The Nature of the Neutrino (Dirac/Majorana) - Double Beta Decay with or without Neutrinos

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History of Neutrino
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Determining the status of lepton charge conservation and the nature - Dirac or Majorana - of massive neutrinos is one of the most challenging and pressing problems in present day elementary particle physics.

ν_j- Dirac or Majorana particles, **fundamental problem**

ν_j-Dirac: **conserved lepton charge exists,**
$L = L_e + L_\mu + L_\tau$, $\nu_j \neq \bar{\nu}_j$

ν_j-Majorana: **no lepton charge is exactly conserved**,
$\nu_j \equiv \bar{\nu}_j$

See-saw mechanism: ν_j- Majorana

The observed patterns of $\nu-$mixing and of Δm^2_{atm} and $\Delta m^2_{\odot}$ can be related to Majorana ν_j and a new fundamental (approximate) symmetry.

$$L' = L_e - L_\mu - L_\tau$$

S.T.P., 1982

Problem with the assumption L=const. leading to Dirac ν_j:

"In modern understanding of particle physics global symmetries are approximate." Global $U(1)$ symmetry leading to L=const. is expected to be broken by quantum gravity effects.

See E. Witten, 1710.01791; S. Weinberg, CERN Courier, 13 October 2017

Establishing that the total lepton charge $L = L_e + L_\mu + L_\tau$ is not conserved in particle interactions by observing the $(\beta\beta)_{0\nu}-$decay would be a fundamental discovery (similar to establishing baryon number nonconservation (e.g., by observing proton decay)).

Establishing that ν_j are Majorana particles would be of fundamental importance, as important as the discovery of $\nu-$ oscillations, and would have far reaching implications.

Current Challenging Problems:

- determination of the neutrino mass ordering (T2K + NOνA; JUNO; PINGU, ORCA; T2HK(K), DUNE);

- determination of the absolute neutrino mass scale, or $\min(m_j)$ (KATRIN, new ideas; cosmology);

- determination of the status of the CP symmetry in the lepton sector (T2K, NOνA; DUNE, T2HK+T2HKK).

The program of research extends beyond 2030.

1930, W. Pauli

Zurich, 4 December 1930
Gloriastr.

Physical Institute of the
Federal Institute of Technology (ETH)
Zurich

Dear radioactive ladies and gentlemen,

As the bearer of these lines, to whom I ask you to listen graciously, will explain more exactly, considering the “false” statistics of the N-14 and the Li-6 nuclei as well as the continuous β-spectrum, I have hit upon a desperate remedy to save the “exchange theorem” of statistics and the energy theorem. Namely [there is] the possibility that there can exist in the nuclei electrically neutral particles that I wish to call neutrons, which have a spin 1/2 and obey the exclusion principle, and additionally differ from the light quanta in that they do not travel with the velocity of light: The mass of the neutrons must be of the same order of magnitude as the electron mass and, in any case, not larger than 0.01 proton masses. – The continuous β-spectrum would then become understandable by the assumption that in β decay a neutron is emitted together with the electron, in such a way that the sum of the energies of neutron and electron is constant.

Now the next question is what forces act upon the neutrons. The most likely model of the neutron seems to me to be, on wave mechanical grounds (more details are known by the bearer of these lines), that the neutron at rest is a magnetic dipole of a certain moment μ. Experiment probably requires that the ionizing effect of such a neutron should not be larger than the of a γ ray, and thus μ should probably not be larger than $e.10^{-13}$ cm.

But I don’t feel secure enough to publish anything about this idea, so I first turn confidently to you, dear radioactives, with the question as to the situation concerning experimental proof of such neutron if it has something like about 10 times the penetrating capacity of a γ ray.

I admit that my remedy may appear to have a small a priori probability because neutrons, if they exist, would probably have long ago been seen. However, only those who wager can win, and the seriousness of the situation of the continuous β-spectrum can be made clear by the saying of my honored predecessor in office, Mr. Debye, who told me a short while ago in Brussels: “One does best not to think about that at all, like the new taxes.” Thus one should earnestly discuss every way of salvation. – So, dear radioactives, put it to the test and set it right.

Unfortunately I cannot personally appear in Tubingen, since I am indispensable here on account of a ball taking place in Zrich in the night from 6 to 7 of December.
With many greetings to you, also to Mr. Back,
Your devoted servant,

W. Pauli

1930: (A,Z) = A p + (A-Z)(e^-); (^{6}Li, ^{14}N???)

Pauli: (A,Z) = A p + (A-Z)(e^-) + ν; ^{6}Li, ^{14}N

Pauli: (A,Z)$\rightarrow$ (A,Z+1) + e^- + $\bar{\nu}$

1933, E. Fermi: $\beta-$ Decay Theory

In 1932 Chadwick discovered the neutron.

Fermi: ν not in (A,Z): n$\rightarrow$ p $+$ e$^-$ $+$ $\bar{\nu}$

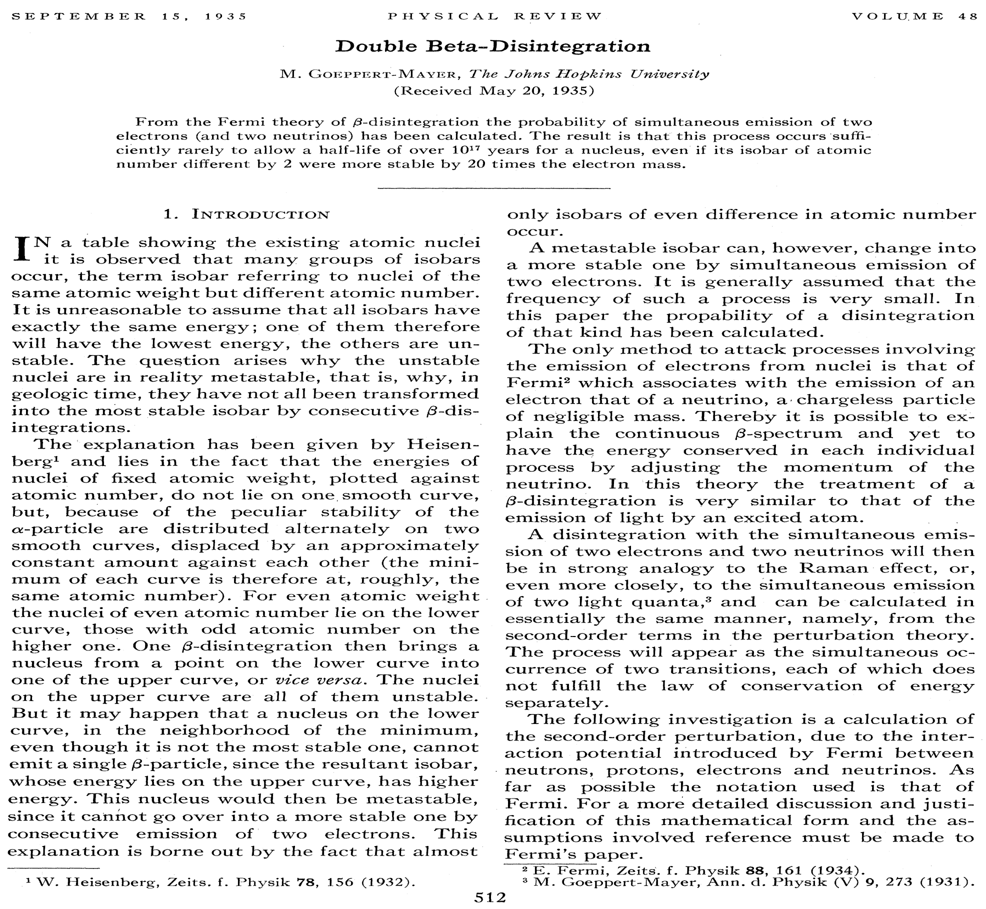
Following a suggestion by E. Amaldi, Fermi called ν “neutrino” (meaning “neutral, little (small)” in Italian).

In analogy with the Hamiltonian of electromagnetic interaction of the proton, Fermi supposed that the β-decay Hamiltonian has $(Vector) \times (Vector)$ form:

$$\mathcal{H}^{\beta}_{\mathcal{I}} = G_F\ \bar{p}(x)\gamma_{\alpha}n(x)\ \bar{e}(x)\gamma^{\alpha}\nu(x)\ +\ h.c.$$

1935, M. Geoppert-Mayer:

$$(A,Z) \rightarrow (A,Z+2) + e^- + e^- + \bar{\nu} + \bar{\nu}$$



SEPTEMBER 15, 1935 PHYSICAL REVIEW VOLUME 48

Double Beta-Disintegration

M. GOEPPERT-MAYER, *The Johns Hopkins University*

(Received May 20, 1935)

From the Fermi theory of β-disintegration the probability of simultaneous emission of two electrons (and two neutrinos) has been calculated. The result is that this process occurs sufficiently rarely to allow a half-life of over 10^{17} years for a nucleus, even if its isobar of atomic number different by 2 were more stable by 20 times the electron mass.

1. INTRODUCTION

IN a table showing the existing atomic nuclei it is observed that many groups of isobars occur, the term isobar referring to nuclei of the same atomic weight but different atomic number. It is unreasonable to assume that all isobars have exactly the same energy; one of them therefore will have the lowest energy, the others are unstable. The question arises why the unstable nuclei are in reality metastable, that is, why, in geologic time, they have not all been transformed into the most stable isobar by consecutive β-disintegrations.

The explanation has been given by Heisenberg[1] and lies in the fact that the energies of nuclei of fixed atomic weight, plotted against atomic number, do not lie on one smooth curve, but, because of the peculiar stability of the α-particle are distributed alternately on two smooth curves, displaced by an approximately constant amount against each other (the minimum of each curve is therefore at, roughly, the same atomic number). For even atomic weight the nuclei of even atomic number lie on the lower curve, those with odd atomic number on the higher one. One β-disintegration then brings a nucleus from a point on the lower curve into one of the upper curve, or *vice versa*. The nuclei on the upper curve are all of them unstable. But it may happen that a nucleus on the lower curve, in the neighborhood of the minimum, even though it is not the most stable one, cannot emit a single β-particle, since the resultant isobar, whose energy lies on the upper curve, has higher energy. This nucleus would then be metastable, since it cannot go over into a more stable one by consecutive emission of two electrons. This explanation is borne out by the fact that almost only isobars of even difference in atomic number occur.

A metastable isobar can, however, change into a more stable one by simultaneous emission of two electrons. It is generally assumed that the frequency of such a process is very small. In this paper the propability of a disintegration of that kind has been calculated.

The only method to attack processes involving the emission of electrons from nuclei is that of Fermi[2] which associates with the emission of an electron that of a neutrino, a chargeless particle of negligible mass. Thereby it is possible to explain the continuous β-spectrum and yet to have the energy conserved in each individual process by adjusting the momentum of the neutrino. In this theory the treatment of a β-disintegration is very similar to that of the emission of light by an excited atom.

A disintegration with the simultaneous emission of two electrons and two neutrinos will then be in strong analogy to the Raman effect, or, even more closely, to the simultaneous emission of two light quanta,[3] and can be calculated in essentially the same manner, namely, from the second-order terms in the perturbation theory. The process will appear as the simultaneous occurrence of two transitions, each of which does not fulfill the law of conservation of energy separately.

The following investigation is a calculation of the second-order perturbation, due to the interaction potential introduced by Fermi between neutrons, protons, electrons and neutrinos. As far as possible the notation used is that of Fermi. For a more detailed discussion and justification of this mathematical form and the assumptions involved reference must be made to Fermi's paper.

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[1] W. Heisenberg, Zeits. f. Physik **78**, 156 (1932).

[2] E. Fermi, Zeits. f. Physik **88**, 161 (1934).

[3] M. Goeppert-Mayer, Ann. d. Physik (V) **9**, 273 (1931).

