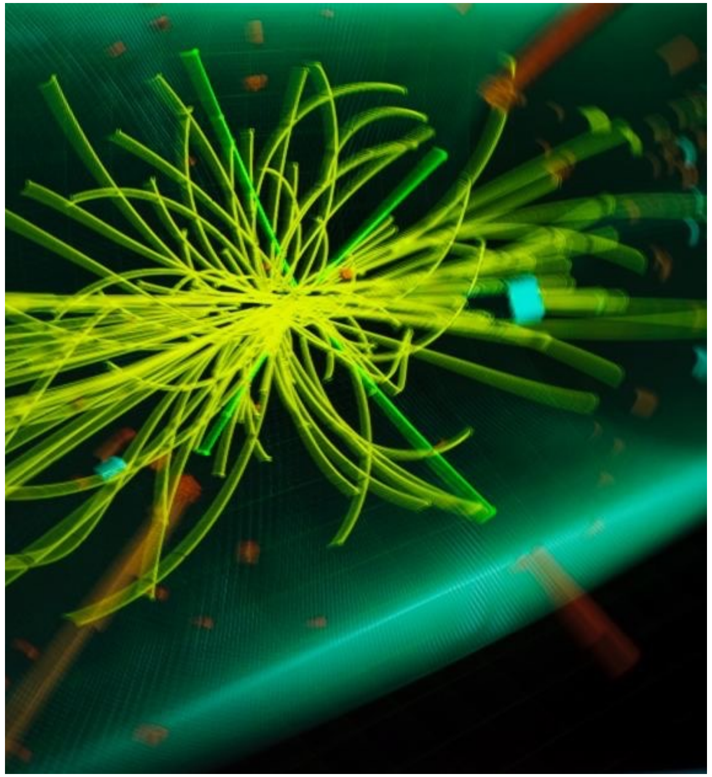
Announcements

Quiz:
- Pick up quiz from last week after class if you haven't yet
- Next quiz today
- Next week: quiz on Wednesday



Homework:
- Second homework due Feb 10 at 3pm. Submit on gradescope.

Paper: Topic due Monday Feb. 17th

Please reply to this google form before then:

https://forms.gle/MmCk8NtrMm7RdfLC7

Is parity conserved?

No indication of parity violation in E&M processes

What about weak processes? $\pi^0, \pi^\pm\ (q\bar{q}):\ P = (+1)(-1) = -1$

Kaons can decay into two pions:

$\mathbf{K} \rightarrow \pi\pi$

What is the parity of the kaon?

Is parity conserved?

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P = (-1)(-1) = 1

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Parity Violation?

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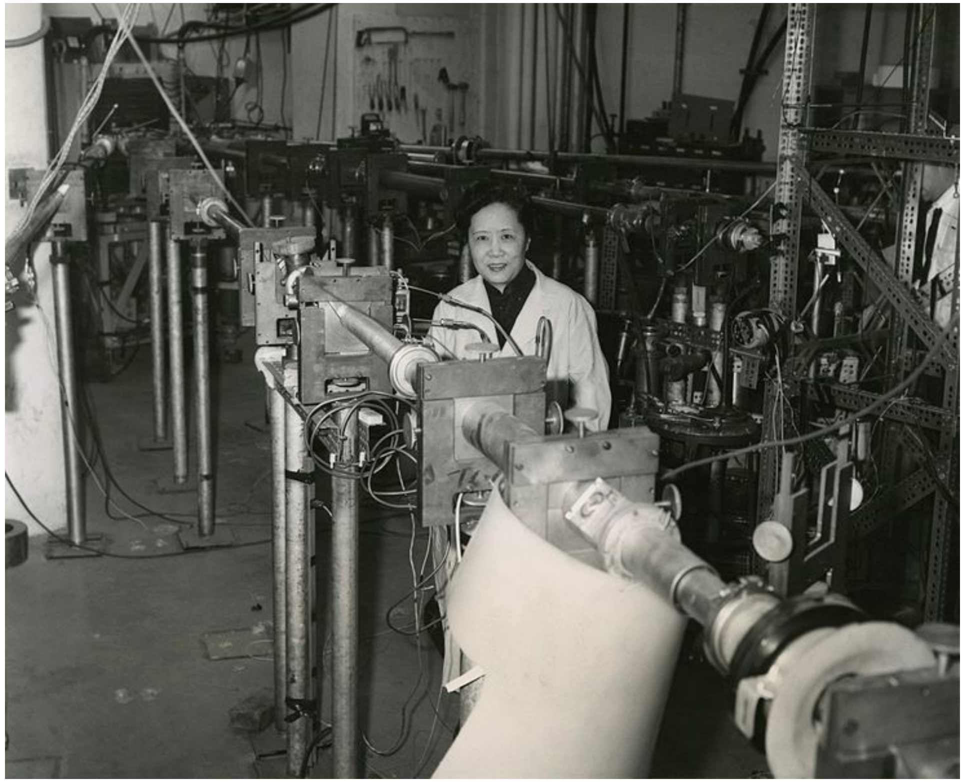
Evidence of parity violation!

Parity Violation?

Parity violation experimental discovery:



Parity Violation?

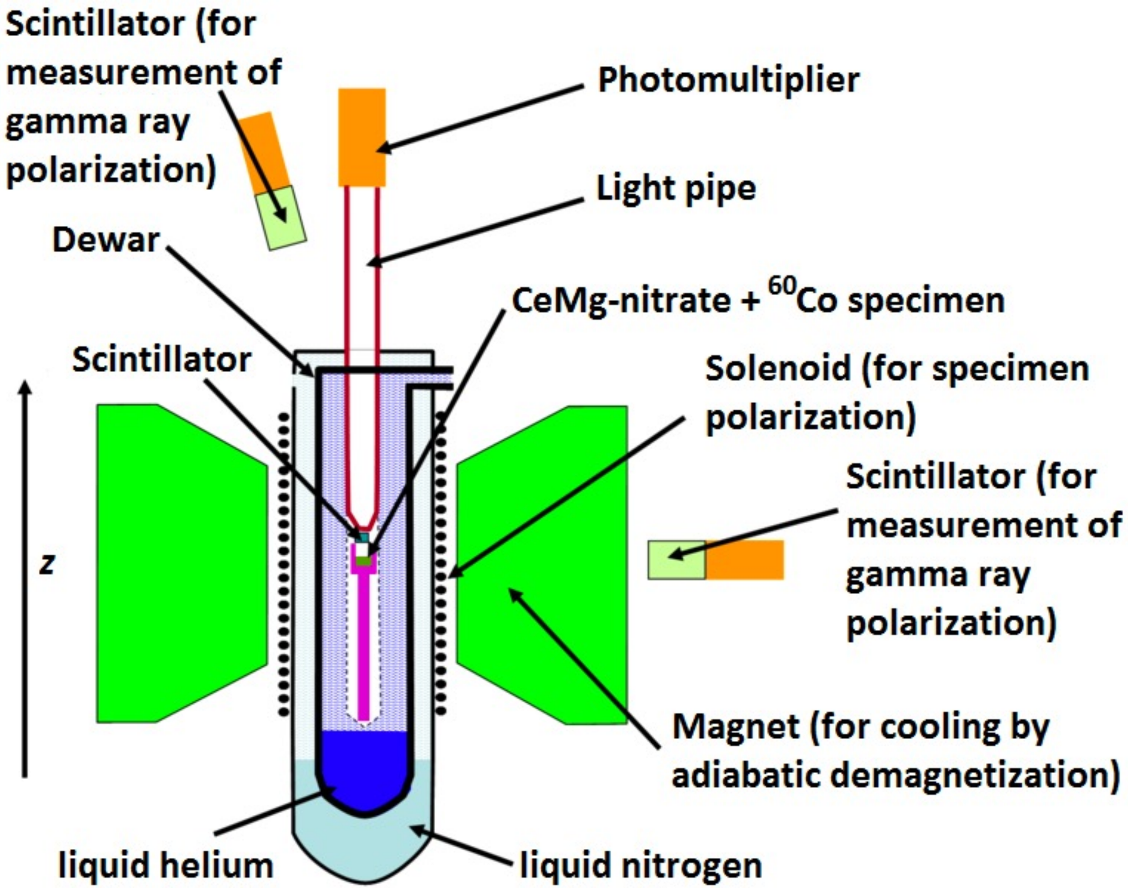
The experiment performed by Wu and co-workers (1957)

