OPEN PROBLEMS IN NEUTRINO PHYSICS

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INTRODUCTION

Unanswered questions in neutrino physics (2017):

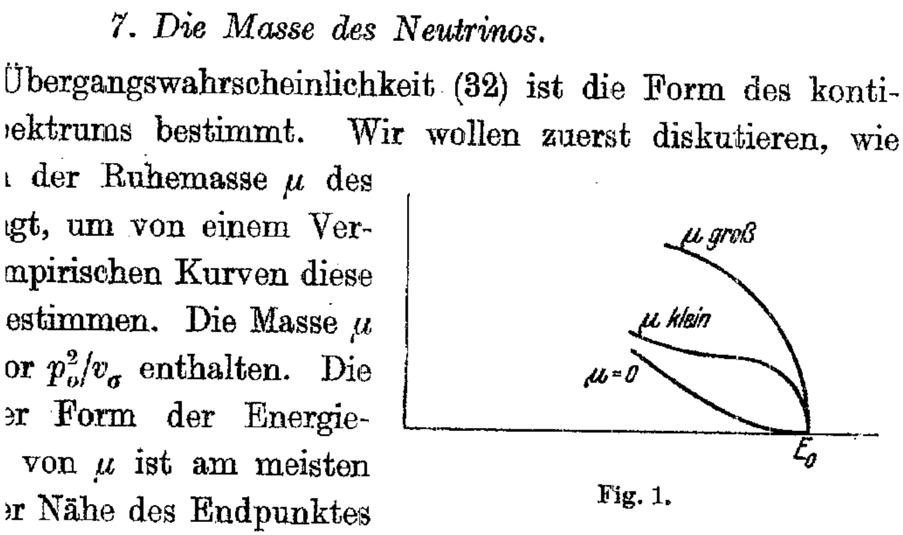
- What is the absolute mass scale of neutrinos? [¶]
- Are neutrinos Dirac or Majorana particles? [§]
- How many neutrino species are there? [#]

[¶] E. Fermi, Z. Phys. 88, 161 (1934)
[§] E. Majorana, Nuovo Cimento 14, 171 (1937)
[#] B. Pontecorvo, Sov. Phys. JEPT 26, 984 (1968)

An answer to the first question can be obtained by a measurement of:

(1) The end-point of the electron spectrum in single beta decay (KATRIN)

$$^{3}_{1}H_2 \rightarrow ^{3}_{2}He_1^{+} + e^{-} + \overline{\nu}_e$$

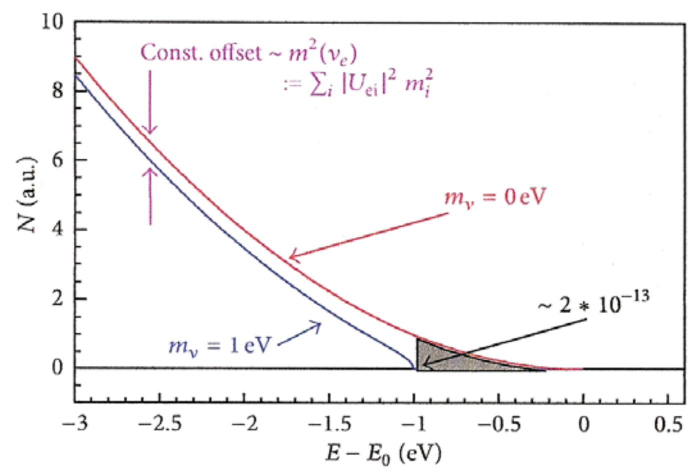


7. *Die Masse des Neutrinos.*

Übergangswahrscheinlichkeit (32) ist die Form des konti-
›ektrums bestimmt. Wir wollen zuerst diskutieren, wie
ı der Ruhemasse μ des
ıgt, um von einem Ver-
mpirischen Kurven diese
estimmen. Die Masse μ
or p_0^2/v_σ enthalten. Die
ǝr Form der Energie-
von μ ist am meisten
ǝr Nähe des Endpunktes

Fig. 1.

From E. Fermi, Versuch einer Theorie der β-Strahlen, Z. Phys. **88**, 161 (1934)



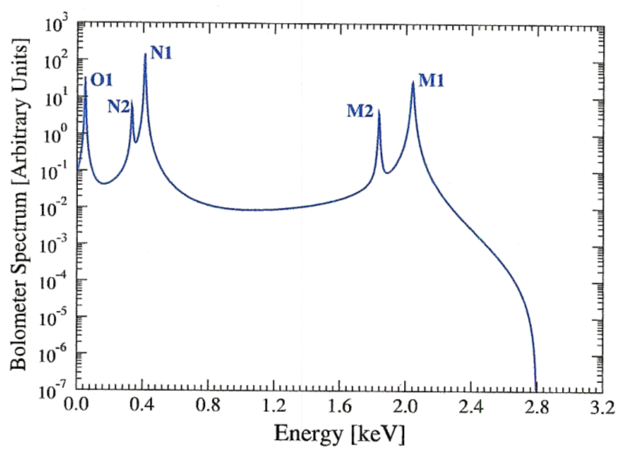
$$m^2(\nu_e) = (-0.6 \pm 2.2 \pm 2.1)\, eV^2$$

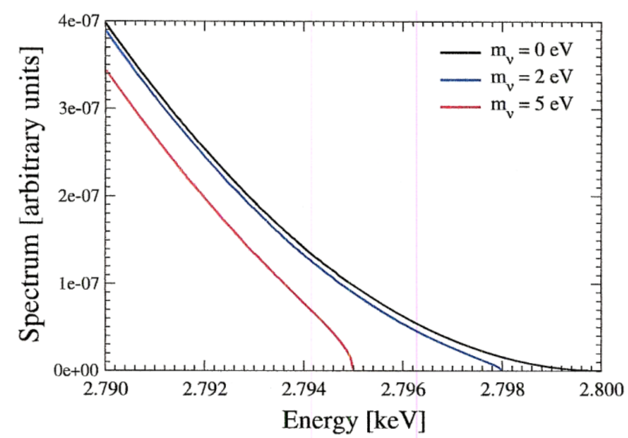
$$m(\nu_e) < 2.3 eV\, (95\% C.L.)$$

From J. Drexlin *et al.*, *Adv. High Energy Phys.* **2013**, 293986

(2) The end-point of the spectrum of single electron capture (ECHO)

$$^{163}_{67}Ho_{96} + e^- \rightarrow ^{163}_{66}Dy_{97}{}^{*i} + \nu_e \rightarrow ^{163}_{66}Dy + E_i + \nu_e$$





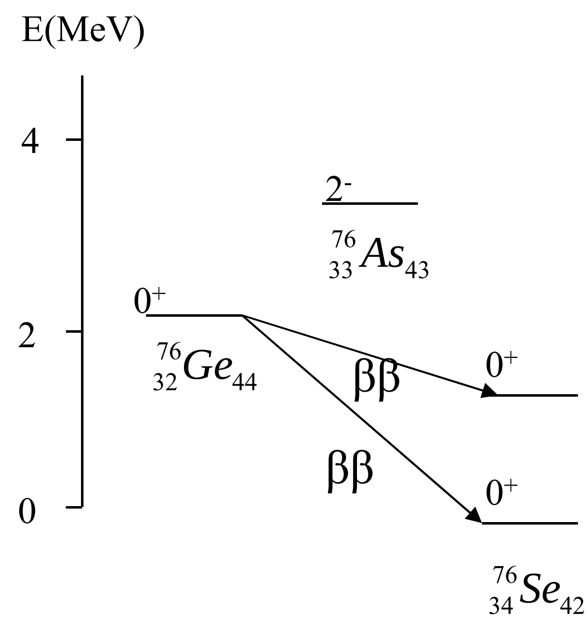
From A. Faessler, L. Gastaldo and F. Šimkovic, J. Phys. G: Nucl. Part. Phys. **42**, 015108 (2015)

