Pinning Down the Mechanism of Neutrinoless Double β Decay with Measurements in Different Nuclei

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A measurement of neutrinoless double beta decay in one isotope does not allow us to determine the underlying physics mechanism. We discuss the discrimination of mechanisms for neutrinoless double beta decay by comparing ratios of half-life measurements for different isotopes. Six prominent examples for specific new physics contributions to neutrinoless double beta decay are analyzed. We find that the change in corresponding ratios of half lives varies from 60% for supersymmetric models up to a factor of 5–20 for extra-dimensional and left-right-symmetric mechanisms.

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An uncontroversial detection of neutrinoless double beta ($0\nu\beta\beta$) decay [1–4] will be a discovery of uttermost significance. Most importantly, it will prove the lepton number to be broken in nature, and neutrinos to be Majorana particles [5]. On the other hand, it will immediately generate another puzzle: what is the mechanism that triggers the decay? The most prominently discussed mechanism for neutrinoless double beta decay is the exchange of light Majorana neutrinos. But other mechanisms, like the exchange of SUSY superpartners with R-parity violating or conserving couplings, leptoquarks, right-handed W bosons, or Kaluza-Klein excitations, among others, have been discussed in the literature as well. Possibilities to disentangle at least some of the possible mechanisms include the analysis of angular correlations between the emitted electrons [1,6] or a comparative study of $0\nu\beta\beta$ and $0\nu\beta^+$ with electron capture (EC) decay [7]. Another possibility seems to be the study of double beta decay to excited 0^+ states [8]. Unfortunately, the search for $0\nu\beta^+/EC$ decay is complicated due to small rates and the experimental challenge to observe the produced x rays or Auger electrons; and most double beta experiments of the next generation are not sensitive to electron tracks or transitions to excited states.

Without identification of the underlying mechanism, an experimental evidence for neutrinoless double beta decay will only provide ambiguous information about the concrete physics underlying the decay. For example, no information about the neutrino mass can be obtained from a measurement of the neutrinoless double beta decay half-life.

In general, contributions to neutrinoless double beta decay can be categorized as either long-range or short-range interactions. In the first case, the diagram involves two vertices which are pointlike at the Fermi scale, and the exchange of a light neutrino in between, and is described by an effective Lagrangian of the type [9]

$$\mathcal{L} = \frac{G_F}{\sqrt{2}}(j^{\mu}_{V-A}J_{V-A,\mu} + \sum \epsilon_{NP} j_{NP} J_{NP}), \qquad (1)$$

where the sum runs over all Lorentz invariant combinations of hadronic and leptonic Lorentz currents of defined helicity, $J_{NP,V-A} = \bar{u}\mathcal{O}_J d$ and $j_{NP,V-A} = \bar{e}\mathcal{O}_j \nu$, respectively. Here $\mathcal{O}_{J,j}$ denotes the corresponding transition operator. The effective coupling strengths in new physics contributions are denoted as ϵ_{NP} throughout. For short-ranged contributions, on the other hand, the interactions are described by a single vertex being pointlike at the Fermi scale. The decay rate therefore results from first order perturbation theory, and is described by the Lagrangian [10]

$$\mathcal{L} = \frac{G_F^2}{2} m_p^{-1} \sum \epsilon_{NP} J_{NP} J_{NP} j'_{NP}. \qquad (2)$$

Here m_p denotes the proton mass and the sum runs over all Lorentz invariant combinations of hadronic, $J_{NP} = \bar{u}\mathcal{O}_J d$, and leptonic, $j'_{NP} = \bar{e}\mathcal{O}_j e^C$, currents of defined chirality.

The combination involving two vertices of the first term in (1) leads to the usual neutrinoless double beta decay half-life formula for the mass mechanism,

$$[T^{m_\nu}_{1/2}]^{-1} = (\langle m_\nu \rangle / m_e)^2 G_{01} |\mathcal{M}^{m_\nu}|^2, \qquad (3)$$

where $\langle m_\nu \rangle$ is the effective neutrino mass in which the contributions of individual neutrino mass eigenstates are weighted by mixing matrix elements squared, $\langle m_\nu \rangle = |\sum U_{ei}^2 m_i|$. The combination of the first term in (1) with any of the latter terms as well as the short-range Lagrangian (2) leads to the expression

$$[T^{NP}_{1/2}]^{-1} = \epsilon^2_{NP} G_{NP} |\mathcal{M}^{NP}|^2. \qquad (4)$$

Here, $\mathcal{M}^{m_\nu}$ and $\mathcal{M}^{NP}$ are the nuclear matrix elements for the mass mechanism and alternative new physics contributions, and G_{01} and G_{NP} denote the corresponding phase space integrals from the list given in [1]. We have assumed, that one mechanism dominates the double beta decay rate, and we do not consider interference between different mechanisms. Calculational details and results for the relevant matrix elements involved have been given elsewhere [9,10], and numerical results for all common double beta emitter isotopes will be published soon [11].

