Neutrinoless $\beta\beta$ Decays and Nuclear Structure

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OUTLINE

- Basics.
- 2ν decays
- The 0ν operators.
- The nuclear wave functions; Discrepancies in the NME's
- The NME's in the Generalized Seniority Scheme.
- The role of correlations; pairing *vs* deformation
- g_A, to quench (2ν), or not to quench (0ν)?
- Renormalization of the 0ν operators.
- Conclusions.

Single beta decays

- In Fermi's theory of the beta decay, the leptonic current has the structure V-A, consistent with maximal parity violation. The terms γ^μ (vector) and $\gamma^\mu\gamma_5$ (axial vector) reduce, in the non-relativistic limit, to the
- Fermi $\sum_i t_i^\pm$ and Gamow Teller $\sum_i \vec{\sigma}_i t_i^\pm$ operators
- In the long wavelength approximation (when $Q_\beta R << \hbar c$) these are the dominant terms, and the transitions are called allowed
- In the the forbidden transitions the Fermi and Gamow-Teller operators are coupled to $r^\lambda Y_\lambda$

Single beta decays

- The half-life of the decay is most often discussed in terms of the *log*ft value
- $\mathbf{ft_{1/2}} = \frac{6140}{|\mathbf{M_{fi}}|^2}$
- f is a phase space factor which depends on the charge of the nucleus and on the maximum energy of the emitted electron.
- $\mathbf{M}_{fi} = \mathbf{M}_{fi}^{F} + (\frac{\mathbf{g_A}}{\mathbf{g_V}})\, \mathbf{M}_{fi}^{GT}$ is the nuclear matrix element which involves the wave functions of the initial and final nuclear states.

Charge exchange reactions

- It turns out that under certain kinematical conditions, the operator responsible for the charge exchange reactions (n,p), (p,n), (d,^{2}He), (^{3}He, t) etc, has also the form of the Gamow Teller operator
- This makes it possible, after appropriate normalizations, to explore the GT response of the nuclei outside the energy windows permitted for the beta decays.
- In particular, to have access to the GT strength functions and total strengths
- An intense experimental program on this topic was initiated in the 80's and is being pursued vigorously nowadays

Strength functions, total strengths and the Ikeda sum rule

- **The strength function of the operator Ω acting on the state Ψ can be written as :**

$$S_\Omega(E) = \sum_i |\langle i|\Omega|\Psi\rangle|^2 \delta(E - E_i)$$

- **The total strength is given by:**

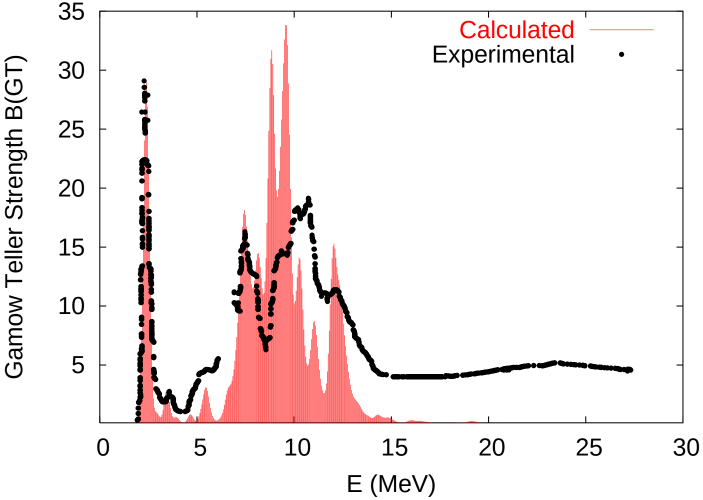
$$S_\Omega = \sum_i |\langle i|\Omega|\Psi\rangle|^2 = \langle\Psi|\Omega^2|\Psi\rangle$$

- **The total Gamow Teller strengths in the n –> p and in the p –> n directions satisfy the Ikeda Sum Rule**
- $S^-_{GT} - S^+_{GT}$ **= 3(N–Z) which is model independent**

Quenching of the Gamow-Teller Strength

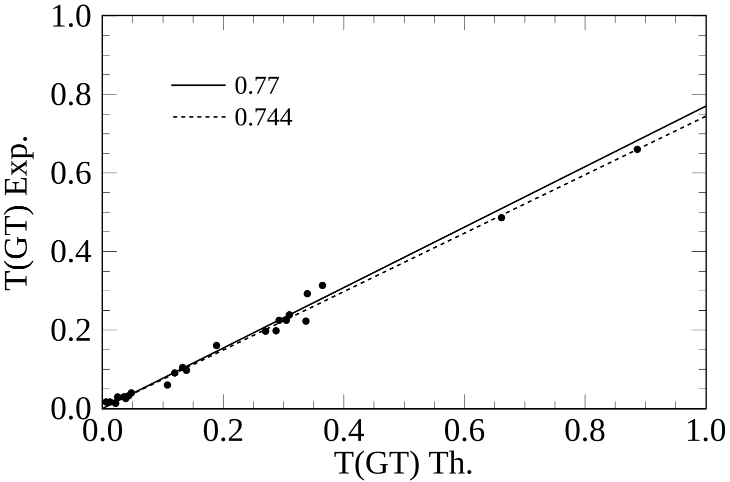
- The charge exchange experiments of the first generation only produced about one half of the Ikeda sum rule, and floods of ink have been spent in this problem
- More recently experiments with higher precision have shown that the missing strength can be recovered almost completely from the background at high energies.
- The missing strength problem is common to all the descriptions that use a basis of independent particles and regularized interactions
- The quenching factor would then be a kind of effective charge for the GT operator, ranging from 0.9 in the p-shell to 0.7 in heavy nuclei

