Neutrino Physics

Neutrino physics is largely an art of learning a great deal by observing nothing

Haim Harari, 1988

Outline

1) Cenni storici (dalla scoperta della radioattivita' alla scoperta del neutrino tau)
2) Fasci di neutrini ed esperimenti per la loro rivelazione
3) Neutrini massivi, oscillazioni di neutrino a 2 e 3 sapori, l'effetto MSW e tipologie di esperimenti per la ricerca di oscillazioni di neutrino
4) Neutrini solari e KamLAND
5) Neutrino atmosferici
6) Esperimenti con neutrini prodotti ai reattori (CHOOZ e Paloverde) e ad acceleratori di media energia (LSND e KARMEN)
7) "Physics potential" dei futuri esperimenti per la ricerca di oscillazioni di neutrino: dal programma CNGS ai beta-beams
8) Metodi per la misura assoluta della massa del neutrino: decadimento beta, tempi di volo con neutrini prodotti da supernovae, decadimento doppio beta senza neutrini, osservazioni cosmologiche

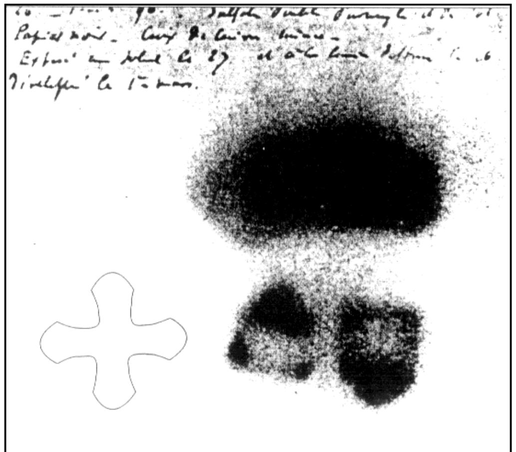
From the discovery of the radioactivity to the discovery of the neutrino

It is difficult to find a case where the word "intuition" characterises a human achievement better than in the case of the neutrino invention by Pauli

Bruno Pontecorvo, 1980

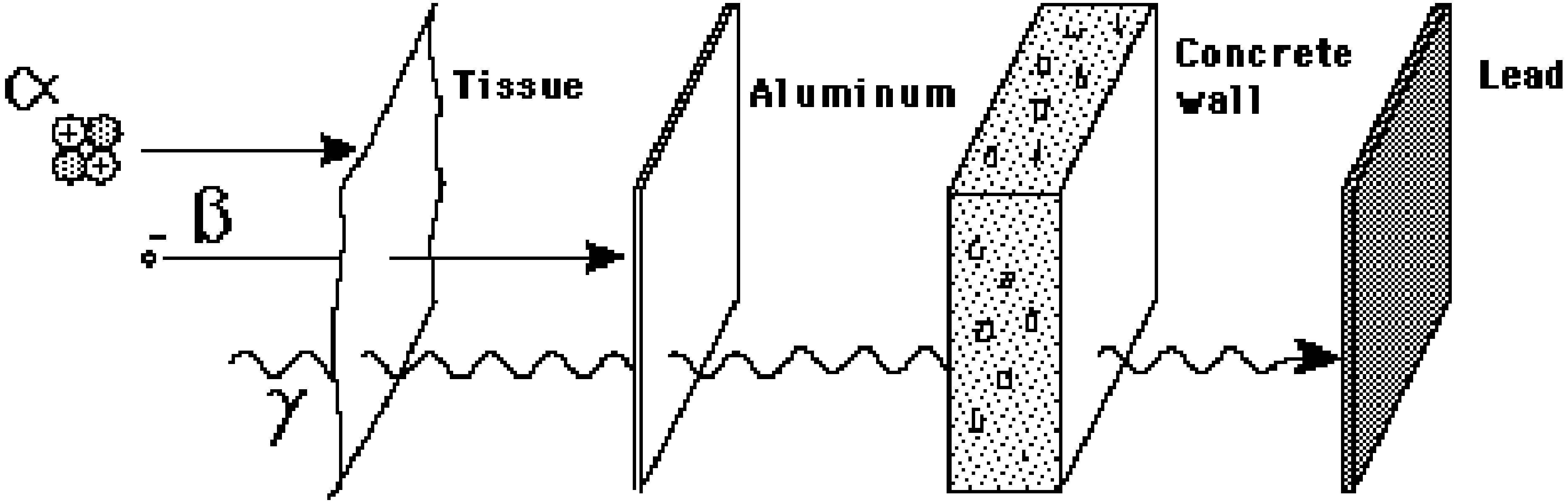
The discovery of the radioactivity

- ✓ In 1895 W. Roentgen discovered X-rays
- ✓ In 1896 H. Becquerel discovered “by chance” that uranium salts emit a new type of radiation (le rayon uraniques)
- ✓ In a series of experiments, from 1897-1902, Rutherford, Chadwick, Curie and Villard show that the emitted radiations are of three types: α radiation (helium nuclei), β radiation (electrons) and γ radiation (very energetic photons)



Une des plaques photographiques de Becquerel impressionnée, malgré le papier opaque à la lumière, par les rayons issus d'une des substances étudiées. On remarque en bas du cliché un « blanc » en forme de croix de Malte. C'est l'empreinte d'une croix de cuivre insérée entre la substance radioactive et le papier enveloppant la plaque. Le cuivre est donc opaque aux rayonnements.

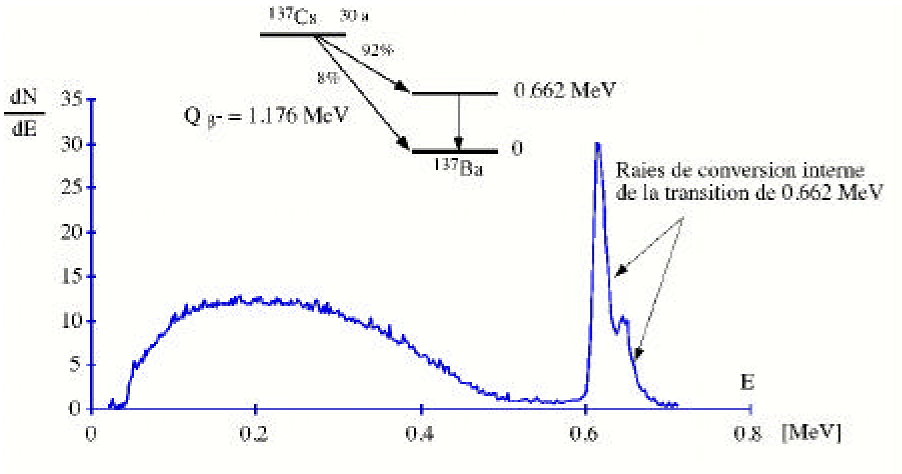
Penetrating power of “rayon uranique”



The continous β spectrum

At that time the common believe was that the electron is emitted alone in a β decay ⇒ mono-energetic electron

BUT several experiments confirmed the continous spectrum of electrons emitted in a β decay

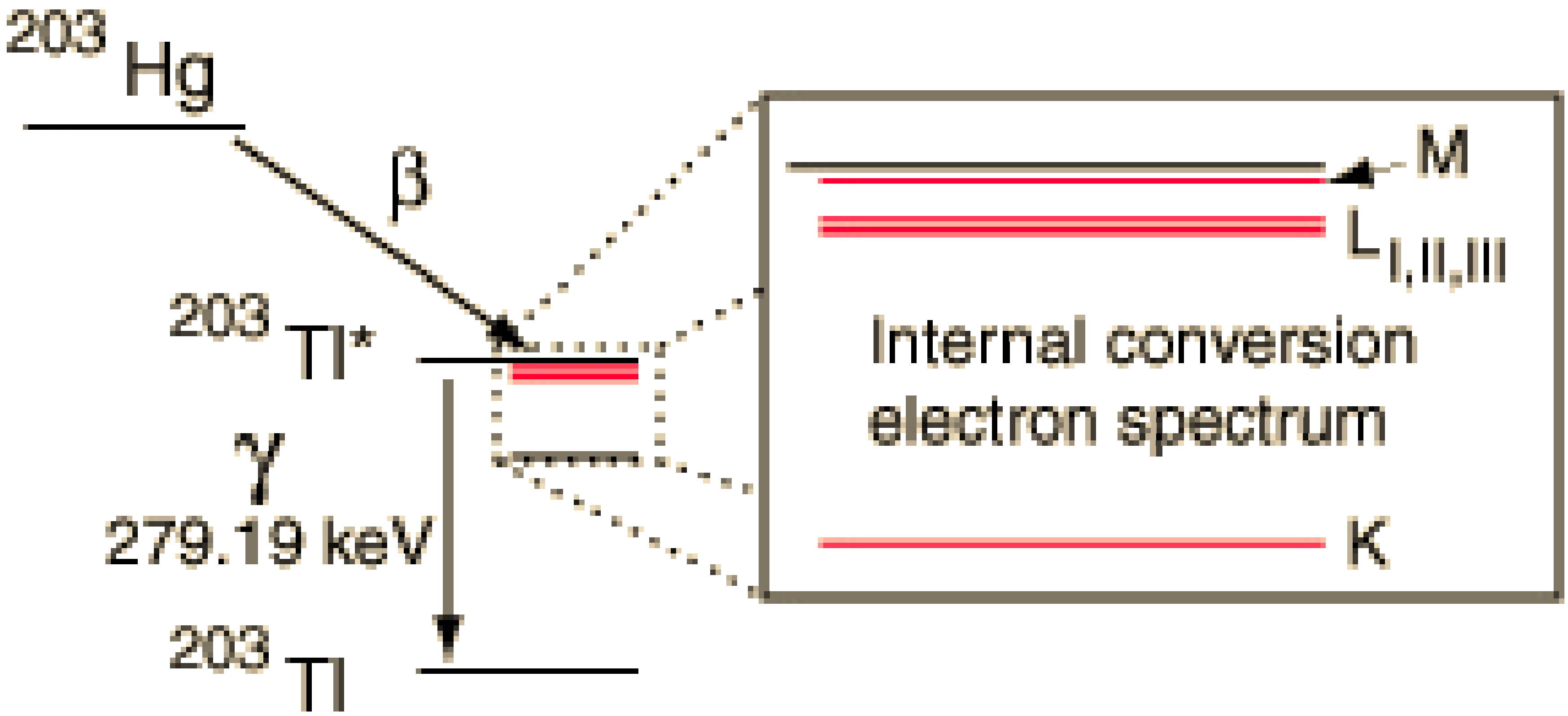


Spectre d'énergie des bêta mesuré à l'IPHE

Meitner theory:

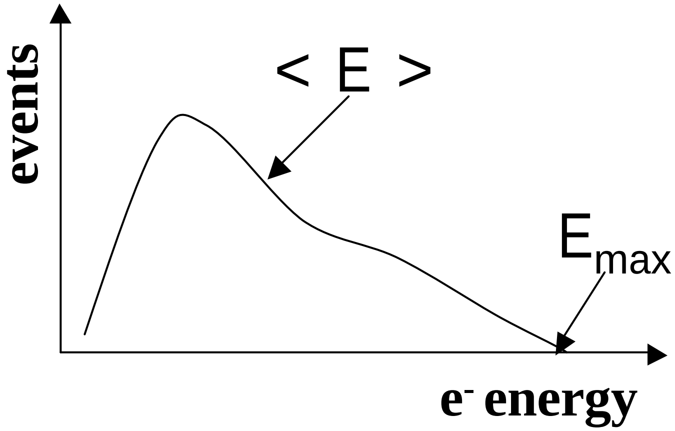
Electrons are emitted with a single energy, but velocities are modified by some "secondary causes"

Internal conversion e spectrum



A crucial experiment to solve the β spectrum puzzle

AIM measure the total energy associated with a single β decay



Two scenarios

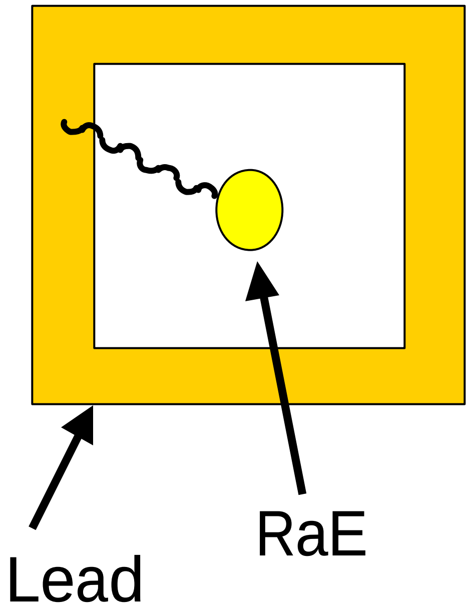
I. The electrons start with a unique energy and loose velocities by “secondary causes” ⇒ total energy=E_{max}
II. The electrons emerge with a whole range of energies ⇒after numerous decays one should measure < E >

Authors J. Ellis and W. Wooster

Ellis and Wooster experiment

Proc. Roy. Soc. (A) 117 (1927) 109

Principle measure the absolute heat in the absorption of e^-



A source of RaE was located inside a lead container and the absolute T measured

$$E_{meas}=0.344 \pm 0.034 \text{ MeV}$$

well below the maximum of the RaE β spectrum which is about 1MeV and consistent with its average value

The b spectrum is continous!

