The Discovery of Parity Violation

Presented by Kenneth Vetter

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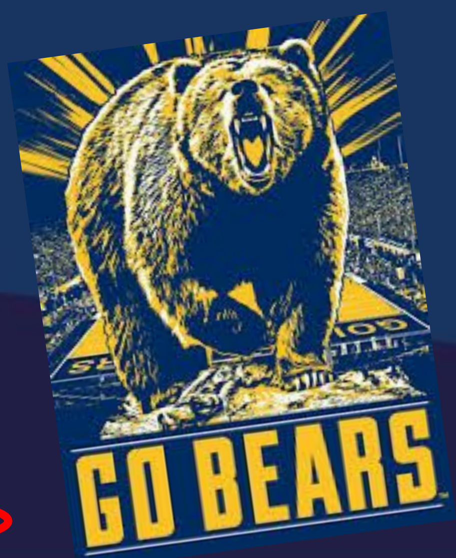

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Overview

- Introduction
  - Symmetries
  - Discrete Symmetries

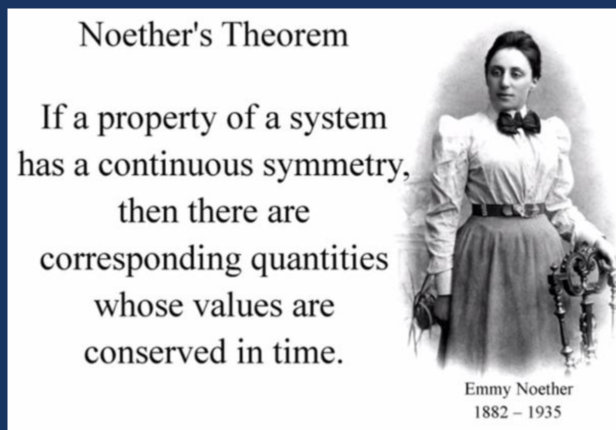
- Parity
  - A note on Mirror Images
  - Parity Conservation in EM
  - Wigner's *About Conservation Laws*

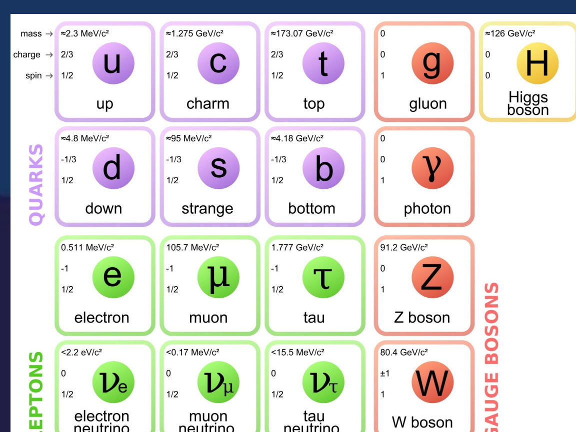
- Parity Violation and the Weak Force
  - Motivations
  - The Experiment
  - The Aftermath

- Future Explorations of Fundamental Symmetries in Physics

INTRODUCTION | SYMMETRIES

$$
\begin{aligned}
\widehat{R}(\Delta\theta, \hat{\mathbf{a}}) &= I - (-\Delta\theta a_k \varepsilon_{kij} r_j)\frac{\partial}{\partial r_i} \\
&= I - (\Delta\theta a_k \varepsilon_{kji} r_j)\frac{\partial}{\partial r_i} \\
&= I - \Delta\theta \hat{\mathbf{a}} \cdot (\mathbf{r} \times \nabla) \\
&= I - \frac{i\Delta\theta}{\hbar}\hat{\mathbf{a}} \cdot \widehat{\mathbf{L}}
\end{aligned}
$$





Why Symmetry?

Symmetries of a system govern its physics

- Quantum mechanics: generators
- Noether's Theorem:
  conservation of specific observables is connected to continuous symmetries of a system
- The Standard Model
  (We will come back to this later)

