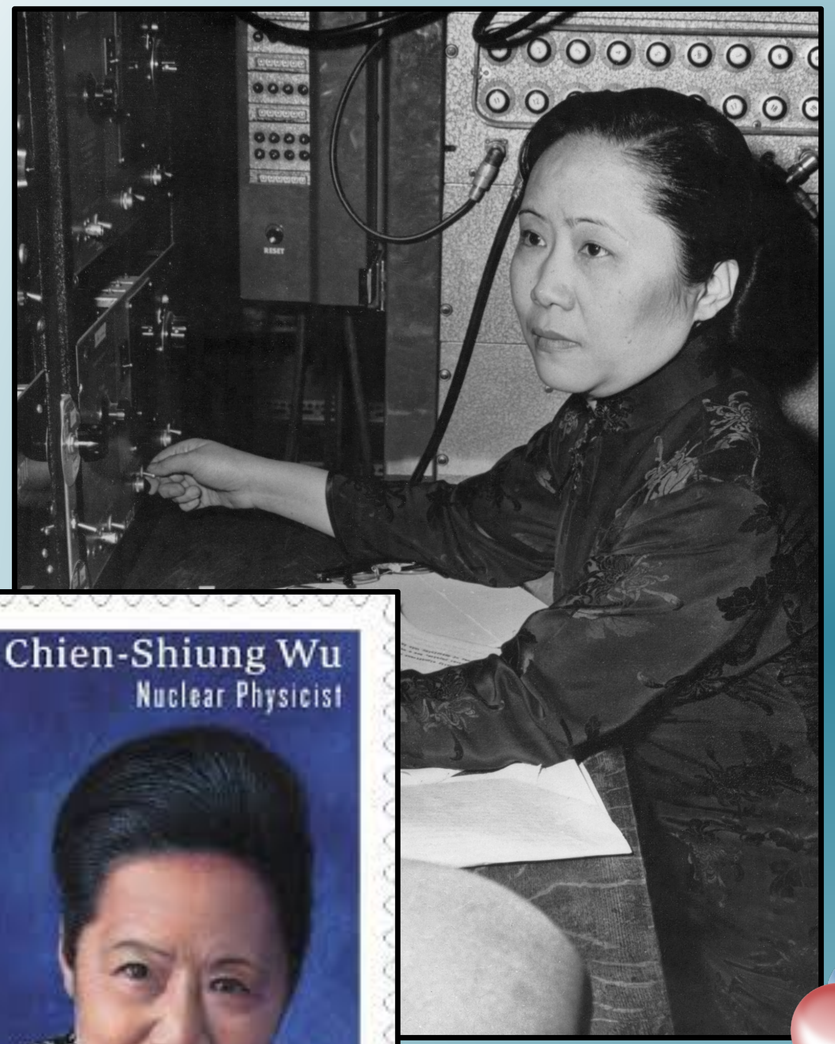
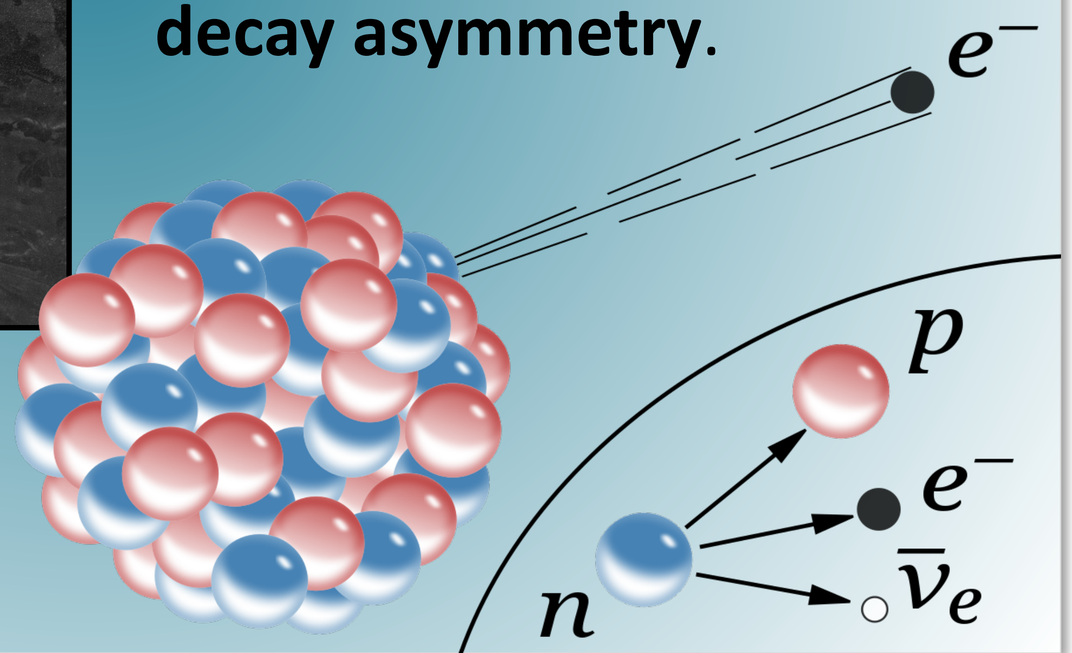


Chien-Shiung Wu was a physicist who pioneered experimental research in **nuclear weak interaction**, showing **parity is not always conserved** through demonstration of **beta decay asymmetry**.





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Wu established the theory of **beta decay**, first theorized by Enrico Fermi.

