Selection Rules of Nuclear Parameters for Neutrinoless Double Beta Decay

M. H. Sidky

Dept. of Eng. Math. And Physics, Faculty of Engineering, Cairo University, EGYPT
Sidkym@yahoo.com

Abstract: Theoretical and experimental nuclear data are collected from different sources to establish selection rules for the probability of the neutrino less double beta decay and neutrino mass. In this work the proposed selection rules have been applied to five double beta decay emitters by using different alterations of the QRPA model within the available range of the strength of the particle- particle interaction $0.8 \le g_{pp} \le 1.2$. It is found that acceptable results have been obtained with the emitters ^{100}Mo, ^{130}Te by using full-RQRPA, pn-RQRPA techniques with small basis of Hilbert space. New value for neutrino mass $m_v \pm \delta m_v = 0.262 \pm 0.009$ eV is determined. Such value agrees with the available experimental determinations and improves the relative uncertainty $\delta m_v / m_v$ from 12.5% to 3.43%.
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1.Introduction

Double beta decay may occur with two neutrino emission (2νββ mode) or without neutrinos emerge (0νββ mode). Nuclear physics can contribute to the solution of questions concerning the nature of neutrinos by investigation of 0νββ mode. This mode can only occur for massive Majorana neutrinos [1]. The discovery of neutrino mass m_v in oscillation experiments [2] makes the search for the nature of massive neutrinos [3] particularly relevant and timely. Kinematic measurements restrict the neutrino mass scale to be below 1 eV [4].

The decay rate of the 0νββ decay mode ω^{0v} is expressed by [5]:

$$\omega^{0v} = \ln 2\ G^{0v} (M^{0v} m_v)^2 \qquad (1)$$

The ratio between the decay rate of the 0νββ decay mode ω^{0v} and the total decay rate ω^T is the probability of occurrence of the 0νββ mode R^{0v}. It can be expressed by using eqn. (1) as follows:

$$R^{0v} = \ln 2\ G^{0v} (M^{0v} m_v)^2 / \omega^T \qquad (2)$$

The phase space factor G^{0v} of the 0νββ decay mode are calculated by using the integral form of the 0νββ decay mode. The results are listed in another work [5] for some double beta decay emitters. Table (1) presents the minimum values of the total decay rate $(\omega^T)_{min}$ for five ββ emitters: ^{82}Se, ^{100}Mo, ^{116}Cd, ^{130}Te, ^{136}Xe. They are calculated as well as the reported experimental lower limits [6-9] of the half lives for the 0νββ decay mode $(T^{0v})_{min}$ of these emitters. M^{0v} is the nuclear matrix element of the 0νββ decay mode of an emitter. It consists of three main factors: (1) Gammow-Teller transition matrix element $(M_{GT})^{0v}$ of the 0νββ decay mode. (2) Fermi transition matrix element $(M_F)^{0v}$ of the same mode. (3) the ratio g_v / g_A, where g_v, g_A are the vector, axial-vector nuclear currents. They are related to M^{0v} by the following relation: $M^{0v} = (M_{GT})^{0v} - (g_v / g_A)^2 (M_F)^{0v}$.

Previously [5] the parameter M^{0v} has been evaluated by pn-QRPA, pn-RQRPA, full-RQRPA, SQRPA techniques with small and large basis of the Hilbert space. The proton-neutron quasi particle random phase approximation (pn-QRPA) have clarified that the particle-particle interaction, which is the counterpart of the particle-hole interaction, enhances the spin-isospin correlations in the ground-state wave functions. The SQRPA technique uses the boson expansion for the phonon and β operators associated with pn-QRPA technique [10]. An alternative approach for extending pn-QRPA is based on the idea of partial restoration of the Pauli exclusion principle by taking into account the next terms in the commutator of the like nucleon operator involved in the derivation of the pn-QRPA equations [5]. The commutator is replaced by its expectation value in the RPA (correlated) g.s and this leads to a renormalization of the relevant operators and of the forward and backward going QRPA amplitudes as well. This technique is called pn-RQRPA. It has been extensively used for both 2νββ and 0νββ decay modes and for transition to g.s. and excited states and for different nuclei [11,12]. The extension of this technique when the proton-neutron pairing interactions, besides the proton-proton and neutron-neutron ones, are also included was called the full-RQRPA[13].

