Mysterious Neutrinos

Talk Historique at Higgs Hunting

(July 15 2025)

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A hundred years ago today

Werner Heisenberg was finishing his “Umdeutung” paper

(rec’d by Zeitschrift für Physik, July 29 1925)

(mail from Gottingen to Berlin?)

β Radioactivity 1900-1927

From H. Becquerel (1900) . . . to O. von Baeyer, O. Hahn, L. Meitner (1911)

experimentalists struggled to understand the β electron energy spectrum

expected β electrons to leave the nucleus with the same velocity

consistent with the observed exponential absorption of β electrons

"... the emission of beta rays from a radioactive substance is in most cases a very complicated phenomenon. If a ray falls on a photographic plate, a number of sharply marked bands are observed indicating that the rays are complex and consist of a number of homogeneous groups of rays, each of which is characterized by a definite velocity".

(Rutherford 1912)

In 1913, Rutherford sent his graduate student, J. Chadwick to Hans Geiger's lab in Berlin

Chadwick repeated von Baeyer's et al experiment with Radium,

using an ionization chamber and of course a Geiger counter

both methods yielded a number of discrete rays

on top of a continuous energy spectrum:

(Verh.Phys.Gessel. 16 (1914) 383-391)

unlike α-radiation, β-electrons leave nuclei with different velocities

this unexpected result by a graduate student deserved scrutiny

It was 1914, and Chadwick was interned for the duration

In 1922, Chadwick and R. D. Ellis repeated the 1914 experiment with the same result

Skeptics like Lise Meitner thought the observed complexity meant that

β-electrons interacted with orbital electrons on their way out of the atom

and/or even that energy was conserved statistically!

By 1925, R. D. Ellis and W. A. Wooster had answered these objections

Their 1927 comprehensive experiment convinced the skeptics

Once and for all: β -electrons leave nuclei with a continuous range of velocities

1930 Solvay Conference

"On Nuclear Magnetic Moments"
E. Fermi

Atoms consist of protons and electrons in equal numbers:

some "nuclear electrons" orbit within the nucleus

electron magnetic moments are much larger than nuclei's

how can it be since nuclei contain electrons?

- even number of nuclear electrons the magnetic moments cancel?
- odd number leaves one magnetic moment vanishes (e. g. Li_6 and N_{14})?

Pauli finds Li_6 "particularly interesting" because the odd magnetic moment vanishes

Nitrogen (14 protons and seven nuclear electrons) satisfies Fermi-Dirac statistics

An experiment found the Nitrogen nucleus to be a Boson

two months later, came the letter

Zurich, December 4, 1930

Dear Radioactive Ladies and Gentlemen,

As a bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, because of the "wrong" statistics of the the N-14 and Li-6 nuclei and the continuous beta spectrum, I have come upon a desperate remedy to save the "exchange theorem of statistics" and the laws of conservation of energy.

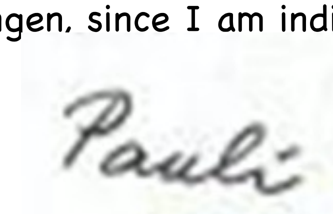
Namely the possibility that in the nuclei there could exist electrically neutral particles, which I will call neutrons, that have spin 1/2 and obey the exclusion principle and that further differ from the light quanta in that they do not travel with the velocity of light.

The continuous beta spectrum would then become understandable …

Now it is also a question of which forces act upon neutrons. For me the most likely model for the neutron seems to be, for wave-mechanical reasons (the bearer of these lines know more), that the neutron at rest's a magnetic dipole with a certain moment. The experiments seem to require that the ionizing effect of such a neutron can not be bigger than the one of a gamma-ray, and then is probably not allowed to be larger than e(10^{-13} cm).

I do not feel secure enough to publish anything about this idea … only those who wager can win.