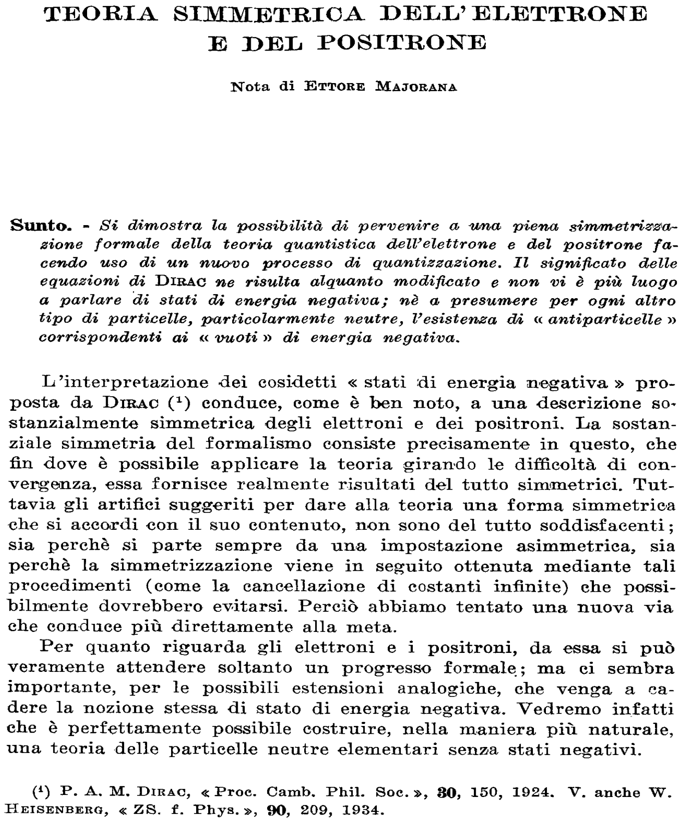
Even-even nuclei metastable ($\beta-$decay forbidden):

(A,Z)$\rightarrow$ (A,Z+2) + e$^-$ + e$^-$ + $\bar{\nu}$ + $\bar{\nu}$

2nd order in $\mathcal{H}_{\mathcal{I}}^{\beta}$: "the process - the simultaneous occurrence of two transitions, each of which does not fulfill the law of conservation of energy separately".

Concluded: $T_{1/2}^{2\nu} > 10^{17}$ y ($\sim 10^{20}$, Z=31).

1937, E. Majorana (Nuovo Cimento 14, p. 171)



TEORIA SIMMETRICA DELL'ELETTRONE E DEL POSITRONE

Nota di Ettore Majorana

Sunto. - *Si dimostra la possibilità di pervenire a una piena simmetrizzazione formale della teoria quantistica dell'elettrone e del positrone facendo uso di un nuovo processo di quantizzazione. Il significato delle equazioni di* Dirac *ne risulta alquanto modificato e non vi è più luogo a parlare di stati di energia negativa; nè a presumere per ogni altro tipo di particelle, particolarmente neutre, l'esistenza di « antiparticelle » corrispondenti ai « vuoti » di energia negativa.*

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. La sostanziale simmetria del formalismo consiste precisamente in questo, che fin dove è possibile applicare la teoria girando le difficoltà di convergenza, essa fornisce realmente risultati del tutto simmetrici. Tuttavia gli artifici suggeriti per dare alla teoria una forma simmetrica che si accordi con il suo contenuto, non sono del tutto soddisfacenti; sia perchè si parte sempre da una impostazione asimmetrica, sia perchè la simmetrizzazione viene in seguito ottenuta mediante tali procedimenti (come la cancellazione di costanti infinite) che possibilmente dovrebbero evitarsi. Perciò abbiamo tentato una nuova via che conduce più direttamente alla meta.

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.

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(1) P. A. M. Dirac, « Proc. Camb. Phil. Soc. », **30**, 150, 1924. V. anche W. Heisenberg, « ZS. f. Phys. », **90**, 209, 1934.

Majorana Neutrinos (Particles)

Can be defined in QFT using fields or states.

Fields: $\chi_k(x)$ - 4 component (spin 1/2), complex, m_k

Majorana condition:

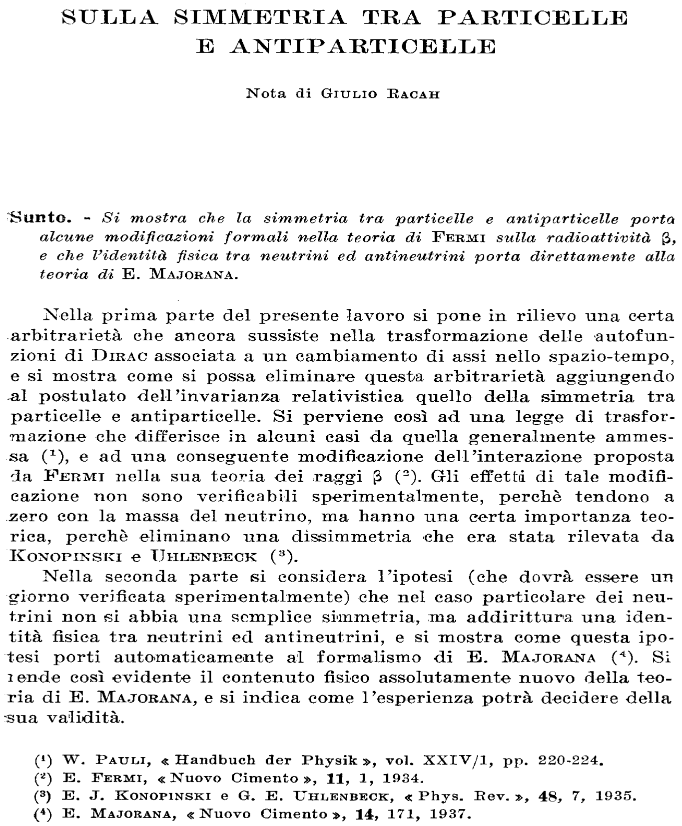
$$C\ (\bar{\chi}_k(x))^{\mathsf{T}} = \xi_k \chi_k(x), \quad |\xi_k|^2 = 1$$

– Invariant under proper Lorentz transformations.
– Reduces by 2 the number of components in $\chi_k(x)$.

Implications:

- $Q_{U(1)} = 0: \ \ Q_{\text{el}} = 0,\ \ L_l = 0,\ \ L = 0, \ldots$
- $\chi_k(x)$: 2 spin states of a spin 1/2 absolutely neutral particle
- $\chi_k \equiv \bar{\chi}_k$

1937, G. Racah (Nuovo Cimento 14, p. 322)



SULLA SIMMETRIA TRA PARTICELLE E ANTIPARTICELLE

Nota di GIULIO RACAH

Sunto. - *Si mostra che la simmetria tra particelle e antiparticelle porta alcune modificazioni formali nella teoria di* FERMI *sulla radioattività β, e che l'identità fisica tra neutrini ed antineutrini porta direttamente alla teoria di* E. MAJORANA.

Nella prima parte del presente lavoro si pone in rilievo una certa arbitrarietà che ancora sussiste nella trasformazione delle autofunzioni di DIRAC associata a un cambiamento di assi nello spazio-tempo, e si mostra come si possa eliminare questa arbitrarietà aggiungendo al postulato dell'invarianza relativistica quello della simmetria tra particelle e antiparticelle. Si perviene così ad una legge di trasformazione che differisce in alcuni casi da quella generalmente ammessa (¹), e ad una conseguente modificazione dell'interazione proposta da FERMI nella sua teoria dei raggi β (²). Gli effetti di tale modificazione non sono verificabili sperimentalmente, perchè tendono a zero con la massa del neutrino, ma hanno una certa importanza teorica, perchè eliminano una dissimmetria che era stata rilevata da KONOPINSKI e UHLENBECK (³).

Nella seconda parte si considera l'ipotesi (che dovrà essere un giorno verificata sperimentalmente) che nel caso particolare dei neutrini non si abbia una semplice simmetria, ma addirittura una identità fisica tra neutrini ed antineutrini, e si mostra come questa ipotesi porti automaticamente al formalismo di E. MAJORANA (⁴). Si rende così evidente il contenuto fisico assolutamente nuovo della teoria di E. MAJORANA, e si indica come l'esperienza potrà decidere della sua validità.

(¹) W. PAULI, « Handbuch der Physik », vol. XXIV/1, pp. 220-224.
(²) E. FERMI, « Nuovo Cimento », **11**, 1, 1934.
(³) E. J. KONOPINSKI e G. E. UHLENBECK, « Phys. Rev. », **48**, 7, 1935.
(⁴) E. MAJORANA, « Nuovo Cimento », **14**, 171, 1937.

"Sunto. - Si mostra che la simmetria tra particelle e antiparticelle porta alcune modificazioni formali nella teoria di Fermi sulla radioattivita' β, e che l'identita' fisica tra neutrini ed antineutrini porta direttamente alla teoria di E. Mjorana."

"...un neutrino emesso in un processo β^- puo' indurre per assorbimento soltanto un processo β^+, e vice versa. Le interazioni (10a) e (10b) portano percio' all'esistenza di due tipi di neutrini perfettamente distinti.
Se l'esperienza dovesse un giorno dimostrare che tale distinzione in natura non esiste, cioe' che qualsiasi neutrino puo' produrre indifferentemente emissione di elettroni e di positrni..."

Racah: if $\nu = \bar{\nu}$, (A,Z) $\rightarrow$ (A,Z+1) + e^- + $\bar{\nu}$,
$\bar{\nu}$ + (A,Z+1) $\rightarrow$ (A,Z+2) + e^- .

If $\nu \neq \bar{\nu}$ - Dirac, (A,Z) $\rightarrow$ (A,Z+1) + e^- + $\bar{\nu}$,
$\bar{\nu}$ + (A,Z+1) $\rightarrow$ (A,Z+2) + e^+ .

Racah did not discuss neutrinoless double beta ($(\beta\beta)_{0\nu}-$)decay, but rather pointed out how it might be possible to distinguish between Majorana and Dirac neutrinos in the processes of inverse $\beta-$ decay using free neutrino fluxes (B. Pontecorvo, 1983).

1939, W. Furry (following Majorana and Racah)

DECEMBER 15, 1939 PHYSICAL REVIEW VOLUME 56

On Transition Probabilities in Double Beta-Disintegration

W. H. Furry
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(Received October 16, 1939)

The phenomenon of double β-disintegration is one for which there is a marked difference between the results of Majorana's symmetrical theory of the neutrino and those of the original Dirac-Fermi theory. In the older theory double β-disintegration involves the emission of four particles, two electrons (or positrons) and two antineutrinos (or neutrinos), and the probability of disintegration is extremely small. In the Majorana theory only two particles—the electrons or positrons—have to be emitted, and the transition probability is much larger. Approximate values of this probability are calculated on the Majorana theory for the various Fermi and Konopinski-Uhlenbeck expressions for the interaction energy. The selection rules are derived, and are found in all cases to allow transitions with $\Delta i = \pm 1, 0$. The results obtained with the Majorana theory indicate that it is not at all certain that double β-disintegration can never be observed. Indeed, if in this theory the interaction expression were of Konopinski-Uhlenbeck type this process would be quite likely to have a bearing on the abundances of isotopes and on the occurrence of observed long-lived radioactivities. If it is of Fermi type this could be so only if the mass difference were fairly large ($\epsilon \gtrsim 20$, $\Delta M \gtrsim 0.01$ unit).

I. INTRODUCTION

THE probability of double β-disintegration was calculated some years ago by Goeppert-Mayer[1] on the basis of the Fermi theory.[2, 3] The result obtained was extremely small, corresponding to a lifetime of the order of 10^{25} years in the case of two isobars whose masses differ by 0.002 mass unit and whose atomic numbers differ by two units. Thus one can account for the large number of isobaric pairs with $\Delta Z = 2$, as compared to the scarcity of isobars with $\Delta Z = 1$. Although not strictly stable, the heavier isobar of a pair with $\Delta Z = 2$ may be supposed to be metastable, having a lifetime large compared to geologic time.

An inspection of the calculations shows that the results would not be changed by any significant factor by the use of an expression for the interaction energy involving derivatives of the neutrino wave function, as suggested by Konopinski and Uhlenbeck.[4] The same is true as regards the generalizations in structure of this expression,[5] which make it possible to obtain selection rules[6] for ordinary β-decay decidedly different from those originally given by Fermi. The original Fermi picture of the fundamental interaction processes concerned in β-decay has now been generally supplanted by a picture in which mesons play the role of mediaries between the heavy particles and the electrons and neutrinos. In this case also, as is evident from a consideration of the arguments of Yukawa,[7] the results of Goeppert-Mayer will remain unchanged.

The situation is, however, decidedly altered if one admits a change in the theory of the neutrino itself as an elementary particle. Such a change was suggested by Majorana[8] in a paper on the symmetry properties of the Dirac theory. Majorana's suggestions have been more generally developed in the case of the positron theory by Kramers,[9] and for the neutral particle by the writer.[10] Racah[11] has also discussed the application to the neutrino theory of β-decay.

The essential difference between the Majorana theory of the neutrino and the usual form of the Dirac theory is that in the former there are only

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[1] M. Goeppert-Mayer, Phys. Rev. **48**, 512 (1935).

[2] E. Fermi, Zeits. f. Physik **88**, 161 (1934).

[3] For a review of the theory and its various modifications and applications up to the beginning of 1936, see pages 186–206 of the article by Bethe and Bacher, Rev. Mod. Phys. **8** (1936).

[4] E. J. Konopinski and G. E. Uhlenbeck, Phys. Rev. **48**, 7 (1935).

[5] Cf. reference 3, pp. 190–192.

[6] G. Gamow and E. Teller, Phys. Rev. **49**, 895 (1936).