This work presents a procedure to determine m_v and its uncertainty δm_v as well as theoretical data [5] of G^{0v}, M^{0v} and experimental determinations of $(\omega^T)_{min}$ gathered from different laboratories [see table (1)].

Table (1) experimental data for five ββ decay emitters

Emitter	$(\omega^T)_{min}$ x 10^{-24} (y^{-1})	Experiment
^{82}Se	1.917	NEM – 3 [6]
^{100}Mo	0.627	NEM – 3 [6]
^{116}Cd	4.059	SOLOTVINO [7]
^{130}Te	0.230	CUORICINO [8]
^{136}Xe	0.153	DAMA [9]

Characteristic of ω^{0v} with g_{pp}

The variation of M^{0v} with the strength of the particle- particle interaction g_{pp} is well known [5]. According to eqn. (1) the variation of ω^{0v} with g_{pp} should be looks like the change of M^{0v} with g_{pp} assuming that m_v is kept constant. The expected behaviour of ω^{0v} versus g_{pp} is presented in fig. (1). In such figure there are two distinct values: $\omega^{0v} = 0.5\ \omega^T$ and $\omega^{0v} = \omega^T$. They correspond to $R^{0v} = 0.5$ and $R^{0v} = 1$. These values form three different regions:

(1) $0 < \omega^{0v} < 0.5\ \omega^T$.

(2) $0.5\ \omega^T < \omega^{0v} < \omega^T$.

(3) $\omega^T < \omega^{0v}$.

In each one of these regions there is a sample for the characteristic of ω^{0v} with g_{pp} [see fig. (1)]. Those samples have different properties as presented in table (2).

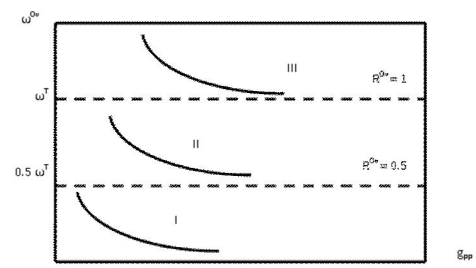

Fig. (1) Characteristics of ω^{0v} with g_{pp}. The two decay modes 2vββ and 0vββ are equally probable at $R^{0v} = 0.5$. They are forbidden for $R^{0v} > 1$

Table (2) Comparison between different regions of ω^{0v}, R^{0v}

ω^{0v}	$0 < \omega^{0v} < 0.5\ \omega^T$	$0.5\ \omega^T < \omega^{0v} < \omega^T$	$\omega^T < \omega^{0v}$
R^{0v}	$0 < R^{0v} < 0.5$	$0.5 < R^{0v} < 1$	$1 < R^{0v}$
Curve	I	II	III
Decay modes	2vββ decay mode is more probable than 0vββ decay mode.	0vββ decay mode is more probable than 2vββ decay mode.	2vββ and 0vββ decay modes are Forbidden.

Limits for R^{0v}, m_v

The variation of M^{0v} with the strength of the particle- particle interaction g_{pp} has been shown graphically [5] by using pn-QRPA, pn-RQRPA, full-RQRPA, SQRPA techniques with small and large basis of the Hilbert space. This has been utilized in this work as well as eqn. (2) to generate another variation for R^{0v} with g_{pp} such that m_v is kept constant. A set of distributions of R^{0v} with g_{pp} are presented in fig. (2). The limits of the available range of g_{pp} are g_s and g_f. According to eqn. (2) the lowest and highest distributions shown in fig. (2) correspond to the lower and upper neutrino mass limits m_1, m_2. The vertical coordinates R_{min}, R_{m1}, R_{m2}, R_{max} shown in fig. (2) are related to m_1, m_2 by [see eqn. (2)]:

$$R_{max} = C\ (M_s m_2)^2 \quad (3)$$

$$R_{m2} = C\ (M_f\ m_2)^2 \quad (4)$$

$$R_{m1} = C\ (M_s\ m_1)^2 \quad (5)$$

$$R_{min} = C\ (M_f\ m_1)^2 \quad (6)$$

In the above equations $C = \ln 2\ G^{0v} / \omega^T$ and M_s, M_f are the nuclear matrix elements of the 0vββ decay mode which correspond to g_s, g_f.