Unfortunately, I cannot personally appear in Tübingen, since I am indispensable here on account of a ball…



The "neutron" was discovered not by experiments, but from Pauli's brain
to save a fundamental principle

treated with suspicion by most physicists

Not everything in the letter was right, but six months later at the Pasadena meeting, Pauli still asserted that "my little neutron is bound in the nucleus"

Things were about to change in 1932

Chadwick discovers a neutral particle inside nuclei, the Neutron

no need for nuclear electrons

Anderson discovers the positron, anticipated by Dirac

Pauli realizes that his little neutron (neutrino by Fermi) is a free particle

Tentativo di una Teoria dei Raggi β

Nota di ENRICO FERMI

"La Ricerca Scientifica", 4, (1933),491-495 1933

Based on the earlier "Nota preliminare in "La Ricerca Scientifica", 2, fasc, 1933",

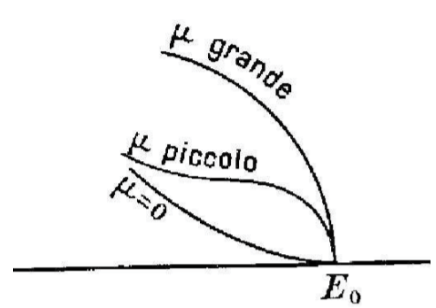
Fermi proposes a theory of beta decay, where electrons and neutrinos are described in the language that describes the emission of a light quantum from an excited atom.

No light particles in nuclei, and Heisenberg's two states of a heavy particle

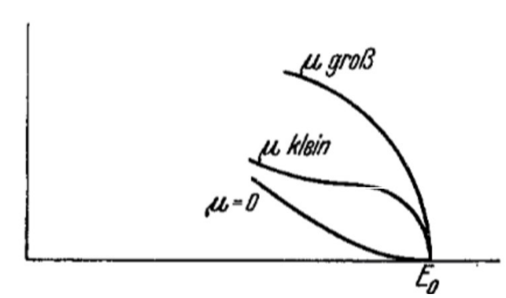
Hamiltonian is such that each transition from neutron to proton is associated with the creation of an electron and neutrino

"non può farsi altro che col criterio della massima semplicità"

("criterion of simplicity"/ "Einfacheitskriterion")



mass determination
From extreme kinematics



Topics: Nuclear Structure (Heisenberg), Gamow's drop model, neutron as (e-p) bound state, Majorana's exchange idea; Theory of the Positron (Dir negative energy states as holes in the (Dirac) sea

Rutherford: "I would have been happier if theory had followed after the experimental facts had been established"

Pauli: "This (Bohr's) hypothesis does not seem satisfactory nor plausible ... the electric charge is conserved and I do not see why charge conservation is more fundamental than energy and momentum"

Pauli: "it is possible that the neutrino mass is equal to zero, and the magnetic moment hypothesis now seems to me unrealistic"

"it is certain that the neutrino, if it exists, will be excessively difficult to detect" (Chadwick)

1936: Bethe-Bacher (Rev Mod Phys)

There is considerable but indirect evidence for the neutrino hypothesis

Neutrinos have to go through 10^{16} km of solid matter to cause inverse beta decay

Present methods must be improved by a factor 10^{13} in sensitivity before it could be detected

Neutrino/antineutrino capture by the nucleus together with emission of an electron/positron

1937 official symbol: neutrino n becomes ν

(L. H. Rumbaugh, R. B. Roberts, L. R. Hafstad)

TEORIA SIMMETRICA DELL'ELETTRONE
E DEL POSITRONE

Nota di ETTORE MAJORANA

(Il Nuovo Cimento 14, 171, 1937)

While developing a manifestly symmetric treatment of electrons and positrons

Majorana discovers a relativistic equation for neutral particles

without negative energy states

(the free Dirac operator is real for a special choice of matrices)

On Transition Probabilities in Double Beta-Disintegration

W. H. Furry

(Phys Rev 56, 1184, rec'd October 16, 1939)

Compares

Dirac-Fermi theory with emission of two electrons and two antineutrinos

Majorana's symmetrical theory with emission of only two electrons

$\beta\beta_{0\nu}$

("with much greater transition probability!")

