Nuclear Physics
(5^{th} lecture)

Content

- **Parity violation in weak interaction, Wu experiment**
- **History of the neutrino, leptons' families. Leptonic charge**
- **Anti-neutrino detection (Reines-Cowan experiment)**
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- **Neutrino oscillation, and neutrino masses**

Parity non-conservation in beta decay

Parity was introduced first by E. Wigner in 1927, for describing symmetry of atomic quantum states against r → –r transformation.

Electromagnetic interaction conserves the parity
Strong interaction conserves the parity
It was assumed that the weak interaction also conserves the parity.

However, in 1956 T.D.Lee and C.N.Yang showed, that there was no experimental evidence for parity conservation in weak interaction. They explained the so called „tau-theta puzzle" assuming that parity is not conserved → Nobel-prize in 1957!

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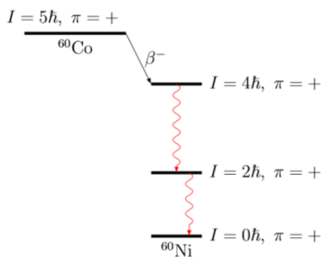
Question of Parity Conservation in Weak Interactions*

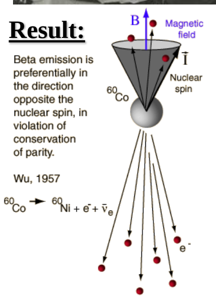
T. D. Lee, *Columbia University, New York, New York*
AND
C. N. Yang,† *Brookhaven National Laboratory, Upton, New York*
(Received June 22, 1956)

The question of parity conservation in β decays and in hyperon and meson decays is examined. Possible experiments are suggested which might test parity conservation in these interactions.

If parity is not conserved in weak interaction, this should be seen also in nuclear β–decay!
Experimental proof: C.S.Wu et al. (1957)



Result:



Polarized ^{60}Co source:
small temperature (~3 mK),
strong magnetic field

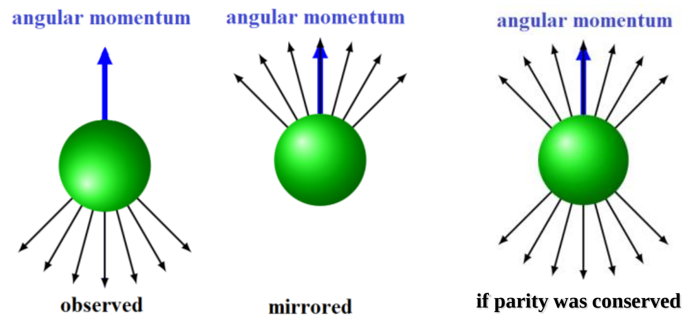
$$\frac{n_\uparrow}{n_\downarrow} = e^{-\frac{2\mu\mathbf{B}}{kT}}$$

$$(\mu\mathbf{B}) >> kT$$

http://hyperphysics.phy-astr.gsu.edu/hbase/quantum/imgqua/wu.gif

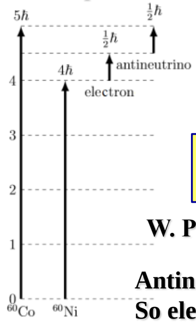
Why does this mean parity violation?

- **Direction of electrons: $\mathbf{p}$ (momentum): vector → –1 if mirrored**
- **Direction of angular momentum $\mathbf{J} = [\mathbf{r} \times \mathbf{p}]$: axial vector → +1 if mirrored**



Mirroring the coordinate axis is not a good symmetry!

Angular momenta in Wu experiment



Explanation of the parity violation (complete violation)

$$\varphi_\nu = \begin{pmatrix} \nu_\uparrow \\ \nu_\downarrow \\ \tilde{\nu}_\uparrow \\ \tilde{\nu}_\downarrow \end{pmatrix} \Longrightarrow \varphi_\nu = \begin{pmatrix} 0 \\ \nu_\downarrow \\ \tilde{\nu}_\uparrow \\ 0 \end{pmatrix}$$

Only right-handed antineutrinos (p↑↑s), and left handed neutrinos (p↑↓s) exist!