In the present context, we will concentrate on the observation that the combinations of leptonic and hadronic currents specific to different mechanisms result in different nuclear matrix elements. This fact taken alone is not of much help in order to disentangle the different mechanisms, since, e.g., a smaller nuclear matrix element for the mass mechanism as compared to any alternative new physics mechanism can be compensated by a larger value for the neutrino mass, at least within the constraints implied by other observations such as Tritium beta decay and cosmology. However, under the assumption that one mechanism dominates in triggering the decay, the new physics parameter $\langle m_\nu \rangle$ or ϵ_{NP} drops out in the ratio of experimentally determined half lives for two different emitter isotopes,

$$\frac{T_{1/2}(^{A}X)}{T_{1/2}(^{76}\mathrm{Ge})} = \frac{|\mathcal{M}(^{76}\mathrm{Ge})|^2 G(^{76}\mathrm{Ge})}{|\mathcal{M}(^{A}X)|^2 G(^{A}X)}. \tag{5}$$

Consequently, half-life ratios depend on the mechanism of double beta decay, but not on the new physics parameter, and thus can be compared with the theoretical prediction for different mechanisms. Moreover, the error in the isotope nuclear matrix element ratio can be reduced compared to the theoretical error in one matrix element, due to cancellations of systematic effects.

In the following, we study several prominent examples of specific alternative new physics contributions by calculating the corresponding ratios of half lives

$$\mathcal{R}^{NP}(^{A}X) = \frac{T^{NP}_{1/2}(^{A}X)}{T^{NP}_{1/2}(^{76}\mathrm{Ge})}, \tag{6}$$

where we concentrate on a comparison with ^{76}Ge as it constitutes the best tested isotope to date. We choose the following mechanisms for a detailed discussion: (i) *SUSY-accompanied neutrinoless double beta decay:* $\mathcal{R}^{\mathrm{SUSYacc}}$.—This mechanism has been first discussed in [12]. The effective Lagrangian for the dominant contribution assumes the form

$$\begin{aligned}\mathcal{L} \supset \frac{G_F U^*_{ei}}{4\sqrt{2}} \epsilon^{\mathrm{SUSYacc}} \Big\{ & [\bar{\nu}_i(1+\gamma_5)e^c][\bar{u}(1+\gamma_5)d] \\ & + \frac{1}{2}[\bar{\nu}_i \sigma^{\mu\nu}(1+\gamma_5)e^c][\bar{u}\sigma^{\mu\nu}(1+\gamma_5)d]\Big\},\end{aligned} \tag{7}$$

and results from integrating out a heavy d squark of the kth generation with R-parity violating couplings λ'_{11k} and λ'_{1k1}, and exchanging a light neutrino of the ith generation between the nucleons. The new physics parameter is given by

$$\epsilon^{\mathrm{SUSYacc}} = \sum_k \frac{\lambda'_{11k}\lambda'_{1k1}}{2\sqrt{2}G_F} \sin 2\theta_k \left(\frac{1}{m^2_{\tilde{d}_1}} - \frac{1}{m^2_{\tilde{d}_2}}\right), \tag{8}$$

where θ_k parametrizes the left-right sfermion mixing of the mass eigenstates $\tilde{d}_1$ and $\tilde{d}_2$.

(ii) *Gluino exchange mechanism in R-parity violating SUSY:* $\mathcal{R}^{\mathrm{SUSY}-\tilde{g}}$.—In this short-range contribution discussed in [13,14], integrating out u and d squarks and a gluino leads to the effective Lagrangian

$$\begin{aligned}\mathcal{L} \supset \frac{G_F^2}{2} m_p^{-1} \epsilon^{\tilde{g}} \Big(& [\bar{u}(1+\gamma_5)d][\bar{u}(1+\gamma_5)d] \\ & - \frac{1}{4}[\bar{u}\sigma^{\mu\nu}(1+\gamma_5)d][\bar{u}\sigma^{\mu\nu}(1+\gamma_5)d]\Big)[\bar{e}(1+\gamma_5)e^c],\end{aligned} \tag{9}$$

with

$$\epsilon^{\tilde{g}} = \frac{2\pi\alpha_s}{9} \frac{\lambda'^2_{111}}{G_F^2 m^4_{\tilde{d}_R}} \frac{m_p}{m_{\tilde{g}}} \left[1 + \left(\frac{m_{\tilde{d}_R}}{m_{\tilde{u}_L}}\right)^4\right]. \tag{10}$$

(iii) *Right-handed currents*: $\mathcal{R}^{LR-\eta\eta}$ and $\mathcal{R}^{LR-\lambda\lambda}$.—Integrating out right-handed W bosons occurring in left-right symmetric models can lead to two types of new contributions with right-handed leptonic currents [1],

$$\begin{aligned}\mathcal{L} \supset \frac{G_F}{\sqrt{2}} [\bar{\nu}_i \gamma_\mu (1+\gamma_5)e^c](\eta & [\bar{u}\gamma^\mu(1-\gamma_5)d] \\ & + \lambda[\bar{u}\gamma^\mu(1+\gamma_5)d]),\end{aligned} \tag{11}$$

where the new physics parameters are given by η and λ.