An answer to the third question can be obtained by a study of neutrino oscillations in the range <1km (Short-Baseline Neutrino, SBN, Program at FERMILAB)
(Part of a larger program looking at sterile neutrinos)

An answer to all three questions can be obtained from neutrinoless double-beta decay (DBD) and related processes

$$ {}^{A}_{Z}X_{N} \rightarrow {}^{A}_{Z+2}Y_{N-2} + 2e^{-} $$

DOUBLE BETA DECAY



$$ {}^{A}_{Z}X_{N} \rightarrow {}^{A}_{Z\pm 2}Y_{N\mp 2} + 2e^{\mp} + anything $$

Half-life for processes not allowed by the standard model:

$$ \left[\tau_{1/2}^{0\nu\beta\beta}(0^{+} \rightarrow 0^{+})\right]^{-1} = G_{0\nu}\left|M_{0\nu}\right|^{2}\left|f(m_i, U_{ei})\right|^{2} $$

Beyond the standard model (Particle physics)

Matrix elements (Nuclear physics)

NME

Phase-space factor (Atomic physics)

PSF

For processes allowed by the standard model, the half-life can be, to a good approximation, factorized in the form

$$\left[\tau_{1/2}^{2\nu}\right]^{-1} = G_{2\nu}\left|M_{2\nu}\right|^2$$

Phase-space factor (Atomic Physics) PSF

Matrix elements (Nuclear Physics) NME

For all processes and to extract physics beyond the standard model one needs to calculate the phase space factors (PSF) and the nuclear matrix elements (NME).

PHASE SPACE FACTORS (PSF)

PSF were calculated in the 1980's by Doi *et al.* [*]. Also, a calculation of phase-space factors is reported in the book of Boehm and Vogel [§]. These calculations use an approximate expression for the electron wave functions at the nucleus.

PSF have been recently recalculated [**] with exact Dirac electron wave functions and including screening by the electron cloud.

These new PSF are available from jenni.m.kotila@jyu.fi and are on the webpage nucleartheory.yale.edu

[*] M. Doi, T. Kotani, N. Nishiura, K. Okuda and E. Takasugi, Prog. Theor. Phys. 66 (1981) 1739.

[§] F. Bohm and P. Vogel, *Physics of massive neutrinos*, Cambridge University Press, 1987.

[**] J. Kotila and F. Iachello, Phys. Rev. C 85, 034316 (2012).

NUCLEAR MATRIX ELEMENTS (NME)

NME can be written as:

$$M_{0\nu} = g_A^2 M^{(0\nu)}$$

$$M^{(0\nu)} \equiv M_{GT}^{(0\nu)} - \left(\frac{g_V}{g_A}\right)^2 M_F^{(0\nu)} + M_T^{(0\nu)}$$

Several methods have been used to evaluate $M_{0\nu}$:
QRPA (Quasiparticle Random Phase Approximation)
ISM (Shell Model)
IBM-2 (Interacting Boson Model)
DFT (Density Functional Theory)
…

For 0ν processes two scenarios have been considered:

(1) Emission and re-absorption of a light ($m_{light} \ll 1keV$) neutrino.

(2) Emission and re-absorption of a heavy ($m_{heav} \gg 1GeV$) neutrino.

$$f = \frac{\langle m_\nu \rangle}{m_e}$$

$$f_h = m_p \left\langle \frac{1}{m_{\nu_h}} \right\rangle$$

$$\langle m_\nu \rangle = \sum_{k=light} \left(U_{ek}\right)^2 m_k$$

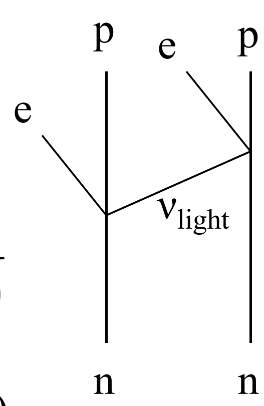
$$\langle m_\nu^{-1} \rangle = \sum_{k=heavy} \left(U_{ek_h}\right)^2 \frac{1}{m_{k_h}}$$