W. Pauli: „Cannot believe that God is left-handed!"

Antineutrinos have to fly in the direction of the $J = 5\hbar$!
So electrons have to fly in opposite direction (Σp ~0)

Consequence for the H_β operator:

$H_\beta = (\cancel{H_{\beta,S}} + H_{\beta,V}) + (H_{\beta,A} + \cancel{H_{\beta,T}})$

Fermi, G.T.

Finally, the interaction operator: $H_\beta = H_{\beta,V} + H_{\beta,A}$

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The story of the neutrino

Early history:

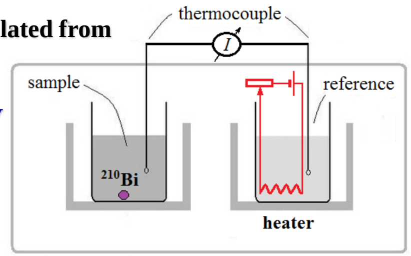
1914: Chadwick discovered the continuous energy spectrum of ^{214}Pb (RaB) using a magnetic spectrometer

Interpretation (Rutherford): monoenergetic electrons come out of the nucleus, but they loose energy in the matter

1927: Ellis and Wooster experiment: total energy released by ^{210}Bi (RaE) β–decays, measured by a differential calorimeter, that could stop all electrons inside.

E_0 = 1050 keV as calculated from the mass difference

$E_{measured}$ = 344±34 keV



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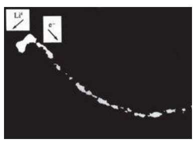
Not only energy was „missing"

$^{14}_{6}C \rightarrow ^{14}_{7}N + e^-$

J: 0 → 1 + ½ (??) **Angular momentum non-conservation?**



$^{6}He \rightarrow ^{6}Li + e^-$

Cloud chamber photo
S. Szalay & Gy. Csikai (Hungary)
Momentum non-conservation?

Ideas for the solution of the puzzle:

N. Bohr, J.C. Slater, L.D.Landau: conservation laws are not valid in microscopic scale, only statistically! (Hmm…)

1930: W. Pauli: hypothesis of the „neutron".
M<<M_{proton} , neutral, spin=1/2
„We will never detect it directly" (Pauli)

1933: E. Fermi renamed it „neutrino", after the discovery of Chadwick of the „massive" neutron (M~M_{proton})

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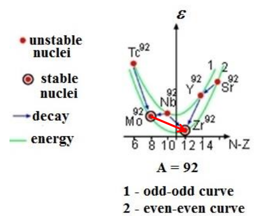
Double beta decay



^{92}Mo cannot beta-decay, since ^{92}Nb is „higher" in energy. However, the energy of ^{92}Zr is lower, so if the nucleus could „jump" ΔZ=2, then it was energetically favorable!

The ordinary double beta decay: $^{A}_{Z}X \rightarrow ^{A}_{Z+2}Y + 2e^- + 2\tilde{\nu}$

It may occur in certain even-even nuclei.

It has been observed at 35 isotopes, with $T_{1/2}$~10^{19}-10^{22} years

The neutrinoless double beta decay $^{A}_{Z}X \rightarrow ^{A}_{Z+2}Y + 2e^-$

It may occur only if the neutrino is its own antiparticle:

$^{A}_{Z}X \rightarrow ^{A}_{Z+1}K + \nu + e^-$
$^{A}_{Z+1}K + \nu \rightarrow ^{A}_{Z+2}Y + e^-$

The neutrino emitted in the first, will induce the second reaction

It has not been observed yet. $T_{1/2}$ >10^{25} years

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By that time it was known (Dirac) that fermions should have antiparticles. neutrino = antineutrino?