$^{60}Co \rightarrow {}^{60}Ni + e^- + \nu_e + 2\gamma$

$^{60}Co \rightarrow {}^{60}Ni$: beta decay (weak process)

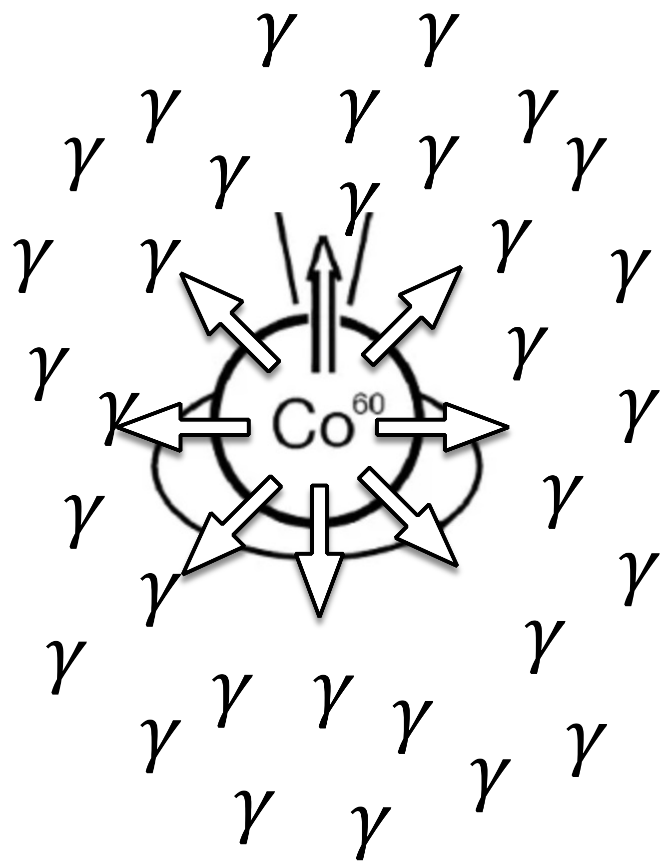
$n \rightarrow p + e^- + \nu_e$

^{60}Ni is in an excited state and promptly emits two photons (EM process)



Parity Violation?

If the angular momentum of cobalt 60 wasn't aligned, then you would expect photons in all directions randomly, due to random L orientation.



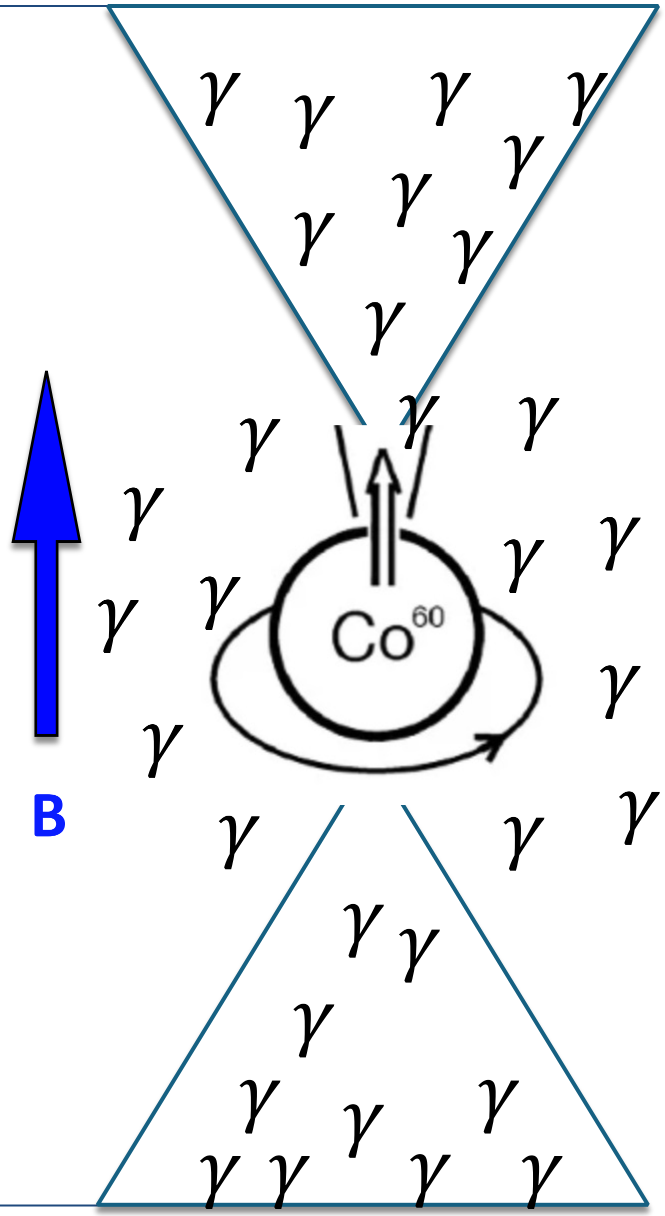
Parity Violation?

"Force" cobalt atoms to align spins:

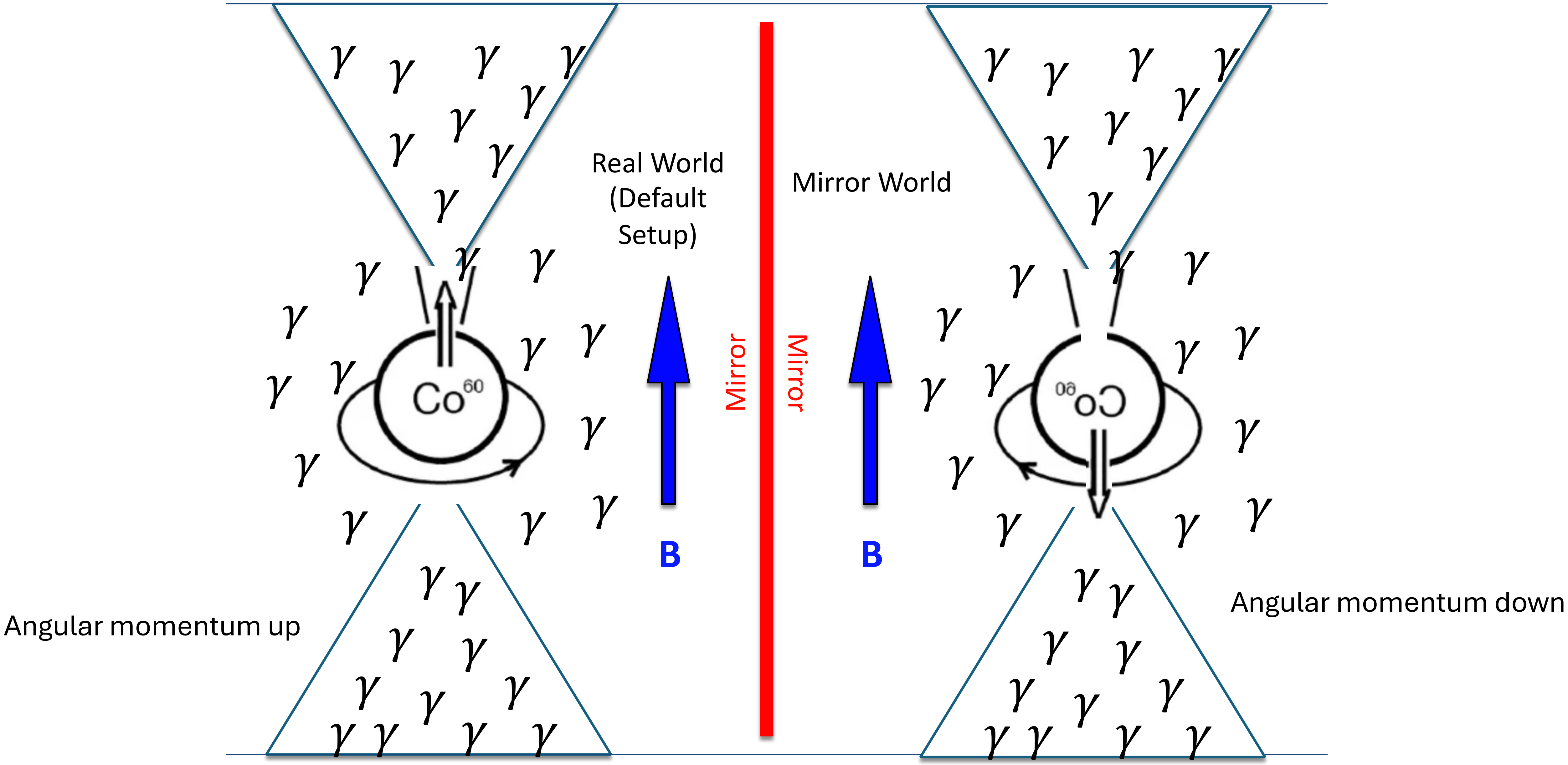
Strong B field and Low Temperature
to align Cobalt60 spins

