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Nuclear and weak interaction aspects of neutrinoless double beta decay: recent results

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Abstract. The determination of the value of the light neutrino mass, as well as the determination of the nature of the neutrino, are two of the fundamental questions which motivate the experimental search of signals of neutrinoless double beta decay transitions. Here, we shall review some of the the essentials of the theory, based on both nuclear structure and elementary particle physics, relevant for the understanding of the problem

1. Introduction

Various experiments conducted during the last decade have confirmed the existence of neutrino oscillations [1]. The experimental findings have therefore confirmed the theoretical notions advanced by Pontecorvo many years ago. The nature of the neutrino (as a Majorana or Dirac particle) was not established yet. It requires to pass a more challenging test, that is the experimental observation of neutrinoless double beta decay [2] and the determination of an associated lepton-number violating mechanism [3].

The double beta decay is a very rare decay which takes place between nuclei which differ in two units of charge and that have the same mass number; $(A, N, Z) \rightarrow (A, N \mp 2, Z \pm 2)$; and it produces two electrons and two antineutrinos (two-neutrino mode) or just two-electrons (neutrinoless mode). The two-neutrino mode is allowed by the Standard Model of Electroweak interactions since it conserves the lepton number, but it is suppressed by kinematical reasons (e.g.: four leptons in the final state) and it is independent of the neutrino properties. The neutrinoless mode is by far the most interesting one, because it is forbidden by the Standard Model of Electroweak interactions (e.g.; it implies lepton number violation), but if it is detected, it will demonstrate that lepton number is not a fundamental symmetry. The two neutrino mode has been observed in direct measurements, for a series of nuclei and it has the longest half-life ($\approx 10^{20}$ years) ever detected directly (that is in a laboratory). The expected half-life for the neutrinoless mode is even larger, of the order of $> 10^{25}$ years [2].

The calculation of nuclear matrix elements (NME) for double beta decay (DBD) transitions is a matter of relevance, both for nuclear and particle physics. We shall referred hereafter to [4, 5] for details. It seems that a consensus has been reached concerning the order of magnitude

of the relevant NME [5], and that the reliability of the theoretical estimations of NME has improved. In this note we review some of the elements which, in our opinion, are crucial to determine the stability of the results. For details about the calculations we shall refer the reader to Refs.[6, 7, 8].

2. Neutrino mixing

The relation between flavor ($\nu_{e,\mu,\tau}$) and mass ($\nu_{1,2,3}$) eigenstates, of the neutrino, assuming light neutrinos and CP invariance is written

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \otimes \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \tag{1}$$

The elements of the mixing matrix U can be determined from oscillation data, and the mass eigenstates can be labelled by hierarchies of the mass values (either by adopting a normal ($m_1 \approx m_2 < m_3$), inverse ($m_3 < m_1 \approx m_2$) or degenerate ($m_1 \approx m_2 \approx m_3$) values). The square mass differences $\delta^2_{ij} = m^2_i - m^2_j$ are fixed by solar and atmospheric neutrino-oscillation data data [1], and the value of the sum of the masses, $\Omega = \sum_i m_i$, may be extracted from astronomical data [9]. The absolute mass scale can be fixed by DBD, once the decay mechanism is determined by data. The average electron-neutrino mass is written

$$< m_\nu >= \sum_{i=1}^{3} m_i U^2_{ei} \lambda^{CP}_i = m_1 U^2_{e1} \pm m_2 U^2_{e2} \tag{2}$$

(we assume CP invariance and $U_{13} = 0$). The average electron-neutrino mass (in units of eV), for the best fit-matrix U and for the three mass hierarchies[6] may vary between 0.10 eV and 0.50 eV.

3. Nuclear structure

The mass mode of the $0\nu\beta\beta$ decay describes the exchange of a light virtual Majorana neutrino between two decaying neutrons of the initial nucleus. The $0\nu\beta\beta$-decay half-life is related to the effective neutrino mass $\langle m_\nu \rangle$ through the relation

$$\left[t^{(0\nu)}_{1/2}(0^+_{\rm i} \to 0^+_{\rm f}) \right]^{-1} = G^{(0\nu)}_1 \left(\frac{\langle m_\nu \rangle}{m_{\rm e}} \right)^2 \left(M^{(0\nu)} \right)^2 \ , \tag{3}$$

where $G^{(0\nu)}_1$ is the leptonic phase-space factor [3]. The $0\nu\beta\beta$ nuclear matrix element $M^{(0\nu)}$ consists of the Gamow–Teller (GT), Fermi (F) and tensor (T) parts as

$$M^{(0\nu)} = M^{(0\nu)}_{\rm GT} - \left(\frac{g_{\rm V}}{g_{\rm A}} \right)^2 M^{(0\nu)}_{\rm F} + M^{(0\nu)}_{\rm T} \ . \tag{4}$$