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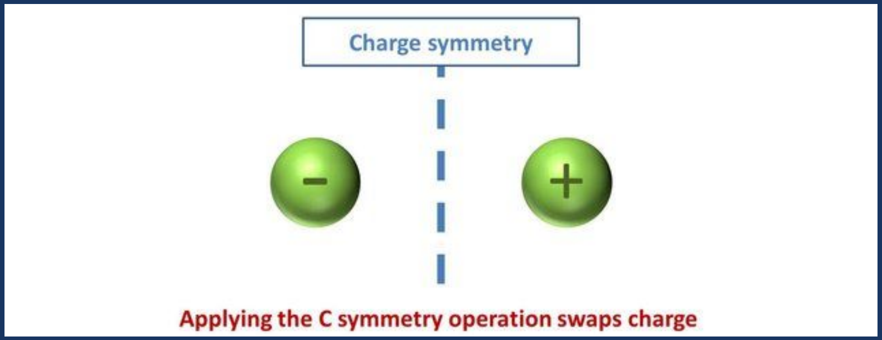
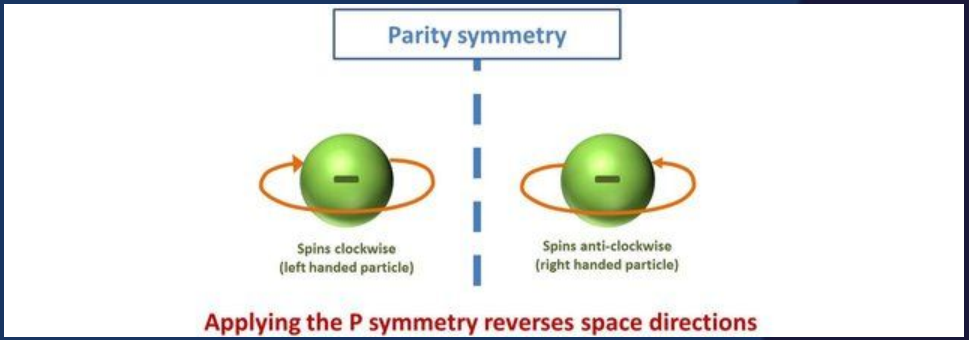
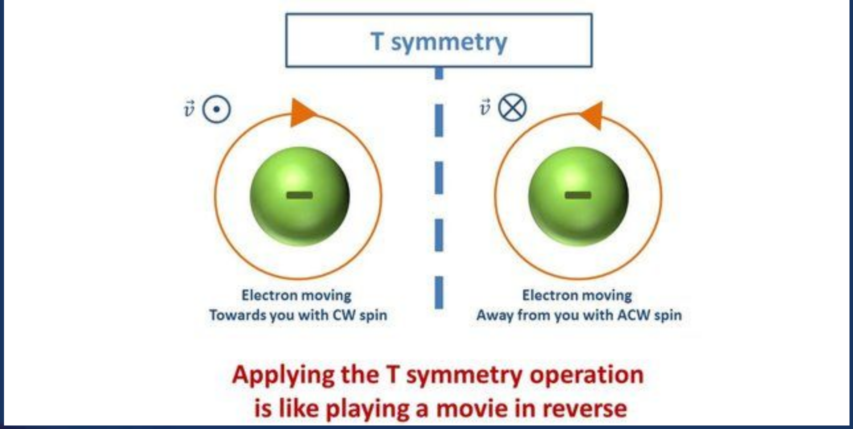
Three Main Discrete Symmetries of Nature (not really)







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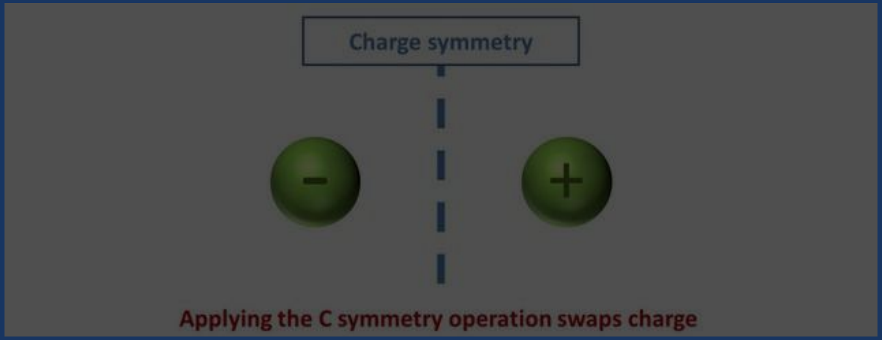
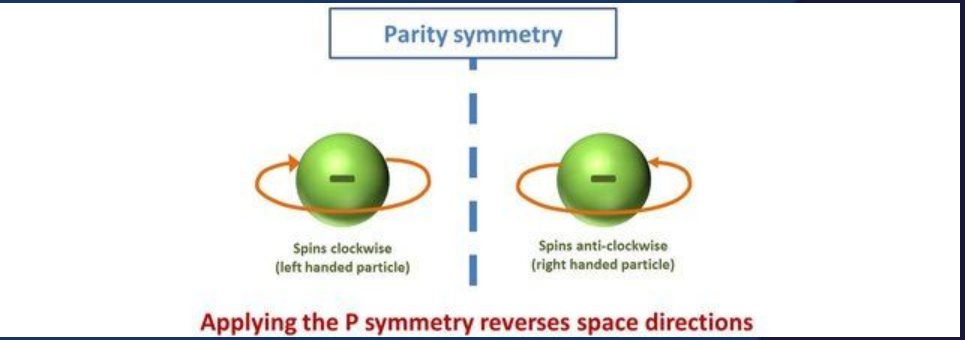
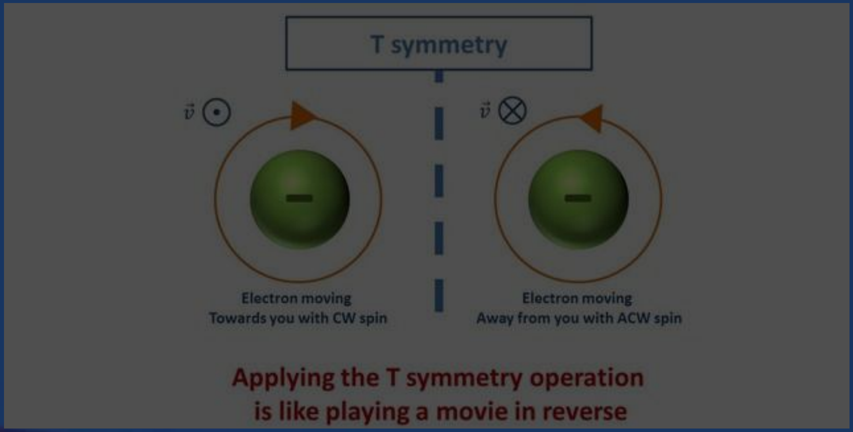
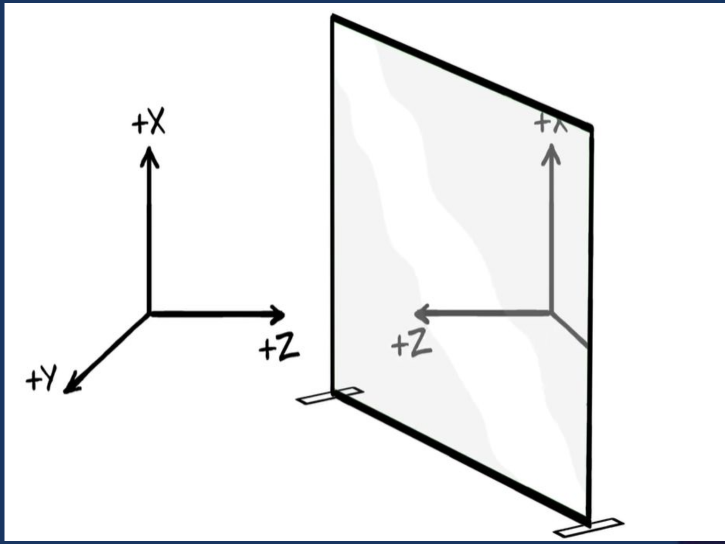