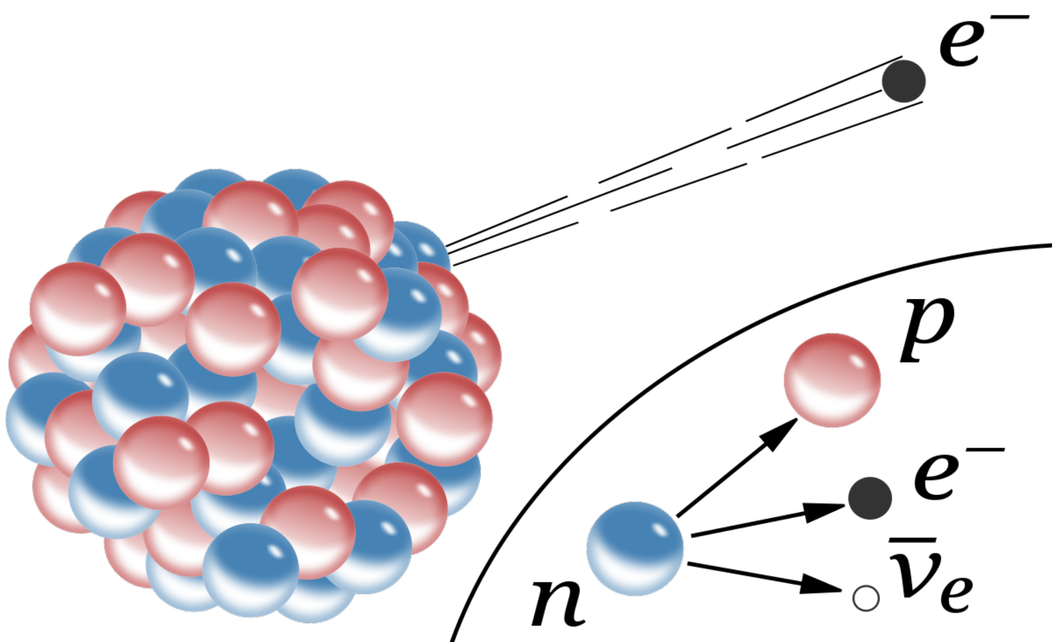
Beta decay: radioactive decay where a **beta particle** (energetic electron or positron) is emitted from an atomic nucleus. This process transforms the original nuclide into an **isobar** of that nuclide (same number of nucleons, same mass, **different atomic number**).

Beta decay of a neutron (β^-) transforms it into a proton, and creates an electron and antineutrino.

Beta decay of a proton (β^+) transforms it into a neutron, and creates a positron and electron neutrino

$$ {}^{1}_{0}n \rightarrow {}^{1}_{1}p \rightarrow {}^{0}_{-1}\beta + \bar{\nu} $$

$$ {}^{60}_{27}\mathrm{Co} \rightarrow {}^{60}_{28}\mathrm{Ni}^{+} + e^{-} + \bar{\nu}_e $$





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Beta decay is due to the **weak force**.

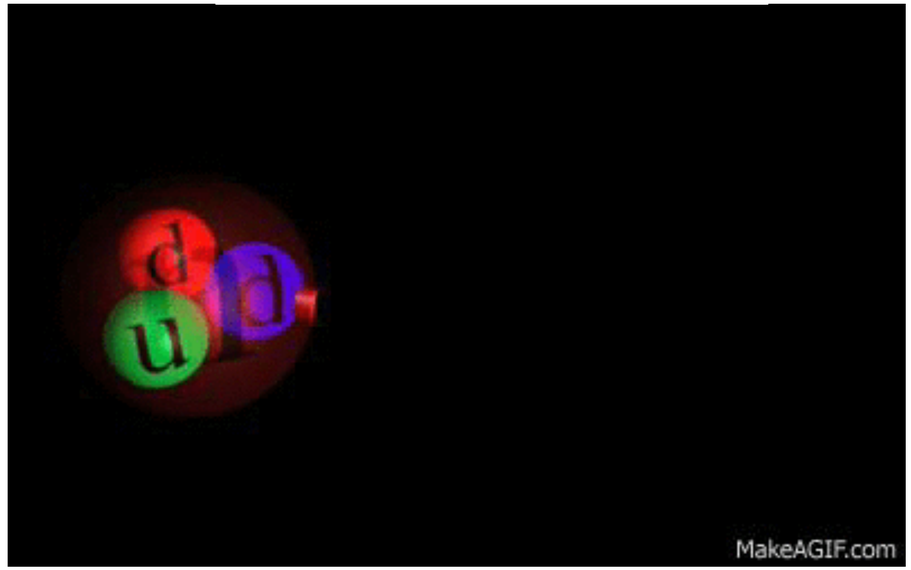
Neutron ➔ two down quarks, one up quark
Proton ➔ two up quarks, one down quark

Weak force allows a **quark** to change its flavour by emission of a **W boson** (intermediate vector boson) which leads to the creation of a beta particle and the corresponding neutrino/antineutrino.

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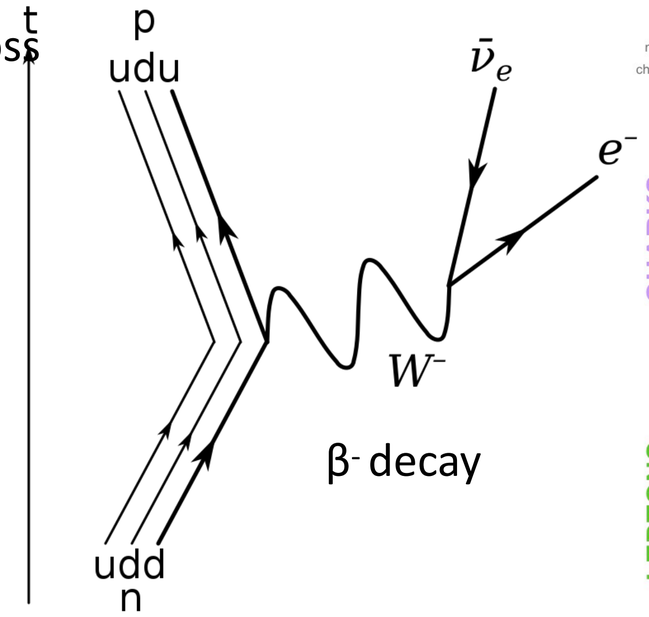


