Selected Topics in Majorana Neutrinos

Three lectures by

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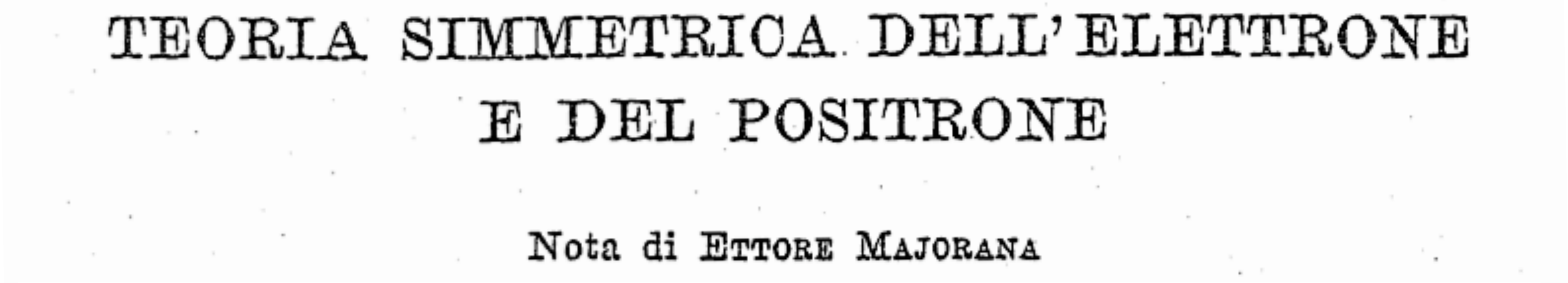
Lecture 1

SUMMARY

1. The Majorana neutrino (1937)
2. Pontecorvo, Fermi and Don Quixote
3. F. Reines e C. Cowan discover the neutrino
4. Surviving the data
5. How can we know ?
6. The rise of Majorana neutrinos: see-saw mechanism

1. Introduction

Il Nuovo Cimento, **14** (1937) 171



TEORIA SIMMETRICA DELL'ELETTRONE E DEL POSITRONE

Nota di ETTORE MAJORANA

Written in 1937, the year before his tragic disappearence in a concise and elegant italian, this article probably represents the best long-lasting contribution of Ettore Majorana to fundamental particle physics.

The article tackles the problem of formulating the Dirac theory without the cumbersome sea of negative energy states.

A cumbersome object

In the late ‘30s, the “Dirac sea” of filled, negative energy states was becoming a rather embarassing object;

what we see as *vacuum* had to be a *plenum*, physically occupied by infinitely many electrons, protons, neutrons, neutrinos...

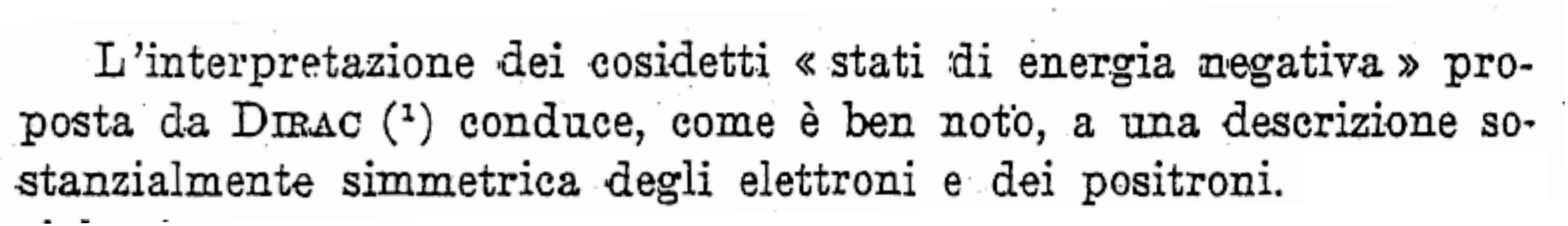
without any detectable property other than to give rise to holes, i.e. antiparticles...

and which is not there for bosons.

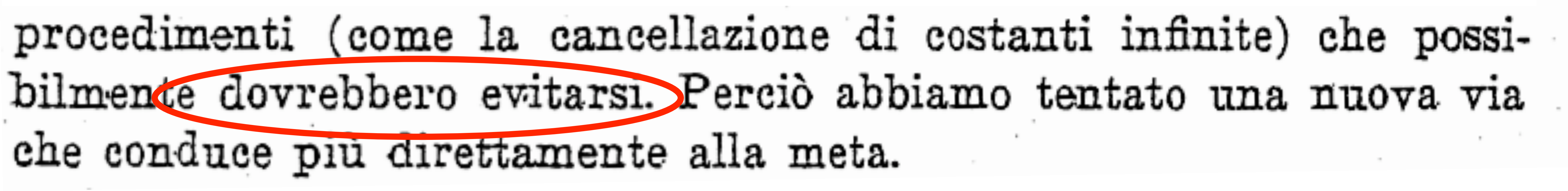
Majorana sets up to eliminate this sort of “ether”;

Along the way, he makes an unexpected discovery.

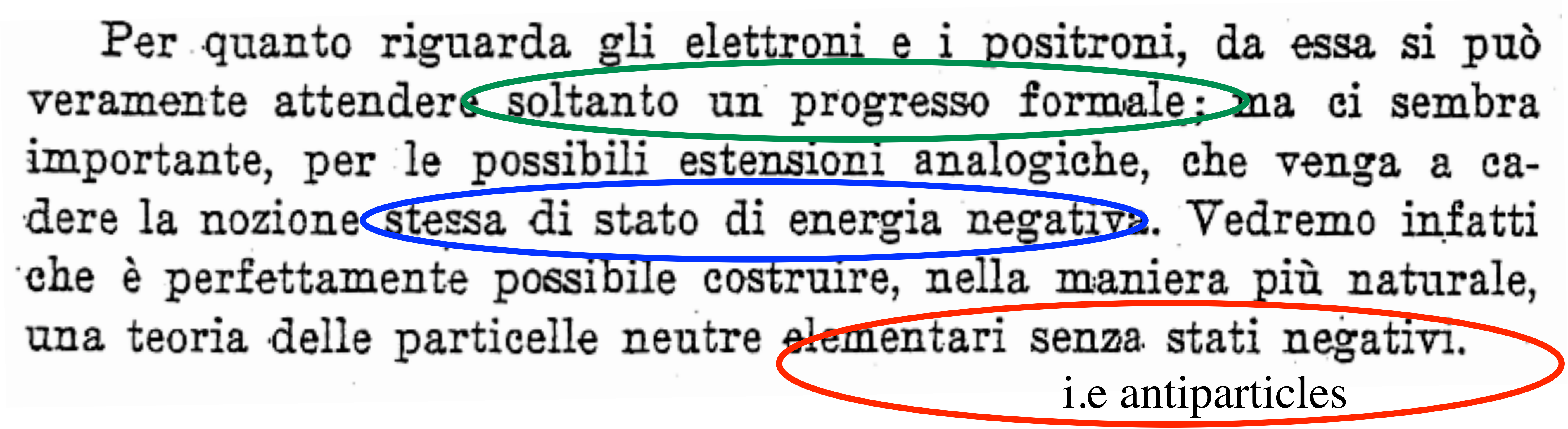
1. The Majorana Neutrino (1937)


L'interpretazione dei cosidetti « stati di energia negativa » proposta da Dirac (1) conduce, come è ben noto, a una descrizione sostanzialmente simmetrica degli elettroni e dei positroni.

- Symmetry is not at all evident...
- Dirac himself had originally speculated that the mass of the hole could be different from the mass of the electron and that, perhaps, hole=Proton;
- It was only after H. Weyl demostrated formally the symmetry from Charge conjugation invariance that Dirac accepted that a new particle, the positron had to exist.
- To obtain the symmetry, one had to use....


procedimenti (come la cancellazione di costanti infinite) che possibilmente dovrebbero evitarsi. Perciò abbiamo tentato una nuova via che conduce più direttamente alla meta.

