JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

New findings on neutrinoless double beta decay matrix elements using IBM-2

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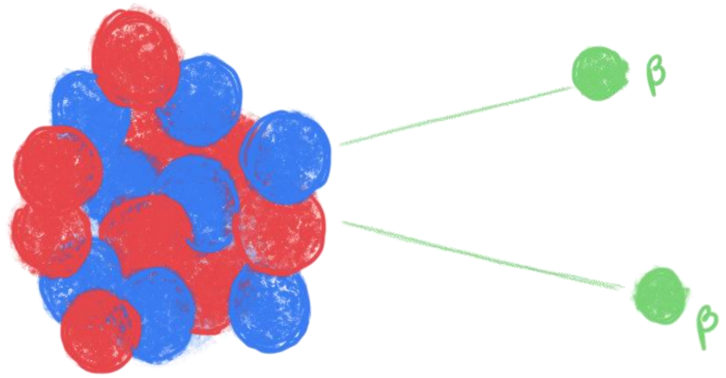
Outline

- Motivation
- Theory: Microscopic interacting boson model
- Short-range nuclear matrix elements
- Total nuclear matrix element
- Uncertainty of effective g_A
- Comparison with pnQRPA and NSM
- Effect on the predicted half-life
- Conclusions

Motivation

- Neutrinoless double beta decay (not yet observed)
  - Half-life
  - Effective neutrino mass
- Lepton number violation, the nature of the neutrino
- The short-range component in double beta decay nuclei has been studied with pnQRPA and NSM *[Jokiniemi, Soriano, Menéndez, Physics Letters B 823 (2021) 136720]*
  - Also: *ab initio* calculations *[Wirth, Yao, Hergert, Phys. Rev. Lett. 127, 242502 (2021). & A. Belley et al., Phys. Rev. Lett. 132, 182502 (2024).]*

$$T_{1/2}^{0\nu} = \left(g_A^4 |M_{0\nu}|^2 G_{0\nu} \left(\frac{m_{\beta\beta}}{m_e} \right)^2 \right)^{-1}$$



Theory: Microscopic interacting boson model

- Microscopic interacting boson model (IBM-2)
  - Closure approximation
  - Isospin restoration formalism
- Hamiltonian parameters for calculations are from *Barea, Kotila, Iachello PRC 87, 014315 (2013)*

$^{76}Ge \rightarrow {}^{76}Se$

$^{82}Se \rightarrow {}^{82}Kr$

$^{96}Zr \rightarrow {}^{96}Mo$

$^{100}Mo \rightarrow {}^{100}Ru$

$^{116}Cd \rightarrow {}^{116}Sn$

$^{124}Sn \rightarrow {}^{124}Te$

$^{128}Te \rightarrow {}^{128}Xe$

$^{130}Te \rightarrow {}^{130}Xe$

$^{136}Xe \rightarrow {}^{136}Ba$

Short-range nuclear matrix element

PHYSICAL REVIEW LETTERS **120,** 202001 (2018)

Editors' Suggestion | Featured in Physics

New Leading Contribution to Neutrinoless Double-β Decay

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Short-range nuclear matrix element

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Editors' Suggestion Featured in Physics

New Leading Contribution to Neutrinoless Double-β Decay

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PHYSICAL REVIEW C **100**, 055504 (2019)

Renormalized approach to neutrinoless double-β decay

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Short-range nuclear matrix element

- Short range nuclear matrix element

$$M_S = \frac{2R}{\pi g_A^2} \langle 0_f^+ | \sum_{m,n} \tau_m^- \tau_n^- \int j_0(qr) h_s(q^2) q^2 dq | 0_i^+ \rangle$$

- Neutrino potential h_S can be written as

$$h_S(q^2) = -2 g_\nu^{NN} e^{-q^2/(2\Lambda^2)}$$

- The coupling g_ν^{NN} is not known
  - Values used are from:
    - *Reinert, Krebs, Epelbaum, European Physical Journal A 54, 86(2018).*
    - *Piarulli et al. Phys. Rev. C 94, 054007 (2016).*
  - Obtained with the methods explained in *Cirigliano et al., Phys. Rev. C 100, 055504 (2019)*

Short-range nuclear matrix element

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    - *Piarulli et al. Phys. Rev. C 94, 054007 (2016).*
  - Obtained with the methods explained in *Cirigliano et al., Phys. Rev. C 100, 055504 (2019)*

g_ν^{NN} (fm^2)	Λ (MeV)
-0.67	450
-1.01	550
-1.44	465
-0.91	465
-1.44	349
-1.03	349

Total nuclear matrix element

- The total nuclear matrix element is calculated as the sum of the long-range and short-range nuclear matrix elements
  - In *ab initio* calculations, the short-range component has been seen to enhance the total nuclear matrix element *[Wirth, Yao, Hergert, Phys. Rev. Lett. 127, 242502 (2021).]*

$$M_{tot} = |M_L| + |M_S|$$

$$M_L = \left(\frac{g_V}{g_A}\right)^2 M_F - M_{GT} + M_T$$

Uncertainty of effective g_A

- Since the true value of effective g_A is not known, we have used three values to estimate it
  - The bare value: $g_A = 1.269$
  - The renormalized value: $g_A = 1.00$
  - The maximally quenched value: $g_A = 1.269A^{-0.18}$ (IBM-2)