The tensor part in (4) is very small, and it can be neglected. The explicit expression of these matrix elements can be found in [6]. The review of the fundamentals of the currently used models can be found in [4, 5] and for the sake of brevity we shall focuss here on the spherical proton-neutron Quasiparticle Random Phase Approximation (pnQRPA) and on the discussion of the theoretical assumptions may affect the results.

3.1. The pnQRPA approximation

The pnQRPA consists of the diagonalization of the residual proton-neutron two body interaction in a subspace of two-quasiparticle (proton-neutron) states. It contains a free parameter, the particle-particle strength parameter, $g_{\rm pp}$, that controls the magnitude of the proton-neutron two-body interactions in the $J^{\pi} = 1^{+}$ channel [10]. The value of this parameter can be fixed by fitting the data on the available two-neutrino double beta ($2\nu\beta\beta$) decay [6] or data on single beta decay [11]. However, since the correlations which are involved in the NME for two-neutrino ($2\nu\beta\beta$) and neutrinoless ($0\nu\beta\beta$) decays are basically different (see next section), the adjustment of this parameter to the observed $2\nu\beta\beta$ may not guarantee the accuracy of the NME for the neutrinoless DBD mode. The non-physical effects associated to attempts to go beyond the point of collapse of the proton-neutron Quasiparticle Random Phase approximation (pnQRPA) are notorious. As a consequence, the results of some extensions , like the pnRQRPA, should be taken with care.

3.2. Jastrow and UCOM-Short Range Correlations

The average exchanged momentum, carried by the neutrino is of the order of 100 MeV/c, and the two nucleons tend to overlap. This is a very distinctive feature of the NME for the neutrinoless double beta decay (the $0\nu\beta\beta$ NME are relatively large, of the order of 3-5) as compared with the two-neutrino mode (the $2\nu\beta\beta$ NME are very small, e.g: ten to hundred times smaller than the $0\nu\beta\beta$ NME). A suitable microscopic approach for the inclusion of short-range correlations is the unitary correlation operator method (UCOM). In [7] it was demonstrated that the conventional Jastrow procedure leads to excessive reductions in the magnitudes of the $0\nu\beta\beta$ nuclear matrix elements. For the Jastrow function, the combined action of the exponential and polynomial factors (which are functions of the relative distance between nucleons) affects the balance between the negative and positive contributions of the radial part of the two-nucleon wave function, suppressing the predominantly positive contribution to the nuclear matrix element. The UCOM correlation function acts upon the surface portion of the two-particle wave function, thus producing a slighter reduction. A consistent description of short-range correlations should include, at the same level of approximation, the treatment of the wave functions and that of the transition operators. This can be achieved by constructing a theory of effective operators. The differences which emerge from the study of the radial dependence of the NME is another element to be considered at the time of adopting the adjustment of the parameter g_{pp}.

Here, as illustration of these concepts, we present the results of nuclear-structure calculations for the $0\nu\beta\beta$ ground-state-to-ground-state decays of ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, and ^{136}Xe [7]. To obtain physical values of the proton-neutron particle-particle interaction strength, $g_{\rm pp}$, of the pnQRPA, it was adjusted to reproduce the experimental rates of the $2\nu\beta\beta$ decay. The fit included the experimental errors and the uncertainty in the value of the axial-vector coupling constant $g_{\rm A}$ ($1.0 \leq g_{\rm A} \leq 1.25$). The extracted values of $g_{\rm pp}$ and the corresponding values of $g_{\rm A}$ are listed in Table 1(see [7] for further details).