Leads to:

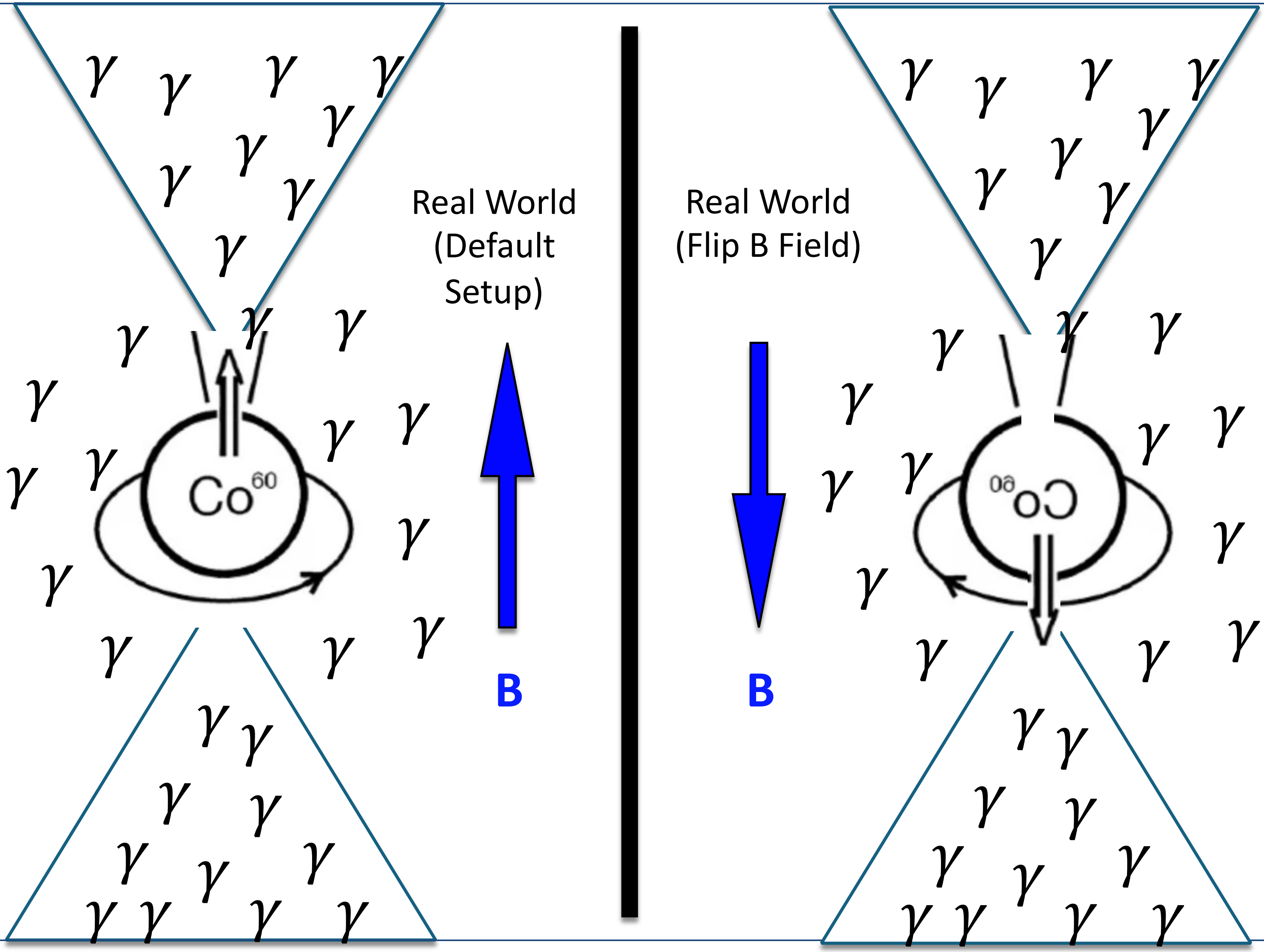
Anisotropy of photons about 60%
(preference for up/down vs left/right)



Parity Violation?: Experiment in a Mirror



Parity Violation: Flip the magnetic field

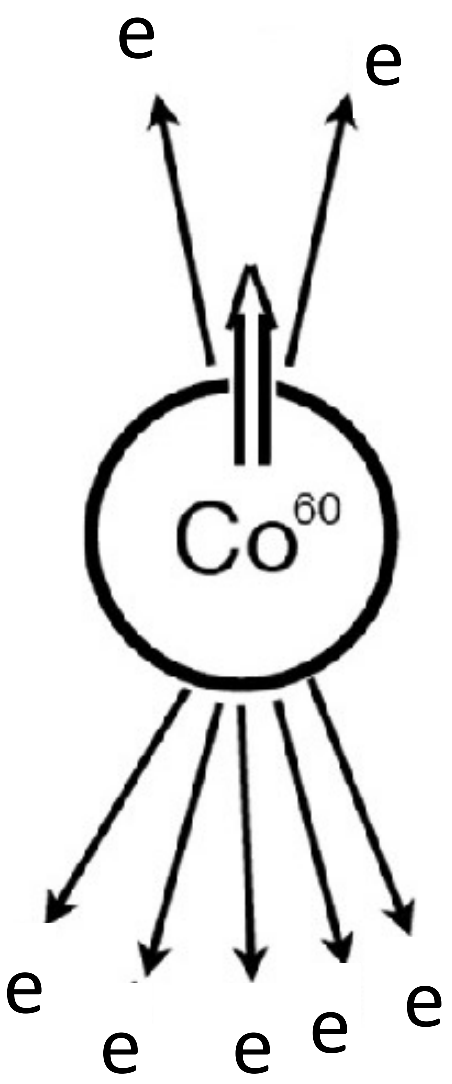


No change:
Expected for E&M!

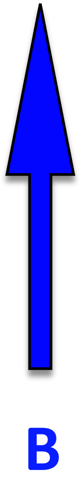
Parity Violation?

Is something different happening in the electrons?