Two possible explanations for the continous β spectrum

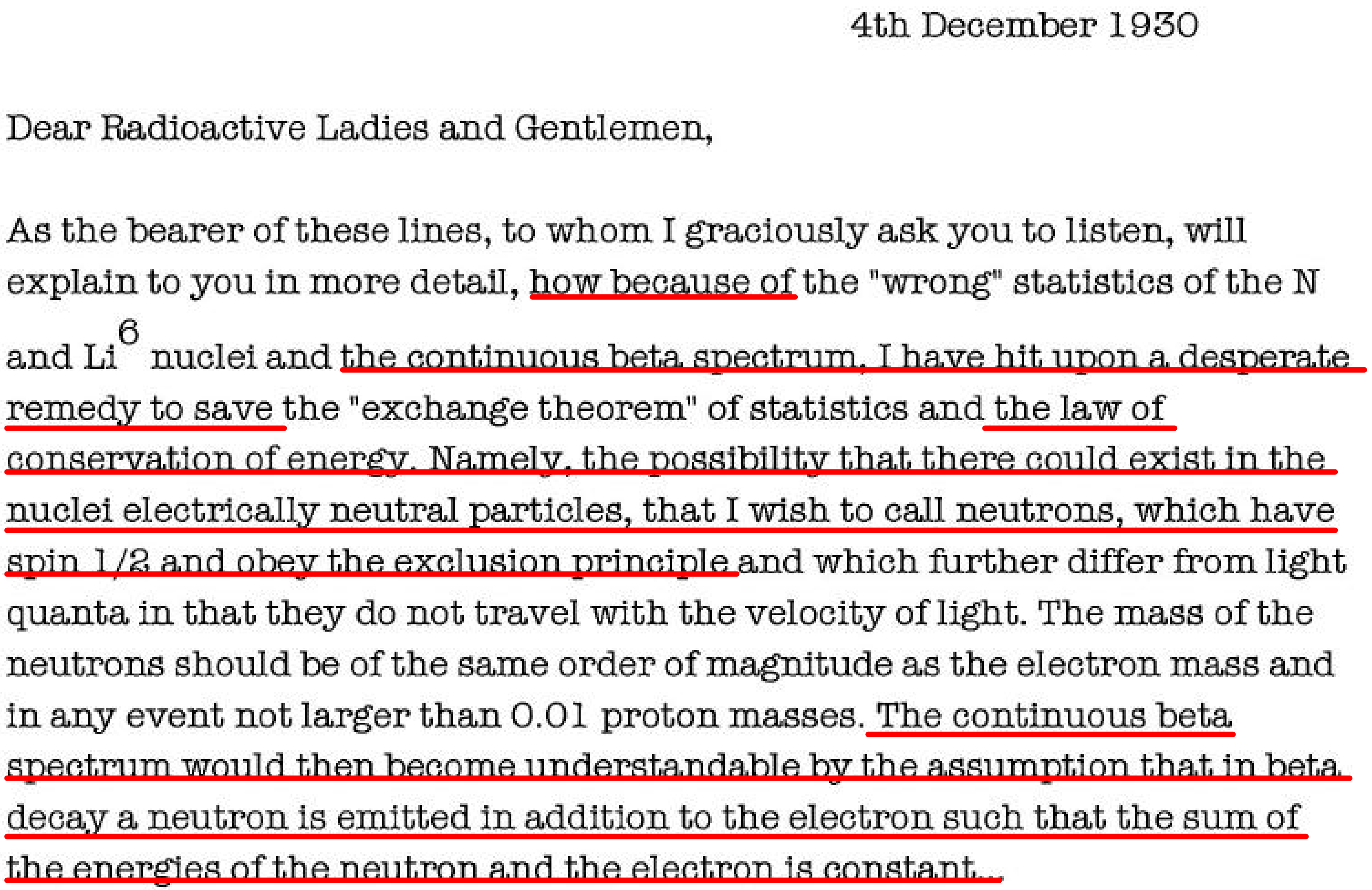
- ✓ **Niels Bohr** Non conservation of the energy

“… at the present stage of atomic theory, however, we may say that we have no argument, either empirical or theoretical, for upholding the energy principle in the case of β decay, are even led to complications in trying to do so. Of course, a radical departure from this principle would imply strange consequences…”

- ✓ **Wolfgang Pauli** “A desperate way out”

“… there could exist in the nucleus electrically neutral particles, which I shall call *neutronen*, which have spin ½ and satisfy the exsclusion principle and which are further distinct from light-quanta in that they move with light velocity. The mass of the *neutronen* should be of the same order of magnitude as the eelctron mass and in any case not larger than 0.01 proton mass. The continous β spectrum would then become understandable from the assumption that in β decay a *neutronen* is emitted along with the electron, in such a way that the sum of the energies of the *neutronen* and the electron is constant.”

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen



4th December 1930

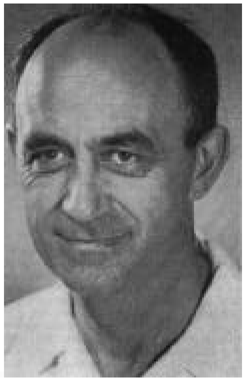
Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li^6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...

From the neutron discovery to the Fermi theory

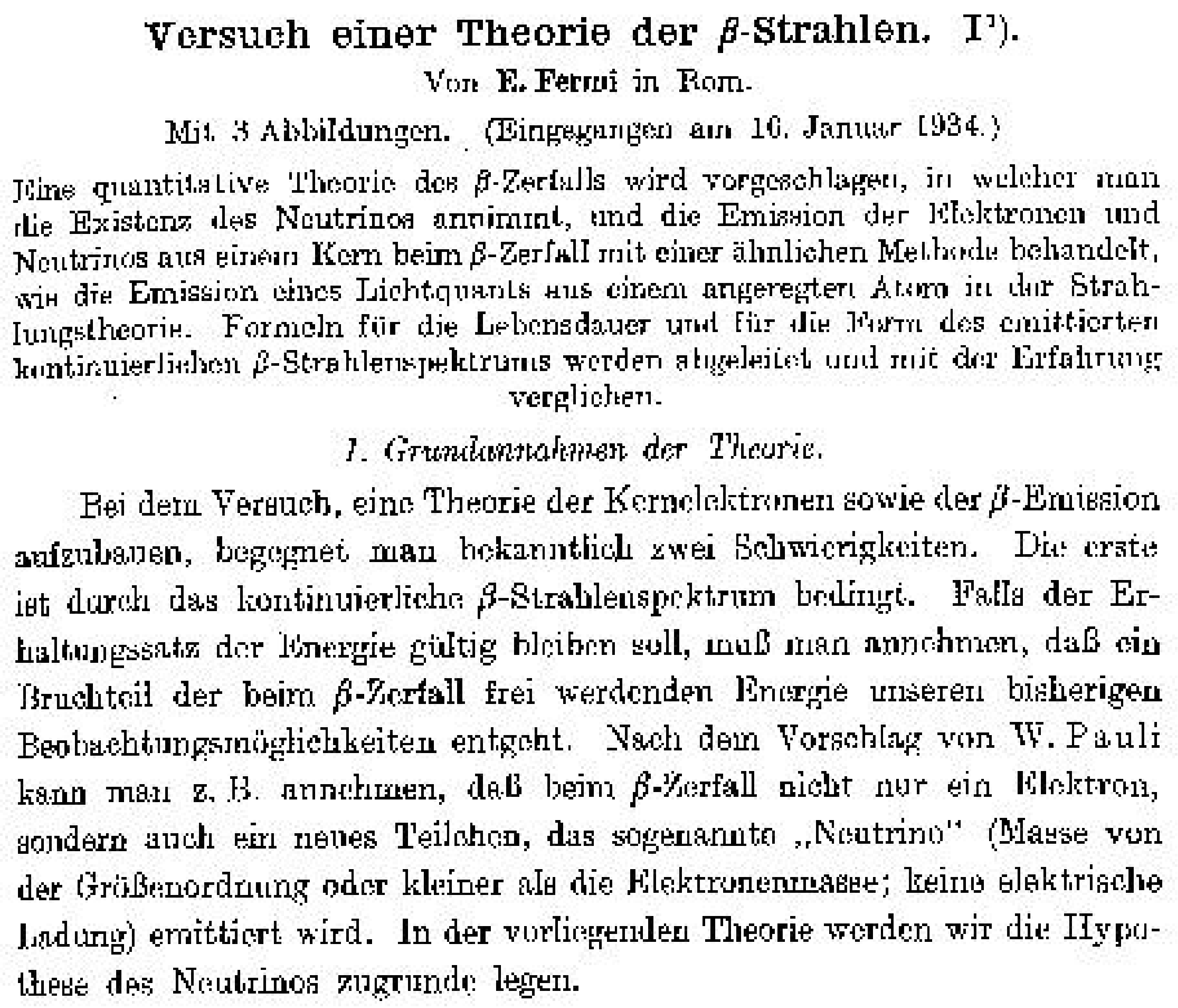
- ✓ In 1932 J. Chadwick discovered a new neutral particle, but too heavy to be identified with the *neutronen*
- ✓ Nevertheless it gave the hint to rethink the nucleus structure which was imagined as containing neutrons and protons
- ✓ If the *neutronen* is not the particle discovered by Chadwick, how to explain the β decay?
- ✓ In 1933 P.A.M. Dirac introduced, with the Quantum ElectroDynamics, the fundamental concept of creation and destruction of a particle

The Fermi theory of β decay



The basic assumptions of the Fermi theory (1933) are

- A neutral particle (called *neutrino* by Fermi) is emitted along with the e^- in β decay.
- The nucleus consists of protons and neutrons
- The total number of e^- and ν is not necessarily constant. Moreover he stated "… to every transition from neutron to proton is correlated the *creation* of an e^- and ν … Note that by this the conservation of the charge is assured…"
- Protons and neutrons might by simply different quantum states of the same basic particle **(Isospin hypothesis W. Heisenberg)**
- The *weak interaction* (the new force responsible for the β decay) is a contact interaction



Versuch einer Theorie der β-Strahlen. I[1]).

Von **E. Fermi** in Rom.

Mit 3 Abbildungen. (Eingegangen am 16. Januar 1934.)

Eine quantitative Theorie des β-Zerfalls wird vorgeschlagen, in welcher man die Existenz des Neutrinos annimmt, und die Emission der Elektronen und Neutrinos aus einem Kern beim β-Zerfall mit einer ähnlichen Methode behandelt, wie die Emission eines Lichtquants aus einem angeregten Atom in der Strahlungstheorie. Formeln für die Lebensdauer und für die Form des emittierten kontinuierlichen β-Strahlenspektrums werden abgeleitet und mit der Erfahrung verglichen.

1. Grundannahmen der Theorie.

Bei dem Versuch, eine Theorie der Kernelektronen sowie der β-Emission aufzubauen, begegnet man bekanntlich zwei Schwierigkeiten. Die erste ist durch das kontinuierliche β-Strahlenspektrum bedingt. Falls der Erhaltungssatz der Energie gültig bleiben soll, muß man annehmen, daß ein Bruchteil der beim β-Zerfall frei werdenden Energie unseren bisherigen Beobachtungsmöglichkeiten entgeht. Nach dem Vorschlag von W. Pauli kann man z. B. annehmen, daß beim β-Zerfall nicht nur ein Elektron, sondern auch ein neues Teilchen, das sogenannte „Neutrino" (Masse von der Größenordnung oder kleiner als die Elektronenmasse; keine elektrische Ladung) emittiert wird. In der vorliegenden Theorie werden wir die Hypothese des Neutrinos zugrunde legen.

Enrico Fermi, Zeitschrift für Physik, volume **88** (1934), page 161 ...