^{48}Ca (p,n) ^{48}Sc



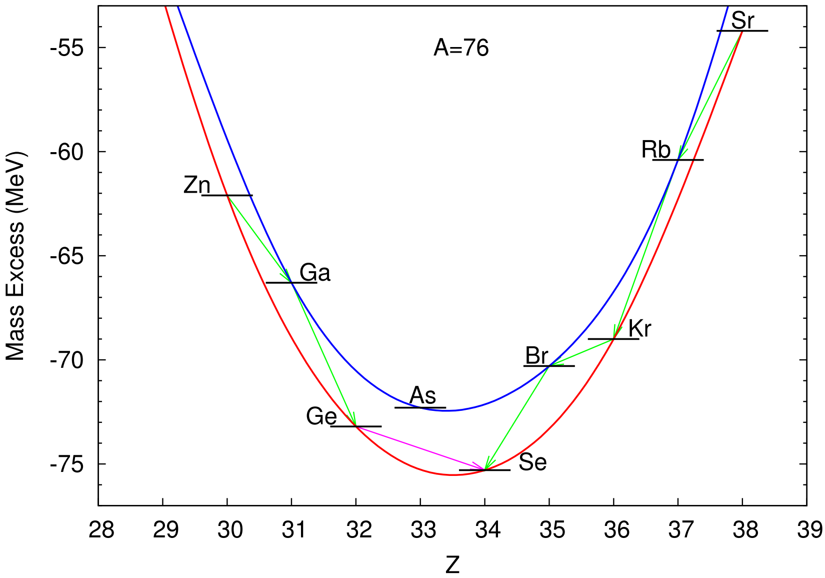
Calculated
Experimental
Gamow Teller Strength B(GT)
E (MeV)
35
30
25
20
15
10
5
0
5
10
15
20
25
30

Standard quenching from single β decays



Double beta decays

- Some nuclei, otherwise nearly stable, can decay emitting two electrons and two neutrinos ($2\nu\ \beta\beta$) by a second order process mediated by the weak interaction. This decay has been experimentally measured in a few cases.
- This process exists due to the nuclear pairing interaction that favors energetically the even-even isobars over the odd-odd ones.
- A nucleus is a potential $\beta\beta$ emitter just by accident. Thus, there cannot be systematic studies in this field. One has to take what Nature gives



A=76
Mass Excess (MeV)
Z
-55
-60
-65
-70
-75
28
29
30
31
32
33
34
35
36
37
38
39
Zn
Ga
Ge
As
Se
Br
Kr
Rb
Sr

Double beta decays

- When the single beta decay to the intermediate odd-odd nucleus is forbidden (or highly suppressed), the favored decay channel is the ($2\nu\ \beta\beta$).
- For instance, ^{76}Ge decays to ^{76}Se because the decay to ^{76}As is energetically forbidden.
- The inverse lifetime of the decay can be written as the product of a phase space factor and the square of a nuclear matrix element

$$[T_{1/2}^{2\nu}]^{-1} = G_{2\nu}|M_{GT}^{2\nu}|^2$$

- For ^{76}Ge, $T_{1/2}^{2\nu} = (1.5 \pm 0.1)\ 10^{21}$ years

The experimental 2ν matrix elements

Decay	$M^{(2\nu)}$	$T^{2\nu}_{1/2}$(y)
^{48}Ca $\rightarrow$ ^{48}Ti	0.05$\pm$0.01	3.9 x 10^{19}
^{76}Ge $\rightarrow$ ^{76}Se	0.13$\pm$0.01	1.5 x 10^{21}
^{82}Se $\rightarrow$ ^{82}Kr	0.10$\pm$0.01	9.6 x 10^{19}
^{96}Zr $\rightarrow$ ^{96}Mo	0.12$\pm$0.01	2.0 x 10^{19}
^{100}Mo $\rightarrow$ ^{100}Ru	0.23$\pm$0.01	7.1 x 10^{18}
^{116}Cd $\rightarrow$ ^{116}Sn	0.13$\pm$0.01	2.8 x 10^{19}
^{128}Te $\rightarrow$ ^{128}Xe	0.05$\pm$0.005	2.0 x 10^{24}
^{130}Te $\rightarrow$ ^{130}Xe	0.032$\pm$0.003	7.6 x 10^{20}
^{136}Xe $\rightarrow$ ^{136}Ba	0.019$\pm$0.003	2.1 x 10^{21}
^{150}Nd $\rightarrow$ ^{150}Sm	0.05$\pm$0.01	9.2 x 10^{18}

That's what I meant by " What Nature Gives "