[7] H. Yukawa, Proc. Phys.-Math. Soc. Japan, **17**, 55–56 (1935); H. Yukawa, S. Sakata, M. Kobayasa and M. Taketani, Proc. Phys.-Math. Soc. Japan **20**, 731–734 (1938).

[8] E. Majorana, Nuovo Cimento **14**, 171 (1937).

[9] H. A. Kramers, Proc. Amsterdam Akad. **40**, 814 (1937).

[10] W. H. Furry, Phys. Rev. **54**, 56 (1938), referred to as *N*.

[11] G. Racah, Nuovo Cimento **14**, 322 (1937).

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Furry: if $\nu = \bar{\nu}$ (Majorana), (A,Z)$\rightarrow$ (A,Z+2) + e^- + e^- possible.

n + n $\rightarrow$ p + p + e^- + e^-: n's exchange virtual ν

Calculations with Fermi-like (4 f) interaction: S×S, PS×PS, V×V, A×A, $m_\nu = 0$.

Concluded: due to the phase space factors, it is possible to have $T^{0\nu}_{1/2} \sim 10^{-5} \times T^{2\nu}_{1/2}$ (compared to $T^{2\nu}_{1/2}$ found by Goeppert-Mayer (Z=31)).

1940 - 1960, Experiments

The main motivation for experiments searching for $(\beta\beta)_{2\nu}-$ and $(\beta\beta)_{0\nu}-$ decays - the question of the nature - Dirac or Majorana - of the neutrino.
Theory: $T^{0\nu}_{1/2} \sim 10^{15}$ yr (M), $T^{2\nu}_{1/2} \sim 10^{21}$ yr (D).

The first experiment: 1948, E.L. Fireman (Phys. Rev. 74 (1948) 1238), ^{124}Sn (25 g, enriched to 54%), Geiger counters: $T^{2\beta}_{1/2} > 3 \times 10^{15}$ yr.

Positive results claimed with
^{124}Sn (E.L. Fireman, Phys. Rev. 75 (1949) 323),
^{100}Mo (J.H. Fremlin, M.C. Walters, Proc.Phys.Soc. London, Sect. A 65 (1952) 911),
^{48}Ca (J.A. McCarthy, Phys. Rev. 97 (1955) 1234),
^{96}Zr (J.A. McCarthy, Phys. Rev. 90 (1953) 853),
disproved by later experiments.

First seraches for (A,Z) → (A,Z-2) + e^+ + e^+ and e^- + (A,Z) → (A,Z-2) + e^+ performed (J.H. Fremlin, M.C. Walters, Proc.Phys.Soc. London, Sect. A 65 (1952) 911; A. Berthelot *et al.*, Compt. Rend. 236 (1953) 1769).

Most advanced experimentalmethods and detectors were used: nuclear emulsion, Geiger, proportional, and scintillation counters, Wilson chamber.

Enriched isotopes (^{48}Ca, ^{94}Zr, ^{96}Zr, ^{124}Sn) were widely used.

Detectors were placed relatively deep underground (to suppress the background from cosmic rays).

Passive and active shieldings were used.

The sensitivity reached was $\sim 10^{17}$–10^{18} yr.

The first experiment searching for $(\beta\beta)_{0\nu}-$ and $(\beta\beta)_{2\nu}-$ decay in the USSR was perform in 1956 (E.N. Dobrokhotov *et al.*, Dokl. Akad. Nauk SSSR 110 (1956) 966 (Sov. Phys. Dokl. 1 (1956) 600)).

A. Barabash, arXiv:1104.2714

In 1949, the first geochemical experiment was performed searching for

$^{130}\text{Te} \rightarrow {}^{130}\text{Xe} + e^- + e^- \, (+\, \bar{\nu} + \bar{\nu})$ (M.G. Inghram, J.H. Reynolds, Phys. Rev. 76 (1949) 1265).

The technique: separation of Xenon from ancient (up to several billion years old) minerals and subsequent isotope analysis. The detection of excess amount of ^{130}Xe (after accounting for contributions from various nuclear reactions induced by neutrons, cosmic rays, etc.) would imply that the decay $(\beta\beta)_{0\nu}$ and/or $(\beta\beta)_{2\nu}$ of ^{130}Te took place.

The authors obtained: $T^{2\beta}_{1/2}(^{130}\text{Te}) > 8\times 10^{19}$ yr.

In 1950 M.G. Inghram and J.H. Reynolds using the same method detected $2\beta^-$ decay of ^{130}Te with $T^{2\beta}_{1/2}(^{130}\text{Te}) = 1.4 \times 10^{21}$ yr (Phys. Rev. 78 (1950) 822).

The 2016 CUORE-0 result on $T^{2\nu}_{1/2}(^{130}\text{Te})$ reads:

$T^{2\nu}_{1/2}(^{130}\text{Te}) = [8.2 \pm 0.2\ (\text{stat.}) \pm 0.6\ (\text{syst.})]\times 10^{20}$ yr

(C. Alduino *et al.*, EPJ C 77 (2017) 13 [arXiv:1609.01666]).

1940 - 1960, Related Developments

1956-1957, Neutrino observed: C.L. Cowan, F. Reines, $\bar{\nu} + \mathrm{p} \rightarrow \mathrm{n} + \mathrm{e}^{+}$

1956 - 1957, Parity Non-Conservation: T.D. Lee, C.N. Yang; C.S. Wu
(T. D. Lee and C. N. Yang, Phys. Rev. 104 (1956) 254; C. S. Wu *et al.*, Phys. Rev. 105 (1957) 1413).

1957, the Two-Component Neutrino Theory: L.D. Landau; T.D. Lee and C.N. Yang; A. Salam.
$m_\nu = 0$; $\nu_L(x)$, $\nu_R(x)$ - independent: only one of the two enters into $\mathcal{H}_{\mathcal{I}}^{\beta}$(x)
(L.D. Landau, Nucl. Phys. 3 (1957) 127; T.D. Lee and C.N. Yang, Phys. Rev. 105 (1957) 1671; A. Salam, Nuovo Cim. 5 (1957) 299).

1958, M. Goldhaber *et al.*: $\nu_L(x)$
($e^{-} + \mathrm{Eu} \rightarrow \mathrm{Sm}^{*} + \nu$, $\mathrm{Sm}^{*} \rightarrow \mathrm{Sm} + \gamma$; the γ-quantum polarization is correlated with the neutrino helicity (M. Goldhaber, L. Grodzins and A.W. Sunyar, Phys. Rev. 109 (1958) 1015)).

1958, The V-A theory: R.P. Feynman and M. Gell-Mann; E.C.G. Sudarshan and R.E. Marshak.
In 1958 the *universal V-A current×current theory of weak interaction* **was proposed; incorporated the idea of μ - e universality (B. Pontecorvo, 1947).**

All fermion fields in $\mathcal{H}_{\mathcal{I}}^{\mathcal{CC}}$ - left-handed: f(x) → f$_L$(x)

$\mathcal{H}_{\mathcal{WI}}^{\mathcal{CC}} = \frac{G_F}{\sqrt{2}}\; j^{\alpha}(x)\; (j_{\alpha}(x))^{\dagger}$,

$j_{\alpha}(x) = 2\left[\bar{p}_L(x)\gamma_{\alpha}n_L(x) + \bar{\nu}_{eL}(x)\gamma_{\alpha}e_L(x) + \bar{\nu}_{\mu L}(x)\gamma_{\alpha}\mu_L(x)\right]$

(R.P. Feynman and M. Gell-Mann, Phys. Rev. 109 (1958) 193; E.C.G. Sudarshan and R.E. Marshak, Phys. Rev. 109 (1958) 1860).

R.P. Feynman and M. Gell-Mann (following Lee, Rosenbluth and Yang (1949, IVB theory):)

$\mathcal{L}_{\mathcal{WI}}^{\mathcal{CC}} = -\frac{g}{2\sqrt{2}}\, j_{\alpha}(x)\, W^{\alpha}(x) + h.c.$, **W$^{\alpha}$(x): W$^{\pm}$-boson field.**

Pontecorvo, 1958:

$\nu(x) = \frac{\chi_1+\chi_2}{\sqrt{2}}$, $\chi_{1,2}$ - **Majorana, $m_1 \neq m_2 > 0$,** $\eta_{1CP} = -\eta_{2CP}$; **maximal mixing.**

The hypothesis of existence of fermion mixing in $\mathcal{H}^{CC}_{\mathcal{WI}}$ put forward for the first time.

Maki, Nakagawa, Sakata, 1962:

$$\nu_{eL}(x) = \Psi_{1L}\cos\theta_C + \Psi_{2L}\sin\theta_C,$$
$$\nu_{\mu L}(x) = -\Psi_{1L}\sin\theta_C + \Psi_{2L}\cos\theta_C,$$

$\Psi_{1,2}$ - **Dirac (composite),** θ_C- **the Cabbibo angle.**

The Period 1960 - 1980

The discovery of the V-A structure of $\mathcal{L}^{CC}_{\mathcal{WI}}$:
$T^{0\nu}_{1/2} >> T^{2\nu}_{1/2}$ possible (and most likely).

1960, Greuling+Whitten

(V-A)$_e$ + ν_e-Majorana with $m_\nu = 0 \rightarrow$ L=const., $\Gamma^{0\nu} = 0$.
$\Gamma^{0\nu} \neq 0$, if ν_e-Majorana with $m_\nu \neq 0$, or with $m_\nu = 0$ but (V-A)$_e$ + δ(V+A)$_e$.
For $\delta = 0$, $m_\nu \neq 0$, $\Gamma^{0\nu} \propto m^2_\nu$;
for $m_\nu = 0$, $\Gamma^{0\nu} \propto (\delta)^2$.
Thus, $T^{0\nu}_{1/2}$ ($\Gamma^{0\nu}$) calculated for the first time assuming Majorana $m_\nu \neq 0$; the presence of concomitant RH (V+A) currents was considered as well (E. Greuling, R.C. Whitten, Ann. Phys (N.Y.) 11 (1960) 510).

1966: Counter experiment with calcium fluoride **crystal** with 11.4 g of ^{48}Ca (enriched to 96.6%) performed; the scheme **"detector ≡ source"** realised for the first time. $T^{2\beta}_{1/2}(^{48}\mathrm{Ca}) > 2 \times 10^{20}$ yr obtained (E. der Mateosian, M. Goldhaber, Phys. Rev. 146 (1966) 810).

1967: Fiorini *et al.* used for the first time **Ge(Li) detector**. $T^{0\nu}_{1/2}(^{76}\mathrm{Ge}) > 3 \times 10^{20}$ yr reported. In 1973 $T^{0\nu}_{1/2}(^{76}\mathrm{Ge}) > 5 \times 10^{21}$ yr reached (E. Fiorini *et al.*, Phys. Lett. B 25 (1967) 602; Nuovo Cimento A 13 (1973) 747).

1967, 1970, 1975: C.S. Wu *et al.* realised two experiments using the "tracking technique" (visualization of tracks and measurement of the energy of electrons). Obtained
$T^{0\nu}_{1/2}(^{48}\mathrm{Ca}) > 2.0 \times 10^{21}$ yr, $T^{0\nu}_{1/2}(^{82}\mathrm{Se}) > 3.1 \times 10^{21}$ yr (R.K. Bardin *et al.*, Phys. Lett. B 26 (1967) 112; Nucl. Phys. A 158 (1970) 337; B.T. Cleveland *et al.*, Phys. Rev. Lett. 35 (1975) 757.).

1966-1975: Several geochemical experiments with ^{130}Te, ^{82}Se and ^{128}Te were performed by N. Takaoka *et al.* (1966), T. Kirsten *et al.* (1967) and O.K. Manuel *et al.* (1975). Confirmed the 1950 result with ^{130}Te,

obseved $(\beta\beta)_{2\nu}$ of ^{82}Se (T. Kirsten *et al.*),
of ^{128}Te (O.K. Manuel *et al.*)

and determined $T^{2\beta}_{1/2}(^{130}\mathrm{Te})/T^{2\beta}_{1/2}(^{128}\mathrm{Te})$

(N. Takaoka *et al.*, Z. Naturforsch. A 21 (1966) 84; T. Kirsten *et al.*, Z. Naturforsch. 22a (1967) 1783 and Z. Phys. 202 (1967) 273; O.K. Manuel *et al.*, Phys. Rev. C 11 (1975) 1378).

1960 - 1980: Related Developments

1967, B. Pontecorvo:
$\nu_R(x)-$ "sterile", "inert"; considered $\nu_e \rightarrow \nu_\mu$ and $\nu_e \rightarrow \nu_s$ (i.e., "active-sterile") neutrino oscillations; predicted the "solar neutrino deficit".

