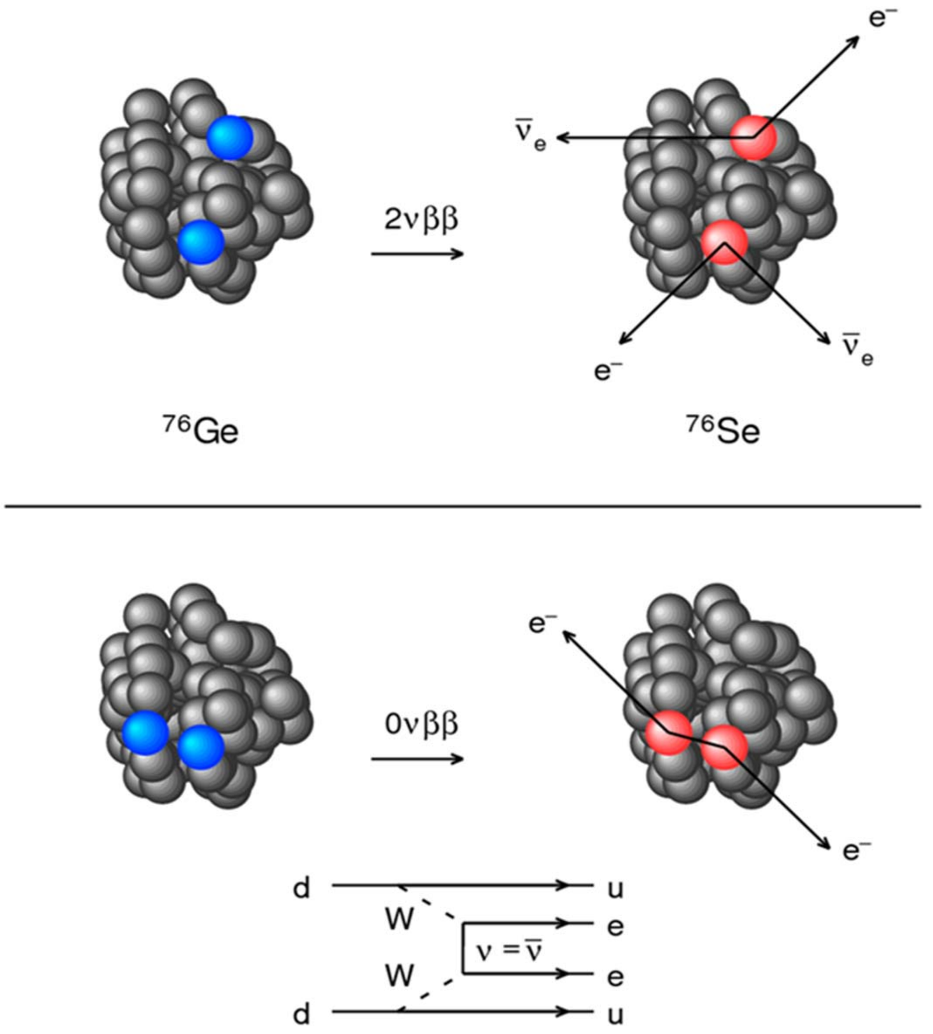
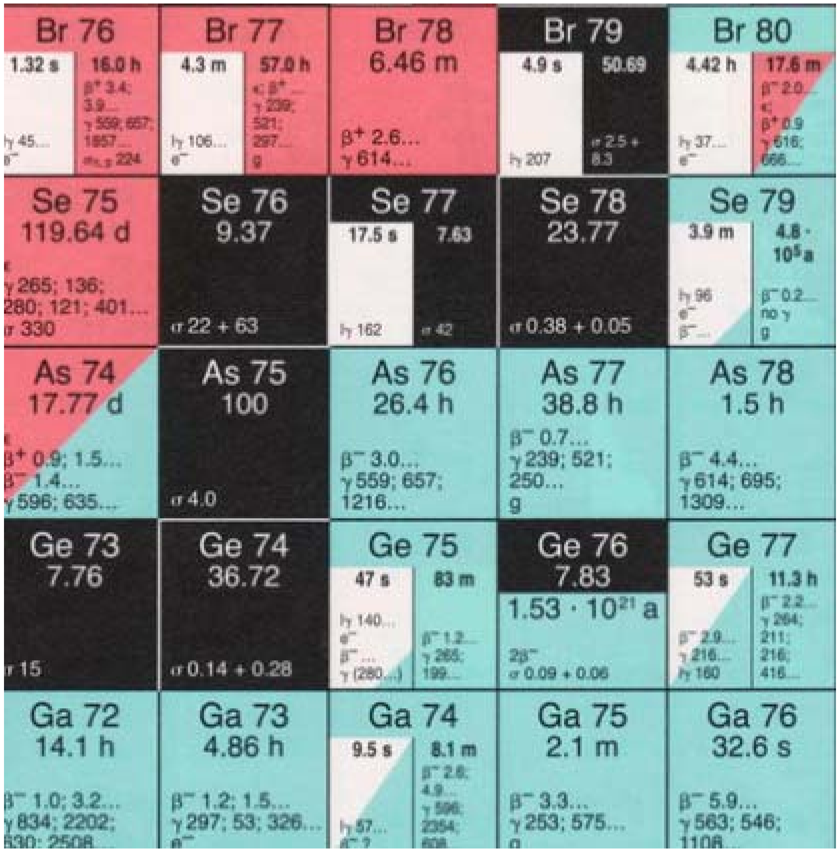
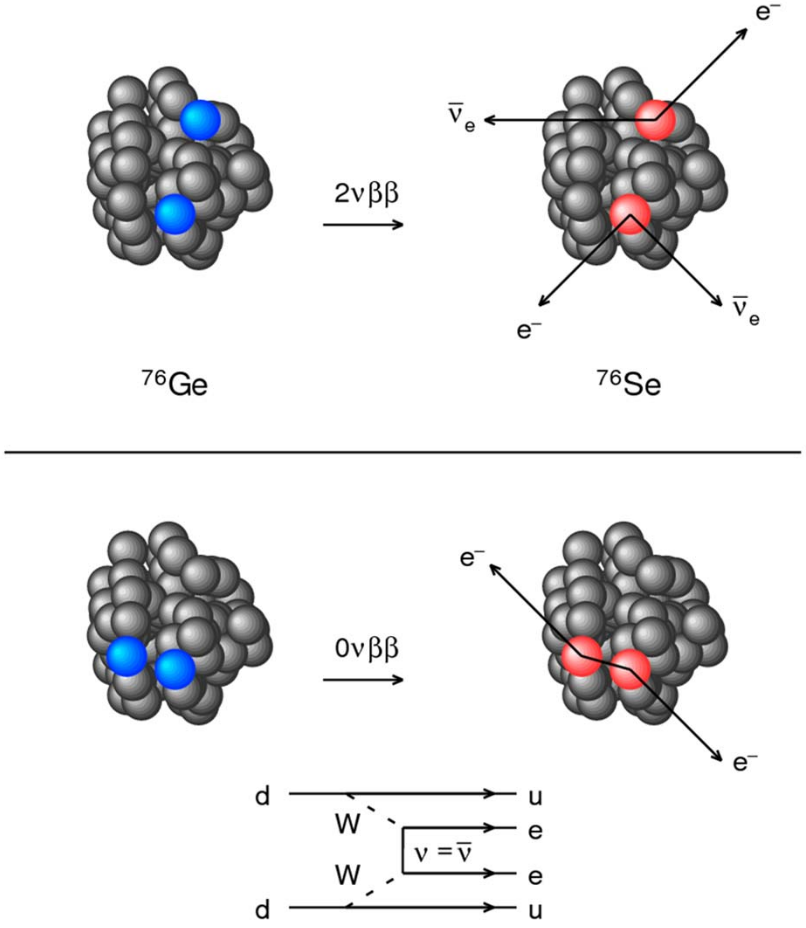
Nuclear Matrix Elements for Double Beta Decay
BAB, Mihai Horoi and Dong-Liang Fang





Br 76 1.32 s 16.0 h β^+ 3.4; 3.9... γ 559; 657; 1857... $I\gamma$ 45... e^- $\sigma_{n,\alpha}$ 224	Br 77 4.3 m 57.0 h ϵ; β^+... γ 239; 521; 297... $I\gamma$ 106... e^- g	Br 78 6.46 m β^+ 2.6... γ 614...	Br 79 4.9 s 50.69 $I\gamma$ 207 σ 2.5 + 8.3	Br 80 4.42 h 17.6 m β^- 2.0... ϵ β^+ 0.9 γ 616; 666... $I\gamma$ 37... e^-
Se 75 119.64 d ϵ γ 265; 136; 280; 121; 401... σ 330	Se 76 9.37 σ 22 + 63	Se 77 17.5 s 7.63 $I\gamma$ 162 σ 42	Se 78 23.77 σ 0.38 + 0.05	Se 79 3.9 m $4.8 \cdot 10^5$ a $I\gamma$ 96 e^- β^-... β^- 0.2... no γ g
As 74 17.77 d ϵ β^+ 0.9; 1.5... β^- 1.4... γ 596; 635...	As 75 100 σ 4.0	As 76 26.4 h β^- 3.0... γ 559; 657; 1216...	As 77 38.8 h β^- 0.7... γ 239; 521; 250... g	As 78 1.5 h β^- 4.4... γ 614; 695; 1309...
Ge 73 7.76 σ 15	Ge 74 36.72 σ 0.14 + 0.28	Ge 75 47 s 83 m $I\gamma$ 140... e^- β^-... γ (280...) β^- 1.2... γ 265; 199...	Ge 76 7.83 $1.53 \cdot 10^{21}$ a $2\beta^-$ σ 0.09 + 0.06	Ge 77 53 s 11.3 h β^- 2.9... γ 216... $I\gamma$ 160 β^- 2.2... γ 264; 211; 216; 416...
Ga 72 14.1 h β^- 1.0; 3.2... γ 834; 2202; 630; 2508...	Ga 73 4.86 h β^- 1.2; 1.5... γ 297; 53; 326... e^-	Ga 74 9.5 s 8.1 m $I\gamma$ 57... β^- ? β^- 2.6; 4.9... γ 596; 2354; 608	Ga 75 2.1 m β^- 3.3... γ 253; 575... g	Ga 76 32.6 s β^- 5.9... γ 563; 546; 1108...



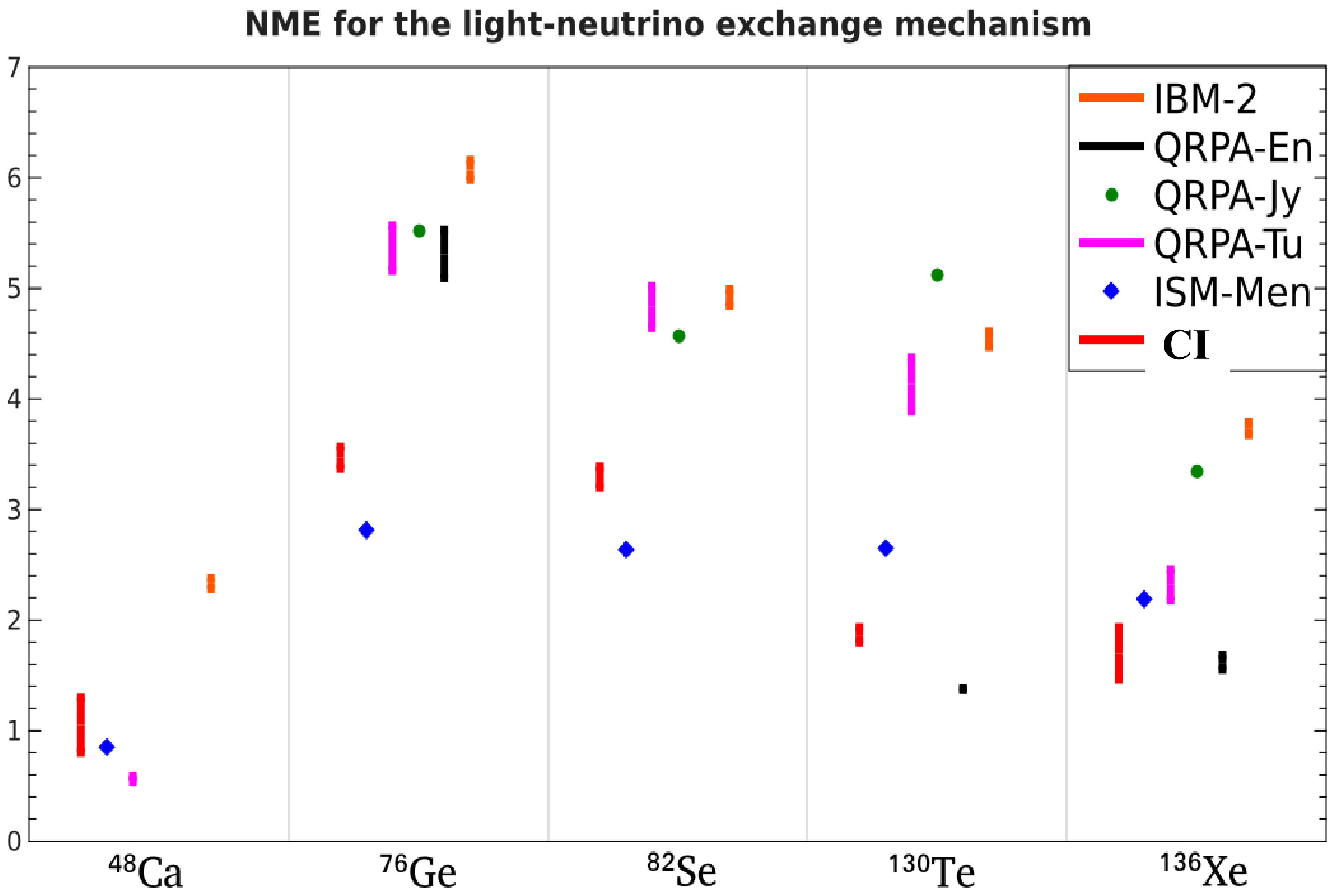
ν = light neutrino
N = heavy neutrino

neutrino mass properties

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G^{0\nu}\left(\left|M_{\nu}^{0\nu}\right|^{2}\left|\eta_{\nu}\right|^{2} + \left|M_{N}^{0\nu}\right|^{2}\left|\eta_{N}\right|^{2}\right)$$

nuclear matrix elements
M=NME

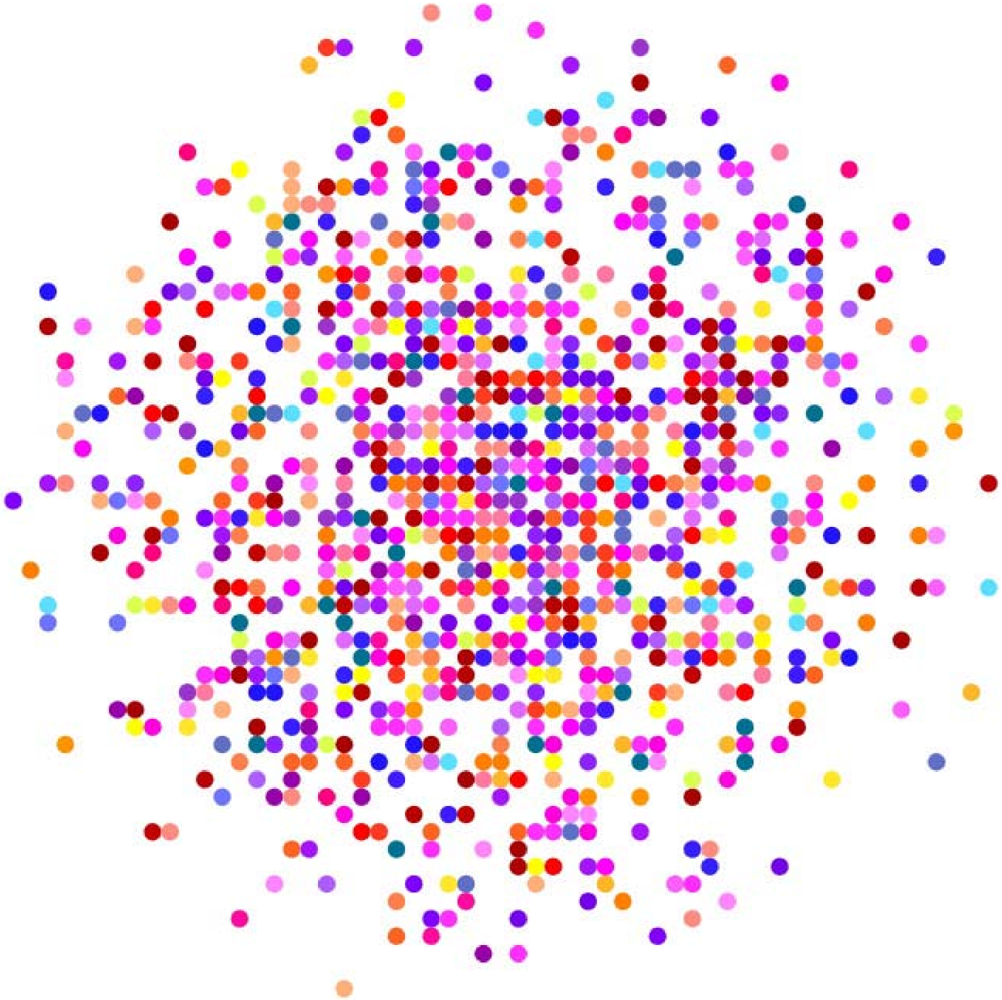
phase space - contains the weak
axial vector coupling factor $(g_A)^4$



IBA-2 J. Barea, J. Kotila, and F. Iachello, Phys. Rev. C **87**, 014315 (2013).
QRPA-En M. T. Mustonen and J. Engel, Phys. Rev. C **87**, 064302 (2013).
QRPA-Jy J. Suhonen, O. Civitarese, Phys. NPA **847** 207–232 (2010).
QRPA-Tu A. Faessler, M. Gonzalez, S. Kovalenko, and F. Simkovic, arXiv:**1408.6077**
ISM-Men J. Menéndez, A. Poves, E. Caurier, F. Nowacki, NPA **818** 139–151 (2009).
SM M. Horoi et. al. PRC **88**, 064312 (2013), PRC **89**, 045502 (2014), PRC **90**, PRC **89**, 054304 (2014), in preparation, PRL **110**, 222502 (2013).