The nuclear structure input to the $2\nu\ \beta\beta$ decay

The nuclear structure information is contained in the nuclear matrix element; only the Gamow-Teller $\sigma\tau$ part contributes in the long wavelength approximation

$$M^{2\nu} = \sum_m \frac{\langle 0_f^+|\vec{\sigma}_i \tau_i^+|m\rangle\langle m|\vec{\sigma}_k \tau_k^+|0_i^+\rangle}{E_m - (M_i + M_f)/2} \; .$$

The nuclear structure input to the $2\nu\ \beta\beta$ decay

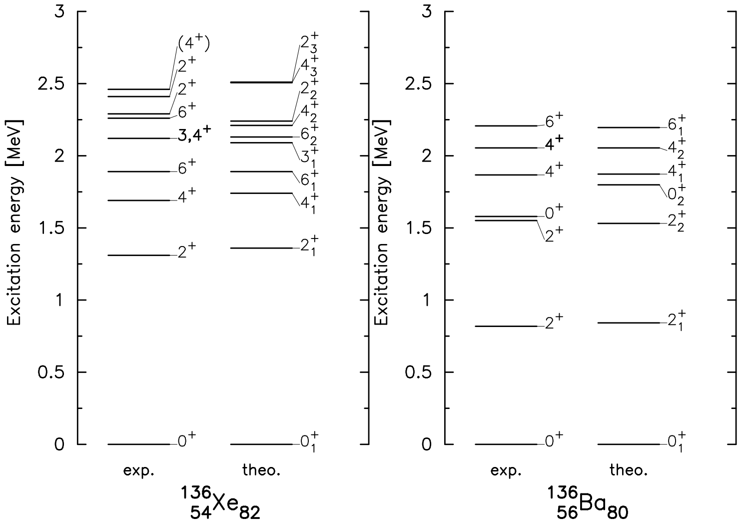
- Therefore, we need to describe properly the ground state of the parent and grand daughter nuclei as well as all the 1^+ excited states of the intermediate odd-odd nucleus.
- In other words, the GT^- strength function of the parent, the GT^+ strength function of the grand daughter and the relative phases of the individual contributions.
- Notice that for some nuclear models the description of odd-odd nuclei is a real challenge

Large Scale Shell-Model (ISM) predictions

$M^{(2\nu)}$	exp	q_0	q_ν	INT
^{48}Ca $\rightarrow$ ^{48}Ti	0.05±0.01	0.048		KB3G
^{76}Ge $\rightarrow$ ^{76}Se	0.13±0.01	0.168	0.107	gcn28:50
^{82}Se $\rightarrow$ ^{82}Kr	0.10±0.01	0.187	0.120	gcn28:50
^{128}Te $\rightarrow$ ^{128}Xe	0.05±0.005	0.092	0.059	gcn50:82
^{130}Te $\rightarrow$ ^{130}Xe	0.032±0.003	0.068	0.043	gcn50:82
^{136}Xe $\rightarrow$ ^{136}Ba	0.019±0.002	0.064	0.041	gcn50:82

q_0 means the standard quenching used in full $0\hbar\omega$ calculations: q_ν incorporates an extra factor due to the truncations at $0\hbar\omega$ level. It is fitted to the GT single beta decays of the region: q_ν=0.6. Thus, the 2ν decays need a quenching factor similar to the one found in the GT processes

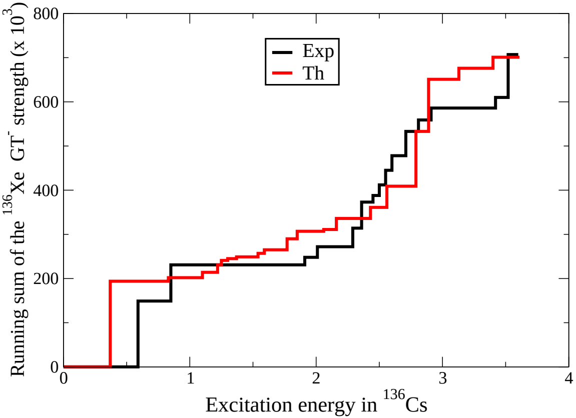
Spectroscopy of ^{136}Xe and ^{136}Ba



^{136}Xe; A lucky strike

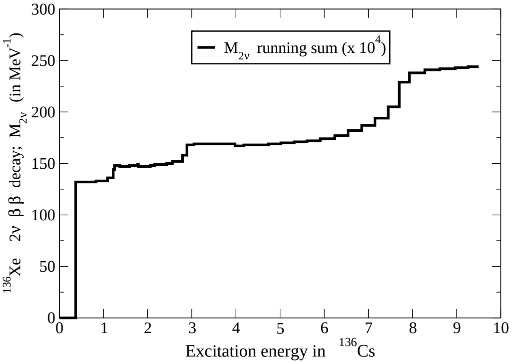
- Another way of estimating the quenching factor is to compare the theoretical Gamow Teller strength functions with the experimental ones obtained in charge exchange reactions. Data have become recently available for the ^{136}Xe (^{3}He, t)^{136}Cs reaction (Freckers et al.)
- They impact in our calculations in two ways; first because they give us the excitation energy of the first 1^+ state in ^{136}Cs, 0.59 MeV, unknown till now, which appears in the energy denominator of the 2ν matrix element. And secondly because it makes it possible to extract directly the quenching factor adequate for this process.

