QNP 2024

Two-neutrino double-beta decay to excited states of heavy nuclei

Beatriz Benavente de Lucas

Collaboration: Javier Ménendez, Dorian Frycz

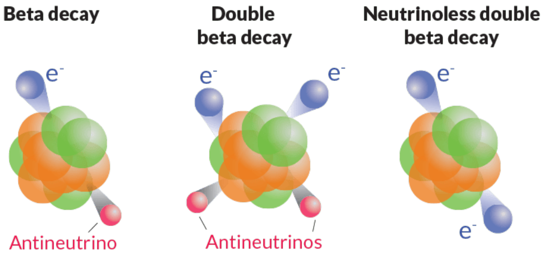
ICCUB Institut de Ciències del Cosmos UNIVERSITAT DE BARCELONA

EXCELENCIA MARÍA DE MAEZTU 2020–2023

UNIVERSITAT DE BARCELONA

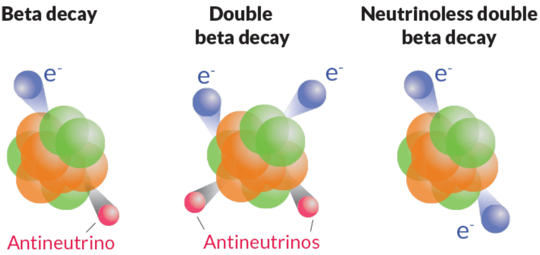
Motivation

- Neutrinoless double-beta decay violates the Standard model of particles physics(**D. Castillo**'s previous talk)
- Two-neutrino double-beta decay is permitted in the Standard model of particles physics



Motivation

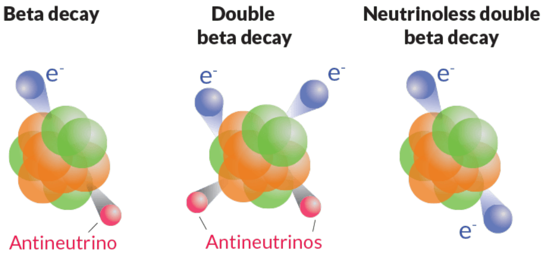
- Neutrinoless double-beta decay violates the Standard model of particles physics(**D. Castillo**'s previous talk)
- Two-neutrino double-beta decay is permitted in the Standard model of particles physics



- Study of $2\nu\beta\beta$ decay $\rightarrow$ information for $0\nu\beta\beta$ decay

Motivation

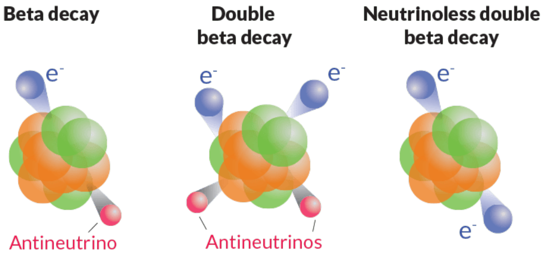
- Neutrinoless double-beta decay violates the Standard model of particles physics(**D. Castillo**'s previous talk)
- Two-neutrino double-beta decay is permitted in the Standard model of particles physics



- Study of $2\nu\beta\beta$ decay $\rightarrow$ information for $0\nu\beta\beta$ decay
- Initial and final states are common in both cases

Motivation

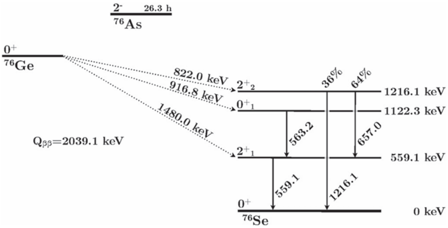
- Neutrinoless double-beta decay violates the Standard model of particles physics(**D. Castillo**'s previous talk)
- Two-neutrino double-beta decay is permitted in the Standard model of particles physics



- Study of $2\nu\beta\beta$ decay $\rightarrow$ information for $0\nu\beta\beta$ decay
- Initial and final states are common in both cases
- Many-body methods applicable in both cases

Motivation

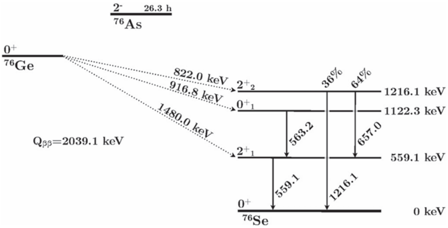
- Experimental interest in the decay to the first excited 0^+ state