NSCL

What are the Nuclear Matrix Elements for the ββ Decay of ^{76}Ge?



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Results and conclusions

1) All of the current results are incomplete in some respect

2) Hamiltonians in a model space that reproduce the low-lying spectra for A=76 are a necessary starting point

3) But this is not enough for double-beta

4) The most important two-body operators are:

$$M_{GT} = < f \mid O_{GT} \mid i > \text{ where}$$

$$O_{GT} \approx \tau_{1-}\tau_{2-}\ (\sigma_1 \cdot \sigma_2)\ f(r)$$

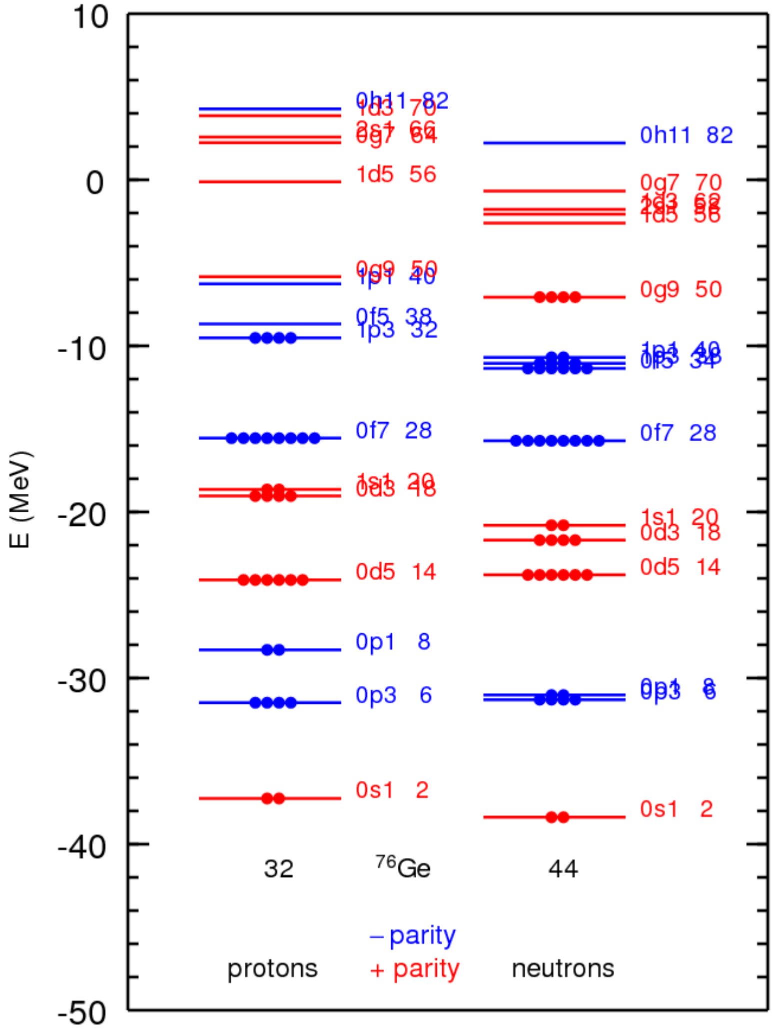
$$f(r) = 1 \text{ for } 2\nu$$

$$f(r) = a/r \text{ for light } 0\nu$$

$$f(r) = b\,\delta(r) \text{ for heavy } 0\nu$$

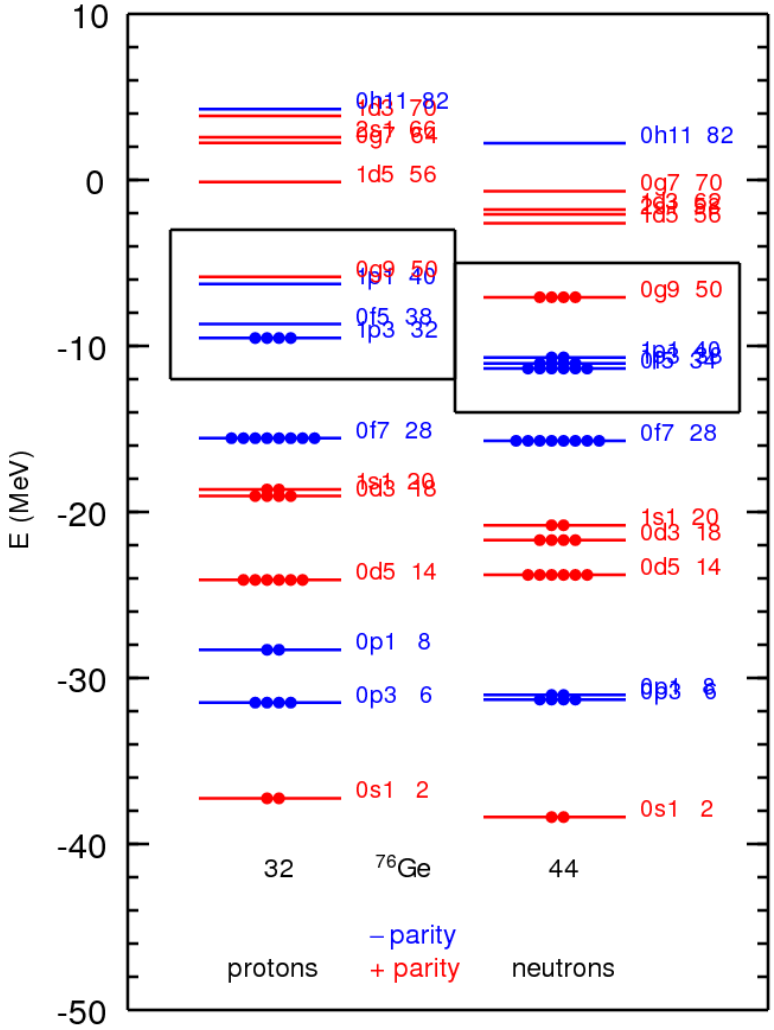
all have a different type of renormalization

model space



Alex Brown, INT, March 28, 2018

model space



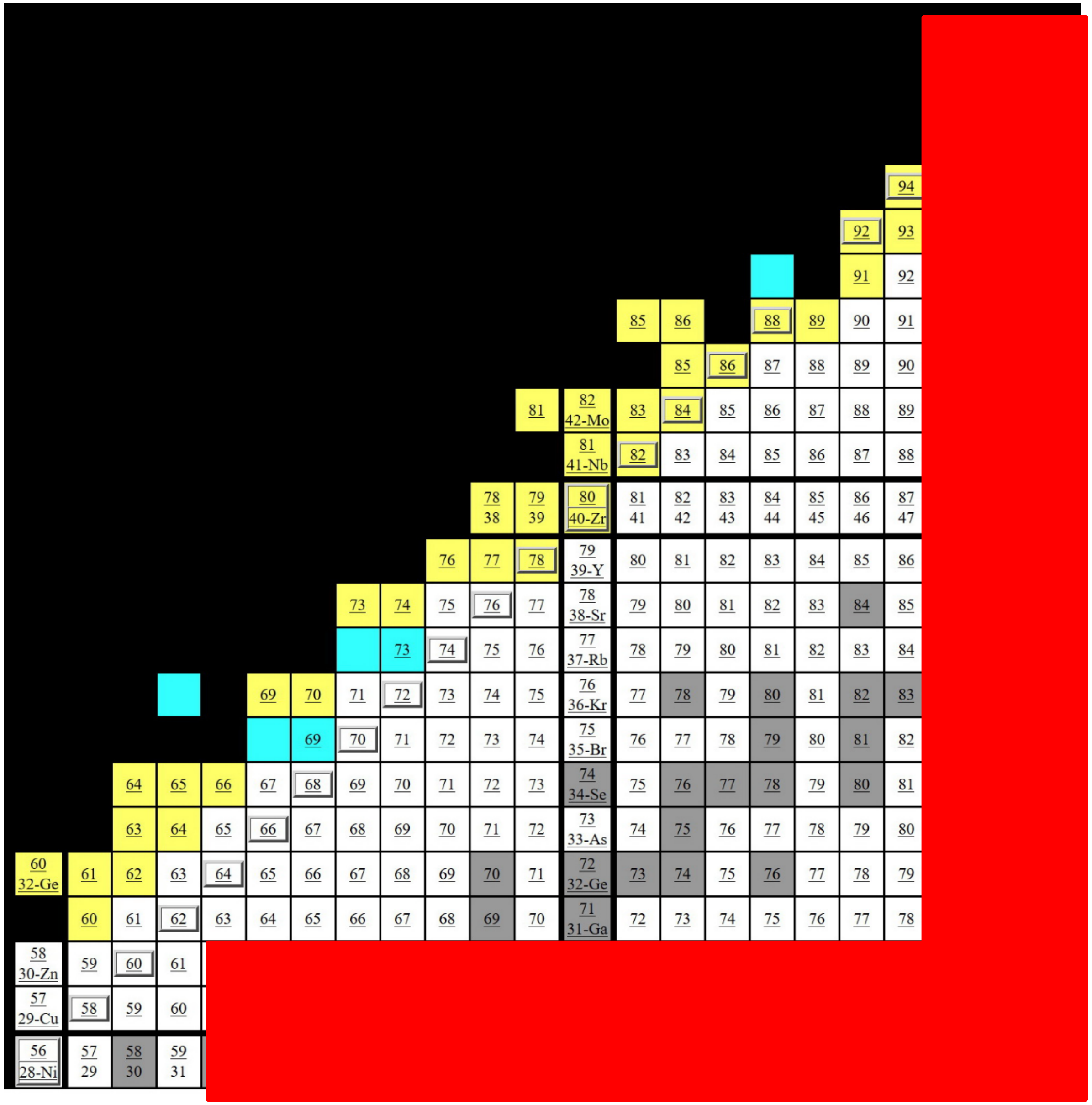
horizontal truncation

configuration interaction (CI) method can include the complete set of configurations for jj44

jj44 means protons and neutrons in the four orbitals $0f_{5/2}$, $1p_{3/2}$, $1p_{1/2}$ and $0g_{9/2}$

1,358,882,246 m-states for ^{76}Se

IBM also evaluated in jj44 but truncated to a s-d boson space



^{100}Sn

^{78}Ni

^{56}Ni

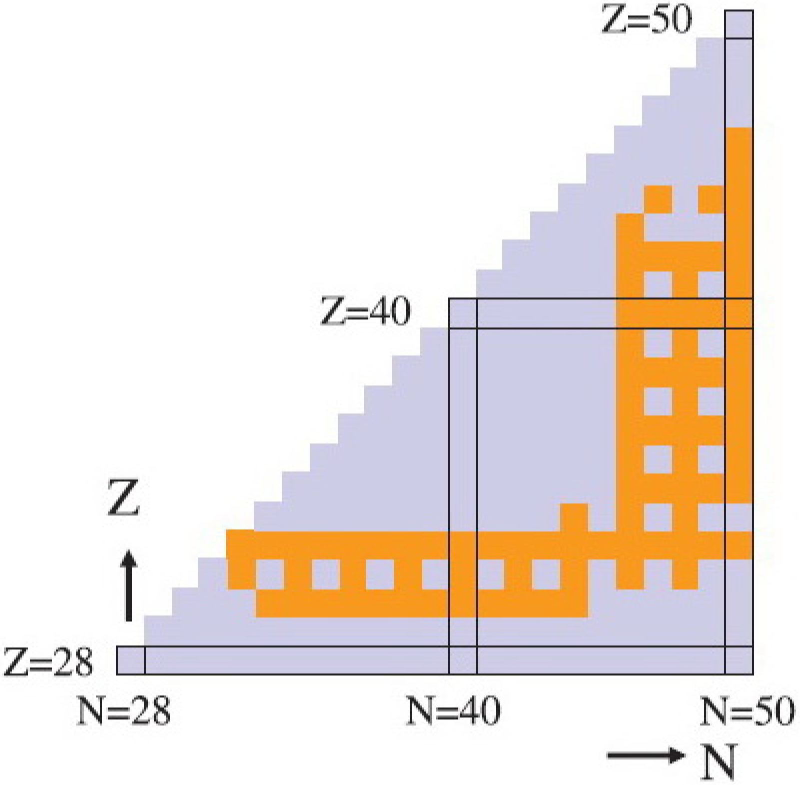
jj44b (2005, unpublished)
jj44 = good isospin

133 TBME + 4 SPE
starting with Bonn-C
550 data
30 SVD
240 keV rms

PHYSICAL REVIEW C **80**, 064323 (2009)

New effective interaction for f_5pg_9-shell nuclei

M. Honma,[1] T. Otsuka,[2,3,4] T. Mizusaki,[5] and M. Hjorth-Jensen[6]



JUN45
jj44 = good isospin

133 TBME + 4 SPE
starting with Bonn-C
400 data
45 SVD
185 keV rms

J = from Hjorth-Jensen
U = trial code
N = version number

PHYSICAL REVIEW C **95**, 014327 (2017)

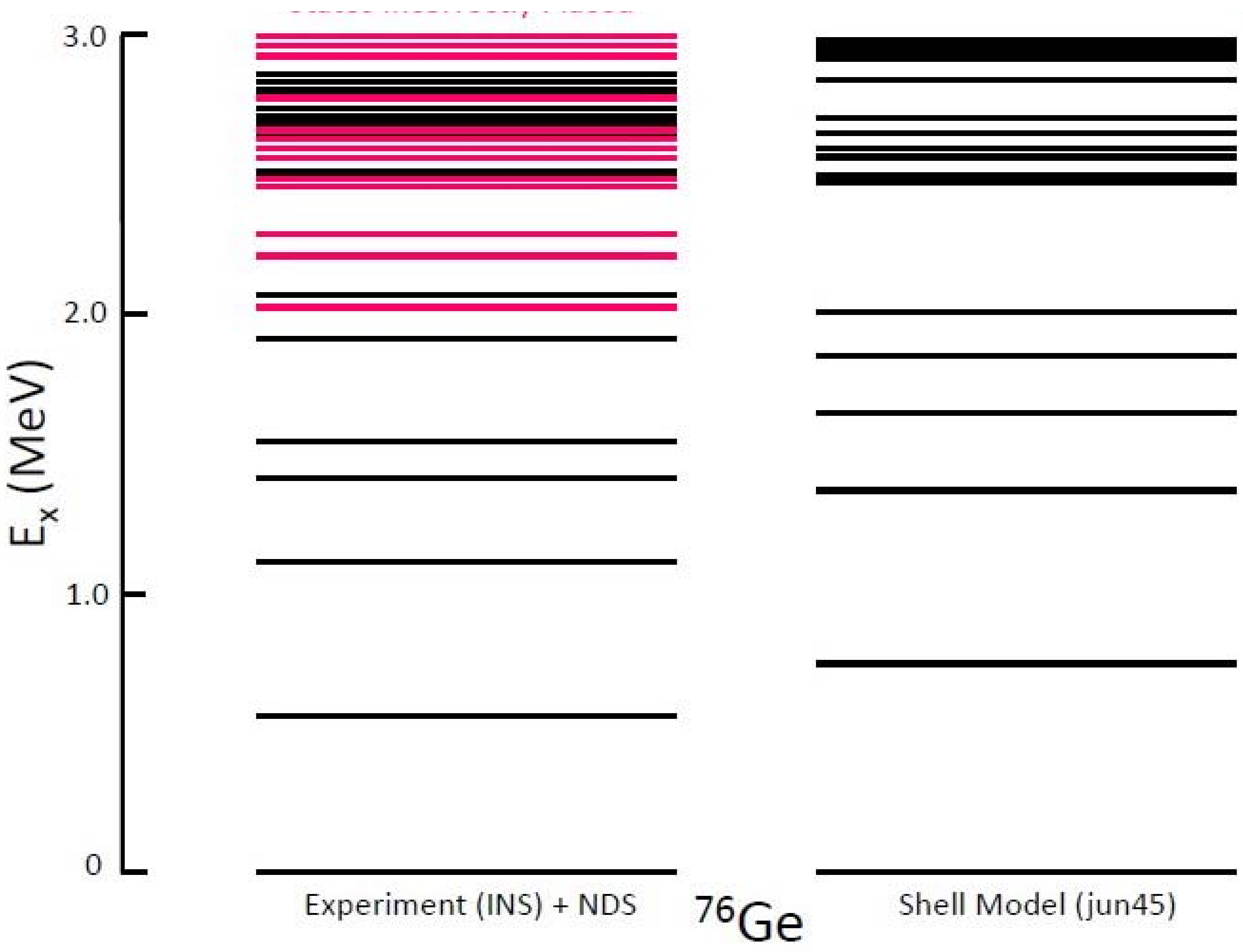
Nuclear structure of ^{76}Ge from inelastic neutron scattering measurements and shell model calculations

S. Mukhopadhyay,[1,2,*] B. P. Crider,[1] B. A. Brown,[3,4] S. F. Ashley,[1,2] A. Chakraborty,[1,2,†] A. Kumar,[1,2] M. T. McEllistrem,[1] E. E. Peters,[2] F. M. Prados-Estévez,[1,2] and S. W. Yates[1,2]