INVERSE β PROCESSES

Bruno Pontecorvo

(Chalk River Report PD-205, 1946)

(Chalk River internal report PD141 in 1945 classified for twenty years)

"shows that the experimental observation of an inverse β process produced by neutrinos is not out of the question with the modern experimental facilities"

Suggests a method which might make an experimental observation feasible

$$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$$

which trades a neutrino for an Argon isotope (33.3 days half-life)

"nice but not practical" says Fermi

1948: H. R. Crane (Rev Mod Phys)

"Not everyone would be willing to say that

he believes in the existence of the neutrino,

but it is safe to say there is hardly one of us

who is not served by the neutrino hypothesis

as an aid in thinking about the beta-decay process"

1954 Ray Davis sets up a pilot experiment to

detect neutrinos à la Pontecorvo

$$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$$

Irradiate the cleaning fluid (CCl_4) with ^{37}Ar

Clean the cleaning fluid: CCl_4 out of ^{37}Ar

Brookhaven reactor neutrinos should generate ^{37}Ar

Finds no ^{37}Ar and sets a limit

"It is of interest to consider the possibility of detecting neutrinos from the Sun"

Reruns the experiment at the Savannah River reactor in 1957 again with no result

Project Poltergeist

1953 Detection of the Free Neutrino

C. L. Cowan Jr and F. Reines
(Phys Rev 92,830 (1953))

Hanford reactor $\nu + p \longrightarrow e^{+} + n$

- first flash: positron meets electron

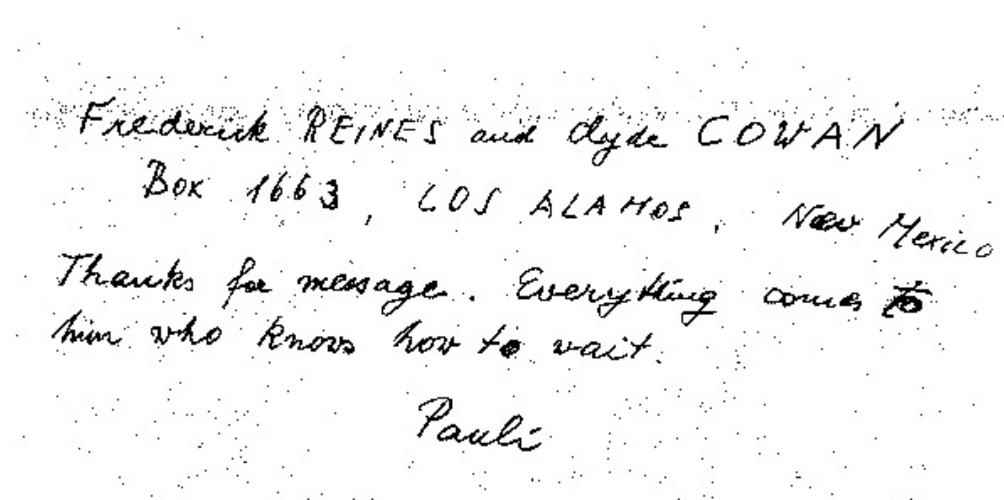
- second flash: neutron absorbed by Cd

1956 Detection of the Free Neutrino: a Confirmation

(Science, 124,3212 (1956))

Savannah River reactor

23 years later discovery!



Frederick REINES and Clyde COWAN
Box 1663, LOS ALAMOS, New Mexico
Thanks for message. Everything comes to him who knows how to wait.
Pauli

Helicity of Neutrinos

M. Goldhaber, L. Grodzins, A. W. Sunyar, 1957

Nucleus A_0 captures one of its electrons and decays
to an excited state of nucleus B^*_1 plus a neutrino

