AIP Conference Proceedings

Nuclear physics of non-standard 0## # - decay

Cite as: AIP Conference Proceedings **2165**, 020017 (2019); https://doi.org/10.1063/1.5130978
Published Online: 25 October 2019

J. Kotila, L. Graf, F. F. Deppisch, and F. Iachello

View Online Export Citation

ARTICLES YOU MAY BE INTERESTED IN

Nuclear responses for double beta decay and muon capture
AIP Conference Proceedings **2165**, 020013 (2019); https://doi.org/10.1063/1.5130974

Anomalies and sterile neutrinos – Implications of new theoretical results
AIP Conference Proceedings **2165**, 020016 (2019); https://doi.org/10.1063/1.5130977

Precise measurement of $2\nu2\beta$ decay of ^{100}Mo with Li_2MoO_4 low temperature detectors: Preliminary results
AIP Conference Proceedings **2165**, 020005 (2019); https://doi.org/10.1063/1.5130966

Lock-in Amplifiers
... and more, from DC to 600 MHz
Watch

AIP Publishing

© 2019 Author(s).

Nuclear Physics of Non-Standard $0\nu\beta\beta$-Decay

J. Kotila,[1, 2, a)] L. Graf,[3] F. F. Deppisch,[4, 5] and F. Iachello[2]

[1)] *Finnish Institute for Educational Research, University of Jyväskylä, P.O. Box 35, FI-40014 Jyväskylä, Finland*
[2)] *Center for Theoretical Physics, Sloane Physics Laboratory, Yale University, New Haven, Connecticut 06520-8120, USA*
[3)] *Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany*
[4)] *Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, UK*
[5)] *Institut für Hochenergiephysik, Österreichische Akademie der Wissenschaften, Nikolsdorfer Gasse 18, 1050 Wien, Austria*

[a)] *Corresponding author: jenni.kotila@jyu.fi*

Abstract. The observation neutrinoless double beta ($0\nu\beta\beta$) decay remains crucial for understanding lepton number violation. In view of the difficulties to observe the mass mechanism of $0\nu\beta\beta$-decay, investigations of other mechanisms are in order. These non-standard mechanisms can be divided into short-range and long-range mechanisms. Recently, we have started systematic study for all possible short-range and long-range non-standard mechanisms. The aim of this study is twofold: I) to provide explicit formulas for the nuclear matrix elements (NMEs) and phase-space factors (PSFs) from which the decay rate for one or a combination of mechanisms operating at the same time can be calculated; II) to provide numerical values of the NMEs and PSFs obtained by making use of the microscopic interacting boson model (IBM-2) for the NMEs and of exact Dirac wave functions for the PSFs.

INTRODUCTION

In spite of many attempts (for review see e.g. [1]), neutrinoless double beta ($0\nu\beta\beta$) decay has not yet been observed. After the discovery of neutrino oscillations [2, 3, 4], attention has been mostly focused on the mass mechanism of $0\nu\beta\beta$. The allowed values of neutrino masses consistent with oscillation experiments are summarized in Fig. 1.

However, in view of the difficulties to observe the mass mechanism, investigations of other mechanisms are also in order. These non-standard mechanisms can be divided into short-range and long-range. They were previously studied by Doi et al. [12, 13] and Tomoda [14], who investigated L-R models [15, 16, 17, 18, 19], and by Ali et al. [20], who provided a general framework for the investigation of non-standard models. Recently, we have performed systematic study for all possible short-range [21, 22] and long-range non-standard mechanisms [23]. The aim of this study is to provide explicit formulas for the nuclear matrix elements (NMEs) and phase-space factors (PSFs) from which the decay rate can be calculated, and to provide numerical values of the NMEs and PSFs obtained by making use of the interacting boson model for the NMEs [24, 25, 26] and of exact Dirac wave functions for the PSFs [27].