(iv) *Kaluza-Klein neutrino exchange in extra-dimensional models*: $\mathcal{R}^{KK}$.—In extra-dimensional theories, the double beta observable is given by a sum over contributions from all Kaluza-Klein excitations with masses $m_{(n)}$, weighted with the mass dependent matrix element $\mathcal{M}^{m_\nu}(m_{(n)})$ [15]:

$$\epsilon^{KK} = \frac{1}{\mathcal{M}^{m_\nu}} \sum_{-\infty}^{\infty} U^2_{en} m_{(n)} (\mathcal{M}^{m_\nu}(m_{(n)}) - \mathcal{M}^{m_\nu}). \tag{12}$$

In this case the effective coupling constant ϵ^{KK} depends on the nuclear matrix element $\mathcal{M}^{m_\nu}(m_{(n)})$, and therefore the particle physics does not decouple from the nuclear physics. This is because the masses of the Kaluza-Klein excitations vary from values much smaller than the nuclear Fermi momentum p_F to values much larger than p_F, while the $m_{(n)}$-dependence of $\mathcal{M}^{m_\nu}(m_{(n)})$ changes around p_F. Therefore the Kaluza-Klein spectrum has to be fixed by choosing specific values for the brane shift parameter a and the radius of the extra dimension R. In the limit of $a \to 0$ or $R \to 0$, $\mathcal{R}^{KK}$ approaches $\mathcal{R}^{m_\nu}$.

TABLE I. Ratios $\mathcal{R}(^{A}X)$ of half lives for various important double beta decay emitter isotopes, normalized to the half-life of ^{76}Ge. For the exchange of Kaluza-Klein excitations in extra-dimensional theories the brane shift parameter and bulk radius do not factorize, and are chosen to be $a = 10$ GeV^{-1}, 0.1 GeV^{-1}, and $R = (1/300)$ eV^{-1}.

	^{82}Se	^{100}Mo	^{128}Te	^{130}Te	^{136}Xe	^{150}Nd	Ref.
$\mathcal{R}^{m_\nu}$	0.26	0.11	3.26	0.18	0.77	0.02	this Letter
$\mathcal{R}^{\mathrm{SUSYacc}}$	0.28	0.11	3.22	0.17	0.53	0.02	this Letter
$\mathcal{R}^{\mathrm{SUSY}-\tilde{g}}$	0.28	0.10	3.16	0.17	0.53	0.01	[14]
$\mathcal{R}^{LR-\eta\eta}$	0.29	0.13	2.96	0.20	0.54	0.02	[17]
$\mathcal{R}^{LR-\lambda\lambda}$	0.14	0.13	18.40	0.13	0.67	0.01	[17]
$\mathcal{R}^{KK}$ (10 GeV^{-1})	0.24	0.08	3.26	0.19	3.31	0.08	[15]
$\mathcal{R}^{KK}$ (0.1 GeV^{-1})	0.26	0.11	3.26	0.18	0.78	0.02	[15]

The matrix elements for the mass mechanism and for the SUSY-accompanied neutrino exchange have been calculated in the pn-QRPA approach of [7,16], in the latter case for the first time. For the other mechanisms, existing numerical values obtained with the same nuclear structure model have been adopted from the literature. The values for the phase space integral factors G_{01}, G_{NP} have been calculated in [1]. Numerical values for $\mathcal{R}^{NP}(^{A}X)$ are given in Table I, and Fig. 1 displays the relative change expected from various new physics contributions, compared to the mass mechanism. An application of the procedure to any other alternative new physics contribution by using the matrix elements listed in [11] is straightforward.

All isotope ratios have been normalized to the half-life of the most extensively studied nucleus ^{76}Ge. Moreover, while at present no experiment using a ^{128}Te source has been proposed, we included this isotope since it provides a particularly powerful discriminator and thus may encourage future experimental efforts to study this nucleus.