GERDA Collaboration et al J. Phys. G: Nucl. Part. Phys. 42 (2015)

Motivation

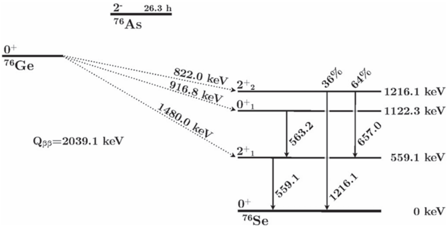
- Experimental interest in the decay to the first excited 0^+ state
- Decay to ground state measured for 13 nuclei



GERDA Collaboration et al J. Phys. G: Nucl. Part. Phys. 42 (2015)

Motivation

- Experimental interest in the decay to the first excited 0^+ state
- Decay to ground state measured for 13 nuclei
- Decay to 0_2^+ excited state measured for ^{100}Mo, ^{150}Nd

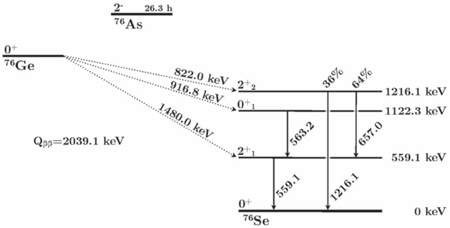


GERDA Collaboration et al J. Phys. G: Nucl. Part. Phys. 42 (2015)

Motivation

- Experimental interest in the decay to the first excited 0^+ state
- Decay to ground state measured for 13 nuclei
- Decay to 0_2^+ excited state measured for ^{100}Mo, ^{150}Nd
- Similar study on ^{136}Xe $\rightarrow$ ^{136}Ba

L. Jokiniemi, B. Romeo, C. Brase, J. Kotila, P. Soriano, A. Schwenk, J. Menéndez. Phys. Lett. B 838 (2023)



GERDA Collaboration et al J. Phys. G: Nucl. Part. Phys. 42 (2015)

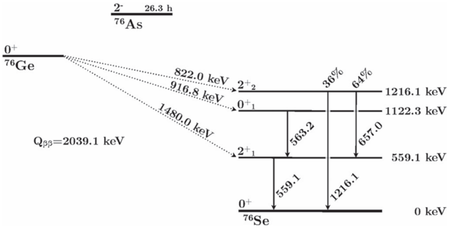
Motivation

- Experimental interest in the decay to the first excited 0^+ state
- Decay to ground state measured for 13 nuclei
- Decay to 0_2^+ excited state measured for ^{100}Mo, ^{150}Nd
- Similar study on $^{136}\text{Xe} \to {}^{136}\text{Ba}$

L. Jokiniemi, B. Romeo, C. Brase, J. Kotila, P. Soriano, A. Schwenk, J. Menéndez. Phys. Lett. B 838 (2023)

- $^{76}\text{Ge} \to {}^{76}\text{Se}$, $\quad E(^{76}\text{Se}, 0_2^+) = 1.122$ MeV.
- $^{82}\text{Se} \to {}^{82}\text{Kr}$, $\quad E(^{82}\text{Kr}, 0_2^+) = 1.488$ MeV.
- $^{130}\text{Te} \to {}^{130}\text{Xe}$, $\quad E(^{130}\text{Xe}, 0_2^+) = 1.793$ MeV.

Brookhaven National Laboratory. National Nuclear Data Center. https://www.nndc.bnl.gov (2023)



GERDA Collaboration et al J. Phys. G: Nucl. Part. Phys. 42 (2015)

Nuclear shell model

Schrödinger equation:

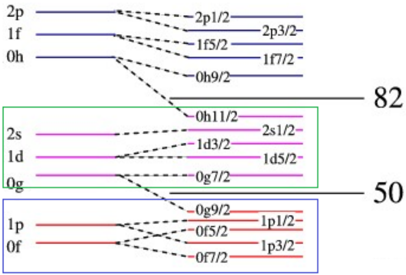
$$H_{eff}|\psi_{eff}\rangle = E|\psi_{eff}\rangle$$