The Fermi lagrangian describing the β decay (I)

In analogy with the QED Fermi wrote the lagrangian of the β decay as

$$\mathcal{L}_\beta = \frac{G_\beta}{\sqrt{2}} \times J_h^w \cdot J_l^w = \frac{G_\beta}{\sqrt{2}} \times \left(\bar{\psi}_p \gamma_\mu \psi_n\right)\left(\bar{\psi}_e \gamma_\mu \psi_\nu\right)$$

G_β is the Fermi constant and replaces e^2

The hadronic current J^w_h induces the p→n transition, whereas the leptonic current J^w_l creates the (e^-, ν) pair from the vacuum

Bilinear covariants

The most general hamiltonian should include all the five scalar interactions corresponding to the following bilinear covariants

Scalar (S)	Vector (V)	Tensor (T)	Axial (A)	Pseudoscalar (P)
$\bar{\psi}\psi$	$\bar{\psi}\gamma^{\mu}\psi$	$\bar{\psi}\sigma^{\mu\nu}\psi$	$\bar{\psi}\gamma^{5}\gamma^{\mu}\psi$	$\bar{\psi}\gamma^{5}\psi$

where $\psi = \begin{pmatrix} \varphi \\ \frac{\vec{\sigma}\cdot\vec{p}}{2M}\varphi \end{pmatrix}$

(neglecting the normalization)

In general

$\bar{\psi}\Gamma^{i}\psi$ with i = S, V, A, T, P

Non-relativistic limit of bilinear covariants

$$\psi = \begin{pmatrix} \varphi \\ \frac{\vec{\sigma}\cdot\vec{p}}{2M}\varphi \end{pmatrix} \xrightarrow{p\to 0} \begin{pmatrix} \varphi \\ 0 \end{pmatrix}$$

Scalar (S)

$$\psi^{+}\psi$$

Vector(V)

$$\psi^{+}\psi \quad \mu=0$$

$$0 \quad \mu=1,2,3$$

Tensor (T)

$$\psi^{+}\sigma^{k}\psi \quad k=1,2,3$$

Axial (A)

$$0 \quad \mu=0$$

$$-\psi^{+}\sigma^{k}\psi \quad \mu=k=1,2,3$$

Pseudoscalar (P)

$$0$$

- ➢ S and V terms do not change the spin (no σ)
- ➢ T and A terms do change the spin (σ)
- ➢ P term gives not contribution in the n.-r. limit

The Fermi lagrangian describing the β decay (II)

The Fermi L_β contained only a V term ⇒ only ΔJ=0 transitions are allowed (Fermi transitions)
These transitions were observed and, in principle, could be explained by the S term as well!
Moreover ΔJ=±1 transitions (Gamow-Teller transitions) were also observed ⇒ T and/or A terms should also be considered

The most general lagrangian is

$$\mathrm{L}_b = \frac{G_b}{\sqrt{2}} \times \sum_i \left(\overline{y}_p \Gamma_i y_n\right)\left(\overline{y}_e \Gamma^i y_n\right)$$

The Kurie plot(I)

In the perturbation theory, at the first order, the transition probability from a given quantum state to another is written

$$\lambda = \frac{2\pi}{\hbar}\left|\langle \psi_f | H | \psi_i \rangle\right|^2 \rho(E)$$

where ρ(E) is density of final states.

For allowed transitions (being $|M_0|^2$ the matrix element)

$$\lambda = \frac{2\pi}{\hbar} G_F^2 \left|M_0\right|^2 \frac{dN_b}{dE_0} \quad \text{being } \rho(E) = \frac{dN_b}{dE_0}$$

The Kurie plot(II)

$$\frac{dN_b}{dE_0}$$

is the number of ways the maximum available energy E_0 is shared between the particles involved in the decay

It can be demonstrated that the β yield is

$$N_b(p)dp \propto p^2\left(E_0 - E\right)^2 dp$$

Kurie plot

The square root of the b yield is linear with E!

First calculation of νp cross-section

✓ In 1934 Bethe and Peierls computed for the first time the cross-section for the process

$$n + p \rightarrow n + e$$

For 2 MeV: $\sigma \approx 10^{-44}$ cm^2!

> I have done a terrible thing, I have postulated a particle that cannot be detected
>
> Wolfgang Pauli

The parity non conservation hypothesis

- ✓ A giant step in understanding weak interactions came in 1956 when T.D. Lee and C.N. Yang pointed out that there was no evidence in favour of parity conservation in weak interactions
  - They were brought to this hypothesis by studying the so-called θ-τ puzzle of the K decay. Namely the same particle may decay in 2π or 3π final states which have different parity!
- ✓ They proposed several experiments which should show parity violation effects
  - We will study the experiment performed by C.S. Wu and Collaborators in 1957

Some definitions...

Let us consider a parity transformation

$x \rightarrow -x'$ $y \rightarrow -y'$ $z \rightarrow -z'$ (reflection)

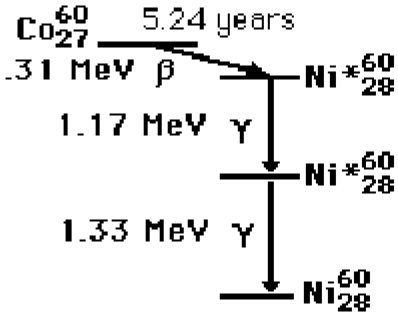
- ✓ Given the vectors **A**(x,y,z) and **A'**(x,y,z)
  - if $x = -x'$, $y = -y'$ and $z = -z'$ ⇒ **A** is a polar vector
- ✓ **L**=**r**×**p** (angular momentum) **r** and **p** are polar vectors
  - if $L_x = L_x'$, $L_y = L_y'$ and $L_z = L_z'$ ⇒ **L** is an axial vector
- ✓ **p•p** and **L•L** do not change sign under parity transformation
  - ⇒ **p•p** and **L•L** are scalars
- ✓ **L•p** does change sign under parity transformation
  - ⇒ **L•p** is a pseudoscalar

The results of an experiment is always a number (scalar or pseudoscalar)

↓

The observation of pseudoscalars different from 0 implies that parity conservation is violated!

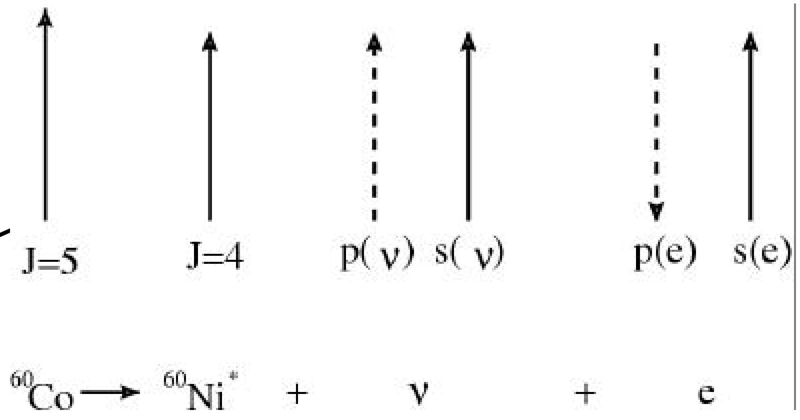
The discovery of parity violation (I)



Cobalt-60

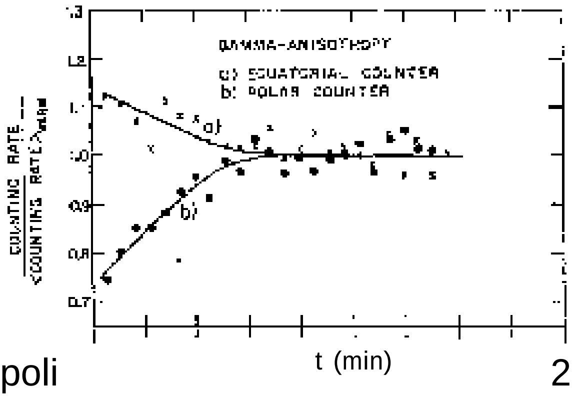
C.-S. Wu and Collaborators studied parity conservation in β-decay by using ^{60}Co at 0.01°K inside a solenoid.

The β-decay with the relative spin configuration is shown in



The ^{60}Ni* immediately decay through two consecutive γ emissions

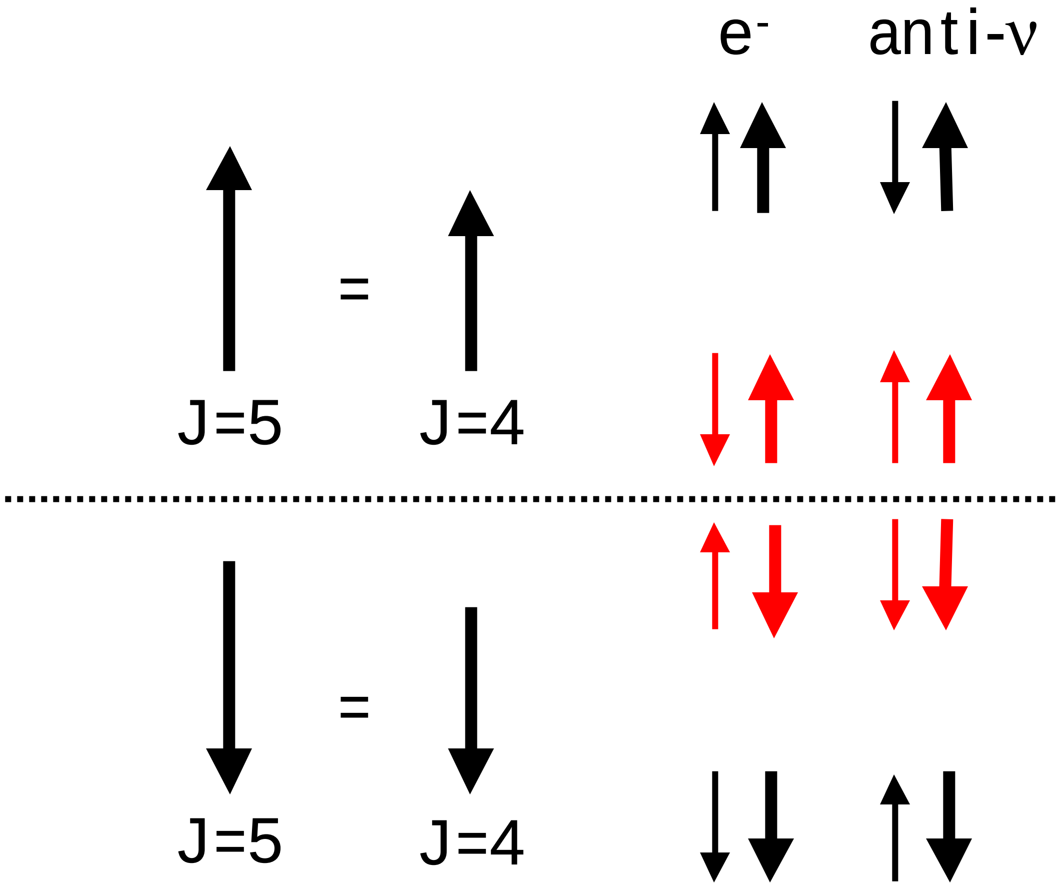
The γ anisotropy gives a measurement of the degree of the ^{60}Co polarisation

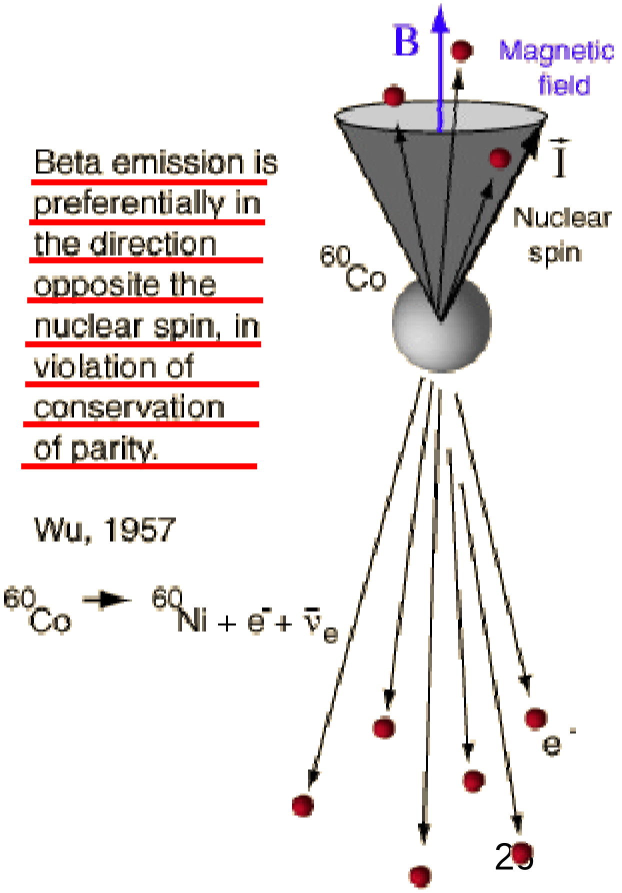


The discovery of parity violation (I I)

(Schematic result of the experiment)

The observed configurations are shown in red





Beta emission is preferentially in the direction opposite the nuclear spin, in violation of conservation of parity.

