The Odd One Out: The Weak Interaction

Parity Violation

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The Paradigm of 1956: The Mirror Universe

Before 1956, physicists assumed all fundamental forces (Gravity, Electromagnetism, Strong, and Weak) behaved identically under discrete spatial and charge transformations:

- **Parity ($\mathcal{P}$):** A process should look the same in a mirror ($\vec{x} \to -\vec{x}$).
- **Charge Conjugation ($\mathcal{C}$):** A process should look the same if we swap all particles for antiparticles ($q \to -q$).

The Theoretical Assumption

In Quantum Mechanics, if a Hamiltonian is invariant under spatial inversion, then $[\hat{H}, \hat{P}] = 0$. Parity was considered a strictly conserved, universal quantum number.

The $\theta - \tau$ Puzzle (1956)

- Cosmic-ray events revealed two strange mesons: the θ^+ and τ^+.
- Their identical masses and lifetimes implied they were the same particle, now identified as the K^+ meson.
- However, they decayed into final states with opposite intrinsic parities. Knowing the intrinsic parity of the pion is $\mathcal{P}_\pi = -1$, we can calculate the final states:

Final State Parity Calculations

$$\theta^+ \to \pi^+ + \pi^0$$
$$\mathcal{P}_\theta = (\mathcal{P}_\pi)^2(-1)^L = (-1)^2(-1)^L = (\mathbf{-1})^{\mathbf{L}}$$

$$\tau^+ \to \pi^+ + \pi^+ + \pi^-$$
$$\mathcal{P}_\tau = (\mathcal{P}_\pi)^3(-1)^{L_{12}}(-1)^{L_3} = (-1)^3(-1)^{L'} = -(\mathbf{-1})^{\mathbf{L'}}$$

- **Theoretical Leap:** If θ and τ are the same Spin-0 particle (meaning $L = L' = 0$), then $\mathcal{P}_\theta = +1$ and $\mathcal{P}_\tau = -1$. T.D. Lee and C.N. Yang realized the Weak force had actually never been tested for parity conservation.

The Experimental Proof: The Wu Experiment (1957)

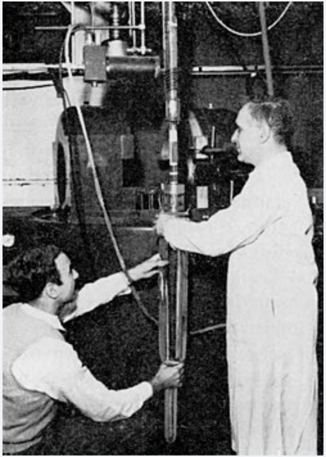
Chien-Shiung Wu designed an experiment to test Lee and Yang's hypothesis, looking at the weak β-decay of Cobalt-60:

$$^{60}\text{Co} \rightarrow {}^{60}\text{Ni}^* + e^- + \overline{\nu}_e$$

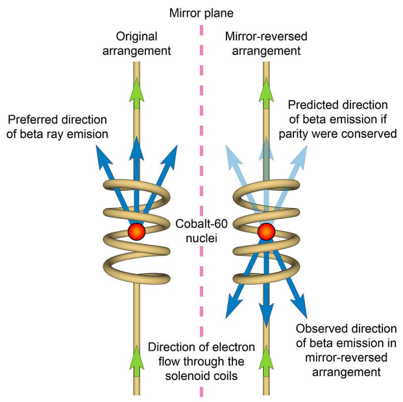
The Setup:

- Co-60 atoms were cooled to a fraction of a Kelvin.
- A strong magnetic field aligned the nuclear spins ($\vec{J}$).
- She measured the direction the electrons ($\vec{p}_e$) were emitted.

If the weak interaction conserves parity, electrons should be emitted equally in the direction of the spin and opposite to it.



The Result: A Left-Handed Universe



The Observation: Electrons were overwhelmingly emitted *opposite* to the nuclear spin.