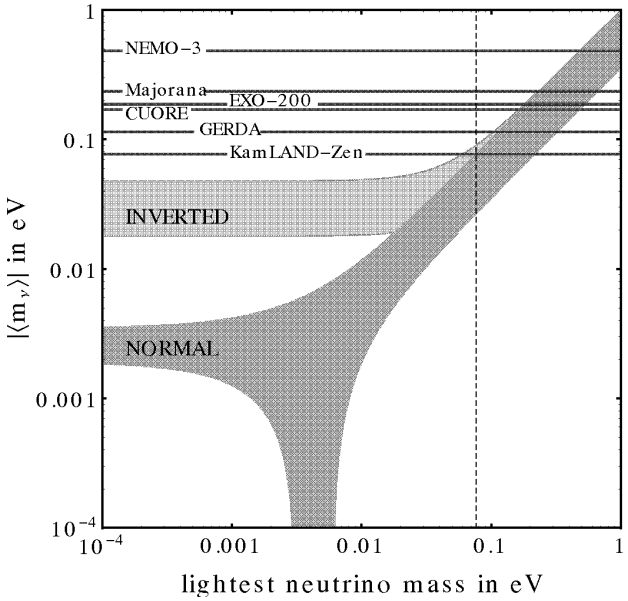

FIGURE 1. Current limits to $\langle m_\nu \rangle$ from CUORE [5], GERDA [6], EXO-200 [7], KamLAND-Zen [8], NEMO-3 [9], and Majorana [10], with IBM-2 NME and $g_A = 1.269$. The limit from Planck Collaboration [11] is shown by vertical line.

Workshop on Calculation of Double-beta-decay Matrix Elements (MEDEX'19)
AIP Conf. Proc. 2165, 020017-1–020017-4; https://doi.org/10.1063/1.5130978
Published by AIP Publishing. 978-0-7354-1910-0/$30.00

NUCLEAR MATRIX ELEMENTS

The matrix elements for the $0\nu\beta\beta$ operators generally depend on the chiralities of the two quark currents involved (see contribution of Lukas Graf in these proceedings). For the first three operators the two quark currents involved are of the same type. Thus, three possible combinations occur corresponding to the chiralities *RR*, *LL* and $(RL+LR)/2$. The resulting NMEs only depend on whether the quark chiralities are equal (*RR*, *LL*) or different $(RL+LR)/2$, represented by the upper and lower sign, respectively:

$$\mathcal{M}_1 = g_S^2 \mathcal{M}_F \pm \frac{g_P^2}{12}\left(\mathcal{M}_{GT}^{'PP} + \mathcal{M}_T^{'PP}\right), \tag{1}$$

$$\mathcal{M}_2 = -2 g_{T_1}^2 \mathcal{M}_{GT}^{T_1 T_1}, \tag{2}$$

$$\mathcal{M}_3 = g_V^2 \mathcal{M}_F + \frac{(g_V + g_W)^2}{12}\left(-2\mathcal{M}_{GT}^{'WW} + \mathcal{M}_T^{'WW}\right) \mp \left(g_A^2 \mathcal{M}_{GT}^{AA} - \frac{g_A g_{PS}}{6}\left(\mathcal{M}_{GT}^{'AP'} + \mathcal{M}_T^{'AP'}\right) + \frac{g_{PS}^2}{48}\left(\mathcal{M}_{GT}^{''P'P'} + \mathcal{M}_T^{''P'P'}\right)\right). \tag{3}$$

For the last two operators the two quark currents involved have different Lorentz structures and thus all four possible combinations of chiralities have to be considered in principle: *RR*, *LL*, *RL* and *LR*. Again, the NMEs only distinguish between the case where the quark current chiralities are the same (upper sign) or different (lower sign),

$$\mathcal{M}_4 = \mp i\left(g_A g_{T_1} \mathcal{M}_{GT}^{AT_1} - \frac{g_{PS} g_{T_1}}{12}\left(\mathcal{M}_{GT}^{'P'T_1} + \mathcal{M}_T^{'P'T_1}\right)\right), \tag{4}$$

$$\mathcal{M}_5 = g_S g_V \mathcal{M}_F \pm \left(\frac{g_A g_P}{12}\left(\tilde{\mathcal{M}}_{GT}^{AP} + \tilde{\mathcal{M}}_T^{AP}\right) - \frac{g_{PS} g_P}{24}\left(\mathcal{M}_{GT}^{'q_0P'P} + \mathcal{M}_T^{'q_0P'P}\right)\right). \tag{5}$$