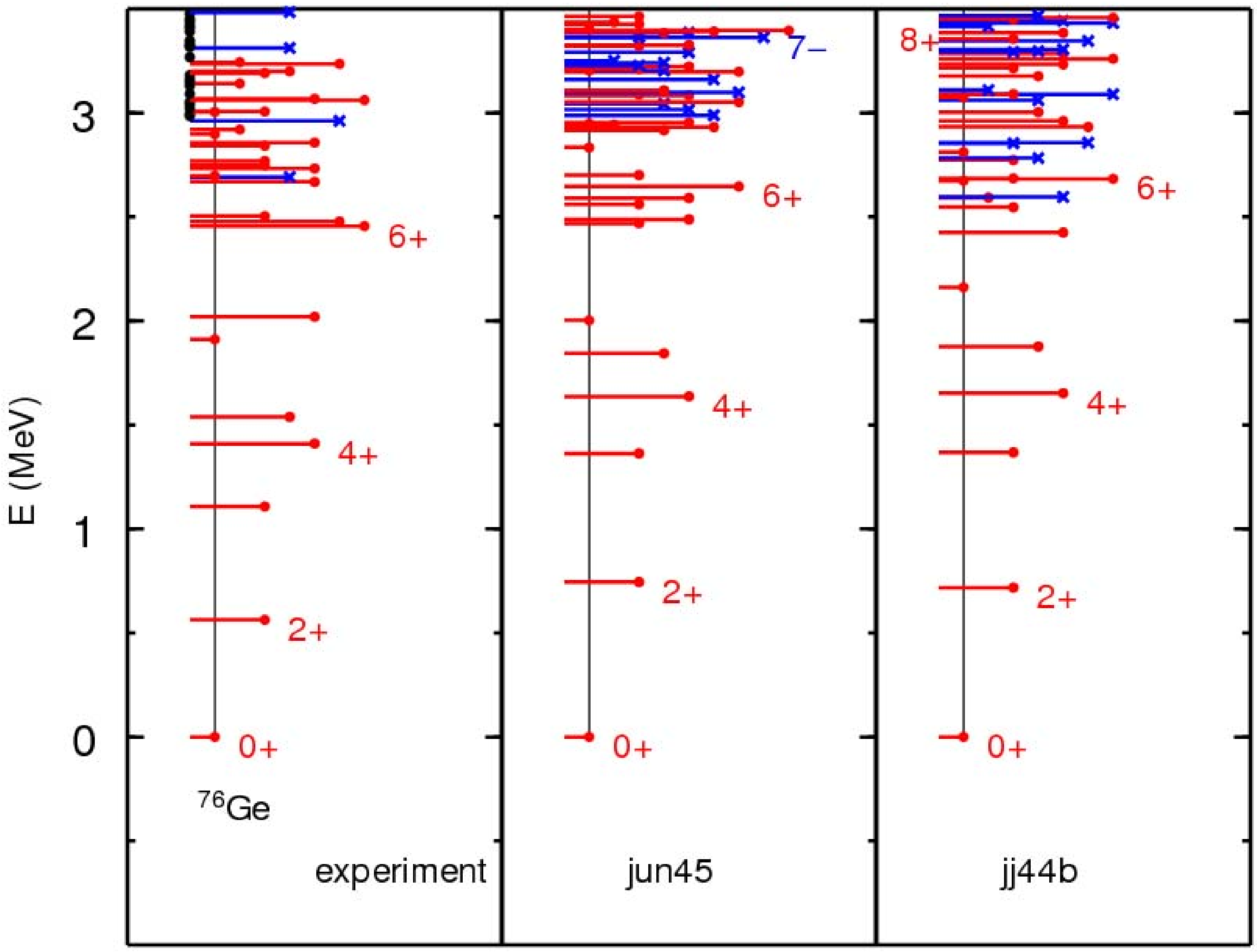
"complete" spectrum up to about 3.5 MeV. Not only many new levels but also removal of many incorrect levels

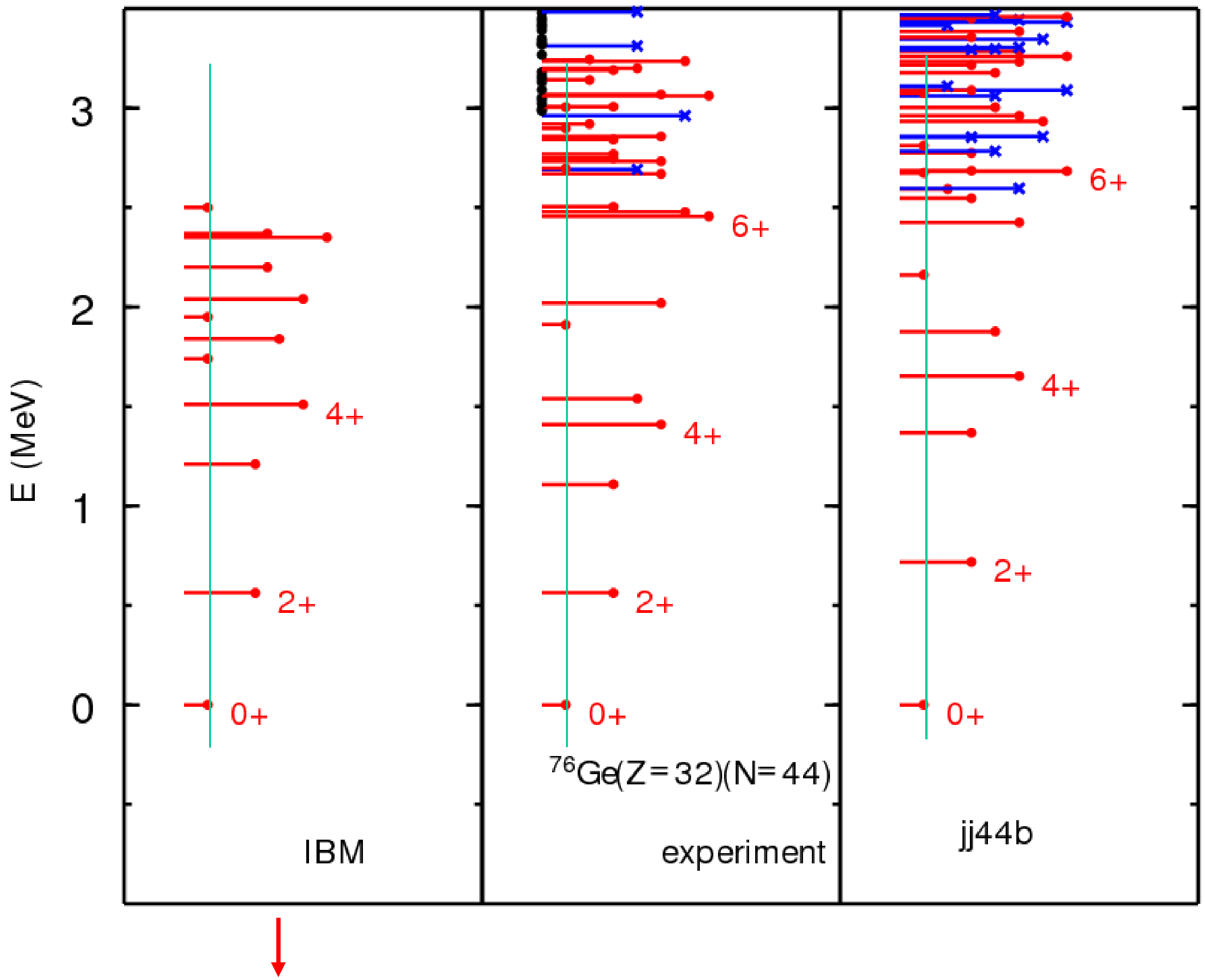
NSCL


3.0
2.0
1.0
0
E_x (MeV)
Data
Theory
Experiment (INS) + NDS
^{76}Ge
Shell Model (jun45)



States incorrectly placed

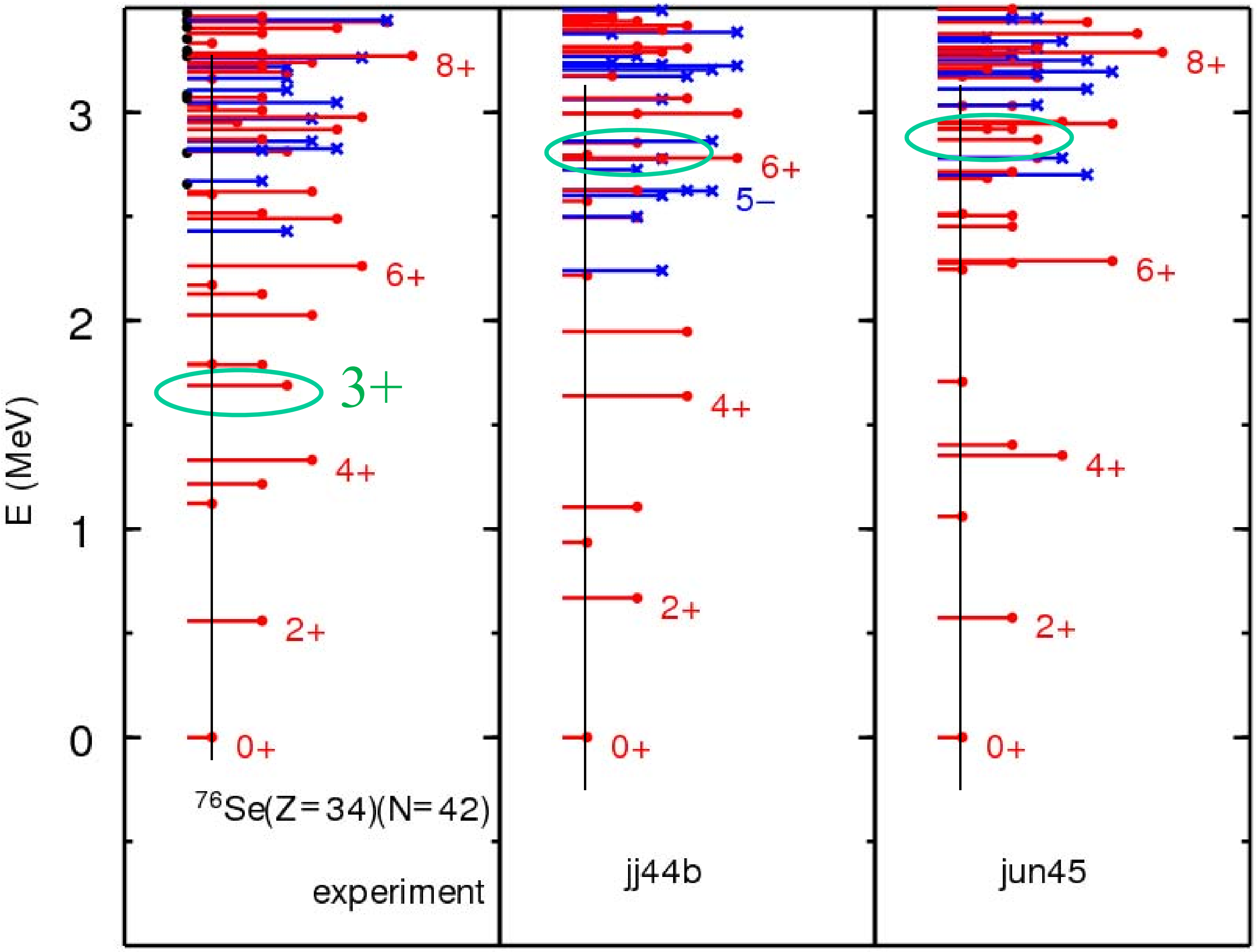

E (MeV)
3
2
1
0
6+
4+
2+
0+
^{76}Ge
experiment
7−
6+
4+
2+
0+
jun45
8+
6+
4+
2+
0+
jj44b



about 45 states
up to 3.5 MeV

IBM parameters for ^{76}Ge: Duval et al., PLB 134B, 297 (1983)

NSCL


3
2
1
0
E (MeV)
8+
6+
3+
4+
2+
0+
^{76}Se(Z=34)(N=42)
experiment
6+
5−
4+
2+
0+
jj44b
8+
6+
4+
2+
0+
jun45

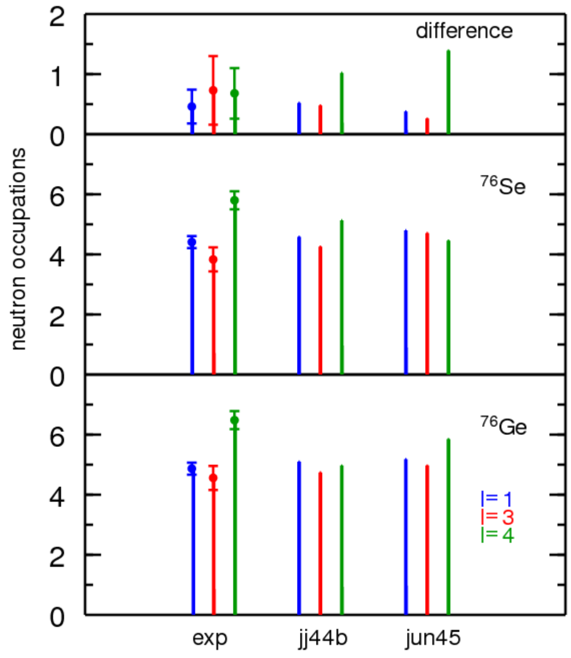
one nucleon transfer – orbital occupations

PRL **100,** 112501 (2008) PHYSICAL REVIEW LETTERS week ending 21 MARCH 2008

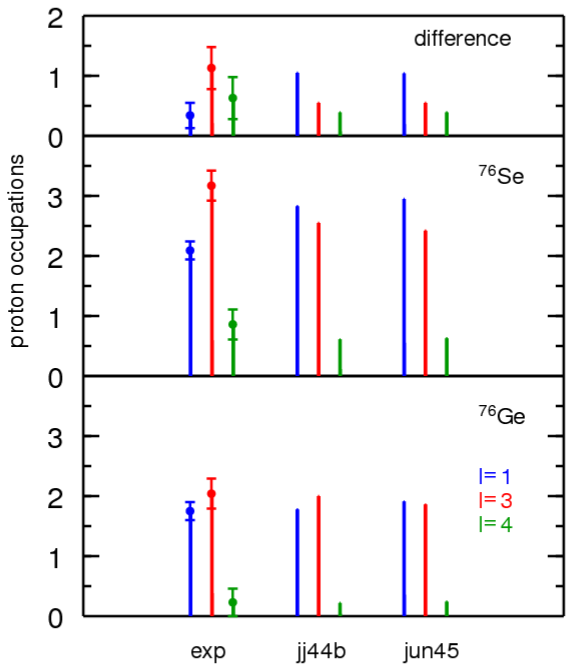
Nuclear Structure Relevant to Neutrinoless Double β Decay: ^{76}Ge and ^{76}Se

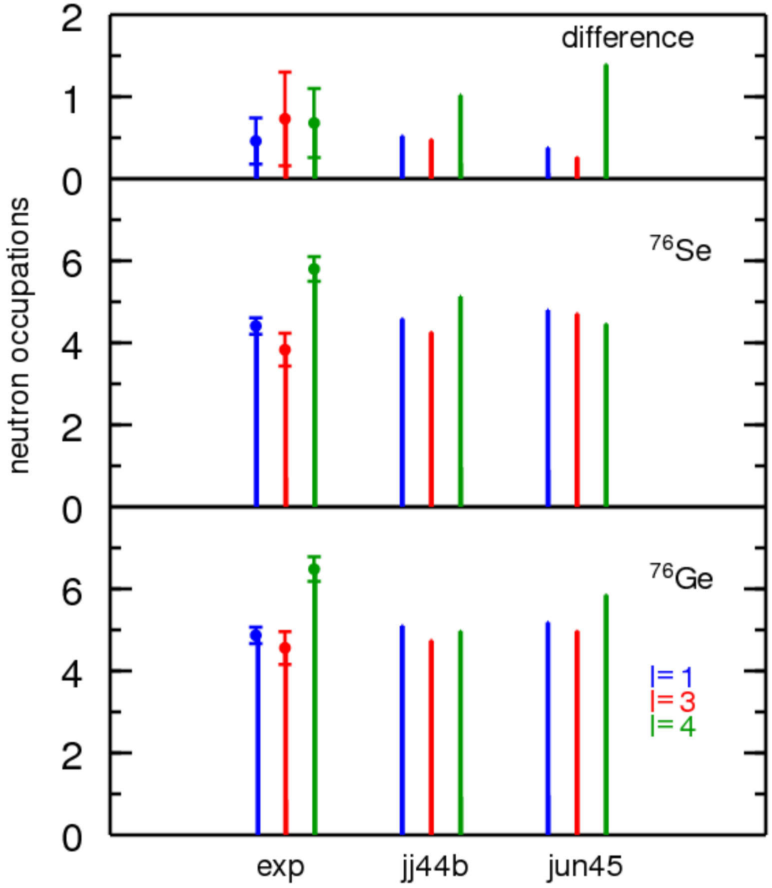
J. P. Schiffer,[1,*] S. J. Freeman,[2] J. A. Clark,[3] C. Deibel,[3] C. R. Fitzpatrick,[2] S. Gros,[1] A. Heinz,[3] D. Hirata,[4,5] C. L. Jiang,[1] B. P. Kay,[2] A. Parikh,[3] P. D. Parker,[3] K. E. Rehm,[1] A. C. C. Villari,[4] V. Werner,[3] and C. Wrede[3]