Results of the new theory



Per quanto riguarda gli elettroni e i positroni, da essa si può veramente attendere soltanto un progresso formale; ma ci sembra importante, per le possibili estensioni analogiche, che venga a cadere la nozione stessa di stato di energia negativa. Vedremo infatti che è perfettamente possibile costruire, nella maniera più naturale, una teoria delle particelle neutre elementari senza stati negativi.

i.e antiparticles

- Particles are described by quantum fields from the start;
- The Dirac sea simply does not exist, bosons and fermions are on a par;
- The real surprise: the minimal description of spin1/2 particle involves *only 2 degrees of freedom* (spin up and spin down) and not 4 as in Dirac’s
- such a particle is absolutely neutral, i.e. it coincides with its antiparticle, as is the case for the photon

How it comes about

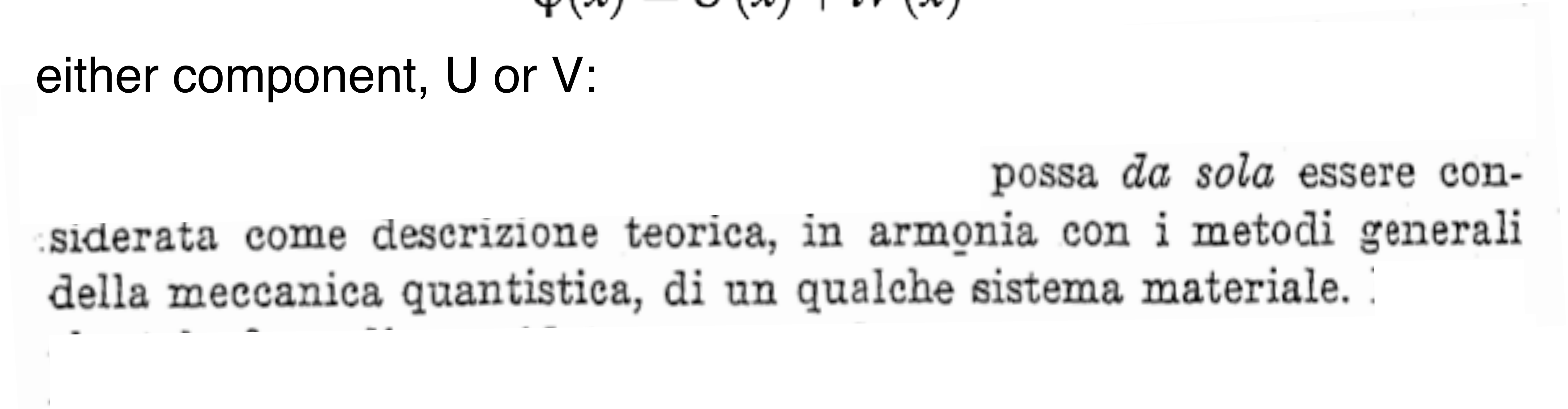
In the representation where the Dirac matrices are *all imaginary* (the Majorana representation), the Dirac equation:

$$(i\gamma^\mu \frac{\partial}{\partial x^\mu} + m)\psi(x) = 0$$

has real coefficients.
Setting:

$$\psi(x) = U(x) + iV(x)$$

either component, U or V:

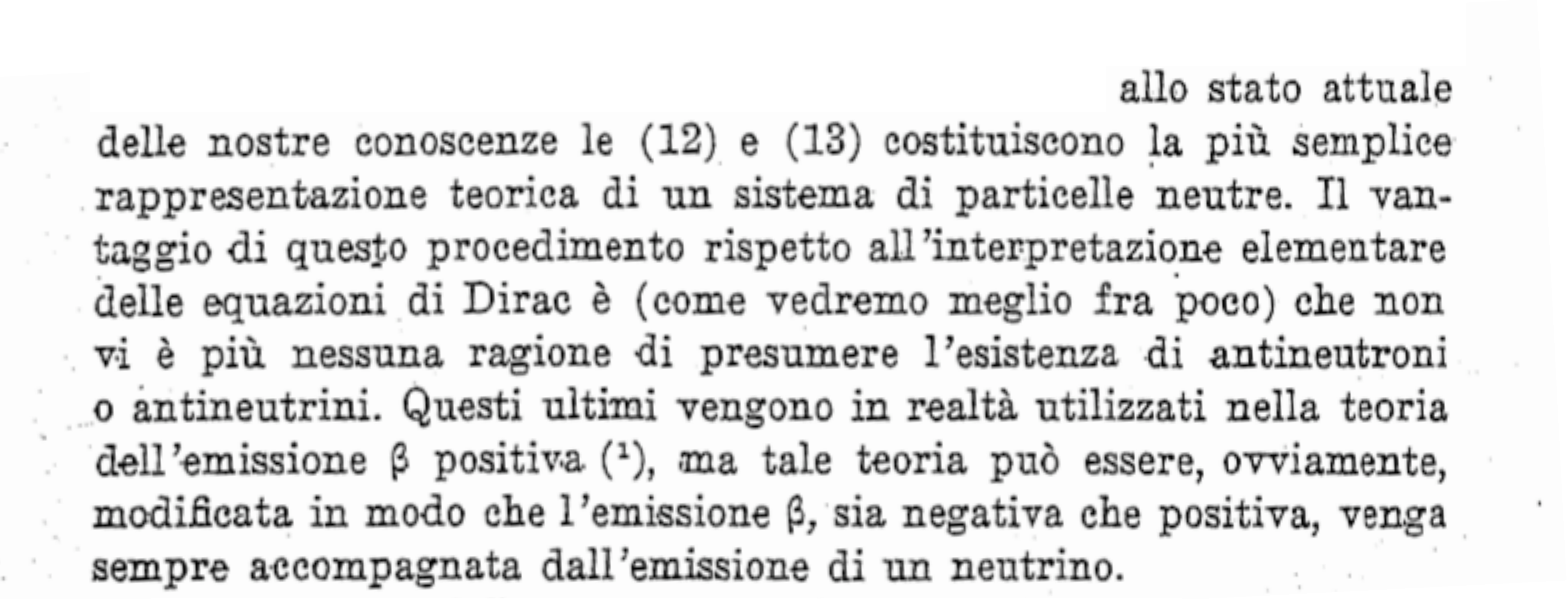


possa *da sola* essere considerata come descrizione teorica, in armonia con i metodi generali della meccanica quantistica, di un qualche sistema materiale.

The Majorana neutrino

M. promply recognizes that one cannot avoid to introduce both U and V for the electron, which admits a conserved charge.

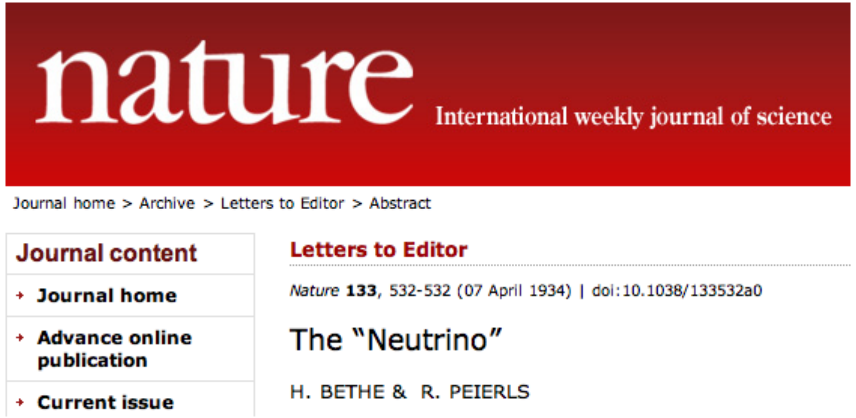
But the simplicity of the scheme leads him to speculate that his theory can find application to the case of electrically neutral particles.



allo stato attuale delle nostre conoscenze le (12) e (13) costituiscono la più semplice rappresentazione teorica di un sistema di particelle neutre. Il vantaggio di questo procedimento rispetto all'interpretazione elementare delle equazioni di Dirac è (come vedremo meglio fra poco) che non vi è più nessuna ragione di presumere l'esistenza di antineutroni o antineutrini. Questi ultimi vengono in realtà utilizzati nella teoria dell'emissione β positiva (1), ma tale teoria può essere, ovviamente, modificata in modo che l'emissione β, sia negativa che positiva, venga sempre accompagnata dall'emissione di un neutrino.

M. refers here to the theory of positive beta rays formulated by G.C. Wick in Roma, two years before.

2. Pontecorvo, Fermi e Don Quixote


nature International weekly journal of science

Journal home > Archive > Letters to Editor > Abstract

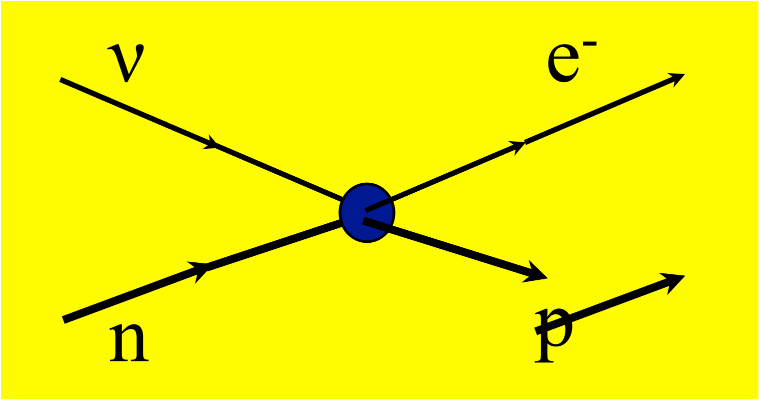
Letters to Editor

Nature **133**, 532-532 (07 April 1934) | doi:10.1038/133532a0

The “Neutrino”

H. BETHE & R. PEIERLS

- Nel 1934, Hans Bethe e Rudolph Peierls calcono la probabilita’ che un neutrino sia rivelato da un urto con la materia, secondo il processo inverso del decadimento beta
- Il processo e’ regolato dalla costante di Fermi G
- Probabilita’ di interazione su un nucleo ≈ $G^2 E_\nu^2$ ($E_\nu << M$)



- Un risultato deprimente: il percorso medio (distanza per avere probabilita’ di interazione ≈ 1) di un neutrino di energia ≈ 1 MeV nel ferro (densita’ ≈ 5 gr/cm^3) e’:

$$L \approx 10 \text{ anni luce} \cdot \frac{1}{[E_\nu(\text{MeV})]^2} \approx 10^{19}\ \text{cm} \cdot \frac{1}{[E_\nu(\text{MeV})]^2}$$

- ovvero, la probabilita’ di vedere una interazione in 1m di ferro e’:

$$P \approx 10^{-17} \cdot [E_\nu(\text{MeV})]^2$$

Il “neutrino” e’ una particella ... o un fantasma???

entra Pontecorvo....

