About the value of g_A and related issues

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Abstract

The upper limit on the mass of the Majorana neutrino, extracted from the limits on the non-observation of the neutrinoless double beta decay, is hampered not only by uncertainties in the matrix elements of the transition operators but also by a possible mass-dependence of the value of the coupling constant of the axial-vector current . In this talk I shall continue with the analysis of the nuclear structure aspects related to the value of g_A. The material of the talk is based on our work with Dr Jun Terasaki, and with work (still in progress) with Dr. Jouni Suhonen.

Plan of the talk

- Reference to previous works and motivations
- The case of the decay of ^{136}Xe
- Correspondence between two and zero neutrino modes
- Diagrammatic corrections to the matrix elements
- Systematics of g_A
- Conclusions

Some notions about the problem I

The calculation of $T^{0\nu}_{1/2}$ of the $0\nu\beta\beta$ decay requires the knowledge of four factors:

- i) the nuclear matrix elements (NME) of the operator acting on the nucleus in the decay
- ii) the coupling constant of the axial-vector current (g_A)
- iii) the electron contribution (the phase space factor)
- iv) the value of the effective mass of the Majorana neutrino $\langle m_\nu \rangle$

Some notions about the problem II

- Out of these points, the one referring to the value of the axial-vector coupling g_A is of particular interest. As pointed out recently by Manque Rho (Symmetry 15, no 9 , 1648 (2023)), the so-called quenched g_A, denoted as $g_A^0 \approx 1$ observed in the Gamow-Teller transitions in light-nuclei has little to do with genuine quenching of the value of g_A in free space ($g_A = 1.276$). Rather it could be the effect of full nuclear correlations driven by some emerging scale symmetry .
- This view is opposed to the notion of a genuine renormalization of g_A within the framework of the effective field theory space defined by the chiral scale ($\leq 4\pi f_\pi$). A
- similar result, about a decreasing value of g_A, as a function of the mass number, was reported years ago by J. Suhonen and myself (Nuc.Phys.A761(2005)313), by J. Suhonen (PRC 96(2017)055501), and more recently by H. Ejiri and J. Suhonen. (Journal of .Phys. G. 42(2015)055201).

Matrix elements and half-life of $2\nu\beta\beta$ decay

The half-life for the $2\nu\beta\beta$ decay $T_{1/2}^{2\nu}$ can be determined by

$$\frac{1}{T_{1/2}^{2\nu}} = G_{2\nu} |M_{2\nu}|^2.$$

$G_{2\nu}$ is the phase space factor of the $2\nu\beta\beta$ decay, and it is again proportional to g_A^4. The $2\nu\beta\beta$ NME $M_{2\nu}$ has the expression corresponding to that of the $M_{0\nu}$;

$$M_{2\nu} = M_{2\nu}^{\mathrm{GT}} - \frac{g_V^2}{g_A^2} M_{2\nu}^{\mathrm{F}},$$
$$M_{2\nu}^{\mathrm{GT}} = M_{2\nu}^{\mathrm{GT(0)}} + M_{2\nu}^{\mathrm{GT(vc)}} + M_{2\nu}^{\mathrm{GT(2bc)}},$$
$$M_{2\nu}^{\mathrm{F}} = M_{2\nu}^{\mathrm{F(0)}} + M_{2\nu}^{\mathrm{F(vc)}} + M_{2\nu}^{\mathrm{F(2bc)}}.$$

Matrix elements and half-life of $0\nu\beta\beta$ decay

The half-life for the $0\nu\beta\beta$ decay is obtained from

$$\frac{1}{T_{1/2}^{0\nu}} = G_{0\nu}|M_{0\nu}|^2 \left(\frac{\langle m_\nu \rangle}{m_e}\right)^2 ,$$

