Neutrinoless Double Beta Decay within the Interacting Shell Model

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Outline

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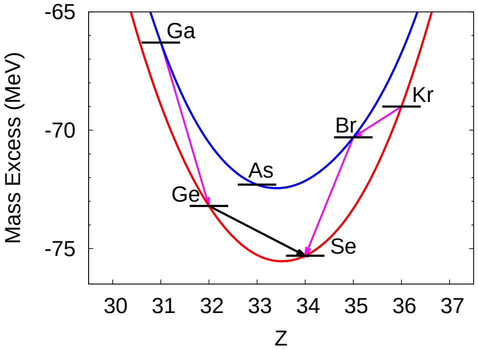
Double beta decay: origin

- Double beta decay is a rare second order weak process
- It only appears when single β decay is energetically forbidden or hindered by large J difference



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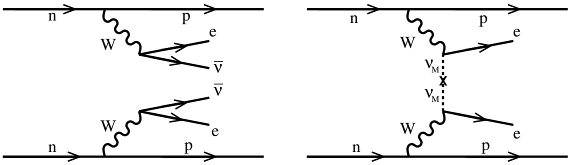
Double Beta Decay: types

- Two different $\beta\beta$ decays may happen:



- Two neutrino double beta decay ($2\nu\beta\beta$)
  Detected for a dozen of nuclei
  Fastest decay, ^{100}Mo: $T_{1/2} = (7.1 \pm 0.4)\,10^{18}$ years
- Neutrinoless double beta decay ($0\nu\beta\beta$)
  Only one unconfirmed claim in ^{76}Ge
  (Klapdor-K. MPLA 16 2409 (2001), PLB 586 198 (2004))
  Claim: $T_{1/2} = (0.69 - 4.18)\,10^{25}$ years

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Double beta decay: transitions with $Q_{\beta\beta} > 2$ MeV

Transition	$Q_{\beta\beta}$ (MeV)	Abundance (%)
^{48}Ca $\rightarrow$ ^{48}Ti	4.274	0.2
^{76}Ge $\rightarrow$ ^{76}Se	2.039	8
^{82}Se $\rightarrow$ ^{82}Kr	2.996	9
^{96}Zr $\rightarrow$ ^{96}Mo	3.350	3
^{100}Mo $\rightarrow$ ^{100}Ru	3.034	10
^{110}Pd $\rightarrow$ ^{110}Cd	2.013	12
^{116}Cd $\rightarrow$ ^{116}Sn	2.802	7
^{124}Sn $\rightarrow$ ^{124}Te	2.288	6
^{130}Te $\rightarrow$ ^{130}Xe	2.530	34
^{136}Xe $\rightarrow$ ^{136}Ba	2.462	9
^{150}Nd $\rightarrow$ ^{150}Sm	3.667	6

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Neutrinoless Double Beta Decay

- $0\nu\beta\beta$ is only possible if neutrinos are of the Majorana type
  $\Rightarrow$ a confirmation will establish the Majorana nature of neutrinos
- The lifetime of the $0\nu\beta\beta$ depends on the Nuclear Matrix Element (NME), $M^{0\nu\beta\beta}$, as:

$$\left(T_{1/2}^{0\nu\beta\beta}\left(0^+ \rightarrow 0^+\right)\right)^{-1} = G_{01}\left|M^{0\nu\beta\beta}\right|^2 \left|\frac{m_{\beta\beta}}{m_e}\right|^2$$

with $m_{\beta\beta} = \sum_k U_{ek}^2 m_k$ the effective $0\nu\beta\beta$ decay neutrino mass

- The NME is required to:
  - Obtain information about $m_{\beta\beta}$ if detection is achieved
  - Predict the more favourable decays

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Nuclear Structure Methods for $0\nu\beta\beta$ decay

Different methods are used to obtain the NMEs for the $0\nu\beta\beta$ decay

- The spherical QRPA method
- The Interacting Boson Model
- Beyond Self Consistent Mean Field
  See T. Rodríguez talk tomorrow
- The Interacting Shell Model
  - It solves the problem in relatively small valence spaces (one Harmonic Oscillator or Spin-Orbit shell)
  - Successfully describles spectroscopy, β and $2\nu\beta\beta$ transitions in regions of interest for $0\nu\beta\beta$ decay.