A Quick Disclaimer

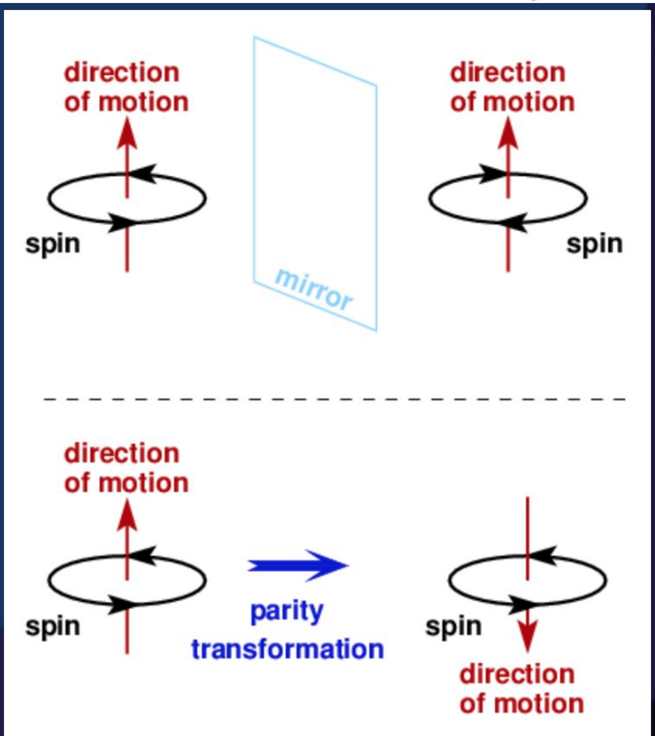


Parity is not quite the same as the "mirror image" we are used to thinking of

The mirror only flips the z direction, so a better description of a mirror is:

$$M(x,y,z)=I(x,y)\otimes P(z)=(x,y,-z)$$

NOTE: Spin is invariant under parity since it has the same algebraic structure as angular momentum. See Right.



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A Quick Disclaimer

Parity is *more* like looking into the concave side of a spoon, which flips x and z, however y still needs to be flipped!

*With this in mind, the idea of a mirror image is still useful for visualizing Parity Violation, so we will continue to use it as a visual aid

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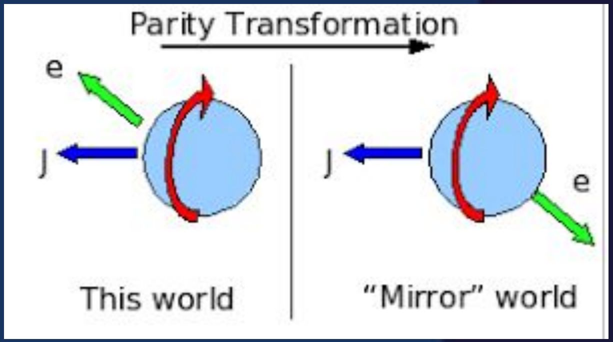
Behavior of Systems under *P*

Objects (and operators) can be classified based on how they transform under Parity:

- *Scalar* – Invariant under Parity
  - Ex. Electric Charge, Mass
- *Pseudoscalar* – Flips under Parity
  - Ex. Magnetic Flux, “Magnetic Charge”
- *Vector* – Flips under Parity
  - Ex. Momentum, Velocity
- *Pseudovector (or Axial Vector)* – Invariant under Parity
  - Ex. Angular Momentum, Spin, Magnetic Fields



Can extend to higher rank objects, but we won’t need to

Maxwell's Equations under *P*

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{j} + \frac{1}{c^2}\frac{\partial \mathbf{E}}{\partial t}$$

P(LHS)	P(RHS)
1 (V · V)	1 (S)
−1 (V · A)	1 (S) Ok because it's 0
1 (V x V)	1 (A)
−1 (V x A)	−1 (V + V)

***Derivative is a *vector* operator (think momentum)**

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P(LHS) = P(RHS) for all four!

PARITY CONSERVATION

***Derivative is a *vector* operator (think momentum)**

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PARITY | WIGNER'S CONSERVATION POSTULATE

"The Conservation Laws in Quantum Mechanics" (1927)

Postulated that parity is *conserved* in nature

Group theoretic approach (of course)

"It was pretty obvious that, in addition to rotation, there is also reflection and I thought it was pretty obvious at that time that it's the LaPorte quantum number."