If no then we call them Dirac neutrino

If yes, we call them Majorana neutrino

Three „family" of the leptons

1936: C. D. Anderson: discovery of the muon (μ^-) (m_μ~200 m_e)

1962: Lederman, Schwartz, Steinberger: discovery of the μ-neutrino (Nobel-prize 1988)

1975: M. L. Perl (SLAC, USA): discovery of tau meson (m_τ~3500 m_e) (Nobel-prize: 1995)

2000: DONUT experiment (Fermilab, USA) discovery of tau neutrino

The lepton families (flavours)

Charged lepton	Mass	Neutral lepton	Mass
electron (e^-)	1 m_e	electron neutrino (ν_e)	?
muon (μ^-)	~200 m_e	muon neutrino (ν_μ)	?
tau meson (τ^-)	~3500 m_e	tau neutrino (ν_τ)	?

… + their antiparticles!

Leptonic charge

The lack of neutrinoless double beta decay (and many other processes) led to the discovery of leptonic charge conservation law

It was discovered by 3 physicists in the same year (1953) independently:

G. Marx (Hungarian) - 1953 January (published in German)
J. B. Zeldovich (Soviet) - 1953 July (published in Russian)
H.M. Mahmoud and
E.J. Konopinsky (USA) - 1953 November (published in English)

$$L = L_e + L_\mu + L_\tau$$

The „family" leptonic charge = 1 for the particles, -1 for the antiparticles, and 0 for the non-leptons.

A conservation law exists for the total leptonic charge!

(And for most reactions also for the family leptonic charge)

A few examples:

${}^A_Z X \rightarrow {}_{Z+1}^{A} Y + e^- + \tilde{\nu}$	Negative β–decay
$0 \rightarrow 0 + 1 + (-1)$	L_e
${}^A_Z X \rightarrow {}_{Z-1}^{A} Y + e^+ + \nu$	Positive β–decay
$0 \rightarrow 0 + (-1) + 1$	L_e
${}^A_Z X + e^- \rightarrow {}_{Z-1}^{A} Y + \nu$	Electron capture
$0 + 1 \rightarrow 0 + 1$	L_e
$\pi^- \rightarrow \mu^- + \tilde{\nu}_\mu$	Pion decay
$0 \rightarrow 1 + (-1)$	L_μ
$\mu^- \rightarrow e^- + \tilde{\nu}_e + \nu_\mu$	Muon decay
$0 \rightarrow 1 + (-1)$	L_e
$1 \rightarrow 0 + 0 + 1$	L_μ

Anti-neutrino detection (Reines-Cowan experiment)

Very small interaction probability ⇒ big amount of interacting particles, easy detection of the reaction products, low background

$$\tilde{\nu} + p \rightarrow n + e^+$$

water (~400 l)

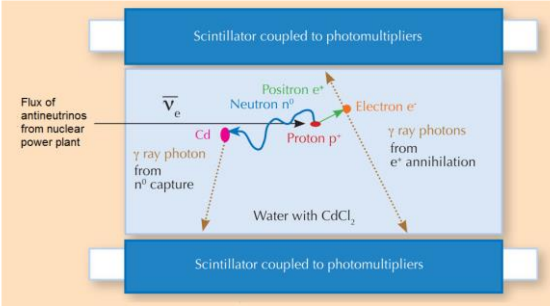
$$N \approx 6{,}6 \cdot 10^{22} \left[\frac{1}{\mathrm{cm}^3}\right]$$

nuclear reactor (Savannah River)
Many β^- decays from the fission products

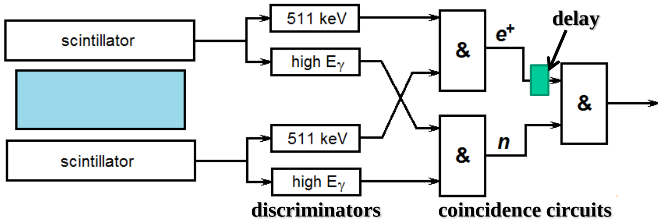
$$\phi \approx 10^{13} \left[\frac{1}{\mathrm{cm}^2 \mathrm{s}}\right]$$