- Nel 1947, Pontecorvo (allora in Canada) realizza che:
  - se la probabilita' di un neutrino di interagire in 1 metro di materia e' astronomicamente piccola...
  - un reattore nucleare produce una quantita' parimenti astronomica di neutrini (dal decadimento in volo dei neutroni che sono il motore delle reazioni nucleari), dell'ordine do 10^{20-23} neutrini al secondo
  - si avrebbe: N(eventi/sec in 1 metro di ferro) $\approx 10^{20}\ 10^{-17} = 10^{3}$ eventi/sec !!!
- Pontecorvo inventa un metodo per rivelare i neutrini da un reattore (ne parleremo piu' avanti) basato su un procedimento radiochimico.
- Durante un viaggio in Europa ne parla con Pauli che si mostra molto interessato;
- ne parla con Fermi che approva ma *non* si dimostra interessato, pensando che ci vorranno decenni per sviluppare il metodo di Pontecorvo.
- Ognuno ha i suoi eroi. Emilio Segre', a questo proposito, scrive: *Don Quixote non era un eroe di Fermi.*

3. F. Reines e C. Cowan scoprono il neutrino

Detecting the Poltergeist, Los Alamos Science n. 25, Nov. 1995 (Letture consigliate_3)

- Nel 1953 , F. Reines e C. Cowan propongono un rivelatore per osservare gli antineutrini prodotti dal reattore di Savannah River, usando la reazione beta inversa: $\bar{\nu} + p \rightarrow e^+ + n$

Rivelatore usato in un primo esperimento non conclusivo, chiamato "El Monstro" per le sue dimensioni

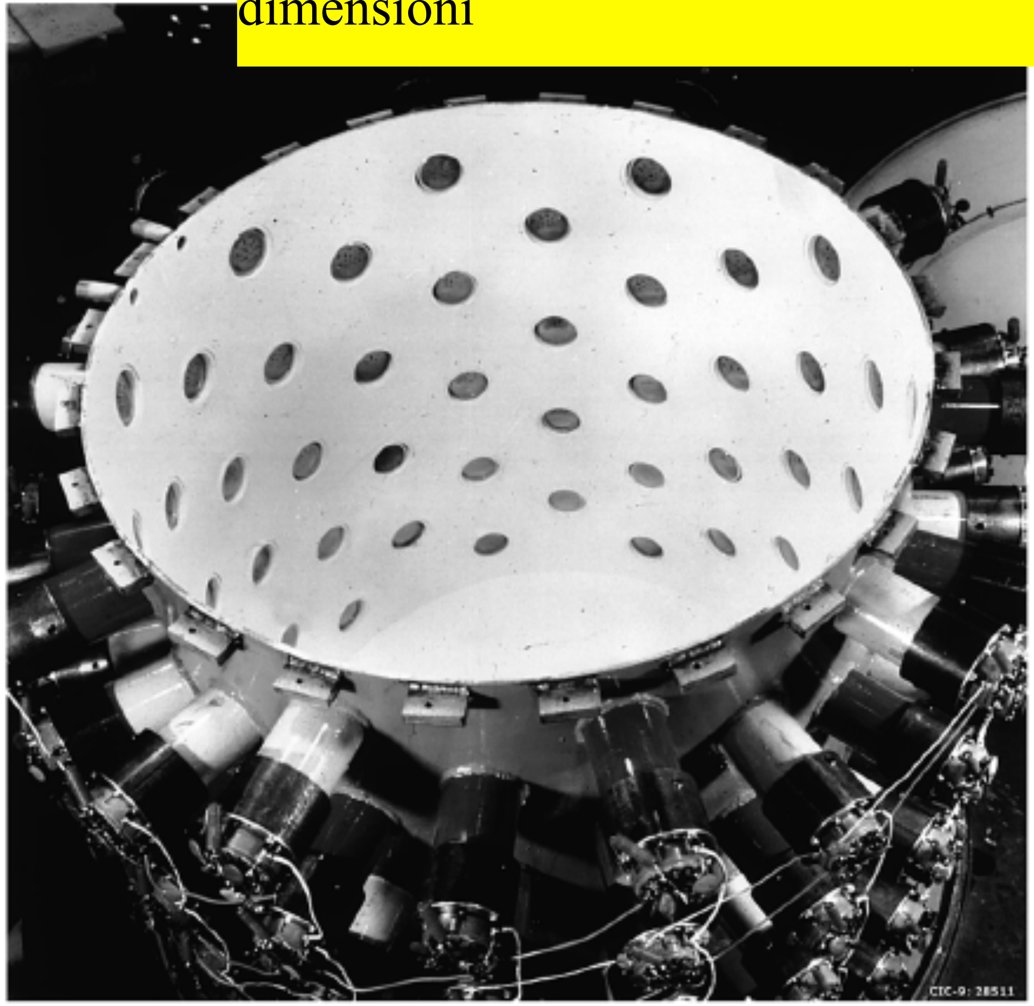
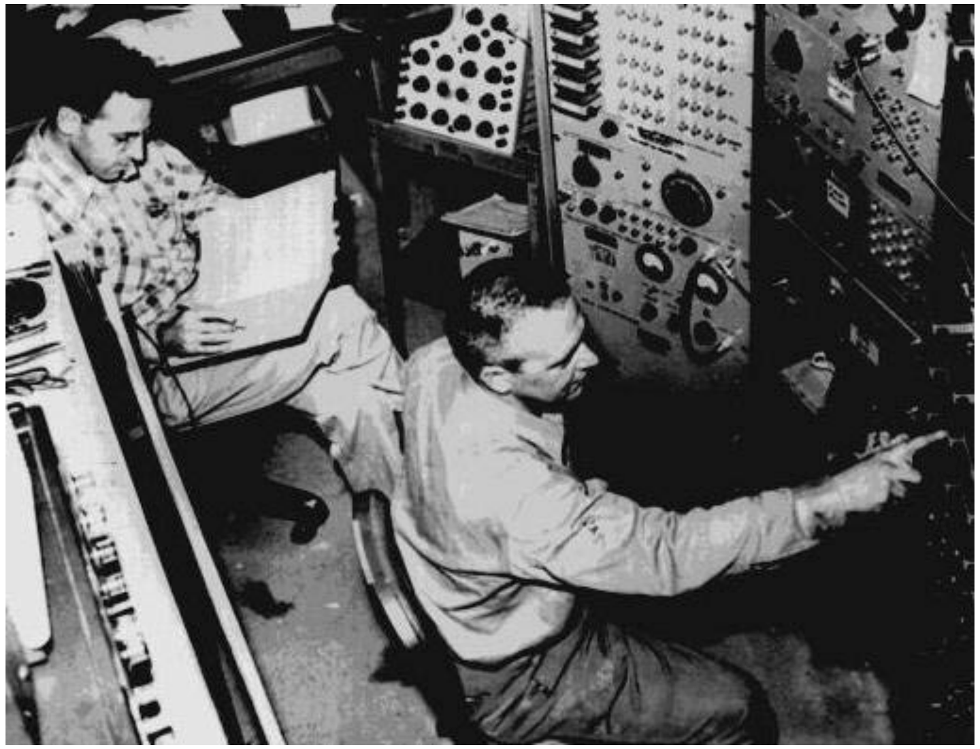
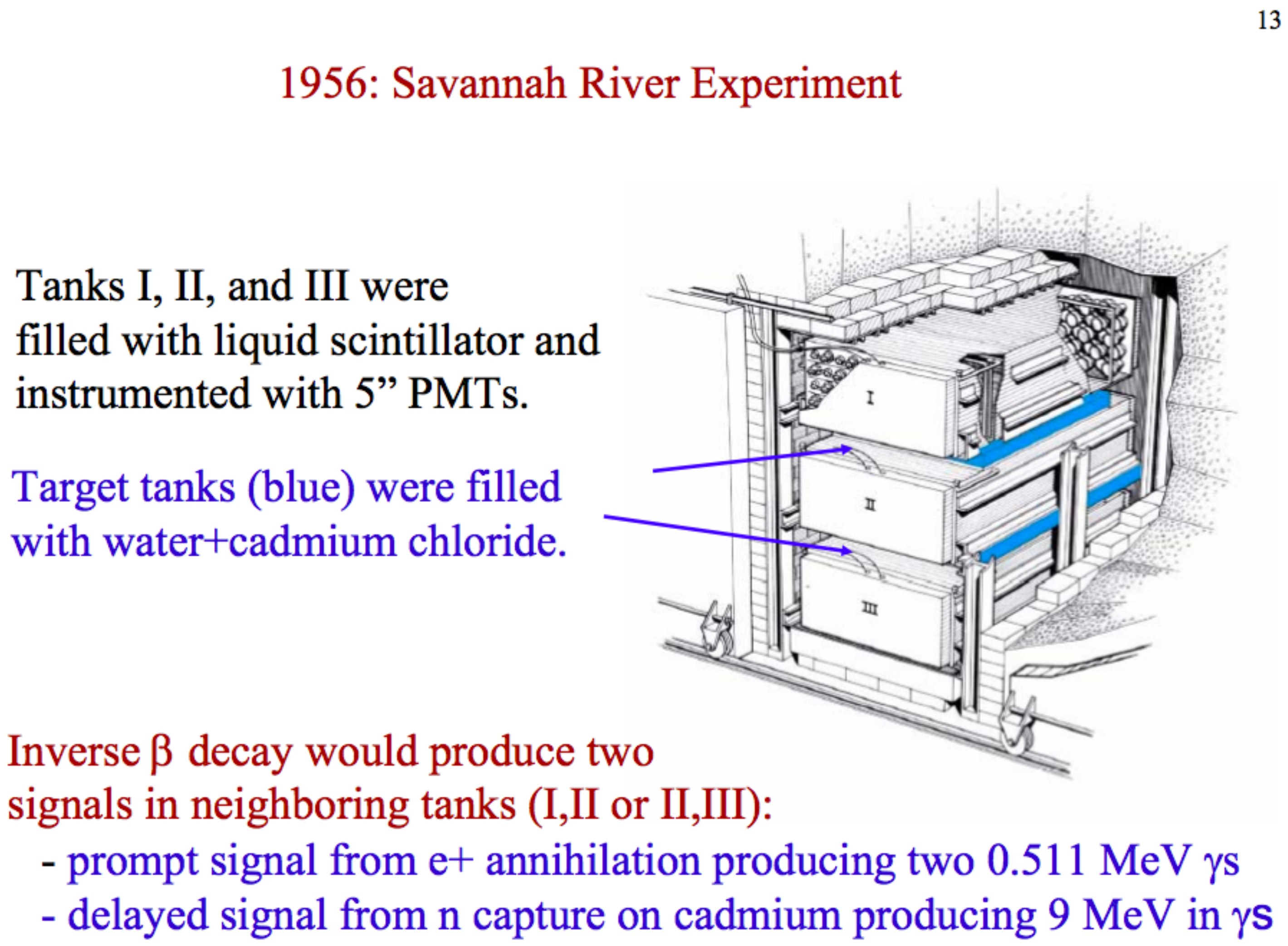