R^{0v}

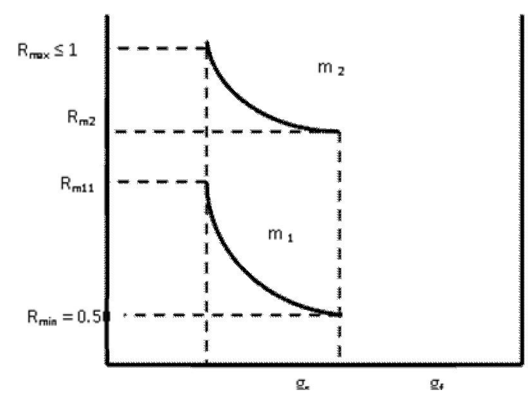

Fig. (2) The lower and upper limits of neutrino mass are m_1, m_2. The available range of g_{pp} is: $g_s \leq g_{pp} \leq g_f$. The 0vββ decay mode is more probable than the 2vββ decay mode within the range $0.5 < R^{0v} < 1$.

Selected range for m_1, m_2

In fig. (2) the lower and upper neutrino mass limits m_1, m_2 are related to the neutrino mass m_v and its uncertainty δm_v by the following relations:

$$m_v = (m_2 + m_1) / 2 \quad (7)$$

$$\delta m_v = (m_2 - m_1) / 2 \quad (8)$$

The neutrino mass m_v and its uncertainty δm_v are determined experimentally to be:

$m_v \pm \delta m_v = 0.240 \pm 0.030$ eV, $\delta m_v / m_v = 12.50$ % [14] (9)

$m_v \pm \delta m_v = 0.225 \pm 0.075$ eV, $\delta m_v / m_v = 33.33$ % [15] (10)

The neutrino mass limits m_1, m_2 should satisfy the following conditions:

(1) Consistency with the results given by eqns. (9), (10). To do that: $m_1 \leq 0.27$ eV,

$m_2 \geq 0.21$ eV

(2) Improve the experimental relative uncertainty $\delta m_v / m_v$ given by eqns. (9), (10)

to be $\delta m_v / m_v < 12.5$ %. According to eqns. (7-10) this means: $m_2 / m_1 < 9 / 7$.

Choice of R_{min}, R_{m1}, R_{m2}, R_{max}

Eqns. (3), (4), (5), (6) can be written in another form:

$$R_{m1} = R_{min} (M_s / M_f)^2 \quad (11)$$

$$R_{m2} = R_{min} (m_2 / m_1)^2 \quad (12)$$

$$R_{m1} = R_{max} (m_1 / m_2)^2 \quad (13)$$

$$R_{m2} = R_{max} (M_f / M_s)^2 \quad (14)$$

It should be noticed that $M_s > M_f$ [5] and $m_2 > m_1$ [see fig. (2)]. Thus according to eqns. (11), (12) the lower limits of R_{m1} and R_{m2} should be greater than R_{min}. Also in eqns. (13), (14) the upper limits of R_{m1} and R_{m2} should be smaller than R_{max}. In this work the lower and upper limits of R_{m1} and R_{m2} are selected to be: (R_{min} + 5%) and (R_{max} – 5%). Also the parameter R_{min} is selected to be 50%. It is the boundary between two regions: $R^{0v} > 0.5$ (0νββ decay mode is more probable than 2νββ decay mode) and $R^{0v} < 0.5$ (2νββ decay mode is more probable than 0νββ decay mode).