$$v(p) = \frac{2}{\pi} \frac{1}{p\left(p + \tilde{A}\right)}$$

$$\tilde{A} = 1.12 A^{1/2} (MeV)$$

Closure energy

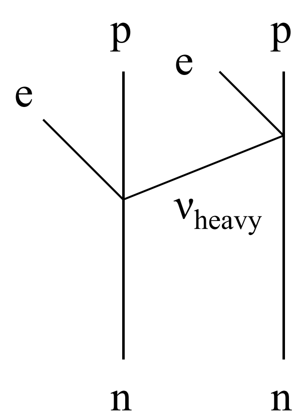
1



$m_{\nu ligth} \ll 1keV$

Long range

2

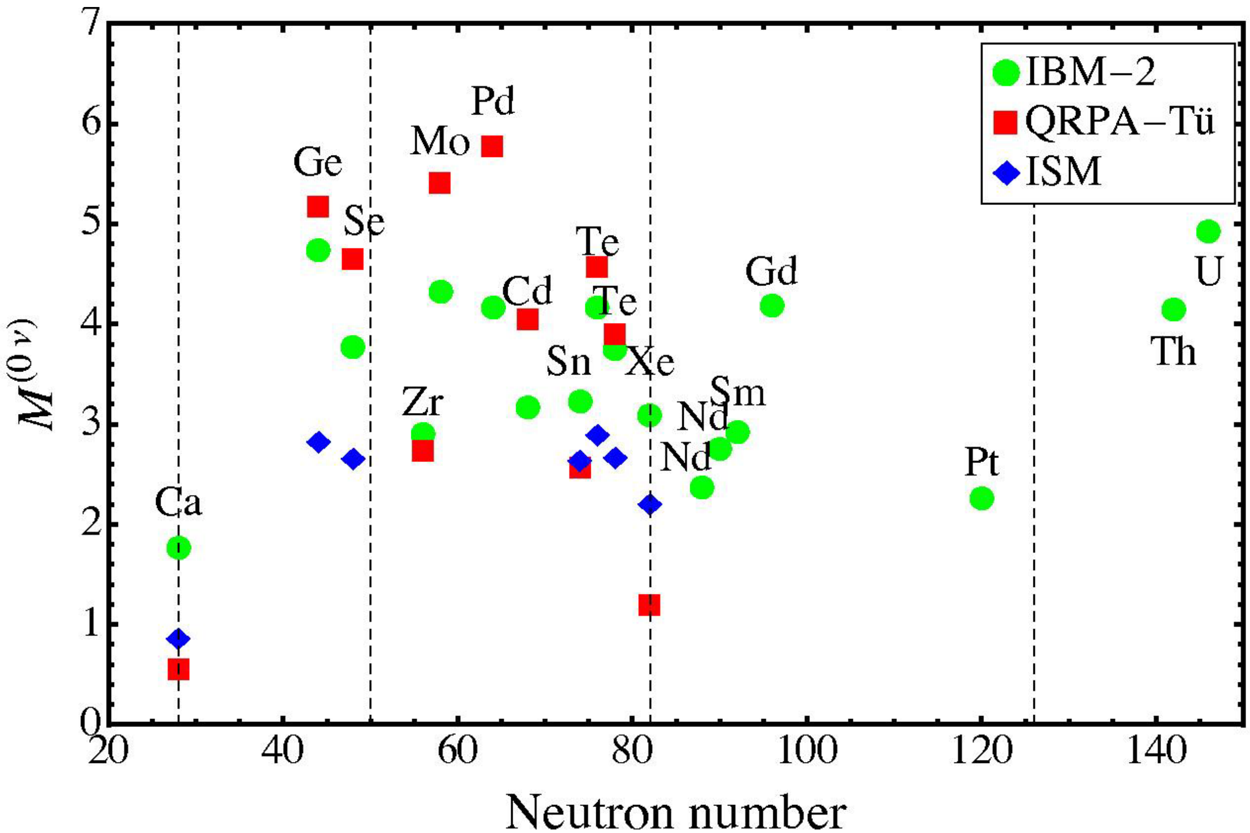


$m_{\nu heavy} \gg 1GeV$

Short range

$$v(p) = \frac{2}{\pi} \frac{1}{m_p m_e}$$

Most recent results for $0\nu\beta^-\beta^-$ (light neutrino exchange)

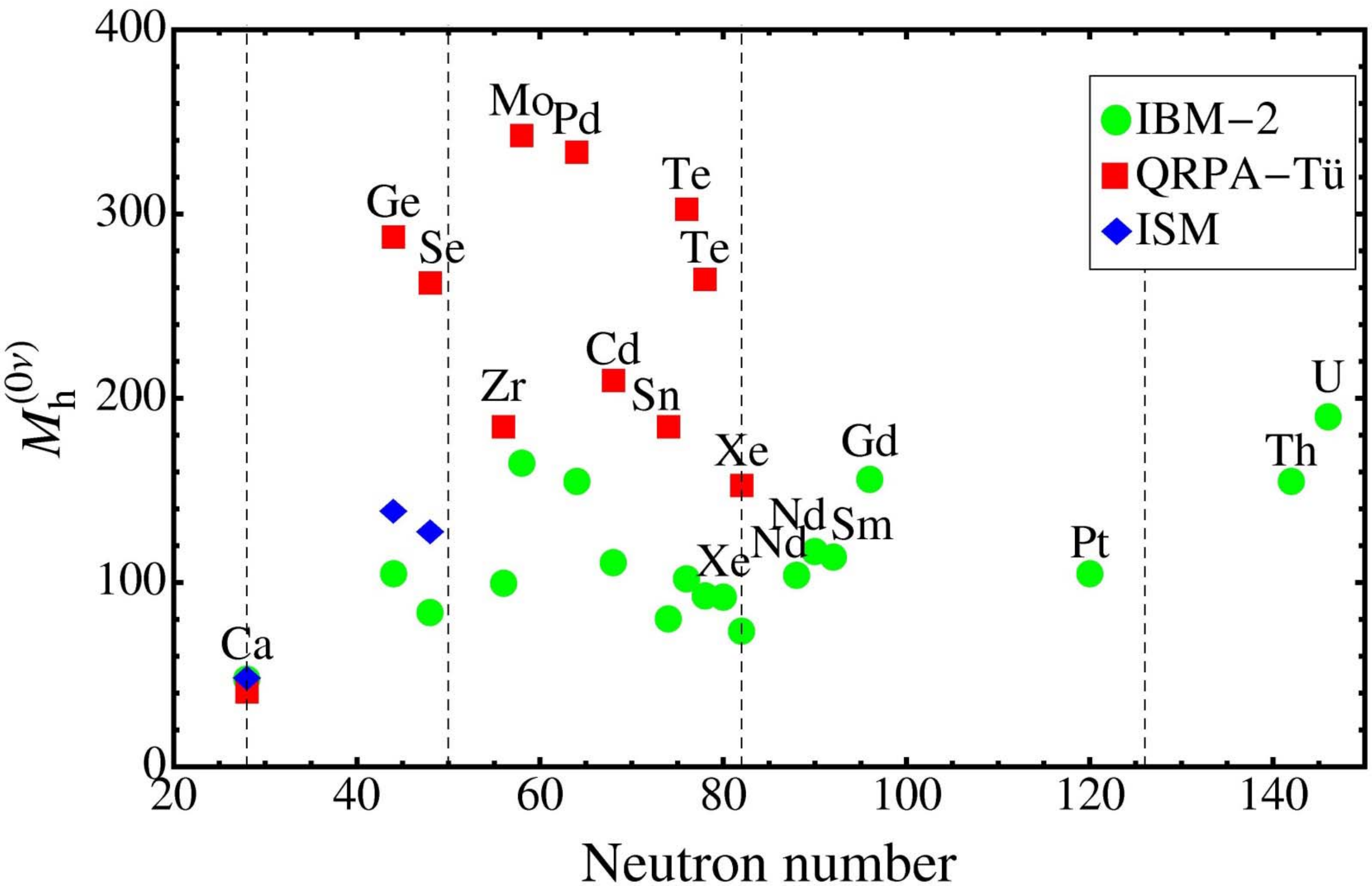


g_A=1.269

IBM-2 *: J. Barea, J. Kotila, and F. Iachello, Phys. Rev. C 91, 034304 (2015).
QRPA-Tu *: F. Simkovic, V. Rodin, A. Faessler, and P. Vogel, Phys. Rev. C 87, 045501 (2013).
ISM: J. Menendez, A. Poves, E. Caurier, and F. Nowacki, Nucl. Phys. A 818, 139 (2009).

* With isospin restoration and Argonne SRC

Most recent results for $0\nu\beta^-\beta^-$ (heavy neutrino exchange)



$g_A=1.269$

* With isospin restoration and Argonne SRC

QUENCHING OF g_A

Results in the previous slides are obtained with g_A=1.269.

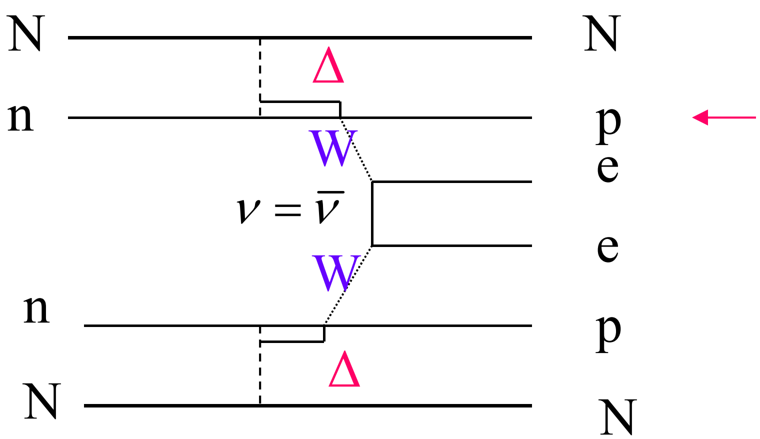
It is well-known from single β-decay/EC ¶ and from 2νββ that g_A is renormalized in models of nuclei. Two reasons:

(i) Limited model space

(ii) Omission of non-nucleonic degrees of freedom (Δ,…)