Weak process

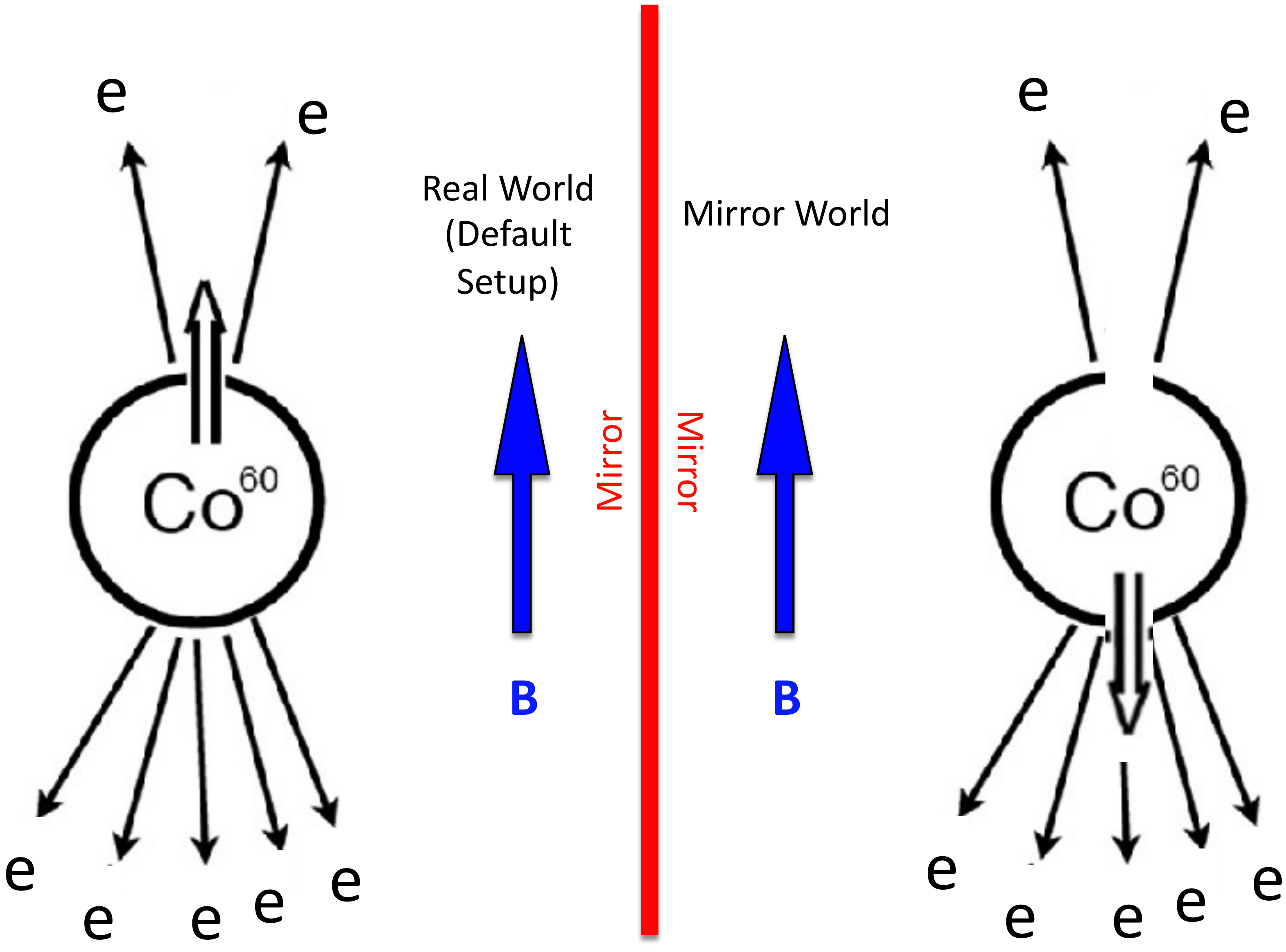


Real World (Default Setup)

