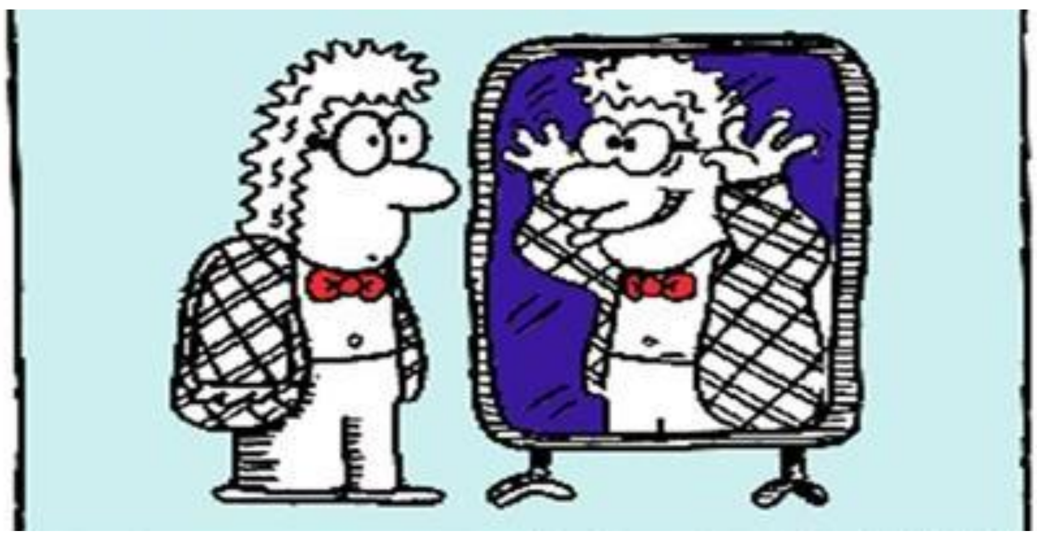
θ-τ puzzle and the discovery of parity violation

Graziano Venanzoni



20/1/2025
Seminar to the Muon group, Liverpool

Wolfgang Pauli (1900 - 1958) und Chien-Shiung Wu (1913 - 1997)

θ-τ puzzle

- θ and τ: "Strange" particles (see https://indico.ph.liv.ac.uk/event/1621/contributions/8077/attachments/3596/5079/discovery%20of%20strangeness_v2.pdf) observed in cosmic rays, with almost identical masses and lifetimes, decaying into 2 pions (θ) and 3 pions (τ), respectively. They had opposite parity (Dalitz, 1947): $P_\theta=+1$; $P_\tau=-1$:
  - $\theta^+ \rightarrow \pi^+\pi^0$ $J^p = 0^+$ (nowdays K^+)
  - $\tau^+ \rightarrow \pi^+\pi^+\pi^-$ $J^p = 0^-$

- **April 1956**: At the Rochester Conference (after a talk by Chen Ning "Frank" Yang), Feynman asked whether these could be the same particle whose decay violates parity.

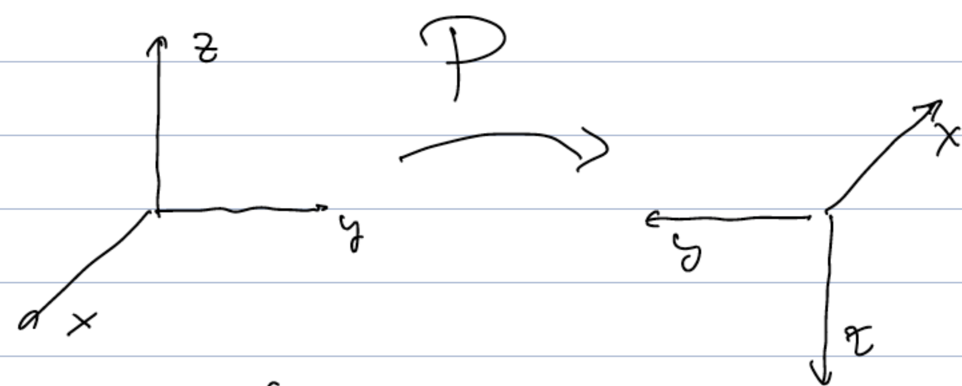
- **June 22, 1956**: T.D. Lee and C.N. Yang published their paper *"Question of Parity Conservation in Weak Interaction"* (PR 104, 1956, 254), in which they proposed conducting an experiment to determine whether weak interactions violates parity.

θ-τ puzzle

- **Madame Wu's Experiment (Columbia U)**: On January 15, 1957, the paper *"Experimental Test of Parity Conservation in Beta Decay"* (PR 105, 1957, 1413) presented clear evidence of parity violation in beta decay.
  - This was almost immediately confirmed by Garwin, Lederman, and Weinrich (spin precession of the muon in a magnetic field) and by Friedman and Telegdi (pi-mu-e transitions without a magnetic field).
- **1958**: The V-A structure of weak interactions was proposed (Feynman and Gell-Mann; Marshak and Sudarshan) after an incorrect experiment with ^{6}He. Goldhaber's experiment [M. Goldhaber et al., PR 109, 1958, 1015] demonstrated left-handed neutrinos and right-handed antineutrinos.
- **The vector nature of weak interactions**: Could weak interactions, like electromagnetic interactions, be part of the same fundamental force? (Yes) → Electroweak interaction → Standard Model

Parity

- Parity is the trasformation associated to the spatial inversion of the coordinates:



$P(x,y,z) \to (-x,-y;-z)$

$P\psi(x,y,z) = \psi(-x,-y,-z)$
If $\psi(-x,-y,-z) = \psi(x,y,z) \rightarrow \psi(x,y,z)$ has positive Parity
If $\psi(-x,-y,-z) = -\psi(x,y,z) \rightarrow \psi(x,y,z)$ has negative Parity

Each particle has also an ”intrinsic” Parity

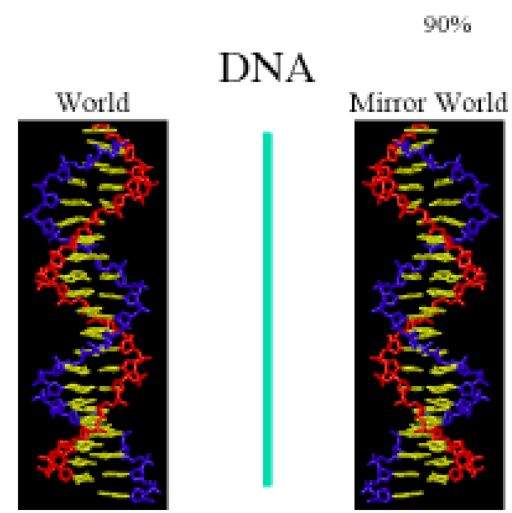
(Parity is also known as “mirror symmetry” as a spatial inversion is equivalet to a reflaction respect to a plane *plus* a rotation of 180 respect to an axis perpendicular to the plan)

How can the violation of parity be observed in a process (or a decay)?