The 2ν double beta decay ^{136}Xe $\rightarrow$ ^{136}Ba



The running sum of the Gamow-Teller strength of ^{136}Xe (energies in MeV). The theoretical strength is normalized to the experimental one.This implies a quenching q=0.45.

The 2ν double beta decay ^{136}Xe $\rightarrow$ ^{136}Ba



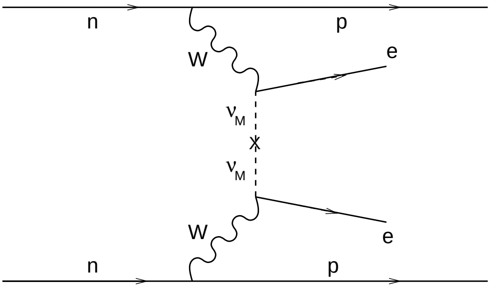
The running sum of the 2ν matrix element of the double beta decay of ^{136}Xe (energies in MeV). The final matrix element $M^{2\nu}$=0.025 MeV^{-1} agrees nicely with the experimental value.

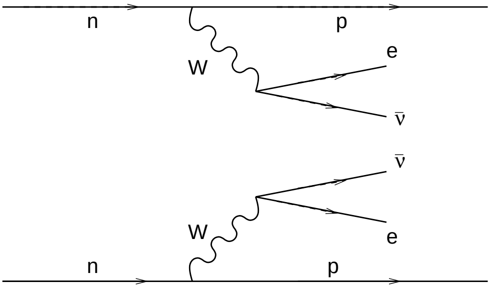
The 2ν double beta decay ^{136}Xe $\rightarrow$ ^{136}Ba

- However, one should bear in mind that the absolute normalization of the Gamow-Teller strength extracted from the charge exchange reactions may be affected by systematic errors, which could lead to modifications of the extracted quenching factor.
- Minor variants of our gcn50:82 interaction, which locally improve the quadrupole properties of ^{136}Ba, lead to q=0.48 and $M^{2\nu}$=0.021 MeV^{-1}.

Double beta decay

If the neutrinos are massive Majorana particles, the double beta decay can also take place without emission of neutrinos ($0\nu\ \beta\beta$).


n
p
W
e
νM
X
νM
W
e
n
p


n
p
W
e
ν̄
ν̄
W
e
n
p

Has the neutrinoless double beta decay been observed?

There is an unconfirmed claim of discovery by (part of) the Heildelberg-Moscow collaboration (Klapdor 2001, 2004) of the ^{76}Ge $\rightarrow$ ^{76}Se neutrinoless decay with a half-life of 2.2 x 10^{25} years.

Recent results from GERDA, EXO200 and Kamland-Zen are in strong tension with this claim.

The neutrinoless double beta decay

The expression for the neutrinoless beta decay half-life, in the mass mode, for the $0^+ \rightarrow 0^+$ decay, can be brought to the following form:

$$[T_{1/2}^{(0\nu)}(0^+ -> 0^+)]^{-1} = G_{0\nu} \left(M^{(0\nu)} \left(\frac{\langle m_\nu \rangle}{m_e} \right) \right)^2$$

$G_{0\nu}$ is the kinematic phase space factor, $M^{0\nu}$ the nuclear matrix element (NME) that has Fermi, Gamow-Teller and Tensor contributions, and $\langle m_\nu \rangle$ the effective neutrino mass.

The neutrinoless double beta decay

$$M^{(0\nu)} = \left(\frac{g_A}{1.25}\right)^2 \left(M_{GT}^{(0\nu)} - \frac{M_F^{(0\nu)}}{g_A^2} - M_T^{(0\nu)} \right)$$

$$\langle m_\nu \rangle = \sum_k U_{ek}^2 m_k$$

The U's are the matrix elements of the weak mixing matrix.

The Nuclear Matrix Elements

The matrix elements $M^{(0\nu)}_{GT,F,T}$ can be written as,

$$M_K^{(0\nu)} = \langle 0_f^+ | H_K(|\vec{r_1} - \vec{r_2}|)(t_1^- \ t_2^-)\Omega_K | 0_i^+ \rangle$$

$$\text{with} \ \ \Omega_F = 1, \ \Omega_{GT} = \vec{\sigma}_1 \cdot \vec{\sigma}_2, \ \Omega_T = S_{12}$$

$H_K(|\vec{r_1} - \vec{r_2}|)$ **are the neutrino potentials (∼1/r) obtained from the neutrino propagator.**

The Nuclear Matrix Elements

The neutrino potentials have the following form:

$$H^m_K(r_{12}) = \frac{2}{\pi g_A^2} R \int_0^\infty f_K(qr_{12}) \frac{h_K(q^2) q dq}{q + E_m - (E_i + E_f)/2}$$

$h_F(q^2) = g_V(q^2)$ **and, neglecting higher order terms in the nuclear current,** $h_{GT}(q^2) = g_A(q^2)$ **and** $h_T(q^2) = 0$**.**

The energy of the virtual neutrino (q) is about 150 MeV. Therefore, to a very good approximation, E$_m$ can be replaced by an average value. This is the closure approximation.