$G_{0\nu}$ is the phase space factor of the $0\nu\beta\beta$ decay, and it is also proportional to g_A^4 and where the $0\nu\beta\beta$ NME $M_{0\nu}$ is defined by

$$\begin{aligned} M_{0\nu} &= M_{0\nu}^{\mathrm{GT}} - \frac{g_V^2}{g_A^2} M_{0\nu}^{\mathrm{F}}, \\ M_{0\nu}^{\mathrm{GT}} &= M_{0\nu}^{\mathrm{GT(0)}} + M_{0\nu}^{\mathrm{GT(vc)}} + M_{0\nu}^{\mathrm{GT(2bc)}}, \\ M_{0\nu}^{\mathrm{F}} &= M_{0\nu}^{\mathrm{F(0)}} + M_{0\nu}^{\mathrm{F(vc)}} + M_{0\nu}^{\mathrm{F(2bc)}}. \end{aligned}$$

Perturbative treatment of the transitions

I shall referrer here to J.Terasaki and O.Civitarese, Phys.Rev.C 112, L 051302 (2025) and to J.Terasaki and O.Civitarese, Phys.Rev.C 112, 024304 (2025).

$$\langle \widetilde{F} | H_W | I \rangle = 0.$$

This procedure results in the modified $M^{(1)}$ as

$$\widetilde{M}^{(1)} = \sum_{\widetilde{B} \neq I} \langle \widetilde{F} | H_W | \widetilde{B} \rangle \frac{1}{E_I - E_{\widetilde{B}}} \langle \widetilde{B} | H_W | I \rangle.$$

H_W is the lepton current-hadron current interaction. Its density is given by

$$\mathcal{H}_W = \frac{G}{\sqrt{2}} j_L^{\rho} \mathcal{J}_{L\rho}^{\dagger} + \mathrm{h.c.}$$

The leading-order $0\nu\beta\beta$ NME

$$
\begin{aligned}
M_{0\nu}^{(0)} \quad = \quad & \frac{4\pi R}{g_A^2} \int d^3\boldsymbol{x}\, d^3\boldsymbol{y} \sum_B \int \frac{d^3\boldsymbol{q}}{(2\pi)^3} \frac{1}{|\boldsymbol{q}|} \frac{\exp[i\boldsymbol{q}\cdot(\boldsymbol{x}-\boldsymbol{y})]}{E_B + |\boldsymbol{q}| - \frac{1}{2}(E_I + E_F)} \\
& \times \langle F|\mathcal{J}^{\mu}(\boldsymbol{x})|B\rangle\langle B|\mathcal{J}_{\mu}(\boldsymbol{y})|I\rangle,
\end{aligned}
$$

Lowest-order correction for nuclear matrix element

$$\mathcal{M}^{(JJV)}_{\beta\beta}(\boldsymbol{x},\boldsymbol{y}) \equiv -\sum_{C\neq I}\sum_{B}\langle F|\mathcal{J}_{\mu}(\boldsymbol{x})|B\rangle \frac{1}{E_B + |\boldsymbol{q}| - \frac{1}{2}(E_I + E_F)}$$

$$\times \quad \langle B|(-\mathcal{J}^{\mu}(\boldsymbol{y}))|C\rangle \frac{1}{E_C - E_I}\langle C| : (-V) : |I\rangle,$$

$$\mathcal{M}^{(VJJ)}_{\beta\beta}(\boldsymbol{x},\boldsymbol{y}) \equiv -\sum_{D\neq F}\sum_{B}\langle F| : (-V) : |D\rangle \frac{1}{E_D - E_F}\langle D|\mathcal{J}_{\mu}(\boldsymbol{x})|B\rangle$$

$$\times \quad \frac{1}{E_B + |\boldsymbol{q}| - \frac{1}{2}(E_I + E_F)}\langle B|(-\mathcal{J}^{\mu}(\boldsymbol{y}))|I\rangle,$$

etc..

Values of the Gamow-Teller and Fermi Matrix elements

Table: The calculated GT and Fermi NMEs of the $0\nu\beta\beta$ and the $2\nu\beta\beta$ decay modes of ^{136}Xe with SkM* . Leading order, vertex correction, and the two-body current terms, respectively.