Wu, 1957

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

The discovery of parity violation (III)

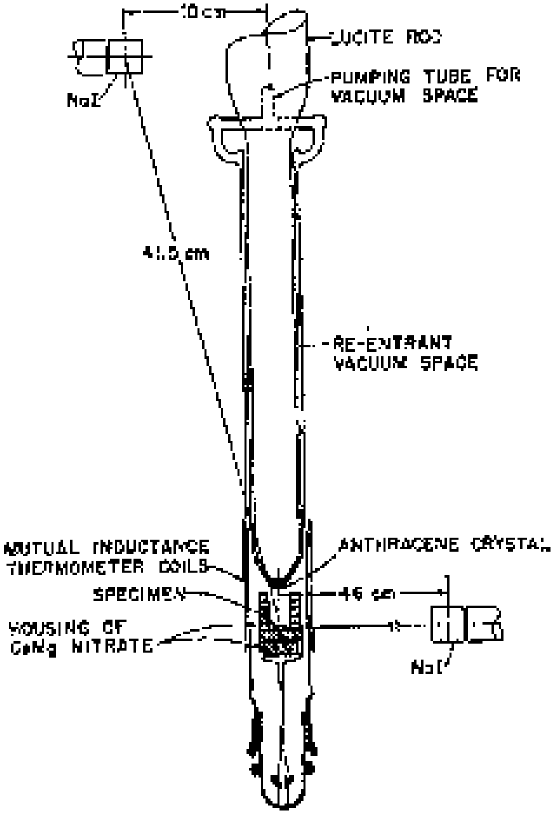


FIG. 1. Schematic drawing of the lower part of the cryostat.

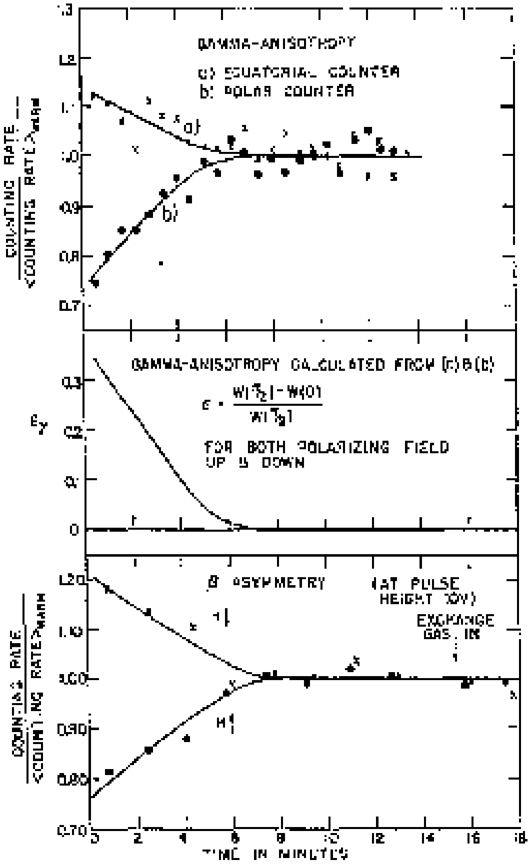


FIG. 2. Gamma anisotropy and beta asymmetry for polarizing field pointing up and pointing down.

About the weak lagrangian (I)

The most general lagrangian that can be written in the case of parity violation is

$$L_\beta = \frac{G_\beta}{\sqrt{2}} \times \sum_i \left(\overline{\psi}_p \Gamma_i \psi_n\right)\left(\overline{\psi}_e \Gamma^i \left(C_i + C_i' \gamma^5\right)\psi_\nu\right) =$$

$$\frac{G_\beta}{\sqrt{2}} \left\{ \begin{array}{l} \overline{\psi}_p \psi_n \overline{\psi}_e \left(C_S + C_S' \gamma^5\right)\psi_\nu + \overline{\psi}_p \gamma_\mu \psi_n \overline{\psi}_e \gamma^\mu \left(C_V + C_V' \gamma^5\right)\psi_\nu \\ + \overline{\psi}_p \sigma_{\mu\nu} \psi_n \overline{\psi}_e \sigma^{\mu\nu} \left(C_T + C_T' \gamma^5\right)\psi_\nu + \overline{\psi}_p \gamma^5 \gamma_\mu \psi_n \overline{\psi}_e \gamma^5 \gamma^\mu \left(C_A + C_A' \gamma^5\right)\psi_\nu \end{array} \right\}$$

C_i and C_i' are coefficients that, in general, are functions of q^2. However, q^2 is small in these processes, so that C_i and C_i' can be taken as constants

About the weak lagrangian (II)

Experiments measuring the electron polarisation showed that it is largely polarised. Furthermore, they gave the following relations among coefficients

$C_S' = C_S$ $C_V' = -C_V$ $C_T' = C_T$ $C_A' = -C_A$

$$L_\beta = \frac{G_\beta}{\sqrt{2}} \left\{ \begin{array}{l} C_S \bar{\psi}_p \psi_n \bar{\psi}_e \left(1+\gamma^5\right)\psi_\nu + C_V \bar{\psi}_p \gamma_\mu \psi_n \bar{\psi}_e \gamma^\mu \left(1-\gamma^5\right)\psi_\nu \\ + C_T \bar{\psi}_p \sigma_{\mu\nu} \psi_n \bar{\psi}_e \sigma^{\mu\nu} \left(1+\gamma^5\right)\psi_\nu + C_A \bar{\psi}_p \gamma^5 \gamma_\mu \psi_n \bar{\psi}_e \gamma^5 \gamma^\mu \left(1-\gamma^5\right)\psi_\nu \end{array} \right\}$$

Comments

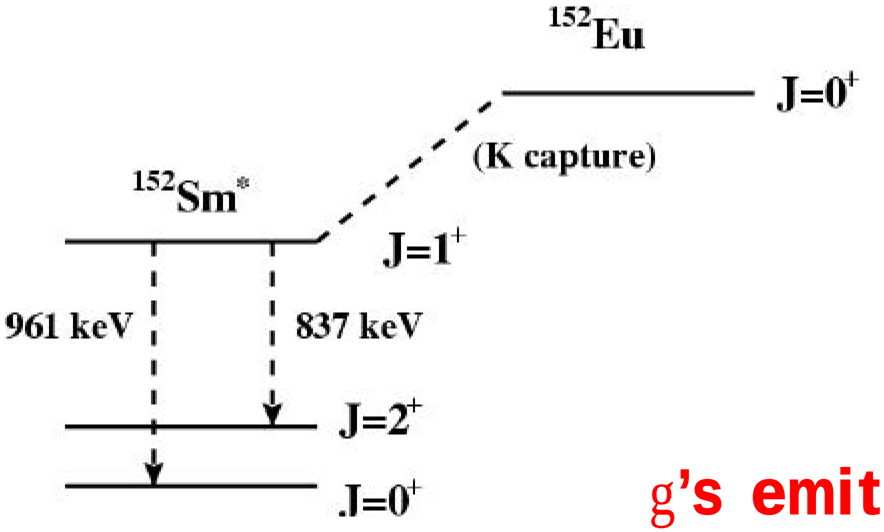
- ✓ ν enters in the L with the form $(1+\gamma^5)\Psi_\nu$ for S and T, but $(1-\gamma^5)\Psi_\nu$ for V and A. This means that ν is right(left)-handed for S and T (V and A)
- ✓ The electron always enters with the form $\overline{\Psi}_e(1+\gamma^5)$

The helicity of the n
has to be measured

The helicity of the ν is measured

(M. Goldhaber et al. 1957)

$$^{152}Eu(J=0^{+})+e^{-}(\text{from K shell})\rightarrow {}^{152}Sm^{*}(J=0^{+})+n$$

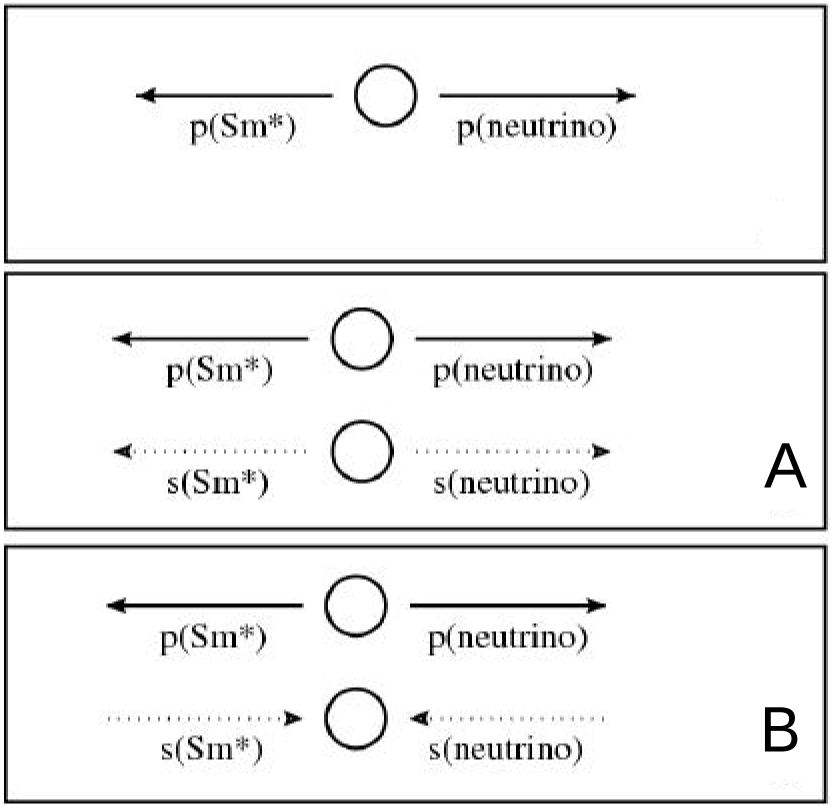


✓ ^{152}Eu undergoes to e capture and transforms into ^{152}Sm*

✓ This state immediately decays emitting two γ's (see figure for the full decay chain)

g’s emitted along the nucleus recoil have higher energy (Doppler effect)

…ctd

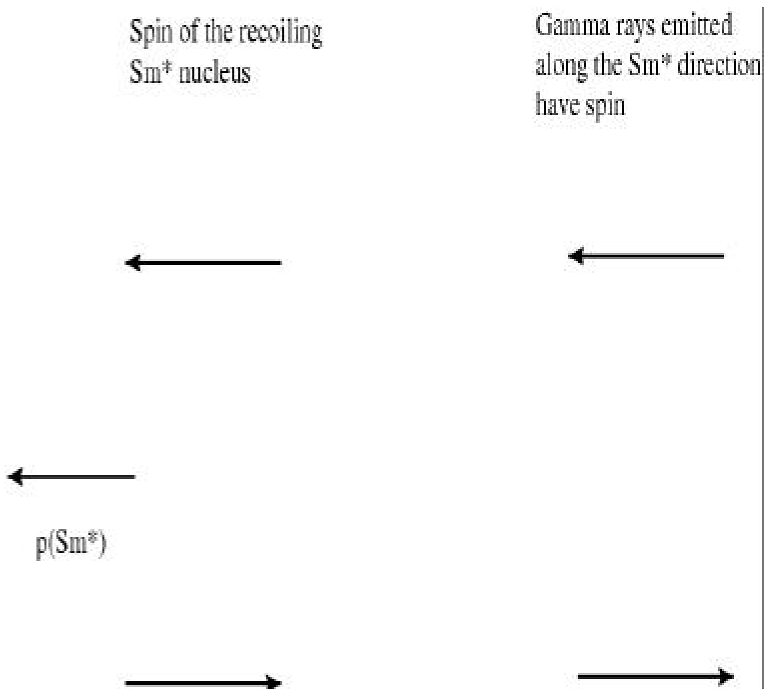


In the nucleus reference system the $^{152}Sm^{*}$ and the ν are emitted in opposite direction

Being the initial angular momentum J=0, the momentum conservation principle implies that the spin is conserved

Two possible scenarios A & B

… ctd



- ✓ Since the γ has spin 0 as well as the ground state of Sm, the γ polarisation reflects the Sm spin orientation
- ✓ The nucleus recoiling direction can be determined by Doppler effects

⬇

By measuring the polarisation of γ emitted along the Sm recoil direction the ν helicity can be measured (see previous transparency)

The apparatus

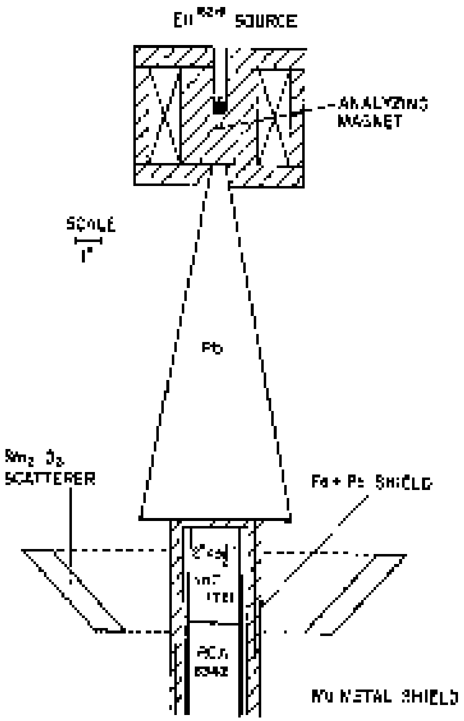


FIG. 1. Experimental arrangement for analyzing circular polarization of resonant scattered γ-rays. Weight of Sm$_2$O$_3$ scatterer: 1850 grams.

