The Wu Experiment
- First Proof of Parity Violation -

Janina Nicolini

25. Oktober 2019

presentation for key experiments seminar

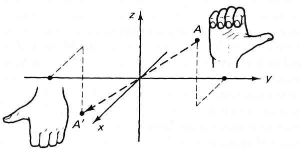
Physics Department

Übersicht

Parity

The parity $\hat{P}$ operator transforms a phenomen into its mirror image.

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



Applying the parity operator two time transform a system in its original state.
$\hat{P}^2 = 1$ →the eigen values are ± 1.

Understanding of the SM in 1956

- the mirror image of any physical process shows the same physics →parity conservation [5]
- a system is invariant under the combination of parity $\hat{p}$, charge conjugation $\hat{C}$ and time reversal $\hat{T}$
  →this is calles CPT theorem
  →assumption: each operation individually leaves the physics invariant as well
- former experiments showed that the electromagnetic and strong interaction conserves parity
  →assumption: same applies for the weak interaction

Reminder: Helicity and Chirality

Two imporant quantities to describe a particles movement:

- the direction of its momentum
- the particle spin $\vec{s}$

these can be described together:

- **helicity**: projection of the spin on the particle direction of movement
  →with two different possiblities
  1. <u>left-handed</u>: spin and the direction of movement are antiparallel
  2. <u>right-handed</u>: spin and the direction of movement are parallel
- **chirality**: disassembly of a dirac spinor in two orthogonal states that transform under parity operation into each other

value of chirality

- a massless particle is lorentz-invariant →helicity = chirality
- a chiral phenomenon is one that is not identical to its mirror image

The τ-θ-puzzle

two charged strange Meson decays were observed:

$$\theta^+ \to \pi^+\pi^0 \qquad \hat{P}\,|\theta\rangle = +1\,|\theta\rangle$$

$$\tau^+ \to \pi^+\pi^+\pi^- \qquad \hat{P}\,|\tau\rangle = -1\,|\tau\rangle$$

→under the idea of parity conservation: two different particles

problem: same spin, charge, mass and lifetime
adressed in 1953 by R.H. Dalitz as the τ-θ-puzzle [4]

Is parity conserved in weak interactions?

Lee and Yang pointed out that the τ-θ-puzzle could describe the **same** particle. [15]
→this leads to the assumption that the weak interaction violates parity conservation

in case of parity nonconservation:

- experimental states are mixture of usual and opposite parity ones
- the degree of mixing can be described by the fraction weight $\mathcal{F}^2$
- mixture would effect angular distributions of nuclear interactions

needs $\mathcal{F}^2$ to be small since selection rules worked, etc.
→so far no experimental prove for parity conservation in weak interactions

numerous possiblities to do so:

- angular distribution of β-decay between electron and nucleus
- $\beta - \gamma$-decays: polarization state of γ to the electron
- meson decays: e.g. strange Meson with non vanishing spin
- angular distribution for $\pi - \mu - e$ decay

Angular distribution studies

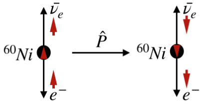
framework uses two sets of operartors, parity conserving and nonconserving ones, leads to:

- C coupling constant of parity conserving interaction
- $C^{'}$ coupling constant of parity nonconserving interaction
- $CC^{'}$ interference terms

previous measurements of β-decay quantities:
→didn't contain interference terms + ν spin needs to be measured to distinguish between C and $C^{'}$

angular distribution:
$I(\vartheta)\mathrm{d}\vartheta \propto (1+\alpha\cos\vartheta)\sin\vartheta\mathrm{d}\vartheta$
with α asymmetry coefficient (contains interference terms $CC^{'}$)

1) ϑ measured between oriented nuclei and emitted electron



2) ϑ measured between muon at rest and emitted electron
$\pi \rightarrow \mu + \nu$
$\mu \rightarrow e + \nu + \nu$
compare distributions for ϑ and $\pi - \vartheta$

The Wu Experiment
angular destribtion study for nucleus β-decay

Principle of the Wu experiment

carried out at the National Bureau of Standards (NBS) in Washington, D.C.