You can use the following general idea:

> If a transformation is an invariance, an initially symmetric state/system (i.e., one that "does not change" under that transformation) remains symmetric over time. Using the language of physicists, we would say that "parity is conserved."

An alternative way to express it is that it is not possible to distinguish what happens in the real world from the process in the mirror (of course, not all systems are invariant under reflection).
However, be careful—here we are talking about invariance in the *evolution* (dynamics) of the process.



World ≠ Mirror World by 100%
Parity is fully violated.

How can we test parity violation in the weak force?

1. Selection of a process (or decay) in which the weak interaction plays a leading role;
2. Preparation of an initial state that is symmetric under parity;
3. Evolution of the system and verification of whether the final state remains symmetric under parity.

In other words, the experiment should not show any difference when observed in a mirror.

Now let's see how Madame Wu (in 1956) structured her experiment, according to the steps mentioned above

1. **Selection of a process (or decay) in which the weak interaction plays a determining role.**

The choice fell on the beta decay of the ^{60}Co nucleus.

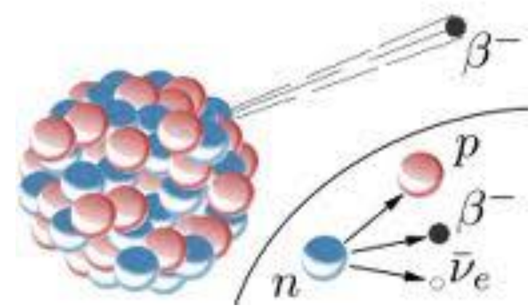
The beta decay describes the decay process responsible for the weak force:

$$n \rightarrow p + e^- + \bar{\nu}_e \, .$$

A neutron of ^{60}Co (Z=27) nucleus transforms into a proton, emitting simultaneously an electron(e) and an anti-neutrino $(\bar{\nu}_e)$. The transformed nucleus becomes ^{60}Ni with a number of protons Z=28.

The reaction proceeds as:

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



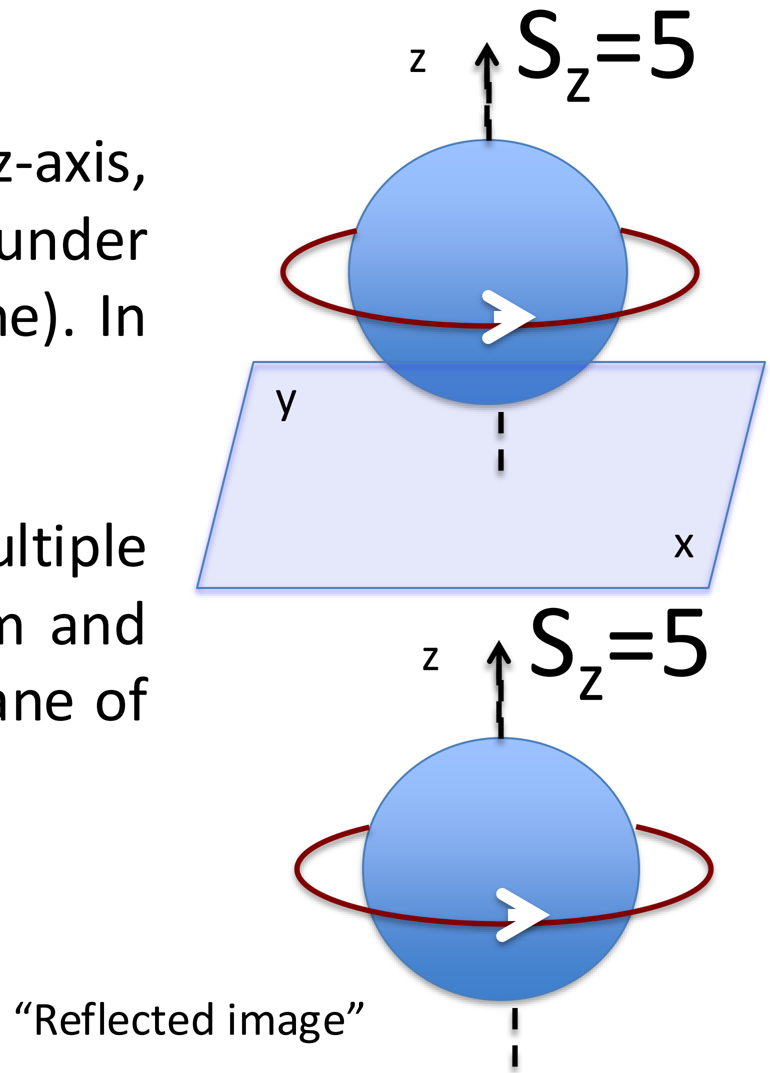
E_{max} e^-=~310 keV

The Ni nucleus, in turn, emits (mainly) two gamma rays (at 1.17 and 1.33 MeV) to reach the ground state (i.e., the two gamma rays are emitted with the electron).

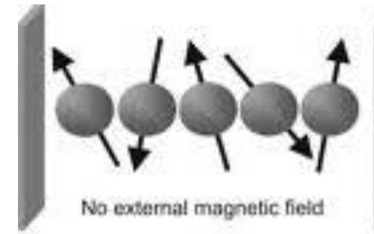
2) Preparation of an initial state symmetric under parity

The ^{60}Co nucleus has spin S=5.
If we align the spin of the ^{60}Co along the z-axis, we will have a state that is symmetric under spatial reflection (respect to the x,y plane). In other words the spin still points upward.

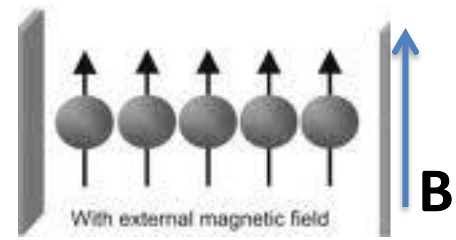
In the experiment, we will have multiple atoms, so we need to orient all of them and ensure that they are stationary in the plane of symmetry.



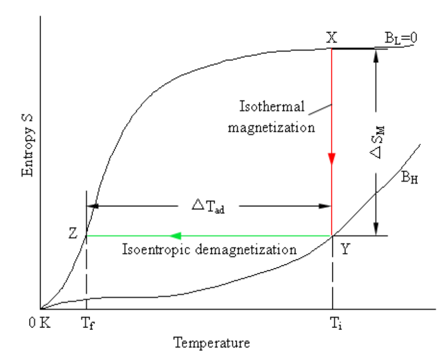
How did Madame Wu align the spins of the ^{60}Co?