Nuclear shell model

Schrödinger equation:

$$H_{eff}|\psi_{eff}\rangle = E|\psi_{eff}\rangle$$

Restriction to the valence space:



^{76}Ge, ^{82}Se: $(1p_{3/2}, 0f_{5/2}, 1p_{1/2}, 0g_{9/2})$

^{130}Te:$(0g_{7/2}, 1d_{5/2}, 1d_{3/2}, 2s_{1/2}, 0h_{11/2})$

Nuclear shell model

Schrödinger equation:

$$H_{eff}|\psi_{eff}\rangle = E|\psi_{eff}\rangle$$

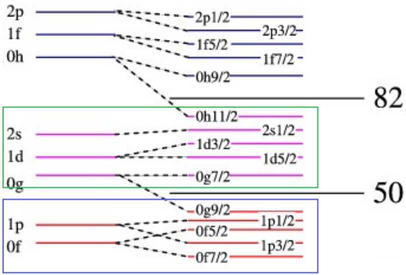
ANTOINE shell-model code:

Lanczos method

E. Caurier, F. Nowacki. Acta Phys. Pol. B 30: 705 (1999)

Caurier E., et al. Rev. Mod. Phys. 77, 427 (2005)

Restriction to the valence space:



^{76}Ge, ^{82}Se: $(1p_{3/2}, 0f_{5/2}, 1p_{1/2}, 0g_{9/2})$
^{130}Te:$(0g_{7/2}, 1d_{5/2}, 1d_{3/2}, 2s_{1/2}, 0h_{11/2})$

Nuclear shell model

Schrödinger equation:

$$H_{eff}|\psi_{eff}\rangle = E|\psi_{eff}\rangle$$

ANTOINE shell-model code:
Lanczos method

E. Caurier, F. Nowacki. Acta Phys. Pol. B 30: 705 (1999)

Caurier E., et al. Rev. Mod. Phys. 77, 427 (2005)

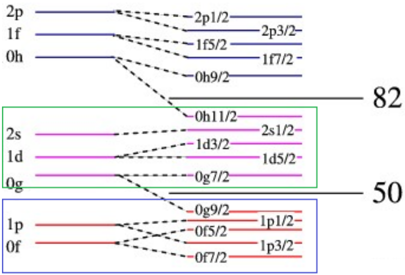
$\downarrow$

Linear combinations of the Slater determinants:

$$|\psi\rangle = \sum_{\alpha} C_{\alpha}|\phi_{\alpha}\rangle$$

$$|\phi_{\alpha}\rangle = \sum_{i=nljm} a_i^{\dagger}|0\rangle$$

Restriction to the valence space:



^{76}Ge, ^{82}Se: $(1p_{3/2}, 0f_{5/2}, 1p_{1/2}, 0g_{9/2})$
^{130}Te: $(0g_{7/2}, 1d_{5/2}, 1d_{3/2}, 2s_{1/2}, 0h_{11/2})$

Two-neutrino $\beta\beta$ decay

- β decay governed by the Gamow-Teller operator: $\sigma\tau^-$

Two-neutrino $\beta\beta$ decay

- β decay governed by the Gamow-Teller operator: $\sigma\tau^-$
- Matrix element:

$$M^{2\nu} = \sum_n \frac{\langle 0_f^+ || \sum_a \sigma_a \tau_a^- || 1_n^+ \rangle \langle 1_n^+ || \sum_b \sigma_b \tau_b^- || 0_i^+ \rangle}{E_n - (E_i - E_f)/2}$$

E_n : Energy of intermediate state

E_i : Energy of initial state

E_f : Energy of final state

Two-neutrino $\beta\beta$ decay

- β decay governed by the Gamow-Teller operator: $\sigma\tau^-$
- Matrix element:

$$M^{2\nu} = \sum_n \frac{\langle 0_f^+ || \sum_a \sigma_a \tau_a^- || 1_n^+ \rangle \langle 1_n^+ || \sum_b \sigma_b \tau_b^- || 0_i^+ \rangle}{E_n - (E_i - E_f)/2}$$