Detecting $e^+ \rightarrow$ annihilation gammas (2 x 511 keV)

Detecting $n \rightarrow$ high energy gammas following n-capture in $CdCl_2$ Cd(n,γ) reactions



http://www.scienceinschool.org/repository/images/issue19neutrinos10_l.jpg



Results:
1953: 24 ±12 counts/h
1956: 2,88 ± 0,22 counts/h
1958: 36,4 ± 4 counts/h

$$\sigma_{\exp} = 1{,}2 \pm 0{,}5 \cdot 10^{-43}\ \mathrm{cm}^2$$
$$\sigma_{theory} = 1{,}0 \pm 0{,}17 \cdot 10^{-43}\ \mathrm{cm}^2$$

Nice agreement!! ☺

Neutrino detection (Davis experiment)

The Reines-Cowan method does not work!

$$\nu + n \rightarrow p + e^-$$

No target can be prepared!

Detecting e^- → not possible, electrons are everywhere

Detecting p → not possible, protons are everywhere

No source!

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B. Pontecorvo: use nuclei as target: $\nu + {}^A_Z X \rightarrow {}^A_{Z+1} Y + e^-$

Problem: big amount of *X* needed ⟷ few atoms of *Y* created
How to separate and detect?

***X* and *Y* must be very different chemically**

***Y* should be radioactive**

$$\nu + {}^{37}_{17}\mathrm{Cl} \rightarrow {}^{37}_{18}\mathrm{Ar} + e^-$$
$${}^{37}_{18}\mathrm{Ar} + \mathrm{e}^- \rightarrow {}^{37}_{17}\mathrm{Cl} + \nu \quad (\mathrm{T}_{1/2} = 35\ \text{days, } e^-\ \text{capture, EC})$$

Source: Sun $4\,{}^1_1\mathrm{H} \rightarrow {}^4_2\mathrm{He} + 2e^+ + 2\nu + 26{,}22\ \mathrm{MeV}$

Production rate: $\dfrac{1}{13{,}11\ \mathrm{MeV}} = 4{,}8 \cdot 10^{11} \left[\dfrac{1}{\mathrm{J}}\right]$

Solar constant: 1361 kW/m² = 136,1 J/(cm²s)

The neutrino flux then: $\phi = 4{,}8 \cdot 10^{11} \cdot 136{,}1 = 6{,}53 \cdot 10^{13}\ \dfrac{1}{\mathrm{cm}^2\mathrm{s}}$

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R. Davis, J. Bahcall
„Homestake" experiment
1957 – 1994
(Nobel-prize 2002)

1478 m underground!

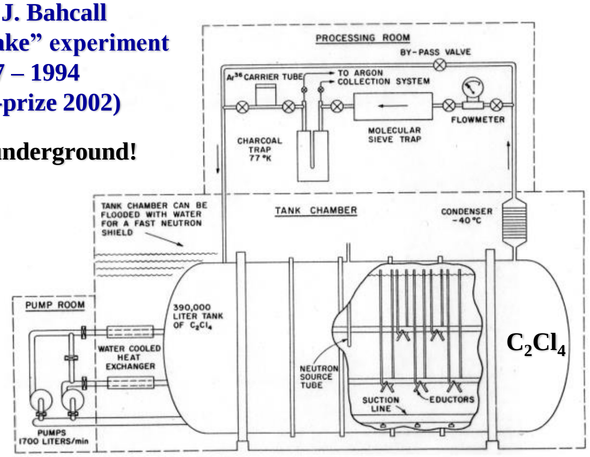

Figure 2.3. Schematic drawing of the argon recovery system. The pump-eductor system forces helium gas through the tetrachloroethylene liquid and provides the helium gas flow through the argon collection system.