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The ISM: basis states and valence space

- The ISM considers the presence of a residual interaction while taking as basis states these of the Harmonic Oscillator

$$H = H_0 + H_{res}$$

- The many body wave function will be a linear combination of the Slater Determinants built upon these single particle states

$$|\phi_\alpha\rangle = a^+_{i1} a^+_{i2} ... a^+_{iA} |0\rangle \qquad |\Psi\rangle = \sum_\alpha c_\alpha |\phi_\alpha\rangle$$

- The configuration space is separated into
  - Inner core: orbits that are always filled
  - Valence space: the space where we solve the problem
  - Outer space: orbits that are always empty

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The ISM: interaction and diagonalization

- In the truncated valence space, an effective interaction is required, either
  - Realistic: potentials adjusted to $n - n$ scattering data regularized to nuclei by G-matrices or the $V_{low\ k}$ method
    Their monopole part needs to be modified
  - Fitted: fit to selected nuclei in the region of interest
- Now, we have to solve the nuclear problem in the valence space

$$H\left|\Psi\right\rangle = E\left|\Psi\right\rangle \rightarrow H_{eff}\left|\Psi\right\rangle_{eff} = E\left|\Psi\right\rangle_{eff}$$

- The ISM code NATHAN (Caurier *et al.* RMP 77 (2005)), has been used throughout this work
- Spaces with up to 10^{11} Slater determinants can be diagonalized.

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The $0\nu\beta\beta$ operator

- The form of the operator is:

$$M^{0\nu\beta\beta} = -\left(\frac{g_V(0)}{g_A(0)}\right)^2 M^F + M^{GT} - M^T$$

where $M^X = \langle 0_f^+ | \sum_{n,m} \tau_n^- \tau_m^- H^X(r)\, \Omega^X |0_i^+\rangle$

- Ω^X is one of the three operators:
Fermi (1), Gamow-Teller ($\sigma_1\sigma_2$) or Tensor (S_{12})
- $H^X(r)$ are the neutrino potentials, calculated by:

$$H^X(r) = \frac{2}{\pi}\frac{R}{g_A^2(0)}\int_0^\infty f^X(qr)\,\frac{h^X(q)}{\left(q + E_a^m - \frac{1}{2}(E_i - E_f)\right)}\,q\,dq$$

Higher Order Current terms

- The potentials are composed of different terms:

$$h^F(q) = h^F_{vv}(q),$$
$$h^{GT}(q) = h^{GT}_{aa}(q) + h^{GT}_{ap}(q) + h^{GT}_{pp}(q) + h^{GT}_{mm}(q),$$
$$h^T(q) = h^T_{ap}(q) + h^T_{pp}(q) + h^T_{mm}(q),$$

- h^{GT}_{aa} will be the dominant term and h^{GT}_{vv} the main correction
- The other six terms h^{GT}_{ap}, h^T_{ap}, h^{GT}_{pp}, h^T_{pp}, h^{GT}_{mm} and h^T_{mm} come from next order, $\frac{q}{m_N}$, in the product of hadronic currents, and they are usually called HOC terms
- Next order terms are suppressed by $\frac{q^2}{m_N^2}$, so are expected $\approx 1\%$

Closure approximation

Remember that the neutrino potentials are calculated by:

$$H^X(r) = \frac{2}{\pi}\frac{R}{g_A^2(0)}\int_0^\infty f^X(qr)\,\frac{h^X(q)}{\left(q + E_a^m - \frac{1}{2}(E_i - E_f)\right)}\,q\,dq$$

The closure approximation is used in the calculation: the various energies of the virtual intermediate states, E_a^m, are averaged by a common $\langle E^m \rangle$

- There is no need to calculate these intermediate virtual states
- Justified by the large momentum of the virtual neutrino $q \approx 100$ MeV, much larger than the difference between E_a^m's
- The error due to this approximation is smaller than 10%

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Finite Nucleon Size

- The Finite Nucleon Size (FNS) is implemented via dipole form factors

$$g_V(q^2) = \frac{g_V(0)}{\left(1 + \frac{\mathbf{q}^2}{\Lambda_V^2}\right)^2}, \qquad g_A(q^2) = \frac{g_A(0)}{\left(1 + \frac{\mathbf{q}^2}{\Lambda_A^2}\right)^2}$$

- The values of the cutoffs of the vector and axial nucleon form factors are $\Lambda_V = 0.85$ GeV and $\Lambda_A = 1.09$ GeV
- $M^{0\nu\beta\beta}$ depends weakly on them, so variation smaller than 5% comes from different reasonable values.

$g_A(0)$ quenching

- The coupling constant $g_A(0)$, needs to be quenched in purely Gamow-Teller processes, single-β and $2\nu\beta\beta$
- But the Gamow-Teller 1^+ channel is not dominant in $0\nu\beta\beta$ decay
- Hence, it is not clear if $g_A(0)$ should be quenched or not
- ISM results have traditionally calculated with $g_A(0) = 1.25$
  If the axial coupling was quenched to $g_A(0) = 1.0$
  ISM results would decrease in $\approx 30\%$
- This is probably the major single source of uncertainty in the $M^{0\nu\beta\beta}$ calculation