In the above expressions the form factor charges $g_X = F_X(0)$ have been explicitly factored. However, the q-dependence arising from the product of the reduced form factors $F_X(q^2)/g_X$ still needs to be included in the various matrix elements appearing in Eqs. (1)-(5). The individual Fermi ($\mathcal{M}_F$), Gamow-Teller ($\mathcal{M}_{GT}$) and tensor ($\mathcal{M}_T$) NMEs along with the associated reduced form factor products $\tilde{h}(q^2)$ are given in Table I, where the NMEs are calculated using the q-dependence functions $h_\circ(q^2) = v(q^2)\tilde{h}_\circ(q^2)$ enhanced by the appropriate neutrino potential describing the q-dependence of the underlying particle physics mediator of $0\nu\beta\beta$-decay [28, 25]. For short range mechanisms the neutrino potential is simple:

$$v(q^2) = \frac{2}{\pi}\frac{1}{m_e m_p}. \tag{6}$$

The theory of short range mechanisms was discussed in detail in Ref. [21] along with some selected cases of numerical values of NMEs. Full set of NMEs will be published soon [22].

In case of long range mechanisms, situation is more complicated and there are three different non-trivial neutrino potentials (labeled as v_1, v_3, and v_4 following the notation of Tomoda [14]) with which the calculation is performed:

$$v_1(q^2) = \frac{2}{\pi}\frac{1}{q(q+\tilde{A})}, \tag{7}$$

$$v_3(q^2) = \frac{2}{\pi}\frac{1}{(q+\tilde{A})^2}, \tag{8}$$

$$v_4(q^2) = \frac{2}{\pi}\frac{q+2\tilde{A}}{q(q+\tilde{A})^2}. \tag{9}$$

NMEs for experimentally most interesting cases i.e ^{76}Ge, ^{82}Se, ^{100}Mo, ^{130}Te, and ^{136}Xe will be published soon [23].

PHASE SPACE FACTORS

The leptonic phase-space factors describe the atomic part of the physics involved in $0\nu\beta\beta$-decay. They quantify the effect of the relativistic electrons emitted in the process. Following the notation and approximations of [27] the PSFs

TABLE I. Double beta decay Fermi, Gamow-Teller, and tensor NMEs appearing in Eqs. (1)-(5) with the associated reduced form factor product $\tilde{h}(q^2)$. The subscript X stands for $X = V, W, T_1$ for which the same form factor shape parameter m_V applies.