Fig. 3. The scintillation detector for the 1953 neutrino detection experiment at Hanford. Courtesy of the Regents of the University of California, operators of Los Alamos National Laboratory.



esperimento di Reines e Cowan



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1956: Savannah River Experiment

Tanks I, II, and III were filled with liquid scintillator and instrumented with 5” PMTs.

Target tanks (blue) were filled with water+cadmium chloride.

Inverse β decay would produce two signals in neighboring tanks (I,II or II,III):

- prompt signal from e+ annihilation producing two 0.511 MeV γs
- delayed signal from n capture on cadmium producing 9 MeV in γs

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

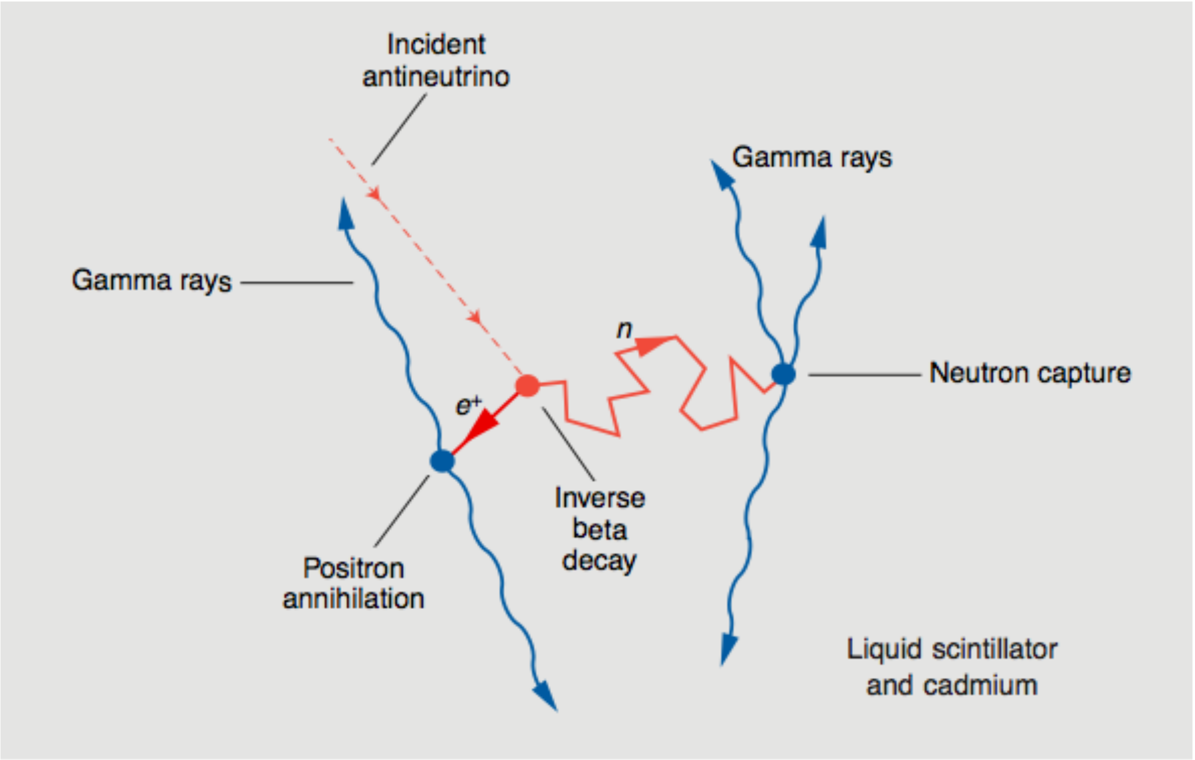


Figure 3. The Double Signature of Inverse Beta Decay

- Nel 1956, Reines e Cowan annunciano di avere osservato inequivocabilmente i segnali associati all’interazione degli antineutrini prodotti dal reattore, con una frequenza compatibile con le previsioni di Bethe e Peierls

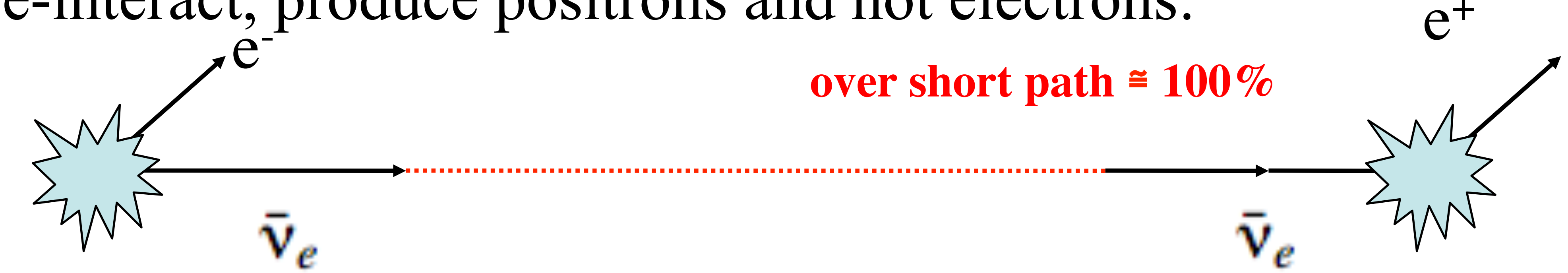
Il “neutrino” e’ una particella come le altre

4. Surviving the data

Basic transitions of the Fermi theory are:

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

neutrinos are Dirac particles since they carry a conserved charge, the lepton number. In fact, neutral particles from neutron's beta decay, when re-interact, produce positrons and not electrons:



One would conclude than that: $\nu \neq \bar{\nu}$

i.e. that even neutrinos cannot be Majorana particles

However, Nature and field theory can be more clever.