Using a magnetic field (B). In fact, it is known that in the presence of B, the spin tends to align along the direction of the field.
To align the spins of the nuclei, an extremely high magnetic field (~0.1 T) is required, which cannot be produced in the laboratory (using coils or other means). Additionally, at room temperature, thermal agitation destroys the polarization. So, what to do?

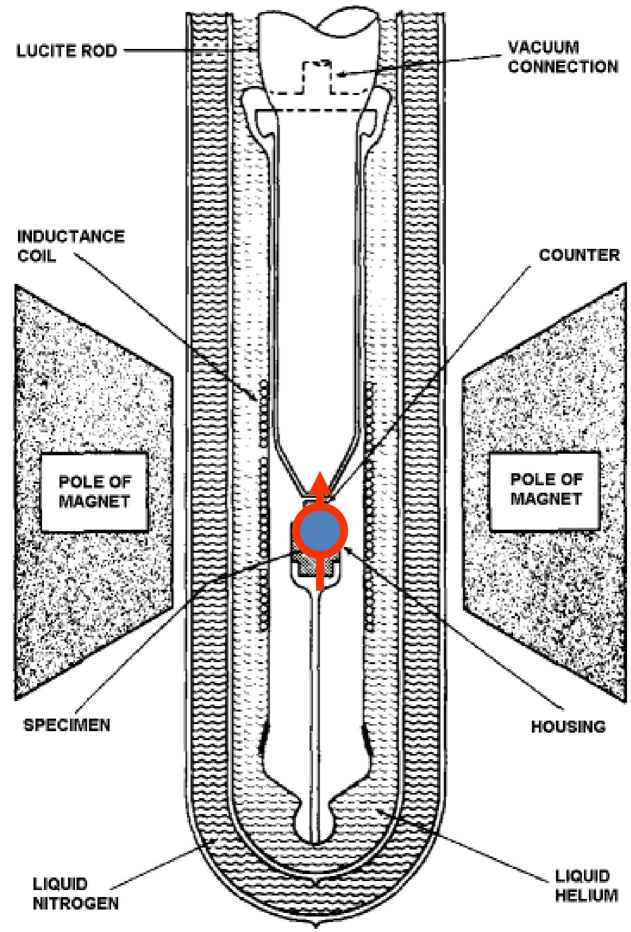


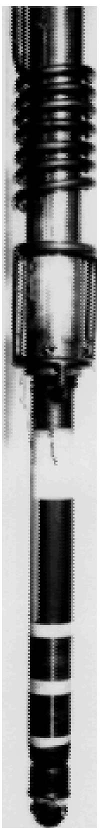
Madame Wu did this in two steps:
1) used the so-called "Adiabatic Demagnetization" (a method, based on the fact that certain atoms (of a paramagnetic salt) placed in a magnetic field B and isolated, release heat (and thus cool down) as B decrease), to cool the ^{60}Co to T ~ 0.01 ^oK.



2) By applying a weak external magnetic field of O(100G), the magnetic moments of the electrons generate a strong local magnetic field of O(10^5–10^6 G), which polarizes the ^{60}Co nuclei.

Thus, a thin film of ^{60}Co was placed on a "cooled" crystal of cerium and magnesium nitrate (CMN) and immersed in an external magnetic field. To preserve the polarization for a longer time, the crystal had to be placed in a bottle-shaped container (which was vacuum-sealed) and thermally insulated (dewar).

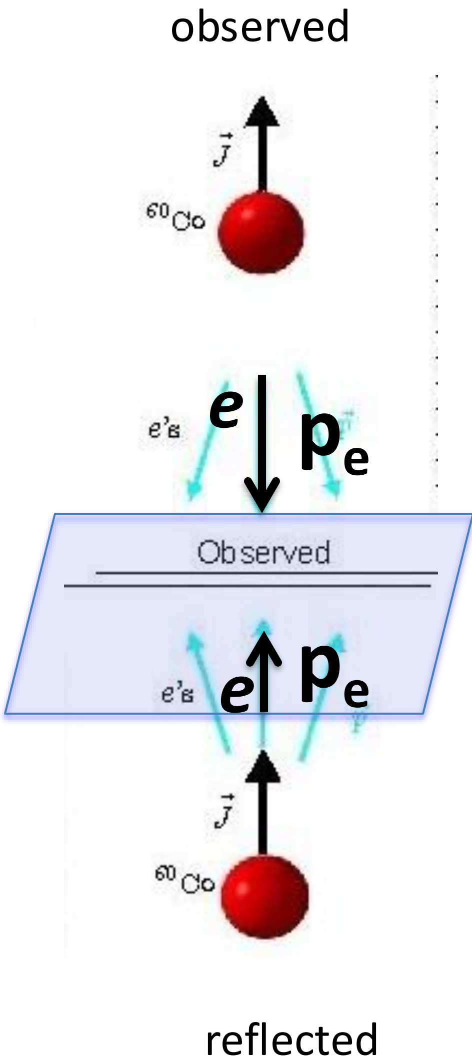




3) Evolution of the system and verification of whether the final state is symmetric under parity

If the final state produced in the β decay ${}^{60}_{27}Co \rightarrow {}^{60}_{28}Ni + e^- + \bar{\nu}_e$ is symmetric under parity, it means (for example) that as many electrons are emitted upwards as downwards (since reflection reverses the direction of momentum).
→ a non-zero value of the Up-Down asymmetry indicates a clear violation of parity (meaning that the observed process and its reflected counterpart do not occur identically in nature).

It is essential to ensure that the ^{60}Co remains polarized during the measurement time.