The 0ν operators; Consensus

There is a broad consensus in the community about the form of the transition operator in the mass mode,

- It must include higher order terms in the nuclear current,
- And the proper nucleon dipole form factors, isovector and isoscalar.
- The consensus extends to the validity of the closure approximation for the calculation of the NME's
- And to the use of very soft short range corrections.

The situation is less clear concerning the use of bare or quenched values of g_A as well shall discuss later.

The Nuclear Wave Functions

Two main approaches have been traditionally used for the description of the initial and final nuclei of the decay .

- The Shell Model with configuration mixing in large valence spaces (ISM) and the Quasi-particle RPA in a spherical basis.
- More recently, there have been calculations using the Interacting Boson Model, and the GCM method based on angular momentum and particle number projected solutions of the HFB equations in a deformed basis with the Gogny functional.

The Nuclear Wave Functions

To assess the validity of the wave functions, quality indicators are needed based upon:

- The spectroscopy of the intervening nuclei
- The occupancies of the orbits around the Fermi level.
- The GT-strengths and strength functions, The 2ν matrix elements, etc.

This quality control should be applied on a decay by decay basis, because a given approach may work well for some cases and not for others.

The Interacting Shell Model (ISM)

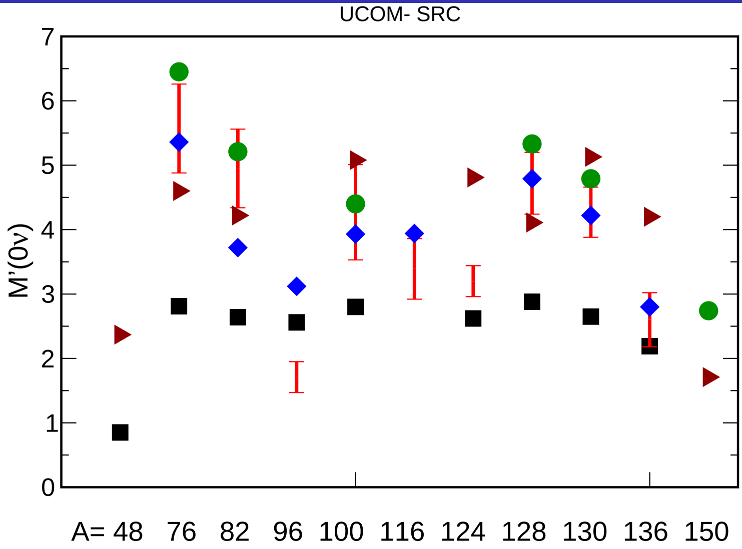
- Interaction: Monopole corrected G-matrices
- Valence space: A limited number of orbits, but all the possible ways of distributing the valence particles among the valence orbits are taken into account.
- Pairing Correlations: Are treated exactly in the valence space. Proton and neutron numbers are exactly conserved. Proton-proton, neutron-neutron, and proton-neutron (isovector and isoscalar) pairing is included
- Multipole Correlations and Deformation: Are described properly in the laboratory frame. Angular momentum conservation is preserved
- Is applicable to all but one of the relevant candidates (A=150)

The NME's. The main players

- QRPA; Rodin, Simkovic, Faessler and Vogel 07
- QRPA; Kortelainen and Suhonen 07
- IBM; Barea and Iachello 09
- ISM; Menéndez, Poves, Caurier and Nowacki 09
- GCM; Rodríguez and Martínez-Pinedo 10

Notice that the presentation of the NME's in a plot with A in the abscissa may give the misleading impression of a kind of functional A dependence. Indeed this is not the case, is just a a way of gathering the results.

The NME's. Dissension



QRPA(Tu) (bars) QRPA(Jy)(lozenges) IBM(circles) ISM(squares) GCM(triangles)

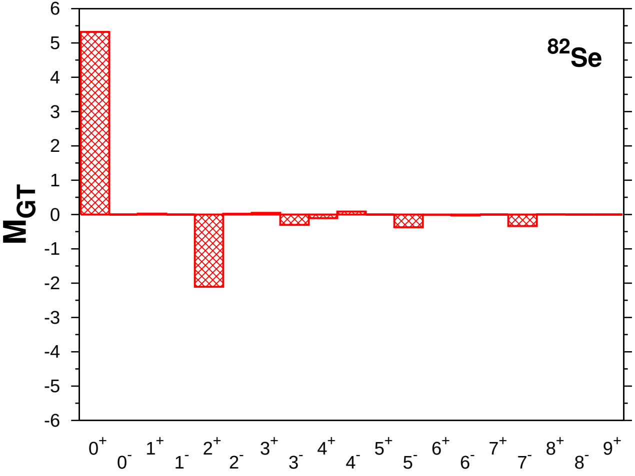
How do the 0ν operators act

The two body transition operators can be written generically as:

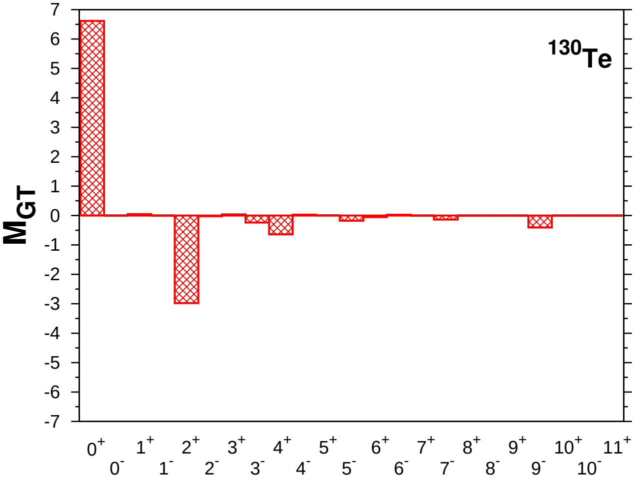
$$\hat{M}^{(0\nu)} = \sum_{J^\pi} \hat{P}^\dagger_{J^\pi} \;\; \hat{P}_{J^\pi}$$

The operators $\hat{P}_{J^\pi}$ annihilate pairs of neutrons coupled to J^π in the parent nucleus and the operators $\hat{P}^\dagger_{J^\pi}$ substitute them by pairs of protons coupled to the same J^π. The overlap of the resulting state with the ground state of the grand daughter nucleus gives the J^π-contribution to the NME. The –a priori complicated– internal structure of these exchanged pairs is dictated by the double beta decay operators.

The contributions to the NME as a function of the J^{π} of the decaying pair: ^{82}Se $\rightarrow$ ^{82}Kr



The contributions to the NME as a function of the J^π of the decaying pair: ^{130}Te $\rightarrow$ ^{130}Sn



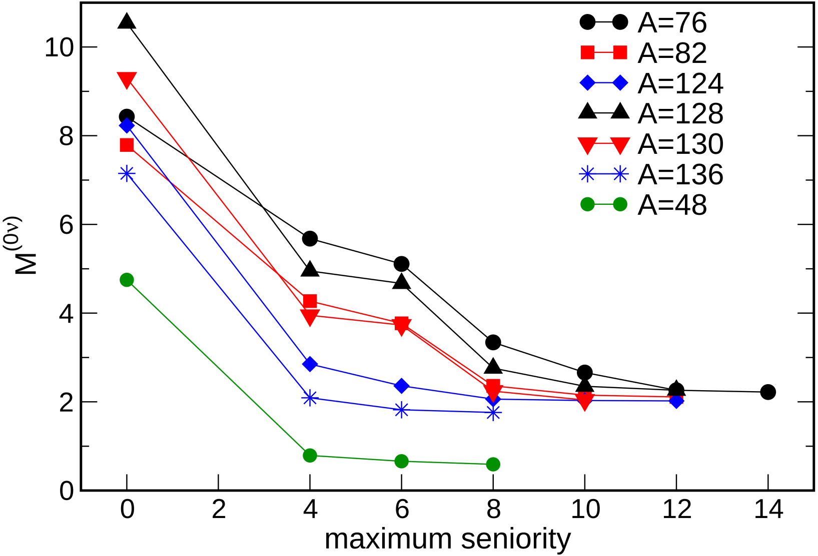
Pairing

These results are very suggestive, because the leading contribution corresponds to the decay of J=0 pairs, whereas the contributions of the pairs with J>0 are either negligible or have opposite sign to the dominant one.

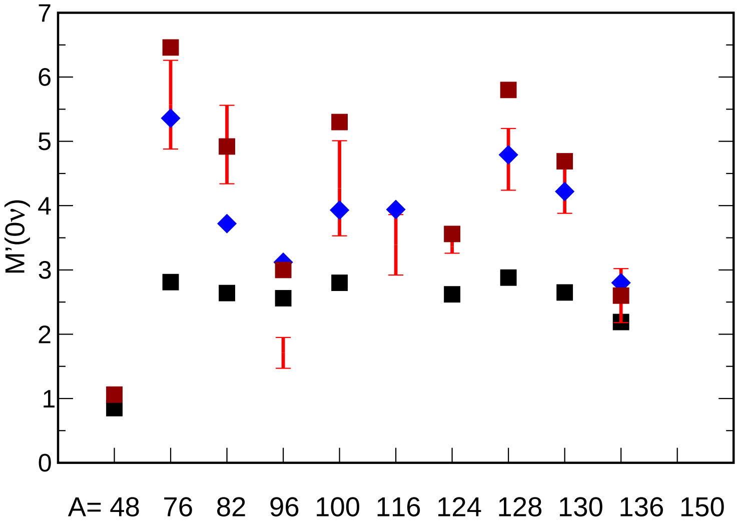
This behavior is common to all the cases that we have studied. It also occurs in the QRPA calculations, in whose context it has been previously discussed by Engel, Vogel et al.

If we went to the limit of pure pairing correlations, i.e. when the initial and final states have generalized seniority zero, there will be no canceling contributions and therefore the matrix element will be maximal.

NME's *vs* the maximum seniority of the ISM WF's



A sleight of hand; The discrepancies disappear



The red squares are the ISM results truncated to seniority ≤ 4.