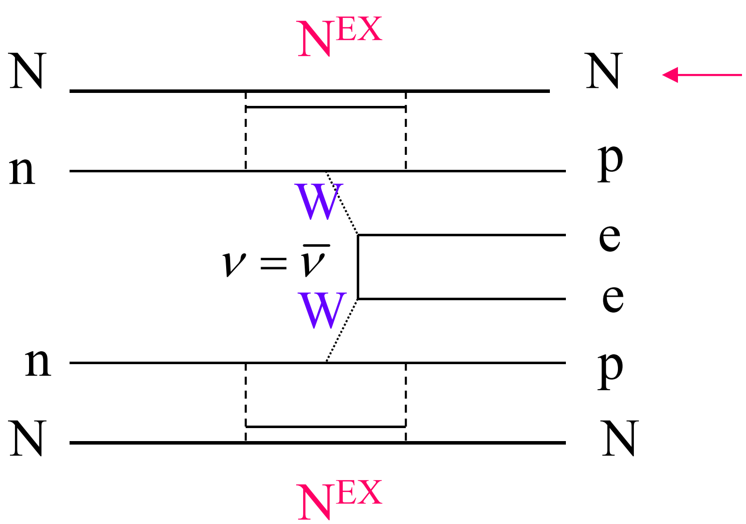
¶ J. Fujita and K. Ikeda, Nucl. Phys. 67, 145 (1965).
D.H. Wilkinson, Nucl. Phys. A225, 365 (1974).

ORIGIN OF QUENCHING OF g_A IN DBD



Quenching factor $q_\Delta \cong 0.7$

(Δ means excited states of the nucleon)



Quenching factor $q_{N^{EX}} \cong 0.7$
(nuclear model dependent)

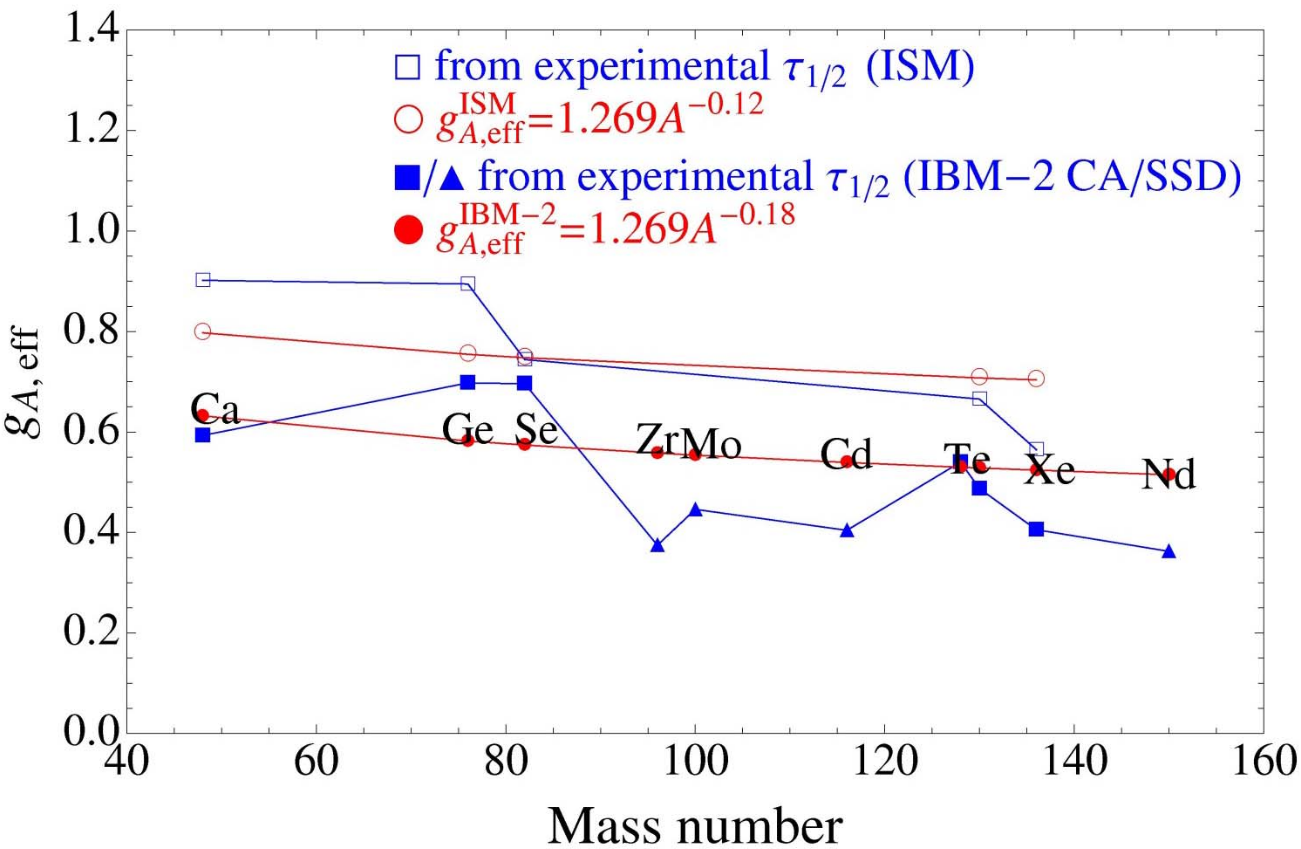
(N^{EX} means excited states of the nucleus not included explicitly)

Maximal quenching:

$$Q = q_\Delta q_{N^{EX}} \cong 0.5$$

Effective axial vector coupling constant in nuclei from 2νββ ¶

Free value →



One obtains $g_{A,eff}^{IBM\text{-}2}$~0.6-0.5.
The extracted values can be parametrized as
A similar analysis can be done for the ISM
for which $g_{A,eff}^{ISM}$~0.8-0.7.

$$g_{A,eff}^{IBM2} = 1.269A^{-0.18}$$

$$g_{A,eff}^{ISM} = 1.269A^{-0.12}$$

¶ J. Barea, J. Kotila and F. Iachello, Phys. Rev. C 91, 034304 (2015).

$g_{A,eff}$, has been extracted also from single β/EC in QRPA, very recently by Suhonen and Civitarese (QRPA-Jy), $g_{A,eff}^{QRPA} \sim 0.8\text{-}0.4$ [§], and a few years ago by Faessler *et al*. (QRPA-Tü) ~ 0.7 [*].

[In some earlier (1989) QRPA papers[¶] , it is claimed that no renormalization of g_A is needed. However, this claim is based on results where the renormalization of g_A is transferred to a renormalization of the free parameter g_{pp} used in the calculation and adjusted to the experimental 2νββ half-life.]

[§] J. Suhonen and O. Civitarese, Phys. Lett. B 725, 153 (2013).
[*] A. Faessler, G.L. Fogli, E. Lisi, V. Rodin, A.M. Rotunno, and F. Šimkovic, J. Phys. G: Nucl. Part. Phys. 35, 075104 (2008).

[¶] K. Muto, E. Bender, H.V. Klapdor, Z. Phys. A334, 177 (1989); 187 (1989).

IMPACT OF THE RENORMALIZATION

The axial vector coupling constant, g_A, appears to the second power in the NME

$$M_{2\nu} = g_A^2 M^{(2\nu)}$$

$$M_{0\nu} = g_A^2 M^{(0\nu)}$$

$$M^{(0\nu)} = M_{GT}^{(0\nu)} - \left(\frac{g_V}{g_A}\right)^2 M_F^{(0\nu)} + M_T^{(0\nu)}$$

and hence to the fourth power in the half-life!