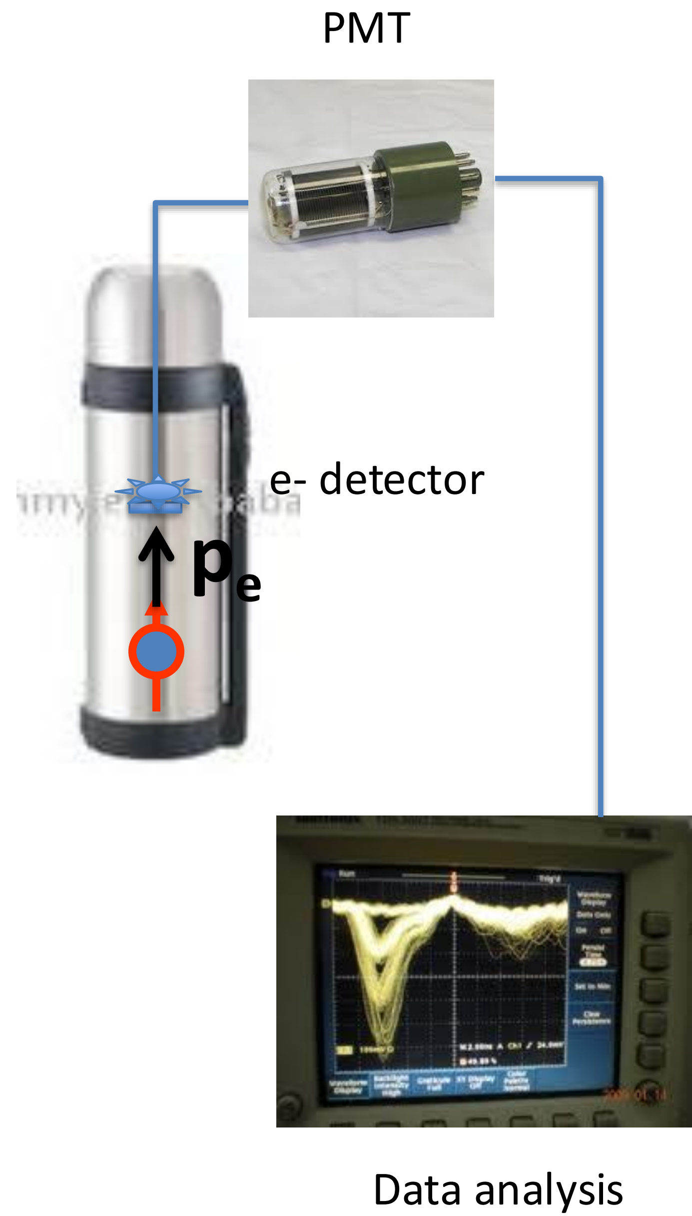


All of this made the experiment particularly complicated (for 1956!)

The electron detector (Anthracene crystal) had to be placed inside the cryostat (otherwise, the electrons would have been absorbed by its walls).

The signal produced (scintillation light) had to be transported outside to the photomultipliers (which do not operate at cryogenic temperatures) through a light guide (made of lucite).

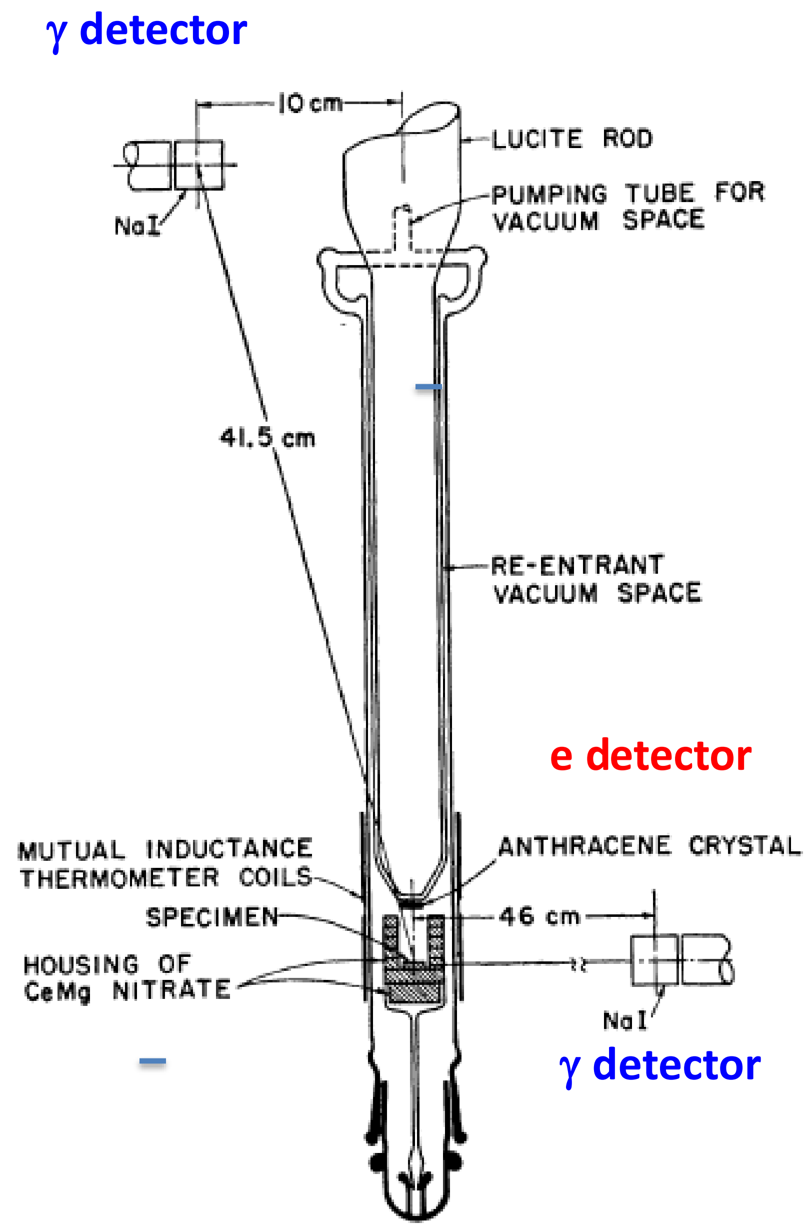
The ^{60}Co source had to be very thin to avoid absorbing the emitted electrons and polarized for a long period to obtain enough counts.



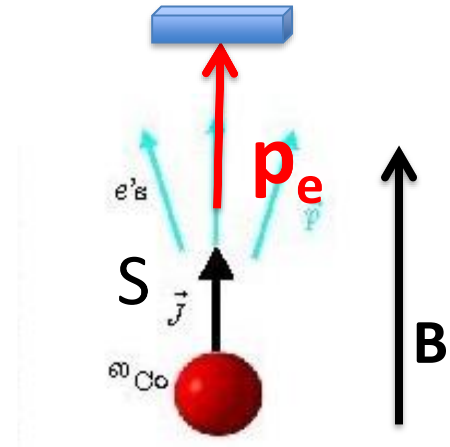
In just 6 months, M.me Wu and her team prepared the experiment:

- The thin layer of ^{60}Co (0.05 mm) was placed on a ”housing" made of CMN crystals.

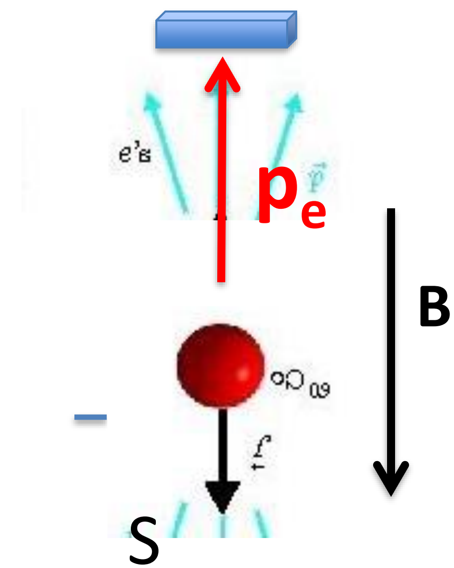
  The polarization was measured by the anisotropy of the gamma rays emitted during the decay of ^{60}Co (higher intensity of γ-rays perpendicular the spin of the nucleus (than parallel the spin))
- For this purpose, two scintillation detectors (NaI) were installed, one in the equatorial plane and the other on the upper part of the cryostat. The electrons were detected in a small anthracene crystal, 1 cm in diameter and 1.5 cm thick, placed 2 cm above the source.