Combining V-A and Majorana, beta- and beta+ emission are described by (M-representation for gamma matrices):

$$\mathrm{MR}:\ \gamma_{0,5} = \text{Imaginary, Antisymmetric}$$

$$J^{\mu} = \bar{\psi}_e \gamma_\mu \frac{1}{2}(1-\gamma_5)U = \bar{\psi}_{eL}\gamma_\mu U_L$$

$$(J^{\mu})^{\dagger} = U^T\gamma^0\gamma_\mu\frac{1}{2}(1-\gamma_5)\psi_e = (\frac{1}{2}(1+\gamma_5)U)^T\gamma_\mu\psi_{eL} = (U_R)^T\gamma_\mu\psi_{eL}$$

$n \rightarrow p + e^- + "\nu"$ helic. +1

$p \rightarrow n + e^+ + "\nu"$ helic. -1

the neutral particles carry different ***helicity*** in the two cases, so they ***are different***, since helicity is conserved for very light particles such as neutrinos. Violations of “lepton number” arise only to order $(m_\nu/E_\nu)^2$, in general undetectably small.

Mathematically, massless neutrinos Majorana neutrino and V-A are equivalent to the two component, Weyl, neutrino theory (as was realized in the late ‘50s).

Weyl, Majorana & Dirac fermions

Fields menu (M-repr.): $\bar{\nu}$

$\psi_1 = \nu_L + (\nu_L)^\dagger$ Majorana

$\psi_2 = (\nu_R)^\dagger + \nu_R$ Majorana

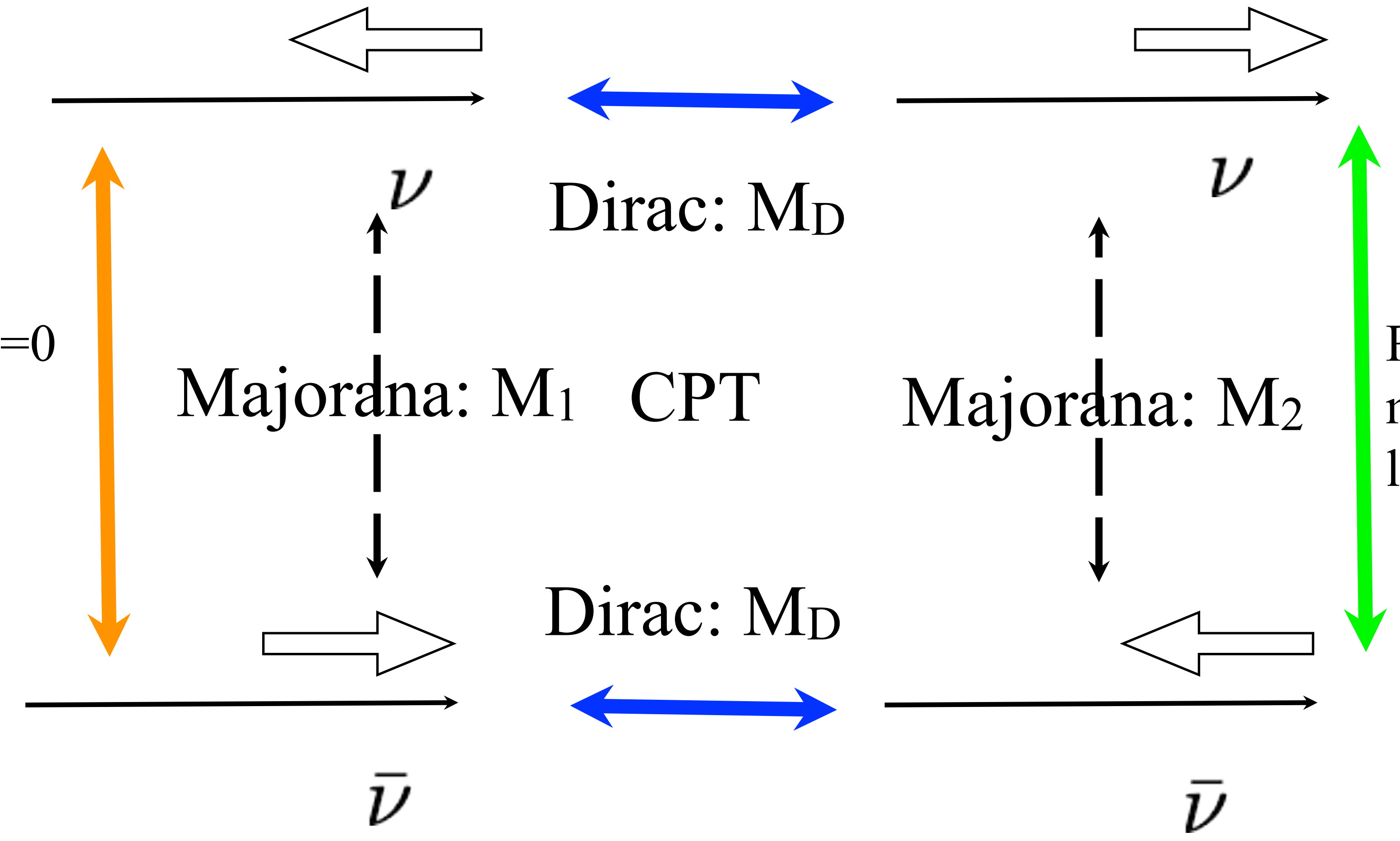
$\psi_D = \nu_L + \nu_R$ Dirac

Mass terms (M-repr.):