1969, V. Gribov, B. Pontecorvo:
Majorana mass term for $\nu_{eL}(x)$ and $\nu_{\mu L}(x)$; massive neutrinos: $\nu_{1,2}$, $m_{1,2} \neq 0$ - Majorana particles.

$\mathcal{L}^{\nu}_{M}(x) = \frac{1}{2}\,\nu^{T}_{l'L}(x)\;C^{-1}\;M_{l'l}\;\nu_{lL}(x)$ + h.c., $C^{-1}\gamma_\alpha C = -\gamma_\alpha^{T}$

$\nu_{lL}(x)-$fermions: $M = M^{T}$, considered real M.

$M^{diag} = O^{T}\,M\,O$, O-orthogonal

$\chi_j(x) = O^{T}_{jl}\nu_{lL}(x) + O_{jl}\nu^{c}_{lR} = C(\overline{\chi_j}(x))^{T}$, $m_j \neq 0$.

B. Pontecorvo, Sov.Phys.JETP 26 (1968) 984, Zh.Eksp.Teor.Fiz. 53 (1967) 1717; V. Gribov, B. Pontecorvo, Phys.Lett. 28B (1969) 493.

1976, S.M. Bilenky, B. Pontecorvo:

Dirac+Majorana mass term with $\nu_{\ell L}(x)$ and $\nu_{\ell R}(x)$ (used in the seesaw mechanism); massive neutrinos: ν_j, j=1,2,...,6, $m_j \neq 0$ - Majorana particles.

$$\mathcal{L}^{\nu}_{D+M}(x) = -\overline{\nu_{l'R}}(x) M_{Dl'l}\, \nu_{lL}(x) + \frac{1}{2}\nu^{T}_{l'L}(x) C^{-1} M^{LL}_{l'l}\, \nu_{lL}(x) + \frac{1}{2}\nu^{T}_{l'R}(x) C^{-1} (M^{RR})^{\dagger}_{l'l}\, \nu_{lR}(x) + \text{h.c.},$$

$$(M^{LL})^{T} = M^{LL},\ (M^{RR})^{T} = M^{RR}$$

$$M = \begin{pmatrix} M^{LL} & M_D \\ M_D^{T} & M^{RR} \end{pmatrix} = M^{T}$$

If $M_{Dl'l} \neq 0$ and $M^{LL}_{l'l} \neq 0$ and/or $M^{RR}_{l'l} \neq 0$:

$L_l \neq const.$, $L \neq const.$; n = 6 (>3)

$M = M^{T}$, complex; $M^{diag} = W^{T} M W$, W-unitary, 6×6; $W^{T} \equiv (U^{T}\ \ V^{T})$; $U \equiv U_{\text{PMNS}}$: 3×6.

$\nu_{lL}(x) = \sum_{j=1}^{6} U_{lj}\chi_j(x)$, $\chi_j(x)$ - Majorana νs, $m_j \neq 0$, $l = e,\mu,\tau$;

$\nu^{C}_{lL}(x) \equiv C(\overline{\nu_{lR}}(x))^{T} = \sum_{j=1}^{6} V_{lj}\,\chi_j(x)$, $\nu^{C}_{lL}(x)$: sterile antineutrino

$\mathcal{L}^{\nu}_{D+M}(x)$ possible in the ST + ν_{lR}: $M^{LL} = 0$.

S.M. Bilenky, B. Pontecorvo, Lett.Nuovo Cim. 17 (1976) 569.

1977, A. Halprin *et al.* (PR D13, 2567):

$j_\alpha^{(e)}(x) = \bar{e}\gamma_\alpha\left[(1+\gamma_5) + \eta(1-\gamma_5)\right]\nu_e$,

$\nu_e -$ **"γ_5 non-invariant Majorana particle".**

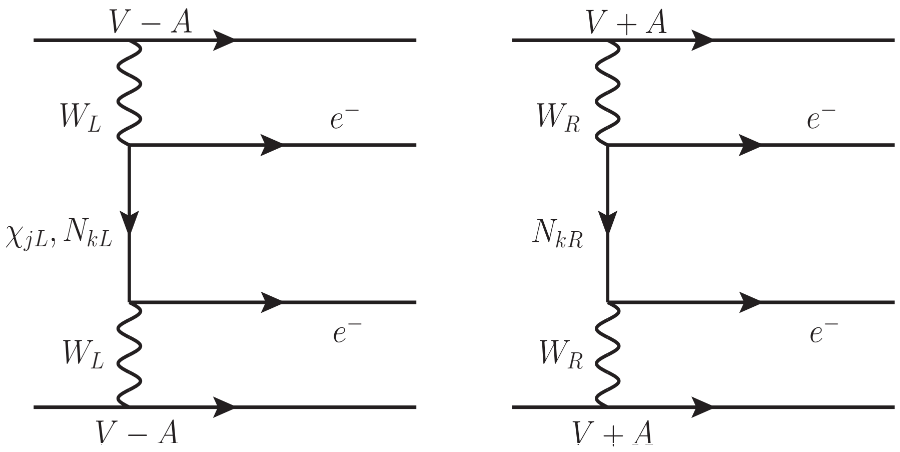
Existing data on $(\beta\beta)_{0\nu}$-decay: m$_\nu$=0, $\eta < 5\times10^{-4}$.

If η=0, m$_\nu$=60 eV (current limit),

$\Gamma_{th}^{0\nu} < (300)^{-1}\Gamma_{exp.lim}^{0\nu}$.

$j_\alpha^{(e)} = \bar{e}\gamma_\alpha(1-\gamma_5)\nu_e + \bar{e}\gamma_\alpha(1\mp\gamma_5)N_e$, **N$_e$-heavy Majorana.**

Existing data on $(\beta\beta)_{0\nu}$-decay: M$_N$ <1 keV, or M$_N$ >3 GeV.

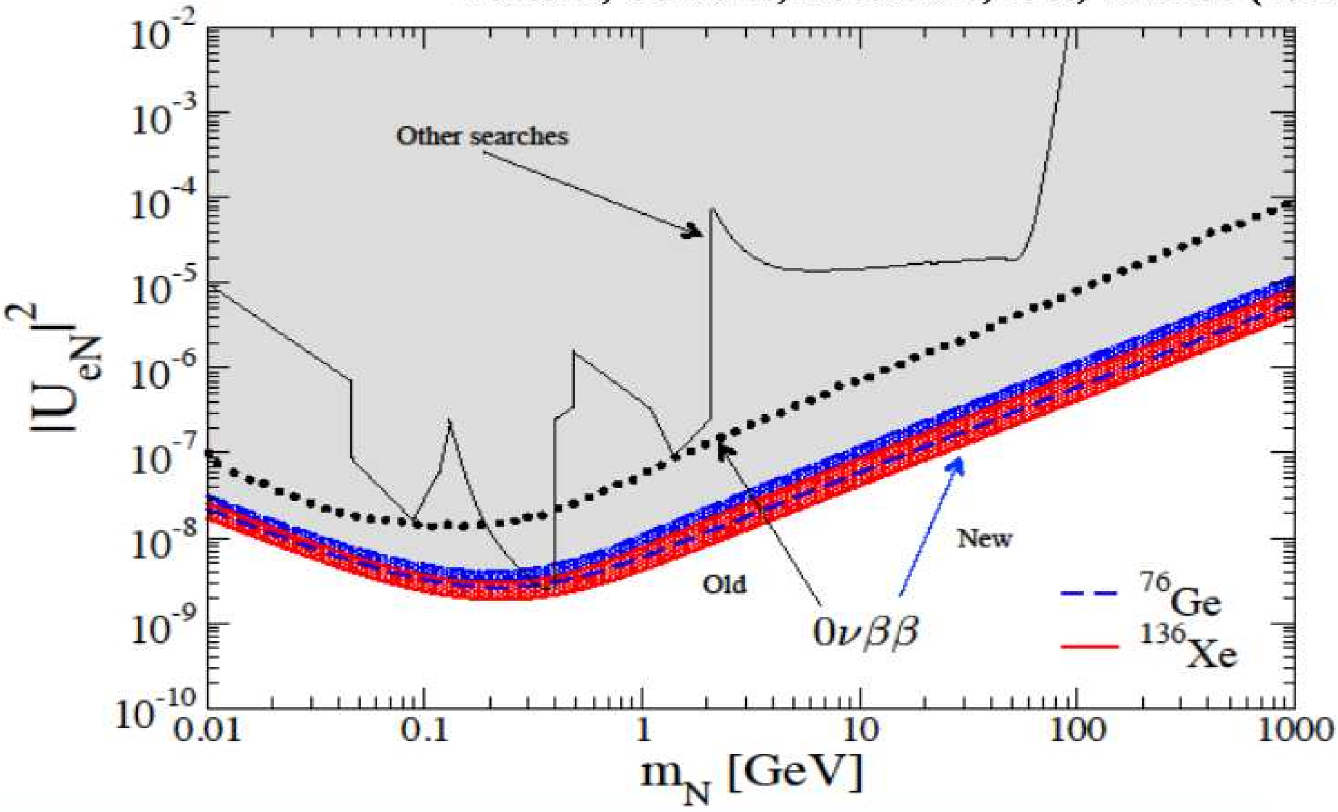


$$j_\alpha^{(e)} = 2\,\bar{e}\,\gamma_\alpha U_{ek}\,\chi_{kL} + 2\bar{e}\,\gamma_\alpha\,U_{ej}^N\,N_{jL}$$

Exclusion plot in $|U_{eN}|^2 - m_N$ plane

$T^{0\nu}_{1/2}(^{76}Ge) \geq 3.0\ 10^{25}$ yr
$T^{0\nu}_{1/2}(^{136}Xe) \geq 3.4\ 10^{25}$ yr

Faessler, Gonzales, Kovalenko, F. Š., PRD 90 (2014) 096010]



Improvements: i) **QRPA** (constrained Hamiltonian by 2νββ half-life, self-consistent treatment of src, restoration of isospin symmetry …), ii) **More stringent limits on the 0νββ half-life**

F. Simkovic, October 2017

The Period 1980s - 1990s (Revival of Interest)

Gauge theories (extensions of the ST, GUTs) naturally incorporating L-nonconservation and massive Majorana neutrinos were proposed.

Seesaw mechanism leading naturally to L-nonconservation and massive Majorana neutrinos was proposed. Leptogensis scenario of BAU, relating the ν-mass generation vis seesaw with the generation of the matter-antimatter asymmtry of the Universe was proposed (M. Fukugita, T. Yanagida, Phys. Lett. B174 (1986) 45).

Massive neutrino ($m_{\nu} \sim$ 40 eV) was cosidered as a plausible (hot) dark matter candidate.

Lubimov et al. claimed in 1980 the observation of a neutrino mass of $\sim$ 20 eV in an ITEP tritium β-decay experiment (V.A. Lubimov et al., Phys. Lett. B94 (1980) 266; this claim was proven to be incorrect later by independent experiments.).

1980, Majorana Phases

S.M. Bilenky, J. Hosek, S.T.P., May 1980;
J. Schechter, J.F.W. Valle, June 1980;
M. Doi, T. Kotani, E. Takasugi, July 1980.

$\chi_k(x)$-4 component (spin 1/2), Majorana, m$_k \neq 0$:

C$(\bar{\chi}_k(x))^{\mathsf{T}} = \xi_k \chi_k(x)$, $|\xi_k|^2 = 1$.

U(1): χ_k(x) $\rightarrow e^{i\beta}\chi_k$(x)- impossible!
$\chi_k(x)$ cannot absorb phases.

j$_\alpha^{(lep)} = 2\,\bar{l}(x)\,\gamma_\alpha\, U_{lk}\, \chi_{kL}(x)$, U = VP; n families,

V: (n-1)(n-2)/2 Dirac CPV phases;

P = diag$(1, e^{i\frac{\alpha_{21}}{2}}, e^{i\frac{\alpha_{31}}{2}}, ..., e^{i\frac{\alpha_{n1}}{2}})$ - (n-1) Majorana CPV phases;
n=3, V: 1 Dirac CPV phase; P: 2 Majorana CPV phases.
n=2, V: CP conserving; P: 1 Majorana CPV phase.

S.M. Bilenky, J. Hosek, S.T.P., May 1980

$\mathbf{j}_{\alpha}^{(lep)} = 2\,\bar{l}(x)\,\gamma_{\alpha}\,U_{lk}\,\chi_{kL}(x)$, **U = VP**

$\nu_l \leftrightarrow \nu_{l'}$, $\bar{\nu}_l \leftrightarrow \bar{\nu}_{l'}$, $l, l' = e, \mu, \tau$, **not sensitive to the Majorana CPV phases and thus to the nature of ν_j.**

$A(\nu_l \leftrightarrow \nu_{l'}) = \sum_j U_{l'j} e^{-i(E_j t - p_j x)} U^{\dagger}_{jl}$,

U = VP: $\mathbf{P}_j e^{-i(E_j t - p_j x)} \mathbf{P}_j^{*} = e^{-i(E_j t - p_j x)}$

P - **diagonal matrix of Majorana phases.**

The result is valid also in the case of oscillations in matter (P. Langacker *et al.*, Nucl. Phys. B282 (1987) 589).