E_n : Energy of intermediate state

E_i : Energy of initial state

E_f : Energy of final state

- Correction by quenching factor, q , on the matrix elements

Two-neutrino $\beta\beta$ decay

- β decay governed by the Gamow-Teller operator: $\sigma\tau^-$
- Matrix element:

$$M^{2\nu} = \sum_n \frac{\langle 0_f^+ || \sum_a \sigma_a \tau_a^- || 1_n^+ \rangle \langle 1_n^+ || \sum_b \sigma_b \tau_b^- || 0_i^+ \rangle}{E_n - (E_i - E_f)/2}$$

E_n : Energy of intermediate state

E_i : Energy of initial state

E_f : Energy of final state

- Correction by quenching factor, q , on the matrix elements
- Half-life:

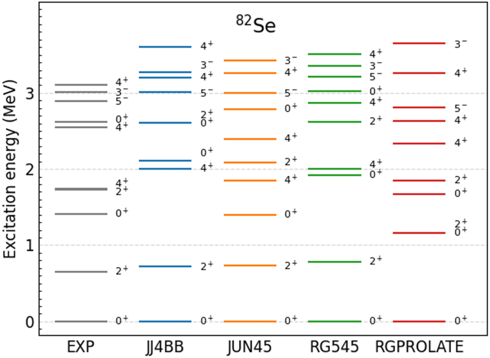
$$\left(T_{1/2}^{2\nu}\right)^{-1} = G^{2\nu} g_A^4 \left(M^{2\nu} m_e c^2\right)^2$$

$G^{2\nu}$: phase-space factor

g_A : axial coupling

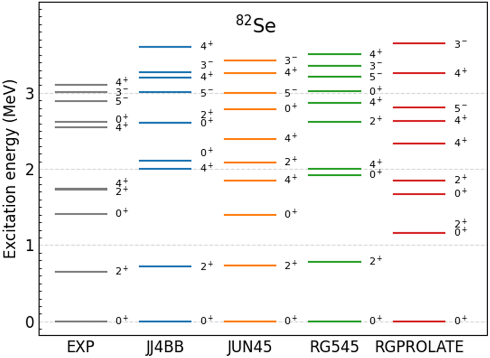
m_e : electron mass

Spectrum



- 4 different interactions
- No interaction significantly better than the others
- RGPROLATE: least descriptive of the nuclear structure

Spectrum



- 4 different interactions
- No interaction significantly better than the others
- RGPROLATE: least descriptive of the nuclear structure

Occupation study: $|n_{g_{9/2}}\, n_{p_{1/2}}\, n_{f_{5/2}}\, n_{p_{3/2}}\, p_{g_{9/2}}\, p_{p_{1/2}}\, p_{f_{5/2}}\, p_{p_{3/2}}\rangle$

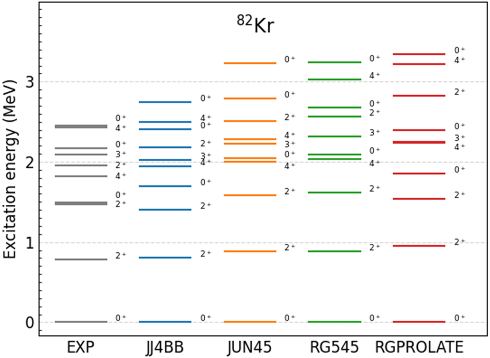
JJ4BB: $|0^+_{gs}\rangle = 0.60|8\,2\,6\,4\,0\,0\,4\,2\rangle + \ldots$

JUN45: $|0^+_{gs}\rangle = 0.62|8\,2\,6\,4\,0\,0\,4\,2\rangle + \ldots$

RG545: $|0^+_{gs}\rangle = 0.61|8\,2\,6\,4\,0\,0\,4\,2\rangle + \ldots$

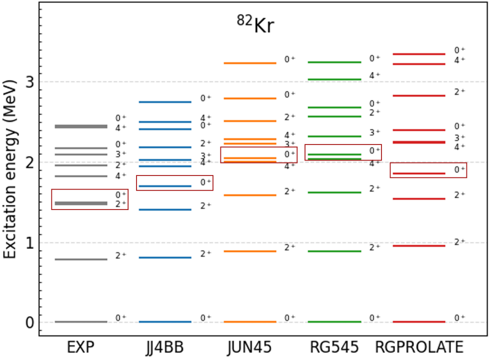
RGPROLATE: $|0^+_{gs}\rangle = 0.44|10\,0\,6\,4\,0\,0\,6\,0\rangle + 0.32|10\,0\,6\,4\,0\,0\,4\,2\rangle + \ldots$