neutron

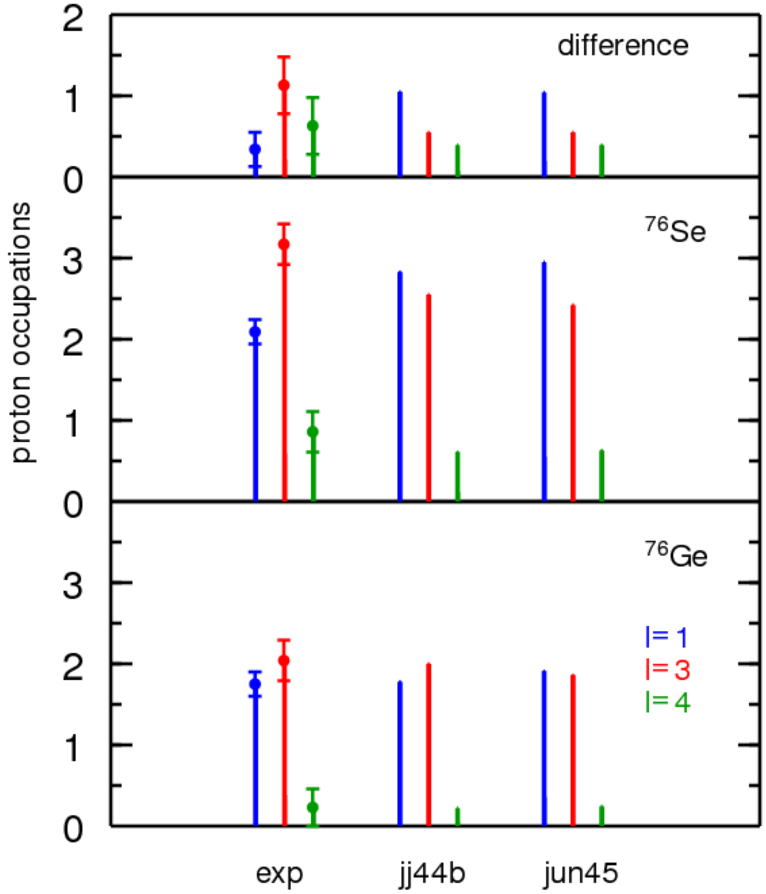


proton

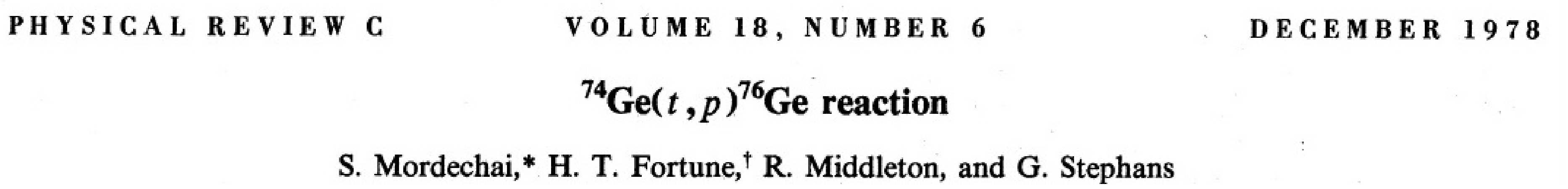




neutron



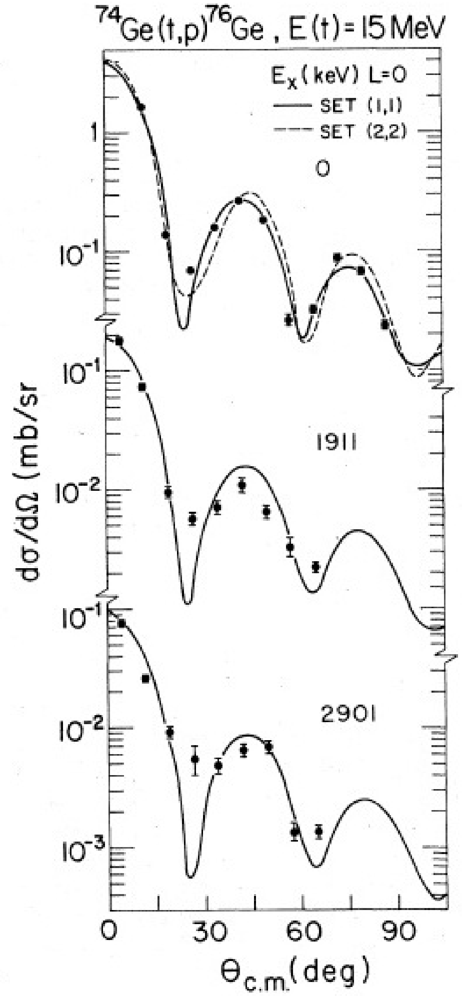
proton



PHYSICAL REVIEW C VOLUME 18, NUMBER 6 DECEMBER 1978

^{74}Ge(t,p)^{76}Ge reaction

S. Mordechai,* H. T. Fortune,† R. Middleton, and G. Stephans



Absolute calculation of two nucleon transfer?

Lots of experimental data in this region

Is the cross section obtained with jj44 a factor of two smaller than experiment?

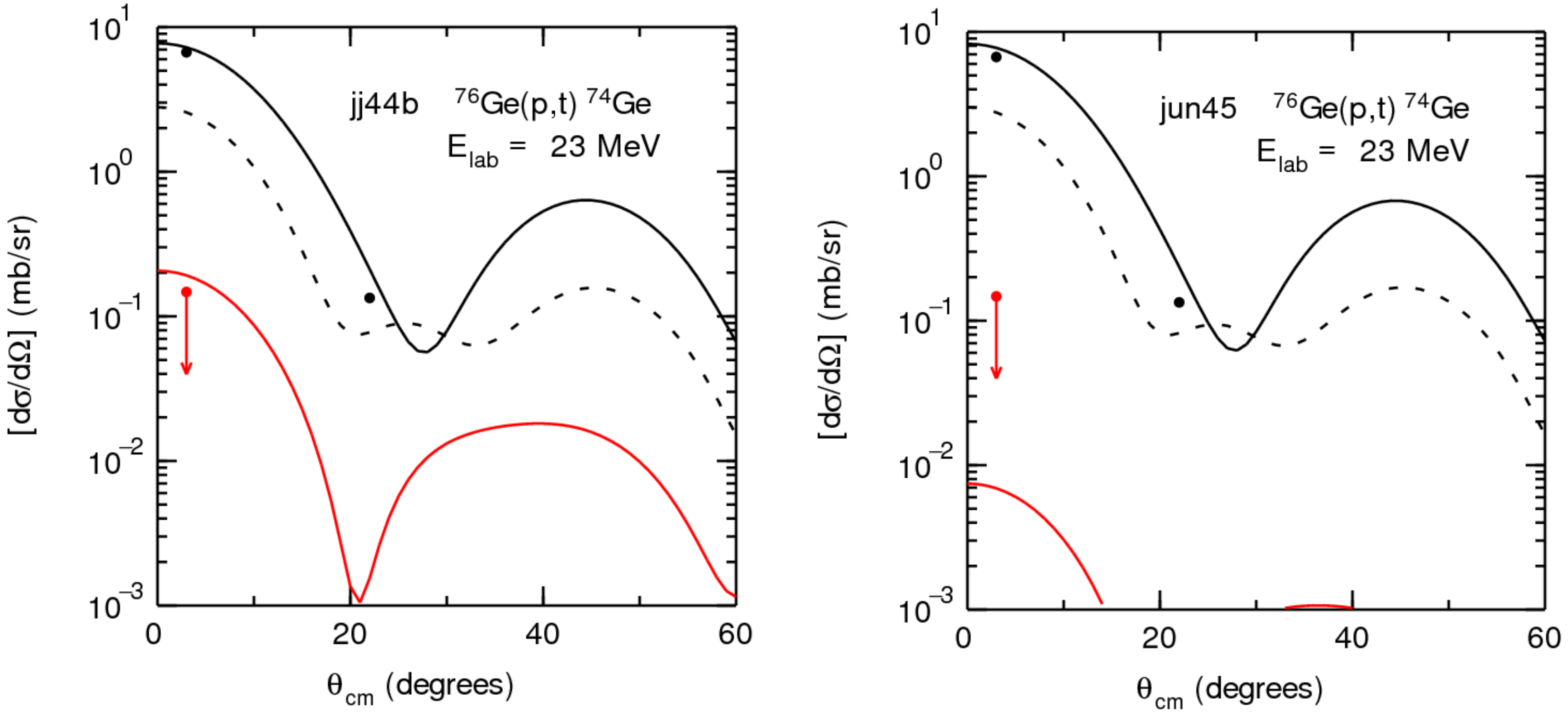
A collaboration with reaction theory is needed to answer this.

two nucleon transfer

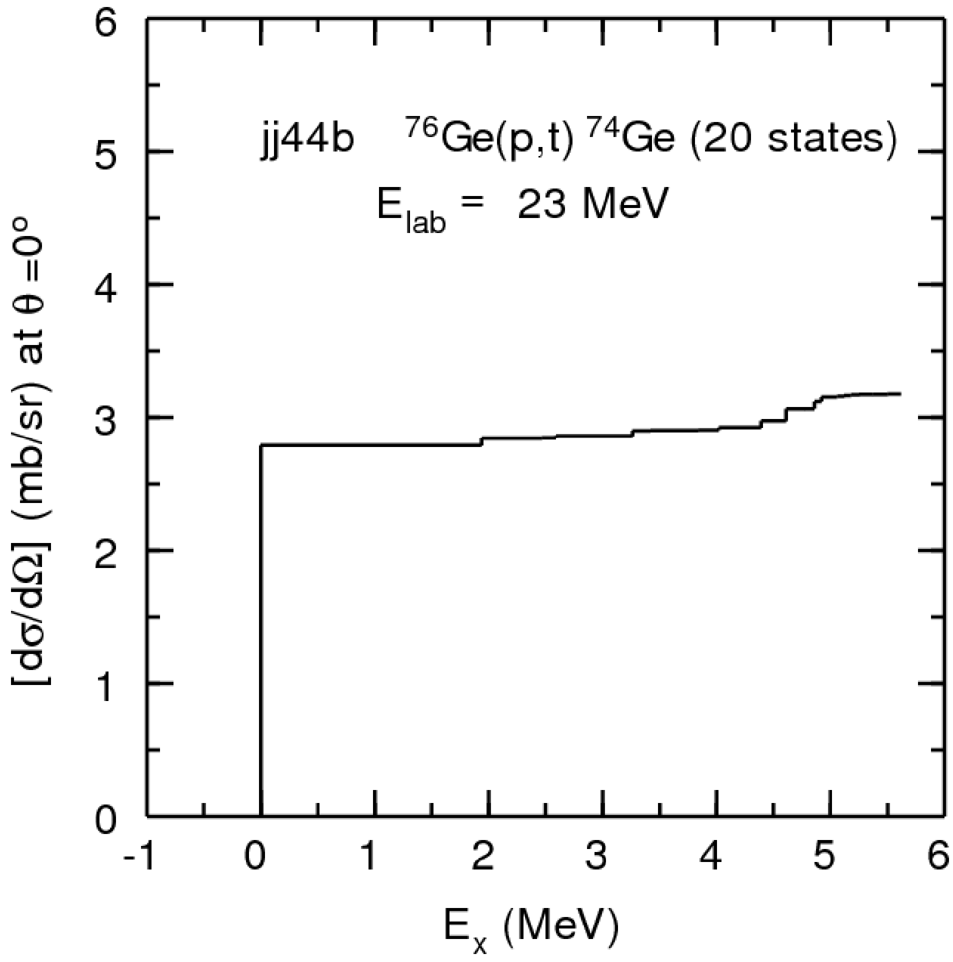
PHYSICAL REVIEW C **75**, 051301(R) (2007)

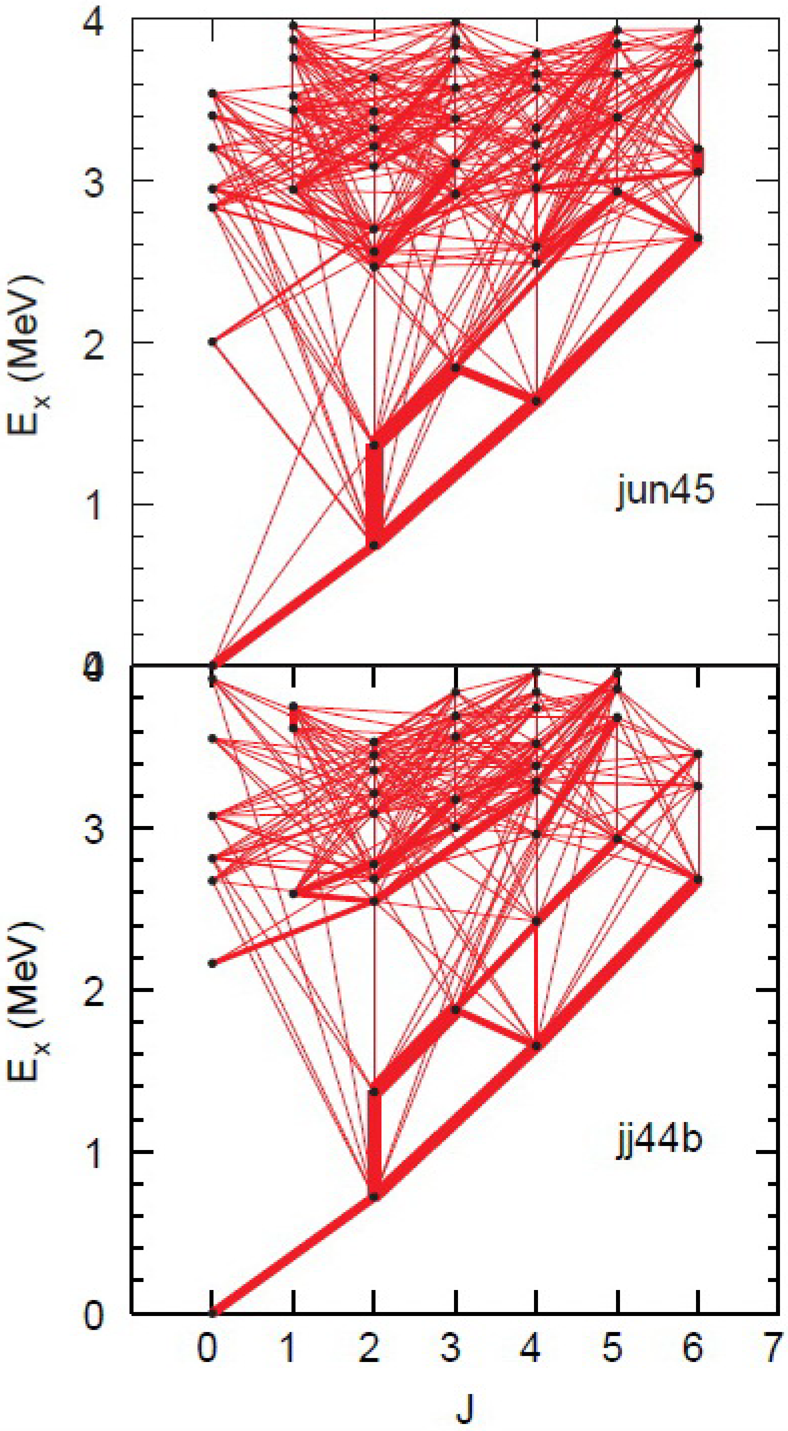
Pair correlations in nuclei involved in neutrinoless double β decay: ^{76}Ge and ^{76}Se

S. J. Freeman,[1] J. P. Schiffer,[2,*] A. C. C. Villari,[3] J. A. Clark,[4] C. Deibel,[4] S. Gros,[2] A. Heinz,[4] D. Hirata,[3,5] C. L. Jiang,[2] B. P. Kay,[1] A. Parikh,[4] P. D. Parker,[4] J. Qian,[4] K. E. Rehm,[2] X. D. Tang,[2] V. Werner,[4] and C. Wrede[4]



Alex Brown, INT, March 28, 2018

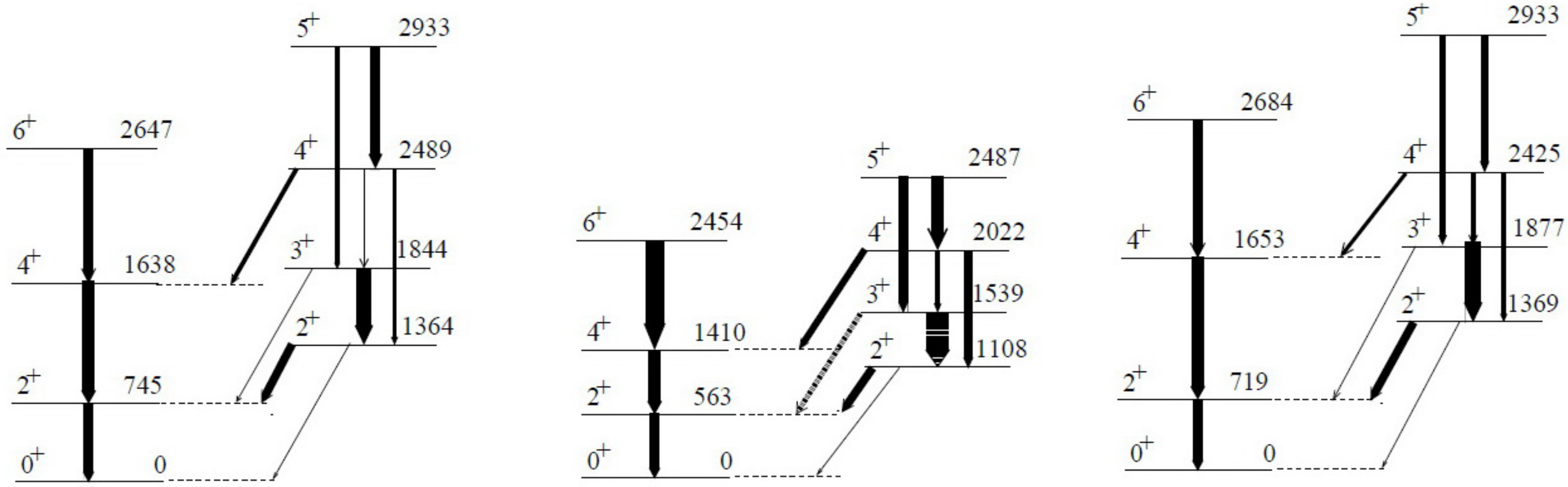

jj44b ^{76}Ge(p,t) ^{74}Ge (20 states)
E_{lab} = 23 MeV
[dσ/dΩ] (mb/sr) at θ =0°
E_x (MeV)
0
1
2
3
4
5
6
-1
0
1
2
3
4
5
6



^{76}Ge E2 map

Width of red line is proportional to the B(E2)

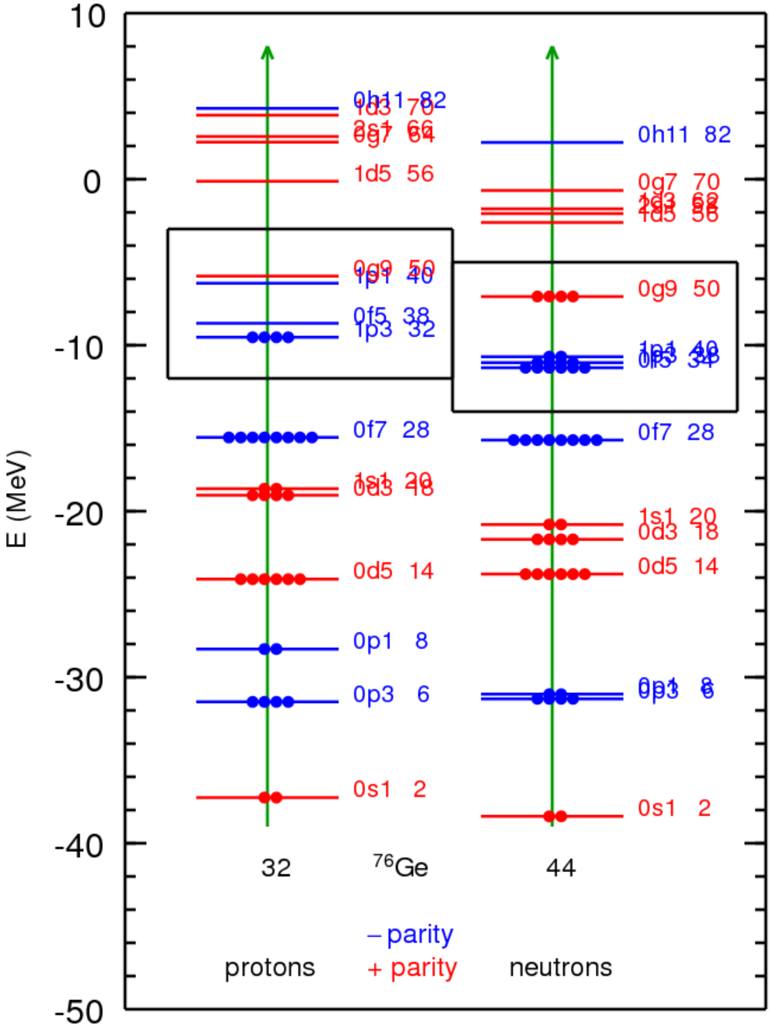
^{76}Ge



(a) jun45 (b) Experiment (c) jj44b

FIG. 7. Partial level scheme of ^{76}Ge from shell model calculations [(a) and (c)] and experiment (b) . The thicknesses of the solid arrows are proportional to the B(E2)s. Dashed arrows indicate that the level lifetime was not determined and the B(E2)s are only approximate.

model space



vertical expansion

particle-hole configurations for all orbitals

1) QRPA in

a) jj44 = $(0f_{5/2}, 1p_{3/2}, 1p_{1/2}, 0g_{9/2})$
b) fpg = $0f_{7/2}, (0f_{5/2}, 1p_{3/2}, 1p_{1/2}, 0g_{9/2})\ 0g_{7/2}$
c) 21 orbits

2) Many-body perturbation theory (MBPT) to include 2 particle-2 hole (2p-2h) excitations to high excitation.