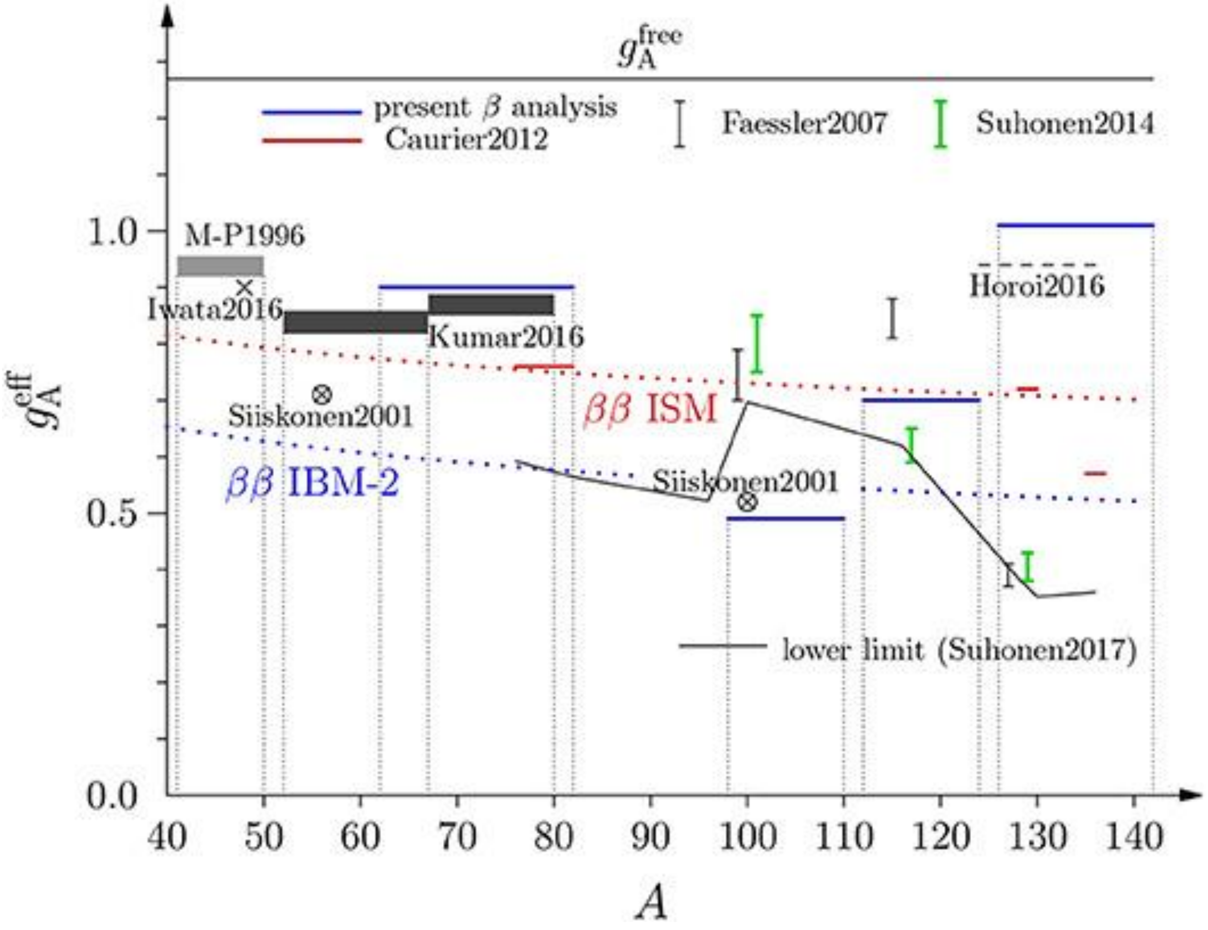

Fig: [Suhonen and Kostensalo, Front. Phys. 7:29 (2019)]

Total nuclear matrix element

Decay	M_L
$^{76}Ge \rightarrow {}^{76}Se$	(6.10)6.49-6.71(8.49)
$^{82}Se \rightarrow {}^{82}Kr$	(5.02)5.35-5.53(7.12)
$^{96}Zr \rightarrow {}^{96}Mo$	(3.83)4.01-4.19(5.07)
$^{100}Mo \rightarrow {}^{100}Ru$	(4.90)5.15-5.45(6.69)
$^{116}Cd \rightarrow {}^{116}Sn$	(2.81)2.98-3.12(4.06)
$^{124}Sn \rightarrow {}^{124}Te$	(3.46)3.73-3.87(5.54)
$^{128}Te \rightarrow {}^{128}Xe$	(4.42)4.76-4.94(7.07)
$^{130}Te \rightarrow {}^{130}Xe$	(3.99)4.30-4.45(6.40)
$^{136}Xe \rightarrow {}^{136}Ba$	(3.25)3.50-3.62(5.20)