Instead of duplicating the electron detector (above and below the source), only one detector was used (above the source), and the direction of the magnetic field was reversed. In this way, the spin of the ^{60}Co was inverted, and electrons emitted parallel or antiparallel to the direction of the spin (= direction of B) were counted.

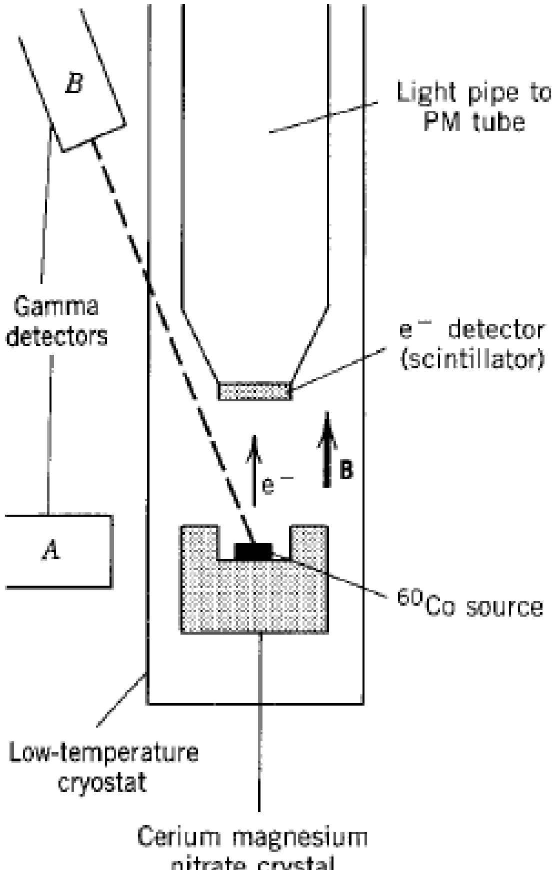


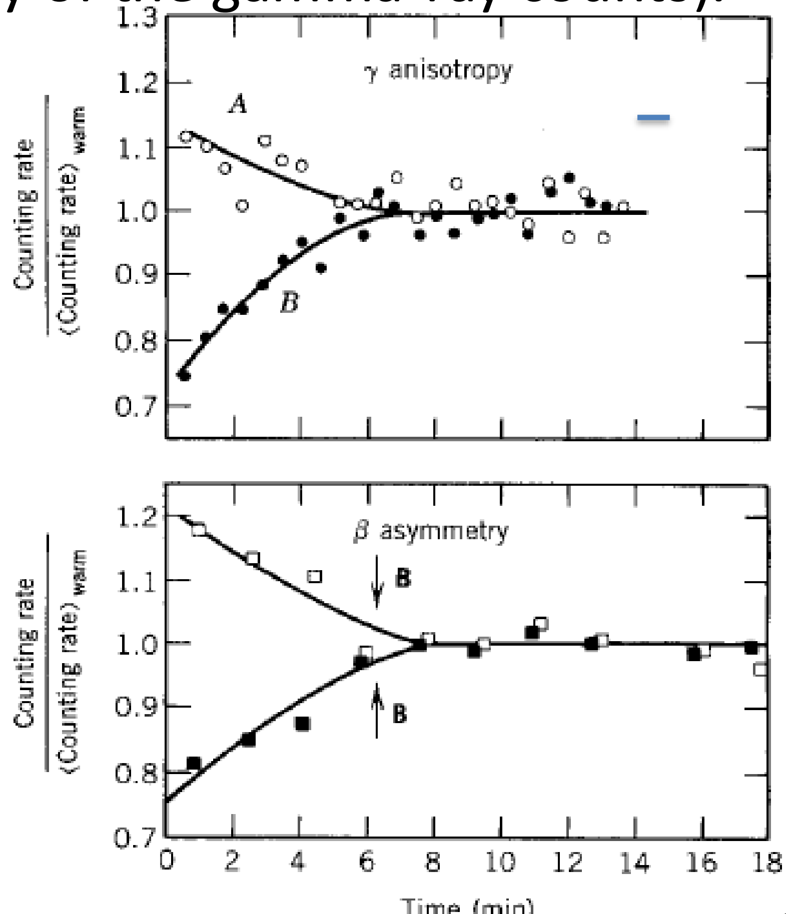
Naturally, this is completely equivalent to spatial reflection (simply rotating the figure with the magnetic field directed downward by 180°).



Which was the result?

M. Me Wu found (December '56) a clear asymmetry in the counting of electrons (more electrons were emitted in the direction opposite to the spin of the nucleus), strongly correlated to the degree of polarization of the ^{60}Co source (measured by the anisotropy of the gamma-ray counts).





Time (min)

Over time, the source heats up and the polarization disappears.

Naturally, it was important to ensure that this was a genuine effect of parity violation:

•It was verified that the electron detector was independent of temperature and magnetic field effects.

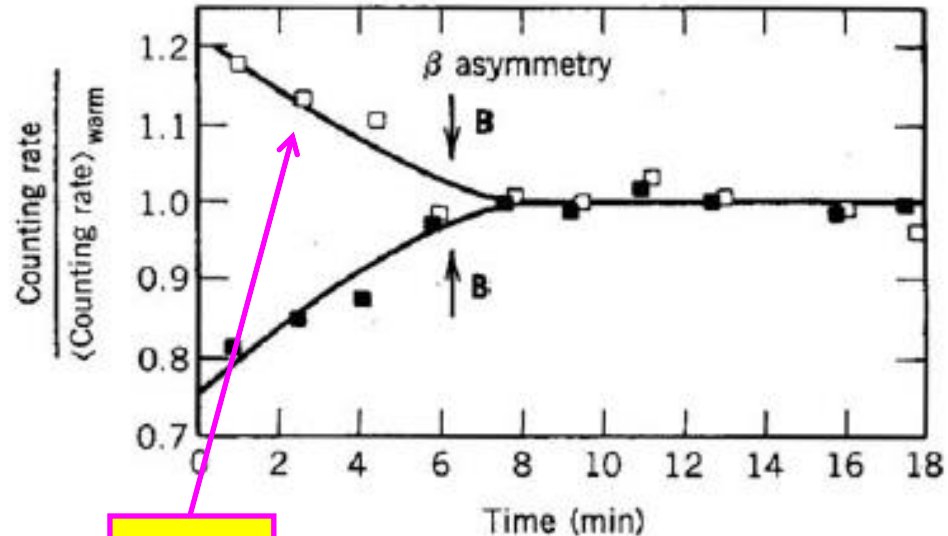
•The back-scattering of electrons from the CMT was found to be negligible.