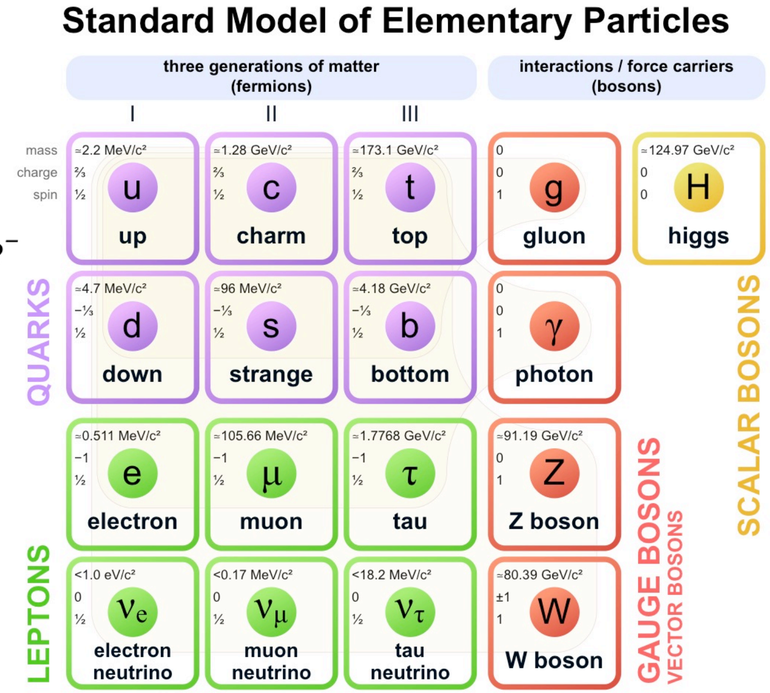
Chien-Shiung Wu was a physicist who pioneered experimental research in **nuclear weak interaction**, showing **parity is not always conserved** through demonstration of **beta decay asymmetry**.

The **weak force** is the mechanism of interaction between subatomic particles that is responsible for the **radioactive decay of atoms**. It's effective range is **less than the diameter of a proton**, and is felt by all fermions.

The weak force is characterized by long lifetimes, and small cross sections.

It's mediated by two massive gauge bosons: the charged ***W*± boson** and the neutral ***Z*⁰ boson**.







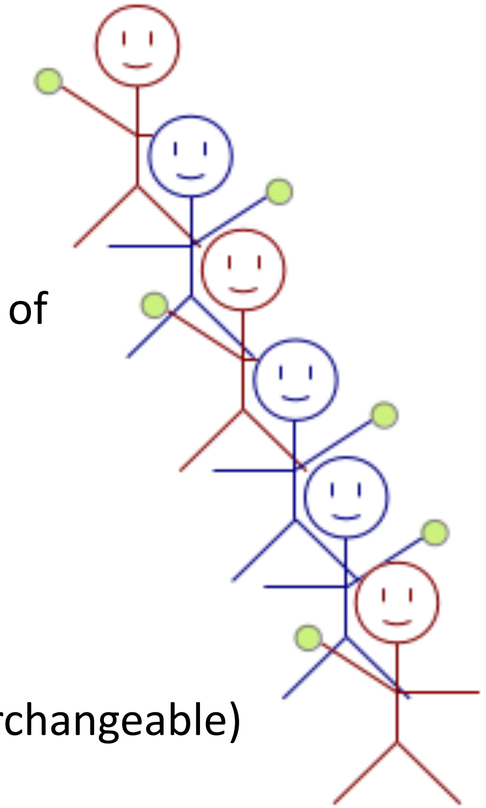
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PARITY CONSERVATION

Parity conservation is a rule that dictates that in a **mirror-image world**, objects should behave in mirror-image ways. In other words, “left” and “right” have no physical definition.

$$\mathbf{P}: \begin{pmatrix} x \\ y \\ z \end{pmatrix} \mapsto \begin{pmatrix} -x \\ -y \\ -z \end{pmatrix}$$

Imagine a lineup of people ready to throw tennis balls, equally made up of left and right-handed throwers.



*In a **parity-conserved** world :*

- Balls would end up the same average distance to the left and right of the throwers.
- This means left-handed and right-handed people throw the same way, but inverted.

*In in **parity-violating** world:*

- Balls on the right might be found to have travelled further
- Right handed people are not a true inversion of the left! (Not interchangeable)

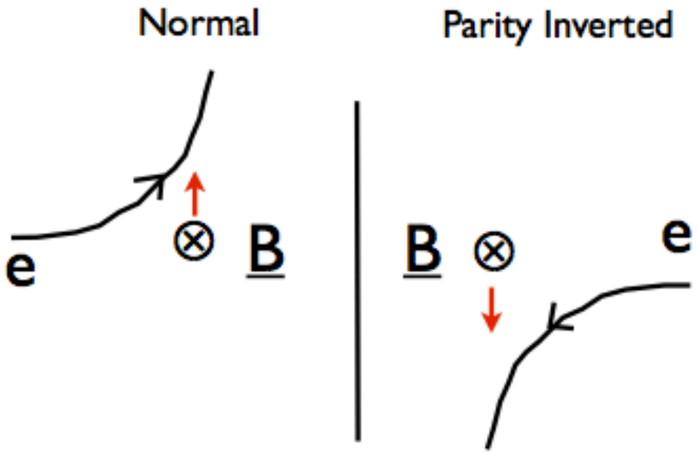


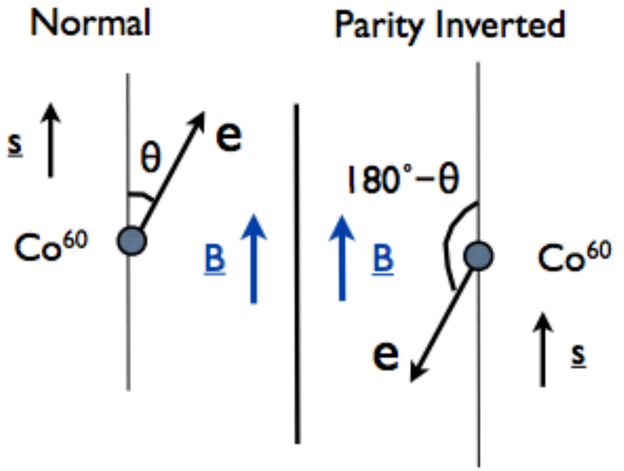
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Axial vectors do not change sign under parity transformation, whereas polar vectors do.