Therefore, the results of the previous slides should be multiplied by 6-34 to have realistic estimates of expected half-lives. [See also, H. Robertson [¶], and S. Dell'Oro, S. Marcocci, F. Vissani[#].]

[¶] R.G.H. Robertson, Modern Phys. Lett. A 28, 1350021 (2013).

[#] S. Dell'Oro, S. Marcocci, and F. Vissani, Phys. Rev. D 90, 033005 (2014).

The question of whether or not g_A in $0\nu\beta\beta$ is renormalized as much as in $2\nu\beta\beta$ is of much debate. The two processes differ by the momentum transferred to the leptons. In $2\nu\beta\beta$ this is of the order of few MeV, while in $0\nu\beta\beta$ it is of the order of 100 MeV. The current (2017) view is that both factors, q_Δ and q_{Nex}, contribute to $2\nu\beta\beta$, while only q_Δ contributes to $0\nu\beta\beta$.

$$[m_\Delta - m_p = 294 \text{ MeV}, \qquad \langle m_{Nex} \rangle - m_N \sim 10 \text{ MeV}]$$

This problem is currently being addressed from various sides. Experimentally by measuring the matrix elements to and from the intermediate odd-odd nucleus in $2\nu\beta\beta$ decay by means of single charge exchange reactions (^{3}He,t)[§]. Theoretically, by using effective field theory (EFT) to estimate the effect of non-nucleonic degrees of freedom (two-body currents) [¶].

§ P. Puppe *et al.*, Phys. Rev. C 86, 044603 (2012).

¶ J. Menendez, D. Gazit, and A. Schwenk, Phys. Rev. Lett. 107, 062501 (2011).

⇨ Very recently, an experimental program (NUMEN) has been set up at LNS in Catania [¶] to measure both single and double charge exchange reaction intensities with heavy ions.

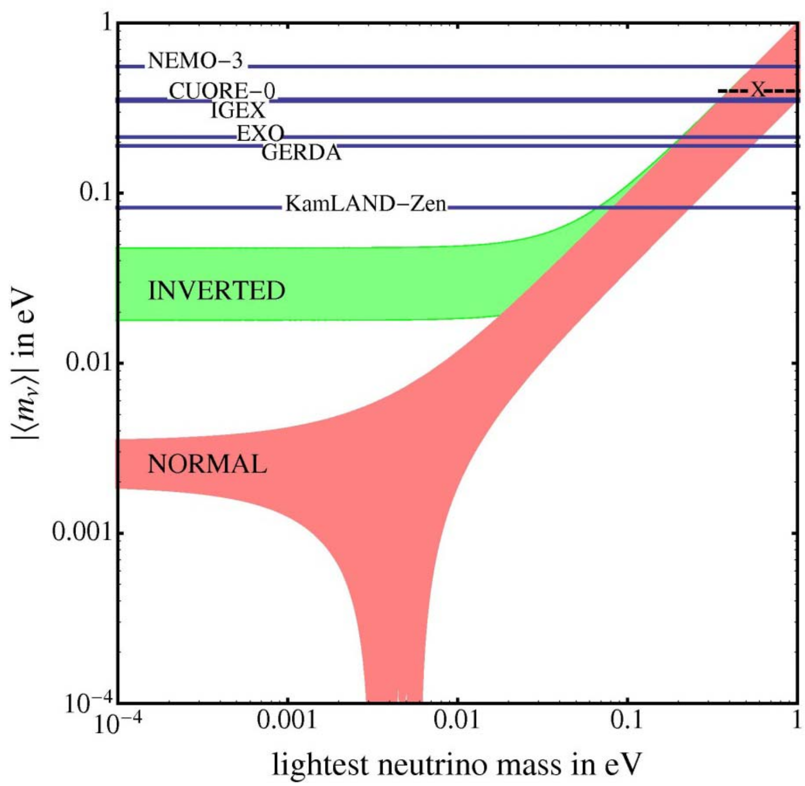
This program will provide useful information on the Fermi and Gamow-Teller matrix elements of interest in $0\nu\beta\beta$ and $2\nu\beta\beta$ decay.

[¶] F. Cappuzzello, C. Agodi *et al.*

CONCLUSIONS

Major progress has been made in the last few years to narrow down predictions of $0\nu\beta\beta$ decay to realistic values in *all* nuclei of interest.

Current limits on the neutrino mass from $0\nu\beta^-\beta^-$ (light neutrino exchange) with g_A=1.269, IBM-2 NME, and KI PSF:



CUORE-0: K. Alfonso *et al.*, PRL 111, 122503 (2013).
EXO: M. Auger *et al.*, Nature 510, 229 (2014).
GERDA: M. Agostini *et al.*, Nature 544, 47 (2017).
KamLAND-Zen: A. Gando *et al.*, PRL 117, 082503 (2016).

The current best limit (with g_A =1.269, IBM-2 NME, KI PSF) is from KamLAND-Zen, $|\langle m_\nu \rangle| < 0.085$ eV.

The major remaining question is the value of g_A. Three scenarios are[¶,§] :

$g_A = 1.269$ ← Free value

$g_A = 1$ ← Quark value *

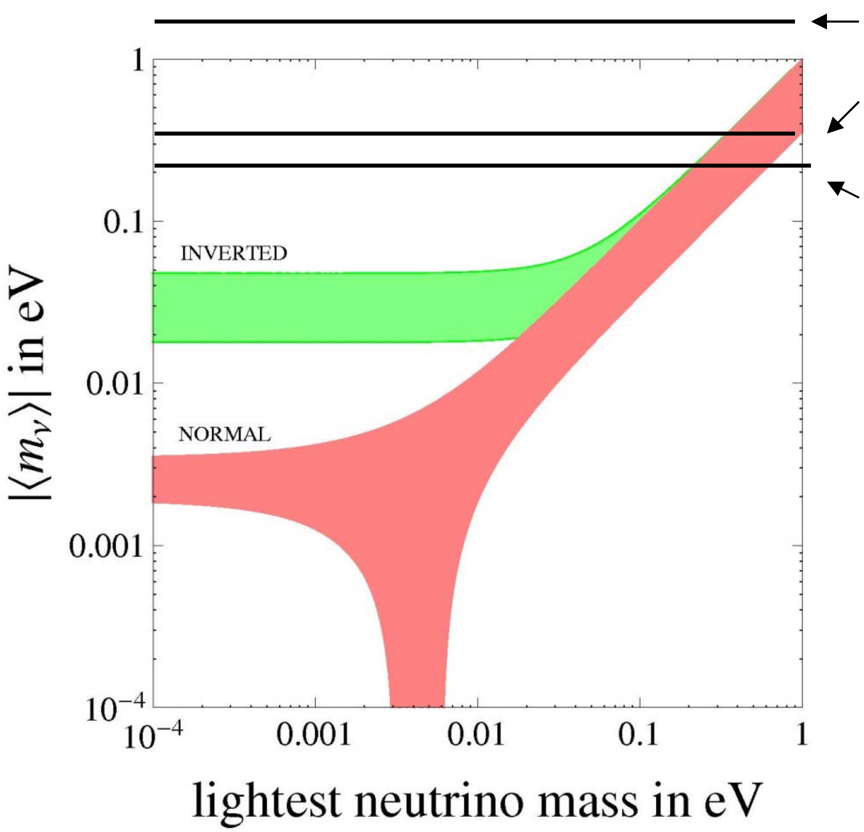
$g_A = 1.269 A^{-0.18}$ ← Maximal quenching

* Most likely value (2017)

¶ J. Barea, J. Kotila, and F. Iachello, Phys. Rev. C 87, 014315 (2013).