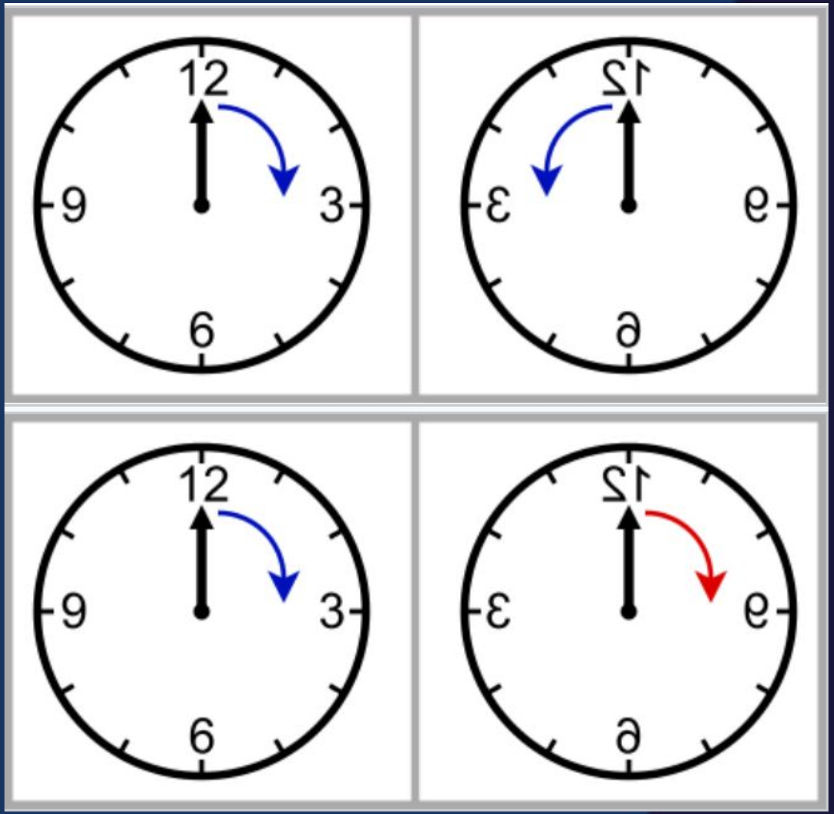
Recall LaPorte's selection rule for atomic transitions

PARITY | A FUNDAMENTAL LAW?

P conserved in EM, widely accepted to be conserved in quantum mechanics

Later, **Strong Force** is found to conserve *P*

Parity seems to be a fundamental symmetry of nature, as Wigner suggests, but…



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THE θ-τ PROBLEM

In the days of old, there were thought to be two particles: θ and τ

$$\theta^+ \longrightarrow \pi^+ + \pi^0$$

$$\tau^+ \longrightarrow \pi^+ + \pi^+ + \pi^-$$

Both particles had similar masses ~ 500 MeV

Pions are *pseudoscalar particles* thus the two final states have different parity.

Could these two particles be the same??

This would imply parity violation

MOTIVATION | THE θ-τ PROBLEM

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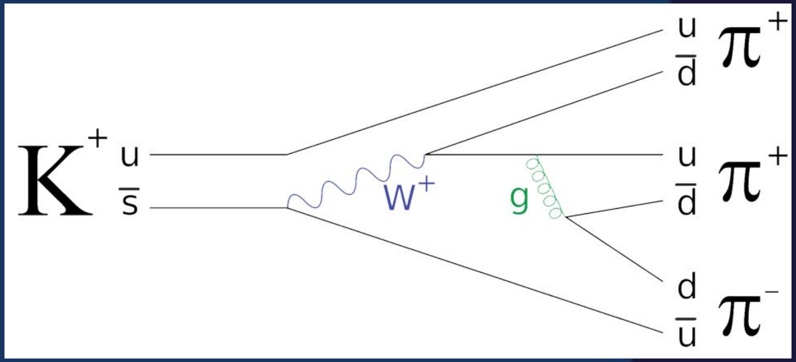
Possible parity violation in weak force processes!

$$\theta^+ \longrightarrow \pi^+ + \pi^0$$

$$\tau^+ \longrightarrow \pi^+ + \pi^+ + \pi^-$$



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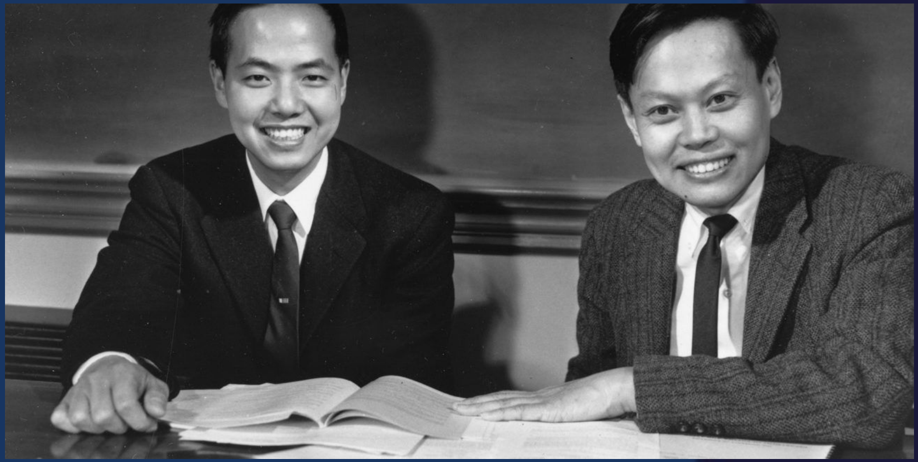
MOTIVATION | THE THEORY