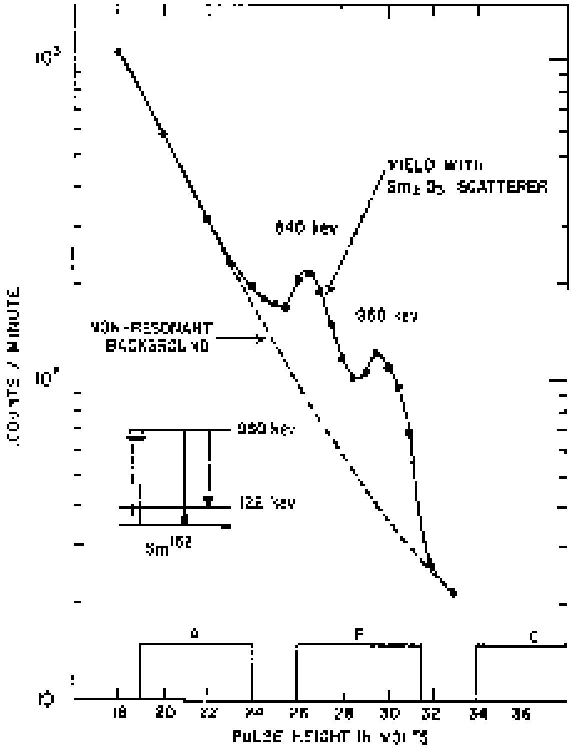
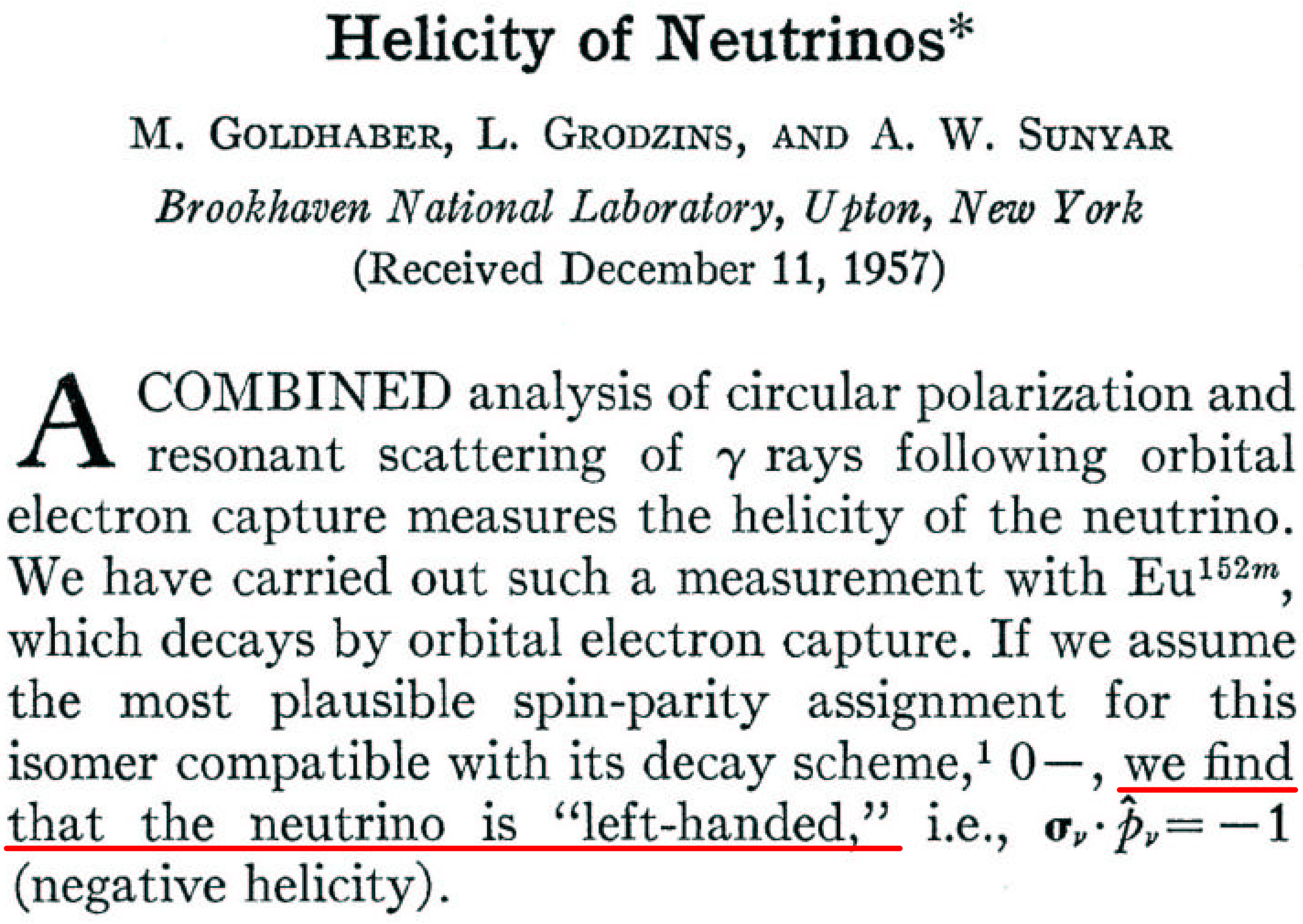


FIG. 2. Resonant-scattered γ rays of Eu^{152m}. Upper curve is taken with arrangement shown in Fig. 1 with unmagnetized iron. Lower curve shows nonresonant background (including natural background).

Neutrino are left-handed



Helicity of Neutrinos*

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

Brookhaven National Laboratory, Upton, New York

(Received December 11, 1957)

A COMBINED analysis of circular polarization and resonant scattering of γ rays following orbital electron capture measures the helicity of the neutrino. We have carried out such a measurement with Eu^{152m}, which decays by orbital electron capture. If we assume the most plausible spin-parity assignment for this isomer compatible with its decay scheme,[1] 0−, we find that the neutrino is "left-handed," i.e., $\boldsymbol{\sigma}_\nu \cdot \hat{p}_\nu = -1$ (negative helicity).

The V-A theory of weak interactions

After many years of both theoretical and experimental efforts it was concluded in the mid ‘50s that all of weak interaction phenomenology could be described by the Fermi lagrangian (Feynman and Gell-Mann 1958)

$$L = \frac{G_F}{\sqrt{2}} J^a(x) J_a^+(x)$$

$J^a(x)$ is the analogue of the e.m. current and is the sum of two parts

$$J^a(x) = \underbrace{l^a(x)}_{leptonic} + \underbrace{h^a(x)}_{hadronic}$$

Weak processes

- ✓ Purely leptonic processes (e.g. $\mu^- \to e^- + \text{anti}\nu_e + \nu_\mu$)

$$J^a(x) = \frac{G_F}{\sqrt{2}} l^a(x) l_a^+(x)$$

- ✓ Semi-leptonic processes (e.g. β decay)

$$J^a(x) = \frac{G_F}{\sqrt{2}} \left\{ l^a(x) h_a^+(x) + h^a(x) l_a^+(x) \right\}$$

- ✓ Purely hadronic processes (e.g. $\Lambda \to p + \pi^-$)

$$J^a(x) = \frac{G_F}{\sqrt{2}} h^a(x) h_a^+(x)$$

Two Weak Interactions

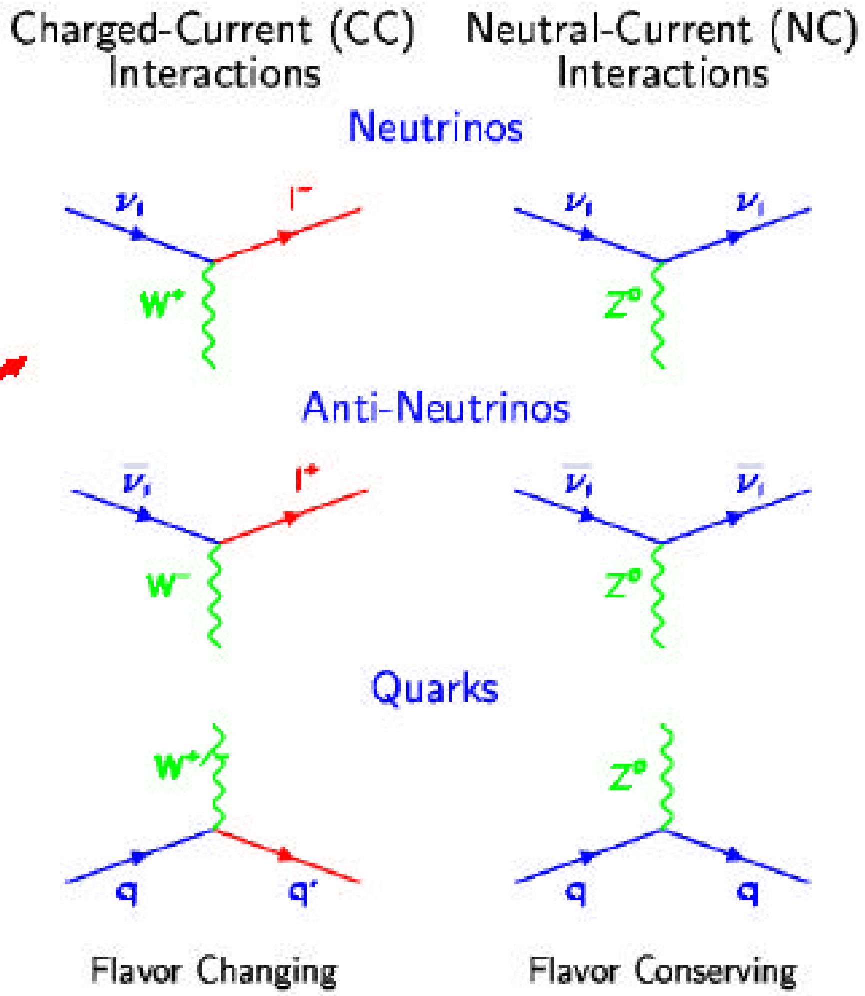
In charged-current events,

Flavor of outgoing lepton tags flavor of neutrino

Charge of outgoing lepton determines if neutrino or antineutrino

$$l^- \rightarrow \nu$$

$$l^+ \rightarrow \bar{\nu}$$



The discovery of the neutrino

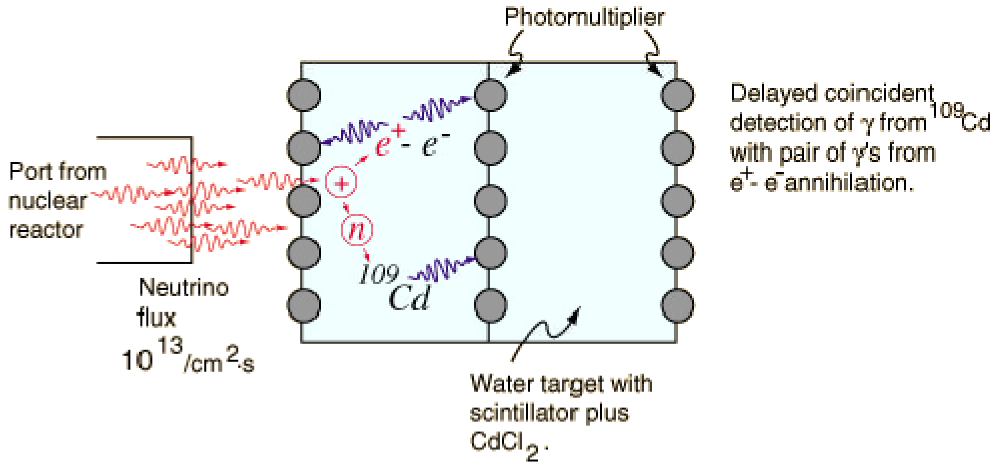
In 1953 C. Cowan and F. Reines proposed to detect neutrinos by using a liquid scintillator