	SkM*			
	$0\nu\beta\beta$ NME		$2\nu\beta\beta$ NME	
	GT	Fermi	GT	Fermi
Leading	3.095	-0.467	0.102	-0.002
vc	1.332	-0.984	0.055	-0.033
2bc	-2.731	1.758	-0.192	0.030
Sum	1.696	0.307	-0.035	-0.005

Systematics of $g_A^{\rm eff}$

Table: Effective axial-vector current coupling $g_A^{\rm eff}$ obtained by different methods

Specification of $g_A^{\rm eff}$	Decay	GT and Fermi NMEs	Half-life	$g_A^{\rm eff}$ SkM*
$g_{A,0\nu}^{\rm eff}$(ld;pt)	$0\nu\beta\beta$	Leading	$T_{1/2}^{0\nu}(g_A^{\rm bare})$	0.796
$g_{A,2\nu}^{\rm eff}$(ld;pt)	$2\nu\beta\beta$	Leading	$T_{1/2}^{2\nu}(g_A^{\rm bare})$	0.696
$g_{A,0\nu}^{\rm eff}$(pt;est)	$0\nu\beta\beta$	Perturbed	$T_{1/2}^{0\nu({\rm exp})}$	0.921
$g_{A,2\nu}^{\rm eff}$(pt;exp)	$2\nu\beta\beta$	Perturbed	$T_{1/2}^{2\nu({\rm exp})}$	0.806

Some diagrammatic expressions

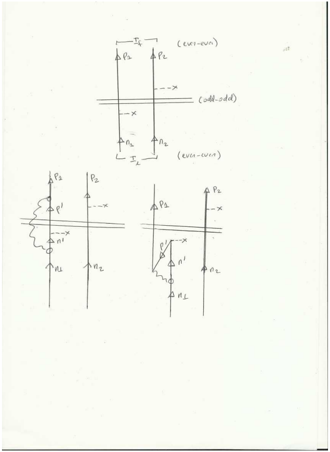
The action of the Electroweak interactions which produces de beta decay in nuclei differs, of course, from it among free nucleons. If we take a pair of neutrons decaying into a pair of protons, the matrix elements of the double beta decay are dressed by nuclear excitations, apart from the proton-neutron ones. Generally speaking, one has to deal with these matrix elements:

$$
\begin{array}{rl}
(zero\ order) & < p_1 p_2 : I_f || M_{\beta\beta} || n_1 n_2 : I_i > \\
(second\ order) & < p_1 p_2 : I_f || H || (p_1' \lambda)_{p_1} p_2 : I_f > \\
 & \times < (p_1' \lambda)_{p_1} p_2 : I_f || M_{\beta\beta} || (n_1' \lambda)_{n_1} n_2 : I_i > \\
 & \times < (n_1' \lambda)_{n_1} n_2 : I_i || H || n_1 n_2 : I_i > \\
 & \times \dfrac{1}{(E_{p'} + \hbar\omega - E_{p_1})(E_{n'} + \hbar\omega - E_{n_1})}
\end{array}
$$

Some diagrammatic expressions

$$
\begin{aligned}
(\textit{zero order}) \quad & < p_1 p_2 : I_f || M_{\beta\beta} || n_1 n_2 : I_i > \\
(\textit{second order}) \quad & < p_1 p_2 : I_f || M_{\beta\beta} || ((p_1 p_1')_\lambda) n')_{n_1} n_2 : I_i > \\
& \times < ((p_1 p_1')_\lambda) n')_{n_1} n_2 : I_i || H || (\lambda n')_{n_1} n_2 : I_i > \\
& \times < (\lambda n')_{n_1} n_2 : I_i || H || n_1 n_2 : I_i > \\
& \times \frac{1}{(E_{n'} + \hbar\omega - E_{n_1})(E_{p'} + E_{p_1} - \hbar\omega)}
\end{aligned}
$$

etc. They are 20 diagrams , after all time order and exchange arrangements are accounted for.