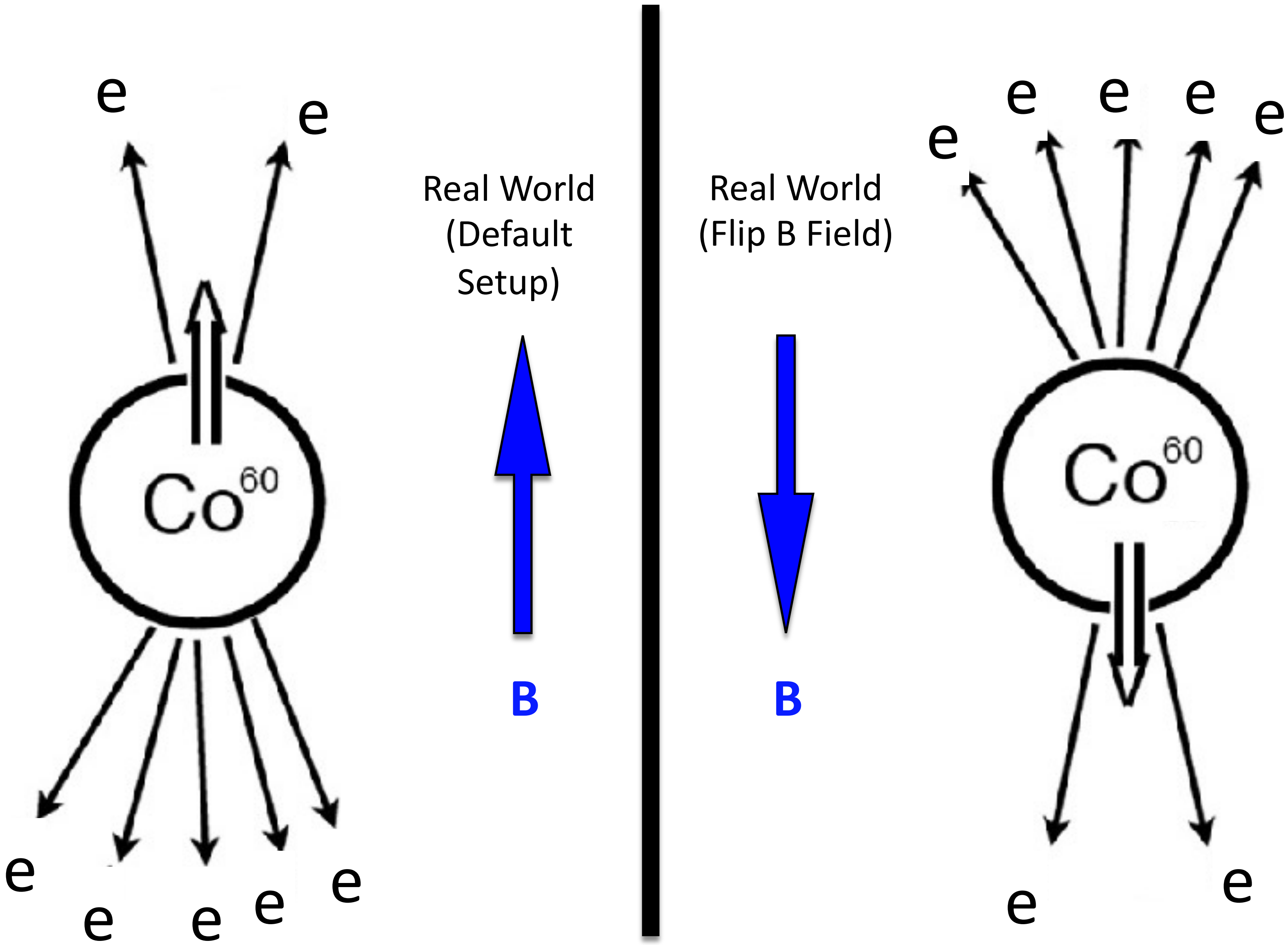


Electrons preferentially in one direction

Parity Violation: Experiment in a Mirror

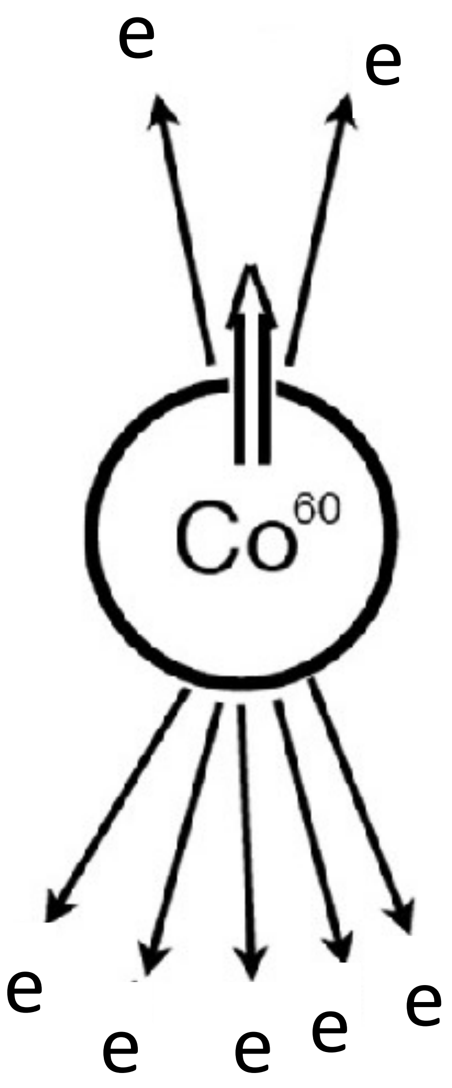


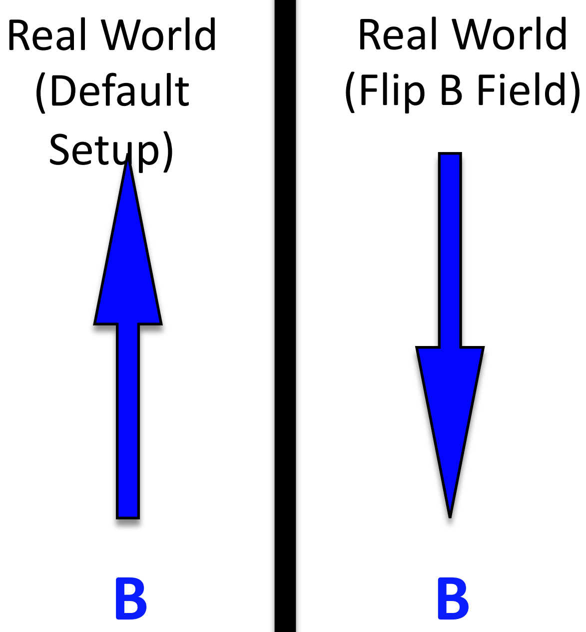
Parity Violation: Flip Magnetic Field

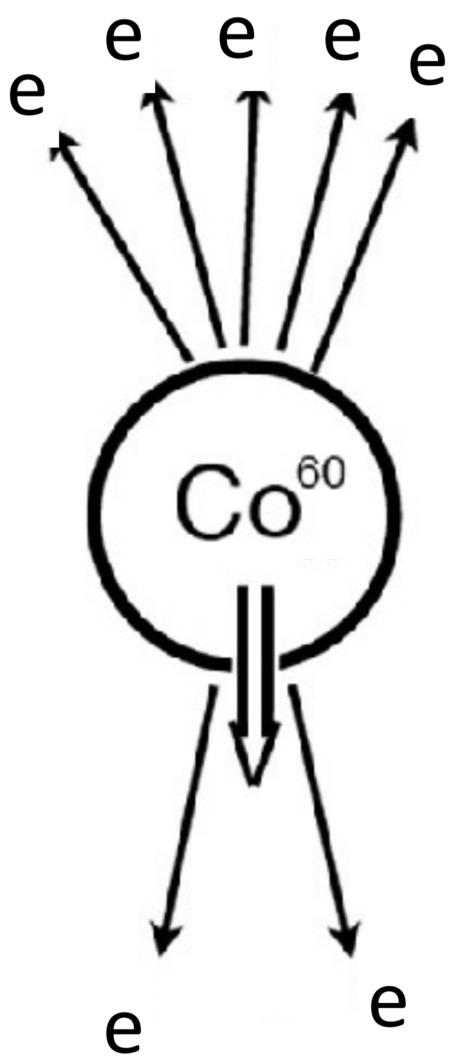


Opposite of expected!

Parity Violation?







Thus, Parity violation had been clearly observed. If Parity had been conserved there would be no correlation between electron spin and momentum.

Parity Violation?: Paper Result

https://journals.aps.org/pr/pdf/10.1103/PhysRev.105.1413

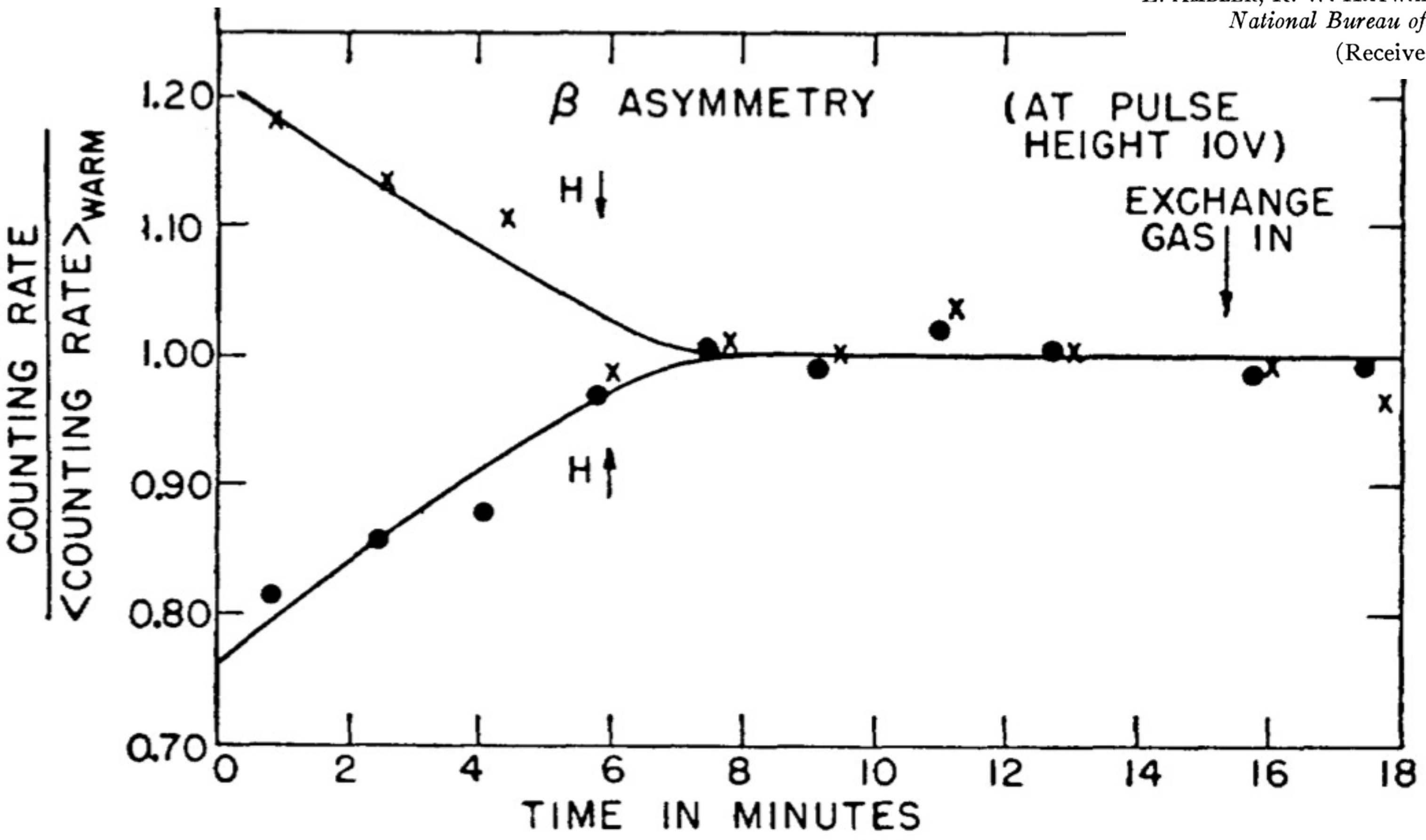
Experimental Test of Parity Conservation in Beta Decay*

C. S. Wu, *Columbia University, New York, New York*

AND

E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson,
National Bureau of Standards, Washington, D. C.