3) Δ particle admixtures and mesonic exchange currents (MEC)

NSCL

Operator and TBME for 0ν double beta

$$M_{\alpha}^{0\nu} = \sum_{\kappa} \sum_{1234} \langle 13 | \mathcal{O}_{\alpha} | 24 \rangle \langle f | \hat{c}_3^{\dagger} \hat{c}_4 | \kappa \rangle \langle \kappa | \hat{c}_1^{\dagger} \hat{c}_2 | i \rangle \qquad \alpha = GT$$

$$\mathcal{O}_{GT} = \tau_{1-} \tau_{2-} \, (\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2) \, H_{GT}(r, E_{\kappa})$$

$$H_{\alpha}(r, E_{\kappa}) = \frac{2R}{\pi} \int_0^{\infty} \frac{f_{\alpha}(qr) h_{\alpha}(q^2) q \, dq}{q + E_{\kappa} - (E_i + E_f)/2}$$

Plus short range correlations (SRC)

$$f_{GT,F}(qr) = j_0(qr)$$

$$h_{GT}(q^2) = \left[1 - \frac{2}{3} \frac{q^2}{q^2 + m_{\pi}^2} + \frac{1}{3} \left(\frac{q^2}{q^2 + m_{\pi}^2} \right)^2 \right] + \frac{2}{3} \frac{g_M^2(q^2)}{g_A^2} \frac{q^2}{4m_p^2}$$

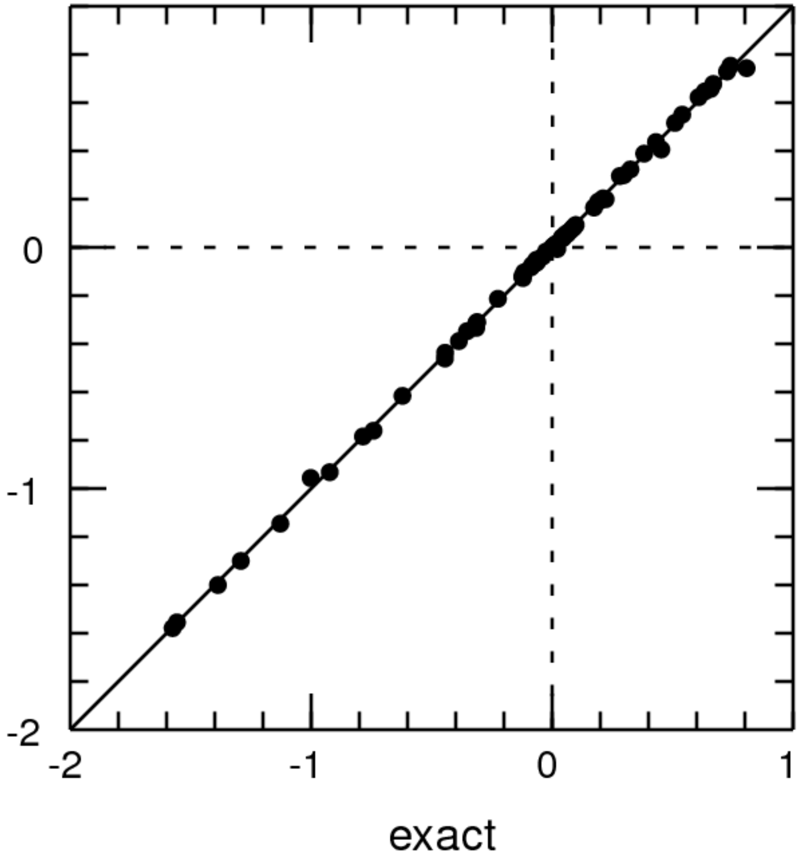
$$[E_{\kappa} - (E_i + E_f)/2] \rightarrow \langle E \rangle$$

$$\sum_{\kappa} \langle f | \hat{c}_3^{\dagger} \hat{c}_4 | \kappa \rangle \langle \kappa | \hat{c}_1^{\dagger} \hat{c}_2 | i \rangle = \langle f | \hat{c}_3^{\dagger} \hat{c}_4 \hat{c}_1^{\dagger} \hat{c}_2 | i \rangle$$

NSCL

$$M_{\alpha}^{0\nu} = \sum_{1234} \langle 13|\mathcal{O}_{\alpha}|24\rangle \; \langle f|\hat{c}_3^{\dagger}\hat{c}_4\hat{c}_1^{\dagger}\hat{c}_2|i\rangle$$

$$O_{GT} \approx \tau_{1-}\tau_{2-} \; (\sigma_1 \cdot \sigma_2) \; a/r$$



$$M^{2\nu} = M^{2\nu}_{GT} - \left(\frac{g_V}{g_A}\right)^2 M^{2\nu}_F$$

$$M^{0\nu} = M^{0\nu}_{GT} - \left(\frac{g_V}{g_A}\right)^2 M^{0\nu}_F + M^{0\nu}_T$$

Gamow-Teller Fermi tensor

$M^{2\nu}_F \approx 0$ due to isospin conservation. This was recently corrected in QRPA (2013) and IBM (2015) and this also reduced $M^{0\nu}_F$ in these models.

tensor term is small

Thus, based on an average of all recent models

we use $M = R_{GT} M_{GT}$ with

$$M^{(2\nu)} = M^{(2\nu)}_{GT}$$

$$M^{(0\nu\,\mathrm{light})} = 1.12(7)\, M^{(0\nu\,\mathrm{light})}_{GT}$$

$$M^{(0\nu\,\mathrm{heavy})} = 1.13(13)\, M^{(0\nu\,\mathrm{heavy})}_{GT}$$

GT operators

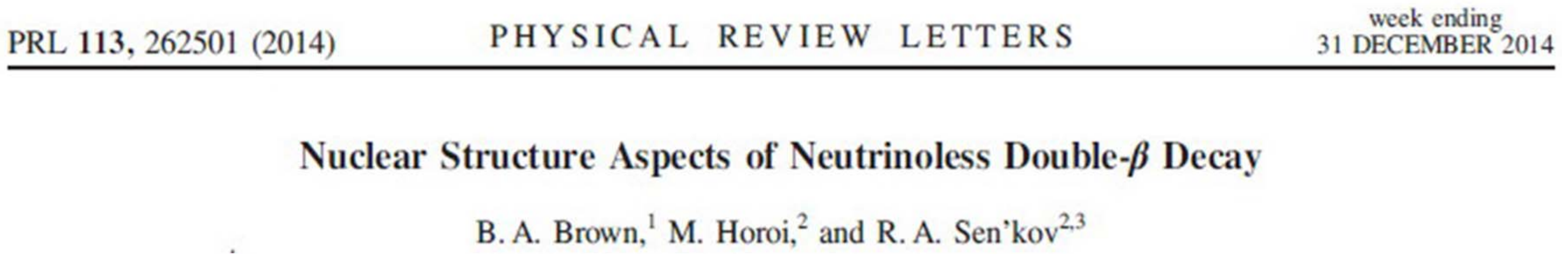
$M_{GT} = < f \mid O_{GT} \mid i >$ where

$$O_{GT} \approx \tau_{1-}\tau_{2-}\ (\sigma_1 \cdot \sigma_2)\ f(r)$$

$f(r) = 1$ for 2ν

$f(r) = a/r$ for light 0ν

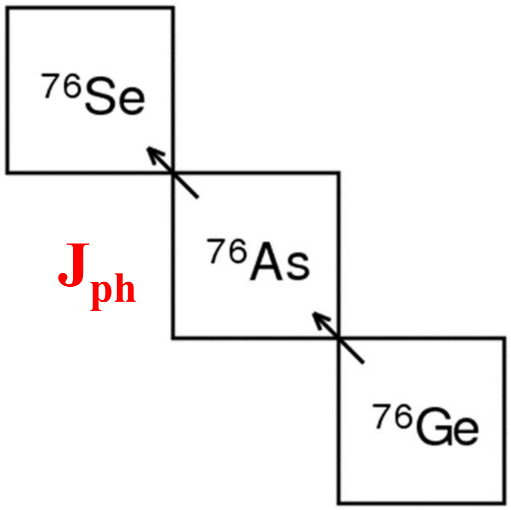
$f(r) = b\,\delta(r)$ for heavy 0ν



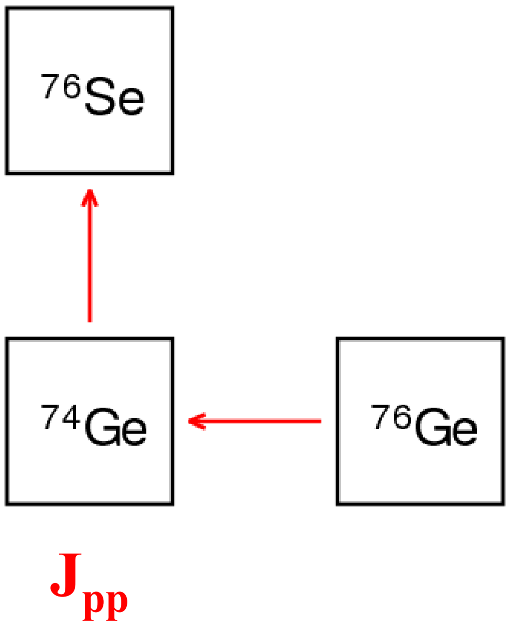
PRL 113, 262501 (2014) PHYSICAL REVIEW LETTERS week ending 31 DECEMBER 2014

Nuclear Structure Aspects of Neutrinoless Double-β Decay

B. A. Brown,[1] M. Horoi,[2] and R. A. Sen'kov[2,3]

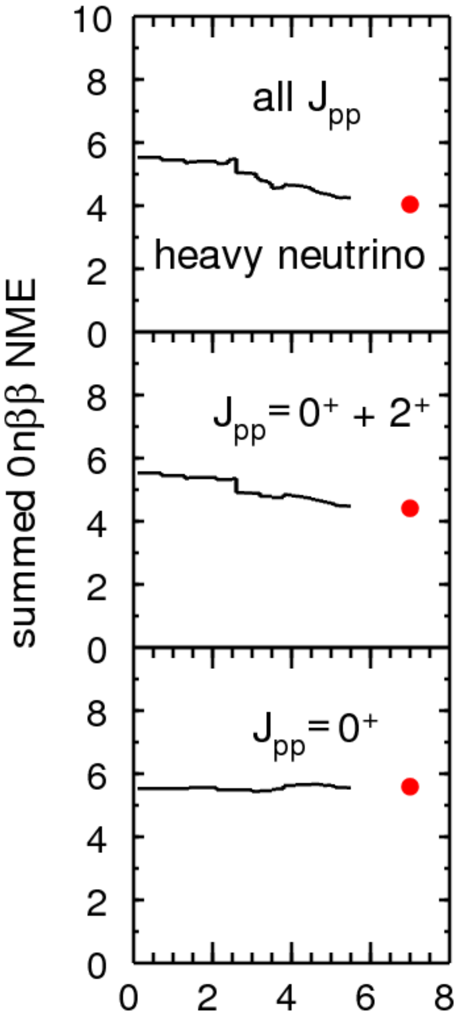


particle-hole

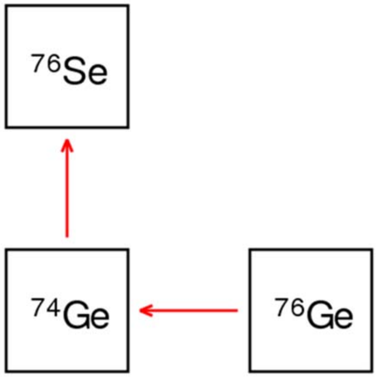


particle-particle

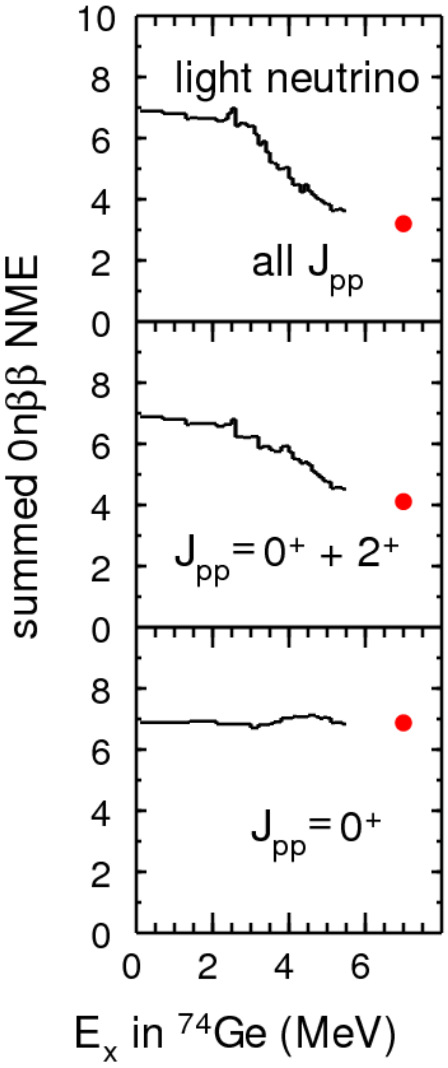
heavy 0νββ decay



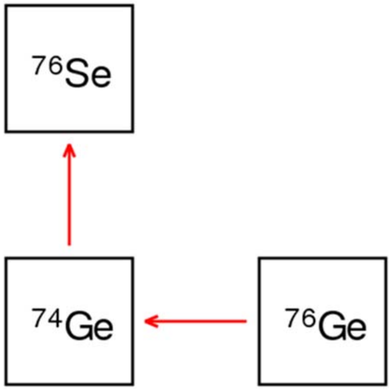
CI conclusion:
The $J_{pp}=0^+$ term is partly cancelled by $J_{pp}=2^+$



light 0νββ decay



CI conclusion:
The $J_{pp}=0^+$ term is reduced by a factor of two from higher J_{pp}.



particle-hole

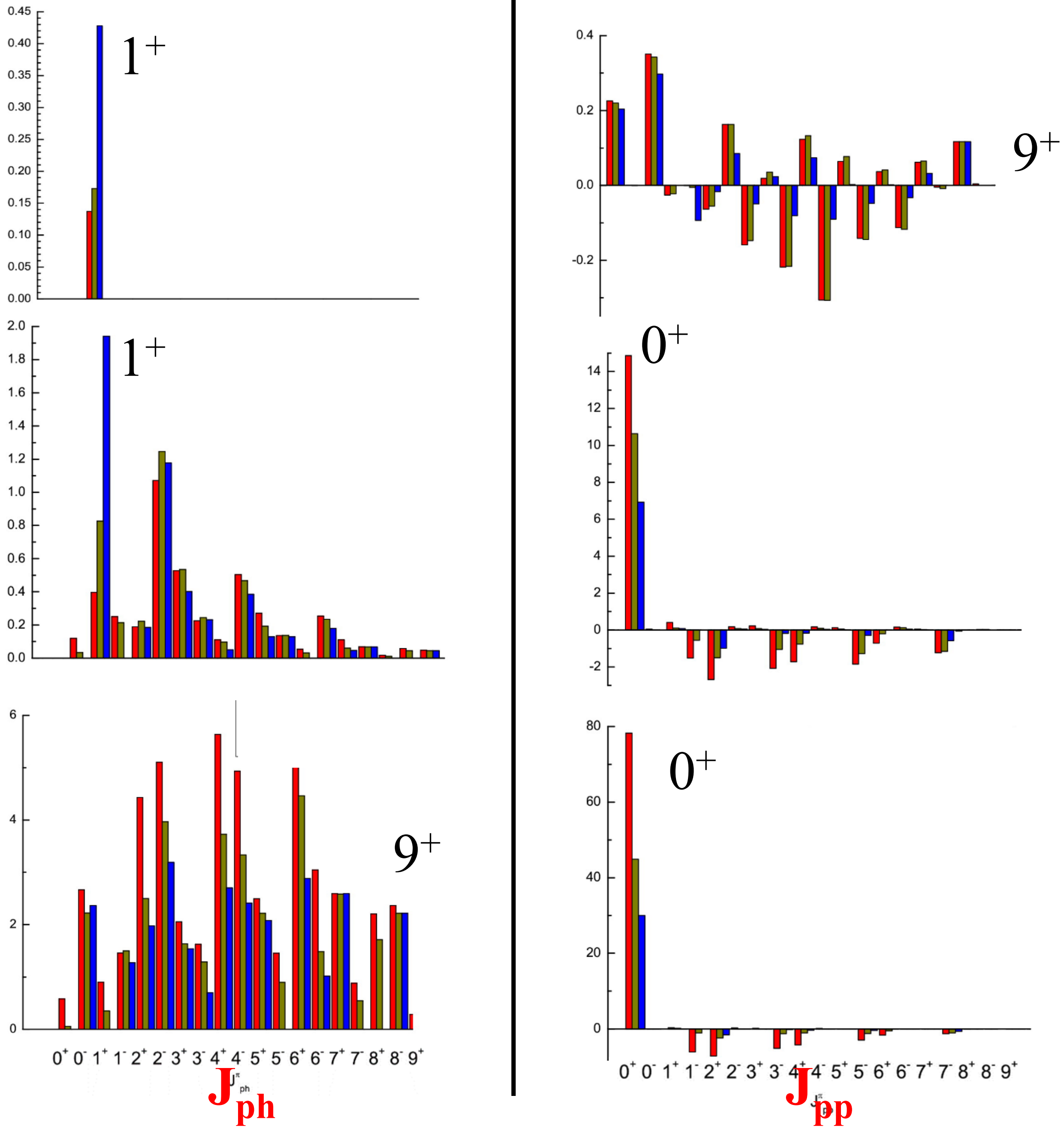
particle-particle

f(r)