I_f
(even-even)
p_1
p_2
(odd-odd)
n_1
n_2
I_i
(even-even)
p_1
p_2
p'
n'
n_1
n_2
p_2
p_1
p'
n'
n_2
n_1

Some diagrammatic expressions

Let us assume that the double beta decay takes place in systems with strong quadrupole correlations. The particle-vibration (p.v) sector of the quadrupole-quadrupole separable interaction is written:

$$H_{(QQ)} = -\chi\sqrt{(}2\lambda + 1).(Q_\lambda(coll).Q_\lambda(particle))_0$$

With this expression for $H_{(p.v)}$ the corrections to the single β decay vertex dressed with the one-phonon exchange are of the form:

$$\begin{aligned} < p1||\beta||n1 >_{perturbed} &= < p1||\beta||n1 > \\ &- f_\lambda^2 \sum_{(n',p')} q_s(n',n1)q_s(p',p1) \\ &\times \frac{1}{(E_{n'} + \hbar\omega - E_{n1})(E_{p'} + \hbar\omega - E_{p1})} \\ &\times < p'||\beta||n' > \\ &\times Sixj(n1,n',\lambda;p',p1,1) \end{aligned}$$

Some diagrammatic expressions

The mixing of a neutron n' with a proton-neutron pair $(p'n')$ gives the perturbed matrix element:

$$
\begin{aligned}
< p1||\beta||n1 >_{perturbed} &= < p1||\beta||n1 > \\
&+ f_\lambda^2 \sum_{(n',p')} q_s(n', n1) q_p(p1, p') \\
&\times \frac{1}{(E_{n'} + \hbar\omega - E_{n1})(E_{p'} + E_{p1} - \hbar\omega)} \\
&\times < p'||\beta||n' > \\
&\times Sixj(p1, p', \lambda; n', n1, 1)
\end{aligned}
$$

Some diagrammatic expressions

In both diagrams the factor $f_\lambda = \chi\sqrt(2\lambda+1)\Delta_\lambda$, with

$$\begin{aligned}
\Delta_\lambda &= \sum_{(i,j)} \frac{2}{1+\delta(i,j)} q_p(1,j)(X(i,j)-Y(i,j)) \\
q_s(i,j) &= (U_iU_j - V_iV_j)\frac{< i||Q_\lambda||j >}{\sqrt(2\lambda+1)} \\
q_p(i,j) &= (U_iV_j + V_iU_j)\frac{< i||Q_\lambda||j >}{\sqrt(2\lambda+1)}
\end{aligned} \tag{1}$$

Note that both series of diagrams do have opposite sign, as it was found in the case of calculations done for the decay of ^{136}Xe (see Dr Jun Terasaki's talk). The calculations for the cases of some typical double beta decay systems (like Ge,Se,Te,Xe), applying the diagrammatic expansion , both for the $2\nu\beta\beta$ and $0\nu\beta\beta$ modes, are in progress. (for further definitions see also D.R.Bes and O. Civitarese, NPA 705(2002)297)

Lateral feeding

The other possible way to gain information about the matrix elements involved in double beta decays which we have explored consisted in performing a systematic study of the lateral single $\beta^{-/+}$ and electron capture channels. The results of the first study of this type are given in Ref. H. Ejiri and J. Suhonen (Journal of .Phys. G. 42(2015)055201).

Example:

$^{80}\mathrm{As} \rightarrow (\beta^{-})^{80}\mathrm{Se} \leftarrow (\beta^{+}/EC)^{80}\mathrm{Br}$

Lateral feeding:method of calculation

We have done a systematic study of these transitions, in the framework of the quasiparticle representation (BCS) and of the quasiparticle random phase approximation (QRPA) and its number projected version (PQRPA) and with the Bonn Potential as two-body interaction. The single particle basis, for proton and neutrons, included some 25 states from the N=Z=20 closed shells, The proton-neutron QRPA and PQRPA equations have been solved including particle-hole g_{ph} and particle-particle g_{pp} channels. The value of g_{pp} was chosen to reproduce the observed energies of low-lying $J^{\pi} = 1^{+}$ states as well as the position of the Gamow-Teller giant resonance. The considered transitions, depending on the mass region, were the allowed beta decay and electron capture transitions between even-odd (and odd-even nuclei) around a even -even central nucleus.