$g_A = 1.00$
Argonne / CD-Bonn
SRC

Total nuclear matrix element

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$^{76}Ge \rightarrow {}^{76}Se$	(6.10)6.49-6.71(8.49)
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$g_A = 1.00$
Argonne / CD-Bonn SRC

$g_A = 1.269$
Argonne SRC

$g_A = 1.269A^{-0.18}$
CD-Bonn SRC

Total nuclear matrix element

Decay	M_L	M_S
$^{76}Ge \rightarrow {}^{76}Se$	(6.10)**6.49-6.71**(8.49)	**0.78-2.20**
$^{82}Se \rightarrow {}^{82}Kr$	(5.02)**5.35-5.53**(7.12)	**0.66-1.84**
$^{96}Zr \rightarrow {}^{96}Mo$	(3.83)**4.01-4.19**(5.07)	**0.60-1.71**
$^{100}Mo \rightarrow {}^{100}Ru$	(4.90)**5.15-5.45**(6.69)	**0.88-2.51**
$^{116}Cd \rightarrow {}^{116}Sn$	(2.81)**2.98-3.12**(4.06)	**0.54-1.54**
$^{124}Sn \rightarrow {}^{124}Te$	(3.46)**3.73-3.87**(5.54)	**0.53-1.48**
$^{128}Te \rightarrow {}^{128}Xe$	(4.42)**4.76-4.94**(7.07)	**0.67-1.87**
$^{130}Te \rightarrow {}^{130}Xe$	(3.99)**4.30-4.45**(6.40)	**0.61-1.70**
$^{136}Xe \rightarrow {}^{136}Ba$	(3.25)**3.50-3.62**(5.20)	**0.47-1.32**

Total nuclear matrix element

Decay	M_L	M_S	M_{tot}
$^{76}Ge \rightarrow ^{76}Se$	(6.10)**6.49-6.71**(8.49)	**0.78-2.20**	(6.88)**7.27-8.91**(10.68)
$^{82}Se \rightarrow ^{82}Kr$	(5.02)**5.35-5.53**(7.12)	**0.66-1.84**	(5.67)**6.00-7.37**(8.96)
$^{96}Zr \rightarrow ^{96}Mo$	(3.83)**4.01-4.19**(5.07)	**0.60-1.71**	(4.43)**4.61-5.90**(6.78)
$^{100}Mo \rightarrow ^{100}Ru$	(4.90)**5.15-5.45**(6.69)	**0.88-2.51**	(5.77)**6.03-7.96**(9.21)
$^{116}Cd \rightarrow ^{116}Sn$	(2.81)**2.98-3.12**(4.06)	**0.54-1.54**	(3.35)**3.52-4.66**(5.61)
$^{124}Sn \rightarrow ^{124}Te$	(3.46)**3.73-3.87**(5.54)	**0.53-1.48**	(3.99)**4.26-5.35**(7.01)
$^{128}Te \rightarrow ^{128}Xe$	(4.42)**4.76-4.94**(7.07)	**0.67-1.87**	(5.09)**5.43-6.80**(8.93)
$^{130}Te \rightarrow ^{130}Xe$	(3.99)**4.30-4.45**(6.40)	**0.61-1.70**	(4.59)**4.90-6.15**(8.10)
$^{136}Xe \rightarrow ^{136}Ba$	(3.25)**3.50-3.62**(5.20)	**0.47-1.32**	(3.72)**3.97-4.94**(6.53)