Selection rules for m_1, m_2, R_{min}, R_{m1}, R_{m2}, R_{max}

In this work the Selection rules for m_1, m_2, R_{min}, R_{m1}, R_{m2}, R_{max} are:

$$m_1 \leq 0.27 \text{ eV} \quad (15)$$

$$m_2 \geq 0.21 \text{ eV} \quad (16)$$

$$m_2 / m_1 < 9/7 \quad (17)$$

$$55\% < R_{max} \leq 100\% \quad (18)$$

$$R_{min} = 50\% \quad (19)$$

$$55\% \leq R_{m1} < R_{max} - 5\% \quad (20)$$

$$55\% \leq R_{m2} < R_{max} - 5\% \quad (21)$$

Determination of m_2, R_{max} for ^{82}Se, ^{100}Mo, ^{116}Cd, ^{130}Te, ^{136}Xe at $g_s = 0.8$ [5]

It has been reported [5] that $g_s = 0.8$ for all the double beta decay emitters and nuclear techniques used in this work. The upper limit of $R_{max} = 100\%$ [see eqn. (18)] has been used in eqn. (3) to calculate m_2 associated with (0νββ) decay mode of ^{82}Se, ^{100}Mo, ^{116}Cd, ^{130}Te, ^{136}Xe. This has been done by using the reported values [5] of M_s obtained from pn-QRPA, pn-RQRPA, full-RQRPA and SQRPA techniques with small (S) and large (L) basis of Hilbert space. The results of calculations are presented in table (3).

In table(3) * denotes the cases which verify eqns. (15), (16), (17). For the other cases another trial is carried out in which the upper limit of m_1= 0.27 eV [see eqn. (15)] has been used in eqn. (17) to give the upper limit of m_2 = 0.347 eV. This limit is used in eqn. (3) to calculate R_{max} as well as M_s [5]. The results of calculations are listed in tables (4,5). The cases presented in table (4) verify eqn. (18). On the other hand the cases shown in table (5) should be disappointed as they fail to satisfy eqn. (18).

Table (3) m_2 in (eV) and R_{max} = 100% for some (0νββ) decay emitters by using different nuclear models with small (S) and large (L) basis of Hilbert space. The values of m_2 which verify eqns. (15), (16), (17) are denoted by *

Pn-QRPA		Pn-RQRPA		Full-RQRPA		SQRPA		
S	L	S	L	S	L	S	L	Emitter
0.902	1.090	1.190	1.648	1.123	1.775	1.225	1.429	^{82}Se
0.264 *	0.376	0.309 *	0.299 *	0.299 *	0.362	0.356	0.377	^{100}Mo
1.478	1.887	1.309	1.727	1.964	2.249	1.215	1.236	^{116}Cd
0.302 *	0.349	0.281 *	0.3797	0.271 *	0.362	0.608	0.745	^{130}Te
0.5445	0.664	0.514	0.560	0.495	0.623	0.279 *	0.296 *	^{136}Xe

Table (4) R_{max} > 55 % for some 0νββ decay emitters with different nuclear techniques

Pn-QRPA		Pn-RQRPA		Full-RQRPA		SQRPA		
S	L	S	L	S	L	S	L	Emitter
	85.17%				91.88%	95.01%	84.72%	^{100}Mo
	98.86%		83.52%		91.88%			^{130}Te

Table (5) R_{max} < 55 % for some 0νββ decay emitters with different nuclear techniques

Pn-QRPA		Pn-RQRPA		Full-RQRPA		SQRPA		
S	L	S	L	S	L	S	L	Element
14.81%	10.15%	8.51%	4.43%	9.55%	3.82%	8.03%	5.90%	^{82}Se
5.52%	3.38%	7.03%	4.03%	3.12%	2.38%	8.16%	7.89%	^{116}Cd
						32.57%	21.69%	^{130}Te
40.61%	27.31%	45.58%	38.39%	49.14%	31.02%			^{136}Xe

Determination of m_1, R_{m2} for ^{100}Mo, ^{130}Te, ^{136}Xe at $g_f = 1.2$

The lower limit of the neutrino mass m_1 is calculated from eqn. (12), (19) to be:

$$m_1 = m_2 \, (0.5 / R_{m2})^{1/2} \qquad (22)$$

Eqn. (4) shows that R_{m2} is calculated as well as M_f. The determination of M_f [5] depends on the choice of g_f. The factor g_f must be carefully selected to keep the parameter $R_{m2} > 55\%$ [see eqn. (21)]. In this work $g_f = 1.2$ has been used to determine M_f [5]. This is done for pn-QRPA, pn-RQRPA, full-RQRPA and SQRPA techniques with small and large basis of Hilbert space to calculate R_{m2} from eqn. (4) for a set of emitters presented in table (6). This set contains all the cases presented in table (4) and those denoted by * in table (3).