NME	$\tilde{h}_\circ(q^2)$
$\mathcal{M}_F = \langle h_{XX}(q^2) \rangle$	$\tilde{h}_{XX}(q^2) = \frac{1}{\left(1+q^2/m_V^2\right)^4}$
$\mathcal{M}'^{PP}_{GT} = \left\langle \frac{\mathbf{q}^2}{m_p^2} h_{PP}(q^2)(\boldsymbol{\sigma}_a \cdot \boldsymbol{\sigma}_b) \right\rangle$	$\tilde{h}_{PP}(q^2) = \frac{1}{\left(1+q^2/m_A^2\right)^4} \frac{1}{\left(1+q^2/m_\pi^2\right)^2}$
$\mathcal{M}'^{PP}_{T} = \left\langle \frac{\mathbf{q}^2}{m_p^2} h_{PP}(q^2) \mathbf{S}_{ab} \right\rangle$	$\tilde{h}_{PP}(q^2)$
$\mathcal{M}^{T_1 T_1}_{GT} = \langle h_{XX}(q^2)(\boldsymbol{\sigma}_a \cdot \boldsymbol{\sigma}_b) \rangle$	$\tilde{h}_{XX}(q^2)$
$\mathcal{M}'^{WW}_{GT} = \left\langle \frac{\mathbf{q}^2}{m_p^2} h_{XX}(q^2)(\boldsymbol{\sigma}_a \cdot \boldsymbol{\sigma}_b) \right\rangle$	$\tilde{h}_{XX}(q^2)$
$\mathcal{M}'^{WW}_{T} = \left\langle \frac{\mathbf{q}^2}{m_p^2} h_{XX}(q^2) \mathbf{S}_{ab} \right\rangle$	$\tilde{h}_{XX}(q^2)$
$\mathcal{M}^{AA}_{GT} = \langle h_{AA}(q^2)(\boldsymbol{\sigma}_a \cdot \boldsymbol{\sigma}_b) \rangle$	$\tilde{h}_{AA}(q^2) = \frac{1}{\left(1+q^2/m_A^2\right)^4}$
$\mathcal{M}'^{AP'}_{GT} = \left\langle \frac{\mathbf{q}^2}{m_p^2} h_{AP}(q^2)(\boldsymbol{\sigma}_a \cdot \boldsymbol{\sigma}_b) \right\rangle$	$\tilde{h}_{AP}(q^2) = \frac{1}{\left(1+q^2/m_A^2\right)^4} \frac{1}{1+q^2/m_\pi^2}$
$\mathcal{M}'^{AP'}_{T} = \left\langle \frac{\mathbf{q}^2}{m_p^2} h_{AP}(q^2) \mathbf{S}_{ab} \right\rangle$	$\tilde{h}_{AP}(q^2)$
$\mathcal{M}''^{PP}_{GT} = \left\langle \frac{\mathbf{q}^4}{m_p^4} h_{PP}(q^2)(\boldsymbol{\sigma}_a \cdot \boldsymbol{\sigma}_b) \right\rangle$	$\tilde{h}_{PP}(q^2)$
$\mathcal{M}''^{PP}_{T} = \left\langle \frac{\mathbf{q}^4}{m_p^4} h_{PP}(q^2) \mathbf{S}_{ab} \right\rangle$	$\tilde{h}_{PP}(q^2)$
$\mathcal{M}^{AT_1}_{GT} = \langle h_{AX}(q^2)(\boldsymbol{\sigma}_a \cdot \boldsymbol{\sigma}_b) \rangle$	$\tilde{h}_{AX}(q^2) = \frac{1}{\left(1+q^2/m_V^2\right)^2} \frac{1}{\left(1+q^2/m_A^2\right)^2}$
$\mathcal{M}'^{P'T_1}_{GT} = \left\langle \frac{\mathbf{q}^2}{m_p^2} h_{XP}(q^2)(\boldsymbol{\sigma}_a \cdot \boldsymbol{\sigma}_b) \right\rangle$	$\tilde{h}_{XP}(q^2) = \frac{1}{\left(1+q^2/m_V^2\right)^2} \frac{1}{\left(1+q^2/m_A^2\right)^2} \frac{1}{1+q^2/m_\pi^2}$
$\mathcal{M}'^{P'T_1}_{T} = \left\langle \frac{\mathbf{q}^2}{m_p^2} h_{XP}(q^2) \mathbf{S}_{ab} \right\rangle$	$\tilde{h}_{XP}(q^2)$
$\tilde{\mathcal{M}}^{AP}_{GT} = \left\langle \frac{\mathbf{Q}\cdot\mathbf{q}}{m_p^2} h_{AP}(q^2)(\boldsymbol{\sigma}_a \cdot \boldsymbol{\sigma}_b) \right\rangle \approx \mathcal{M}'^{AP}_{GT}$	$\tilde{h}_{AP}(q^2)$
$\tilde{\mathcal{M}}^{AP}_{T} = \left\langle \frac{\mathbf{Q}\cdot\mathbf{q}}{m_p^2} h_{AP}(q^2) \mathbf{S}_{ab} \right\rangle \approx \mathcal{M}'^{AP}_{T}$	$\tilde{h}_{AP}(q^2)$
$\mathcal{M}'^{q_0 P' P}_{GT} = \left\langle \frac{q_0 \mathbf{q}^2}{m_p^3} h_{PP}(q^2)(\boldsymbol{\sigma}_a \cdot \boldsymbol{\sigma}_b) \right\rangle \approx 10^{-2} \mathcal{M}'^{PP}_{GT}$	$\tilde{h}_{PP}(q^2)$
$\mathcal{M}'^{q_0 P' P}_{T} = \left\langle \frac{q_0 \mathbf{q}^2}{m_p^3} h_{PP}(q^2) \mathbf{S}_{ab} \right\rangle \approx 10^{-2} \mathcal{M}'^{PP}_{T}$	$\tilde{h}_{PP}(q^2)$

needed for the description of short range mechanisms read as

$$f^{(0)}_{11} = |f^{-1-1}|^2 + |f_{11}|^2 + |f^{-1}{}_1|^2 + |f_1{}^{-1}|^2, \qquad f^{(1)}_{11\pm} = -2\left[f^{-1}{}_1 f_1{}^{-1} \pm f^{-1-1} f_{11}\right], \tag{10}$$

$$f^{(0)}_{66} = 16\left[|f^{-1-1}|^2 + |f_{11}|^2\right], \qquad f^{(1)}_{66} = 32\left[f^{-1-1} f_{11}\right], \tag{11}$$

$$f^{(0)}_{16} = 4\left[|f_{11}|^2 - |f^{-1-1}|^2\right], \qquad f^{(1)}_{16} = 0. \tag{12}$$