Spectrum



- JJ4BB, RGPROLATE: best description of 0_2^+ energy
- JUN45, RG545: higher 0_2^+ energy prediction
- Wf describing 0_2^+ state fragmented across all interactions

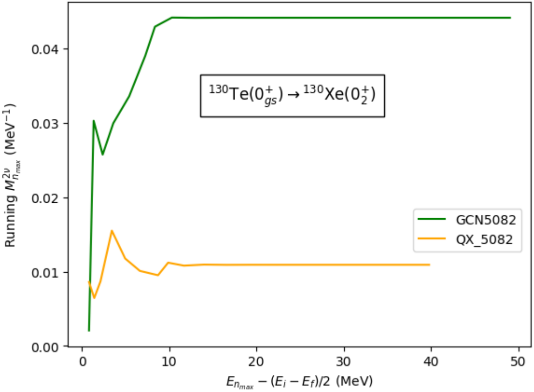
Spectrum



- JJ4BB, RGPROLATE: best description of 0_2^+ energy
- JUN45, RG545: higher 0_2^+ energy prediction
- Wf describing 0_2^+ state fragmented across all interactions

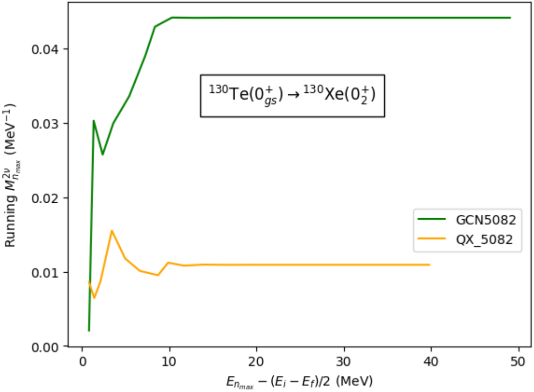
Matrix elements

$$M^{2\nu} = \sum_n \frac{\langle 0_f^+ || \sum_a \sigma_a \tau_a^- || 1_n^+ \rangle \langle 1_n^+ || \sum_b \sigma_b \tau_b^- || 0_i^+ \rangle}{E_n - (E_i - E_f)/2}$$



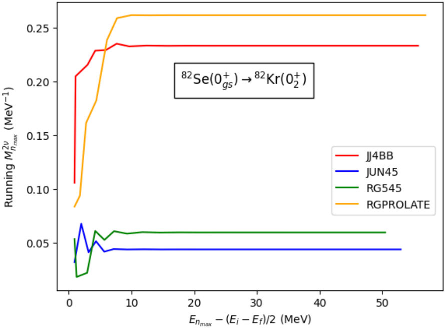
Matrix elements

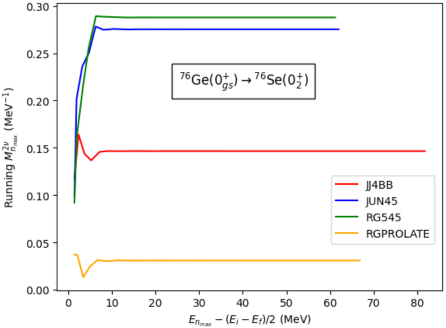
$$M^{2\nu}_{n_{max}} = \sum_{n}^{n_{max}} \frac{\langle 0_f^+ || \sum_a \sigma_a \tau_a^- || 1_n^+ \rangle \langle 1_n^+ || \sum_b \sigma_b \tau_b^- || 0_i^+ \rangle}{E_n - (E_i - E_f)/2}$$



- Convergence of matrix elements
- Running matrix element: truncation of matrix elements for *n* intermediate states
- Calculated using Lanczos strength function