http://www.bnl.gov/bnlweb/raydavis/images/hires/recovery_schematic.gif

R. Davis, J. Bahcall „Homestake” experiment

Results: 1 SNU = $10^{-36}\frac{1}{^{37}\mathrm{Cl}\cdot\mathrm{s}}$

Expected value ~ 9 SNU
Measured value ~ 3 SNU → **Solar neutrino puzzle**

Attempts to solve the puzzle:

- **Experimental error? NO! Several other neutrino experiments confirmed the results**
- **Error in the Sun model? (Pulsating Sun?)**
- **Neutrino oscillations? (Yeah!) ☺**

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Neutrino oscillation

Main idea: neutrinos have masses,
ν_e, ν_μ, ν_τ are NOT mass-eigenstates! (B. Pontecorvo 1957)
The weak interaction selects according to the „flavours”

Creation according to flavours → mixed mass state
Propagation → according to masses → mixing changes
Detection (Davis) → according to flavours again

$$\underset{\text{flavour eigenstates}}{\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}}=\underset{\text{MNS matrix (1962)}}{\begin{bmatrix}U_{1,1} & U_{1,2} & U_{1,3}\\ U_{2,1} & U_{2,2} & U_{2,3}\\ U_{3,1} & U_{3,2} & U_{3,3}\end{bmatrix}}\underset{\text{mass eigenstates}}{\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}}$$

flavour eigenstates **mass eigenstates**

MNS matrix (1962)
(Maki, Nakagawa, Sakata)

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Neutrino oscillation (contd.)

Simple example: 2 neutrinos $\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}=\begin{bmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{bmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$

The ν_e neutrino was created with p momentum at $t = 0$. **mixing „angle”**

Since $E_k=\sqrt{p^2c^2+m_k^2c^4}$

at t time we have: $|\nu\rangle=\exp\left(\frac{-iE_1t}{\hbar}\right)\cos\theta|\nu_1\rangle+\exp\left(\frac{-iE_2t}{\hbar}\right)\sin\theta|\nu_2\rangle$

The probability to detect a ν_e again after $L \sim c\cdot t$ distance:

$$P\left(t\approx\frac{L}{c}\right)=1-\sin^2 2\theta\cdot\sin^2\left[\frac{(E_2-E_1)L}{2\hbar c}\right]$$

Can be shown that: $\frac{(E_2-E_1)L}{2\hbar c}=1{,}27\frac{\Delta m^2L}{pc}$ **, where** $\Delta m^2=m_2^2-m_1^2$ **[eV]²**
L [m], pc [MeV]

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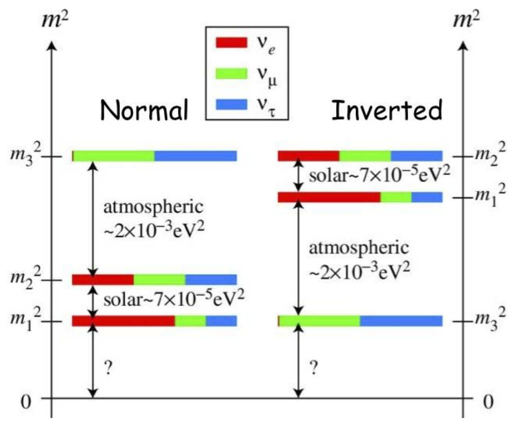
For 3 neutrinos obviously $\Delta m_{12}^2+\Delta m_{23}^2+\Delta m_{31}^2=0$



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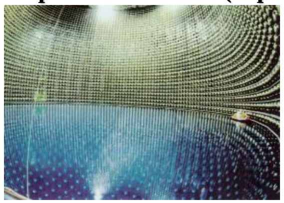
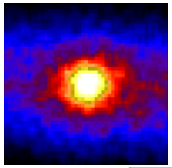
Neutrino oscillation (contd.)