$\vec{L}$ is an axial vector
$\vec{p}$ is a polar vector

EM β Decay

Parity is conserved in electromagnetism. What about beta decay?



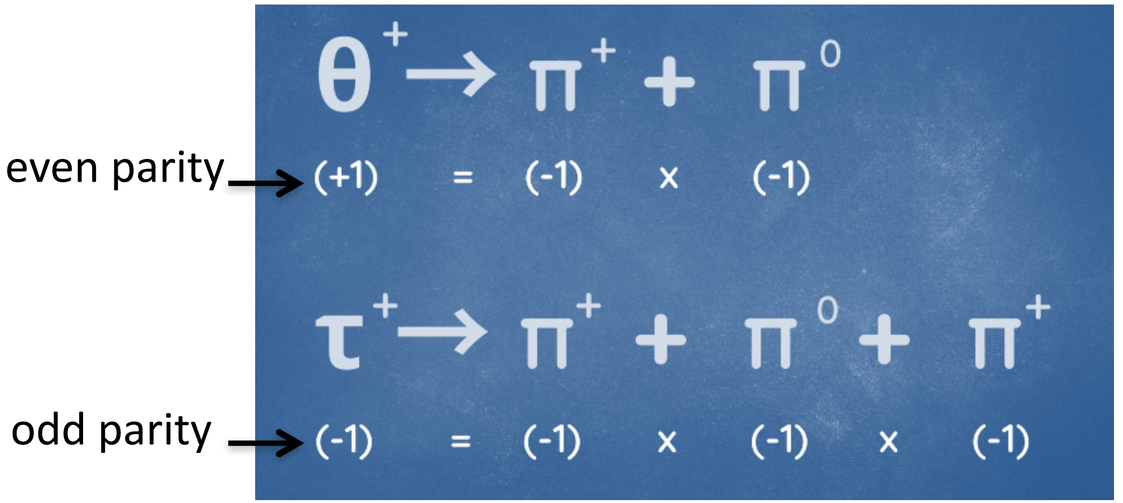
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➢ The electromagnetic force and strong nuclear force had both been deemed to conserve parity. The weak force, however, had no such proof!

In the 1950's, the **decay of ϑ and τ kaons** could not be explained by existing theories in which parity conservation was true. Although identical in every respect (mass, spin, charge, etc.), the mesons decayed into different parity states.

After observing this, C.D. Yang and T.D. Lee in 1956 theorized that **parity was not conserved in the weak interaction** and these particles were indeed the same.

Chien-Shiung Wu devised the elegant experiment to test the possibility of parity violation in beta-decay.





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Wu set up the following system to test parity violation in beta decay:

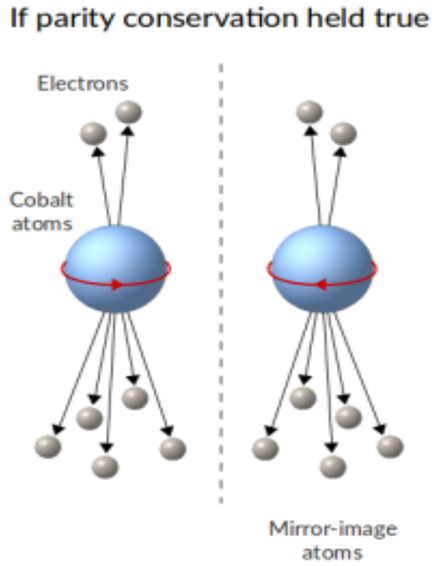
$$^{60}_{27}\mathrm{Co} \rightarrow {}^{60}_{28}\mathrm{Ni} + e^{-} + \bar{\nu}_e + 2\gamma$$

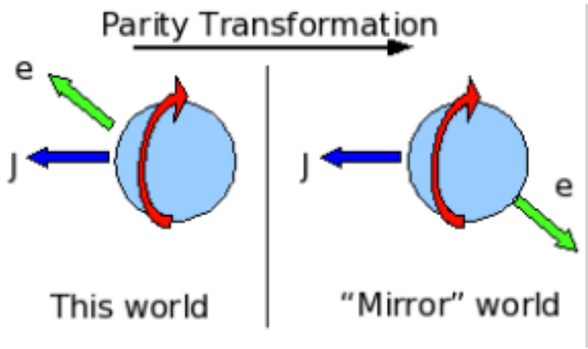
- Aligned all Co^{60} spin vectors with a magnetic field, cooled to near absolute zero, and let them decay.
- Detected **electron and gamma-ray emission** (EM emission conserves parity, acts as a control measure of anisotropy of alignment).

The spin vector remains in same direction in parity-transformed world , but electron emission vector is inverted.

Parity symmetric ➔ observe no preference in emission direction of electrons, and isotropic emission in both real and mirror world.

Parity breaking ➔ observe emission aligned in a preferential direction, making mirror image asymmetric.