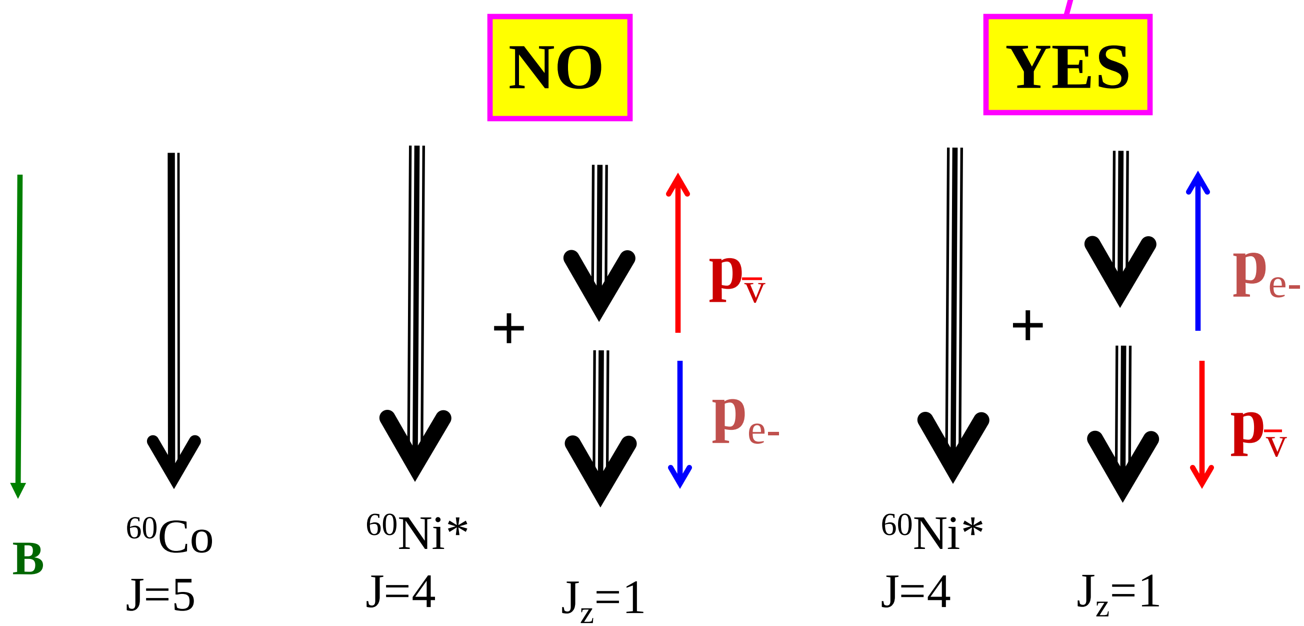
•The asymmetry in counting was not due to anisotropies in the magnetic field of the CMT or residual demagnetization fields. For example, they placed the ^{60}Co under a CMT crystal and saw no asymmetry, inverted the direction of the demagnetization field, and so on.

In short... this experiment, despite being conducted 70 years ago, contained all the characteristics of a modern experiment in elementary particle physics: data analysis, reproducibility of the result, and control of systematic effects.

What did it imply that the electrons were preferentially emitted in the direction opposite to the spin of the ^{60}Co?

That in the weak interaction electrons with negative helicity (opposite spin and momentum), and antineutrinos with positive helicity (spin and momentum in the same direction) are "preferentially" involved.





It was later verified that neutrinos only have negative helicity, while antineutrinos only have positive helicity.

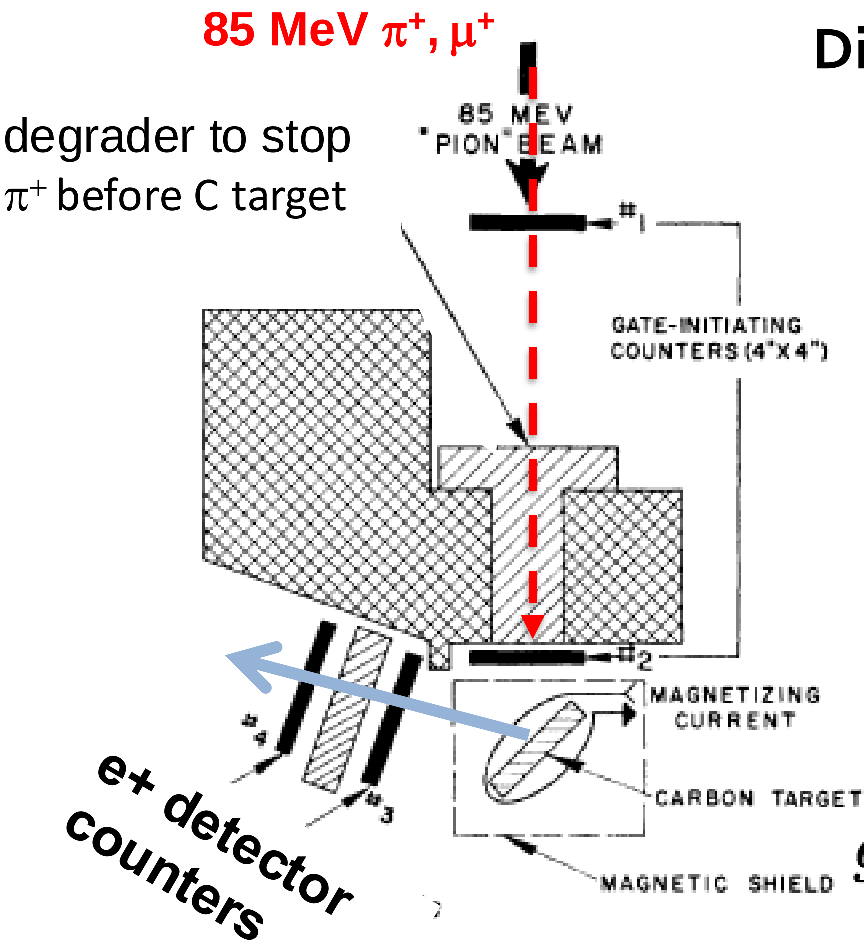
The result of Mme Wu was a major blow to the scientific community.

It showed that there is a class of processes (governed by the weak force) where parity is maximally violated, and it is possible to unambiguously define left versus right. Immediately after Wu's result (as often happens), parity violation was confirmed in two other experiments (L. Lederman and V. Telegdi).