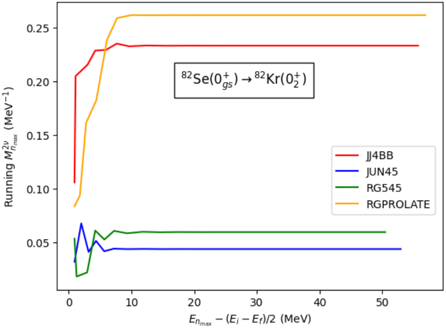
Matrix elements

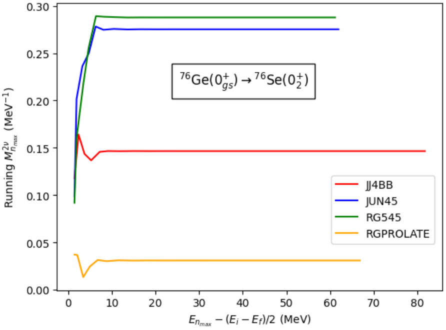




- JJ4BB and RGPROLATE: no cancellation of terms, larger running matrix element
- JUN45 and RG545: no cancellation of terms, larger running matrix element

Matrix elements





- JJ4BB and RGPROLATE: no cancellation of terms, larger running matrix element
- JUN45 and RG545: cancellation of terms, smaller running matrix element

- JUN45 and RG545: no cancellation of terms, larger running matrix element
- JJ4BB and RGPROLATE: cancellation of terms, smaller running matrix element

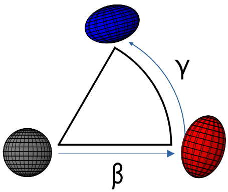
Projected generator coordinate method (PGCM)

Variational approach:

- Configuration mixing of Hartree-Fock-Bogoliubov (HFB) states: $|\Psi_{GCM}\rangle = \sum_q f_q |\phi_{HFB}(q)\rangle$

  B. Bally, et al. Eur. Phys. J. A **60**, 62 (2024)

- Similar deformations for all interactions



D. Frycz: 11/07, 17:30h, M1

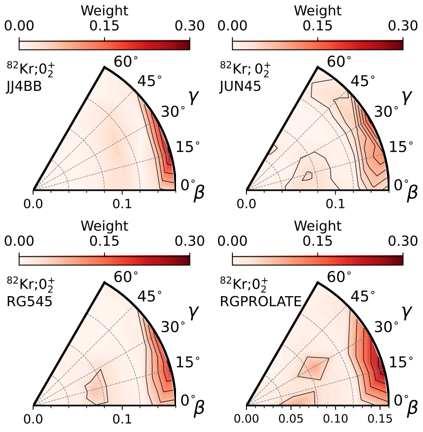


Figure: Contribution of each HFB wavefunction to fully mixed state for ^{82}Kr (0_2^+) with all interactions

Quenching

Quenching factor to correct the overestimation of matrix elements

- $q_\beta = 0.6$, from previous β decay studies from literature
  E. Caurier et al. Phys. Lett. B 711: 1, 62-64 (2012)

Quenching

Quenching factor to correct the overestimation of matrix elements

- $q_\beta = 0.6$, from previous β decay studies from literature
  E. Caurier et al. Phys. Lett. B 711: 1, 62-64 (2012)
- $q_{2\nu}$, from the study of the decay to the ground state (g.s.)
  Predicted half-life g.s. to g.s. $\xrightarrow{q_{2\nu}}$ Experimental half-life g.s. to g.s.

  A. Barabash. Universe. 6(10): 159 (2020)

Quenching

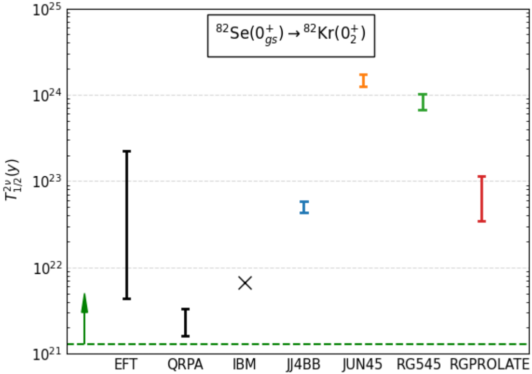
Quenching factor to correct the overestimation of matrix elements

- $q_\beta = 0.6$, from previous β decay studies from literature
  E. Caurier et al. Phys. Lett. B 711: 1, 62-64 (2012)
- $q_{2\nu}$, from the study of the decay to the ground state (g.s.)
  Predicted half-life g.s. to g.s. $\xrightarrow{q_{2\nu}}$ Experimental half-life g.s. to g.s.