Total nuclear matrix element

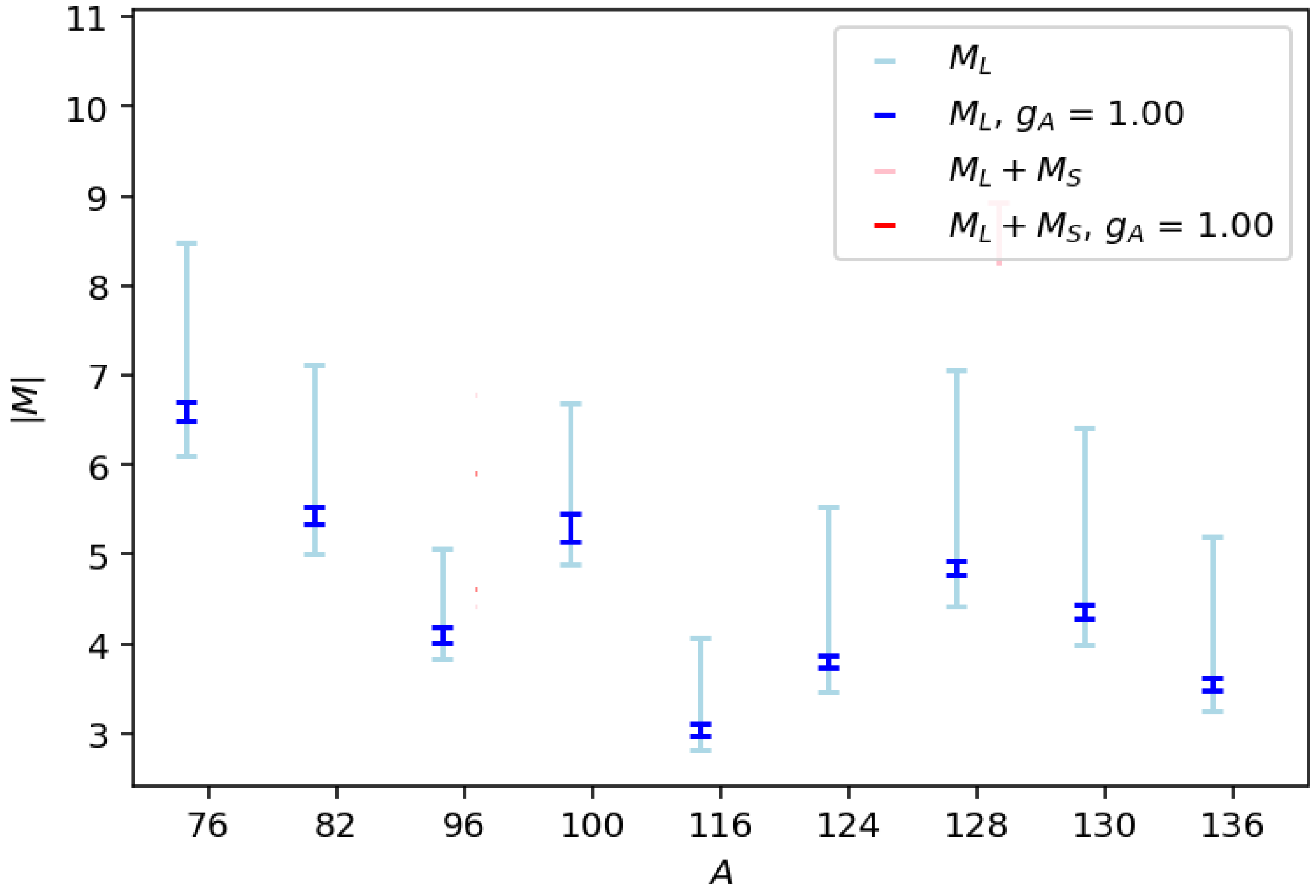
Decay	M_L	M_S	M_{tot}
^{76}Ge → ^{76}Se	(6.10)**6.49-6.71**(8.49)	**0.78-2.20**	(6.88)**7.27-8.91**(10.68)
^{82}Se → ^{82}Kr	(5.02)**5.35-5.53**(7.12)	**0.66-1.84**	(5.67)**6.00-7.37**(8.96)
^{96}Zr → ^{96}Mo	(3.83)**4.01-4.19**(5.07)	**0.60-1.71**	(4.43)**4.61-5.90**(6.78)
^{100}Mo → ^{100}Ru	(4.90)**5.15-5.45**(6.69)	**0.88-2.51**	(5.77)**6.03-7.96**(9.21)
^{116}Cd → ^{116}Sn	[illegible]	[illegible]**54**	(3.35)**3.52-4.66**(5.61)
^{124}Sn → ^{124}Te	[illegible]	[illegible]**48**	(3.99)**4.26-5.35**(7.01)
^{128}Te → ^{128}Xe	[illegible]	[illegible]**87**	(5.09)**5.43-6.80**(8.93)
^{130}Te → ^{130}Xe	[illegible]	[illegible]**70**	(4.59)**4.90-6.15**(8.10)
^{136}Xe → ^{136}Ba	[illegible]	[illegible]**32**	(3.72)**3.97-4.94**(6.53)

Ab initio ^{76}Ge:

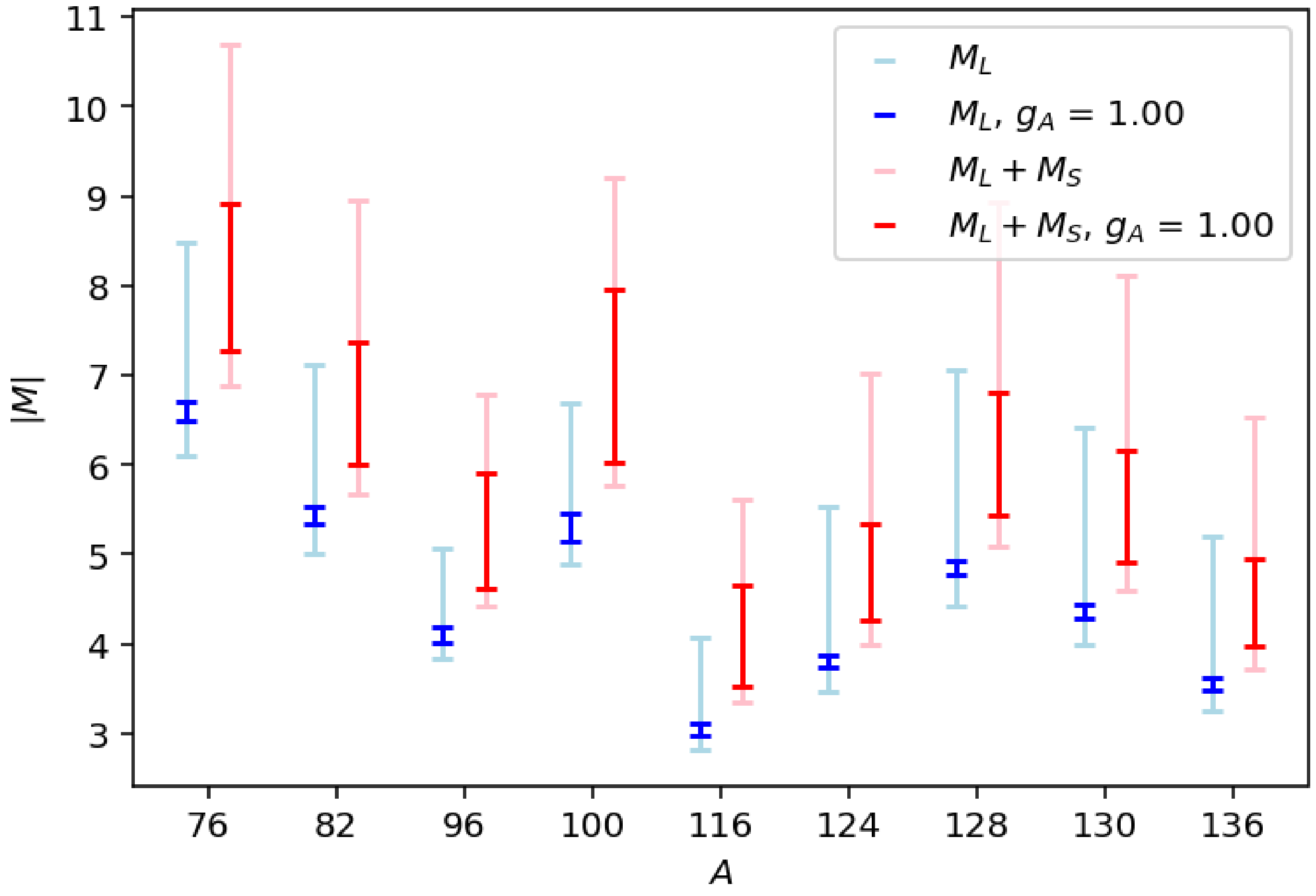
$$M_{tot} = 2.60^{+1.28}_{-1.36}$$

Belley et al., Phys. Rev. Lett. 132, 182502 (2024).

Total nuclear matrix element



Total nuclear matrix element



Total nuclear matrix element

Decay	M_L	M_S	M_S/M_L (%)
$^{76}Ge \rightarrow {}^{76}Se$	(6.10)**6.49-6.71**(8.49)	**0.78-2.20**	(9)**12-34**(36)
$^{82}Se \rightarrow {}^{82}Kr$	(5.02)**5.35-5.53**(7.12)	**0.66-1.84**	(9)**12-34**(37)
$^{96}Zr \rightarrow {}^{96}Mo$	(3.83)**4.01-4.19**(5.07)	**0.60-1.71**	(12)**14-43**(45)
$^{100}Mo \rightarrow {}^{100}Ru$	(4.90)**5.15-5.45**(6.69)	**0.88-2.51**	(13)**16-49**(51)
$^{116}Cd \rightarrow {}^{116}Sn$	(2.81)**2.98-3.12**(4.06)	**0.54-1.54**	(13)**17-52**(55)
$^{124}Sn \rightarrow {}^{124}Te$	(3.46)**3.73-3.87**(5.54)	**0.53-1.48**	(10)**14-40**(43)
$^{128}Te \rightarrow {}^{128}Xe$	(4.42)**4.76-4.94**(7.07)	**0.67-1.87**	(9)**14-39**(42)
$^{130}Te \rightarrow {}^{130}Xe$	(3.99)**4.30-4.45**(6.40)	**0.61-1.70**	(10)**14-40**(43)
$^{136}Xe \rightarrow {}^{136}Ba$	(3.25)**3.50-3.62**(5.20)	**0.47-1.32**	(9)**13-38**(41)