$$A_0 + e^- \longrightarrow B^*_1 + \nu$$

excited state of nucleus B decays to its ground state and emits a photon

$$B^*_1 \longrightarrow B_0 + \gamma$$

Photons which resonant scatter on B yield are aligned with the neutrino

$$\gamma + B_0 \longrightarrow B^*_1 \longrightarrow B_0 + \gamma$$

their circular polarization yields the (left-handed) neutrino helicity

one of the great table-top experiments

Had it run a year earlier, Golhaber's experiment would have

discovered parity violation in the weak interactions

Neutrinos became the center of attention among elementary particles

In 1964 André Lagarrigue proposed a freon bubble chamber

specifically designed to detect neutrinos and antineutrinos

Constructed here at Saclay, Gargamelle was shipped to CERN

where it discovered neutral current interactions

Inspired by oscillations in the neutral kaon system, Pontecorvo

(J. Exptl. Theoret. Phys. (U.S.S.R) 33, 549-551 (August 1957))

suggested an antineutrino from the reactor had oscillated to a neutrino

$$\bar{\nu} \longleftrightarrow \nu$$

Idea of neutrino-antineutrino oscillations born from a false rumor!

Z. Maki, M. Nakagawa, S. Sakata

(Prog Theo Phys 28, 870, (1962))

introduced an electron and a muon neutrino, ν_e , ν_μ

independently conserved electron and muon numbers

as linear combinations of mass eigenstates ν_1 and ν_2

causing a flavor "transmutation"/flavor oscillation

$$\nu_e \longleftrightarrow \nu_\mu$$

Lepton Mixing Matrix PMNS Matrix

In 1970 Ray Davis sets up the ^{37}Ar experiment

at the Homestake gold mine in Lead, SD

to count solar neutrinos

The Standard Solar Model anticipates 4.7 snu

(snu= 1 capture for 10^{36} ^{37}Cl atoms/second)

After eight years Davis measures only a third 1.7 ± 0.4 snu

Maybe ...

The Solar Model is wrong?

The counting is inaccurate?

The Sun has turned off? (W. Fowler)

Solar electron neutrinos are oscillating to?

MSW Effect 1978-1985

L. Wolfenstein

(Phys. Rev. D, 17, 2369-2374 (1978))

regeneration of K_S from a K_L beam passing through matter

even if neutrinos are massless oscillations occur when they pass through matter (coherent forward scattering)

oscillation length and mixing angles are affected

S. P. Mikheyev and A. Yu Smirnov

(Il Nuovo Cimento, 9, 17-25 (1986))

Three oscillation lengths:

L_v without matter, L_0 without masses and L_m (L_0, L_v) with matter

Resonance effect when $L_v = \sin 2\theta \, L_m$

Enhanced oscillations for the right parameters

IMB(1981) and Kamiokande(1982) underground experiments designed to test

proton decay, motivated by Grand-Unified theories

No proton decay except in 1987 when a train of eight neutrinos showed up

cosmic messengers from the 1987A Supernova

(nucleon decay becomes neutrino detection)

1996: The more powerful Super-Kamiokande detector comes on line

1998: measure a deficit of muon neutrinos inconsistent
with the atmospheric neutrino flux

Neutrinos have masses and flavor oscillate!

$$\nu_\mu \longleftrightarrow \nu_\tau$$

Sudbury Neutrino Observatory (SNO)

Hunts for solar neutrinos with a tank of heavy water monitored by phototubes, deep underground at Vale's Creighton nickel mine at Sudbury in Ontario

Funded in 1990, SNO is operating by 1999

Heavy water distinguishes charged and neutral currents processes

$$\nu_e + d \longrightarrow p + p + e$$

$$\nu_x + d \longrightarrow p + n + \nu_x$$

$$\nu_x + e \longrightarrow e + \nu_x$$

First results in 2001 are consistent with Homestake and Super-K

with a surprise view of the neutrino oscillation landscape

Atmospheric neutrino mixing angle $\sin\theta_{23} \approx 1/\sqrt{2}$

Solar neutrino mixing angle $\sin\theta_{12} \approx 1/\sqrt{3}$

Third neutrino mixing angle $\sin\theta_{13} \approx 0$

Reactor experiments with long baseline add precision

and measure the "reactor angle" θ_{13}

KamLAND (2001): Kamiokande from grid reactors (large angle)