  A. Barabash. Universe. 6(10): 159 (2020)

	$q_{2\nu}$	INT
$^{82}Se \rightarrow ^{82}Kr$	0.56	JJ4BB
$^{82}Se \rightarrow ^{82}Kr$	0.55	JUN45
$^{82}Se \rightarrow ^{82}Kr$	0.54	RG545
$^{82}Se \rightarrow ^{82}Kr$	0.44	RGPROLATE
$^{76}Ge \rightarrow ^{76}Se$	0.64	JJ4BB
$^{76}Ge \rightarrow ^{76}Se$	0.61	JUN45
$^{76}Ge \rightarrow ^{76}Se$	0.62	RG545
$^{76}Ge \rightarrow ^{76}Se$	0.54	RGPROLATE
$^{130}Te \rightarrow ^{130}Xe$	0.47	GCN5082
$^{130}Te \rightarrow ^{130}Xe$	0.75	QX_5082

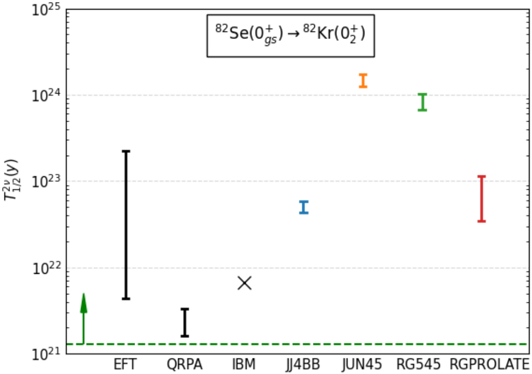
Half-life predictions



NEMO-3 collaboration. Nuc. Phys. A 996: 121701 (2020)
E. A. Coello Pérez, J. Menéndez, A. Schwenk. Phys. Rev. C 98: 045501 (2018)
J. Toivanen, J. Suhonen. Phys. Rev. C 55: 2314 (1997)
J. Barea, J. Kotila, F. Iachello. Phys. Rev. C 91: 034304 (2015)

Experimental limit: $T^{2\nu}_{1/2}(^{82}\text{Se}, 0^+_{gs} \to ^{82}\text{Kr}, 0^+_2) > 1.3 \cdot 10^{21}\text{yr}$
Range of predictions: $T^{2\nu}_{1/2}(^{82}\text{Se}, 0^+_{gs} \to ^{82}\text{Kr}, 0^+_2) = (3.5 - 170) \cdot 10^{21}\text{yr}$

Half-life predictions



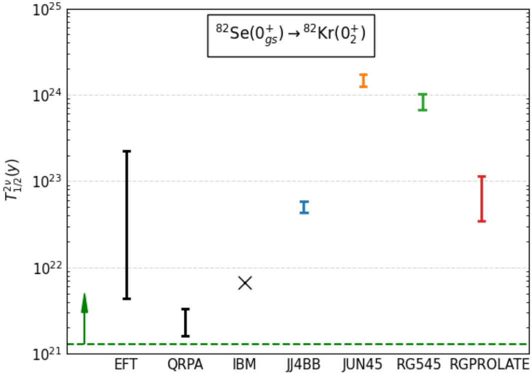
- Prediction: longer half-lives than most obtained with other methods

NEMO-3 collaboration. Nuc. Phys. A 996: 121701 (2020)
E. A. Coello Pérez, J. Menéndez, A. Schwenk. Phys. Rev. C 98: 045501 (2018)
J. Toivanen, J. Suhonen. Phys. Rev. C 55: 2314 (1997)
J. Barea, J. Kotila, F. Iachello. Phys. Rev. C 91: 034304 (2015)

Experimental limit: $T^{2\nu}_{1/2}(^{82}\mathrm{Se}, 0^+_{gs} \to ^{82}\mathrm{Kr}, 0^+_2) > 1.3 \cdot 10^{21}\mathrm{yr}$

Range of predictions: $T^{2\nu}_{1/2}(^{82}\mathrm{Se}, 0^+_{gs} \to ^{82}\mathrm{Kr}, 0^+_2) = (3.5 - 170) \cdot 10^{21}\mathrm{yr}$