$\nu_l \leftrightarrow \nu_{l'}$ **oscillations are not sensitive to the nature of ν_j.**

M. Doi, T. Kotani, E. Takasugi, July 1980

$\mathbf{A}(\beta\beta)_{0\nu} \propto <m>$ **M(A,Z),** **M(A,Z) - NME,**

$$|<m>| = \left| m_1 |U_{e1}|^2 + m_2 |U_{e2}|^2\ e^{i\alpha_{21}} + m_3 |U_{e3}|^2\ e^{i\alpha_{31}} \right|$$

α_{21}, α_{31} $((\alpha_{31} - 2\delta) \rightarrow \alpha_{31})$ - **the two Majorana CPVP of the PMNS matrix.**

$\mathbf{A}(\beta\beta)_{0\nu}$ - **strong dependence on the Majorana CPVP; cancellations between the three terms in** $|<m>|$ **possible.**

L. Wolfenstein, 1981: $\chi(x)$- **Majorana**

$\mathbf{U}_{CP}\,\chi(\mathbf{x})\mathbf{U}_{CP}^{\dagger} = \eta_{CP}\,\gamma_0\,\chi(x')$, $\eta_{CP} = \pm i$

CP-invariance: $\alpha_{21} = 0, \pm\pi$, $\alpha_{31} = 0, \pm\pi$;

$\eta_{21} \equiv e^{i\alpha_{21}} = \pm 1, \quad \eta_{31} \equiv e^{i\alpha_{31}} = \pm 1$

relative CP-parities of ν_1 **and** ν_2**, and of** ν_1 **and** ν_3**.**

(L. Wolfenstein, Phys. Lett. B107 (1981) 77;
S.M. Bilenky, N.P. Nedelcheva and S.T. Petcov, Nucl. Phys. B247 (1984) 61; B. Kayser, Phys. Rev. D30 (1984) 1023).

1980, Wigner's question: ν_L, ν_R, D+M (seesaw) mass term,

$$M \;=\; \begin{pmatrix} 0 & m_D \\ m_D & M^{RR} \end{pmatrix} = M^T \,,\;\; m_D \ll M^{RR} - \text{real}\,;$$

Wigner: χ, **m** $\cong -\frac{m_D^2}{M^{RR}}$; **C**$(\bar{\chi}(x))^{\mathsf{T}}$**=**$\chi(x)$;
N, M $\cong$ **M**^{RR}, **C**$(\bar{N}(x))^{\mathsf{T}}$**=**$N(x)$.

If, e.g., M> 0, **m=**$\rho\,|m|$ $<$**0,** $\rho = -1$**???**

1981: M - CP invariant: M***=M (M**^{T}**=M);**
m=$\rho\,|m|$ $<$**0,** $\rho = -1$ **- physical;**
χ'**=**$\gamma_5\chi$, **m′=**$|m| > 0$: $\eta_{CP}(\chi') = i\,\rho = -\,i$
($\eta_{CP}(\chi)$**=**i, η_{CP}**(N)=**i).

M***=M, M**^{T}**=M:** $|n_+ - n_-|$ **- invariant of M**
(n_+ **(**n_-**) - the number of positive (negative) eigenvalues).**

1981: 2β decay + emission of Majoron:

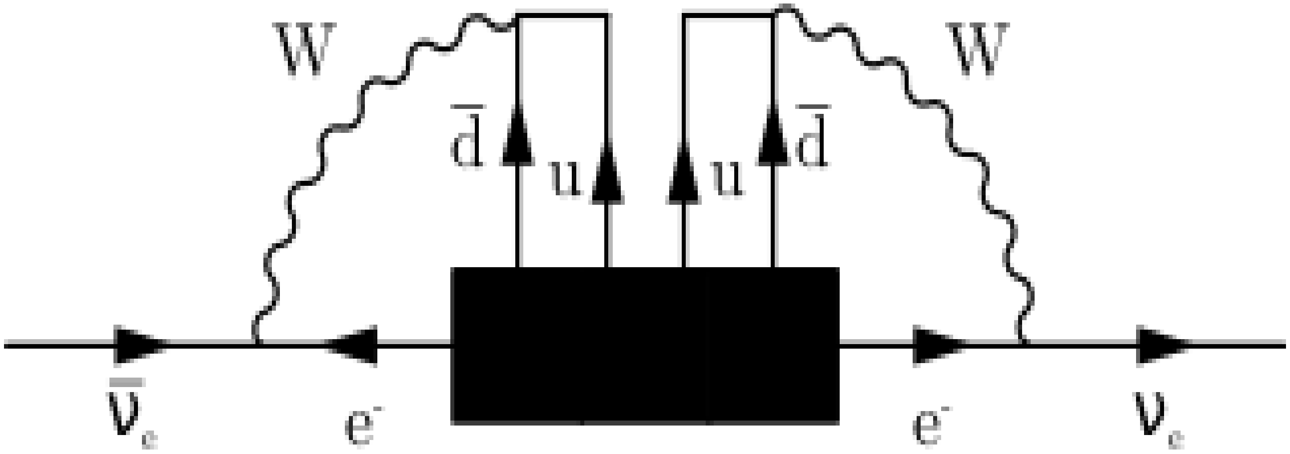
$(A, Z) \rightarrow (A, Z+2) + 2e^{-} + \phi^{0}$;

The Majoron ϕ^0 - massless Goldstone boson associated with the spontaneous breaking of $U(1)_L$ symmetry related to L=const. (ϕ^0 can play important role in cosmology and astrophysics).
(H.M. Georgi, S.L. Glashow, S. Nussinov, Nucl. Phys. B193 (1981) 297 (see also Y. Chikashige, R.N. Mohapatra, R.D. Peccei, Phys. Lett. B98 (1981) 265; C.S. Aulakh, R.N. Mohapatra, Phys. Lett. B119 (1982) 136; G.B. Gelmini, M. Roncadelli, Phys. Lett. B99 (1981) 411)).

1982, J. Schechter, J.F.W. Valle (Black Box Theorem):

The observation of $(\beta\beta)_{0\nu}$−decay imply (in GT) the existence of a Majorana mass term of ν_e.

(Became serious theoretical motivation for continuing the experimental seraches for $(\beta\beta)_{0\nu}$−decay with increasing sensitivity.)



d + d → u + u + e$^-$ + e$^-$ - EOs

+ β−decay $\mathcal{L}^{CC}_{\mathcal{WI}}$ + m$_{u,d}$ ≠0, m$_e$ ≠0;

u → d + virtual W$^+$, virtual W$^+$ → e$^+$ + ν_e:

virtual u + virtual $\bar{d}$ → virtual W$^+$ + virtual e$^-$ → ν_e.

(J. Schechter, J.F.W. Valle, Phys. Rev. D25 (1982) 2951)

2011, M. Duerr, M. Lindner, A. Merle:

"We evaluate the Schechter-Valle (Black Box) theorem quantitatively by considering the most general Lorentz invariant Lagrangian consisting of point-like operators for neutrinoless double beta decay. It is well known that the Black Box operators induce Majorana neutrino masses at four-loop level. This warrants the statement that an observation of neutrinoless double beta decay guarantees the Majorana nature of neutrinos. We calculate these radiatively generated masses and find that they are many orders of magnitude smaller than the observed neutrino masses and splittings:

$$\delta \mathbf{m}_\nu = \delta \mathbf{m}_\nu(\mathbf{m}_u,\mathbf{m}_d,\mathbf{m}_e,\mathbf{M}_W,\mu,\mathbf{G}_F,\mathbf{m}_p,\epsilon_3) = 5\times 10^{-28}\ \mathbf{eV}\ (\mu = 100\ \mathbf{MeV}, \epsilon_3 = 1.5\times 10^{-8}).$$

Although the principal statement of the Schechter-Valle theorem remains valid, we conclude that the Black Box diagram itself generates radiatively only mass terms which are many orders of magnitude too small to explain neutrino masses. Therefore, other operators must give the leading contributions to neutrino masses, which could be of Dirac or Majorana nature." (M. Duerr, M. Lindner, A. Merle, arXiv:1105.0901, JHEP (2011))

($\mathcal{L}^{0\nu} = \frac{G_F^2}{2m_p}[\epsilon_1 \mathbf{J}\mathbf{J}\mathbf{j} + \epsilon_2 \mathbf{J}^{\alpha\beta}\mathbf{J}_{\alpha\beta}\mathbf{j} + \epsilon_3 \mathbf{J}^{\alpha}\mathbf{J}_{\alpha}\mathbf{j}\ \epsilon_3 \mathbf{J}^{\alpha}\mathbf{J}_{\alpha}\mathbf{j} + \epsilon_4 \mathbf{J}^{\alpha}\mathbf{J}_{\alpha\beta}\mathbf{j}^{\beta} + \epsilon_5 \mathbf{J}^{\alpha}\mathbf{J}\mathbf{j}_{\alpha}]$,
$\mathbf{J} = \bar{u}(1\pm\gamma_5)\mathbf{d}$, $\mathbf{J}^{\alpha} = \bar{u}\gamma^{\alpha}(1\pm\gamma_5)\mathbf{d}$, $\mathbf{J}^{\alpha\beta} = \bar{u}\sigma^{\alpha\beta}(1\pm\gamma_5)\mathbf{d}$,
$\mathbf{j} = \bar{e}(1\pm\gamma_5)\mathbf{e}^c$, $\mathbf{j}^{\alpha} = \bar{e}\gamma^{\alpha}(1\pm\gamma_5)\mathbf{e}^c$; $\delta\mathbf{m}_\nu$ due to the term $\propto \epsilon_3 \mathbf{J}_R^{\alpha}\mathbf{J}_{\alpha R}\mathbf{j}_L$)

1984-1986, NME Calculation Problem Discussed

W. Haxton, G.J. Stephenson,Jr., 1984

(Prog. Part. Nucl. Phys. 12 (1984) 409).

Pointed out, in particular, that the NMEs for $(\beta\beta)_{0\nu}$ and $(\beta\beta)_{2\nu}$ are not related.

M. Doi, T. Kotani, E. Takasugi, 1985

(Prog. Theor. Phys. Suppl. 83 (1985) 1).

Basic theoretical work on the calculation of the NME for the $(\beta\beta)_{2\nu}$ and $(\beta\beta)_{0\nu}$ decays. Energy and angular distribution of the two e^{-} calculated for the ν mass and RH current mechanisms; pointed out to the possibility to distinguish experimentaly between the two mechanisms using the difference between the respective distributions.

P. Vogel, M.R. Zirnbauer, 1986

(Phys. Rev. Lett. 57, 3148 (1986) 3148)

Demonstrated that the inclusion of the particle-particle interaction in a nucleus within the quasiparticle random phase approximation (QRPA) method permits to calculate the rate of the $(\beta\beta)_{2\nu}$ decay with a relatively small uncertainties. This result led to extensive use of the QRPA models for the calculation of NME for $(\beta\beta)_{2\nu}$ and $(\beta\beta)_{0\nu}$ decays.

Experimental Activity (1980-2000)

The experimental activity increased significantly. The use of detectors with passive and active shielding located very deep underground (e.g., Gran Sasso Lab.) built with low background materials led to a substantial reduction of the background. Large (several to few$\times$10 kg relatively cheap high purity germanium (HPGe) detectors became) available and many experiments were performed with ^{76}Ge. These developments led to an increase of sensitivity by several orders of magnitude: several collaborations reported limits on $T^{0\nu}_{1/2}$ of $\sim 10^{23}$-10^{25} y.

$T^{0\nu}_{1/2}(^{76}\mathrm{Ge}) > 1.2 \times 10^{24}$ y (90% C.L.) was reported by D. Caldwell using ~7.2-kg high-purity natural Ge (7.8% ^{76}Ge) semiconductor detectors (inside of NaI anticoincedence shield, which was inside a high purity Pb shield, at a depth of 600 m w.e.) (D.O. Caldwell, J. Phys. G17 (1991) S137).