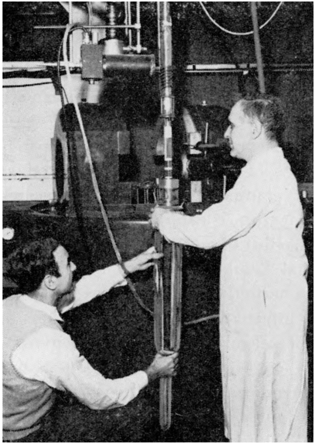
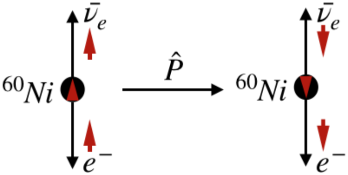


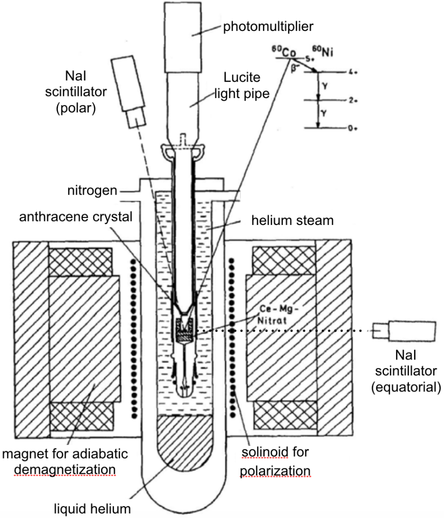
Abbildung: Picture of the experimental setup of the Wu

Principle of the measurement

- β-decay of a nucleus to verify if the weak interaction is chiral or not
- changing the direction of polarization of the nuclei is equivalent to a parity operation
- measure the angular distribution of the electrons →check if independent from the nucleus polarization



The experimental setup



Setup components

- anthracen crystall $\rightarrow \beta$ particle detection
- Lucite light pipe with photomultiplier
- two NaI gamma scintillator
- specimen: cerium magnesium nitrate crystal with vaporised layer of ^{60}Co
- cooling system $\rightarrow$helium (nitrogen), magnet (adiabatic demagnetization)
- solinoid $\rightarrow$polarization

difficulties

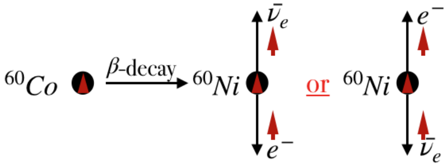
- anthracen crystal needs to be inside of the cryostat
- polarization of the nuclei

Selection of the right nucleus

There are two types of β decay

- **Fermi transition**: particles have antiparallel spin ($\Delta S = 0$)
- **Gamow-Teller transition**: particles have parallel spin ($\Delta S = 1$)

→if weak interaction is chiral only a Gamow-Teller transition
can prove that
→^{60}Co has a Gamow-Teller β decay



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

$$I_{z,Co} = I_{z,Ni} + I_{z,e} + I_{z,\nu} = 5$$

$$I_{z,Ni} = 4$$

$$I_{z,e} = I_{z,\nu} = \frac{1}{2}$$

Second benefit

- photons are emitted in the direction of the nucleus polarization
  →indicator of polarization degree
- controll of the polarization of the emitted electrons

Polarization of nuclei

nuclear moments can couple to an external field →aligns nuclear spin

→**problem**: surrounded by electrons $\mu_N \ll \mu_B$

nuclear Polarization factor according to M. E. Rose [16]:

$$f_N = \frac{1}{I} \frac{\sum m_i \exp - \frac{m_i \mu_N H}{k_B T I}}{\sum \exp - \frac{m_i \mu_N H}{k_B T I}}$$

$$\implies f_N \left(\frac{m_{Ni} = 4}{m_{Co} = 5} \right) \propto \exp - \frac{g \mu_N B}{k_B T}$$

at $T = 1\,\mathrm{K}$ and $B = 1\,\mathrm{T}$ is $\mu_N \propto \mathcal{O}\left(\frac{\mu_B}{1000}\right)$