Some examples of $\sqrt{M_l \times M_r}$

Central nucleus	PQRPA	QRPA
^{62}Ni	0.292	0.257
^{62}Zn	0.313	0.315
^{68}Zn	0.246	0.389
^{70}Zn	0.341	0.385
^{80}Ge	0.275	0.237
^{80}Kr	0.230	0.388
^{80}Se	0.313	0.379
^{80}Sr	0.422	0.369
^{82}Sr	0.267	0.361
^{82}Kr	=0.331	0.398

Some examples of $\sqrt{M_l \times M_r}$

Central nucleus	QRPA	PQRPA
^{100}Zr	0.679	0.677
^{114}Cd	0.761	0.793
^{116}Cd	0.744	0.745
^{122}Te	0.390	0.390
^{122}Xe	0.594	0.507
^{128}Xe	0.357	0.361
^{140}Nd	0.301	0.307
^{140}Sm	0.406	0.314
^{142}Sm	0.342	0.298

Some examples of $\sqrt{M_l \times M_r}$:comparison with data

Central nucleus	Exp.	Theory(QRPA)
^{62}Cu	0.236	0.311
^{64}Cu	0.293	0.375
^{66}Cu	0.323	0.407
^{80}As	0.231	0.371
^{80}Br	0.313	0.449
^{80}Rb	0.357	0.431
^{116}In	0.548	0.784
^{118}Sb	0.340	0.564
^{118}In	0.548	0.784
^{138}Pr	0.305	0.378
^{140}Eu	0.464	0.564
^{142}Pm	0.308	0.375

Values of g_A : some systematics

The symbols $M(L)$ and $M(R)$ stand for the single β decays to a central nucleus, A(N,Z) $\rightarrow$A(N-1,Z+1)$\leftarrow$A(N-2,Z+2), thus , we define $M = \sqrt{M(L)M(R)}$ and $g_A^{eff}(exp)M_{theory} = 1.267 M_{exp}$.

Nucleus	$g_A^{eff}(exp)$	$g^{eff}(QRPA)$	$g^{eff}(PQRPA)$
^{106}Ag	0.437	0.420	0.417
^{108}Ag	0.498	0.500	0.503
^{110}Ag	0.703	0.703	0.712
^{114}Ag	0.549	0.559	0.581
^{124}Cs	0.386	0.386	0.422
^{126}Cs	0.444	0.432	0.466
^{128}Cs	0.624	0.619	0.650
^{130}Cs	0.804	0.819	0.817

Values of g_A : some other cases

^{mass}A	$g^{eff}(exp)$	$g^{eff}(QRPA)$	$g^{eff}(PQRPA)$
^{102}Tc	0.483	0.481	0.472
^{106}Tc	0.416	0.394	0.396
^{104}Rh	0.585	0.586	0.583
^{106}Rh	0.325	0.326	0.328
^{122}I	0.498	0.495	0.518
^{128}I	0.669	0.656	0.667
^{134}La	0.748	0.745	0.752

More Values of g_A : a plateau??

^{mass}A	g^{eff} (*theory*)
^{62}Cu	0.961
^{64}Cu	0.989
^{66}Cu	1.005
^{80}As	0.789
^{80}Br	0.883
^{80}Rb	0.820
^{116}In	0.879
^{118}Sb	0.764
^{118}In	0.743
^{138}Pr	1.022
^{140}Eu	1.040
^{142}Pm	1.041

Conclusions

- I have shown that for both the neutrinoless and the two-neutrino modes of decays, the effective values of g_A differ strongly from the bare value ($g_A(bare)$=1.267). This result was obtained by including vertex corrections and two-body currents in the calculation of the matrix elements.
- This finding is in agreement with previsions studies done by making a comparison between two-neutrino and neutrinoless double beta decay transitions

Related References

The material discussed in this talk is based on the following references:

- J.Terasaki and O.Civitarese, Phys.Rev.C 112, L 051302 (2025)
- J.Terasaki and O.Civitarese, Phys.Rev.C 112, 024304 (2025)
- J.Terasaki and O.Civitarese, (to be submitted)
- O. Civitarese and J. Suhonen, Nucl.Phys. A. 761 (2005) 313
- D.R.Bes and O. Civitarese, NPA 924(2014)1.
- O.C and J. S.(to be submitted)

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