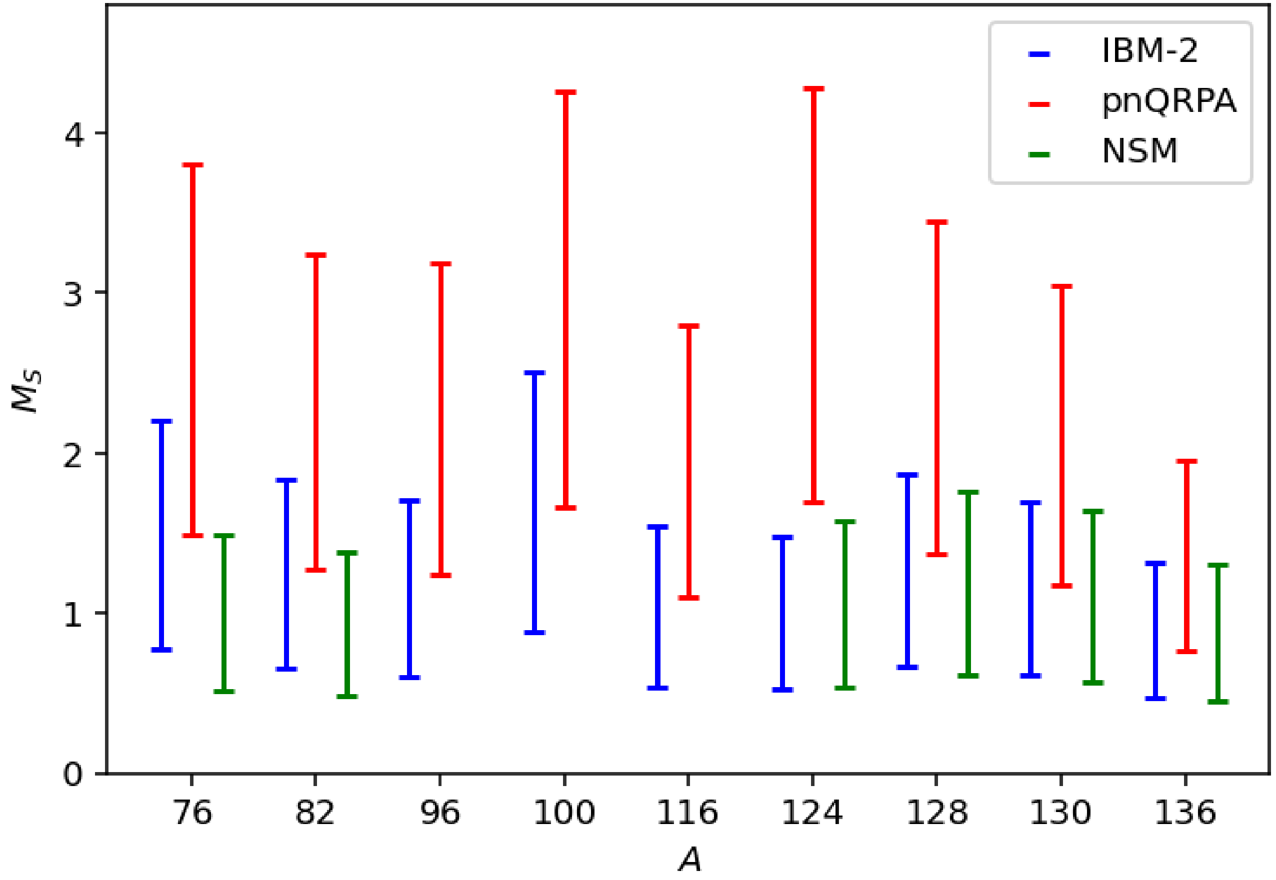
Comparison with pnQRPA and NSM

Short-range NMEs

Decay	IBM-2	pnQRPA	NSM
$^{76}Ge \rightarrow {}^{76}Se$	0.78-2.20	1.49-3.80	0.52-1.49
$^{82}Se \rightarrow {}^{82}Kr$	0.66-1.84	1.27-3.24	0.48-1.38
$^{96}Zr \rightarrow {}^{96}Mo$	0.60-1.71	1.24-3.19	-
$^{100}Mo \rightarrow {}^{100}Ru$	0.88-2.51	1.66-4.26	-
$^{116}Cd \rightarrow {}^{116}Sn$	0.54-1.54	1.10-2.80	-
$^{124}Sn \rightarrow {}^{124}Te$	0.53-1.48	1.69-4.28	0.54-1.58
$^{128}Te \rightarrow {}^{128}Xe$	0.67-1.87	1.37-3.45	0.61-1.76
$^{130}Te \rightarrow {}^{130}Xe$	0.61-1.70	1.18-3.05	0.57-1.64
$^{136}Xe \rightarrow {}^{136}Ba$	0.47-1.32	0.76-1.95	0.45-1.31