In 1987, semiconductor Ge(Li) detectors grown from Ge enriched in ^{76}Ge at 85% were used for the first time in the ITEP/YePI experiment: $T^{0\nu}_{1/2}(^{76}\mathrm{Ge}) > 2 \times 10^{24}$ y (68% C.L.), $T^{2\nu}_{1/2}(^{76}\mathrm{Ge}) = (9 \pm 1) \times 10^{20}$ y, $T^{0\nu,M}_{1/2}(^{76}\mathrm{Ge}) > 1.2 \times 10^{20}$ y (A.A. Vasenko et al., in ***Proc. of the 2nd Int. Symposium on Underground Physics'87*****, Baksan Valley, USSR, Aug. 17–19, 1987 (Nauka, Moscow, 1988), p. 288; Mod. Phys. Lett. A 5 (1990) 1299).**

This progress led to Heidelberg–Moscow and IGEX experiments with enriched ^{76}Ge with sensitivity to $T^{0\nu}_{1/2}(^{76}\mathrm{Ge})$ of $\sim 10^{25}$ y (H.V. Klapdor-Kleingrothaus et al., Eur. Phys. J. A12 (2001) 147; C.E. Aalseth et al. [IGEX Collab.], Phys. Rev. C65 (2002) 09007).

$T^{0\nu}_{1/2}$(^{136}Xe)$>3.4\times10^{23}$ y was obtained by R. Luescher et al. in a time projection chamber experiment with 3.3-kg Xe enriched in ^{136}Xe to 62%, in which E_{2e} was measured, events with the simultaneous emission of $2e^-$ from one point were selected and the tracks of electrons were reconstructed (R. Luescher et al., Phys. Lett. B434 (1998) 407).

In 1984 Fiorini and Niinikoski proposed (following the idea of G.V. Mizelmaher, B.S. Neganov, V.N. Trofimov from JINR Dubna (Communication JINR P8-82-549, Dubna, 1982 (in Russian))
to use low-temperature (bolometer) detectors to search for $(\beta\beta)_{2\nu}$ and $(\beta\beta)_{0\nu}$ decays (E. Fiorini, T.O. Niinikoski, Nucl. Instrum. Methods Phys. Res. 224, 83 (1984) 83). The Milano group successfully developed this method (in CUORICINO, CUORE experiments).

Breakthrough experimental result: in 1987 M. Moe et al. observed for the first time $(\beta\beta)_{2\nu}$ decay of ^{82}Se (36 events detected in a direct counter experiment with a time projection chamber): $\mathrm{T}^{2\nu}_{1/2}(^{82}\mathrm{Se})=1.1^{+0.8}_{-0.3}\times 10^{20}$ y (S.R. Elliott, A.A. Hahn, M.K. Moe, Phys. Rev. Lett. 59 (1987) 2020).

In the 1990s the $(\beta\beta)_{2\nu}$ decay was observed
of ^{76}Ge by ITEP/YePI Collaboration (245 m under ground)
(A.A. Vasenko et al., Mod. Phys. Lett. A5 (1990) 1299),
of ^{100}Mo, ^{150}Nd, and ^{48}Ca by M. Moe et al. (S.R. Elliott et al., J. Phys. G17 (1991) S145; A. De Silva et al., Phys. Rev. C56 (1997) 2451; A. Balysh et al., Phys. Rev. Lett. 77 (1996) 5186),
of ^{100}Mo and ^{116}Cd by H. Ejiri et al. (H. Ejiri et al., Phys. Lett. B258 (1991) 17 and J. Phys. Soc. Jpn 64 (1995) 339),
of ^{100}Mo, ^{116}Cd, ^{82}Se and ^{96}Zr by NEMO-2 Collaboration (measured also the energy spectra and angular distributions of electrons) (D. Dassié et al., Phys. Rev. D51 (1995) 2090; R. Arnold et al., JETP Lett. 61 (1995) 170, Z. Phys. C72 (1996) 239, Nucl. Phys. A636 (1998) 209 and Nucl. Phys. A658 (1999) 299).

Geochemical experiments: actively conducted in the 1980s; essentially stopped to the end of the 1990s.
In 1993, the first geochemical experiment with ^{96}Zr was performed, $T^{2\beta}_{1/2}(^{96}\text{Zr}-^{96}\text{Mo})=(3.9\pm0.9)\times10^{19}$ y (A. Kawashima et al., Phys. Rev. C47 (1993) 2452).

T. Kirsten et al. found $T^{2\beta}_{1/2}(^{130}\text{Te})\sim2.7\times10^{21}$ y,

while O.K. Manuel reported $T^{2\beta}_{1/2}(^{130}\text{Te})\sim0.8\times10^{21}$ y

(T. Kirsten et al., in *Proc. of the Int. Symposium on Nuclear Beta Decay and Neutrino (Osaka'86)* (World Sci., Singapore, 1986), p. 81; O.K. Manuel, *ibid.*, p. 71).

Similarly, T. Bernatowicz et al. obtained $T^{2\beta}_{1/2}(^{128}\text{Te})\sim7.7\times10^{24}$ y, while N. Takaoka et al. found $T^{2\beta}_{1/2}(^{128}\text{Te})\sim2\times10^{24}$ y

(T. Bernatowicz et al., Phys. Rev. C47 (1993) 806; N. Takaoka et al.,Z. Naturforsch. A21 (1966) 84 and Phys. Rev. C53 (1996) 1557).

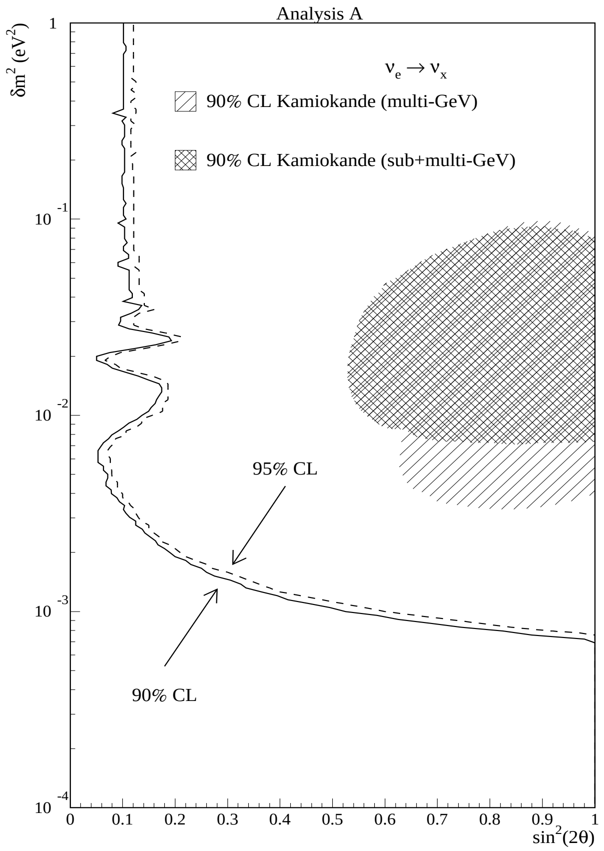
The origins of these discrepancies were not understood at the time; later the smaller values were shown to be correct.

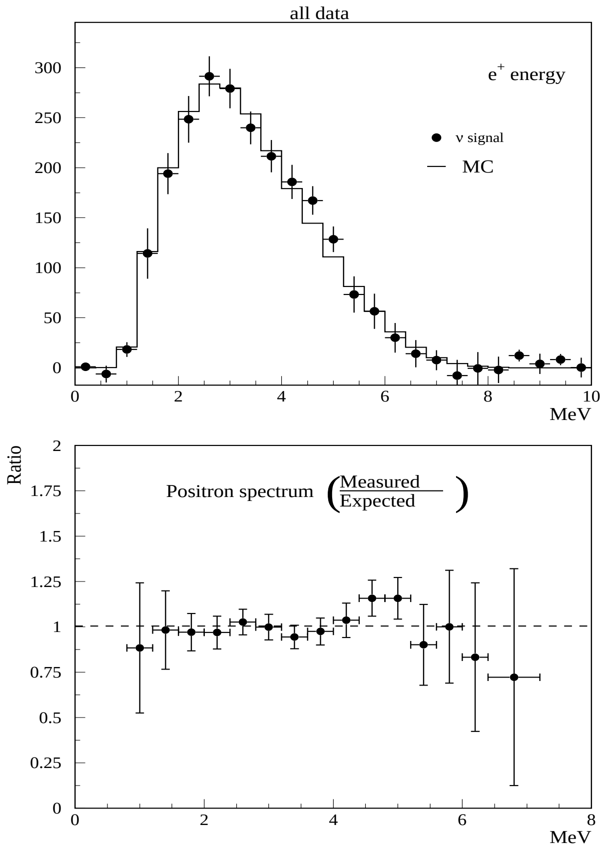
First Decade of 21st Century

1998: atmospheric ν_μ, $\bar{\nu}_\mu$ oscillations discovered.

2001-2002: solar ν_e flavour conversion proven to take place.

1998: the CHOOZ experiment obtained a strong limit on $\sin^2 2\theta_{13}$.

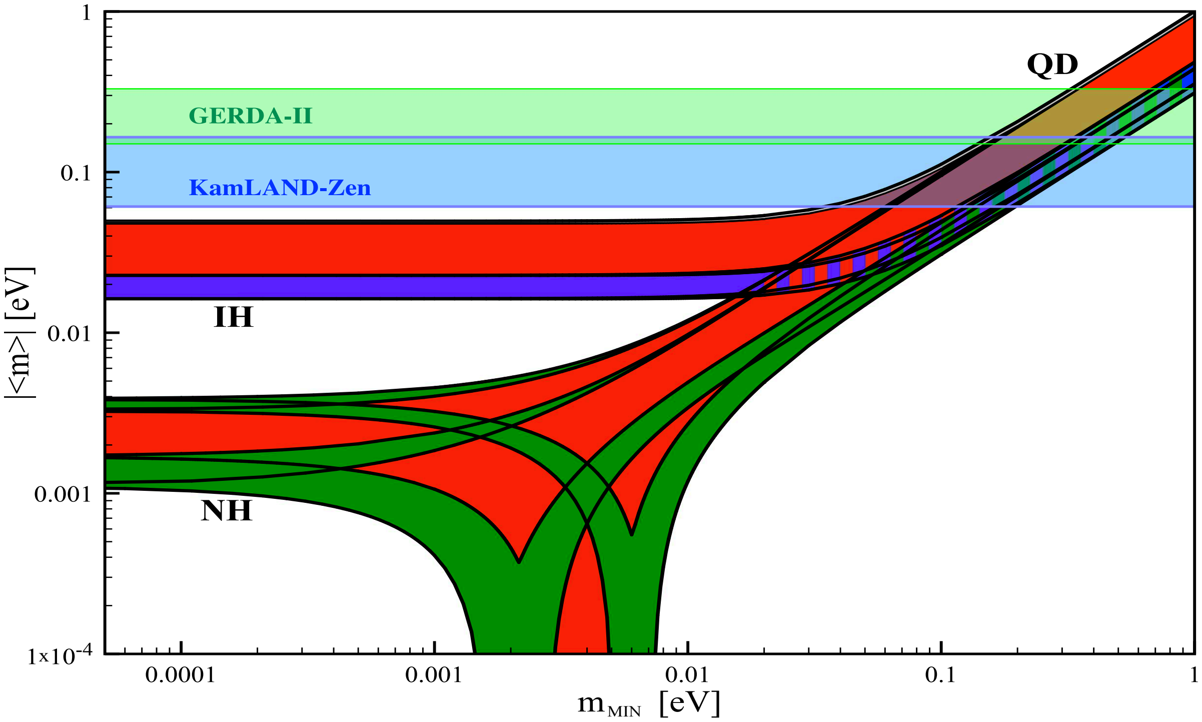




$\Delta m^2_{\rm atm}$, $\Delta m^2_{\odot}$, $\sin^2\theta_{12}$ **determined with a relatively good precision;**
$\sin^2\theta_{13} < 0.05$ **(CHOOZ).**

These developments led to the realisation that the $(\beta\beta)_{0\nu}$–decay experiments (via the measurement of $|<m>|$) can provide information on:

- **the neutrino mass spectrum (NH, IH, QD),**
- **absolute neutrino mass scale,**
- **on the Majorana phases (requires input on $\min(m_j)$).**



S. Pascoli, RPP (PDG), 2017

Experiments with ^{76}Ge: IGEX, Heidelberg-Moscow

IGEX experiment with ^{76}Ge (6.5 kg Ge enriched in ^{76}Ge at 85%; Canfranc tunnel, Spain)

$T^{0\nu}_{1/2}(^{76}\mathrm{Ge}) > 1.57\times 10^{25}$ y (90% C.L.)
(C.E. Aalseth et al., Phys. Rev. C 65 (2002) 09007).

Heidelberg–Moscow experiment with ^{76}Ge (11 kg Ge enriched in ^{76}Ge at 85%)

2001: $T^{0\nu}_{1/2}(^{76}\mathrm{Ge}) > 1.9 \times 10^{25}$ y

(H.V. Klapdor-Kleingrothaus et al. [H-M Collab.], Eur. Phys. J. A 12 (2001) 147).