2ν (1)

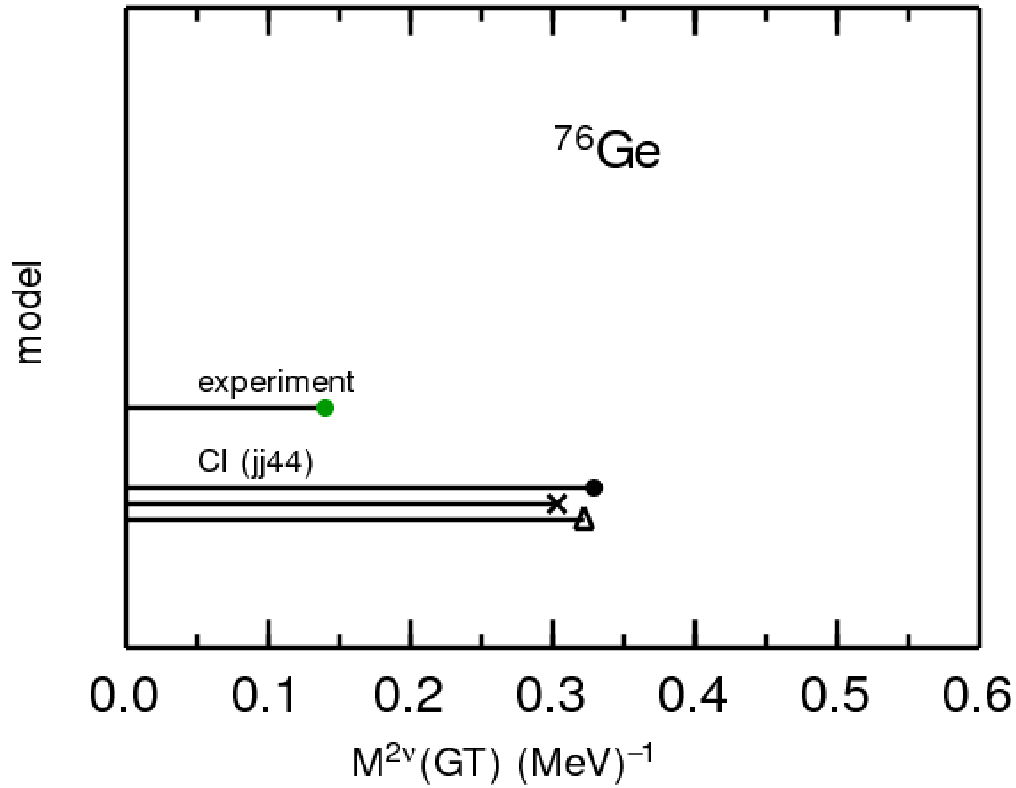
0ν light (1/r)

0ν heavy δ(r)



2νββ decay

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



Observation (old):
CI theory for 2ν decay
is a factor of 2.5 too large

We will write

$M = R_V\ M(CI)$ where $R_V = 0.4$

Where R_V is a correction factor that takes into account the "vertical expansion" of the model space (beyond jj44)

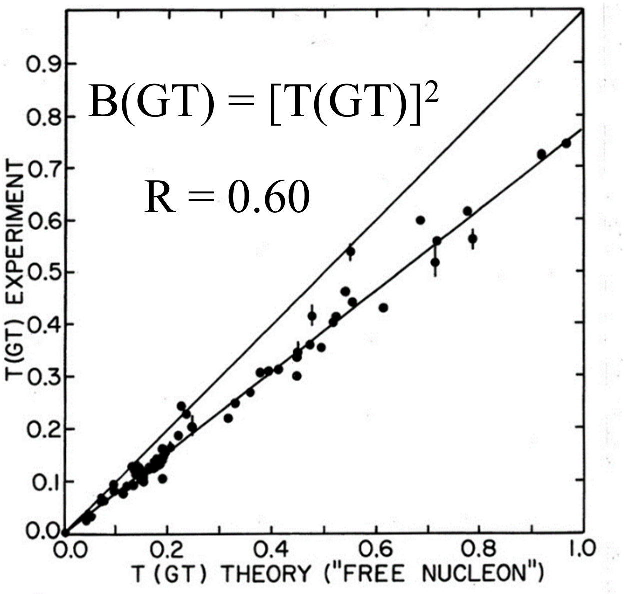
β decay

We have known for 30 years that the experimental B(GT) strengths observed in experiment are systematically smaller than that obtained in sd and pf shell-model calculations by a factor of R=0.5 to 0.6.

Compilations:

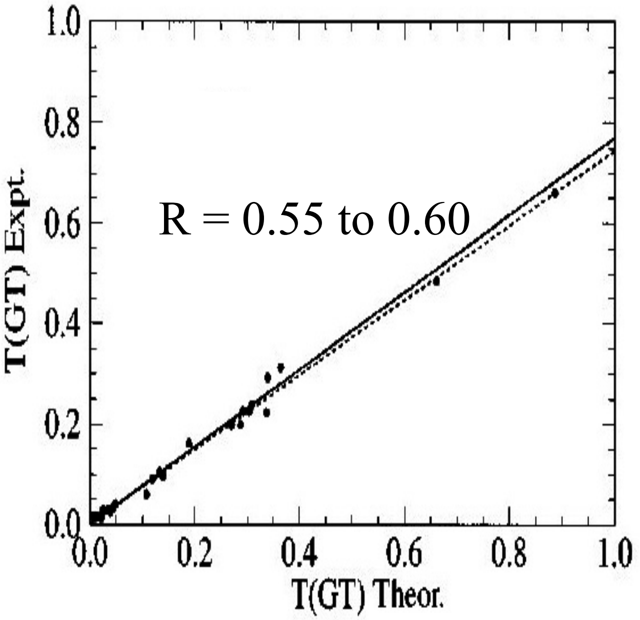
sd shell Brown and Wildenthal
ADNDT 33, 345 (1985)

pf shell Martinez-Pinedo et al
PRC 53, R2602 (1996).

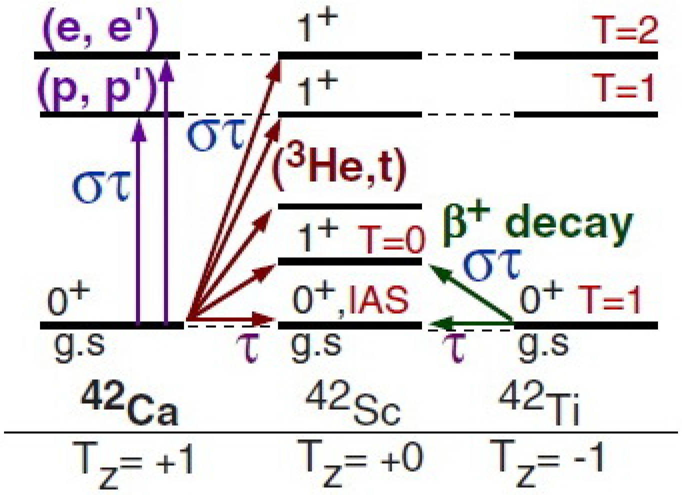


$B(GT) = [T(GT)]^2$

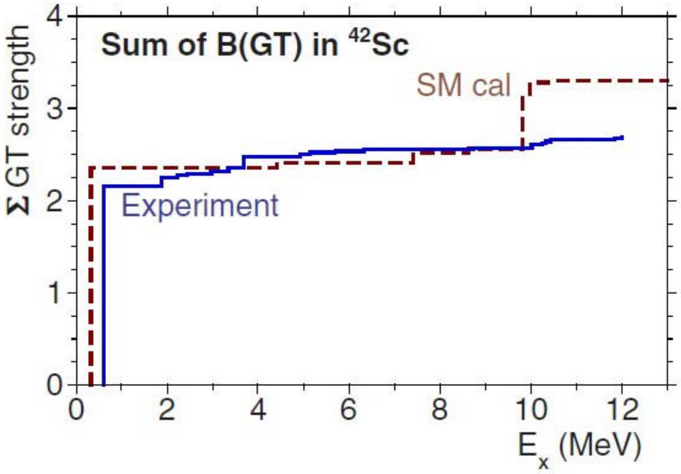
R = 0.60



R = 0.55 to 0.60



pf shell model with R=0.55



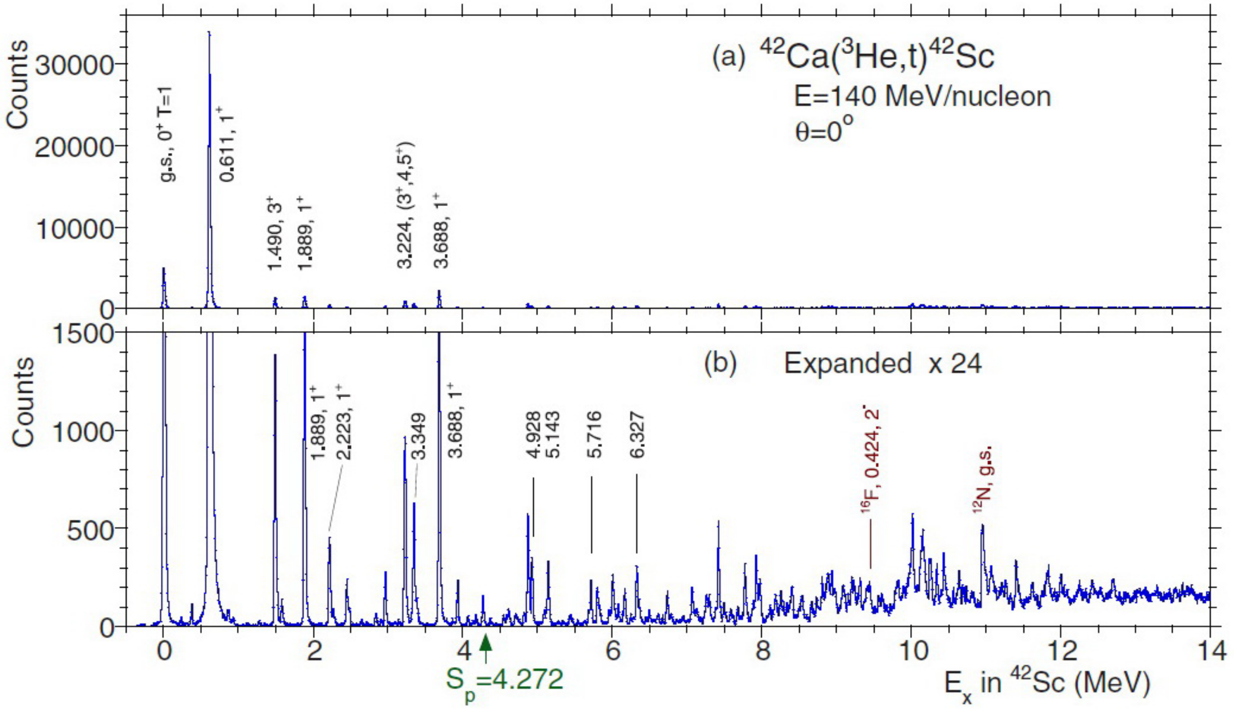
In this case the Ikeda sum rule 3(N-Z) = 6

β decay: some recent examples

PHYSICAL REVIEW C **91**, 064316 (2015)

High-resolution study of Gamow-Teller excitations in the ^{42}Ca(^{3}He,*t*) ^{42}Sc reaction and the observation of a “low-energy super-Gamow-Teller state”

Y. Fujita,[1,2,*] H. Fujita,[1,2] T. Adachi,[1] G. Susoy,[1,3] A. Algora,[4,5] C. L. Bai,[6] G. Colò,[7] M. Csatlós,[5] J. M. Deaven,[8,9,10]
E. Estevez-Aguado,[4] C. J. Guess,[8,9,10,†] J. Gulyás,[5] K. Hatanaka,[1] K. Hirota,[1] M. Honma,[11] D. Ishikawa,[1] A. Krasznahorkay,[5]
H. Matsubara,[1,‡] R. Meharchand,[8,9,10,§] F. Molina,[4,‖] H. Nakada,[12] H. Okamura,[1,¶] H. J. Ong,[1] T. Otsuka,[13] G. Perdikakis,[8,14]
B. Rubio,[4] H. Sagawa,[15,16] P. Sarriguren,[17] C. Scholl,[18,#] Y. Shimbara,[19] E. J. Stephenson,[20] T. Suzuki,[1] A. Tamii,[1]
J. H. Thies,[21] K. Yoshida,[22] R. G. T. Zegers,[8,9,10] and J. Zenihiro[1,**]



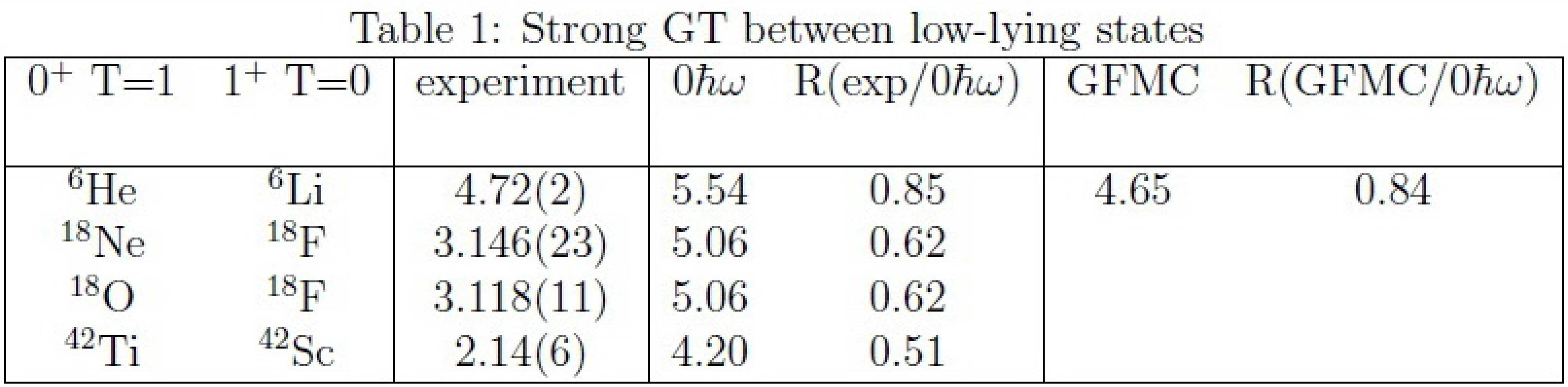


Table 1: Strong GT between low-lying states

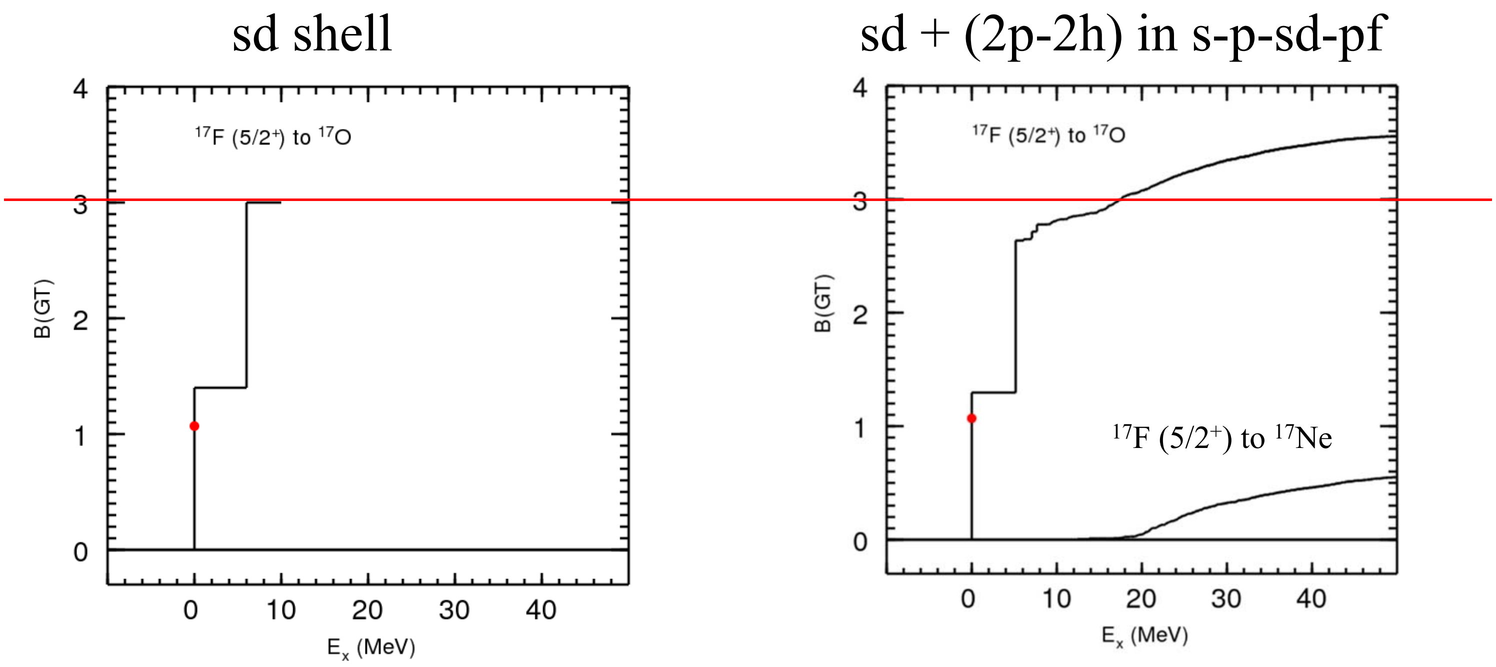
0^+ T=1	1^+ T=0	experiment	$0\hbar\omega$	R(exp/$0\hbar\omega$)	GFMC	R(GFMC/$0\hbar\omega$)
^{6}He	^{6}Li	4.72(2)	5.54	0.85	4.65	0.84
^{18}Ne	^{18}F	3.146(23)	5.06	0.62		
^{18}O	^{18}F	3.118(11)	5.06	0.62		
^{42}Ti	^{42}Sc	2.14(6)	4.20	0.51		

B(GT-) – B(GT+) = 3(N-Z) sum rule is always satisfied but we must go up to about 50 MeV.