Principle

Detection of the reaction

antiν_e+p $\rightarrow$n+e^+

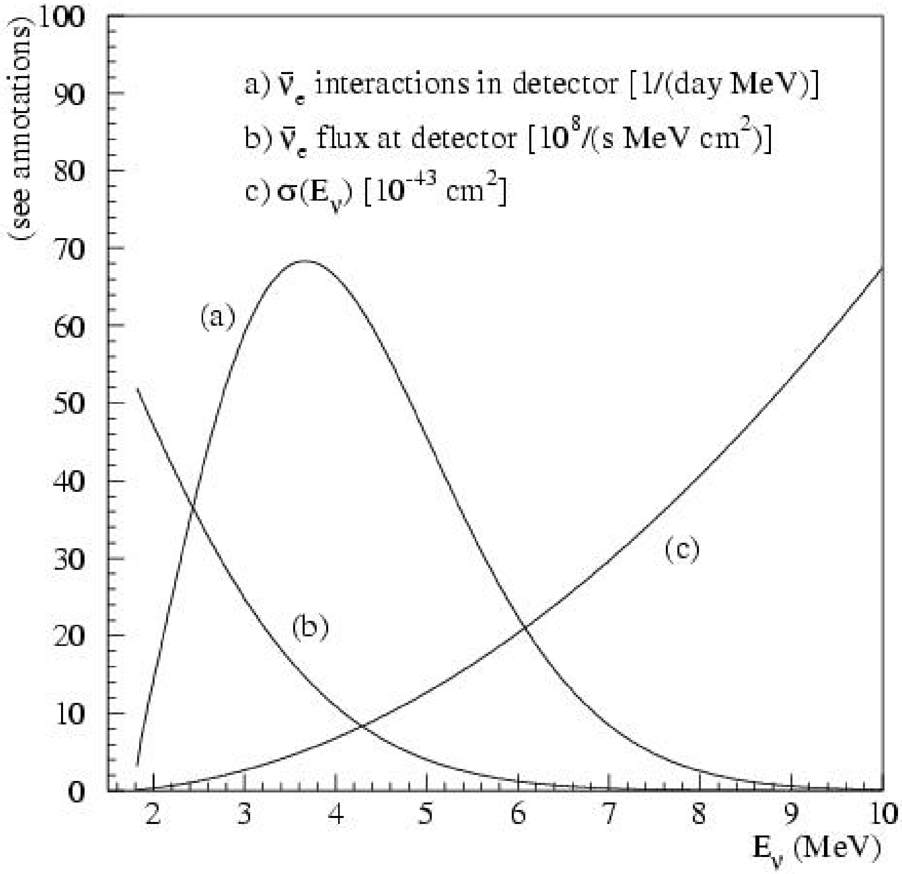
through the detection the coincidence of the signals induced by the two γ, from positron annihilation, and the γ's produced in the neutron capture (see figure)



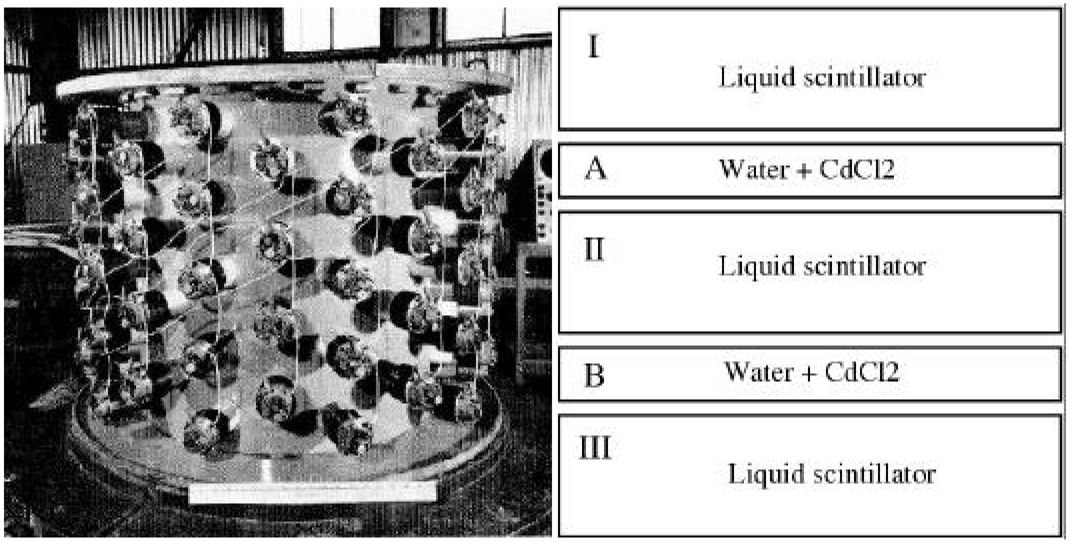
How to produce a high intensity neutrino flux?

Neutrino from reactors

The original idea of Reines and Cowan was to detect ν emitted from a fission bomb! (Un)Fortunately the nuclear reactors became available and they turned out to be more practical



The detector



✓Tanks I-II-III contain 140l of triethylbenzene (TEB) liquid scintillator solution

✓Tanks A and B contain 200l of water (target) and 40kg of $CdCl_2$ (to capture the neutrons)

✓The neutrino flux 11m far from the reactor was $1.2\text{x}10^{13}\text{cm}^{-2}\text{s}^{-1}$

The results

- ✓ The measured cross-section ((6.7±1.5)x10^{-44} cm^2) was consistent with the prediction ((6±1)x10^{-44} cm^2)
- ✓ The first pulse of the delayed-coincidence signal was due to positron annihilation
- ✓ The second pulse of the delayed-coincidence signal was due neutron capture
- ✓ The signal was a function of the number of target protons
- ✓ Radiation other than neutrinos was ruled out as the cause of the signal by means of an absorption experiment

Counting neutrinos

The discovery of the ν_μ

The discovery that $\nu_e \neq \nu_\mu$ was possible thanks to the realisation of the first ν beam from an accelerator (BNL 1962, Lederman, Steinberger, Schwartz)

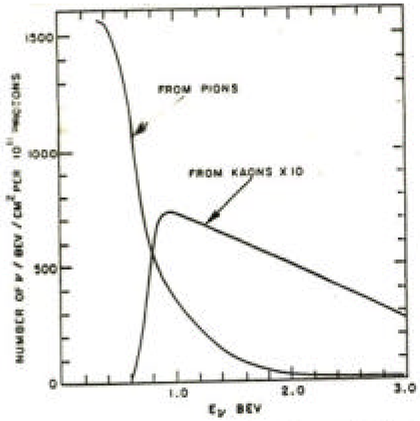
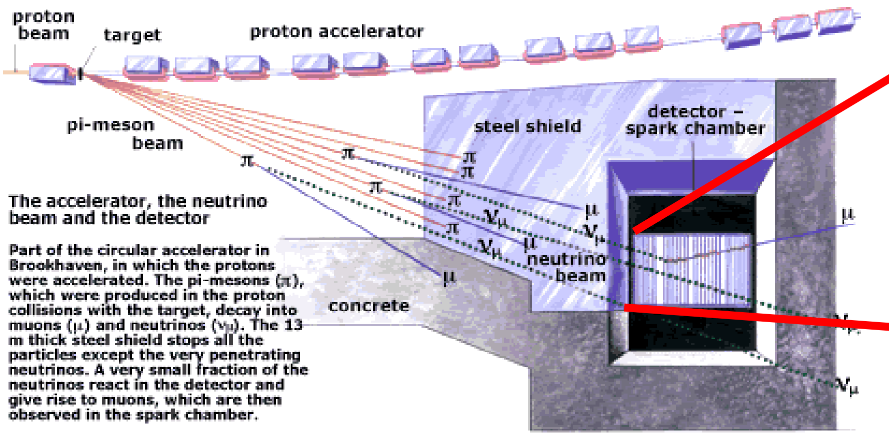


FIG. 2. Energy spectrum of neutrinos expected in the arrangement of Fig. 1 for 15-BeV protons on Be.



The accelerator, the neutrino beam and the detector

Part of the circular accelerator in Brookhaven, in which the protons were accelerated. The pi-mesons (π), which were produced in the proton collisions with the target, decay into muons (μ) and neutrinos (ν_μ). The 13 m thick steel shield stops all the particles except the very penetrating neutrinos. A very small fraction of the neutrinos react in the detector and give rise to muons, which are then observed in the spark chamber.

Based on a drawing in Scientific American, March 1963.

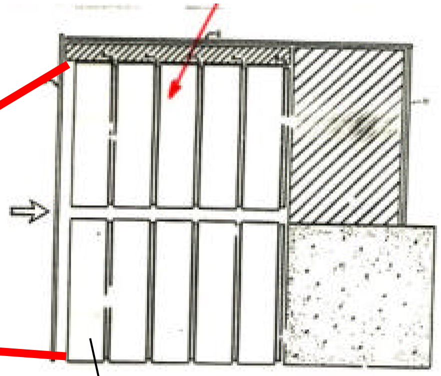


FIG. 3. Spark chamber and counter arrangement. *A* are the triggering slabs; *B*, *C*, and *D* are anticoincidence slabs. This is the front view seen by the four-camera stereo system.

Contains 9 Al plates which act as target

The selection criteria

A genuine ν interaction should

- originate in a fiducial volume whose boundaries lie 4" from the front and back walls of the chamber and 2" from the top and bottom walls
- have the first two gaps not fired, in order to exclude events whose origins lie outside the chambers
- for single track events, have an extrapolation backward (towards the neutrino source) that remains for two gaps within the fiducial volume
- for single track events, have a track with an angle, relative to the neutrino direction, less than 60°

The selected sample

113 events survived the previous cuts

- 49 single tracks. Visible momentum, if interpreted as μ, less than 300 MeV. A run with an improved shielding yielded a smaller number of these events ⇒ background events
- 34 single muons with momentum above 300 MeV
- 22 vertex events. More than one track at the primary vertex and substantial energy release
- 8 shower events. They are in general single tracks, too irregular to be typical of μ, and more typical of electron of photon showers

Some pictures

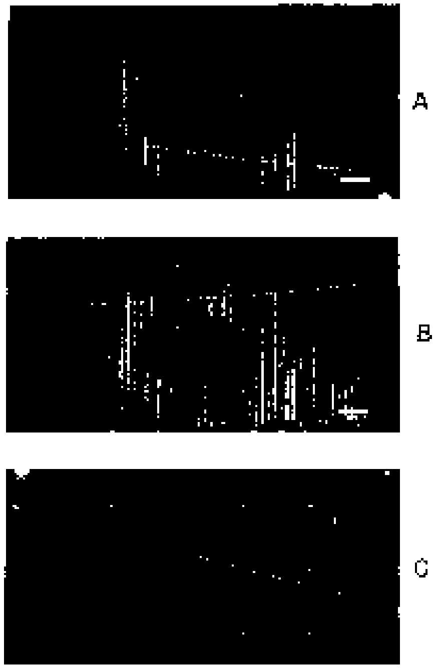


FIG. 5. Single muon events. (A) $p_\mu > 540$ MeV and δ ray indicating direction of motion (neutrino beam incident from left); (B) $p_\mu > 700$ MeV/c; (C) $p_\mu > 440$ with δ ray.

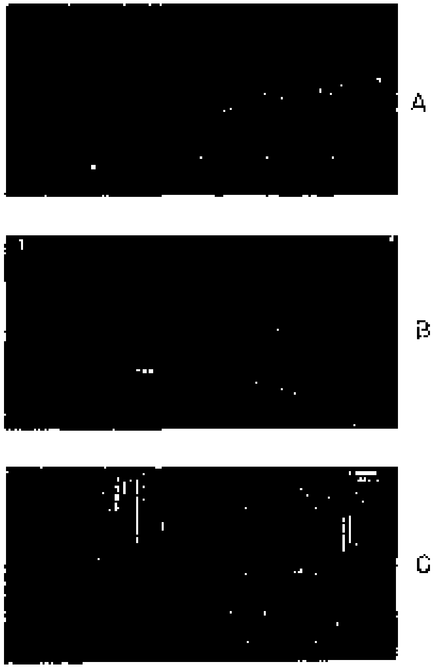


FIG. 6. Vertex events. (A) Single muon of $p_\mu > 300$ MeV and electron-type track; (B) possible example of two muons, both leave chamber; (C) four prong star with one long track of $p_\mu > 600$ MeV/c.

The analysis of the 56 events with a μ in the final state

- ✓ The observed events are not entirely due to cosmic-rays. A run with the accelerator off ⇒ 5±1 events observed ⇒ 51 events are left
- ✓ The 51 events are not induced by neutrons
  - ▪ They are uniformly distributed over the fiducial volume
  - ▪ By removing part of the shielding the observed rate does not change
- ✓ The observed mean free path of tracks produced in single track events is consistent with the one expected for μ
- ✓ The observed reactions are due to the decay products of π and K

⇒ 34 single events were observed of which 5 are considered to be cosmic-ray background

Conclusion: $\nu_e \neq \nu_\mu$

- ✓ If $\nu_e = \nu_\mu$ there should be of the order of 29 electron showers, but only 8 shower candidates were observed
- ✓ A test experiment with electrons confirmed the good electron identification of the apparatus

⇓

"… the most plausible explanation for the absence of the electron showers, and the only one which preserve the universality, is then that $\nu_e \neq \nu_\mu$; that is, that there are at least two types of neutrinos. This also resolves the problem raised by the forbidness of the $\mu^+ \to e^+ \gamma$ decay"

The ν_τ discovery

The aim of the DONUT experiment was the direct observation of the ν_τ

The basic elements of the experiment are

✓ A ν_τ beam
✓ A detector capable to observe directly the τ produced in CC interactions of the ν_τ

How to produce a ν_τ beam?