2001, H.V. Klapdor-Kleingrothaus et al.:
$T^{0\nu}_{1/2}(^{76}\mathrm{Ge}) = 1.5 \times 10^{25}$ y (H.V. Klapdor-Kleingrothaus et al., Mod. Phys. Lett. A 16 (2001) 2409).
The Moscow part of the H-M Collab. disagreed with this claim (A.M. Bakalyarov et al., Phys. Part. Nucl. Lett. 2 (2005) 77; hep-ex/0309016).
2004: $T^{0\nu}_{1/2}(^{76}\mathrm{Ge}) = 1.19 \times 10^{25}$ y (H.V. Klapdor-Kleingrothaus, I.V. Krivosheina, A. Dietz, O. Chkvorets, Phys. Lett. B 586 (2004) 198).
2006: $T^{0\nu}_{1/2}(^{76}\mathrm{Ge}) = 2.23^{+0.44}_{-0.31} \times 10^{25}$ y (H.V. Klapdor-Kleingrothaus, I.V. Krivosheina, Mod. Phys. Lett. A 21 (2006) 1547).

Critisised in a number of articles.

Proven to be incorrect by the results of GERDA experiment:

$$T^{0\nu}_{1/2}(^{76}\mathrm{Ge}) > 8.0 \times 10^{25}\mathrm{yr\,at\,90\%\,C.L.,}\ \ \mathrm{GERDA\ II}\,.$$

$$|\!<m>\!|\ < (0.16 - 0.26)\ \mathrm{eV}\,.$$

M. Agostini et al., arXiv:1710.07776

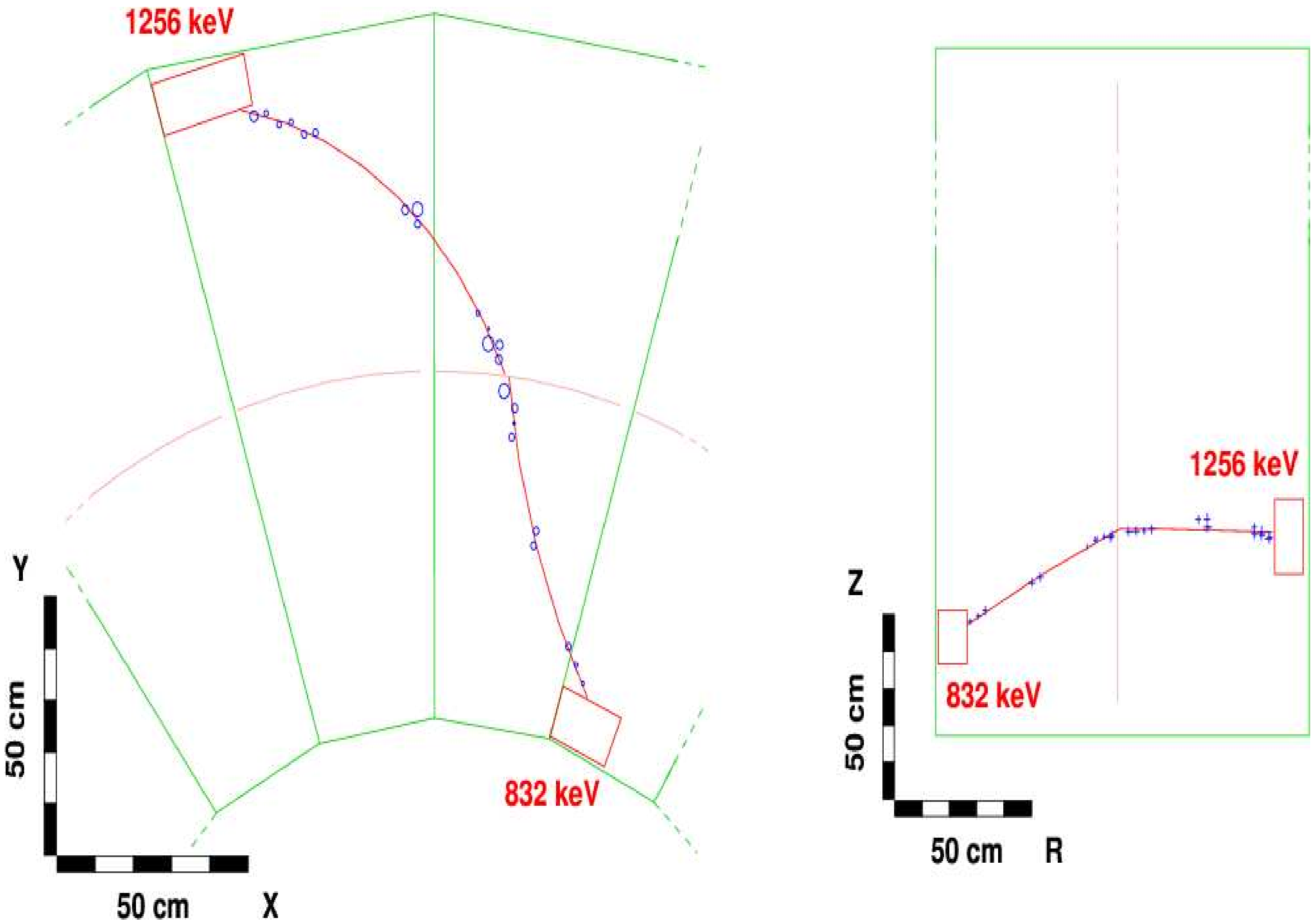
CUORICINO (completed in 2008) and NEMO-3 (completed in 2011) Experiments.

CUORICINO, ^{130}Te (40 kg): $T^{0\nu}_{1/2}(^{130}\text{Te}) > 2.8 \times 10^{24}$ y

(C. Arnaboldi et al., Phys. Rev. Lett. 95 (2005) 142501; E. Andreotti et al., Astropart. Phys. 34 (2011) 822).

NEMO-3, ^{100}Mo (10 kg) and other nuclei:
$T^{0\nu}_{1/2}(^{100}\text{Mo}) > 1.1 \times 10^{24}$ y (90%)

(R. Arnold et al., Nucl. Phys. A 765 (2006) 483; J. Argyriades et al., *ibid.* A 847 (2010) 168).
More than 700 000 (!) $(\beta\beta)_{2\nu}$ events were detected for ^{100}Mo with almost zero background; measured also the individual energy spectra and angular distribution of electrons. The $(\beta\beta)_{2\nu}$ half-lifes of ^{48}Ca, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{130}Te and ^{15}Nd measured.



NEMO-3 event.

Isotope	$T_{1/2}(2\nu)$**, yr**
^{48}**Ca**	$4.4^{+0.6}_{-0.5} \times 10^{19}$
^{76}**Ge**	$(1.5 \pm 0.1) \times 10^{21}$
^{82}**Se**	$(0.92 \pm 0.07) \times 10^{20}$
^{96}**Zr**	$(2.3 \pm 0.2) \times 10^{19}$
^{100}**Mo**	$(7.1 \pm 0.4) \times 10^{18}$
^{100}**Mo–**^{100}**Ru(**0^+_1**)**	$5.9^{+0.8}_{-0.6} \times 10^{20}$
^{116}**Cd**	$(2.8 \pm 0.2) \times 10^{19}$
^{128}**Te**	$(1.9 \pm 0.4) \times 10^{24}$
^{130}**Te**	$6.8^{+1.2}_{-1.1} \times 10^{20}$
^{150}**Nd**	$(8.2 \pm 0.9) \times 10^{18}$
^{150}**Nd–**^{150}**Sm(**0^+_1**)**	$1.33^{+0.45}_{-0.26} \times 10^{20}$
^{238}**U**	$(2.0 \pm 0.6) \times 10^{21}$
^{130}**Ba, ECEC(**2ν**)**	$(2.2 \pm 0.5) \times 10^{21}$

Values of $T^{2\nu}_{1/2}$ measured by 2010
(from A.S. Barabash, Phys. Rev. C 81 (2010) 035501).

Geochemical experiments were revived.
Experiments with ^{96}**Zr** (M.E. Wieser, J.R. De Laeter, Phys. Rev. C 64 (2001) 024308),
^{100}**Mo** (H. Hidaka, C.V. Ly, K. Suzuki, Phys. Rev. C 70 025501 (2004) 025501),
^{130}**Ba** (A.P. Meshik et al., Phys. Rev. C 64 (2001) 035205),
and ^{130}**Te** (A.P. Meshik et al., Nucl. Phys. A 809 (2008) 275; H.V. Tomas et al., Phys. Rev. C 78 (2008) 054606)
were performed.
Attempts was made to explain the existing discrepancies in the geochemical experiments with ^{130}Te (A.P. Meshik et al., Nucl. Phys. A 809 (2008) 275; H.V. Tomas et al., Phys. Rev. C 78 (2008) 054606).
The results found for ^{96}Zr and ^{100}Mo were not consistent with the results of the counter experiments.

Latest Results (2017 - 2018):

$$\mathbf{T(^{76}Ge)} > 8.0 \times 10^{25}\mathrm{yr\ at\ 90\%\ C.L.,\ \ GERDA\ \ II}\,.$$

M. Agostini et al., arXiv:1710.07776

$$\mathbf{T(^{130}Te)} > 1.5 \times 10^{25}\mathrm{yr\ at\ 90\%\ C.L.}\,,$$

$$|\!<\!m\!>\!| \ < (0.14 - 0.40)\ \mathrm{eV}\,,\ \ \mathrm{CUORE} + \mathrm{CUORICINO}\,.$$

S. Alduino et al., arXiv:1710.07988

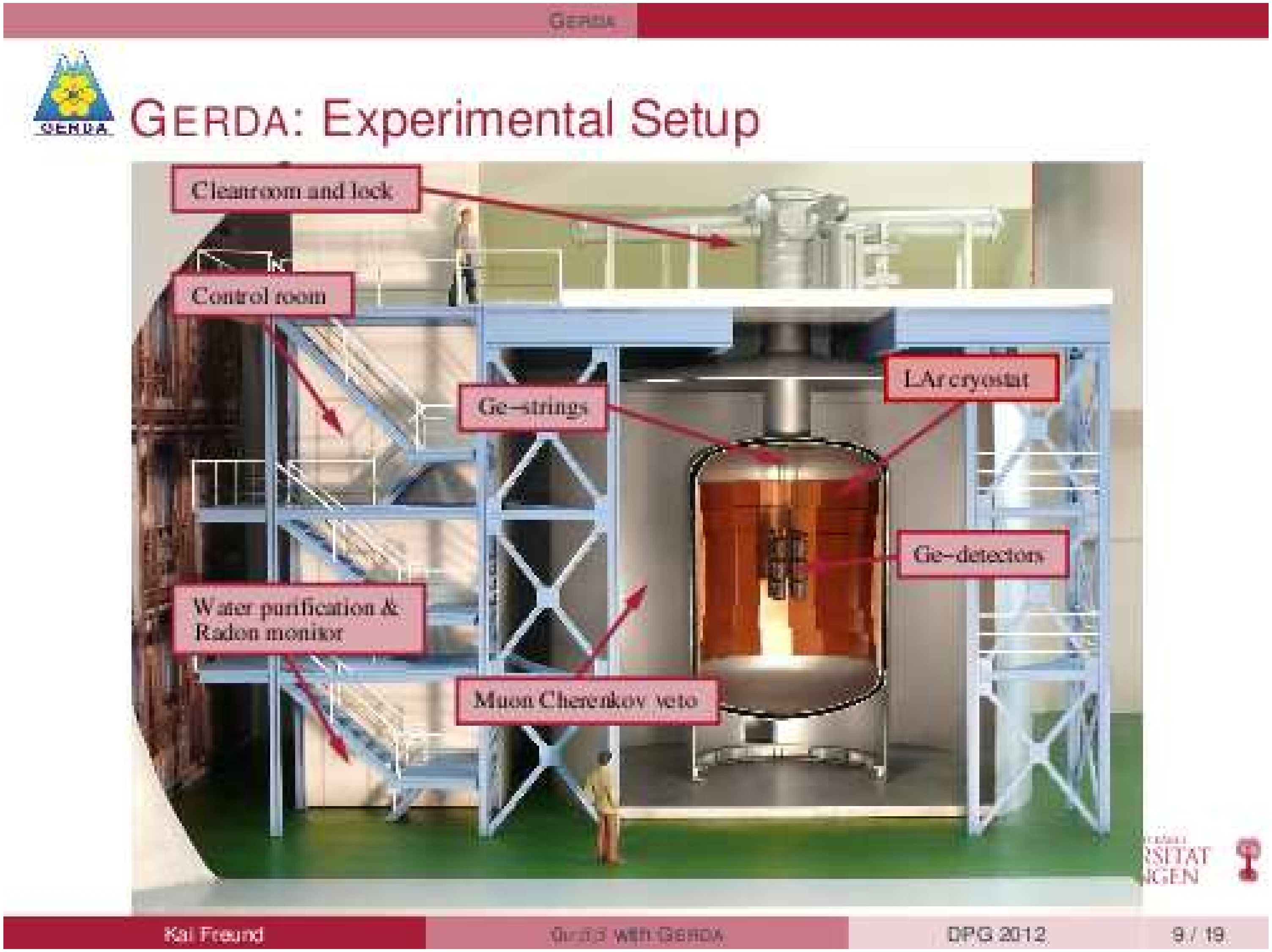
$$\mathbf{T(^{136}Xe)} > 1.07 \times 10^{26}\mathrm{yr\ at\ 90\%\ C.L.,\ \ KamLAND - Zen}$$

$$|\!<\!m\!>\!| \ < (0.061 - 0.165)\ \mathrm{eV}\,.$$

$$\mathrm{min}(m_j) < \frac{0.165\ \mathrm{eV}}{\cos 2\theta_{12}} \cong 0.57\ \mathrm{eV}\ \ (\cos 2\theta_{12} \gtrsim\ 0.29,\ \ 3\sigma)\,.$$

Large number of experiments: $|<m>|$ $\sim$ (0.01-0.05) eV

CUORE - ^{130}Te;
GERDA-II - ^{76}Ge; MAJORANA - ^{76}Ge;
LEGEND - ^{76}Ge;
KamLAND-ZEN - ^{136}Xe;
(n)EXO - ^{136}Xe;
SNO+ - ^{130}Te;
AMoRE - ^{100}Mo (S. Korea);
CANDLES - ^{48}Ca;
SuperNEMO - ^{82}Se, ^{150}Nd;
MAJORANA - ^{76}Ge;
NEXT - ^{136}Xe;
DCBA - ^{82}Se, ^{150}Nd;
XMASS - ^{136}Xe;
PANDAX-III - ^{136}Xe;
ZICOS - ^{96}Zr;
MOON - ^{100}Mo;
...