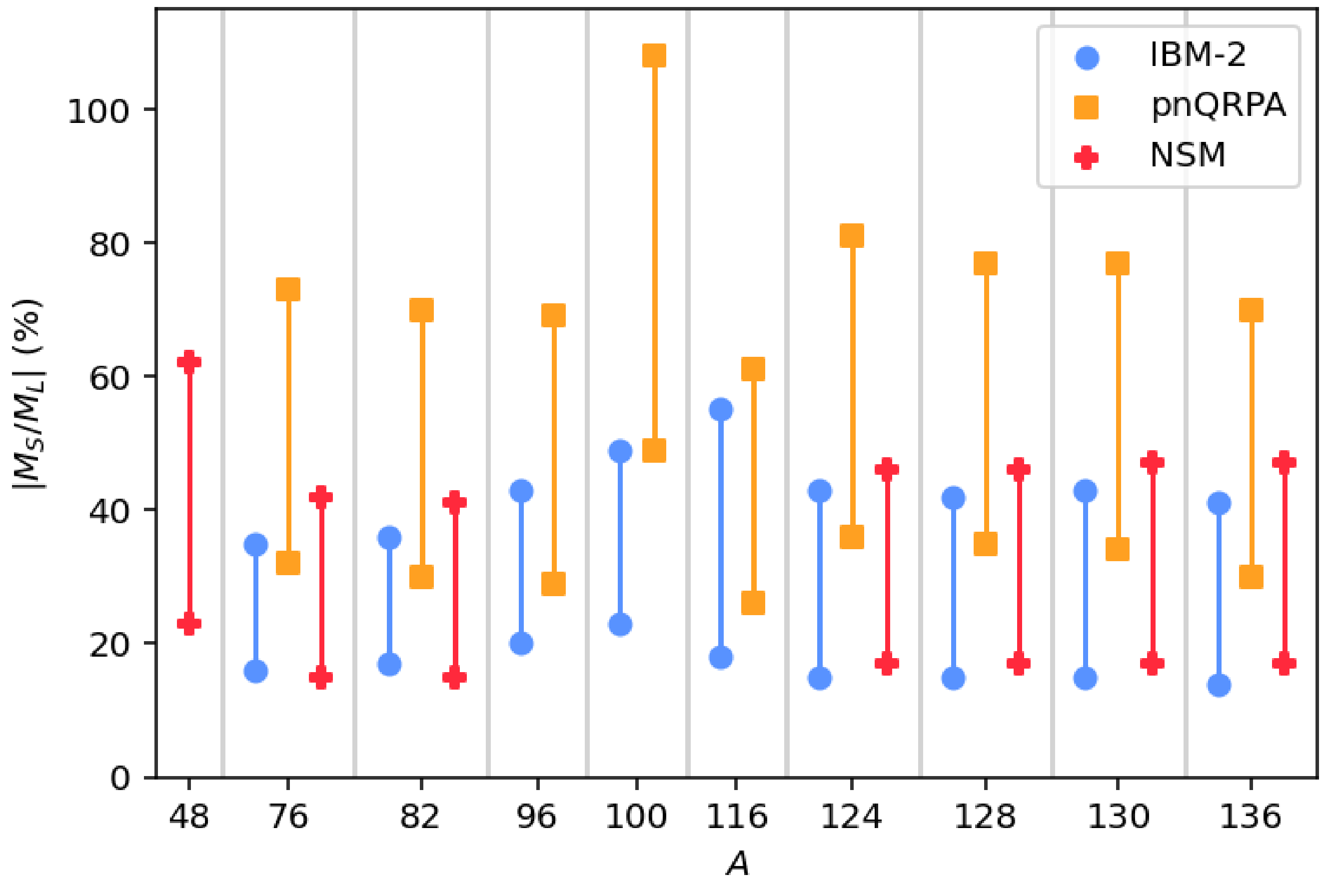
pnQRPA and NSM: *[Jokiniemi, Soriano, Menéndez, Physics Letters B 823 (2021) 136720]*

Comparison with pnQRPA and NSM



Comparison with pnQRPA and NSM

$g_A = 1.269$



Effect on the predicted half-life

$$T_{1/2}^{0\nu} = \left(g_A^4 |M_{0\nu}|^2 G_{0\nu} \left(\frac{m_{\beta\beta}}{m_e} \right)^2 \right)^{-1}$$

- The phase-space factors for all decays considered are from *Kotila, Iachello Phys. Rev. C 85, 034316 (2012)*
- The effective mass of the neutrino was set to be 0.1 eV