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Short Range Correlations

- If we do not renormalize the operator to our configuration space, new correlations, Short Range Correlations (SRC), are needed.
- after FNS they have been calculated to be $\sim 5\%$
  they can be parametrized by an UCOM transformation
  or Jastrow-like functions
  Engel *et al.* PRC 79 064317 (2009) and Šimkovic *et al.* PRC 79 055501 (2009)
- Thus, the uncertainty due to SRC is only $\approx 5\%$

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ISM Valence spaces and Interactions

- The ISM interactions are monopole modified *G* matrices
- The valence spaces and interactions used are the following
  - *pf* shell for ^{48}Ca
    KB3 interaction
  - $1p_{3/2}$, $0f_{5/2}$, $1p_{1/2}$ and $0g_{9/2}$ space
    for ^{76}Ge and ^{82}Se
    gcn.28-50 interaction
  - $0g_{7/2}$, $1d_{3/2}$, $1d_{5/2}$, $2s_{1/2}$ and $0h_{11/2}$ space
    for ^{124}Sn, ^{128}Te, ^{130}Te and ^{136}Xe
    gcn.50-82 interaction

Uncertainty related to ISM valence space

- ISM study of the contributions of
  2p-2h jumps from $0f_{7/2}$ in the ^{82}Se decay
  2p-2h from proton $0g_{7/2}$ and to neutron $0h_{11/2}$, $1f_{7/2}$ for ^{136}Xe
  Results show an increase in $M^{0\nu\beta\beta}$ of $15\% - 20\%$

  Caurier *et al.* EPJA 36 195 (2008)

- QRPA study the contribution of ISM-like orbits to $M^{0\nu\beta\beta}$ for ^{76}Ge finding 15% reduction of their QRPA values.

  Šimkovic *et al.* PRC 79 055501(2009)

- Contribution of the orbits absent in the ISM valence space
  Estimated to increase the NME in $\approx 15 - 20\%$

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Uncertainty of the effective interaction

- Different interactions studied for the ^{48}Ca decay
  Results show uncertainty in $M^{0\nu\beta\beta}$ of $\approx$ 10%

  Caurier *et al.* EPJA 36 195 (2008)

- New experimental neutron and proton occupancies of nuclei involved in the ^{76}Ge transition

  Schieffer *et al.* PRL 100 112501 021301 (2008), Kay *et al.* PRC 79 (2009)

  A new interaction improved agreement with experiment
  The value of $M^{0\nu\beta\beta}$ increased in 15%

- Then, the uncertainty in $M^{0\nu\beta\beta}$ due to the effective interaction can be estimated in $\approx$ 10%

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Global uncertainty of the NME

- The global uncertainty has contribution from the valence space, effective interaction, closure approximation, terms neglected in the nuclear current, finite nucleon size terms (FNS), short range correlations (SRC) and $g_A(0)$ (axial-coupling) (non)quenching.
- Quadratic sum gives $\sim^{+25\ \%}_{-35\ \%}$
- Direct sum would give $\sim^{+45\ \%}_{-55\ \%}$

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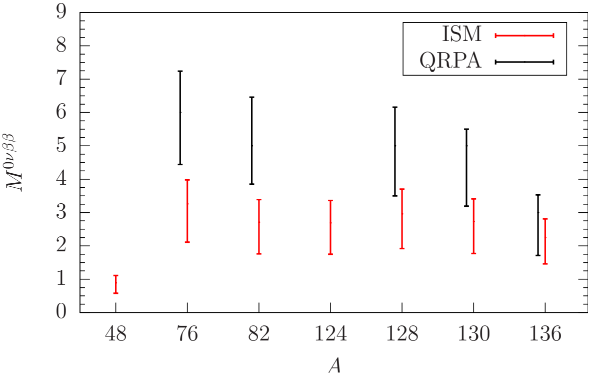
ISM Results



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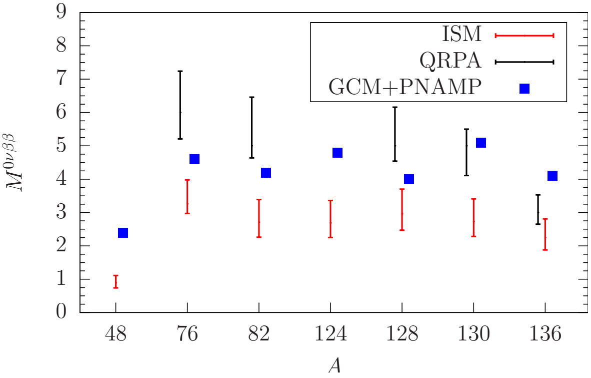
ISM Results excluding axial quenching