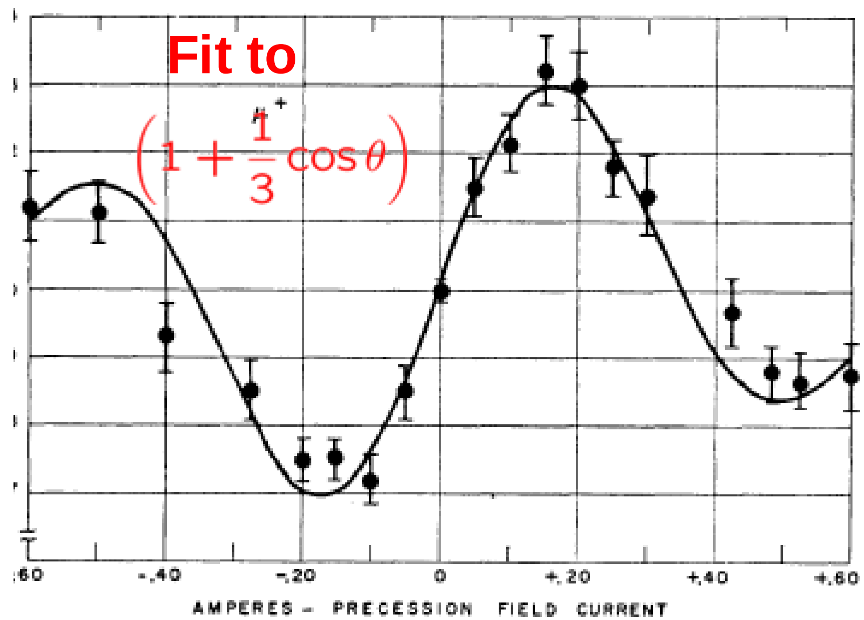
Twenty years after Fermi's formulation (1938), parity violation marked the first significant step in understanding the weak force. It would take another twenty years to include this force in a unified description of the fundamental interactions: the Standard Model.

History: the first measurement of g_μ

- 1957: Garwin, Lederman, Weinrich at Nevis (Just after Yang and Lee parity violation paper - confirmation)



Direct measurement of *g* -- asym vs field



$$g_\mu = 2.00 \pm 0.10$$

muons behave like electrons

5% uncertainty

Photo from the Nobel Foundation archive.

Chen Ning Yang

Prize share: 1/2

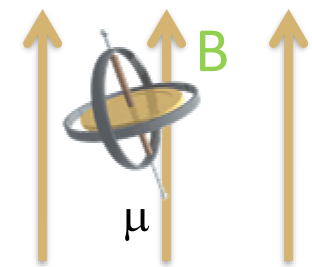
Photo from the Nobel Foundation archive.

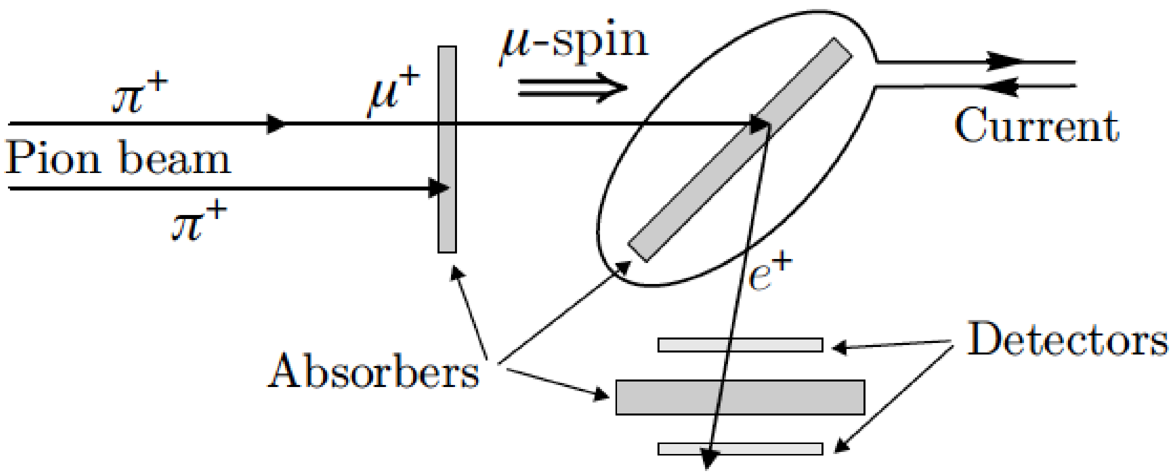
Tsung-Dao (T.D.) Lee

Prize share: 1/2

Lee and Yang (1956)

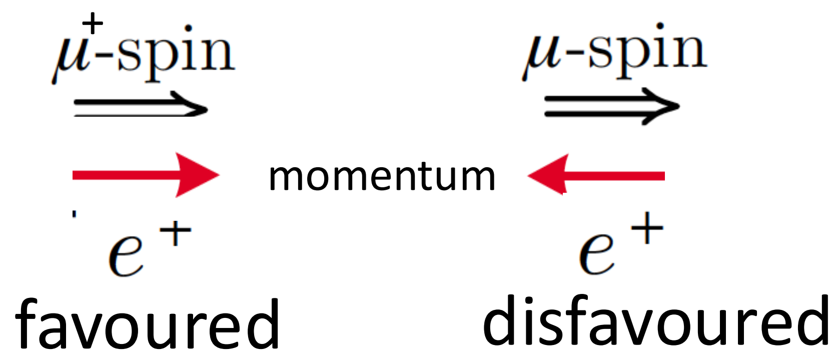
The parity violation in the production and decay of the muon offers a way to measure the muon magnetic moment





$$\omega_s = g\frac{eB}{2mc}$$

+



The rate of high energy decay electrons is time modulated by the precession of the magnetic moment with a frequency which depends on g

Some reactions to M.me Wu experiment

- Letter of Pauli to Weisskopf:

“Now, after the initial shock, I’m starting to pull myself together [...]. Yes, it was very dramatic [...]. What bothers me is not the fact that 'God is left-handed,' but that, despite this, when He expresses Himself most strongly, He shows a right-left symmetry... How can the intensity of an interaction produce and create symmetry groups, invariances, or conservation laws?... Many questions, no answers!

- Oppenheimer to Yang (after being informed of the result of Mme Wu's experiment):
  "Crossed the threshold."
- I. I. Rabi: "[...] a fairly complete theoretical structure has been destroyed at its foundation, and we are unsure how its pieces will be recomposed."

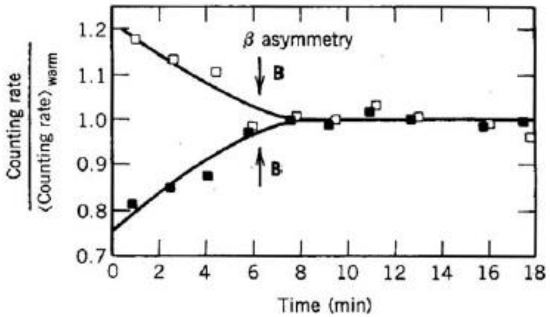
...and some sociological effects...