The Trick

- The QRPA , IBM and GCM results are reasonably close to the ISM ones at s$\leq$4.
- The ISM values at s$\leq$4 are far from converged, except in the A=48, A=96, A=124 and A=136 decays
- Indeed, only in these cases the NME's agree (roughly)
- Let's try to understand why

NME's in the Generalized Seniority. A=82

Decomposition of the $0\nu\beta\beta$ NME as a function of the seniority components of the initial, s_i, and final, s_f, wave functions. Results for the A=82 decay. The coefficients in parenthesis indicate the percentage of the wave function that belongs to each particular seniority.

	$s_f = 0$ **(44)**	$s_f = 4$ **(41)**	$s_f = 6$ **(6)**	$s_f = 8$ **(8)**	$s_f = 10$ **(1)**	$s_f = 12$ **(0.1)**
$s_i = 0$ **(50)**	**8.8**	**-5.6**	-	-	-	-
$s_i = 4$ **(39)**	**-0.3**	**4.9**	**-1.2**	**-6.2**	-	-
$s_i = 6$ **(10)**	-	**-0.2**	**2.2**	**-0.3**	**-3.0**	-
$s_i = 8$ **(1)**	-	**-0.02**	**-0.07**	**0.6**	**-0.08**	**-4.3**

NME's and Generalized Seniority. A=82

- Notice that the diagonal matrix elements decrease rapidly with the seniority
- And that the Δs=4 matrix elements are of the same size than the largest diagonal one, but of opposite sign, being responsible for the cancellations that lead to small final values of the NME's
- This behavior is common to all the decays that we have studied

The nuclear WF's in the generalized seniority basis

	s=0	s=4	s=6	s=8	s=10	s=12	s=14	s=16
					ISM			
^{76}Ge	43	41	7	8	1	-	-	-
^{76}Se	26	41	11	16	4	1	-	-
^{82}Se	50	39	10	1	-	-	-	-
^{82}Kr	44	41	6	8	1	-	-	-
^{128}Te	70	26	3	1	-	-	-	-
^{128}Xe	37	41	9	10	2	-	-	-
					QRPA			
^{76}Ge	55	33	-	10	-	2	-	-
^{76}Se	59	31	-	8	-	2	-	-
^{82}Se	56	32	-	9	-	2	-	-
^{82}Kr	54	34	-	11	-	2	-	-
^{128}Te	52	34	-	11	-	3	-	-
^{128}Xe	40	37	-	17	-	5	-	1

The nuclear WF's in the generalized seniority basis

It is evident that in the ISM the mismatch in seniority between the initial and final nuclei is much larger than in the QRPA. And mismatch in seniority means different deformation in whatever channel it may happen.

Let's develop the ISM matrix elements in a basis of generalized seniority;

$$M_{F,GT,T} = \sum_{\alpha,\beta} A_{\nu_i(\alpha)} B_{\nu_f(\beta)} \langle \nu_f(\beta) | O_{F,GT,T} | \nu_i(\alpha) \rangle$$

where the A's and B's are the amplitudes of the different seniority components of the wave functions of the initial and final nuclei.

A refreshing surprise

- Obviously, when we plug the ISM amplitudes in this formula, we recover the ISM NME's.
- But, what shall we obtain if we use the QRPA amplitudes instead?
- Indeed, we get approximately the QRPA NME's! (5.73 for A=76 and 4.15 for A=82).
- Therefore, the quenching of the NME's is due to the difference in the seniority structure of the initial and final nuclei.

The nuclear WF's in the generalized seniority basis

A very spectacular example of the cancellation of the NME by the seniority mismatch is provided by the ^{48}Ca decay. We have seen that the seniority structures of the two nuclei are very different. The matrix elements $\langle \nu_f(\beta)|O_{GT}|\nu_i(\alpha)\rangle$ are gathered below. There are two large matrix elements; one diagonal and another off-diagonal of the same size and opposite sign. If the two nuclei were dominated by the seniority zero components one should obtain $M_{GT}\sim4$. If ^{48}Ti were a bit more deformed, M_{GT} will be essentially zero. The value produced by the KB3 interaction is 0.75 that is more than a factor five reduction with respect to the seniority zero limit.

^{48}Ti	$s=0$	$s=4$	$s=6$	$s=8$
^{48}Ca $s=0$	3.95	-3.68	-	-
^{48}Ca $s=4$	0.00	-0.26	0.08	-0.02

The nuclear WF's in the generalized seniority basis

- **This result strongly suggests that there is some kind of universal behavior in the NME's of the neutrinoless double beta decay when they are computed in a basis of generalized seniority.**
- **If this is so, the only relevant difference between the different theoretical approaches would reside in the seniority structure of the wave functions that they produce.**

Benchmarking with the occupation numbers

Recently, the spectroscopic factors of the nuclei ^{76}Ge and ^{76}Se have been measured by a team led by J. P. Schiffer

It turns out that the ISM occupancies are much closer to the experiment than those produced by the QRPA

New QRPA calculations have been performed, modifying the single particle energies as to reproduce the experimental occupancies