Discrepancies ISM vs QRPA

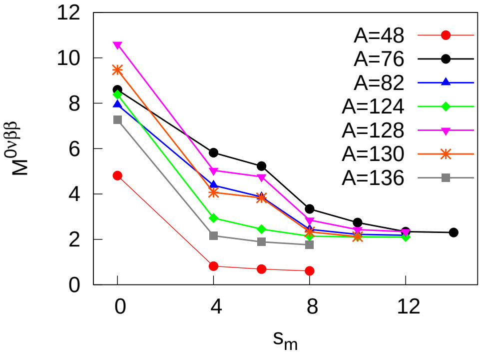
- Contribution of the orbits absent in the ISM valence space underestimated within the ISM
- Contribution of correlations missing in the QRPA approach underestimated within QRPA
- Quasiparticle excitations missing in the GCM+PNAMP approach

Outline

1. Introduction
   - Double Beta Decay
   - The Interacting Shell Model
2. ISM Results and Uncertainty
   - The $0\nu\beta\beta$ operator
   - ISM $0\nu\beta\beta$ calculations
   - Results and Uncertainty
   - Structure of the NMEs
3. Application to neutrino masses
   - Application to neutrino masses
4. Summary

Pairing and NMEs

- $0\nu\beta\beta$ decay is favoured by pairing correlations in nuclei involved
  It would be maximum between superfluid nuclei
  Unfortunately there is not such a candidate



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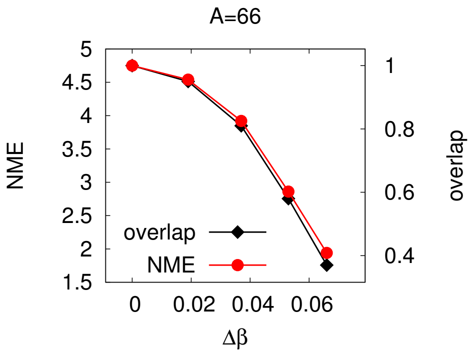
Deformation and NMEs

- $0\nu\beta\beta$ decay is disfavoured by quadrupole correlations
  It is very suppressed when nuclei have different structure



Almost constant NMEs

- This explains the small value for the ^{48}Ca transition
- On the same fashion, the ^{150}Nd NME
  is also expected to be suppressed
  See T. Rodríguez talk tomorrow
- In the rest of the candidates the (difference of) structure
  between the initial and final states is similar
  which is the reason for the relatively constant value for $M^{0\nu\beta\beta}$

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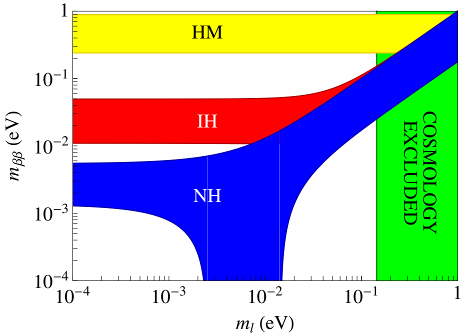
Application to neutrino masses

- With $M^{0\nu\beta\beta}$ value we obtain $m_{\beta\beta}$ using claim for $A = 76$ decay

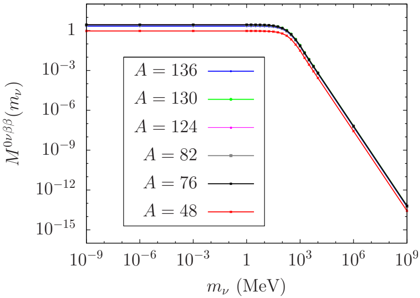
Blennow *et al.* JHEP 07 096 (2010)



Solving the incompatibility

- If we believe our $M^{0\nu\beta\beta}$, the ^{76}Ge $0\nu\beta\beta$ decay claim, cosmology neutrino mass measurements and the Standard Model seem to be in conflict
    - The ^{76}Ge $0\nu\beta\beta$ decay claim will be tested by GERDA experiment
    - Cosmology bounds on neutrino masses will be tested by KATRIN experiment
    - The mechanism for $0\nu\beta\beta$ decay might not be Standard Model light neutrinos: Heavy Neutrinos, Right Handed Currents, Supersymmetry

Heavy neutrinos in Seesaw model



- The NME is smaller for heavy neutrinos
- If $\sum_{i\in \mathrm{SM}} m_i U_{ei}^2 + \sum_{I\in \mathrm{l+h}} m_I U_{eI}^2 = 0$ as required by *ee* element of Majorana mass matrix heavy neutrinos can never be dominant
- $<$ 100 MeV sterile neutrinos could be a possibility

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Summary

- We have obtained within the ISM NMEs for seven $0\nu\beta\beta$ emitters
- We have estimated uncertainty in the calculation to be $\sim^{+25\ \%}_{-35\ \%}$
- Pairing like correlations favour the $0\nu\beta\beta$ decay
  Difference in structure (deformation) reduces the NME
- NMEs can be applied to obtain information on neutrino masses

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