→just enough to polarise the shell electrons, not the nucleus

requirements for the polarization

- strong magnetic field
- temperature close to absolute zero

Gorter-Rose method for nucleus polarization

- 1948: Gorter [8] and Rose [16] describe the possiblity of polarising a nucleus by adiabatic demagnetization process:

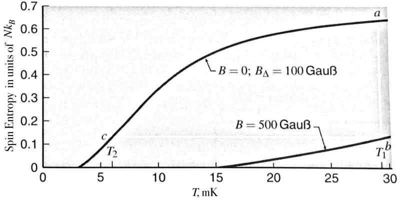


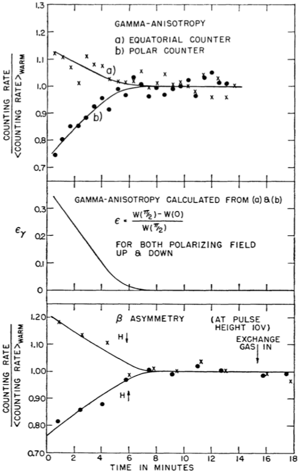
Abbildung: Principle of adiabatic demagnetization.[13]

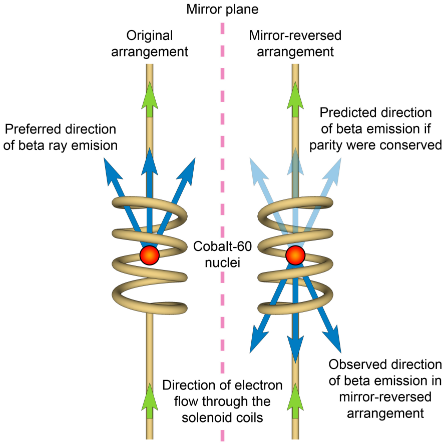
1. magnetic field reduses the entropy of the magnetic moments in the salt ($B_1 \sim 1$ T)
2. adiabatic isolation and switching off the magnetic field
3. entropy corresponds to a lower temperature →cooling to ~ 0.003 K

- small magnetic field B_2 vertical to cooling magnet (here solinoid) →polarization of the shell electrons causes ~ 1 T field →polaises the nucleus
- using CeMg nitrate with a high anisotropic Landé g-factor ($g_1 \ll g_2$)
- 1953: method successfully tested for ^{60}Co [1]

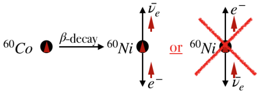
Results of the experiment

→60 % of the nuclei are polarised





observation



- asymmetry in the observed angular distribution of the electron for θ and $180^\circ - \theta$
- the observed β asymmetry matches exactly the observed gamma anisotropy

Results and cross checks

reminder

$I(\vartheta)\mathrm{d}\vartheta \propto (1+\alpha\cos\vartheta)\sin\vartheta\mathrm{d}\vartheta$
with α asymmetry coefficient (contains interference terms CC')

result

$\alpha \sim -0.4$ for a velocity of $\frac{v}{c} \approx 0.6$
→ β particle more favoured in opposite direction of nucleus spin

cross checks

1. check for remanent magnetization by reversal of the direction of the demagnetization field →no effect
2. check if a small magnetic field can cause the asymmetry (misalignment)→$CoCL_2$ solution on the bottom of the housing →disturbs cooling →no β asymmetry was seen
3. check if internal magnetic effects change the electron path to the surface →dissolve the crystal surface with the $CoCL_2$ solution →no β asymmetry was seen

Interpretation by Lee and Yang

The observed asymmetry in the angular distributions shows a maximum violation of parity conservation.
→the weak interaction is chiral

quote from the paper[19]

”According to Lee and Yang[14] the present experiment indicates
not only that conversation of parity is violated but also
that invariance under charge conjugation is violated.”