Our results agree with those of Päs et al. [29] and Tomoda [14], except for the extra interference term $f^{(1)}_{11-}$ in Eq. (10) between the left- and right-handed scalar electron currents. Note that the electron phase space distribution f_{11} is identical to that of the standard mass mechanism. The normalized single energy distributions and the angular correlation as functions of the kinetic energy $E_1^{\mathrm{kin}} = E_1 - m_e$ are shown in Fig. 2 for the $0\nu\beta\beta$-decay isotopes ^{76}Ge, ^{130}Te, and ^{136}Xe. The angular correlation $\alpha(E_1^{\mathrm{kin}})$ is negative for f_{11} and positive for f_{66}, i.e. in the former case, the electrons are preferably emitted back-to-back whereas in the latter case they preferably fly in a similar direction. This allows to potentially distinguish the scenarios resulting in f_{66} from the standard mass mechanism as well as from scenarios corresponding to f_{11}. The integrated PSFs are obtained following [27] and numerical values of selected cases are listed in Ref. [21]. Full set of short range PSFs will be published soon [22].

For long range mechanisms there are 34 PSFs, of which 11 were calculated by Tomoda [14] using approximate wavefunctions for electrons. All 34 PSFs will be published soon for ^{76}Ge, ^{82}Se, ^{100}Mo, ^{130}Te, and ^{136}Xe [23].

CONCLUSION

No matter what the mechanism of $0\nu\beta\beta$-decay is, its observation will answer fundamental questions about neutrino properties and their nature. Furthermore, it is much more than a measurement of the neutrino mass, it is a search for

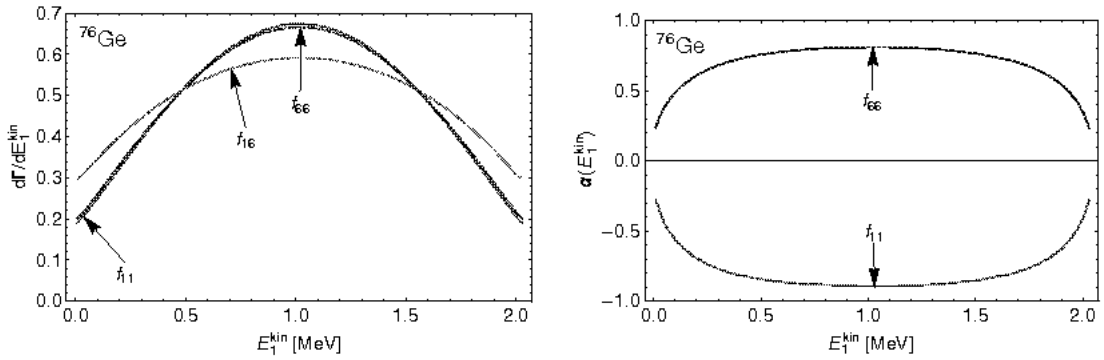

FIGURE 2. Left panel: Single electron energy distribution $d\Gamma/dE_1^{\rm kin}$ as function of the kinetic energy $E_1^{\rm kin} = E_1 - m_e$ for the different phase space factors f_{11}, f_{66} and f_{16} for ^{76}Ge. Right panel: Energy-dependent angular correlation $\alpha(E_1^{\rm kin})$ between the two electrons as function of the kinetic energy $E_1^{\rm kin}$ for the phase space factors f_{11} and f_{66} (identically zero for f_{16}) for ^{76}Ge.

lepton number violation. If observed, $0\nu\beta\beta$ may provide evidence for physics beyond the standard model other than the mass mechanism. On the other hand, its non-observation will set stringent limits on non-standard mechanisms as well as other scenarios, like sterile neutrinos [30].