Angular momentum = axial vector
Momentum = polar vector



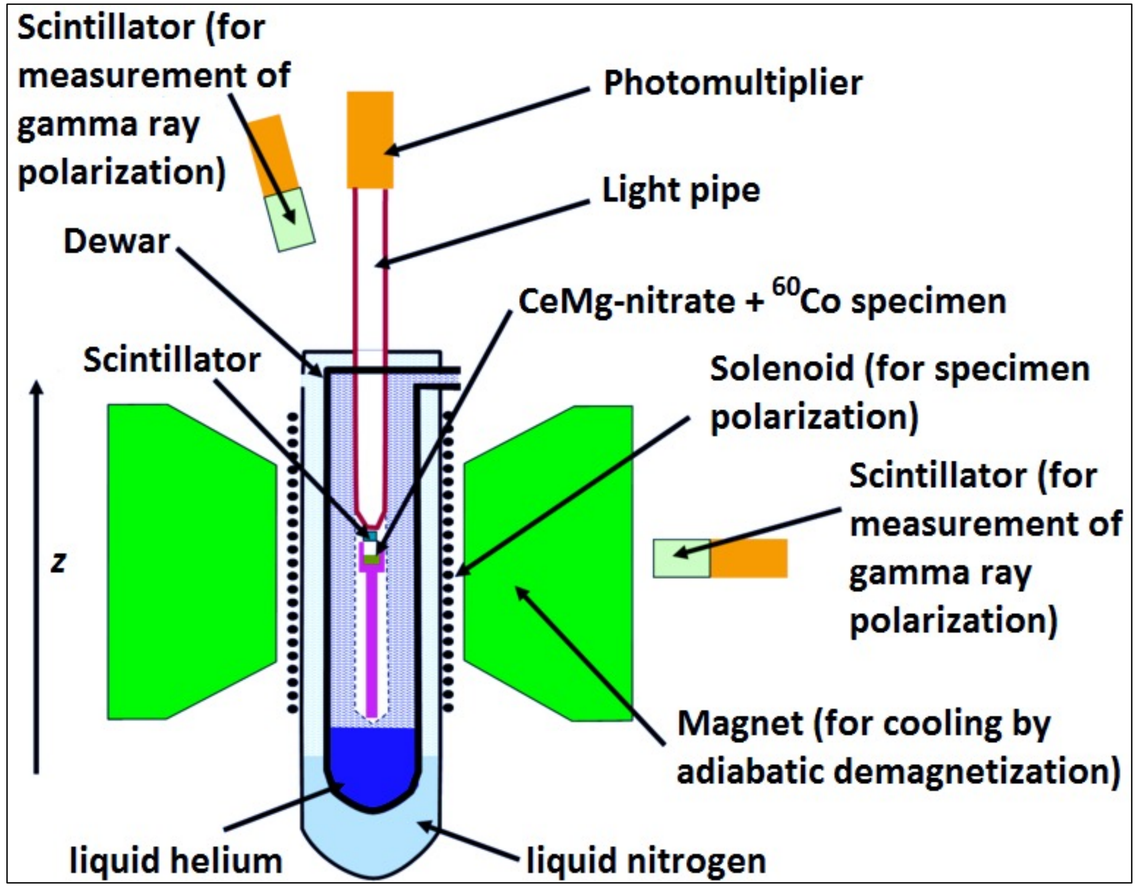
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The small magnetic moments of Co^{60} required **strong magnetic fields at extremely low temperatures** to polarize the sample as much as possible, through **adiabatic demagnetization.**

$$^{60}_{27}\mathrm{Co} \rightarrow ^{60}_{28}\mathrm{Ni} + e^{-} + \bar{\nu}_e + 2\gamma$$

<u>Experiment:</u>

a. Reverse the direction of the magnetic field and measure asymmetry in the beta decay rates to test parity conservation.
b. Measure the gamma-ray anisotropy to confirm the polarization.