1956 - Lee and Yang conduct a review of parity experiments previously conducted in the field

Found that parity conservation had not been tested in the weak sector

Proposed several possible experiments to answer the question



Tsung-Dao Lee (Left) and Chen Ning Yang (Right)

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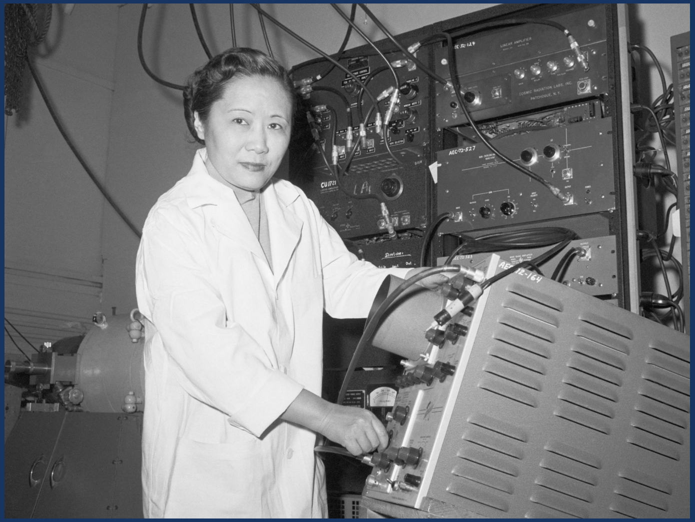


Chien-Shiung Wu

1956 - The Wu Experiment

Conducted during Columbia's Winter Break

Expert in Beta Decay Spectroscopy

Collaborated with Lee & Yang to design an experiment:

Tested the direction properties of Co-60 decay

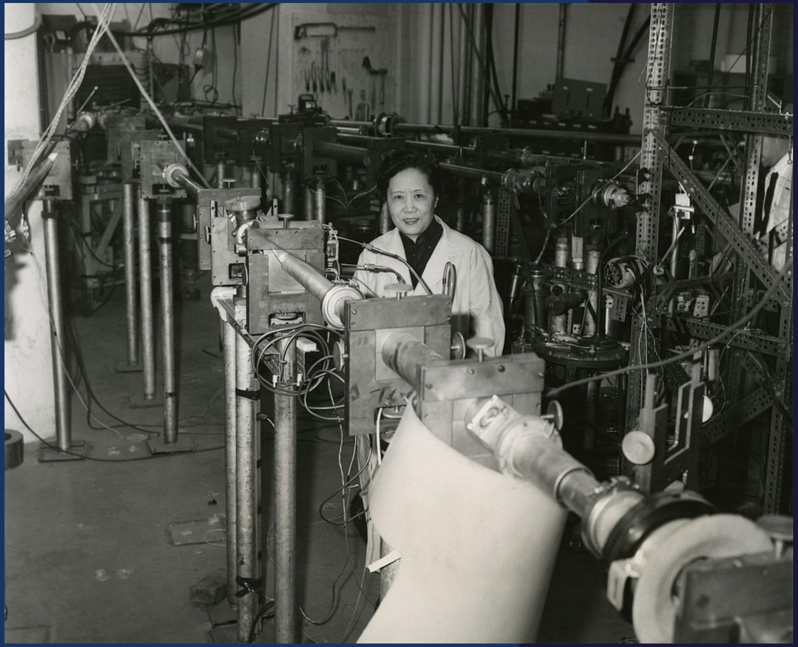
Experimental Challenges

Needed to create extremely low-temperature conditions

Why? Cobalt nuclei have comparatively weak magnetic moments to electrons.

High magnetic fields needed to **align spins.** Low temps needed to overcome reduce thermal energy.

Low temps made use of **adabatic demagnetization**.



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MOTIVATION | THE EXPERIMENT

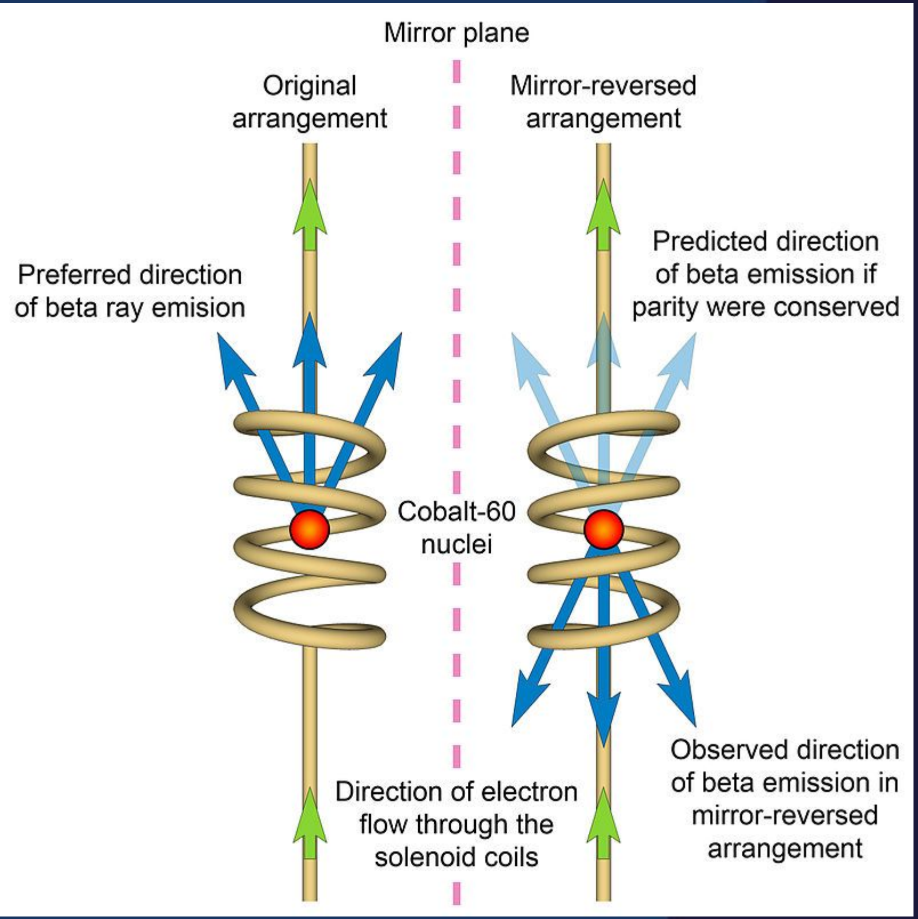
Idea of the experiment:

Nuclear spin is a *pseudovector* quantity

Step 1: Align all the spins of the nuclei

Step 2: Measure the direction of the emitted electrons

In the “Mirror Universe” the nuclear spin is the same, so there should not be a preferred direction of the beta particles (recall momentum is a *vector* quantity)…



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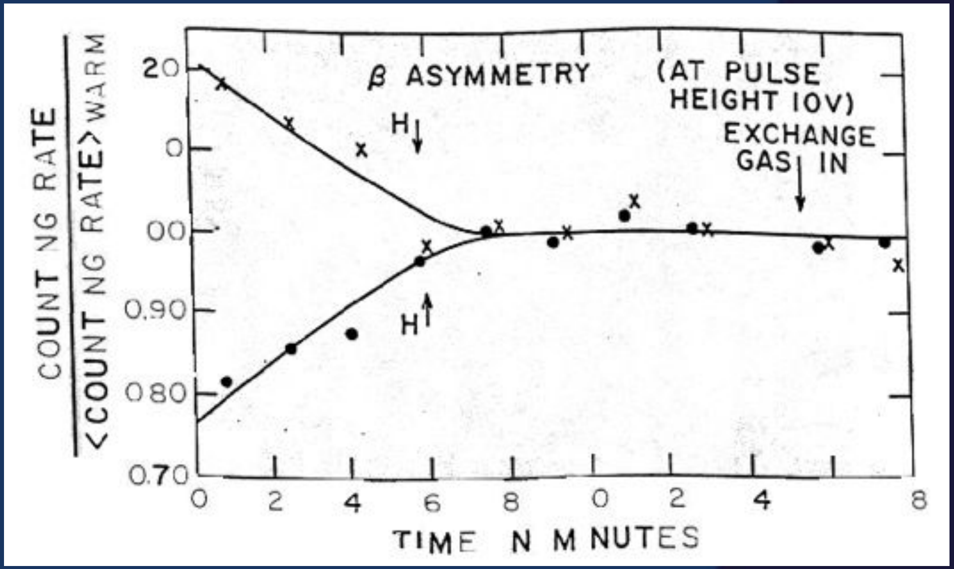

In the "Mirror Universe" the nuclear spin is the same, so there should not be a preferred direction of the beta particles (recall momentum is a *vector* quantity)…

…BUT THERE IS!!

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PARITY VIOLATION | THE AFTERMATH