Why this breaks Parity:

- Momentum $\vec{p}$ is a **polar vector**: $\mathcal{P}(\vec{p}) = -\vec{p}$
- Spin $\vec{J}$ is an **axial vector**: $\mathcal{P}(\vec{J}) = \vec{J}$

In a mirror, the spin direction stays the same, but the electron emission flips. The fact that the physical decay prefers one direction proves that the Weak Interaction fundamentally distinguishes left from right.

The Perspective Problem: Helicity vs. Chirality

To describe this asymmetry, we must distinguish between two properties:

1. **Helicity (The Geometric Shadow)**
   - The projection of spin onto momentum: $h = \frac{\vec{\Sigma} \cdot \vec{p}}{|\vec{p}|}$.
   - Problem: For a massive particle ($v < c$), helicity is not Lorentz invariant. You can change a particle's helicity simply by moving faster than it, reversing its apparent momentum $\vec{p}$.
2. **Chirality (The Fundamental Structure)**
   - A rigid, Lorentz-invariant label defining how a state transforms under the symmetries of spacetime.
   - It is immune to changes in velocity or perspective.

Mathematical Origin: The Lorentz Algebra

Why does Chirality exist? It arises from the geometry of spacetime itself. The Lorentz algebra of rotations ($\vec{J}$) and boosts ($\vec{K}$) can be decoupled using complex combinations:

$$\vec{N}_L = \frac{1}{2}(\vec{J} + i\vec{K}) \quad \text{and} \quad \vec{N}_R = \frac{1}{2}(\vec{J} - i\vec{K})$$

The Resulting Symmetry: $[\vec{N}_L, \vec{N}_R] = 0$.

- Spacetime mathematically splits into two completely independent vector spaces: $SU(2)_L \otimes SU(2)_R$.
- Therefore, a Dirac spinor must be constructed from two independent pieces: a **Left-Chiral spinor (ψ_L)** and a **Right-Chiral spinor (ψ_R)**.

The V-A Current: Nature's Polarizing Filter

In Quantum Electrodynamics (QED), the interaction current is a pure Vector ($\overline{\psi}\gamma^\mu\psi$), which interacts equally with ψ_L and ψ_R.
To mathematically break parity, the Weak Interaction subtracts an Axial-Vector (A) from the Vector (V) current:

The Weak Charged Current

$$j^\mu_{\text{weak}} \propto \overline{\psi}\gamma^\mu(1-\gamma^5)\psi = \underbrace{\overline{\psi}\gamma^\mu\psi}_{\text{Vector (V)}} - \underbrace{\overline{\psi}\gamma^\mu\gamma^5\psi}_{\text{Axial (A)}}$$

The Mathematical Consequence: The matrix $(1-\gamma^5)$ is a strict **Chiral Projection Operator**. It completely annihilates the Right-Chiral state. The $W^\pm$ bosons are hard-coded to only "see" ψ_L.

The Loophole: Mass and Chirality Mixing

If the Weak Force only interacts with Left-Chiral states, how do particles ever decay into "wrong-handed" helicity states (like the electron in pion decay)?

The Dirac Equation for Massive Particles:

$$i\sigma^{\mu}\partial_{\mu}\psi_R - m\psi_L = 0$$
$$i\bar{\sigma}^{\mu}\partial_{\mu}\psi_L - m\psi_R = 0$$

- The mass term m mathematically couples the independent L and R spaces.
- A massive particle is in a constant quantum superposition, oscillating between Left-Chiral and Right-Chiral.
- Conclusion: The Weak force ignores the Right-Chiral part of the electron, but it can grab onto the tiny fraction of Left-Chirality induced by the electron's mass!

Summary: How Weak is Different

- **It breaks Parity ($\mathcal{P}$):** Discovered theoretically by Lee/Yang and experimentally by Wu (1957). It distinguishes Left from Right.
- **It is a Chiral Force:** Described by the V-A theory, it only couples to Left-handed particles.

Thank you.