GERDA

GERDA: Experimental Setup

Kai Freund | 0νββ with GERDA | DPG 2012 | 9 / 19

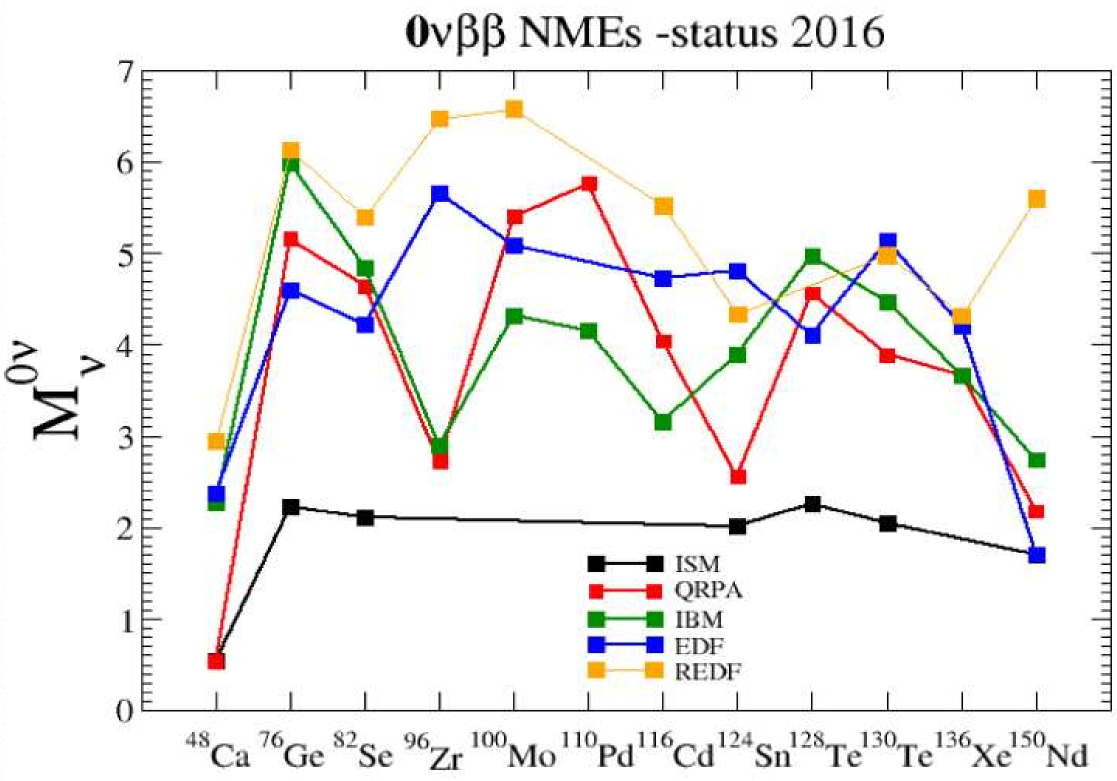
Theoretical Developments

Non-standard mechanisms of $(\beta\beta)_{0\nu}$-decay considered; the corresponding EO classified. Predictions of possible L$\neq$ const. effects at LHC investigated.

It was shown that the existence of ν_s with masses at the eV scale can change drastically the "standard mechanism" picture of $(\beta\beta)_{0\nu}$-decay.

Considerable efforts were made to solve the problem of the calculations of the NMEs. The problem is not solved yet.

NMEs for Light ν Exchange



	mean field meth.	ISM	IBM	QRPA
Large model space	yes	no	yes	yes
Constr. Interm. States	no	yes	no	yes
Nucl. Correlations	limited	all	restricted	restricted

F. Simkovic, September, 2016

The g_A Quenching Problem

g_A: related to the weak charged axial current (Gamow-Teller transitions), which is not conserved and therefore can be and is renormalised, i.e., quenched, by the nuclear medium. This implies that g_A is reduced from its free value $g_A = 1.269$.

The reduction of g_A can have important implications for the $(\beta\beta)_{0\nu}-$decay searches since to a good approximation $T^{0\nu}_{1/2} \propto (g_A^{eff})^{-4}$.

The reduction of g_A necessary in various model NME calculations of $T^{2\nu}_{1/2}$ to reproduce the data;

does not imply the same reduction of g_A takes place in the $(\beta\beta)_{0\nu}-$decay NME, there are indications that the reduction is much smaller.

The mechanism of quenching is not understood at present. Thus, the degree of quenching cannot be firmly determined quantitatively and is subject to debates.

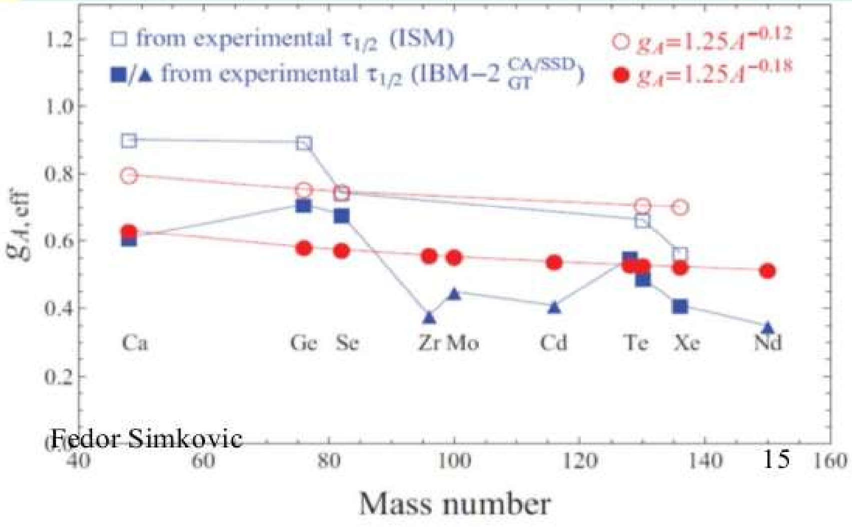
Quenching of g_A *(from theory: $T_{1/2}^{0\nu}$ up 50 x larger)*

$(g^{eff}_A)^4 \simeq 0.66$ (^{48}Ca), 0.66 (^{76}Ge), 0.30 (^{76}Se), 0.20 (^{130}Te) and 0.11 (^{136}Xe)
The Interacting Shell Model (ISM), which describes qualitatively well energy spectra, does reproduce experimental values of $M^{2\nu}$ only by consideration of significant quenching of the Gamow-Teller operator, typically by 0.45 to 70%.

$(g^{eff}_A)^4 \simeq (1.269\ A^{-0.18})4 = 0.063$ (The Interacting Boson Model). This is an incredible result. The quenching of the axial-vector coupling within the IBM-2 is more like 60%.

J. Barea, J. Kotila, F. Iachello, PRC 87, 014315 (2013).

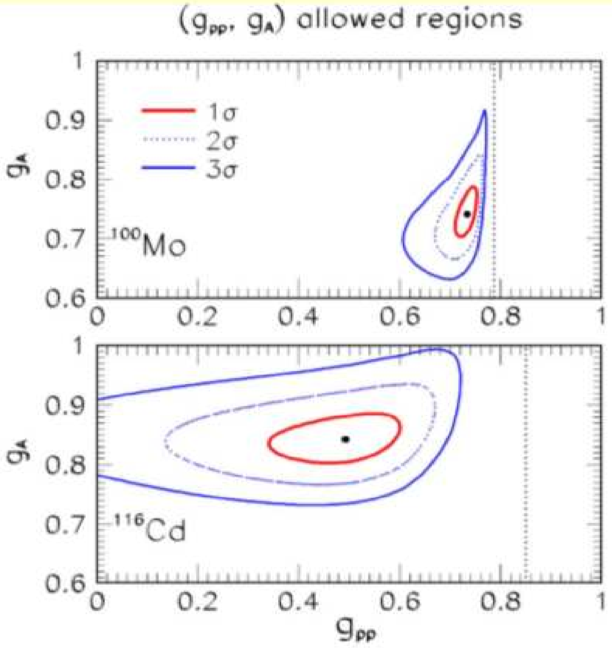
It has been determined by theoretical prediction for the 2νββ-decay half-lives, which were based on within closure approximation calculated corresponding NMEs, with the measured half-lives.

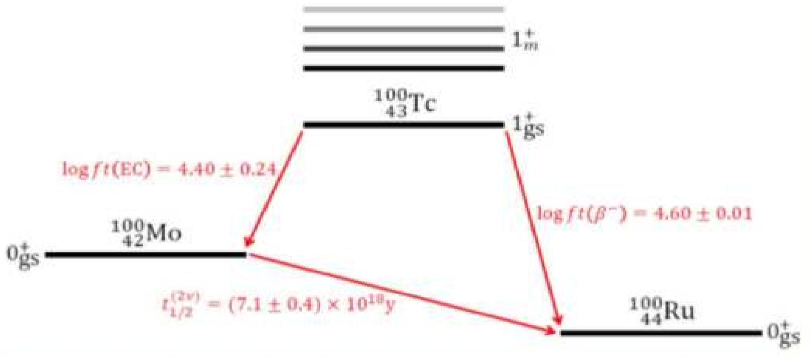


F. Simkovic, September, 2016

Faessler, Fogli, Lisi, Rodin, Rotunno, F. Š, J. Phys. G 35, 075104 (2008).

$(g^{eff}_A)^4 = 0.30$ and 0.50 for ^{100}Mo and ^{116}Cd, respectively (The QRPA prediction).
g^{eff}_A was treated as a completely free parameter alongside g_{pp} (used to renormalize particl-particle interaction) by performing calculations within the QRPA and RQRPA. It was found that a least-squares fit of g^{eff}_A and g_{pp}, where possible, to the β-decay rate and β+/EC rate of the J = 1$^+$ ground state in the intermediate nuclei involved in double-beta decay in addition to the 2νββ rates of the initial nuclei, leads to an effective g^{eff}_A of about 0.7 or 0.8.





Extended calculation also for neighbour isotopes performed by

F.F. Depisch and J. Suhonen, arXiv:1606.02908[nucl-th]

r Simkovic

Dependence of g^{eff}_A on A was not established.

The authors of the first experiment searching for $(\beta\beta)_{0\nu}-$ and $(\beta\beta)_{2\nu}-$ decay in the USSR E.N. Dobrokhotov *et al.* wrote in 1956:

"The search for double beta-decay is an amazing example of a fantastic succession of periods of hope and of disillusionment. Two times in the course of a single decade this phenomenon has been discovered, and both times the discovery has been found to be erroneous. The history of the question is still not complete; the phenomenon has not been observed experimentally, and the succession of journal articles in recent years only gradually sets larger and larger lower limits on the lifetime of a nucleus capable of double beta-decay. In the present research we have again not succeeded in observing the event, but the limit of the halflife of the process (^{48}Ca $(\beta\beta)_{0\nu}$-decay) has been raised to about 0.7×10^{19} years, and further steps in this direction (if indeed they are worth-while) will depend on achieving considerable increases in the amount of material subjected to study."

The quest for the nature of massive neutrinos and for the status of L=const. continues.