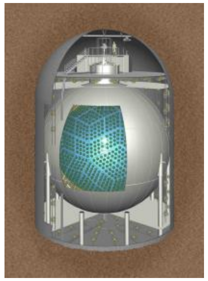
Several experiments confirmed

Super Kamiokande (Japan)



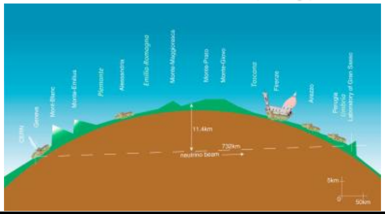
Sun picture taken with ν

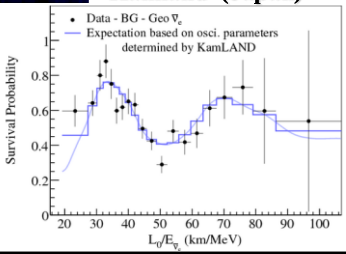




Kamland (Japan)

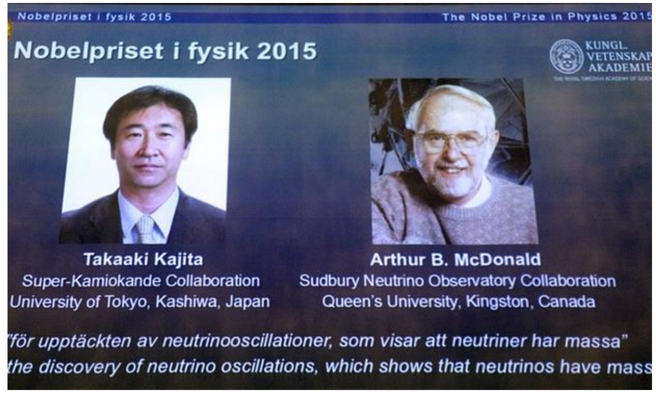
CERN to Gran Sasso (Italy)



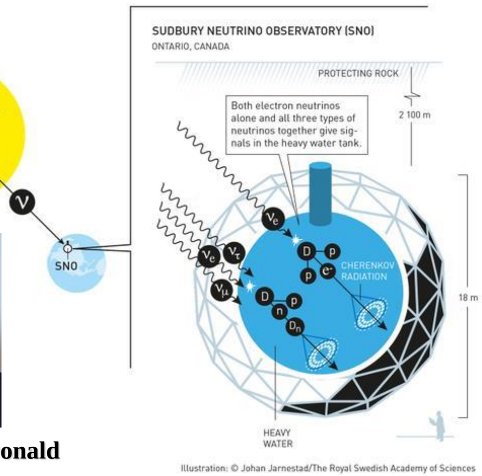


Nobel-prize in Physics 2015

„for the discovery of neutrino oscillations, which shows that neutrinos have mass"



Nobel-prize in Physics 2015



Arthur B. McDonald

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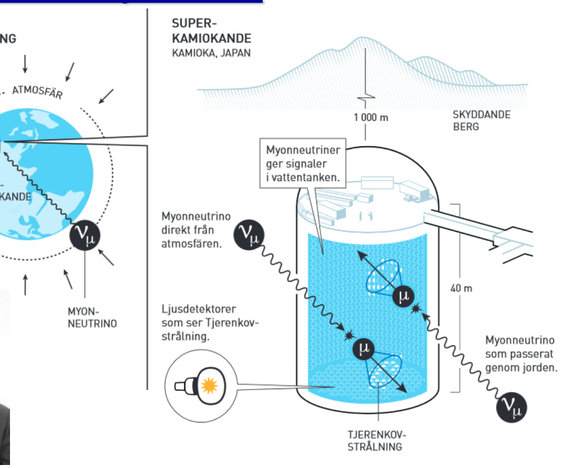
Nobel-prize in Physics 2015



Takaaki Kajita

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