§ S. Dell'Oro, S. Marcocci, and F. Vissani, Phys. Rev. D 90, 033005 (2014).

If g_A is renormalized to ~ 1-0.5, all estimates for half-lives should be increased by a factor of ~ 4-34 and limits on the average neutrino mass should be increased by a factor ~ 1.6-6, making it very difficult to reach in the foreseeable future even the inverted region.



$g_A = 0.5$ $\langle m_\nu \rangle < 1.3 eV$

$g_A = 1$ $\langle m_\nu \rangle < 0.3 eV$

$g_A = 1.269$ $\langle m_\nu \rangle < 0.2 eV$

Limits from EXO in ^{136}Xe decay

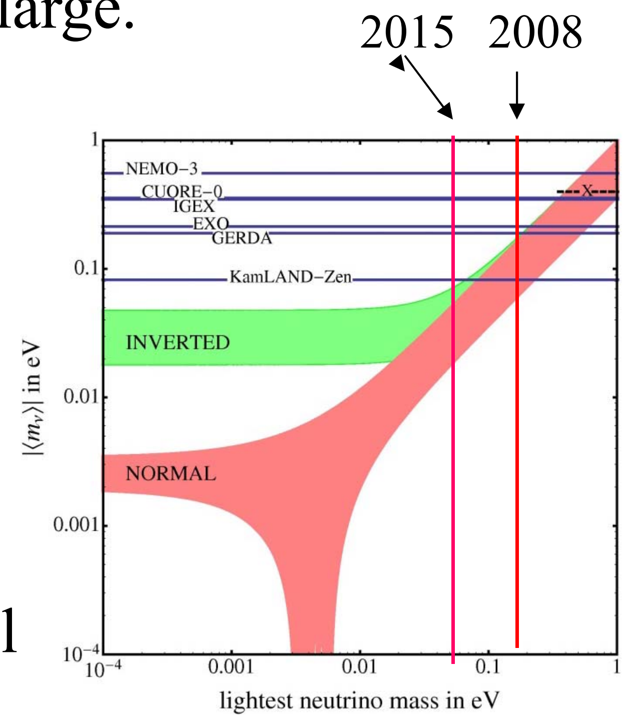
Possibilities to escape this negative conclusion are:
(1) Neutrino masses are degenerate and large.

This possibility will be in tension with the cosmological bound on the sum of the neutrino masses

$$\sum_i m_i \le 0.6eV \qquad (2008)$$

$$\sum_i m_i \le 0.230eV \qquad \text{(2015) Planck ¶}$$

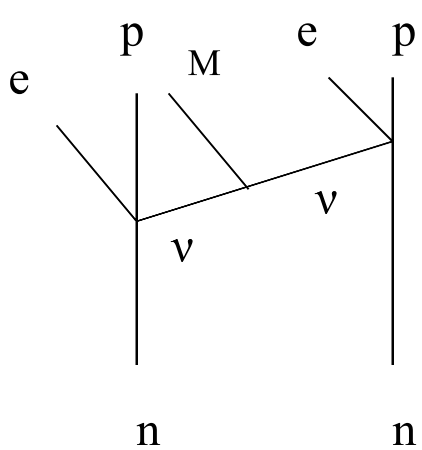
68% confidence level



¶ S. Matarrese for the Planck collaboration, Proc. XVI Int. Workshop NEUTEL 2015.

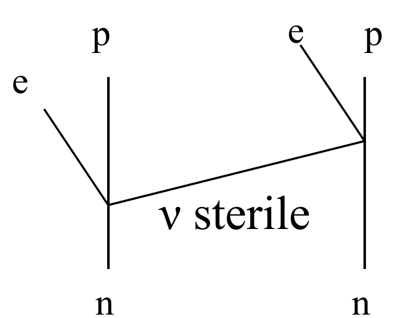
(2) Other scenarios (Majoron emission, sterile neutrinos, …) must be considered.

3



Majoron means a massless neutral boson

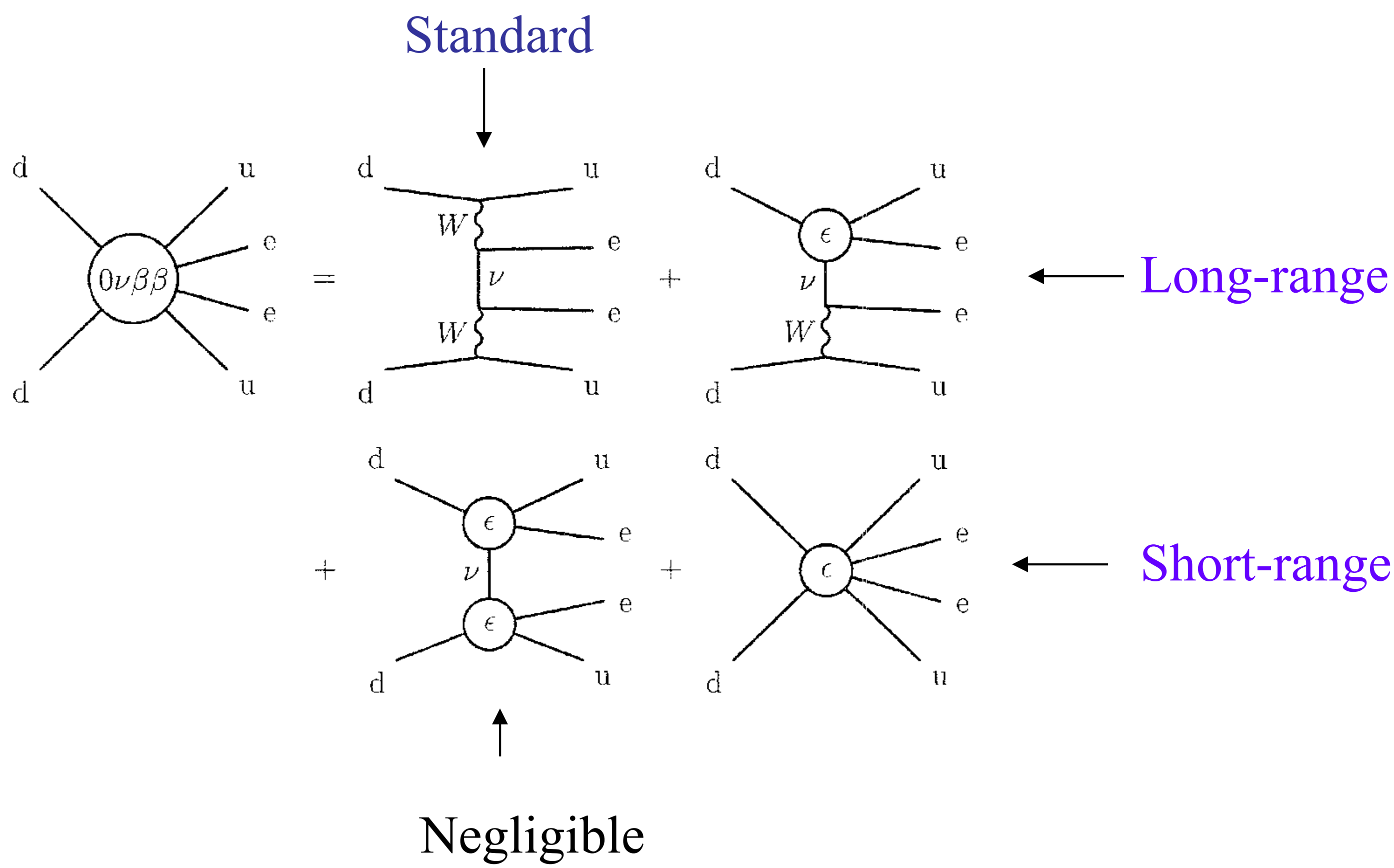
4



Sterile means no standard model interactions §

§B. Pontecorvo, Sov. Phys. JETP 26 (1968) 984

(3) Other non-standard mechanisms contribute



Scenario 2: STERILE NEUTRINOS

A scenario currently being extensively discussed is the mixing of additional "sterile" neutrinos.
[The question on whether or not "sterile" neutrinos exist is an active areas of research at the present time with experiments planned at FERMILAB and CERN-LHC.]