$\frac{1}{2} M_1 \psi_1 \gamma^0 \psi_1 + h.c.$ Majorana

$\frac{1}{2} M_2 \psi_2 \gamma^0 \psi_2 + h.c.$ Majorana

$M_D \nu_R \nu_L + h.c.$ Dirac



$\nu_L(x)$

Left-handed Weyl, m=0
lepton n.=helicity

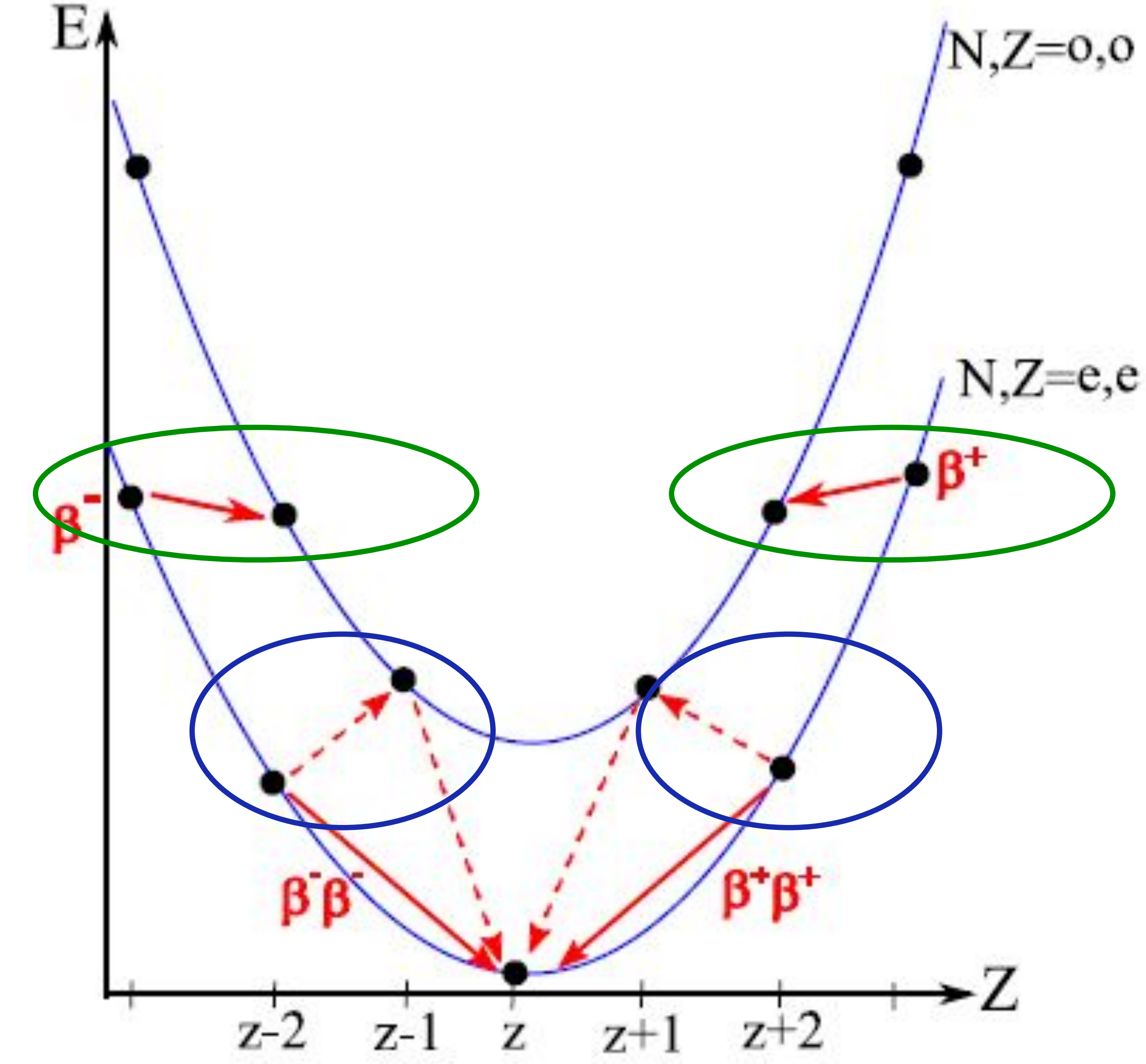
$\nu_R(x)$

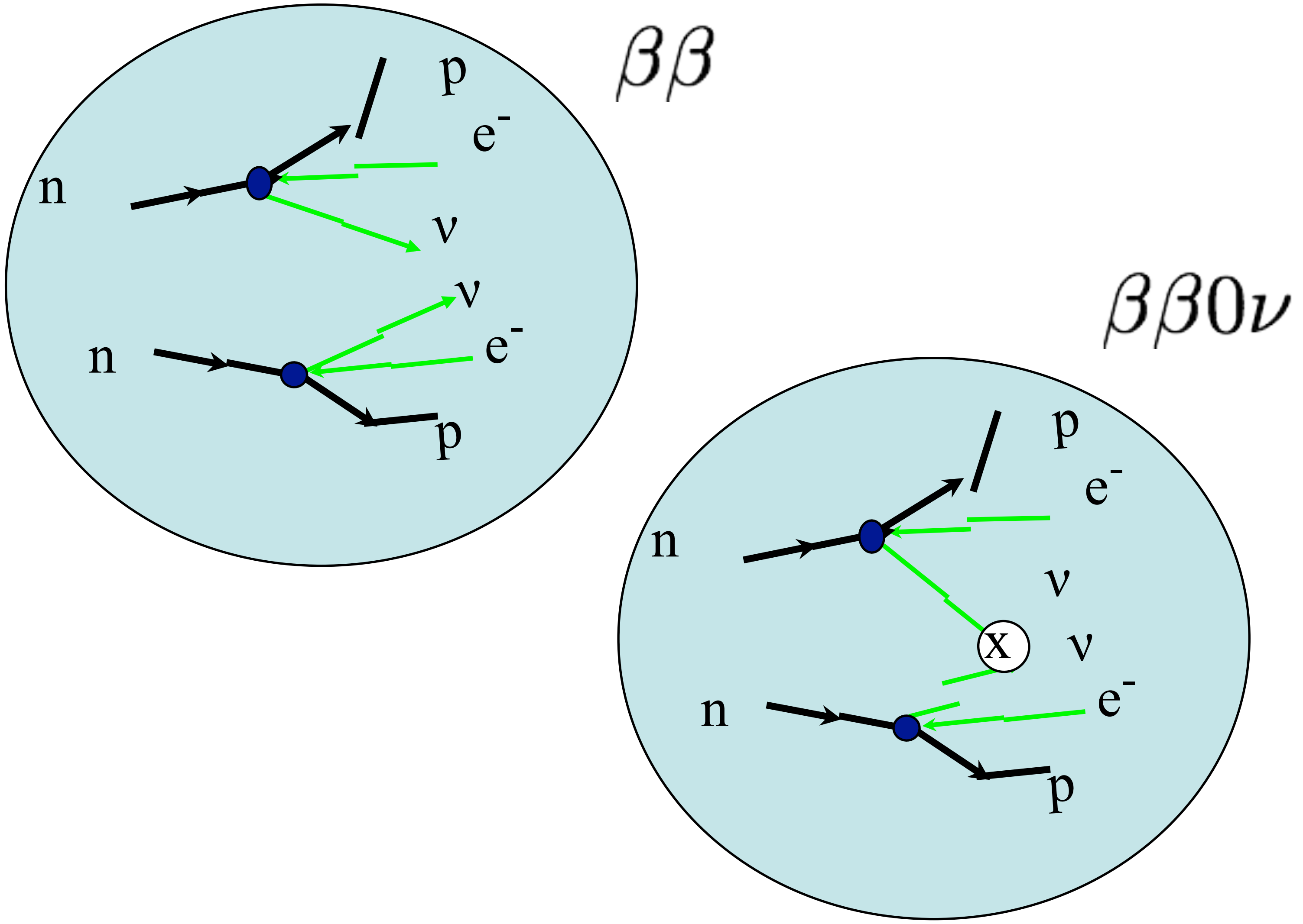
Right-handed Weyl,
m=0
lepton n.=helicity

5. How can we know ?

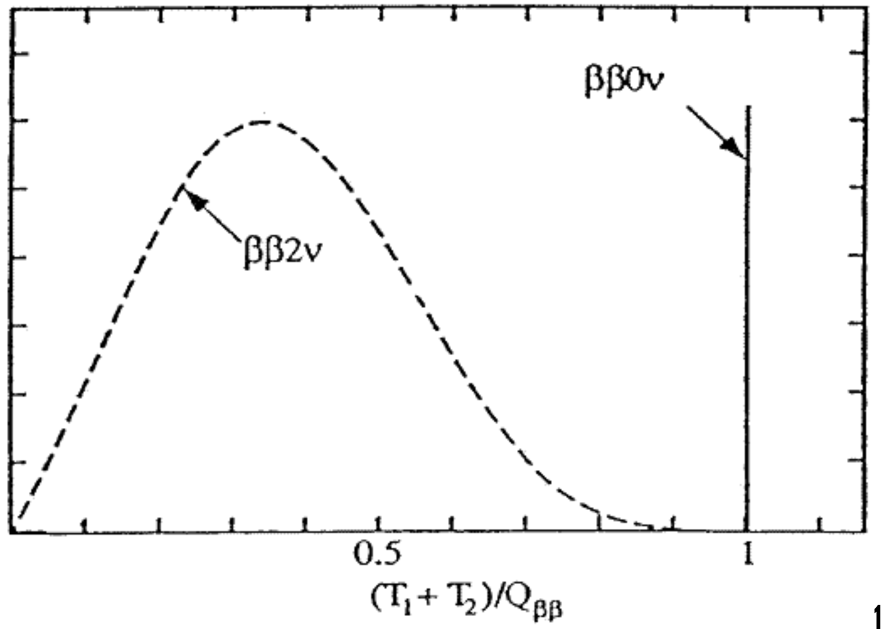
- β decays and neutrino reactions have too large energy to allow detecting effects of order $(m_\nu/E_\nu)^2$
- there is only one process where we can hope to decide between Majoran and Dirac-Weyl neutrinos: ***double-beta decay without neutrinos*** (ββ 0ν)
- for long, searching for ββ 0ν has been a superspecialized matter, restricted to a club of happy fews (among them, Ettore Fiorini)
- today it is one of the future main lines of particle physics, in particular experiments are prepared in the Grans Sasso Laboratory of INFN in Italy