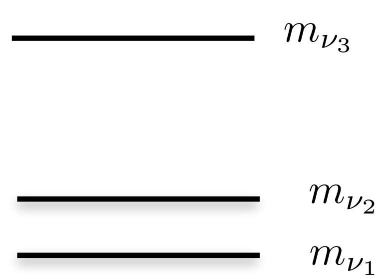
Chooz (2001): detector 1km from reactor puts upper bound on θ_{13}

Double Chooz (2011): with a second detector obtain θ_{13} value at 2.9σ

2012: Daya Bay and RENO determine θ_{13} at 5.2σ and 4.9σ

What we know today

$\sin^2\theta_{12} = 0.307 \pm 0.013$ $\sin^2\theta_{23} = 0.558 \pm 0.015$ $\sin^2\theta_{13} = .00219 \pm .0007$



$$\Delta^2_{32} = m_3^2 - m_2^2 = (2.455 \pm 0.028) \times 10^{-3}\ eV^2$$

$$\Delta^2_{21} = m_2^2 - m_1^2 = (0.0753 \pm 0.18) \times 10^{-3}\ eV^2$$

$$58.8 < \sum_i m_{\nu_i} < \ 63.34\ meV$$

Theorist's Musings

Large angles in neutrino mixings $\begin{pmatrix} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \\ \sqrt{\frac{1}{6}} & -\sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \end{pmatrix}$

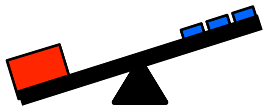
A tale of two scales

electroweak $m <<$ ultraviolet M

Dirac mass m $\begin{pmatrix} 0 & m \\ m & M \end{pmatrix}$ Majorana mass M

$$m\frac{m}{M} << M$$

Leptogenesis Matter asymmetry



"stupid little matrix"(M. G-M)

Thanks to all Neutrinophiles

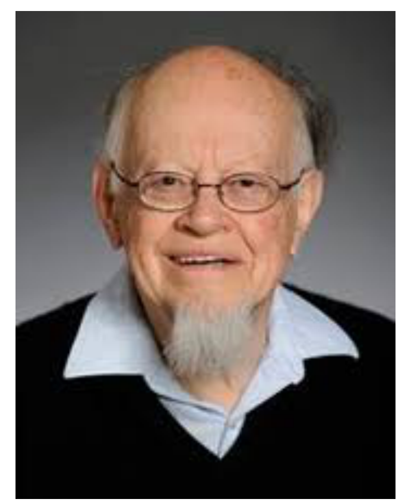
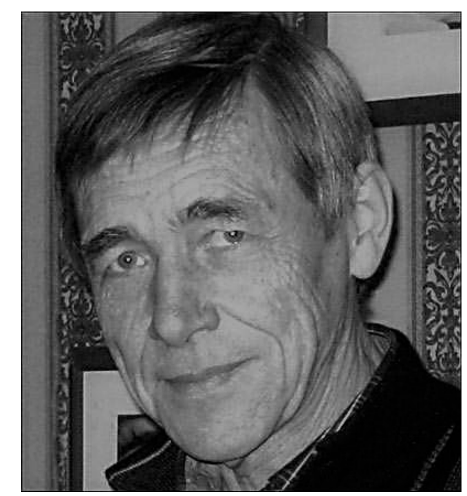

NAT·
MDCCC
XXXIII
OB·
MDCCC
XCVI
ALFR·
NOBEL











Some neutrino detectors

Super K

SNO

SUPER K

KamLAND

Kamioka Liquid scintillator Anti-Neutrino Detector

Gallex

T2K

Main
Injector
Neutrino
Oscillation
Search

DOUBLE CHOOZ

Daya Bay

θ_{13}

RENO

ν θ_{13}

KATRIN
Karlsruhe
Tritium
Neutrino
Experiment

NOvA

DUNE

Neutrino Chronology

	Invention	1930
2(13) yrs later	Detection	1956
2^2(17) yrs later	Oscillations	1998
2^3(19) yrs later	$\beta\beta_{0\nu}$ decay	2052

longevity required for

neutrino prospecting