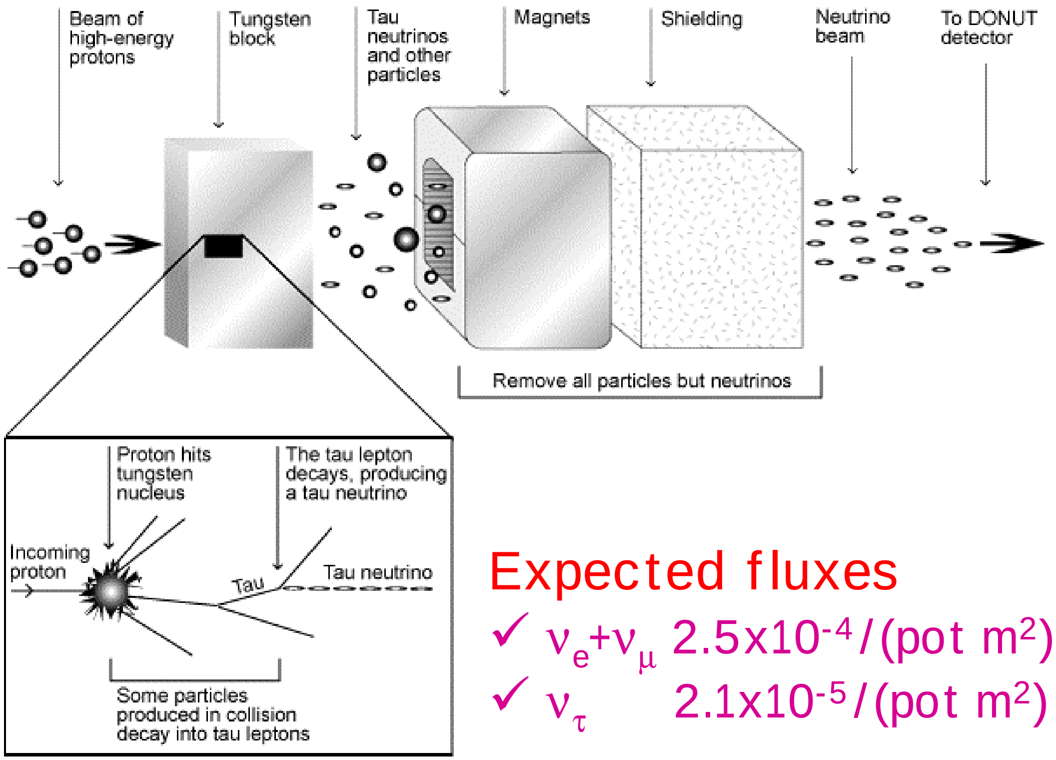
✓ 800 GeV protons are sent into a block of tungsten

✓ In the interactions charmed particles can be produced

✓ Among them D_s mesons are produced and are the primary source of ν_τ

$$D_s \rightarrow tn_t$$

✓ Downstream from the dump a magnet plus an iron shielding stop all charged particles produced into the dump



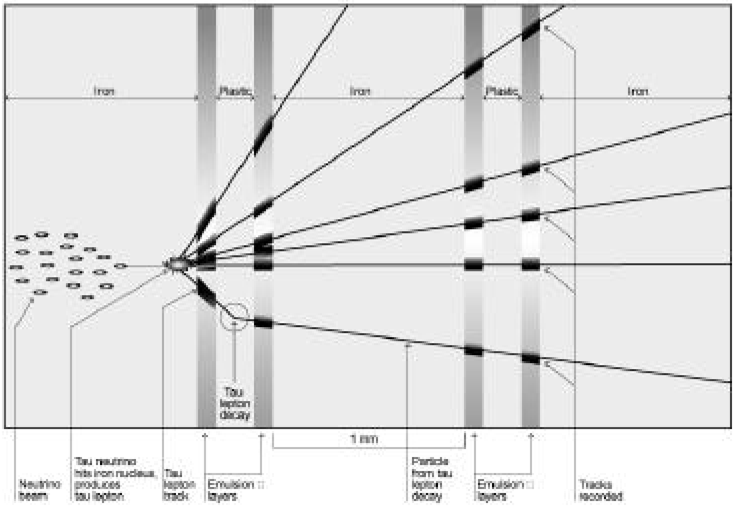
Expected fluxes

✓ $\nu_e+\nu_\mu$ $2.5\text{x}10^{-4}/(\text{pot m}^2)$

✓ ν_τ $2.1\text{x}10^{-5}/(\text{pot m}^2)$

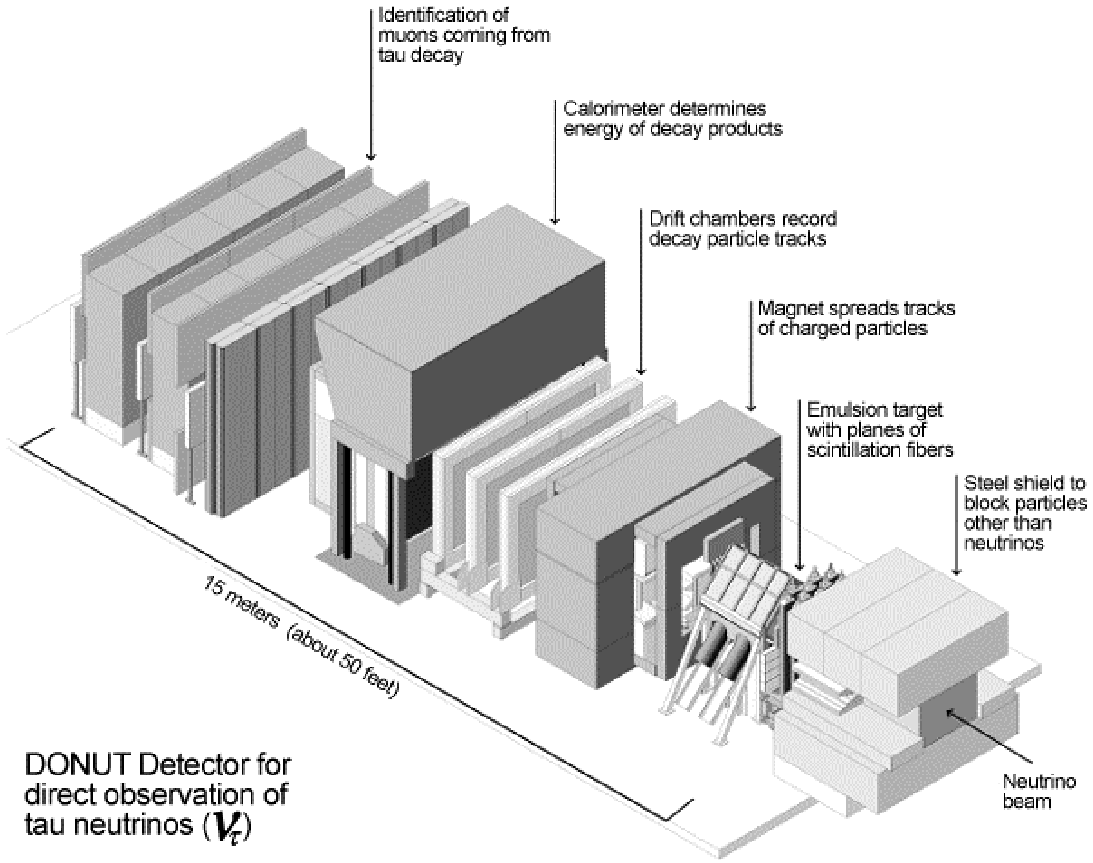
The DONUT detector

Detecting a Tau Neutrino



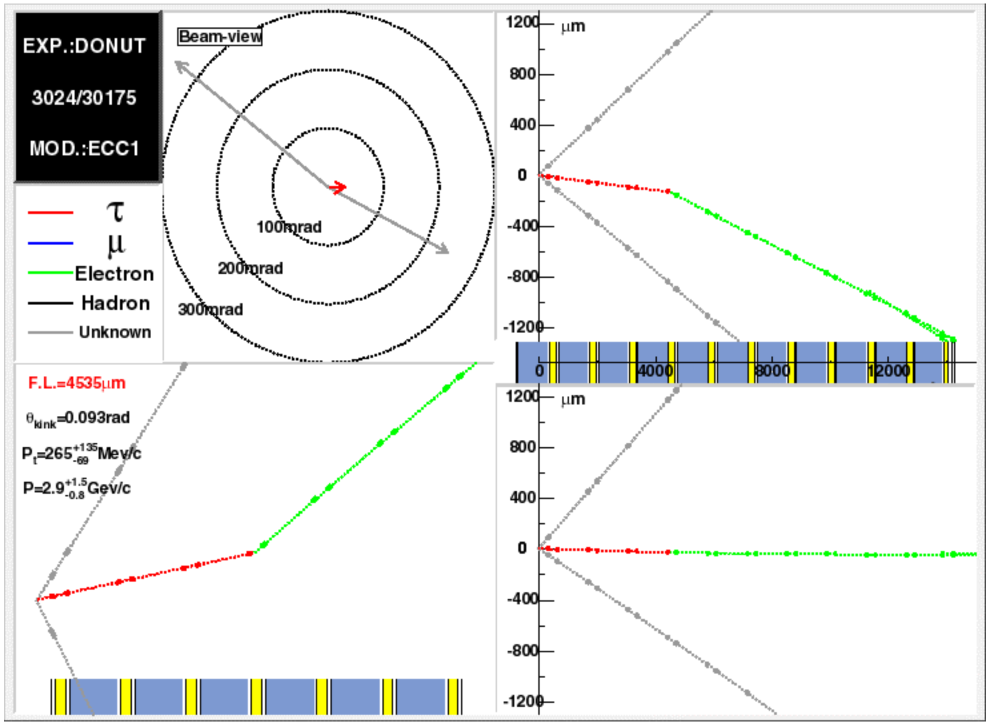
Of one million million tau neutrinos crossing the DONUT detector, scientists expect about one to interact with an iron nucleus.

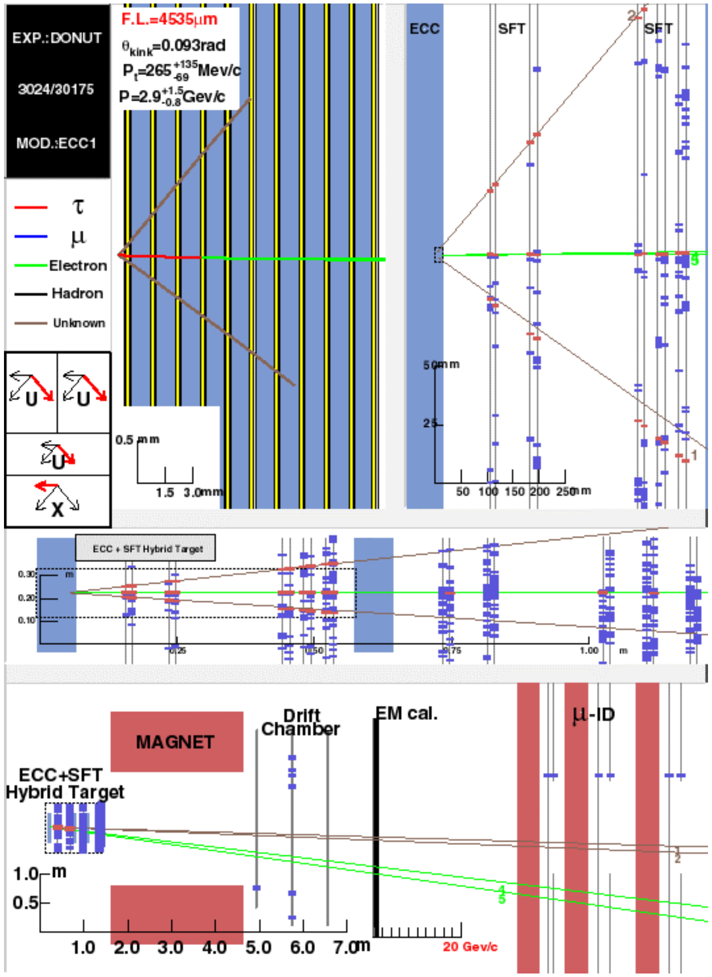
DONUT Detector



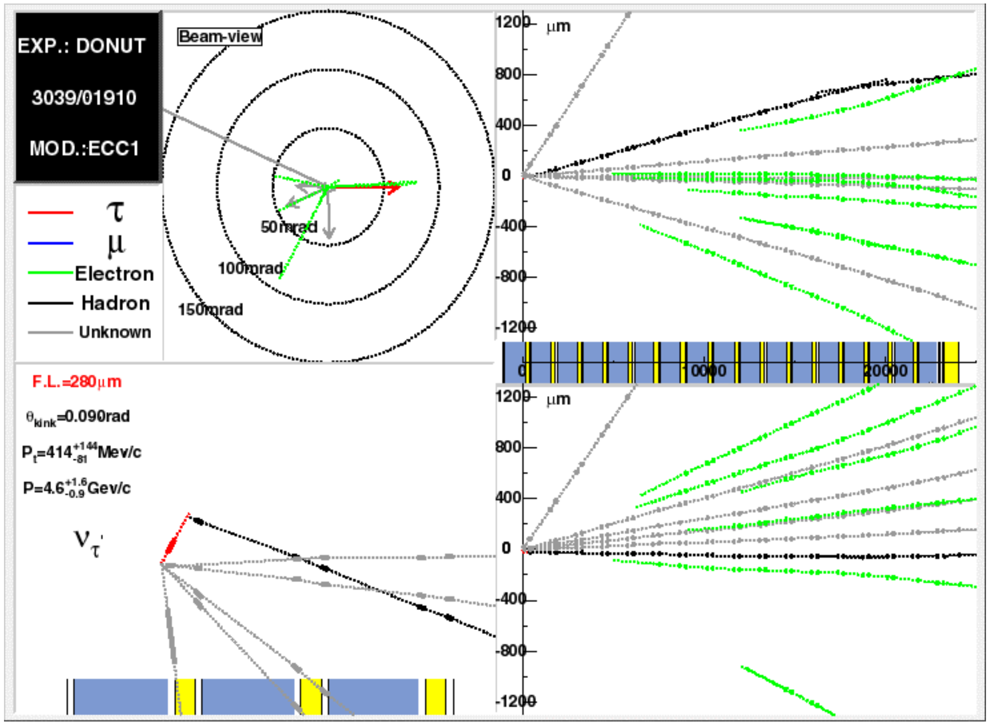
DONUT Detector for direct observation of tau neutrinos (ν_τ)