(Received January 15, 1957)

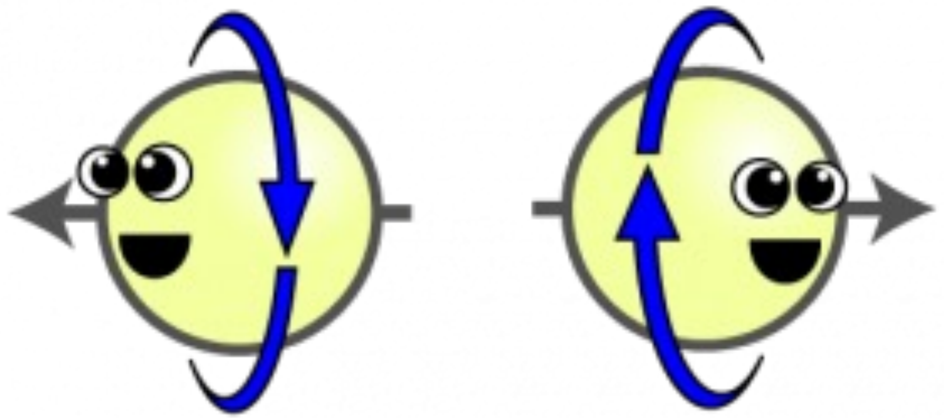


Low temps, spins aligned

High temps, could not control spins

Understanding/Consequences

Matter particles "oscillate" between left- and right-handed states depending on angular momentum.



However, Parity violation tells us that the weak interaction only acts on the left-handed parts of particles (right-handed anti-particles).

This produces a preference in the decay direction for the (left-handed) electron spin relative to the cobalt 60 momentum.

Understanding/Consequences

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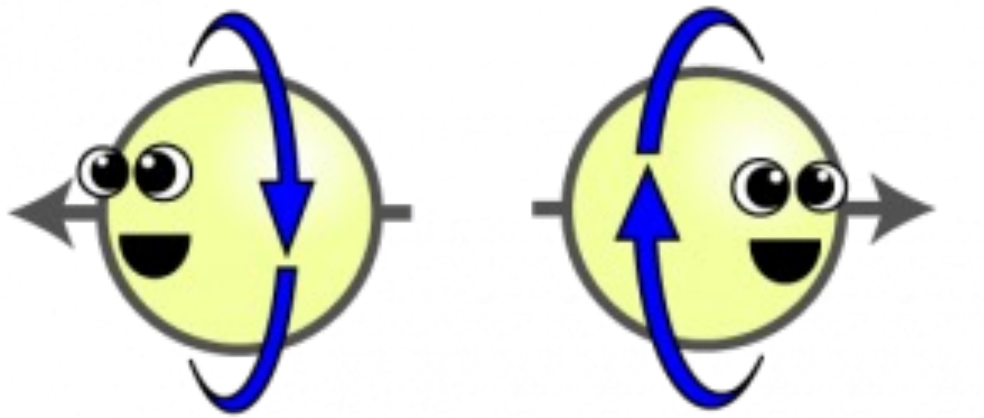


Electromagnetic and Strong Interactions conserve parity, but Weak Interactions do not!

What about Charge Conjugation and Time Reversal?

Charge Conjugation (C)

The operation of changing a particle into its antiparticle

1. Apply operator to particle

C |particle> = |anti-particle>

2. Applied again:

C |anti-particle> = |particle>

-> $C^2 = 1$, so eigenstates $C_a = \pm 1$

Only particles that are their own anti-particles are eigenstates of C operator:

C |particle> = +/- |particle> = |anti-particle> (photon, neutral mesons)

Charge Conjugation (C)

The operation of changing a particle into its antiparticle

Particles that do not have distinct antiparticles ($\gamma,\pi^0,\ldots$)

$\hat{C}\,|a,\Psi a> \;=\; C_a\,|a,\Psi a>$ $\qquad C^2 = 1$, so $C_a = \pm 1$

Example:

The C invariance in the π^0 decay:

$C\gamma = -1$

$C\pi^0 = 1$ (Can look these up in the PDG)

$\pi^0 \rightarrow \gamma\,\gamma$: $C=1 \rightarrow C=(-1)(-1)=1$ allowed

$\pi^0 \rightarrow \gamma\,\gamma\,\gamma$: $C=1 \rightarrow C=(-1)(-1)(-1)= -1$ forbidden (rate $< 3\times10^{-8}$)

Charge Conjugation (C)

The operation of changing a particle into its antiparticle

Particles that have distinct antiparticles (e, p, π^+,…):

$$\hat{C}\ |p,\Psi b > \ = \ |\bar{p},\Psi\bar{p} >$$

For a particle: **C** $|e^+> = |e^->$

For a composite particle like the proton:

C $|p> =$ **C(** $|u>|u>|d>) = |\bar{u}>|\bar{u}>|\bar{d}>) = |\bar{p}>$

Conserved in EM and strong interactions, not in weak interactions.

Time Reversal (T)

Time reversal corresponds to inverting the time axis, namely

$$t \rightarrow t' = -t$$

With this transformation momentum goes backwards, energy is the same:

$$\boldsymbol{T}(p) \rightarrow -p\,, \quad \mathbf{T}(E) \rightarrow E$$

A free-particle wavefunction,

$$\Psi p(\boldsymbol{r},t) = \exp[i(\boldsymbol{p}\cdot\boldsymbol{r} - E\cdot t)/h]$$

must transform into

$$\boldsymbol{T}\,(\Psi p(\boldsymbol{r},t)) = \exp[i(-\boldsymbol{p}\cdot\boldsymbol{r} - E\cdot t)/h]$$
$$= \exp[-i(\boldsymbol{p}\cdot\boldsymbol{r} + E\cdot t)/h]$$

So,

$$\boldsymbol{T}\,(\Psi p(\boldsymbol{r},t)) = \Psi p^{*}(\boldsymbol{r}, -t)$$

Combined Operations

We have already seen that operations are generally multiplicative in their eigenvalues. Recall the argument about parity eigenvalues:

$$\hat{P}^2\,\Psi(\boldsymbol{r},t) = \Psi(\boldsymbol{r},t)$$

$$\hat{P}^2\,\Psi(\boldsymbol{r},t) = P\hat{P}\,\Psi(\boldsymbol{r},t) = P^2\,\Psi(\boldsymbol{r},t)$$

And recall that intrinsic and bulk parity operations combine multiplicatively:

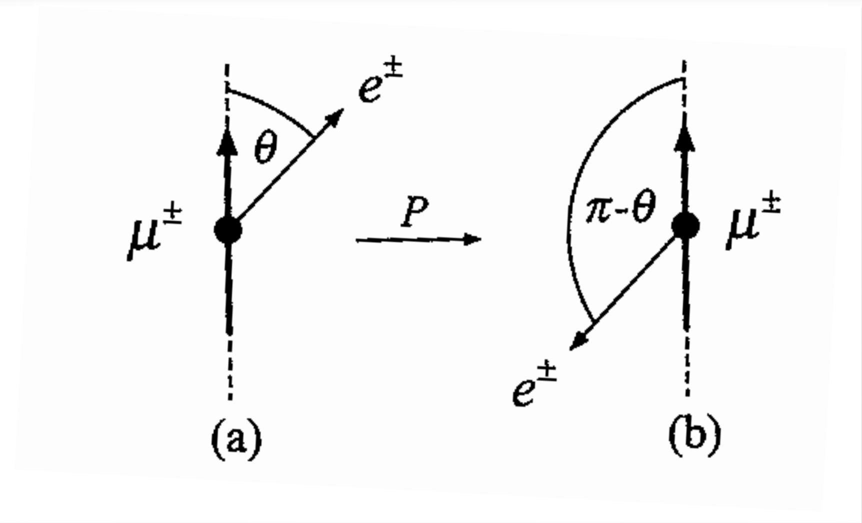
$$\hat{P}\,Y^l{}_m(\theta,\phi) = P(-1)^l\,Y^l{}_m(\theta,\phi)$$