The two-neutrino double-beta only depends on the low-lying strength (up to about 10 MeV) that is reduced (quenched) due to configuration mixing

β decay – where does the GT strength go?

example of ^{17}F with the Ikeda sum rule S = B(GT-) – B(GT+) = 3(Z-N) = 3



2ν decay depends on low-lying strength

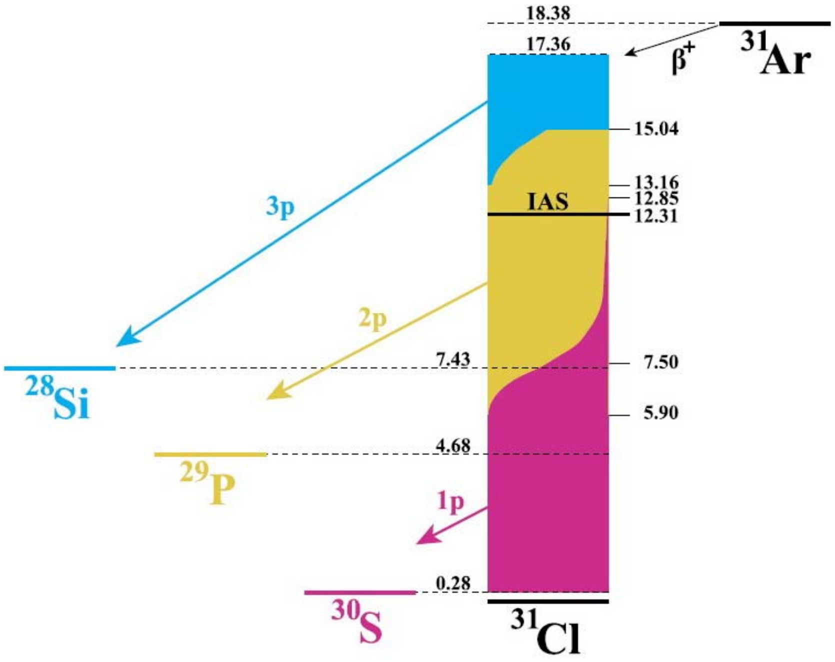
$$M^{2\nu} = \sum_m \frac{\langle 0_f^+|\vec{\sigma}t^-|m\rangle\langle m|\vec{\sigma}t^-|0_i^+\rangle}{E_m - (M_i + M_f)/2}$$

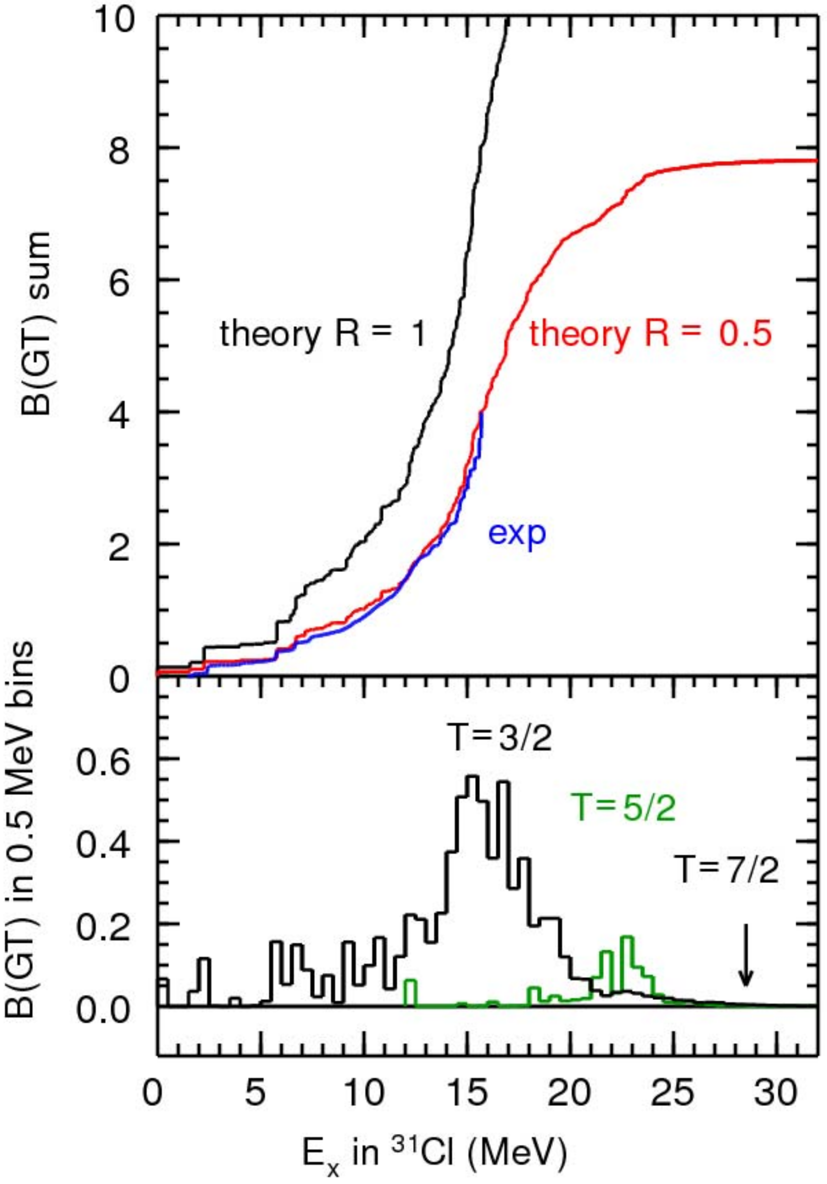
β decay: recent example

Physics Letters B 737 (2014) 383–387

Sizeable beta-strength in ^{31}Ar (β3p) decay

G.T. Koldste [a], B. Blank [b], M.J.G. Borge [c], J.A. Briz [c], M. Carmona-Gallardo [c], L.M. Fraile [d], H.O.U. Fynbo [a,*], J. Giovinazzo [b], J.G. Johansen [a,1], A. Jokinen [e], B. Jonson [f], T. Kurturkian-Nieto [b], T. Nilsson [f], A. Perea [c], V. Pesudo [c], E. Picado [c,g], K. Riisager [a], A. Saastamoinen [e,2], O. Tengblad [c], J.-C. Thomas [h], J. Van de Walle [i]




10
8
6
4
2
0
B(GT) sum
theory R = 1
theory R = 0.5
exp
0.6
0.4
0.2
0.0
B(GT) in 0.5 MeV bins
T=3/2
T=5/2
T=7/2
0
5
10
15
20
25
30
E_x in ^31Cl (MeV)

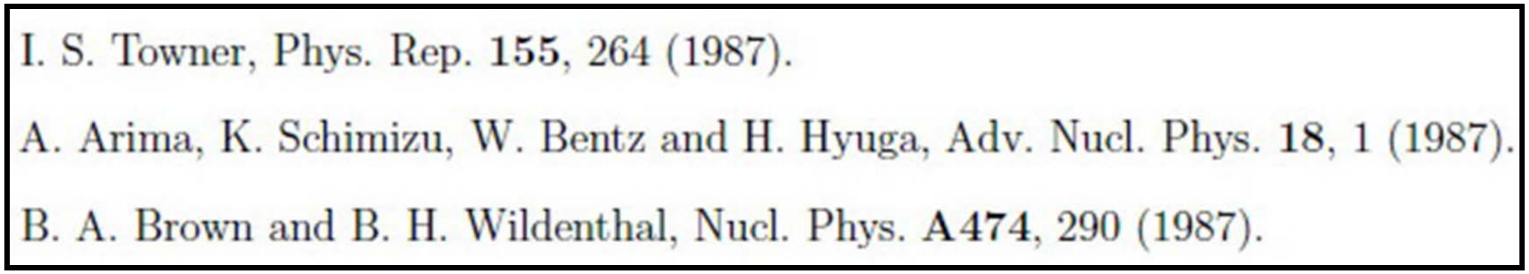
β decay for sd and pf shell

$B_{exp} = 0.60\ B_{CI} = (1 - 0.223)^2\ B_{CI}$

Explained (1980’s) using MBPT as being due to 2p-2h admixtures up to high excitations, and mesonic exchange currents (MEC) including the Δ isobar:

Arima, Shimizu, Bentz and Hyuga (for sd shell) (1987):
$B_{ASBH} = 0.65\ B_{CI} = (1 - 0.220 + 0.025\ )^2\ B_{CI}$

Towner and Khanna (for sd shell) (1987):
$B_{TK} = 0.65\ B_{CI} = (1 - 0.175 - 0.020\ )^2\ B_{CI}$

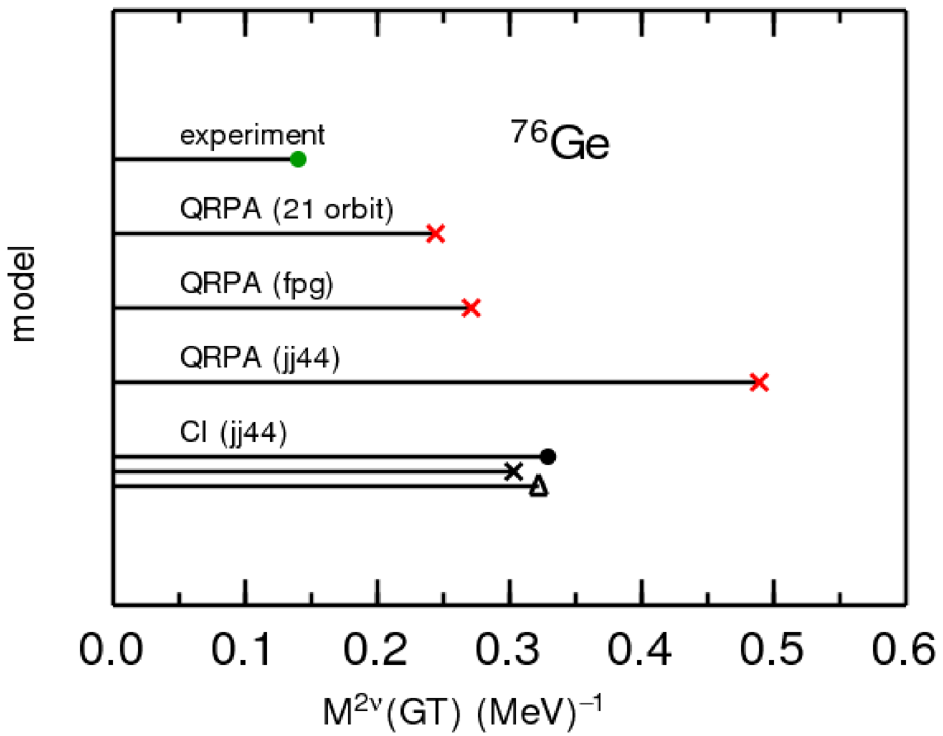


I. S. Towner, Phys. Rep. **155**, 264 (1987).

A. Arima, K. Schimizu, W. Bentz and H. Hyuga, Adv. Nucl. Phys. **18**, 1 (1987).

B. A. Brown and B. H. Wildenthal, Nucl. Phys. **A474**, 290 (1987).

$2\nu\beta\beta$ decay



Conclusion I: from QRPA
Inclusion of both spin-orbit pairs reduces the 2ν NME by about a factor of about 0.5

Conclusion II:
2p-2h beyond QRPA reduces the low-lying GT strength further by a factor of about 0.6

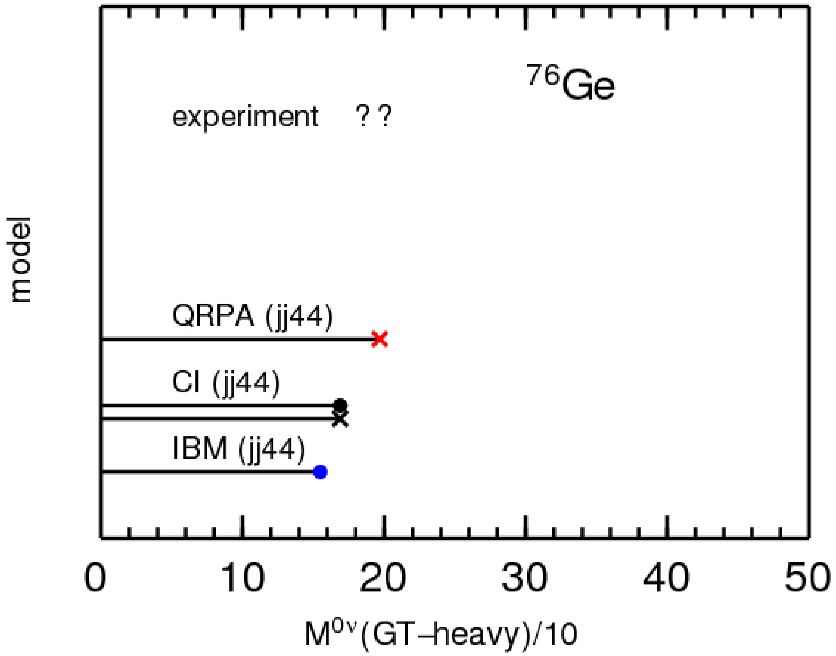
III – the total reduction is thus (0.5) x (0.6) = 0.30

Compared to 0.40 from exp

NSCL

Alex Brown, INT, March 28, 2018

heavy $0\nu\beta\beta$ decay



Experiment is not known

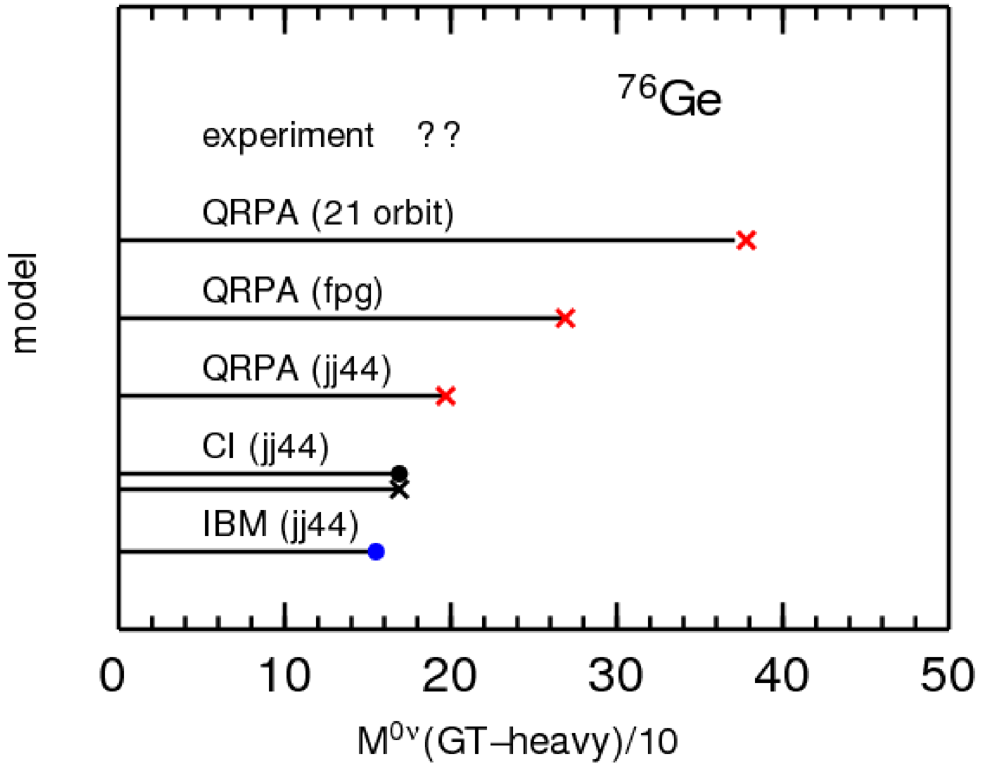
- we must predict this

Within jj44 all model are rather consistent.

Should CI should be reduced by a factor of 0.4?