Table (6) R_{m2} for some $0\nu\beta\beta$ decay emitters with different nuclear techniques

Pn-QRPA		Pn-RQRPA		Full-RQRPA		SQRPA		
S	L	S	L	S	L	S	L	Emitter
54.67%	26.94%	45.92%	51.16%	59%	32.08%	9.93%	4.83%	^{100}Mo
30.98%	3.74%	67.38%	39.60%	57.56%	50.82%			^{130}Te
						8.73%	7.94%	^{136}Xe

The values of R_{m2} presented in table (6) indicate that the cases which verify eqn. (21) are

(1) ^{100}Mo with small basis of Hilbert space in full-RQRPA technique.

(2) ^{130}Te with small basis of Hilbert space in pn-RQRPA and full-RQRPA techniques.

The upper and lower limits of $R^{0\nu}$, m_ν for these emitters are in the shown distributions of figs. (3-5). A new values of m_ν, δm_ν are determined and listed in table (7).

All the listed values of $m_\nu \pm \delta m_\nu$ in table (7) agree with the available experimental determinations [see eqns. (9), (10)]. In table (7) the most precise result is $m_\nu \pm \delta m_\nu = 0.262 \pm 0.009$ (eV). Its relative uncertainty $\delta m_\nu / m_\nu = 3.43$ % is better than the previous experimental one 12.5 % [see eqn. (9)] by a factor of about 4.

Table (7) new determinations for $m_\nu \pm \delta m_\nu$

Emitter	technique	Base	$m_\nu \pm \delta m_\nu$ (eV)	$\delta m_\nu / m_\nu$ %
^{100}Mo	full-RQRPA	Small	0.287 ± 0.012	4.18
^{130}Te	pn-RQRPA	Small	0.262 ± 0.02	7.46
^{130}Te	full-RQRPA	Small	0.262 ± 0.009	3.43

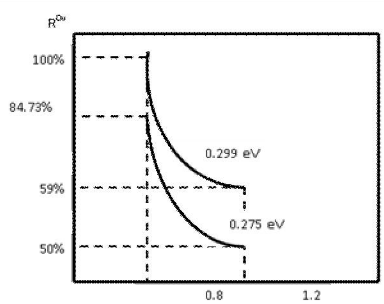

Fig. (3) Limits of $R^{0\nu}$, m_ν for ^{100}Mo with small basis of Hilbert space in Full-RQRPA technique.
$50\ \% \le R^{0\nu} \le 84.73\ \%$ for $m_\nu = 0.275$ eV
$59\ \% \le R^{0\nu} \le 100\ \%$ for $m_\nu = 0.299$ eV

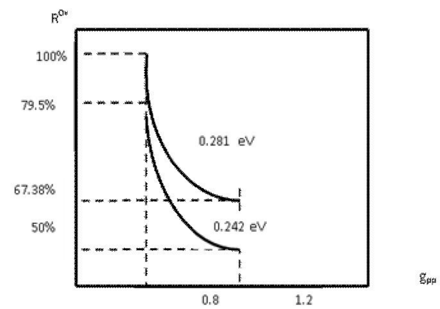

Fig. (4) Limits of $R^{0\nu}$, m_ν for ^{130}Te with small basis of Hilbert spaceused in Pn-RQRPA technique
$50\ \% \le R^{0\nu} \le 79.5\ \%$ for $m_\nu = 0.242$ eV
$67.38\ \% \le R^{0\nu} \le 100\ \%$ for $m_\nu = 0.281$ eV