4. Adjusted single-particle energies and BCS occupation factors

The results of charge-exchange and one particle transfer measurements in A=76 nuclei can be used as a guideline to adjust single-particle energies and occupation factors [12]. The proton energies were inspected by using the odd-mass nuclei adjacent to ^{76}Ge and ^{76}Se as spectroscopic tools [8]. The standard method to determine single-particle energies is to use the Woods–Saxon mean-field potential in conjunction with spectroscopic data. Small adjustments of the resulting energies can be done based on the data, particularly by looking at the sequence of energy levels of odd-mass nuclei in the neighborhood of the nucleus where the pnQRPA calculation are

Table 1. Calculated $0\nu\beta\beta$ NME for some of the DBD emitters. The $g_{\rm pp}$ and $g_{\rm A}$ values and the resulting half-lives $t^{(0\nu)}_{1/2}$, are given in the table. Jastrow (J) and UCOM (U) matrix elements are given in the last columns. The half-lives $t^{(0\nu)}_{1/2}$ are expressed in units of $\mathrm{yr}/(\langle m_\nu\rangle[\mathrm{eV}])^2$.

Nucleus	$g_{\rm pp}$	$g_{\rm A}$	$M^{(0\nu)}$(J)	$t^{(0\nu)}_{1/2}$(J)	$M^{(0\nu)}$(U)	$t^{(0\nu)}_{1/2}$(U)
^{76}Ge	1.02	1.00	5.077	4.0×10^{24}	6.555	2.4×10^{24}
	1.06	1.25	4.029	2.6×10^{24}	5.355	1.4×10^{24}
^{82}Se	0.96	1.00	3.535	1.9×10^{24}	4.597	1.1×10^{24}
	1.00	1.25	2.771	1.2×10^{24}	3.722	6.9×10^{23}
^{96}Zr	1.06	1.00	3.131	1.2×10^{24}	4.319	6.1×10^{23}
	1.11	1.25	2.065	1.1×10^{24}	3.117	4.7×10^{23}
^{100}Mo	1.07	1.00	3.526	1.2×10^{24}	4.849	6.2×10^{23}
	1.09	1.25	2.737	7.9×10^{23}	3.931	3.8×10^{23}
^{116}Cd	0.82 (β^- decay)	1.25	3.981	3.5×10^{23}	4.928	2.3×10^{23}
	0.97	1.00	3.681	1.0×10^{24}	4.682	6.3×10^{23}
	1.01	1.25	3.034	6.1×10^{23}	3.935	3.6×10^{23}
^{128}Te	0.86 (β^- decay)	1.25	4.068	9.5×10^{24}	5.509	5.2×10^{24}
	0.89	1.00	4.279	2.1×10^{25}	5.841	1.1×10^{25}
	0.92	1.25	3.383	1.4×10^{25}	4.790	6.9×10^{24}
^{130}Te	0.84	1.00	4.061	9.5×10^{23}	5.442	5.3×10^{23}
	0.90	1.25	2.993	7.0×10^{23}	4.221	3.5×10^{23}
^{136}Xe	0.74	1.00	2.864	1.8×10^{24}	3.719	1.1×10^{24}
	0.83	1.25	2.053	1.4×10^{24}	2.802	7.6×10^{23}

performed. In [12] the neutron pair correlations in the ^{76}Ge and ^{76}Se nuclei were measured by (p,t) reactions. As a model space we have used the $N = 3$ and $N = 4$ oscillator shells and the $0h_{11/2}$ single-particle orbital, both for protons and neutrons. The single-particle energies were obtained from the Coulomb-corrected Woods–Saxon potential. In Ref. [6, 7, 8] we describe the details of the systematics.

4.1. DBD-NME results

The calculated NME ($0\nu\beta\beta$ mode), for the decay of some DBD systems are shown in Table 2.

Table 2. NME for neutrinoless DBD transitions from the ground state of the mother nuclei. The NME are given for two extreme values of the axial-vector coupling g_A. The factor $C^{(0\nu)}$ contains the phase space factor and the calculated NME [8].

System	NME($g_A = 1$)	NME ($g_A = 1.25$)	$C^{(0\nu)}$
^{76}Ge	3.23	5.52	1.36-3.96
^{82}Se	2.77	4.57	0.46-1.24
^{128}Te	3.74	5.62	4.98-11.2
^{130}Te	3.48	5.12	0.24-0.52
^{136}Xe	2.38	3.35	0.53-1.06

The magnitude of the pnQRPA (UCOM) calculated NME is rather close to the shell-model result. The reason for the reduction of the magnitude of the $0\nu\beta\beta$ NME, as compared with

previous pnQRPA results, can be found by performing the multipole decomposition of the NME [8]. For the Fermi matrix element the reduction stems from the 0^+ intermediate states. For the Gamow–Teller matrix element $M_{\rm GT}^{(0\nu)}$ the significant changes concentrate on the 1^+ and 2^- contributions. The wave function of the 2_1^- state plays a key role when seeking the reason for the reduction of the magnitude of the Gamow–Teller matrix element.