decadimenti beta, doppio beta e doppio beta 0ν

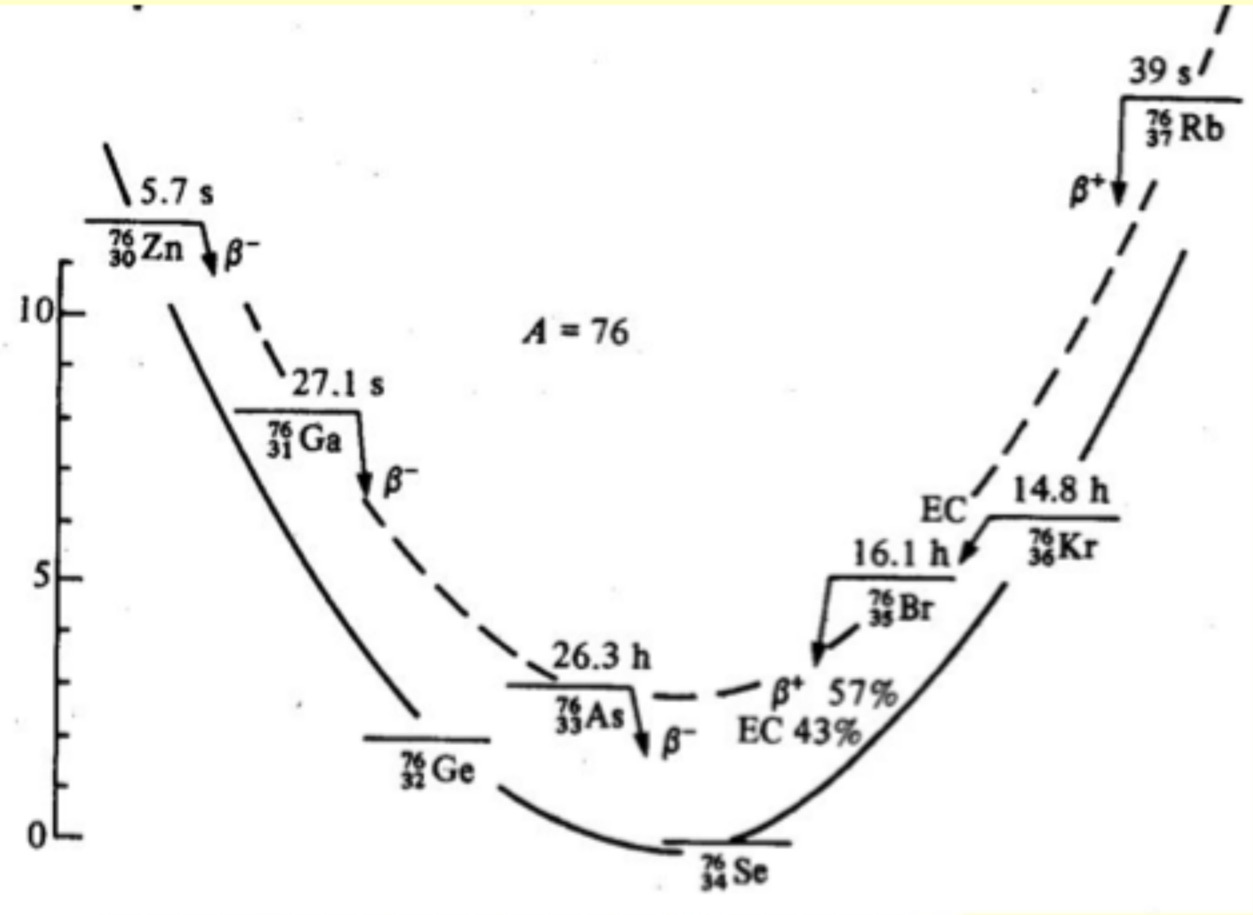


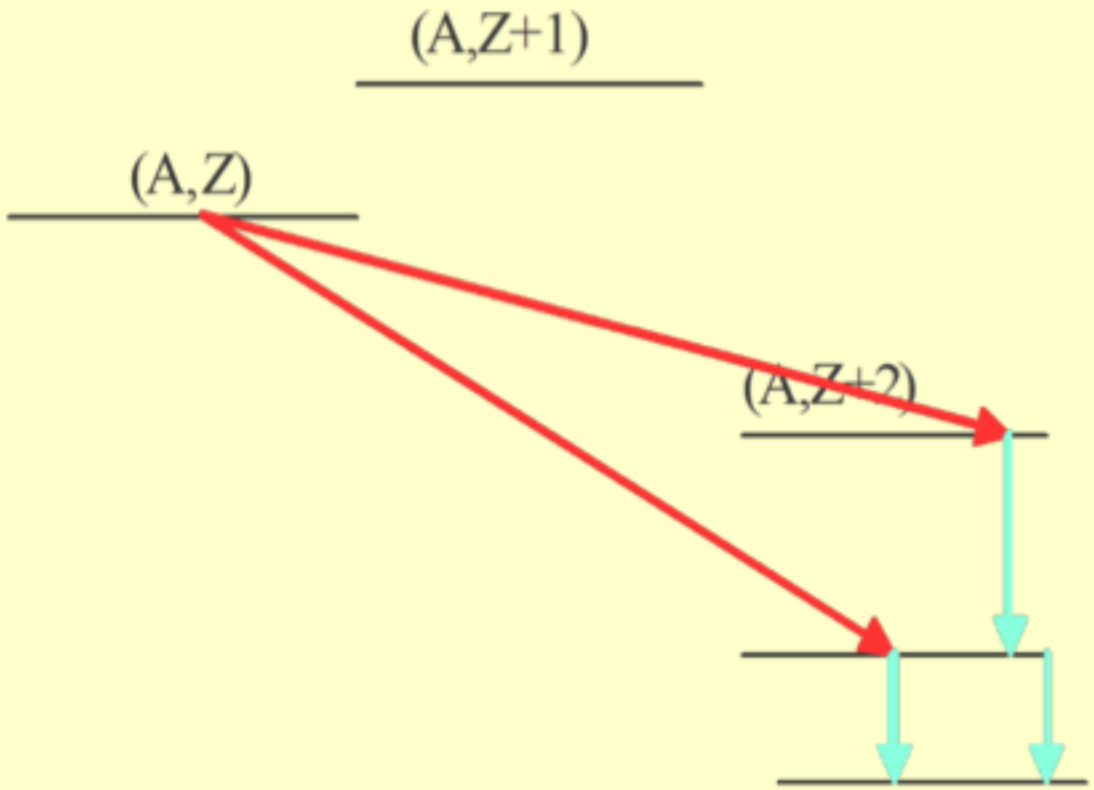


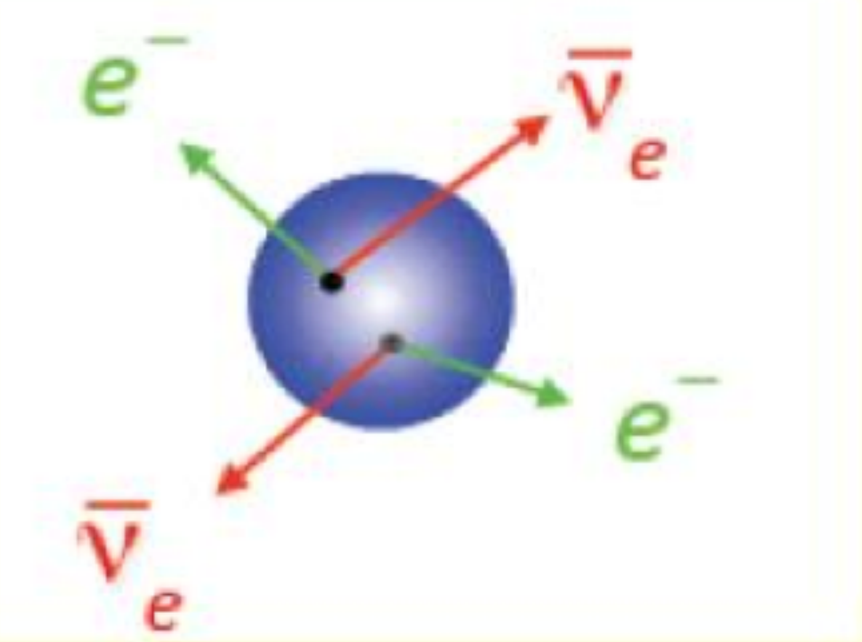
quando non ci sono neutrini, la somma delle energie dei raggi beta e' fissata dalla differenza di energia dei nuclei iniziale e finale

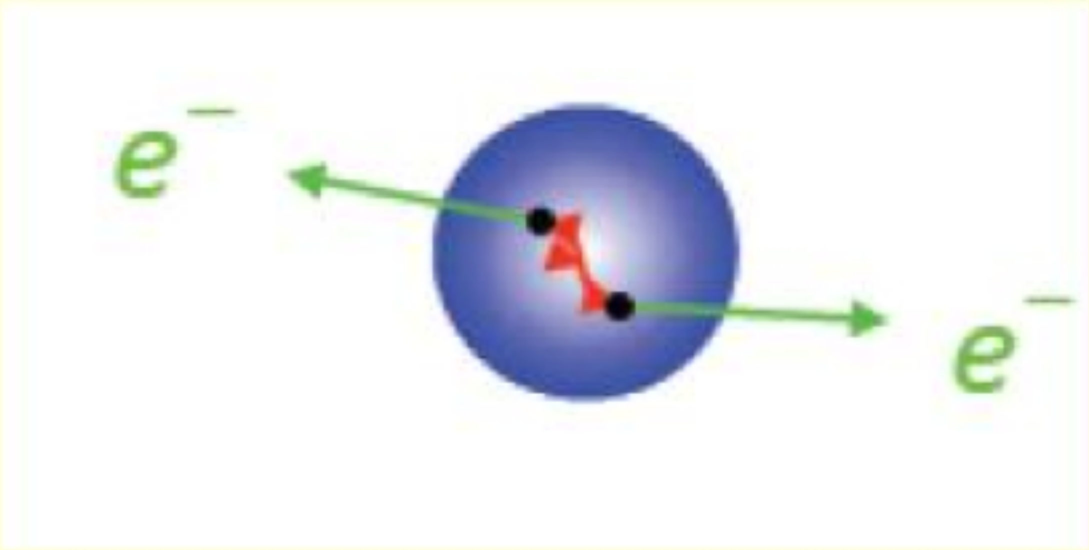


1. Double beta decay









in formule

$$J^\mu = \bar{\psi}_e \gamma_\mu \frac{1}{2}(1-\gamma_5)U$$

$$\text{All Reps}: \gamma^0 \gamma^{\mu\,\dagger} \gamma^0 = \gamma^\mu$$
$$\text{MR}: \gamma^0 \gamma^{\mu\,T} \gamma^0 = -\gamma^\mu$$

ovvero:

$$J^\mu = -U^T \frac{1}{2}(1+\gamma_5)\gamma^{\mu\,T}\gamma^0 \psi_e^C =$$
$$= U^T \gamma^0 \frac{1}{2}(1-\gamma_5)\gamma^\mu \psi_e^C$$