ACKNOWLEDGMENTS

This work was supported in part by the U.S. DOE (Grant No. DEFG- 02-91ER-40608) and the UK Royal Society International Exchange program. The work of JK was supported by the Academy of Finland (Grant No. 314733). The work of LG and FFD was supported by a UK Science & Technology Facilities Council Consolidated Grant.

REFERENCES

1. M. J. Dolinski, A. W. P. Poon, and W. Rodejohann, to be published in the Annu. Rev. of Nucl. Part. Sci. 69 (2019) [arXiv:1902.04097].
2. Y. Fukuda et al. [Super-Kamiokande Collaboration], Phys. Rev. Lett. 81, 1562 (1998).
3. Q. R. Ahmad et al. [SNO Collaboration], Phys. Rev. Lett. 89, 011301 (2002).
4. K. Eguchi et al. [KamLAND Collaboration], Phys. Rev. Lett. 90, 021802 (2003).
5. C. Alduino et al. (CUORE collaboration), Phys. Rev. Lett 120 , 132501 (2018).
6. M. Agostini et al. (GERDA Collaboration), Phys. Rev. Lett. 120 , 132503 (2018).
7. J.B. Albert et al. (EXO-200 collaboration) Phys. Rev. Lett. 120 , 072701 (2018).
8. A. Gando et al. (KamLAND-Zen collaboration), Phys. Rev. Lett. 117 , 082503 (2016).
9. R. Arnold, et al. (NEMO-3 collaboration), Phys. Rev. D 92 , 072011 (2015).
10. C. E. Aalseth et al. (Majorana Collaboration), Phys. Rev. Lett. 120 , 132502 (2018).
11. P. A. R. Ade et al. (Planck Collaboration), Astron. Astrophys. 594, A13 (2016).
12. M. Doi, T. Kotani, H. Nishiura, K. Okuda, and E. Takasugi, Prog. Theor. Phys. 66, 1739 (1981) Erratum: [Prog. Theor. Phys. 68, 347 (1982)].
13. M. Doi, T. Kotani, H. Nishiura, and E. Takasugi, Prog. Theor. Phys. 69, 602 (1983).
14. T. Tomoda, Rept. Prog. Phys. 54, 53 (1991).
15. J. C. Pati and A. Salam, Phys. Rev. D 10, 275 (1974) Erratum: [Phys. Rev. D 11, 703 (1975)].
16. R. N. Mohapatra and J. C. Pati, Phys. Rev. D 11, 566 (1975).
17. G. Senjanovic and R. N. Mohapatra, Phys. Rev. D 12, 1502 (1975).
18. M. Doi, T. Kotani, and E. Takasugi, Prog. Theor. Phys. Suppl. 83, 1 (1985).
19. M. Hirsch, H. V. Klapdor-Kleingrothaus, and O. Panella, Phys. Lett. B 374, 7 (1996).
20. A. Ali, A. V. Borisov and D. V. Zhuridov, Phys. Rev. D 76, 093009 (2007) .
21. L. Graf, F. F. Deppisch, F. Iachello, and J. Kotila, Phys. Rev. D 98, 095023 (2018).
22. L. Graf, F. F. Deppisch, F. Iachello, and J. Kotila, to be published.
23. L. Graf, F. F. Deppisch, F. Iachello, J. Kotila and J. Ferretti, to be published.
24. J. Barea and F. Iachello, Phys. Rev. C 79, 044301 (2009).
25. J. Barea, J. Kotila, and F. Iachello, Phys. Rev. C 87, 014315 (2013).
26. J. Barea, J. Kotila, and F. Iachello, Phys. Rev. C 91, 034304 (2015).
27. J. Kotila and F. Iachello, Phys. Rev. C 85, 034316 (2012).
28. F. Simkovic, G. Pantis, J. D. Vergados, and A. Faessler, Phys. Rev. C60, 055502 (1999).
29. H. Päs, M. Hirsch, H. V. Klapdor-Kleingrothaus, and S. G. Kovalenko, Phys. Lett. B498, 35 (2001).
30. J. Barea, J. Kotila, and F. Iachello, Phys. Rev. D 92, 093001 (2015).