Concerning the decay of ^{76}Ge, the quality of the lowest 2^- state in the intermediate nucleus ^{76}As can be tested by computing the β^- decay $\log ft$ values for transitions from this state to the ground state and one- and two-phonon states in ^{76}Se. This transition tests exclusively the 2_1^- wave function whereas the rest of the transitions depend also on wave function of the final state. The single β^- decay is a non-trivial way to check the reduction of the $0\nu\beta\beta$ NME. In the calculation of [8] the wave function of the 2_1^- state is more fragmented and thus reduces the pnQRPA amplitude responsible for the transitions.

The computed $0\nu\beta\beta$ NME of Table 2 can be converted to half-life limits,

$$t_{1/2}^{(0\nu)} \;=\; C^{(0\nu)} \times 10^{24}\,\mathrm{yr}/(\langle m_\nu\rangle[\mathrm{eV}])^2 \qquad (5)$$

which yield, for an average electron-neutrino mass of the order of 0.1 eV, half-life lower limits of the order of 10^{26} years. These limits are of the order of magnitude of the values which may be accessible to the next generation of DBD experiments.

5. Conclusions

To conclude, we have presented the results of pnQRPA-based calculations of the nuclear matrix elements involved in the neutrinoless double beta decay, and discuss some of the aspects related to the sensitivity of the NME. Particularly, we have discussed the use of the available data on particle transfer to adjust the single particle sector of the calculations, and the sensitivity of the results upon the method adopted to account for short range correlations.

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References

[1] SNO Collaboration, Ahmad Q R *et al.* 2002 *Phys Rev Lett* **89** 011301, SK-Collaboration, Fukuda S *et al.* 2001 *Phys Rev Lett* **86** 5651, KamLAND Collaboration, Eguchi K *et al.* 2003 *Phys Rev Lett* **90** 021802, Appollonio M *et al.* 1999 *Phys Lett B* **466** 415
[2] Avignone F T, Elliott S R, Engel J 2008 *Rev Mod Phys* **80** 481
[3] Vergados J D 2002 *Phys Rep* **361** 1, Doi M, Kotani T, Takasugi E 1985 *Prog Theor Phys Suppl* **83** 1
[4] Suhonen J and Civitarese O 1998 *Phys Rep* **300** 123; Faessler A and Simkovic F 1998 *J Phys G* **24** 2139
[5] Barea J and Iachello F 2009 *Phys Rev C* **79** 044301; Suhonen J and Kortelainen M 2008 *Int J Mod Phys E* **17** 1; Simkovic F, Faessler A and Vogel P 2009 *Phys Rev C* **79** 015502; Simkovic F, Faessler A, Rodin V, Vogel P, Engel J 2008 *Phys Rev C* **77** 045503
[6] Civitarese O and Suhonen J 2005 *Phys Lett B* **626** 80; Civitarese O and Suhonen J 2005 *Nucl Phys A* **761** 313; Civitarese O and Suhonen J 2003 *Nucl Phys A* **729** 867
[7] Kortelainen M, Civitarese O, Suhonen J, Toivanen J 2007 *Phys Lett B* **647** 128; Kortelainen M, Suhonen J 2007 *Phys Rev C* **75** 051303(R); Kortelainen M, Suhonen J 2007 *Phys Rev C* **76** 024315
[8] Suhonen J and Civitarese O 2010 *Nucl Phys A* **847** 207
[9] Larson D *et al.* 2011 *Ap J S* **192** 16
[10] Vogel P and Zirnbauer M 1986 *Phys Rev Lett* **57** 3148; Civitarese O, Faessler A and Tomoda T 1987 *Phys Lett B* **194** 11
[11] Suhonen J 1993 *Nucl Phys A* **563** 205
[12] Schiffer J P *et al.* 2008 *Phys Rev Lett* **100** 112501; Kay B P *et al.* 2009 *Phys Rev C* **79** 021301(R)