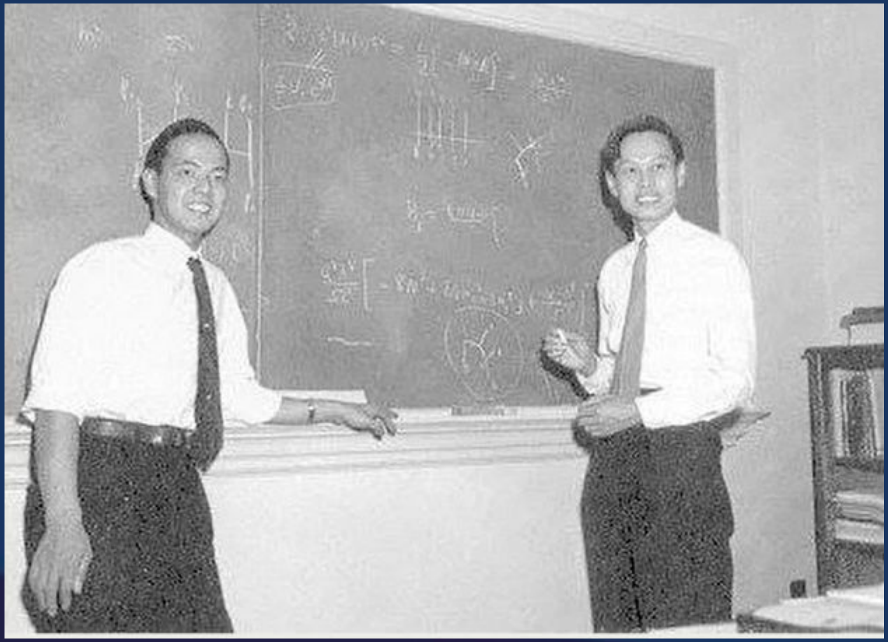
Resolving the θ - τ puzzle

$$K = u\bar{s}$$

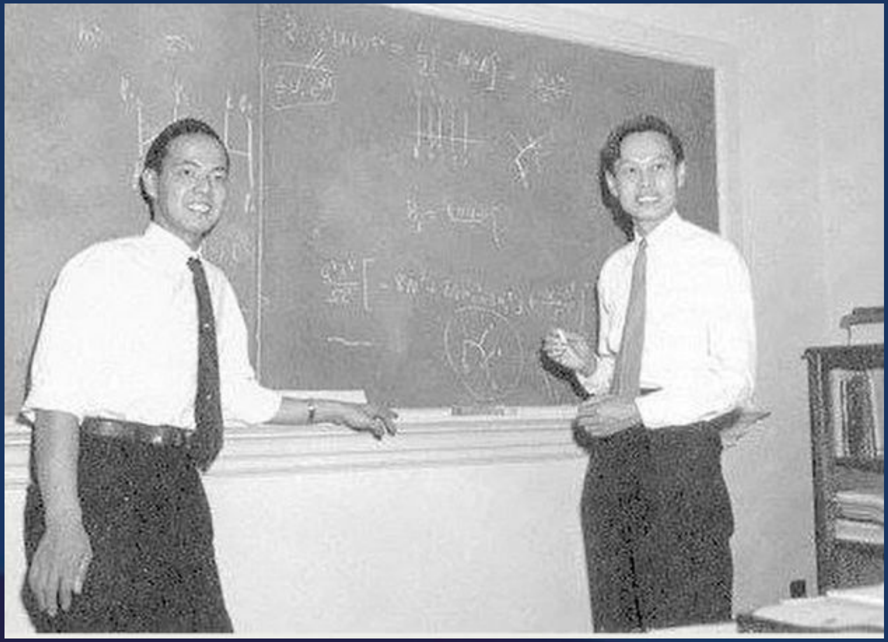
Two particles are both in fact the K meson, which can be decomposed into two states:

"K-long" and "K-short"

PARITY VIOLATION | THE AFTERMATH



PARITY VIOLATION | THE AFTERMATH



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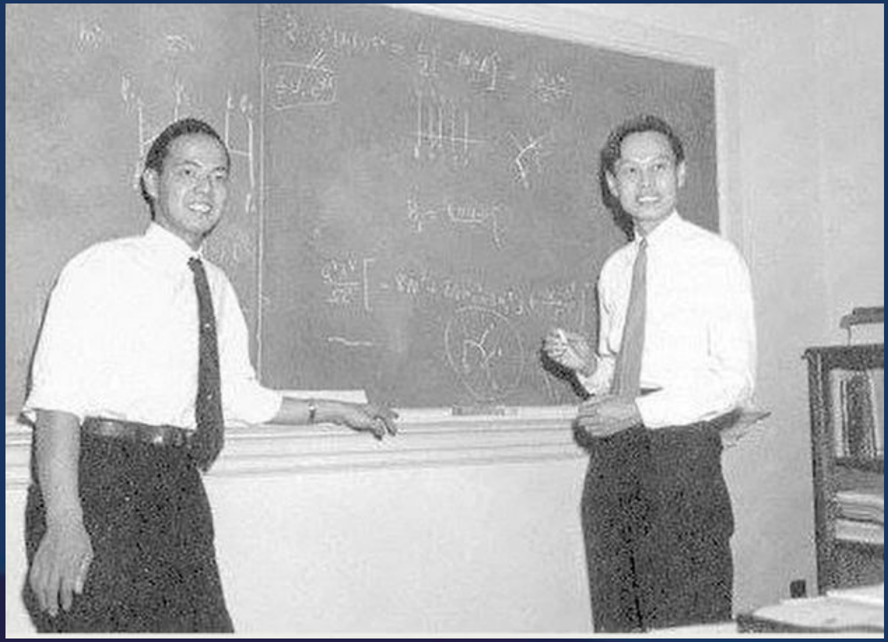
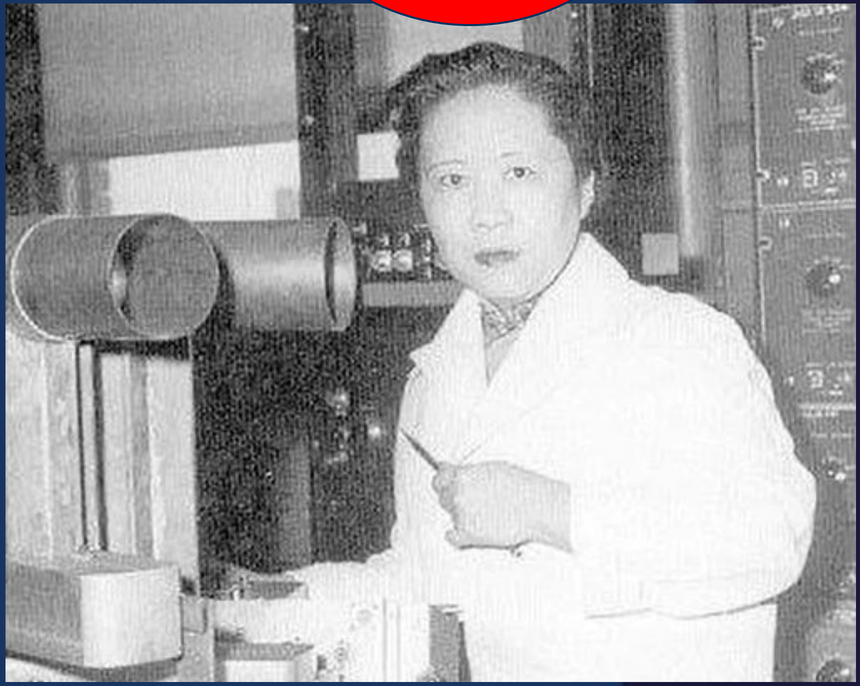
PARITY VIOLATION | THE AFTERMATH