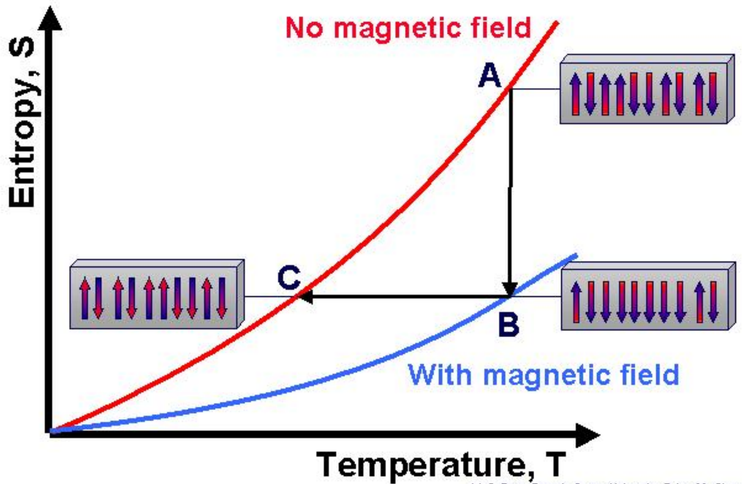




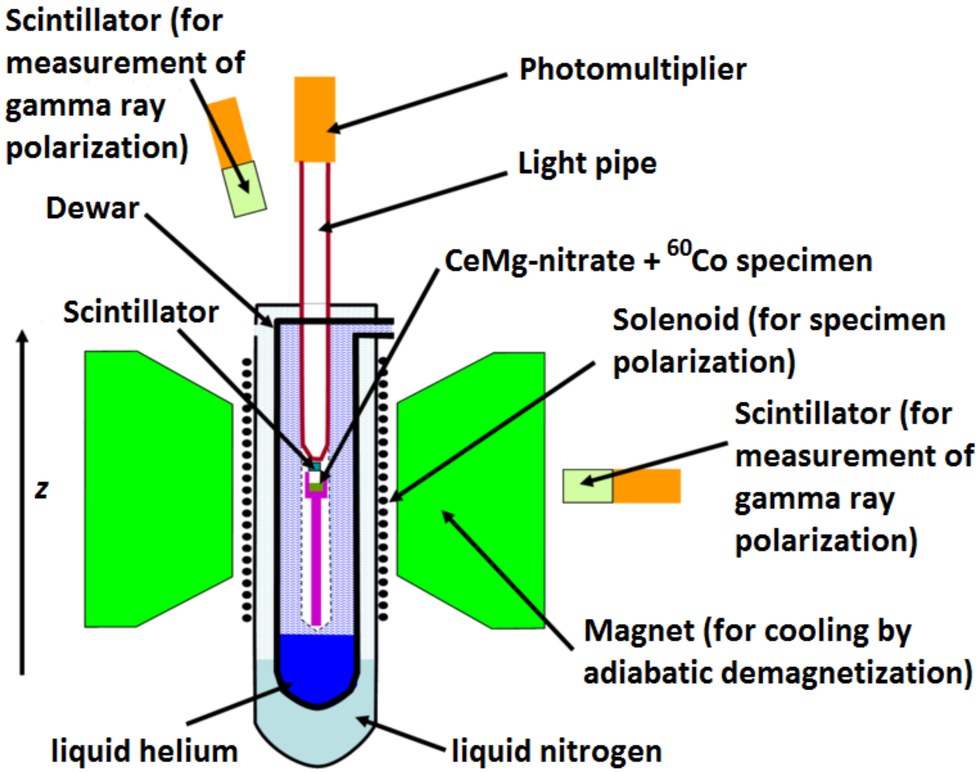
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The small magnetic moments of Co^{60} required **strong magnetic fields at extremely low temperatures** to polarize the sample as much as possible, through **adiabatic demagnetization.**

- Cobalt was deposited on a paramagnetic salt magnetized along the axis of high g-factor.
- Cooled to 1.2K via low pressure helium.
- Magnetic field replaced by solenoid along low g-factor axis, reducing temperature to 0.003K



$$^{60}_{27}\mathrm{Co} \rightarrow {}^{60}_{28}\mathrm{Ni} + e^{-} + \bar{\nu}_e + 2\gamma$$





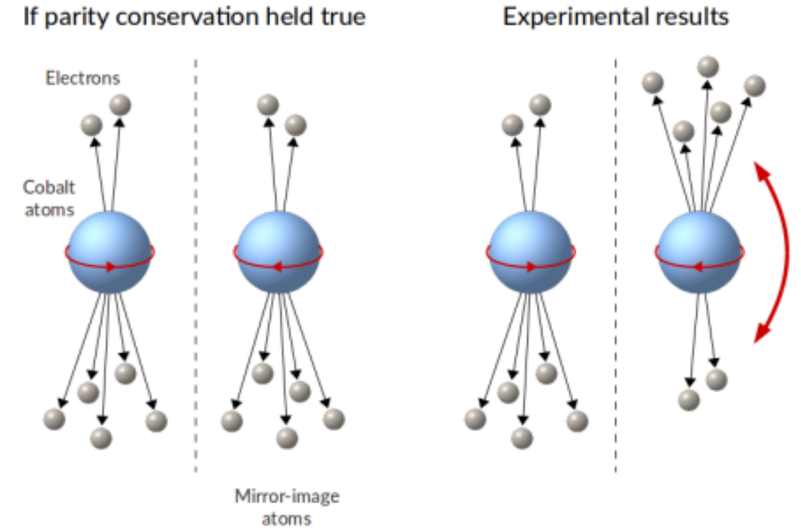
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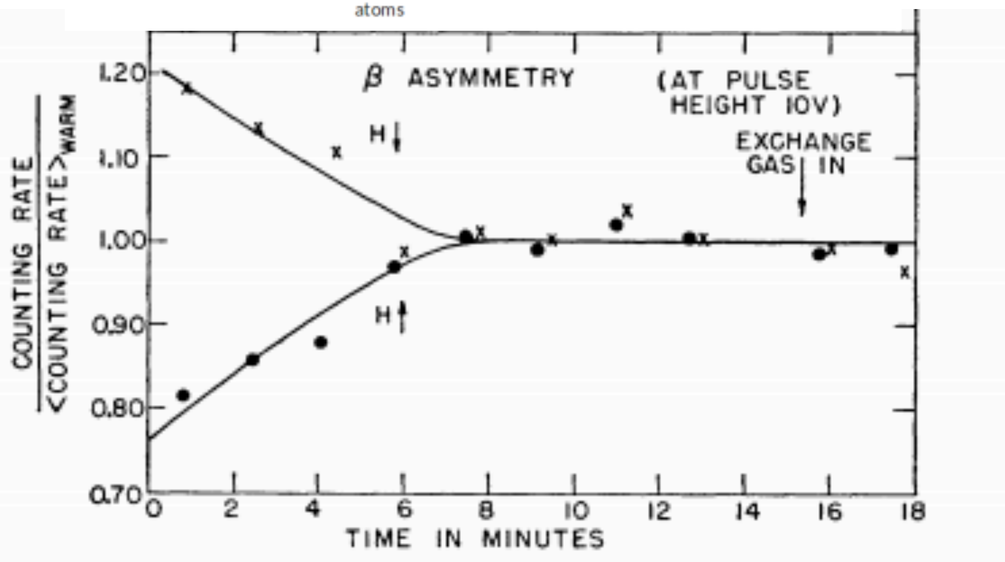
Observations from Wu's experiment:

- 60% of gamma rays emitted in one direction, 40% in the other
- Electron asymmetry much greater than gamma-ray anisotropy
- Electrons emitted in a direction **preferentially opposite to nuclear spin** direction
- Electron asymmetry did not change sign when magnetic field was reversed (*not due to remnant magnetization!*)

Conclusion:

- **Parity violation was maximal!**



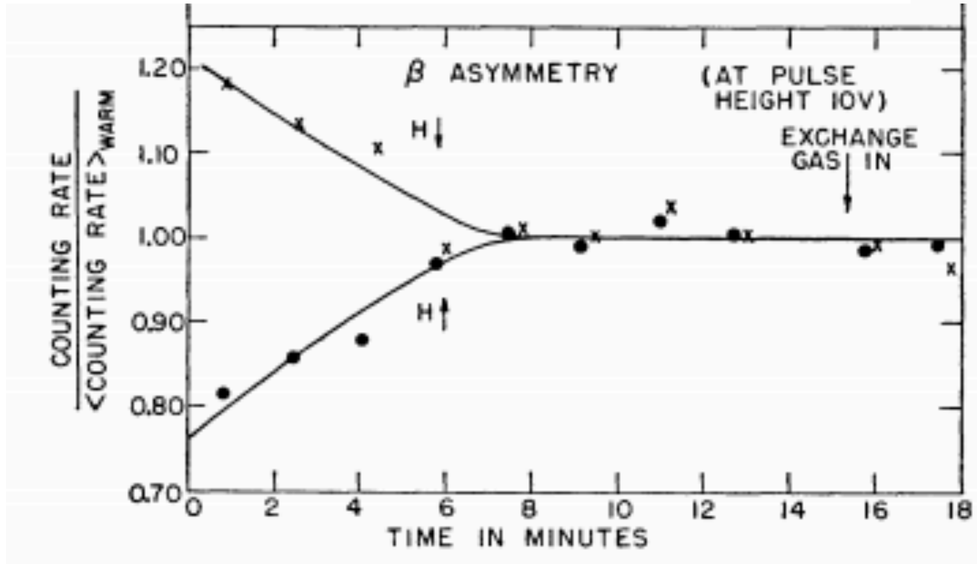


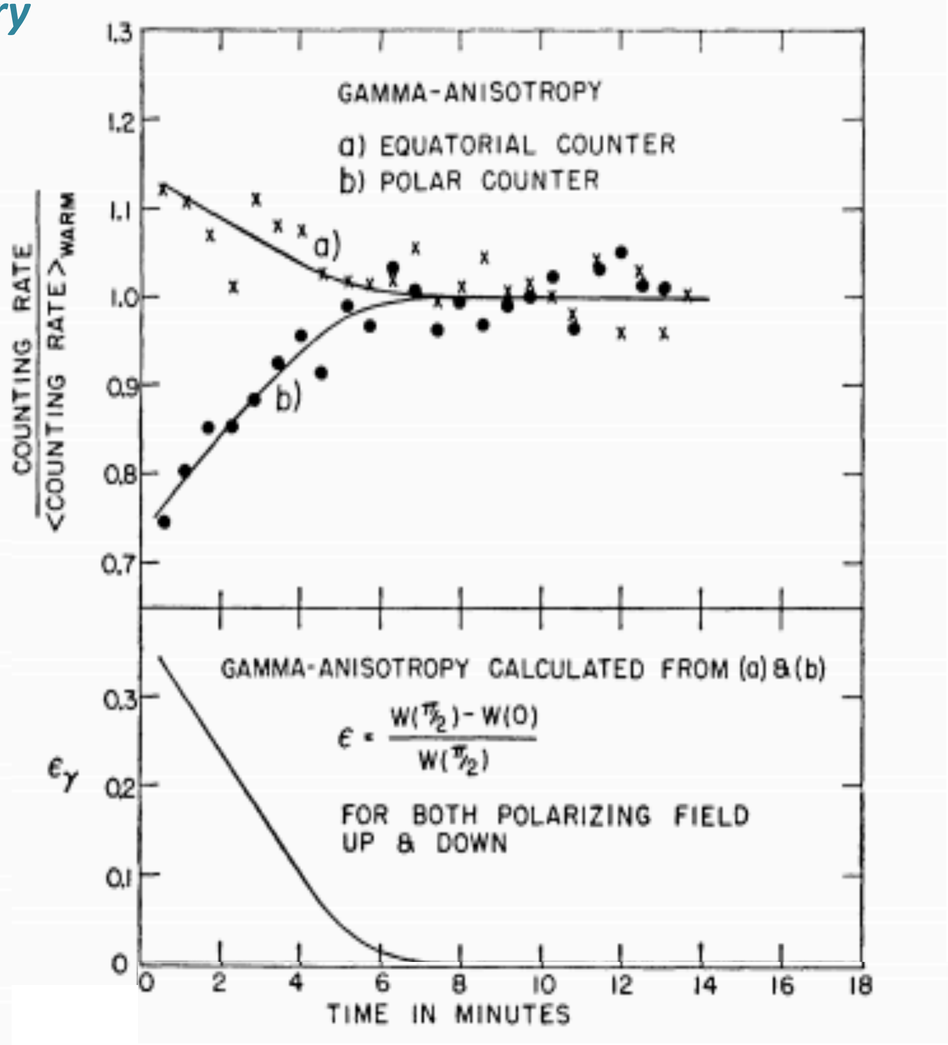


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Figure: Gamma anisotropy and beta asymmetry for polarizing field pointing up and pointing down.

- After about 6 minutes the sample warms up and polarization is lost (same time for both beta and gamma anisotropy)
- Clear beta asymmetry
- Sign of beta asymmetry is negative, beta emission opposite direction to spin







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Chien-Shiung Wu's legacy

C.D. Yang and T.D. Lee were awarded the Nobel Prize for their theory of parity violation in the weak interaction, and Wu was mentioned in the award speech.

Many believe she was greatly overlooked for the Nobel Prize as she conducted the experimental work that brought their theory to fruition.

Wu has since received recognition, including but not limited to the Wolf Prize, National Medal of Science in Physics, and election as president of the American Physical Society in 1975.