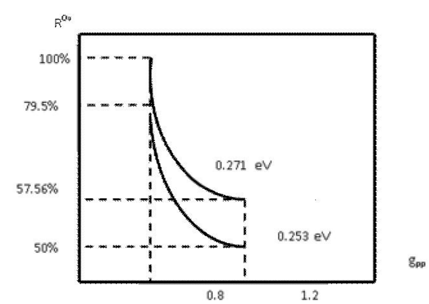

Fig. (5) Limits of $R^{0\nu}$, m_ν for ^{130}Te with small basis of Hilbert spaceused in full-RQRPA technique
$50\ \% \le R^{0\nu} \le 79.5\ \%$ for $m_\nu = 0.253$ eV
$57.56\ \% \le R^{0\nu} \le 100\ \%$ for $m_\nu = 0.271$ eV

Recommendations

There are some recommendations for the emitters used in this work:

(I) ^{100}Mo, ^{130}Te:

The pn-RQRPA and full-RQRPA techniques with small basis of the Hilbert space have been used successfully with these emitters to give acceptable results for neutrino mass and probability of the $0\nu\beta\beta$ decay mode. This means that renormalization of the

g_{pp}

relevant operators and of the forward and backward going QRPA amplitudes used in pn-RQRPA and full-RQRPA techniques with small basis of the Hilbert space is appropriate to describe the 0νββ decay mode of ^{100}Mo, ^{130}Te.

(II) ^{82}Se, ^{116}Cd, ^{136}Xe:

These emitters fail to give an acceptable results for all the techniques used in this work.

It may be possible to improve the unaccepted values of neutrino mass listed in table (3) for the emitters ^{82}Se, ^{116}Cd, ^{136}Xe. This can be done by reducing such values by a factors of about 5, 7, 2 respectively to make consistency with the experimental results given by eqns. (9), (10). According to eqn. (2) this reduction corresponds to 3 different cases:

Case (1):

In this case R^{0v}, M^{0v}, ω^T are kept without change and the reported values of G^{0v} [5] are multiplied by a factors of about 25, 50, 4. This corresponds to multiply the Q-values of these emitters by another factors: 1.9, 2.2, 1.3 because G^{0v} is approximately proportional to Q^5 [16]. It is not possible to verify this case because the Q-values of the emitters ^{82}Se, ^{116}Cd, ^{136}Xe are well determined by the Atomic Mass Evaluation [17].

Case (2):

In this case ω^T, G^{0v}, R^{0v} are kept constant while the values of M^{0v} of the emitters ^{82}Se, ^{116}Cd, ^{136}Xe [5] are multiplied by a factors of about 5, 7, 2 respectively. Such multiplication produces a new values of M^{0v} which are far from the normal range determined by many groups [5,18,19,20,21,22]. Therefore this case is not acceptable.

Case (3):

In such case G^{0v}, M^{0v}, R^{0v} are kept constant. The values of ω^T listed in table (1) should be

divided approximately by 25, 50, 4 to be: 0.0767×10^{-24} y^{-1}, 0.0811×10^{-24} y^{-1}, 0.038×10^{-24} y^{-1} for the emitters ^{82}Se, ^{116}Cd, ^{136}Xe respectively.

Conclusion

This work presents a procedure to determine the probability of the 0νββ decay mode and neutrino mass by using two conditions. These conditions are: (1) consistency between the theoretical and experimental determinations of neutrino mass (2) the 0νββ mode is more probable than the 2νββ mode. These conditions have been applied for five

double beta decay emitters: ^{82}Se, ^{100}Mo, ^{116}Cd, ^{130}Te, ^{136}Xe by using pn-QRPA, pn-RQRPA, full-RQRPA, SQRPA techniques with small and large basis of the Hilbert space. This is carried out within the available range of the strength of the particle-particle interaction $0.8 \leq g_{pp} \leq 1.2$. The emitters ^{100}Mo, ^{130}Te are succeeding in verifying the above conditions by using pn-RQRPA and full-RQRPA techniques with small basis of the Hilbert space. A new theoretical limits for neutrino mass has been calculated to be: $0.271 \leq m_v \leq 0.253$ eV. Such limits agree with the available experimental determinations and improve the relative uncertainty $\delta m_v / m_v$ by a factor of about 4. The probability of the 0νββ decay mode varies between 50 % and 100 % within the range $0.271 \leq m_v \leq 0.253$.

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