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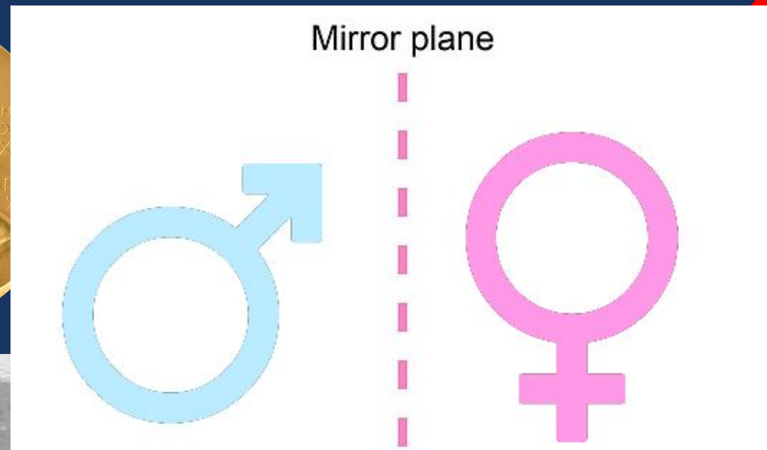
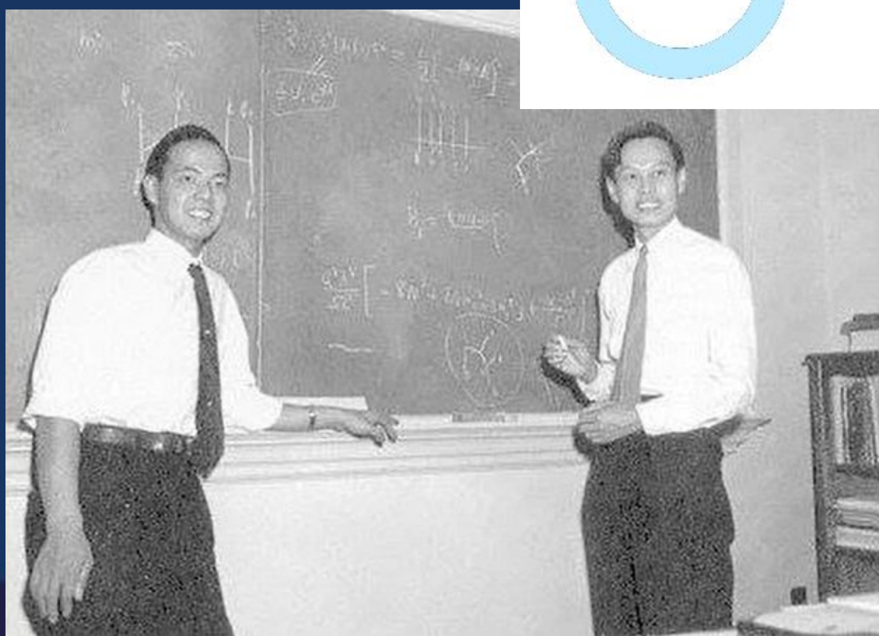
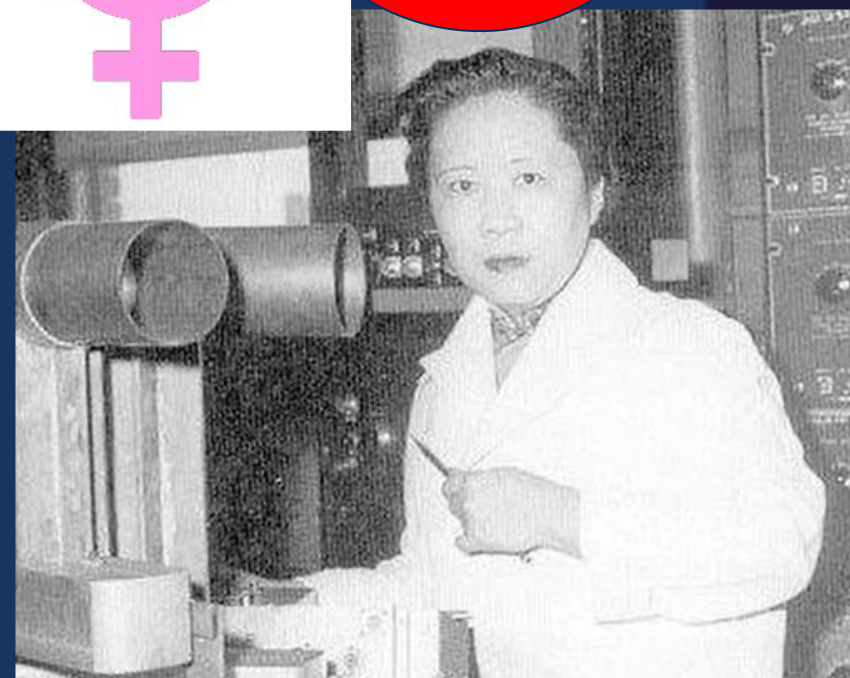
PARITY VIOLATION | THE AFTERMATH







FUTURE EXPLORATIONS OF FUNDAMENTAL SYMMETRIES IN PHYSICS

Natural Questions:

If *P* is violated, is *CP* conserved??

Spoiler alert: No.

If *CP* is not conserved, is CPT conserved??

Hopefully.

THANK YOU