NME for sterile neutrinos of arbitrary mass can be calculated by using a transition operator as in scenario 1 and 2 but with

$$f = \frac{m_{\nu I}}{m_e}$$

$$v(p) = \frac{2}{\pi} \frac{1}{\sqrt{p^2 + m_{\nu I}^2}\left(\sqrt{p^2 + m_{\nu I}^2} + \tilde{A}\right)}$$

Effective mass of the sterile neutrinos

IBM-2 NME for this scenario have been calculated ¶.
PSF are the same as in scenarios 1 and 2.

¶ J. Barea, J. Kotila and F. Iachello, Phys. Rev. D 92, 093001 (2015).

Several types of sterile neutrinos have been suggested.

Scenario a: HEAVY STERILE NEUTRINOS

Sterile neutrinos with masses $m_{\nu I} \gg 1eV$

Possible values of the sterile neutrino, 4a,5a, 6a,…, masses in the keV-GeV range have been suggested by T. Asaka and M. Shaposhnikov, Phys. Lett. B620, 17 (2005) and T. Asaka, S. Blanchet, and M. Shaposhnikov, Phys. Lett. B631, 151 (2005).

Scenario b: LIGHT STERILE NEUTRINOS

Sterile neutrinos with masses $m_{\nu I} \sim 1eV$

Very recently C. Giunti and M. Laveder have suggested sterile neutrinos, 4b,…, with masses in the eV range to account for the reactor anomaly in oscillation experiments, G. Giunti, XVI International Workshop on Neutrino Telescopes, Venice, Italy, March 4, 2015.

CONTRIBUTIONS OF HYPOTHETICAL NEUTRINOS ALL ¶

Known neutrinos

Unknown light sterile

eV

keV

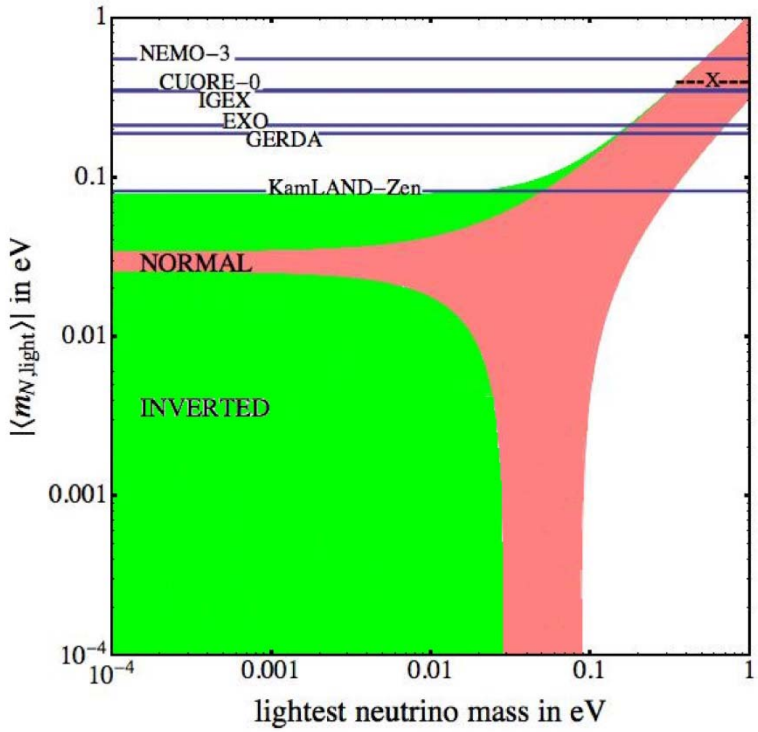
$$\left[\tau_{1/2}^{0\nu}\right]^{-1} = G_{0\nu}\left|\left[\frac{1}{m_e}\sum_{k=1}^{3}U_{ek}^{2}m_k + \frac{1}{m_e}\sum_{i}U_{ei}^{2}m_i + \frac{1}{m_e}\sum_{j}U_{ej}^{2}\right]M^{(0\nu)} + \left[m_p\sum_{N}U_{eN}^{2}\frac{m_N}{\left\langle p^2\right\rangle + m_N^2} + m_p\sum_{k_h=1}^{3}U_{ek_h}^{2}\frac{1}{m_{k_h}}\right]M^{(0\nu_h)}\right|$$

Unknown heavy sterile

Unknown heavy neutrinos

¶ J. Barea, J. Kotila and F. Iachello, Phys. Rev. D 92, 093001 (2015).

The presence of sterile neutrinos changes completely the picture



g_A=1.269

Figure courtesy of Jenni Kotila, adapted from J. Barea, J. Kotila and F. Iachello, *loc.cit*. (2015).

With sterile neutrinos (with properties of scenario 4b ¶) and g_A=1.269, the inverted hierarchy is reachable by GERDA-PHASE II and CUORE.

¶ C. Giunti and M. Laveder, *loc.cit*. (2015).

Scenario 3: NON-STANDARD MECHANISMS

Long-range mechanism (Ali *et al.*) ¶

$$L_{Long} = \frac{G_F}{\sqrt{2}}\left[J^{\dagger}_{V-A,\mu} j^{\mu}_{V-A} + \sum_{\alpha,\beta}{}' \varepsilon_{\alpha\beta} J^{\dagger}_{\alpha} j_{\beta} \right] \qquad \alpha, \beta = S \pm P, V \pm A, T \pm T_5$$

Short-range mechanism (Graf *et al.*) §

$$L_{Short} = \frac{G_F^2}{2m_p}\left[\varepsilon_1 JJj + \varepsilon_2 J^{\mu\nu} J_{\mu\nu} j + \varepsilon_3 J^{\mu} J_{\mu} j + \varepsilon_4 J^{\mu} J_{\mu\nu} j^{\nu} + \varepsilon_5 J^{\mu} J j_{\mu} \right]$$

Predictions and limits will be available in early 2018

¶ A. Ali, A.V. Borisov and D.V. Zhuridov, arXiv:0706.4165v3[hep-ph]

§ L. Graf, F. Deppisch and F. Iachello, in preparation

No matter what the mechanism of neutrinoless DBD is, its observation will answer the fundamental questions:

- What is the absolute neutrino mass scale?
- Are neutrinos Dirac or Majorana particles?
- How many neutrino species are there?

Indeed, if observed, neutrinoless DBD may provide evidence for physics beyond the standard model other than the mass mechanism.

Conversely, its non-observation will set stringent limits on other scenarios (sterile, …), and on non-standard mechanisms.