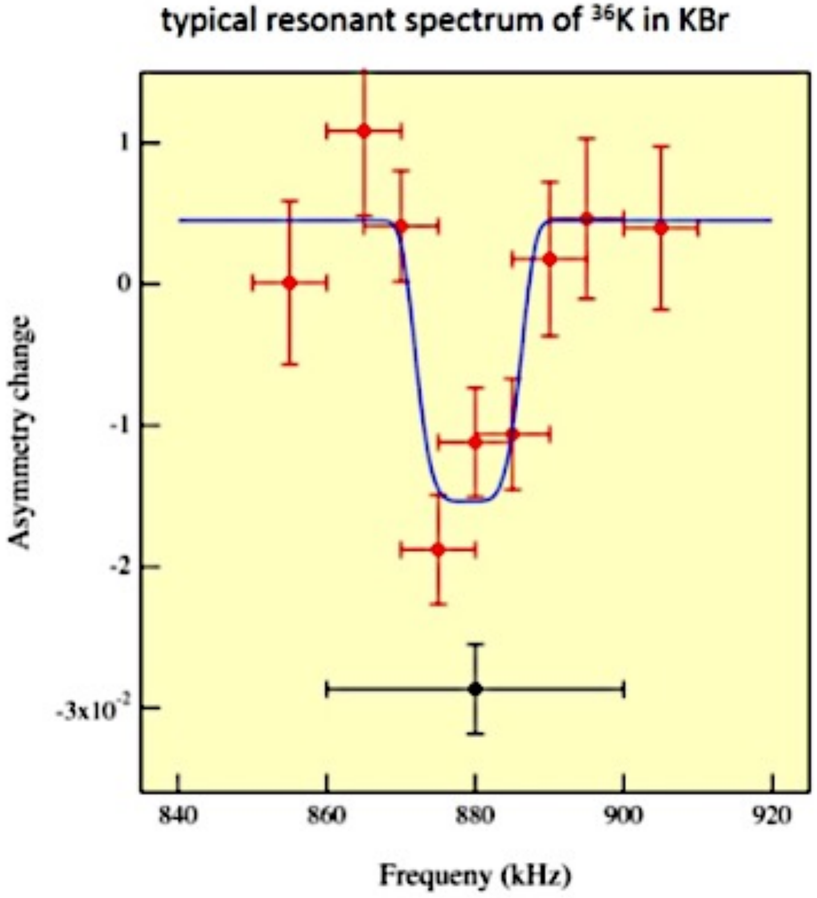
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Chien-Shiung Wu's legacy: Beta-NMR

The discovery of anisotropic emission of beta particles from polarized nuclei, allowed for the development of **Beta-detected Nuclear Magnetic Resonance** (Beta-NMR). Beta-NMR is one of the **most sensitive methods for determining electric quadrupole and magnetic dipole moments**.

Radio frequencies are used to induce **transitions between Zeeman levels** at the **Larmor Frequency** of spin-aligned beta-decaying radioactive nuclei, destroying the asymmetric beta-ray distribution in such a way that this resonant frequency can be retrieved. The magnetic dipole moment can be deduced from the Larmor frequency if the nuclear spin is known.

Beta-NMR has wide applications, including material characterization, and detecting metal-ion interactions with biomolecules.



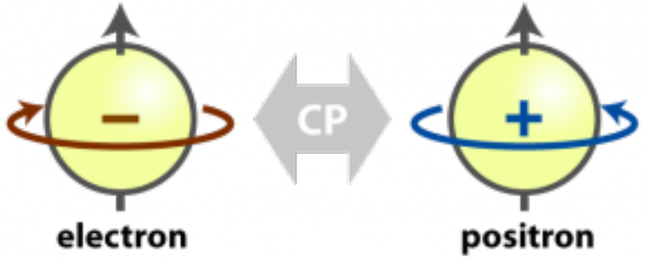


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Chien-Shiung Wu's legacy: Cosmology

Following Wu's discover of parity-violation**, charge conjugation parity symmetry (CP symmetry)** was proposed to restore order, a rule which dictated that laws of physics remained the same when:

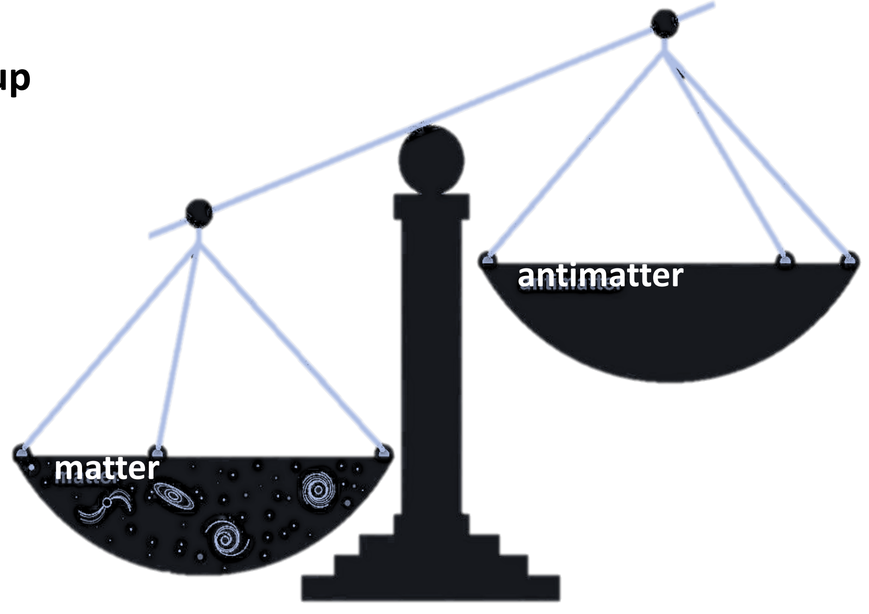
- all particles are exchanged with their antiparticles
- spatial coordinates are mirrored.



CP violation was directly observed in strange B-meson decays by LHCb in 2013.

The non-dark-matter part of our Universe is **mostly made up of matter**, as opposed to 50-50 matter and antimatter.

This imbalance has been theorized by cosmologists as a direct result of CP violation occurring in the first seconds after the big-bang (**Sakharov Conditions**).



Physical laws **must have acted differently for matter and anti-matter (CP violation)** to produce a matter-dominated universe instead of a radiation dominated universe caused by matter-antimatter annihilation.