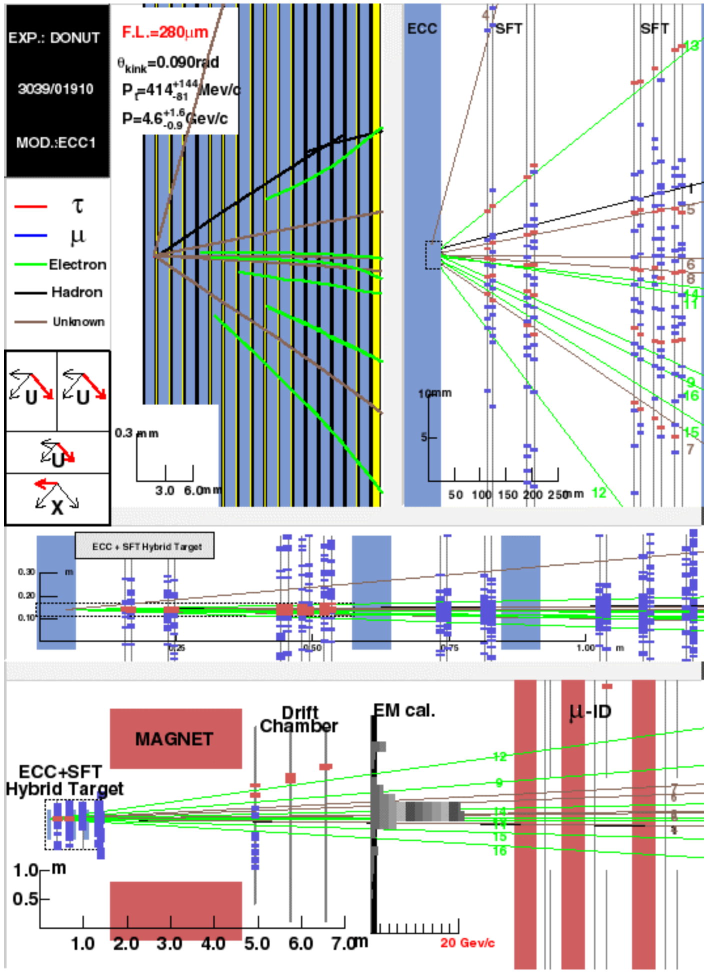
τ→e candidate





$\tau \to h$ candidate



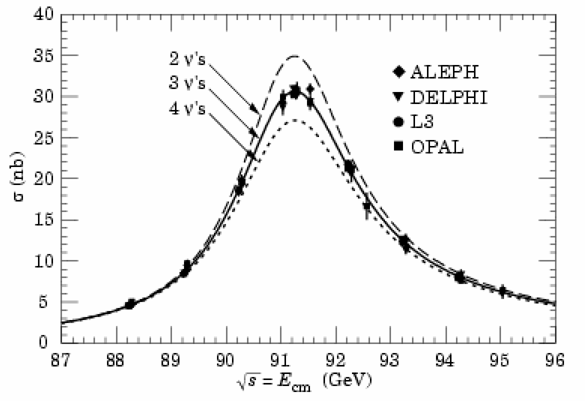


Counting active neutrinos

The number of active neutrino can be inferred by measuring the width of Z (due to Z→ν anti-ν)

From measurement at LEP

$$N_n = 2.9841 \pm 0.0083$$



NB This measurement does not exclude active neutrinos with mass larger than 45 GeV and the existence of weak isosinglets decoupled for the Z (sterile neutrinos)

Counting ν with CMB and BBN

- ✓ The Cosmic Microwave background (CMB) anisotropies and Big Bang Nucleosynthesis (BBN) probe the effective number of neutrinos ($N_\nu = 3 + \Delta N_\nu$) that were present in the early Universe
- ✓ The extra relativistic energy density due to sterile neutrinos, or other possible light particles is given by

$$\rho_x = \Delta N_\nu \, \rho_\nu = 7/8 \, \Delta N_\nu \, \rho_\gamma$$

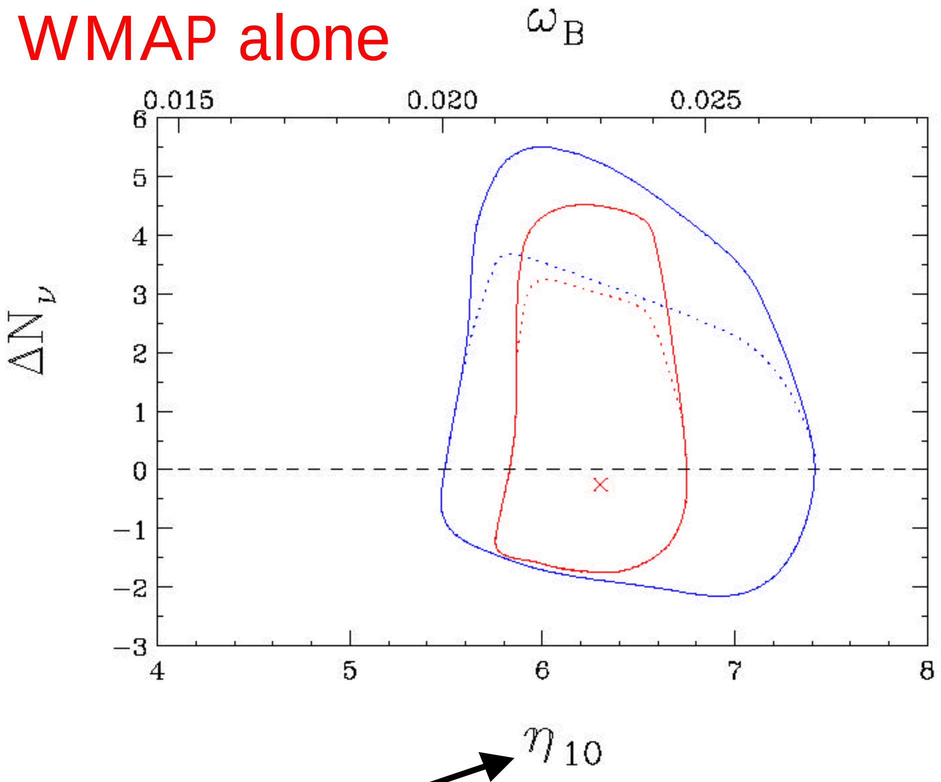
where ρ_γ is the photon density

- ✓ Notice that sterile neutrinos would contribute to ΔN_ν, but so could other new physics sources

Recent WMAP results

(later I'll give more details on this exp)

WMAP alone



Proportional to the baryon density

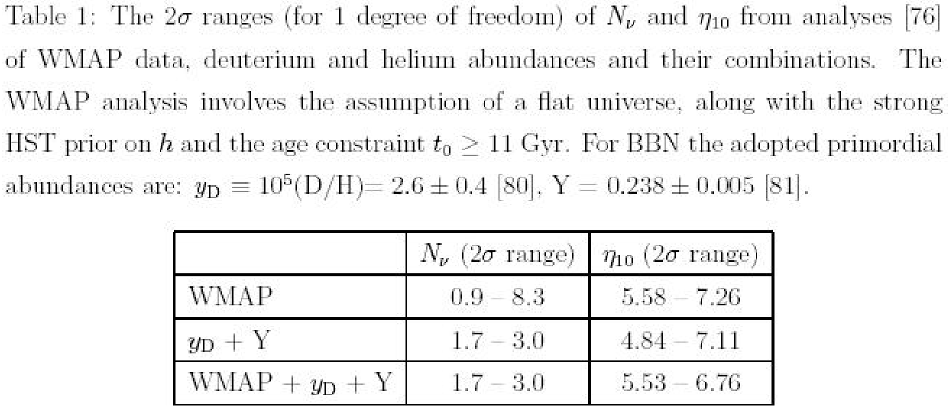
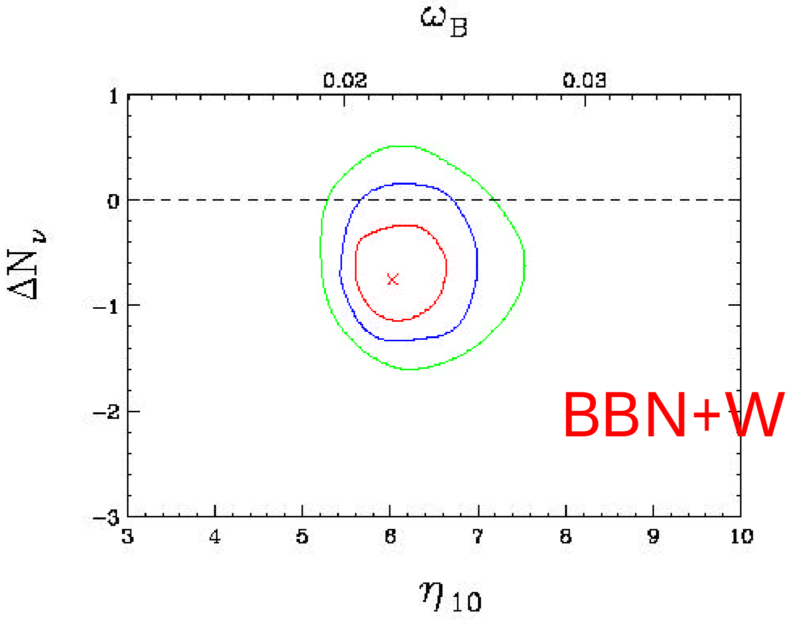


Table 1: The 2σ ranges (for 1 degree of freedom) of N_ν and η_{10} from analyses [76] of WMAP data, deuterium and helium abundances and their combinations. The WMAP analysis involves the assumption of a flat universe, along with the strong HST prior on h and the age constraint $t_0 \geq 11$ Gyr. For BBN the adopted primordial abundances are: $y_D \equiv 10^5(\mathrm{D/H}) = 2.6 \pm 0.4$ [80], $\mathrm{Y} = 0.238 \pm 0.005$ [81].

	N_ν (2σ range)	η_{10} (2σ range)
WMAP	0.9 – 8.3	5.58 – 7.26
y_D + Y	1.7 – 3.0	4.84 – 7.11
WMAP + y_D + Y	1.7 – 3.0	5.53 – 6.76



BBN+WMAP

Age 73. Still in a good shape

1930	ν existence postulated	Pauli
1934	ν interaction theory and name	Fermi
1938	Solar ν flux calculation	Bethe
1946	Idea of ν chlorine detector	Pontecorvo
1956	ν interactions observed	Reines & Cowan
1957	Idea of ν oscillation	Pontecorvo
1958	Left-handed ν	Goldhaber
1962	2 ν's, $\nu_\mu \neq \nu_e$	Lederman, Schwartz & Steinberger
1968	Solar neutrino deficit	Davis
1973	ν NC interactions observed	Gargamelle
1975	τ and the third ν	Perl
1986	Solar deficit again	Kamiokande
1987	ν from SN1987A	Kamiokande, IMB
1989	3 light neutrino families	LEP Collaborations
1991	Still solar deficit	Gallex, SAGE
1998	Atmospheric ν oscillation	Super-Kamiokande
2002	Solar ν oscillation confirmed	SNO, KamLand