The new QRPA NME's are much closer to the ISM ones

Isospin violation

The standard QRPA, IBM and GCM calculations violate badly isospin conservation

The consequence is an overestimation of the Fermi contribution to the NME

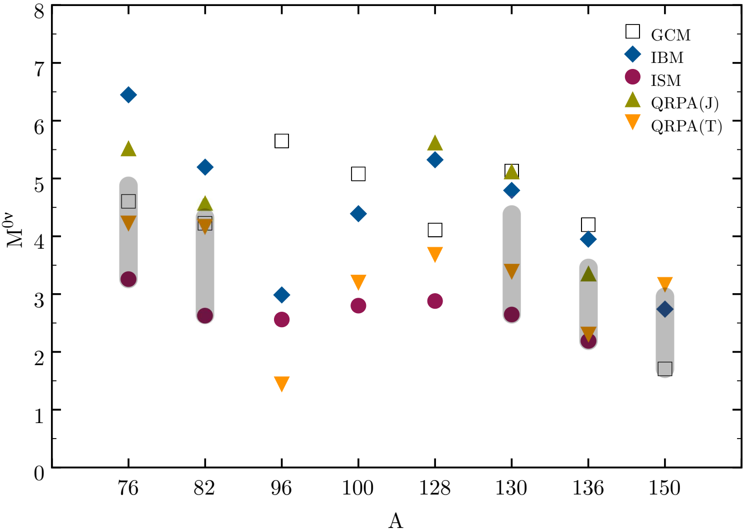
When isospin is restored the NME's are reduced typically a 20%

Which diminishes again the discrepancy between the ISM results and all the others

Approaching consensus

- In view of all this arguments, one can surmise that the QRPA, IBM and GCM tend to overestimate the NME's
- On the other side, increasing the valence space of the ISM calculations tends to increase moderately the NME's
- Therefore, we can propose the following "safe" range of values

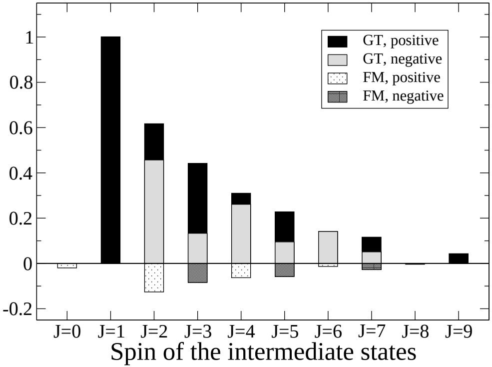
A modest proposal . . .



g_A, to quench (2ν), or not to quench (0ν)?

- To reproduce the experimental $2\nu\beta\beta$ lifetimes, it is compulsory to invoke the quenching factors discussed before
- We can distinguish between a secular quenching factor of 0.7 for calculations in complete major oscillator shells, and local quenching factors due to the limitations of the ISM valence spaces
- The open question is whether these quenching factors must be applied to the 0ν decays
- To be consistent with the closure approximation, the quenching factors must be the same for all the multipole channels.

The contributions to the NME as a function of the J^π of the intermediate states: ^{82}Se $\rightarrow$ ^{82}Kr



R. A. Senkov, M. Horoi, and B. A. Brown, Phys. Rev. C 89, 054304

Recent attempts to go beyond the standard approaches

- Menéndez, Gazit and Schwenk (2011) have studied the effect of two-body currents on single GT decays and on neutrinoless $\beta\beta$ decays using χEFT. They find that the quenching of the matrix elements of the GT decays is greater than that of the $0\nu\beta\beta$ NME's. In fact, the range of the modifications of the latter varies between +10% and –35% (corresponding to q(GT)=0.96 and q(GT)=0.74).
- One important open issue is what fraction of the standard quenching, q(GT)$\sim$0.7, is due to the two-body currents and which to many body purely nucleonic effects

Recent attempts to go beyond the standard approaches

- **The many body renormalization of the $0\nu\beta\beta$r and $\vec{\sigma}\vec{\tau}$ operators, in a purely nucleonic description, has been recently addressed by Holt, Engel, Hagen and Navratil among others. Holt and Engel report an increase of 20-30% of the $0\nu\beta\beta$ NME's of ^{82}Se and ^{76}Ge respectively, correlated with values of q(GT) in the 0.85 range.**
- **This issue needs to be settled asap, but it seems that (if there is any) the quenching of g_A in the $0\nu\beta\beta$ decays is much smaller than in the $2\nu\beta\beta$ process**

Conclusions

- Large scale shell model calculations with high quality effective interactions are available for most of the experimentally relevant neutrinoless double beta decay candidates
- We have found that when the pairing correlations are dominant in the parent and grand daughter nuclei, the NME's of the 0ν decays are very large.
- When multipole correlations lead, the NME's are strongly quenched. The more so if the initial and final nuclei have different deformations
- The reduction of the ISM NME's relative to the QRPA ones originates in the seniority mismatch between the initial and final nuclei, which is larger in the ISM. The same is surely true for the IBM and GCM approaches.

Conclusions

- When these considerations are taken into account, and quality controls applied, the dispersion of the values of the NME's can be reduced. That's good news
- Recent calculations of the effects of the Chiral two-body currents on the $0\nu\beta\beta$ and in the single GT beta decays show that the quenching factor of the latter cannot be directly translated into the former. More good news
- Many body PT shows that one can get a certain enhancement of the NME's due to purely nucleonic effects, while at the same time producing about half of the standard quenching. Even better!