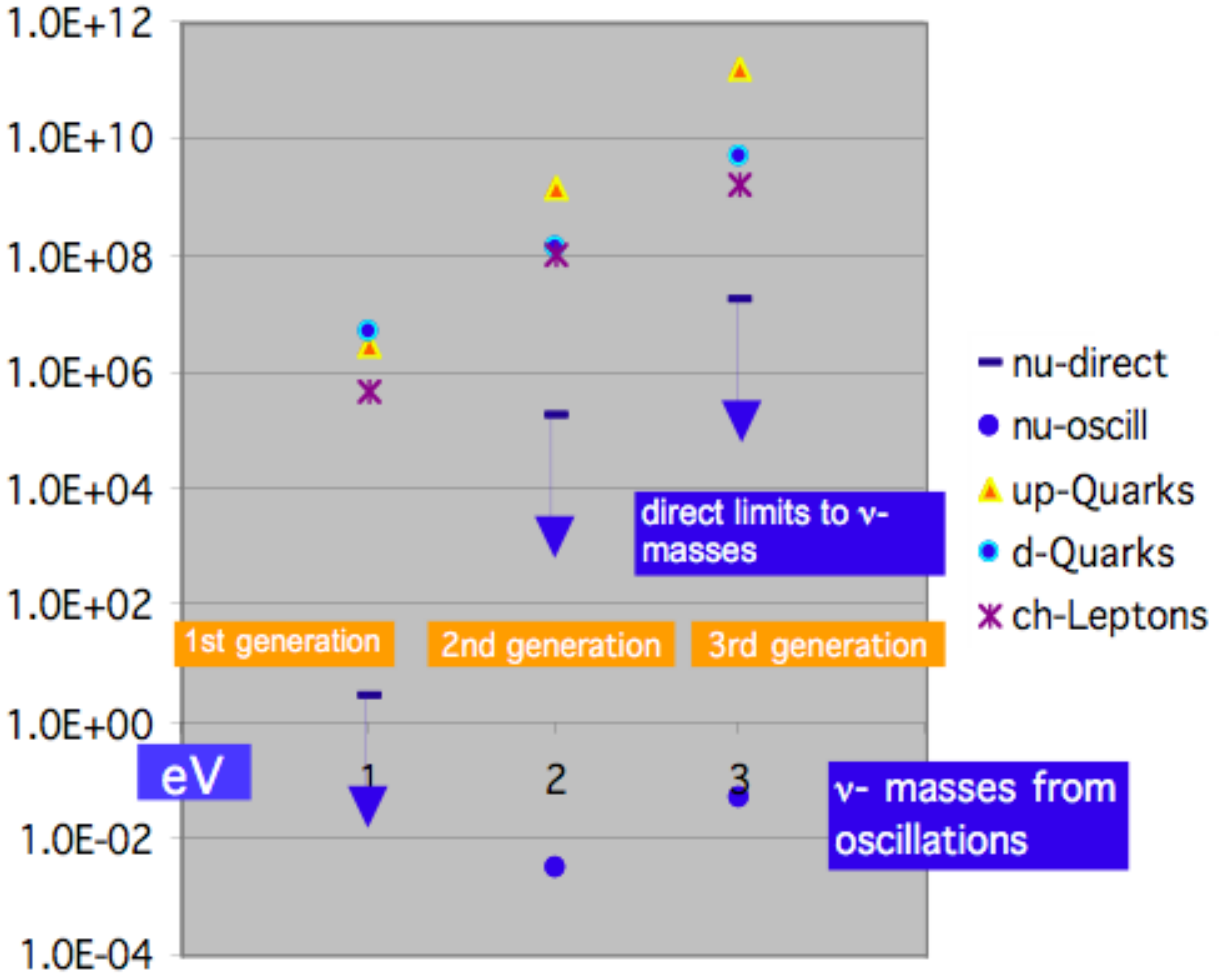
$$\beta\beta 0\nu = \mathrm{J}^\mu(x)\mathrm{J}^\nu(0) =$$
$$= \bar{\psi}_e \gamma_\mu \frac{1}{2}(1-\gamma_5) < 0|U(x)\ U^T(0)\gamma^0|0 > \frac{1}{2}(1-\gamma_5)\gamma^\nu \psi_e^C$$

$$< 0|U(x)\ U^T(0)\gamma^0|0 > \rightarrow \frac{\hat{k}+m}{k^2+m^2}$$

⇨

l' ampiezza doppio beta senza neutrini e' proporzionale a m_ν !

The spectrum of the elementary fermions



heaviest neutrino mass: 4 10^{-2} eV; top quark mass: 1.7 10^{+11} eV
about 13 orders of magnitude !!!

6. The rise of Majorana neutrinos: see-saw mechanism

In the 60s, no much attention was paid to the issue of Majorana neutrino:

if neutrinos are massless, as everybody believed, it did'nt matter.

The Standard Theory changed the situation and it came (slowly) to be realized that:

- chiral symmetry is broken, there is no reason a priori to expect massless neutrinos
- Dirac neutrino mass requires a right-handed (sterile) neutrino, but then why neutrinos are not as heavy as the charged leptons ?
- Majorana mass & weak isospin selection rule make it possible to find a natural explanation to the smallness of neutrino mass: the see-saw (Gell-Mann, Ramond & Slanski; Glashow...)

Neutrinos ***have to be*** Majorana !!!!

Selection rules for neutrino masses

$$\psi_1 = \nu_L + (\nu_L)^\dagger;\quad \frac{1}{2}M_1\psi_1\gamma^0\psi_1 = \frac{1}{2}M_1[\nu_L\gamma^0\nu_L + h.c.]$$

- this term has weak isospin=1, it cannot be produced by I=1/2 Higgs doublet: we expect $M_1 \approx 0$, or very small;

$$\frac{1}{2}M_D\psi_2\gamma^0\psi_1 = \frac{1}{2}M_D[(\nu_R)^\dagger\gamma^0\nu_L + h.c.]$$

- this term has I=1/2, so $M_D \approx$ normal lepton and quark masses;

$$\frac{1}{2}M_2\psi_2\gamma^0\psi_2 = \frac{1}{2}M_2[(\nu_R)^\dagger\gamma^0(\nu_R)^\dagger + h.c.]$$

- this term has I=0, does not violate the gauge symmetry and M_2 can be anything;
- most naturally: $M_2 \approx M_{GUT} \approx 10^{14\text{-}15}$ GeV.

Neutrino masses & mixing

- elegant solution, the see-saw:
  - ν_R exists with mass = M_{GUT}
  - the usual source (Higgs field) gives no mass to ν_L , but an off-diagonal ν_L-ν_R mass

$$\begin{pmatrix} 0 & M_D \\ M_D & M_{GUT} \end{pmatrix}$$

  - then ν_L acquires a Majorana mass:

$$m_\nu = \frac{M_D^2}{M_{GUT}}$$

- for the 3rd generation neutrino, we take M_D=m_{top}, M_{GUT}= 10^{15} GeV, and get: m_ν= 3 10^{-2} eV
- For comparison, the neutrino mass difference from SK oscillations (see later) is:

$$\sqrt{\Delta m_{23}^2} \approx 5 \cdot 10^{-2}\mathrm{eV}$$

see-saw gives the correct range obtained by SuperKamiokande from the oscillation of atmospheric neutrinos !!!

Other points of view

$$\mathcal{L}_{mass} = Cost\ \nu_L \gamma^0 \nu_L$$

- IW=1
- can ne obtained from a Higgs non renormalizabe coupling

$$\frac{1}{2}\bar{\ell}_L Y_\nu \tilde{H} \tilde{H}^T Y_\nu^T \ell_L^C + \mathrm{h.c.}$$

- natural to have a large scale in the denominator: Cost=m $^2/\Lambda$
- can be obtained in different way from renormalizable couplings with heaby particles