- Valentine Telegdi (the leader of one of the other two experiments that observed parity violation) resigned from the American Physical Society after his paper was rejected and subsequently published a couple of weeks after the other two.
- Martin Block, Richard Feynman's roommate at the 1956 Rochester conference, who was the first to hypothesize that parity was not conserved (Feynman, after privately calling him "stupid," explicitly asked this question at the end of Yang's presentation, receiving a confused answer), believed he was the unrecognized architect of the entire process.
- The relationship between Lee and Yang couldn't withstand their growing fame: in 1962, they formally ended their collaboration and from that point on, tried to avoid each other.

Unfortunately, M.me Wu's discovery was not rewarded with a Nobel Prize.

Despite this, her fame, mainly tied to this first experiment, makes her one of the most prominent figures in the field of experimental physics of the last century.

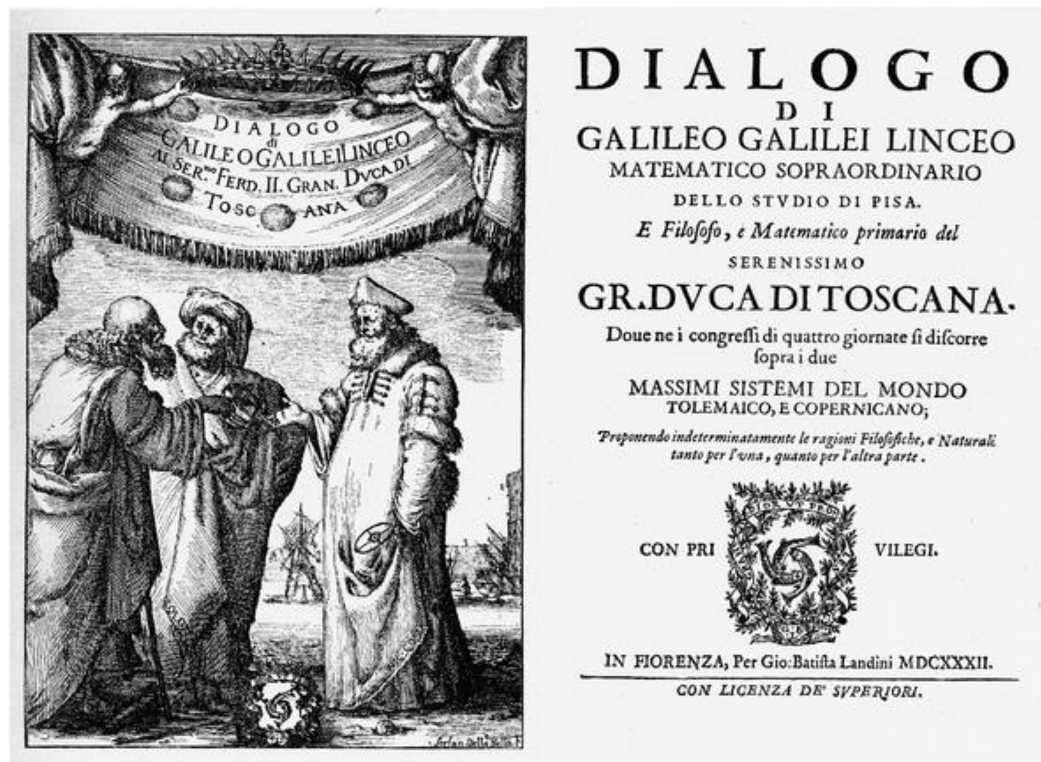
Wolfgang Pauli (1900 - 1958) und Chien-Shiung Wu (1913 - 1997)



Dialogue Concerning the Two Chief World Systems (Dialogo sopra i due massimi sistemi)

Galileo Galilei 1632

Salviati: Did he [Aristotle] not affirm that what experience and the senses demonstrate to us must be preferred over any reasoning, no matter how well-founded it might appear?
(Il medesimo non afferm’egli che quello che l’esperienza e il senso ci dimostra, si deve anteporre ad ogni discorso, ancorché’ ne paresse assai ben fondato?)



DIALOGO
DI
GALILEO GALILEI LINCEO
MATEMATICO SOPRAORDINARIO
DELLO STVDIO DI PISA.
E Filosofo, e Matematico primario del
SERENISSIMO
GR.DVCA DI TOSCANA.
Doue ne i congressi di quattro giornate si discorre
sopra i due
MASSIMI SISTEMI DEL MONDO
TOLEMAICO, E COPERNICANO;
Proponendo indeterminatamente le ragioni Filosofiche, e Naturali
tanto per l'una, quanto per l'altra parte.

CON PRI VILEGI.

IN FIORENZA, Per Gio:Batista Landini MDCXXXII.
CON LICENZA DE' SVPERIORI.

In Latin: Contra facta non valet argumentum (Argument does not prevail against facts)

References

- Lee and Yang «Question of Parity Conservation in Weak Interaction» PR 104 (1956) 254
- Wu et al. «Experimental Test of Parity Conservation in β Decay» PR 105 (1957) 1413
- F G Brickwedde, , R P Hudson, and , and E Ambler «Cryogenics» Vol. 6, 1955, pp. 25–44 (https://www.annualreviews.org/doi/abs/10.1146/annurev.pc.06.100155.000325)
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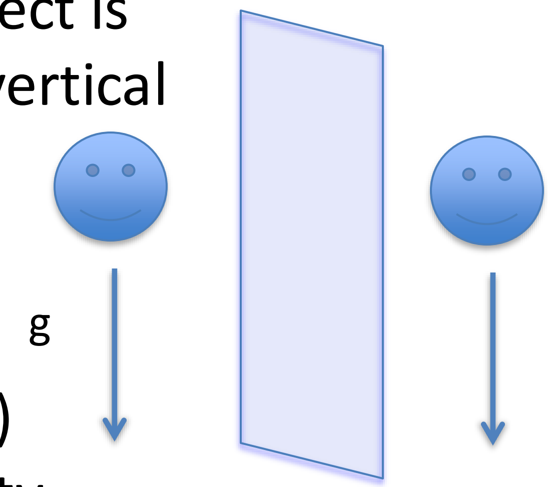
backup

A physical example of invariance: a falling object is invariant under reflections with respect to a vertical plane (but not a horizontal one).



Similarly, a nucleus placed at the origin of the axes with spin s (intrinsic angular momentum) directed along the z-axis is symmetric for parity (= reflection with respect to the (x, y) plane).
Indeed, for parity (coordinates and momentum):
$x'=x$, $y'=y$, $z'=-z$; $p'_x=p_x$, $p'_y=p_y$, $p'_z= -p_z$

spin:
$s'_x=-s_x$, $s'_y=-s_y$, $s'_z= s_z$

and the direction of rotation (of the spin) does not change (it always points upwards).