In the same way, consider particle wavefunctions that are simultaneous eigenstates of multiple symmetries. **For example:**

$$\hat{C}\,\hat{P}\,|a,\Psi_a> \;=\; C_a\,P_a\,|a,\Psi_a>$$

Charge Conjugation and Parity in Muon Decays

Muon Decay:
$$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$$
$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$



In the rest frame of μ, decay rates are given by:

$$\Gamma_{\mu^\pm}(\cos\theta) = \frac{1}{2}\Gamma^\pm(1 - \frac{\xi^\pm}{3}\cos\theta)$$

$\xi^\pm = \text{asymmetry parameter}$

θ = angle between muon spin and electron direction

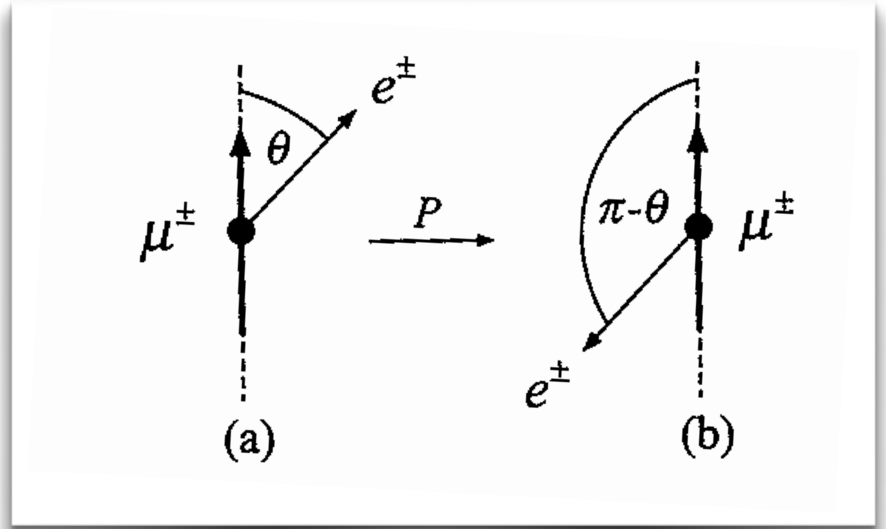
If invariant, decay rates and distributions should be the same if:

Charge Invariance ($\mu^+ \to \mu^-$): $\Gamma^+ = \Gamma^-$ and $\xi^+ = \xi^-$

Parity Invariance ($\theta \to \pi - \theta$): $\Gamma_{\mu^\pm}(\cos\theta) = \Gamma_{\mu^\pm}(-\cos\theta)$ which means $\xi^\pm = 0$

Charge Conjugation and Parity in Muon Decays

Muon Decay:
$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$



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Experimentally $\xi^- = -\xi^+ = 1.00 \pm 0.04$ **Both C and P invariance violated!**

CP Conservation?

So why do μ^+ and μ^- have the same lifetime if C invariance is violated? Answer: **CP conservation**

CP combined operator: P operator : $\theta \to \pi - \theta$ and C operator : $\mu^+ \to \mu^-$

$$\Gamma_{\mu^+}(\cos\theta) = \Gamma_{\mu^-}(-\cos\theta)$$

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(Even though C and P are separately violated)

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(Even though C and P are separately violated)

Experimentally $\quad \xi^- = -\xi^+ = 1.00 \pm 0.04$

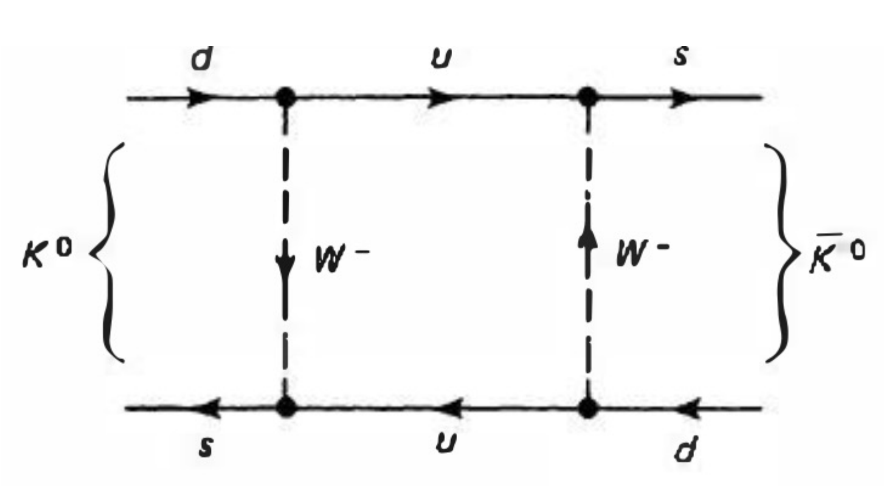
Combined CP invariance holds in this weak decay!

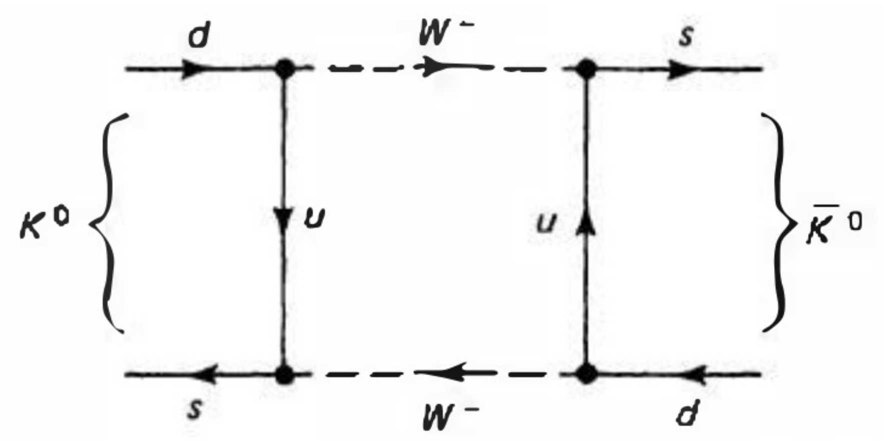
Neutral Kaons and CP

Consider the neutral kaon and its antiparticle

$$K^0 = d\bar{s} \qquad \bar{K}^0 = s\bar{d}$$

They can turn into their own anti-particles through a weak interaction:





So, the particles we observe in the lab are really linear combinations of these!

$$K_1 = a\,K^0 + b\,\bar{K}^0 \qquad K_2 = c\,K^0 + \bar{d}\,K^0$$

How do Kaons transform under CP?

Consider the neutral kaon and its antiparticle

$$K^0 = d\bar{s} \qquad \bar{K}^0 = s\bar{d}$$

Kaons are pseudoscalars: $\hat{P}|K^0> = -|K^0>$

And they are their own anti-particles: $\hat{C}|K^0> = |\bar{K}^0>$

$$\hat{C}\hat{P}|K^0> = -|\bar{K}^0>$$
$$\hat{C}\hat{P}|\bar{K}^0> = -|K^0>$$

We can thus form CP eigenstates

$$|K_1> = \frac{1}{\sqrt{2}}(|K^0> - |\bar{K}^0>)$$
$$|K_2> = \frac{1}{\sqrt{2}}(|K^0> + |\bar{K}^0>)$$

Useful states for behavior under CP:

$$\hat{C}\hat{P}|K_1> = |K_1>$$
$$\hat{C}\hat{P}|K_2> = -|K_2>$$

Assume CP is Conserved in Weak Interactions

So, K_1 should only decay to states with CP =1 and K_2 to states with CP= -1:

$$\hat{C}\hat{P}|K_1> = |K_1>$$
$$\hat{C}\hat{P}|K_2> = -|K_2>$$

If the weak force conserves CP,
we should expect only:

$$K_1 \to 2\pi$$
$$K_2 \to 3\pi$$

But K^0s are typically produced as:

$$|K^0> = \frac{1}{\sqrt{2}}(|K_1> + |K_2>)$$
$$|\bar{K}^0> = \frac{1}{\sqrt{2}}(|K_1> - |K_2>)$$

So what happens if we start with a beam of K^0, and let them decay?