Effect on the predicted half-life

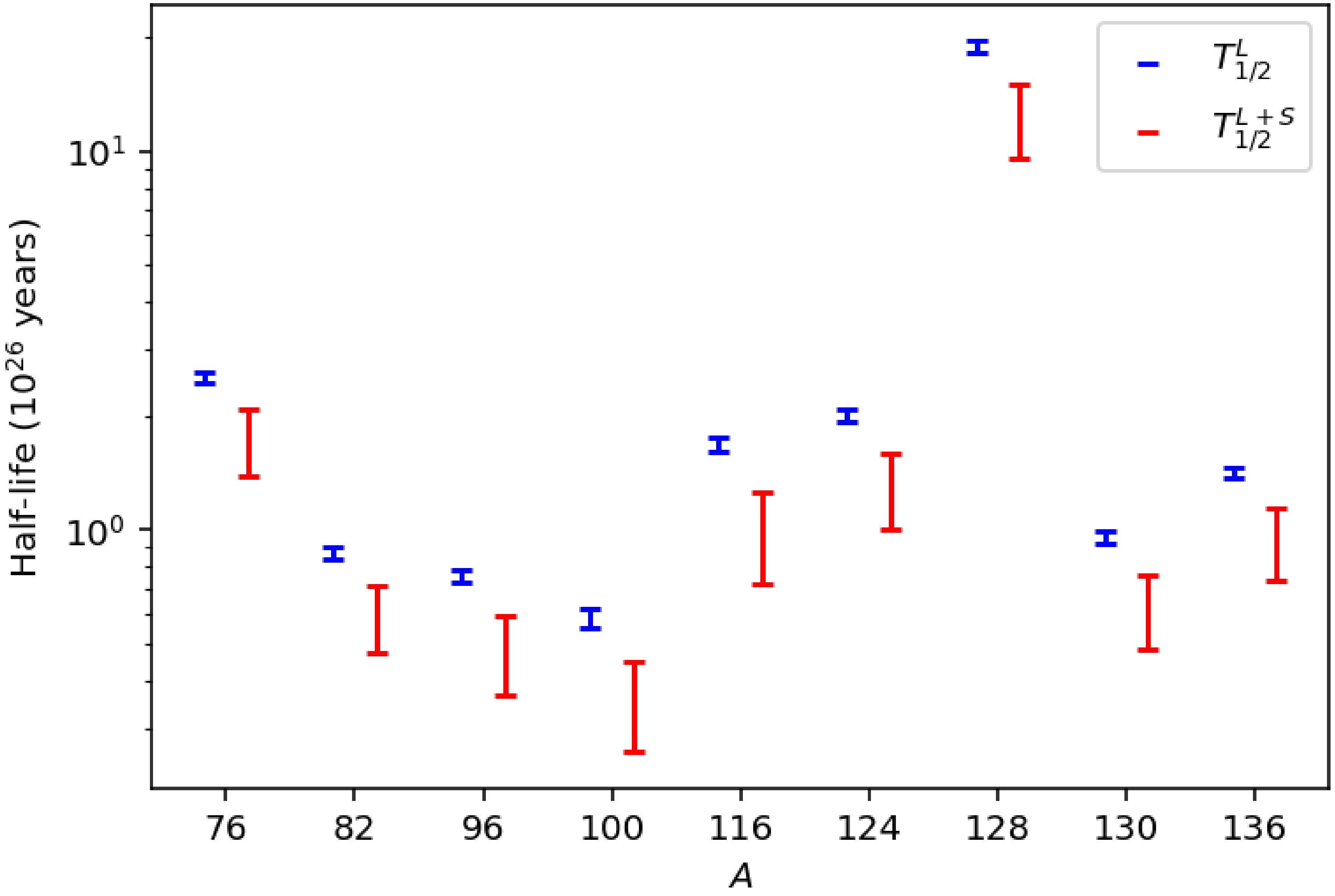
Decay	$T^{L}_{1/2}$ ($\times 10^{26}$ years)	$T^{L+S}_{1/2}$ ($\times 10^{26}$ years)
$^{76}Ge \rightarrow {}^{76}Se$	(1.08)**2.45-2.62**(15.6)	(0.59)**1.39-2.10**(12.9)
$^{82}Se \rightarrow {}^{82}Kr$	(0.37)**0.84-0.90**(5.54)	(0.20)**0.47-0.71**(4.57)
$^{96}Zr \rightarrow {}^{96}Mo$	(0.31)**0.72-0.79**(5.66)	(0.15)**0.36-0.60**(4.47)
$^{100}Mo \rightarrow {}^{100}Ru$	(0.24)**0.55-0.62**(4.36)	(0.11)**0.26-0.45**(3.36)
$^{116}Cd \rightarrow {}^{116}Sn$	(0.70)**1.61-1.76**(13.1)	(0.30)**0.72-1.26**(9.99)
$^{124}Sn \rightarrow {}^{124}Te$	(0.87)**1.93-2.08**(15.4)	(0.44)**1.01-1.59**(12.5)
$^{128}Te \rightarrow {}^{128}Xe$	(8.20)**18.2-19.6**(149)	(4.13)**9.60-15.1**(121)
$^{130}Te \rightarrow {}^{130}Xe$	(0.42)**0.93-1.00**(7.62)	(0.21)**0.49-0.76**(6.20)
$^{136}Xe \rightarrow {}^{136}Ba$	(0.61)**1.37-1.47**(11.7)	(0.32)**0.73-1.14**(9.57)

Effect on the predicted half-life

Decay	$T^{L}_{1/2}$ ($\times 10^{26}$ years)	$T^{L+S}_{1/2}$ ($\times 10^{26}$ years)
$^{76}Ge \rightarrow {}^{76}Se$	(1.08)**2.45-2.62**(15.6)	(0.59)**1.39-2.10**(12.9)
$^{82}Se \rightarrow {}^{82}Kr$	(0.37)**0.84-0.90**(5.54)	(0.20)**0.47-0.71**(4.57)
$^{96}Zr \rightarrow {}^{96}Mo$	(0.31)**0.72-0.79**(5.66)	(0.15)**0.36-0.60**(4.47)
$^{100}Mo \rightarrow {}^{100}Ru$	(0.24)**0.55-0.62**(4.36)	(0.11)**0.26-0.45**(3.36)
$^{116}Cd \rightarrow {}^{116}Sn$	(0.70)**1.61-1.76**(13.1)	(0.30)**0.72-1.26**(9.99)
$^{124}Sn \rightarrow {}^{124}Te$	(0.87)**1.93-2.08**(15.4)	(0.44)**1.01-1.59**(12.5)
$^{128}Te \rightarrow {}^{128}Xe$	(8.20)**18.2-19.6**(149)	(4.13)**9.60-15.1**(121)
$^{130}Te \rightarrow {}^{130}Xe$	(0.42)**0.93-1.00**(7.62)	(0.21)**0.49-0.76**(6.20)
$^{136}Xe \rightarrow {}^{136}Ba$	(0.61)**1.37-1.47**(11.7)	(0.32)**0.73-1.14**(9.57)

Effect on the predicted half-life

Here $g_A = 1.00$



Conclusions

- The short-range component of the matrix element enhances the total NME
  - The effect can be very notable
  - Possibly shorter half-life estimates
- IBM-2 and NSM behave similarly, pnQRPA differs from those

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Thank you!