APPENDIX A: REFERENCES

PSF

$2\nu\beta^-\beta^-/0\nu\beta^-\beta^-$

J. Kotila and F. Iachello, Phys. Rev. C 85, 034316 (2012).

$2\nu\beta^+\beta^+/0\nu\beta^+\beta^+$

J. Kotila and F. Iachello, Phys. Rev. C 87, 024313 (2013).

NME

$2\nu\beta^-\beta^-/0\nu\beta^-\beta^-$

J. Barea and F. Iachello, Phys. Rev. C 79, 044301 (2009).

J. Barea, J. Kotila and F. Iachello, Phys. Rev. C 87, 014315 (2013).

J. Barea, J. Kotila and F. Iachello, Phys. Rev. C 91, 034304 (2015).

$2\nu\beta^+\beta^+/0\nu\beta^+\beta^+$

J. Barea, J. Kotila and F. Iachello, Phys. Rev. C87, 057301 (2013).

R0νECEC

J. Kotila, J. Barea, and F. Iachello, Phys. Rev. C 89, 064319 (2014).

STERILE

J. Barea, J. Kotila, and F. Iachello, Phys. Rev. D 92, 093001 (2015).

APPENDIX B : RECENT IBM-2 RESULTS WITH ERROR FOR 0νββ (2015)

Decay	Light neutrino exchange	Heavy neutrino exchange
^{48}Ca	1.75(28)	47(13)
^{76}Ge	4.68(75)	104(29)
^{82}Se	3.73(60)	83(23)
^{96}Zr	2.83(45)	99(28)
^{100}Mo	4.22(68)	164(46)
^{110}Pd	4.05(65)	154(43)
^{116}Cd	3.10(50)	110(31)
^{124}Sn	3.19(51)	79(22)
^{128}Te	4.10(66)	101(28)
^{130}Te	3.70(59)	92(26)
^{134}Xe	4.05(65)	91(26)
^{136}Xe	3.05(59)	73(20)
^{148}Nd	2.31(37)	103(29)
^{150}Nd	2.67(43)	116(32)
^{154}Sm	2.82(45)	113(32)
^{160}Gd	4.08(65)	155(43)
^{198}Pt	2.19(35)	104(29)
^{232}Th	4.04(65)	159(45)
^{238}U	4.81(77)	189(53)

$^{76}Ge \rightarrow ^{76}Se$

4.68 ± 0.75

GERDA

$^{130}Te \rightarrow ^{130}Xe$

3.70 ± 0.59

CUORE

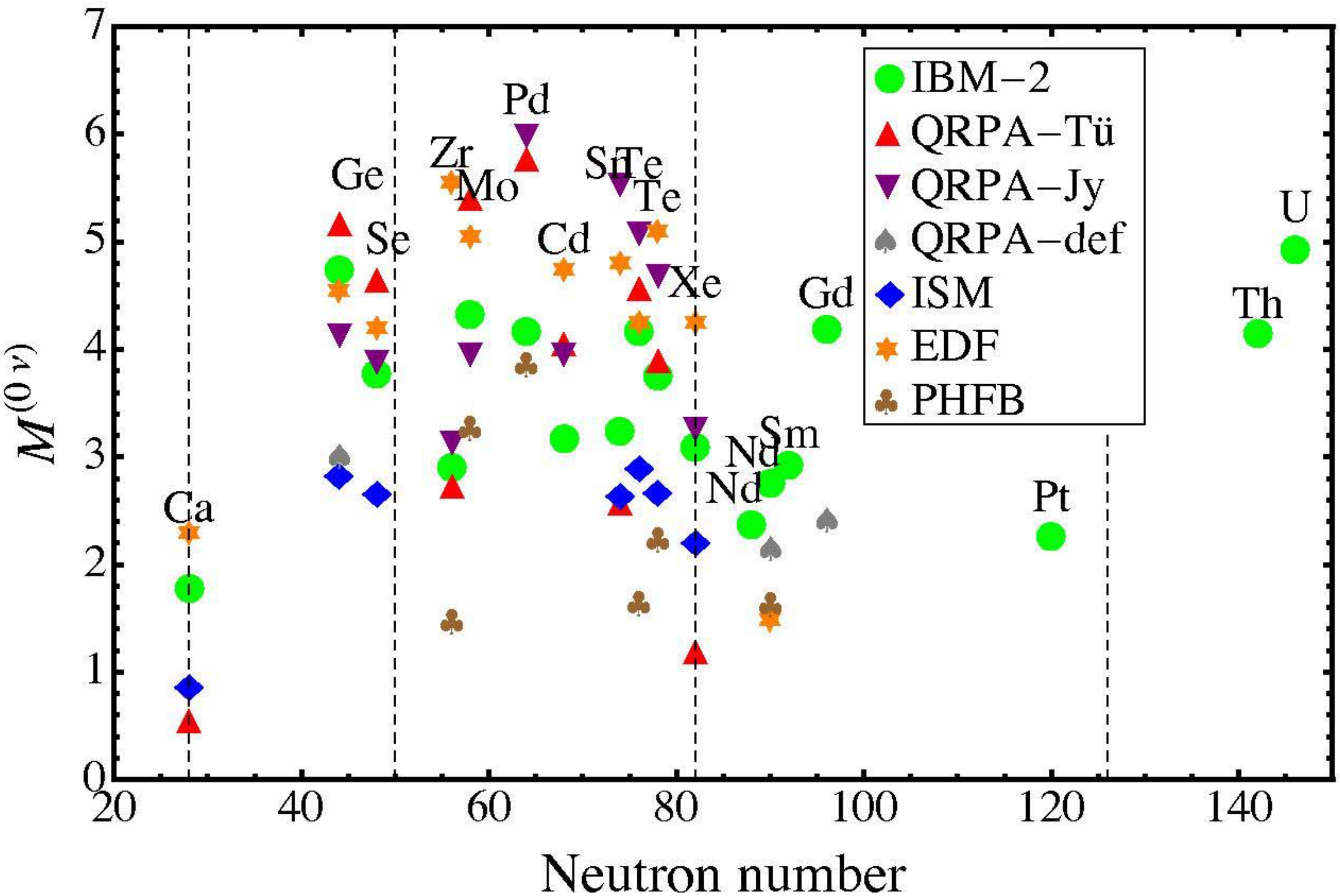
$^{136}Xe \rightarrow ^{136}Ba$

3.05 ± 0.59

EXO
KamLAND-Zen

APPENDIX C: MATRIX ELEMENTS ALL

$g_A = 1.269$



APPENDIX D: MAJORON EMISSION

The inverse half-life for this scenario (0νββφ decay) is given by

$$\left[\tau_{1/2}^{0\nu\beta\beta\varphi}\left(0^{+}\rightarrow 0^{+}\right)\right]^{-1}=G_{0\nu\varphi}\left|M_{0\nu}\right|^{2}\left\langle g\right\rangle^{2}$$

effective Majoron coupling constant

NME are the same as for scenario 1 and 2.
PSF have been recalculated recently.
Best limit ¶ with IBM-2 NME, KBI PSF and g_A=1.269 from KamLAND-Zen

$$\left\langle g^{2}\right\rangle < 1.2\times 10^{-5}$$

¶ J. Kotila, J. Barea and F. Iachello, Phys. Rev. D **91**, 064310 (2015).

This scenario was suggested by H.M. Georgi, S.L. Glashow, and S. Nussinov, Nucl. Phys. B193, 297 (1981).