Half-life predictions



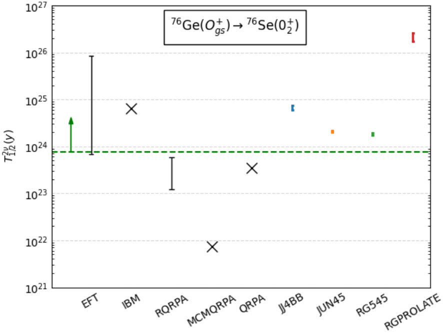
NEMO-3 collaboration. Nuc. Phys. A 996: 121701 (2020)
E. A. Coello Pérez, J. Menéndez, A. Schwenk. Phys. Rev. C 98: 045501 (2018)
J. Toivanen, J. Suhonen. Phys. Rev. C 55: 2314 (1997)
J. Barea, J. Kotila, F. Iachello. Phys. Rev. C 91: 034304 (2015)

- Prediction: longer half-lives than most obtained with other methods
- Prediction consistent with experimental limit

Experimental limit: $T^{2\nu}_{1/2}(^{82}\mathrm{Se}, 0^+_{gs} \to ^{82}\mathrm{Kr}, 0^+_2) > 1.3 \cdot 10^{21}\mathrm{yr}$

Range of predictions: $T^{2\nu}_{1/2}(^{82}\mathrm{Se}, 0^+_{gs} \to ^{82}\mathrm{Kr}, 0^+_2) = (3.5 - 170) \cdot 10^{21}\mathrm{yr}$

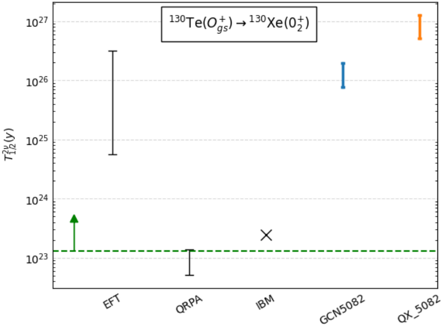
Half-life predictions



S. Stoica, I. Mihut. Nucl. Phys. A 602: 197 (1996)
M. Aunola, J. Suhonen. Nucl. Phys. A 602: 133 (1996)
MAJORANA Collaboration. Phys.Rev.C 103: 1, 015501 (2021)
J. Barea, J. Kotila, F. Iachello. Phys. Rev. C 91: 034304 (2015)
E. A. Coello Pérez, J. Menéndez, A. Schwenk. Phys. Rev. C 98: 045501 (2018)

Range of predictions:

$$T^{2\nu}_{1/2}(^{76}\text{Ge}, 0^+_{gs} \rightarrow ^{76}\text{Se}, 0^+_2) = (2 - 260)\cdot 10^{24}\text{yr}$$

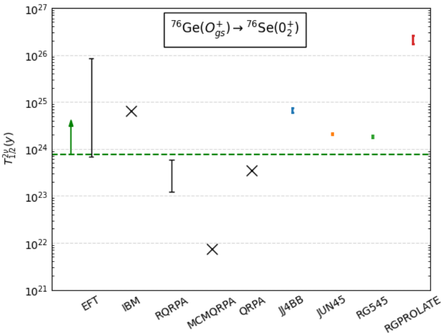


J. Barea, J. Kotila, F. Iachello. Phys. Rev. C 91: 034304 (2015)
E. Andreotti et al. Phys. Rev. C 85: 045503 (2012)
E. A. Coello Pérez, J. Menéndez, A. Schwenk. Phys. Rev. C 98: 045501 (2018)

Range of predictions:

$$T^{2\nu}_{1/2}(^{130}\text{Te}, 0^+_{gs} \rightarrow ^{130}\text{Xe}, 0^+_2) = (7.7 - 130)\cdot 10^{25}\text{yr}$$

Summary



- Study of 3 different $2\nu\beta\beta$ decays with different interactions in the context of the NSM
- Many-body methods applicable in the study of the neutrinoless double-beta decay
- Different running matrix elements, but are yet to find a plausible explanation for it
- Predicted half-lives consistent with experimental limits, close to it in some cases

The discrepancies between the prediction of half-lives makes the testing of these values a good way of validating the many-body methods used in the study. We really look forward to these results being tested!

QNP 2024

Thank you!

ICCUB Institut de Ciències del Cosmos UNIVERSITAT DE BARCELONA

EXCELENCIA MARÍA DE MAEZTU 2020-2023

UNIVERSITAT DE BARCELONA