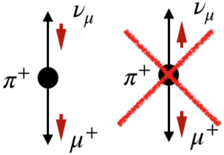
This was a false conclusion!
By the time it was believed that CP is also conserved, so if parity conservation is violated
→invariance under charge conjugation as well

The Columbia Experiment
angular destribtion study for $\pi^+ - \mu^+ - e^+$-decay

The Columbia experiment

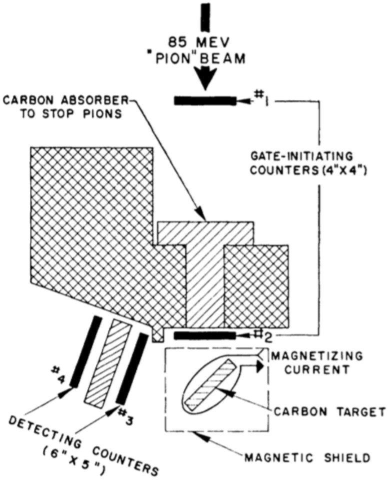
After Lee and Yang reported that the Wu experiment proved parity violation in a conversation L.M. Lederman, R.L. Garwin and his gradute student M. Weinrich examine the $\pi - \mu - e$ angular distribution [7]

concept:
if parity conservation is violated the muons are highly polarised:



electron spin is the same as the muon spin (conversation of momentum)
in this case they should measure asymmetric angular distributions for ϑ and $\pi - \vartheta$

The experimental setup



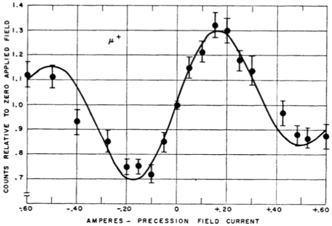
Setup components

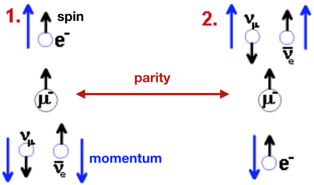
- 85 MeV pion beam provided by a cyclotron
- 20 cm carbon target to stop the pions
- 2.5 cm carbon target to stop the muons
- fast coincidence between counter 1 and 2 →stopped muons
- electron telescope out of counter 3 and 4 $(E_e\rangle$25 MeV)
- delayed coincidence between 1+2 and 3+4 →just muon decay electrons
- rectangular solinoid above the muon carbon target

Results

reminder

$I(\vartheta)\mathrm{d}\vartheta \propto (1+\alpha\cos\vartheta)\sin\vartheta\mathrm{d}\vartheta$
with α asymmetry coefficient (contains interference terms CC')
ϑ is measured between the muon velocity vector and the electron, assumption that the gyromagnetic ratio is $+2.00$





results:
large asymmetry was observed with $\alpha = -0.33 \pm 0.03$ from fit of $(1+\alpha\cos\vartheta)$
→shows again that parity and charge conservation is violated (same results where seen for μ^- decay)

Chronology of the discovery of parity violation

1925

1935

1928

Cox [3] and Chase [2] start studying double scattering of beta rays actuall first proof of parity violation

1933

Fermi and Pauli propose the β decay

1955

1958

1956

Yang gives a talk at a conference in April, Yang + Lee submit the paper parity violation in June

1957

early: Wu+Lederman publish their results on parity violation, later Telegdi + Friedman[6], late: Goldhaber experiment confirms that neutrinos are left-handed

1958

Sudarshan+Marshak/Feynman+Gell-Mann: develop V-A structure

Conclusion

- both experiments showed a high asymmetry in the angular distributions
- that shows that the electron and the muon are highly polarised
- prove that parity violation is maximal
- therefore the weak interaction must be chiral
- at this point it wasn’t proved that neutrinos are left-handed
  (later proved by the Goldhaber experiment)

Thank you for your attention.
Questions?