The two supersymmetric contributions show similar deviations, which are rather small for all isotopes. It is obvious that these mechanisms are most effectively discriminated from the mass mechanism by comparing the half-life ratios between ^{82}Se and ^{136}Xe which vary by 60%. In left-right symmetric models, strong deviations can be found for the $\lambda\lambda$ combinations, while deviations for the $\eta\eta$ combination are rather small. A comparison of half-life ratios between ^{100}Mo and ^{136}Xe yields a variation of 70% for the $\eta\eta$ contribution with right-handed hadronic currents, while a comparison of measurements in ^{128}Te and ^{150}Nd will provide a powerful discriminator with a variation of more than a factor of 20 for the $\lambda\lambda$ contribution with left-handed hadronic currents. Similarly in extra-dimensional neutrino models with a large brane shift parameter, large deviations can be found for ^{136}Xe and ^{150}Nd, and the half-life ratios for ^{150}Nd and ^{100}Mo vary by more than a factor of 5. Some caution is necessary when referring to the half-life ratio of the heavily deformed ^{150}Nd, which is ignored in most QRPA calculations (compare the discussion in [18]). Finally, it should be stressed that not necessarily two positive results are needed—already the comparison of one half-life measurement and one upper bound in another isotope could provide nontrivial information on the double beta mechanism.

Since the theoretical errors of the nuclear matrix element calculation dominate the experimental errors, it is difficult to determine the confidence level with which either mechanism can be excluded to generate the observed double beta evidence. If, for example, a statistical distribution of matrix element values is assumed, a relative variation of 60% in $\mathcal{R}^{\mathrm{NP}}(^{A}X)$ with respect to $\mathcal{R}^{m_\nu}(^{A}X)$ is significant only if the corresponding nuclear matrix elements would be known with an accuracy of 15%, which seems to be unrealistic, if only one pair of isotopes is being analyzed. Indeed, estimates of errors in nuclear matrix elements vary from a factor 3–5, when the spread of published values is used as a measure, to only 30%, according to an assessment of uncertainties inherent in QRPA [19].

However, the significance of the comparison of two isotopes will increase if a whole set of measurements in different isotopes resembles the expected pattern. Moreover, one would expect that systematical effects, like an overestimation of the nuclear matrix elements due to a too small value for the particle-particle interaction g_{pp} in the pn-QRPA approach, a different value for the axial-vector coupling g_A, the inclusion of higher-order terms or a different model-space would influence calculations for the different isotopes in a similar way, and thereby cancel in the half-life ratios discussed. This expectation is confirmed

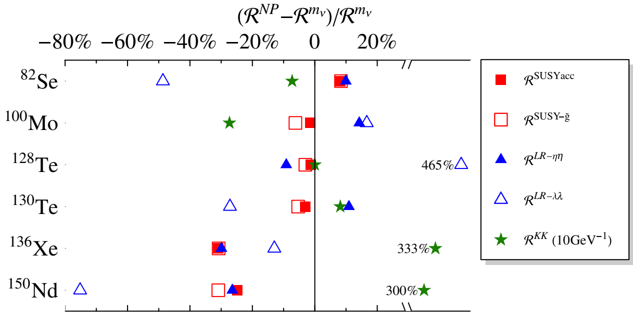

FIG. 1 (color online). Relative deviations of half-life ratios $\mathcal{R}^{\mathrm{NP}}(^{A}X)$, normalized to the half-life of ^{76}Ge, compared to the ratio in the mass mechanism $\mathcal{R}^{m_\nu}(^{A}X)$.

by the comparison of the results of different QRPA codes in [19], and of QRPA and shell model codes in [3]. Finally, it has been pointed out in [20] that the half-life ratios (6) can also be used to single out the correct nuclear structure model. In this case the correct combination of mechanism and nuclear structure code can be determined by the best fit of the theoretical half-life ratios to half-life measurements in various nuclei. Thus the results presented in this Letter should be complemented and checked with alternative codes for the nuclear matrix element calculation. Moreover, other mechanisms, including pion exchange [21], may be dominating in some of the models discussed, and should be discussed as well.

In summary, we discussed how different mechanisms of neutrinoless double beta decay would manifest themselves in half-life ratios involving different isotopes. We thus conclude that complementary measurements in different isotopes would be strongly encouraged. At present, next-generation experiment proposals exist for ^{76}Ge (GERDA, MAJORANA, GEM, GeH$_4$), ^{82}Se (Super-NEMO, DCBA, SeF$_6$), ^{100}Mo (MOON), ^{130}Te (CUORE), ^{136}Xe (EXO, XMASS, Xe), as well as for the isotopes ^{48}Ca, ^{116}Cd, and ^{160}Gd not discussed in this Letter (CANDLES, COBRA, and GSO) (for recent overviews of the experimental status see [22]). An experimental study of this kind should be complemented by neutrino mass searches in Tritium beta decay experiments and cosmology, as well as searches for effects of the alternative new physics source of lepton number violation in other processes, such as lepton flavor violating decays [23].

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Note added.—After this Letter had been submitted for publication, the paper [24] appeared, which comes to similar conclusions and estimates the number of required measurements and their precision needed.

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