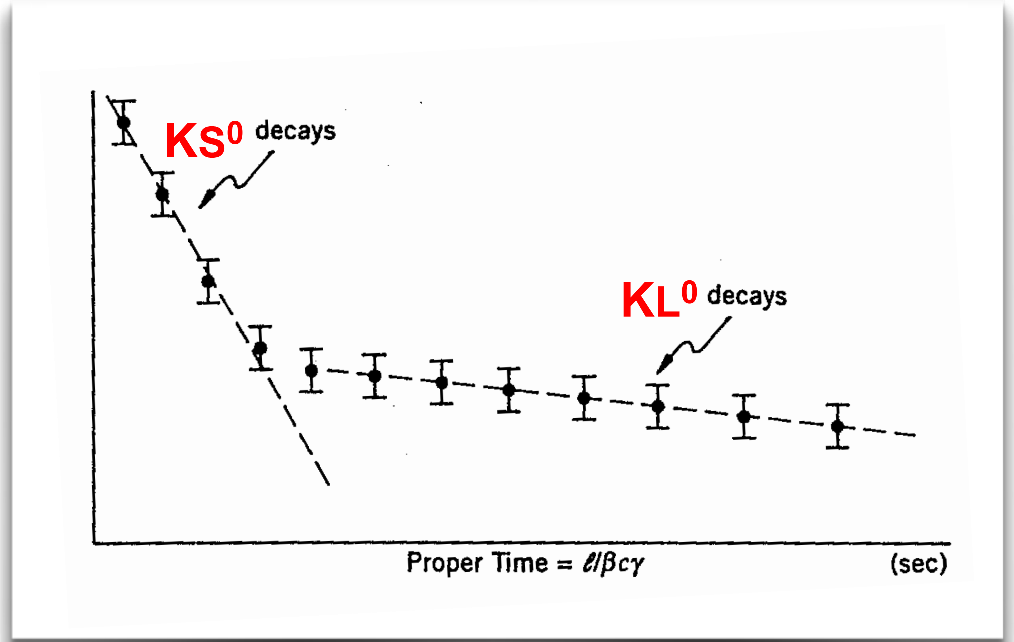
Kaons and CP

The results of lifetime experiments of the K^0 are remarkable, showing two distinct lifetimes and decay modes instead of a single characteristic exponential decay.

One can understand that two different kaons are observed;

K_S^0 lifetime $\tau = 9\times10^{-11}$ s, (2 pions)
K_L^0 lifetime $\tau = 5\times10^{-8}$ s, (3 pions)

and K^0 includes both components K_S^0 and K_L^0 (particle mixing).



$$K_S^0 = K_1(?)$$
$$K_L^0 = K_2(?)$$

K_S^0 mostly gone after a few cm
K_L^0 can last for meters

CP Violation?

What happens if you let kaons decay over a long distance, so all the particles are K^0_L? Will you eventually observe a 2π state?

Yes!

In 1964, it was discovered that the K^0_L also decays to two pions, $K^0_L \to \pi^+ + \pi^-$ with a very small branching ratio (order 10^{-3}).

K_L is not an eigenstate of CP
Contains some K_1

$$|K_L\rangle = \frac{1}{\sqrt{1+|\epsilon|^2}}(|K_2\rangle + \epsilon|K_1\rangle)$$

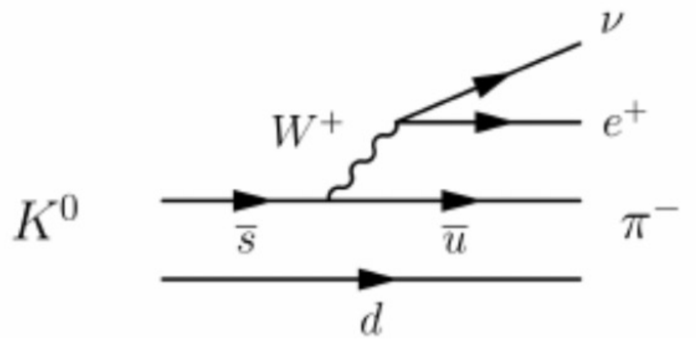
This indicates *CP* violation in weak decays.

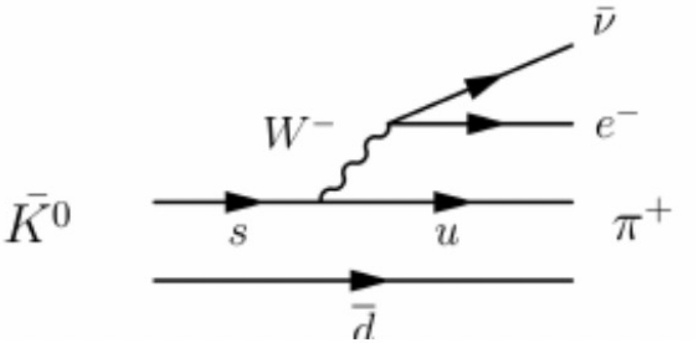
CP Violation

Doesn't have to decay to pions; can also be leptonic decays

$$|K_L\rangle = \frac{1}{\sqrt{1+|\epsilon|^2}}(|K_2\rangle + \epsilon|K_1\rangle)$$

~ 32% of the time decays to 3π
~41% decay through a pion and a W to leptons.





$$K^0_L \rightarrow \pi^+ + e^- + \underline{\nu}_e$$

$$K^0_L \rightarrow \pi^- + e^+ + \nu_e$$

$$CP[\pi^+ + e^- + \underline{\nu}_e] = \pi^- + e^+ + \nu_e$$

These should happen equally often if CP is conserved

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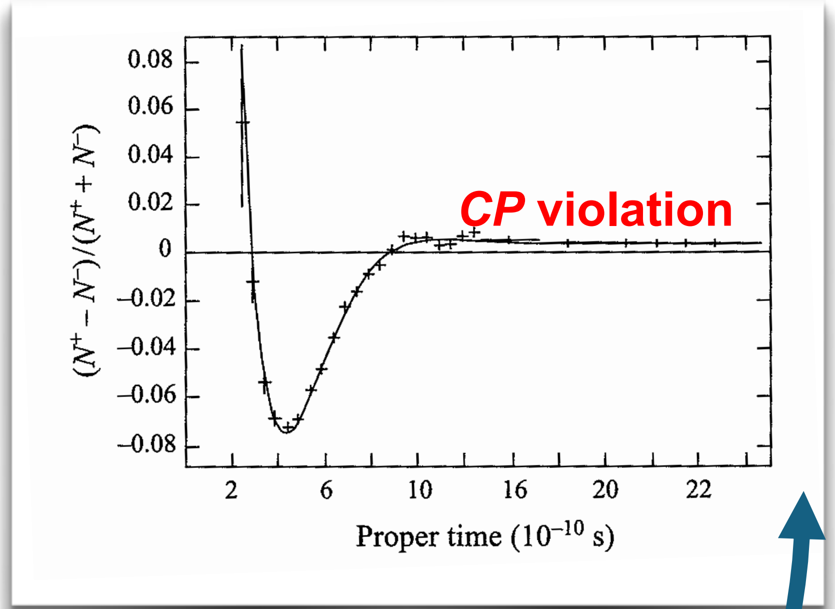
e+ vs e- Asymmetry



But this is not the case!