Literatur I

E. Ambler u. a. „Nuclear polarization of cobalt 60“. In: The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science 44.349 (1953), S. 216–218. DOI: 10.1080/14786440208520296.

C.T. Chase. „The scattering of fast electrons by metals. II. Polarization by double scattering at right angles“. In: Phys. Rev. Lett. 36 (1930), S. 1060–1065.

R. T. Cox, C. G. McIlwraith und B. Kurrelmeyer. „Apparent Evidence of Polarization in a Beam of β-Rays“. In: Proceedings of the National Academy of Sciences 14.7 (1928), S. 544–549. ISSN: 0027-8424. DOI: 10.1073/pnas.14.7.544.

R.H. Dalitz. „CXII. On the analysis of τ-meson data and the nature of the τ-meson“. In: The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science 44.357 (1953), S. 1068–1080. DOI: 10.1080/14786441008520365.

Richard P. Feynman. The Feynman Lectures on Physics, Vol.III. Adison-Wesley, 1965, S. 17–22.

J. I. Friedman und V. L. Telegdi. „Nuclear Emulsion Evidence for Parity Nonconservation in the Decay Chain $\pi^+ - \mu^+ - e^+$“. In: Phys. Rev. 105 (5 März 1957), S. 1681–1682. DOI: 10.1103/PhysRev.105.1681.2.

Literatur II

Richard L. Garwin, Leon M. Lederman und Marcel Weinrich. „Observations of the Failure of Conservation of Parity and Charge Conjugation in Meson Decays: the Magnetic Moment of the Free Muon“. In: Phys. Rev. 105 (4 Feb. 1957), S. 1415–1417. DOI: 10.1103/PhysRev.105.1415.

C.J Gorter. „A new suggestion for aligning certain atomic nucleï“. In: Physica 14.8 (1948), S. 504. ISSN: 0031-8914. DOI: https://doi.org/10.1016/0031-8914(48)90004-4.

David Griffiths. Introduction to Elementary Particles. Wiley-VCH, 2008, S. 136–145.

German Hacker. Die schwache Wechselwirkung - Die Paritätsverletzung. URL: https://www.solstice.de/grundl_d_tph/sm_ww/sm_ww_sch8a.html (besucht am 23. 10. 2019).

Ludmil Hadjiivanov. „Neutrino, parity violaton, V-A: a historical survey“. In: (2018). arXiv: 1812.11629 [physics.hist-ph].

Magdolna Hargittai. Credit where credit's due? URL: https://physicsworld.com/a/credit-where-credits-due/ (besucht am 22. 10. 2019).

Charles Kittel. Einführung in die Festkörperphysik. Oldenburg, 2002.

Literatur III

T. D. Lee, Reinhard Oehme und C. N. Yang. „Remarks on Possible Noninvariance under Time Reversal and Charge Conjugation“. In: Phys. Rev. 106 (2 Apr. 1957), S. 340–345. DOI: 10.1103/PhysRev.106.340.

T. D. Lee und C. N. Yang. „Question of Parity Conservation in Weak Interactions“. In: Phys. Rev. 104 (1 Okt. 1956), S. 254–258. DOI: 10.1103/PhysRev.104.254.

M. E. Rose. „On the Production of Nuclear Polarization“. In: Phys. Rev. 75 (1 Jan. 1949), S. 213–213. DOI: 10.1103/PhysRev.75.213.

Dietrich B. Wegener. Vorlesung Einführung in die Kern- und Elementarteilchenphysik. 2002.

Wikipedia. Wu experiment. URL: https://en.wikipedia.org/wiki/Wu_experiment (besucht am 21. 10. 2019).

C. S. Wu u. a. „Experimental Test of Parity Conservation in Beta Decay“. In: Phys. Rev. 105 (4 Feb. 1957), S. 1413–1415. DOI: 10.1103/PhysRev.105.1413.