(equivalent to reducing g_A from 1.27 to about 0.8)

heavy 0νββ decay



QRPA conclusion:
Vertical expansion enhances the heavy 0ν NME by about a factor of 2.

particle-hole

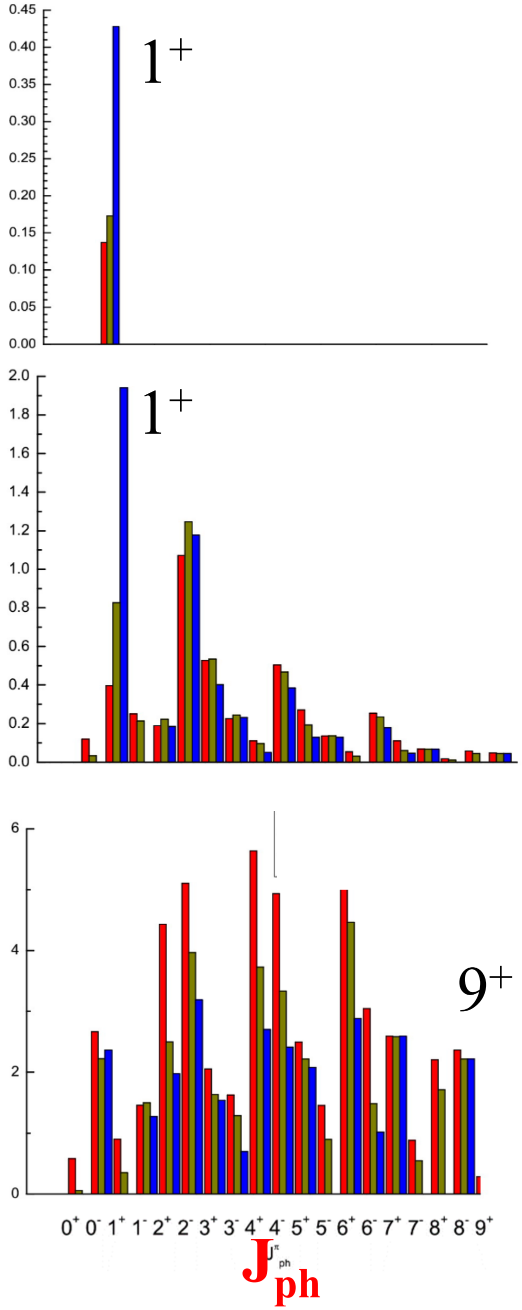
particle-particle

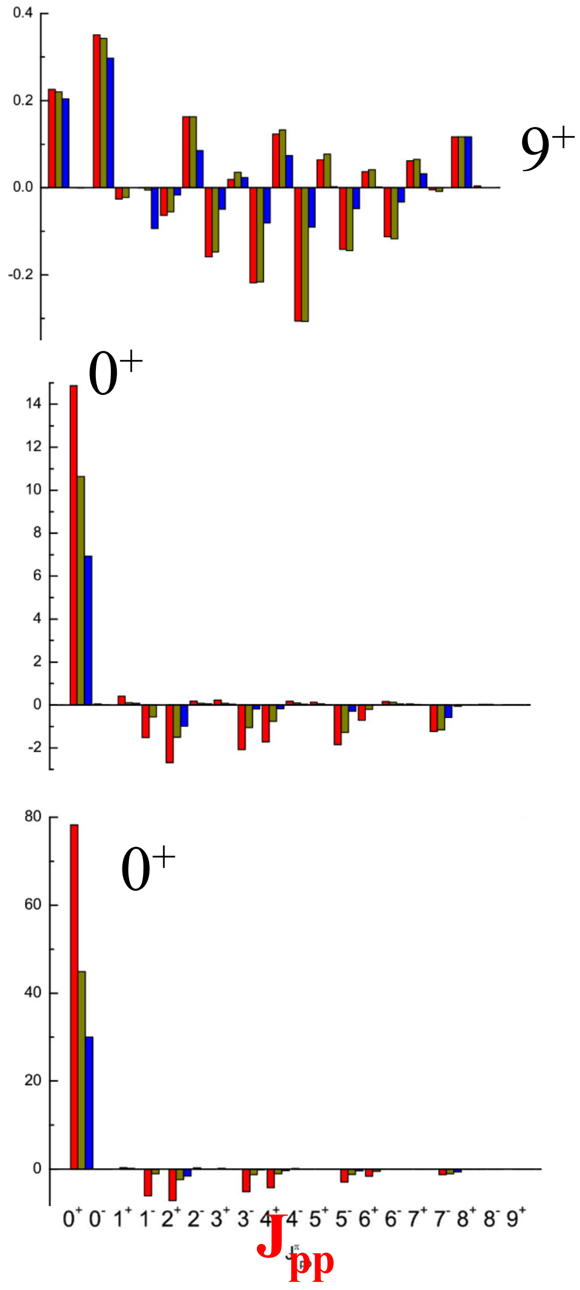
f(r)

2ν (1)

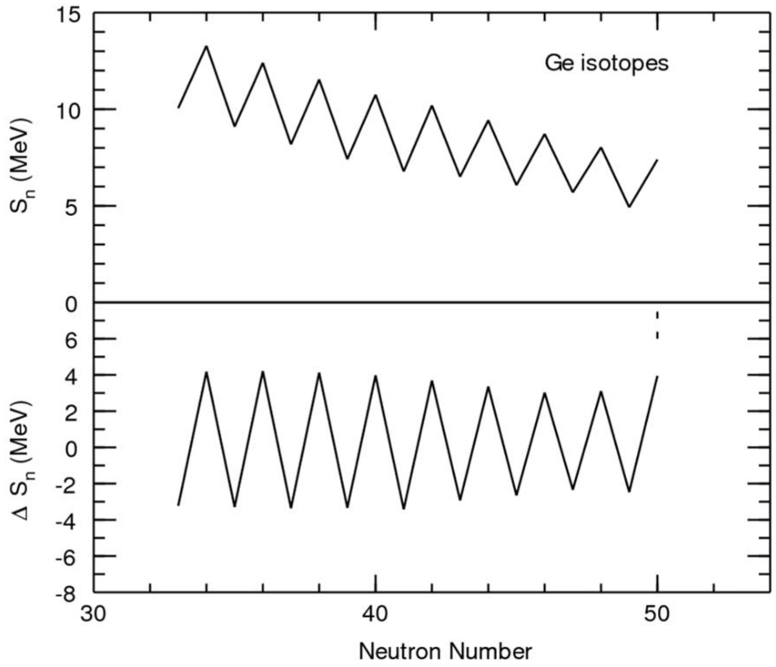
0ν light (1/r)

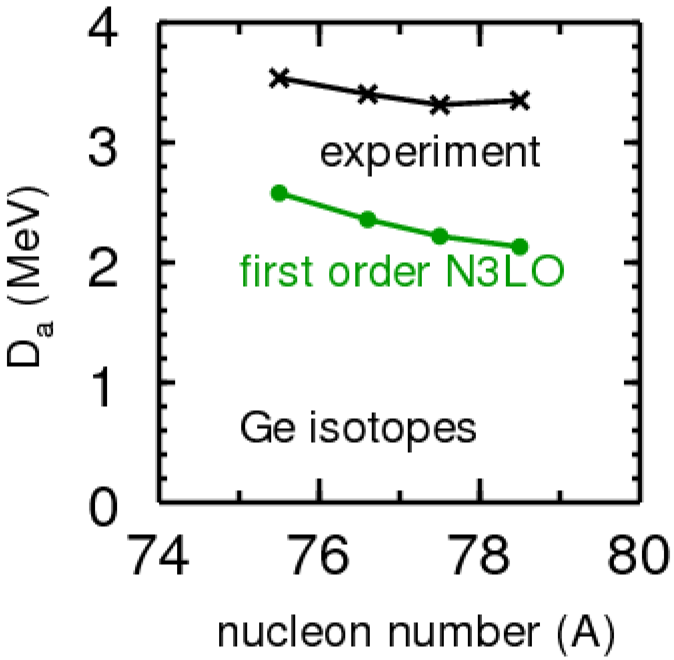
0ν heavy δ(r)





The short-range pairing interaction causes an odd-even oscillations in the separation energies. This can be used to extract a vertical correction to the jj44 model space for a similar operator of about $R_V = 1.65(25)$





Particle transfer cross section calculated within the jj44 model space should under-predict the data and must be corrected for the pairing from other orbitals using MBPT.

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Corrections to the calculated observables depend on the observable and the model space. Examples in the sd shell from the 1980's

	exp/theory (average)
B(GT)	0.6
One particle removal cross sections	0.7
B(M1)	0.8
B(E2)	4.0

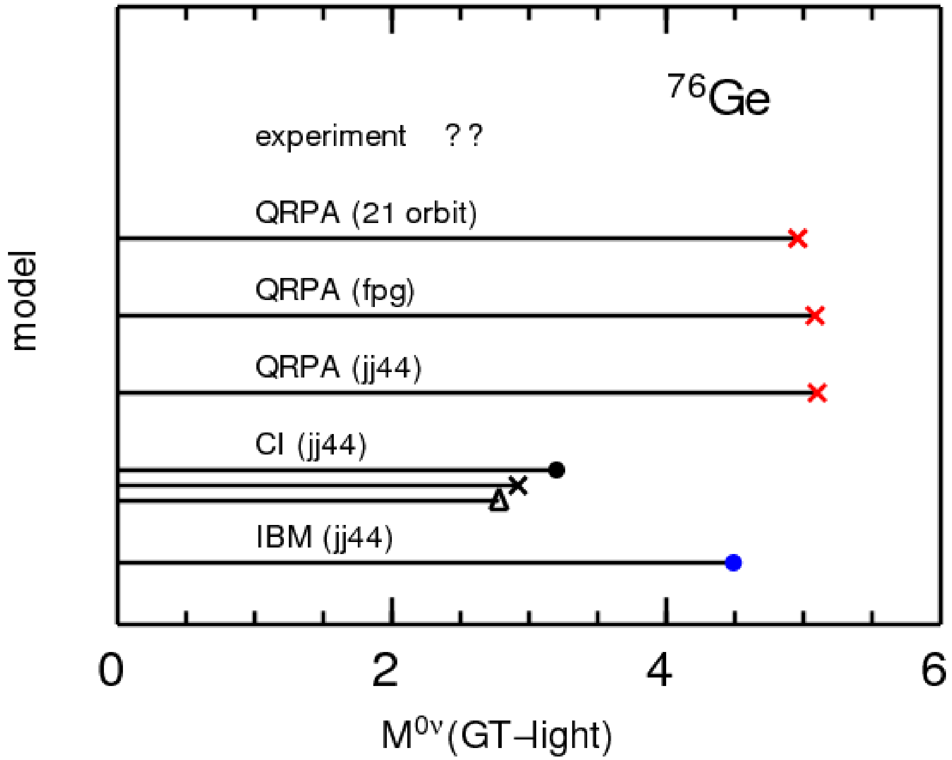
All of these have been understood in terms of MBPT and the vertical expansion

We write $M_{GT} = R_V \, M_{GT\text{-}CI}$ where R_V is the vertical expansion correction factor

2ν	$R_V = 0.40$	$f(r) = 1$	empirical value consistent with other data
0ν heavy	$R_V = 1.65(25)$	$f(r) = b\,\delta(r)$	pairing enhancement from other data
0ν light	$R_V = ?$	$f(r) = a/r$	

light $0\nu\beta\beta$ decay f(r) = a/r

light $0\nu\beta\beta$ decay $f(r) = a/r$



Effects of vertical expansion within QRPA are small. This due to competition between ph (1^+) reduction and pp (0^+) enhancement.

IBM and QRPA are too large within jj44. Due to lack of cancellation from $J_{pp} = 2^+$ contributions in those models.

particle-hole

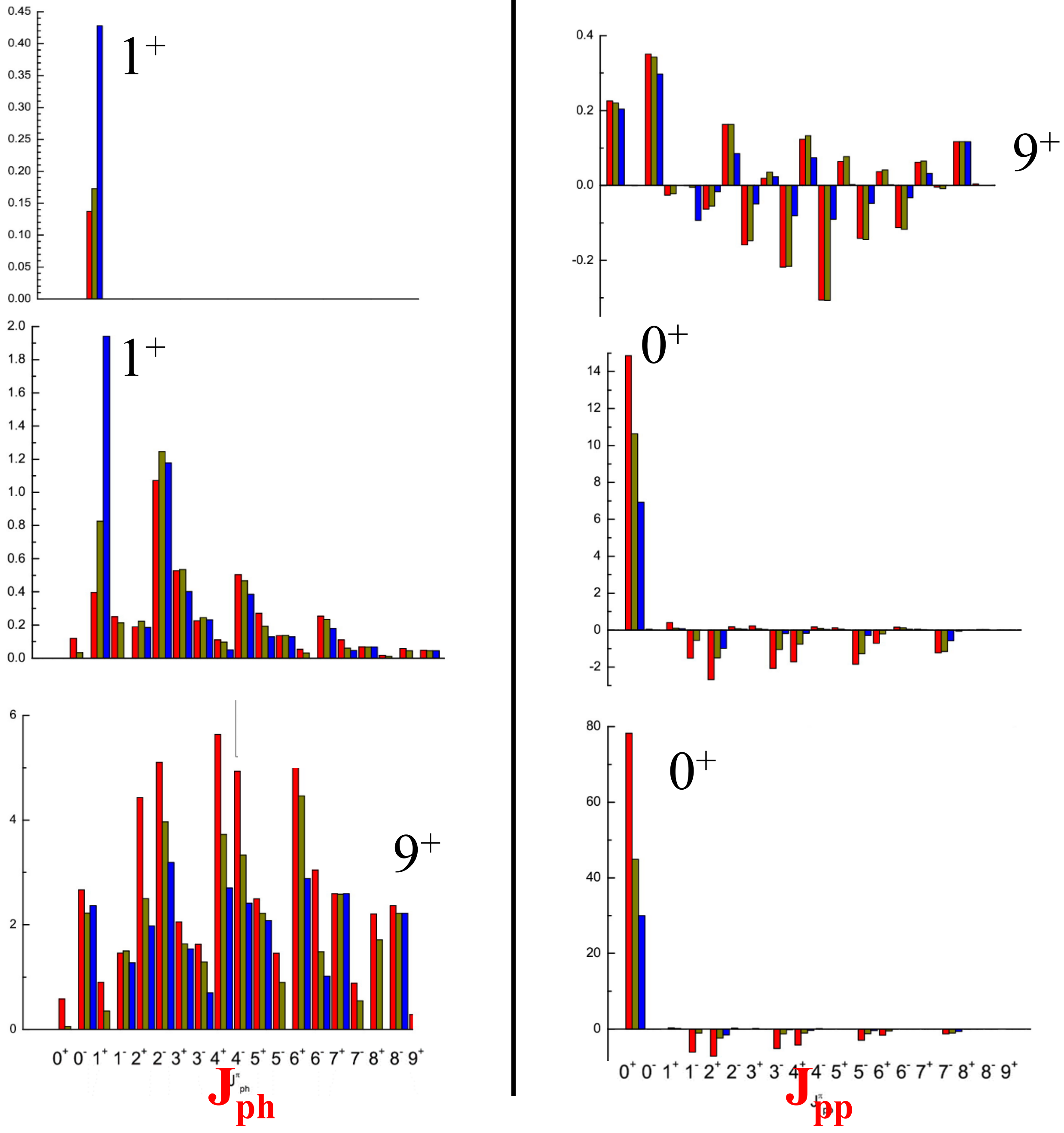
particle-particle

f(r)

2ν (1)

0ν light (1/r)

0ν heavy δ(r)



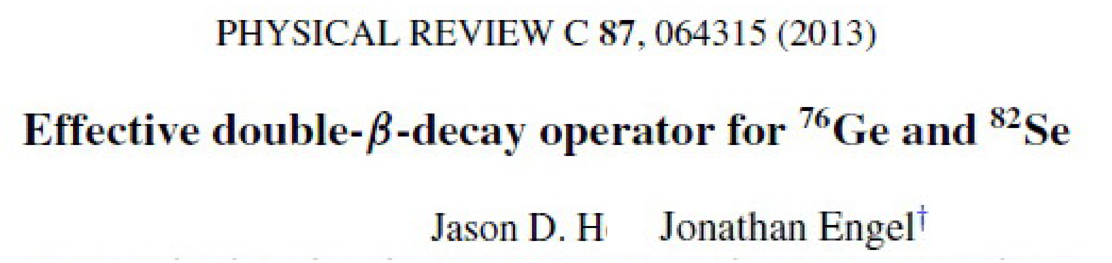
$J_{pp} = 0 \qquad 2 \qquad \text{other} \qquad \text{total}$

CI: 6.83 – 2.31 – 0.90 = 3.62

IBM: 4.98 – 0.49 – 0.00 = 4.49

QRPA: 6.92 – 1.00 – 0.95 = 4.97

light 0νββ decay



PHYSICAL REVIEW C **87**, 064315 (2013)

Effective double-β-decay operator for ^{76}Ge and ^{82}Se

Jason D. H Jonathan Engel[†]

Used 2p-2h MBPT:

0ν NME for ^{76}Ge was increased by about 20%

So we use $M_{GT} = R_V\, M_{GT\text{-}CI}$ with $R_V = 1.20(20)$

Short range correlations – repulsive part of NN potential pushes out the relative wave function at short distance and reduced the radial matrix elements for 1/r and δ(r)

Several options exits – I started with the CD-Bonn – the weakest.

Others are AV18 (the strongest) and UCOM (in between).

So for now I take the mean with the error coming from the difference.

Heavy neutrino – NME reduced by $R_S = 0.80(20)$
Light neutrino – NME reduced by $R_S = 0.97(3)$

Final results for ^{76}Ge starting with CI in jj44 called M_{CI}

2ν $\quad M_{exp} = 0.140(5)$

$= (R_V)\ (R_S)\ (R_{GT})\ \ M_{CI}$

$= (0.40)\ (1)\quad (1)\quad 0.31(3)$

$= (1 - 0.37)^2\ 0.31(3)$

$= (1 - 0.10 - 0.27 - 0.02)^2\ 0.31(3)$

2p-2h 1p-1h MEC

(number are a guess – need to be confirmed)

Results for ^{76}Ge starting with CI in jj44 called $M_{CI\text{-}GT}$

0ν heavy neutrino

$$M = R_V \quad R_S \quad R_{GT} \quad M_{CI\text{-}GT}$$

$$= 1.65(25) \quad 0.80(20) \quad 1.13(13) \quad 155(10)$$

$$= 232(80)$$

Results for ^{76}Ge starting with CI in jj44 called $M_{CI\text{-}GT}$

0ν light neutrino

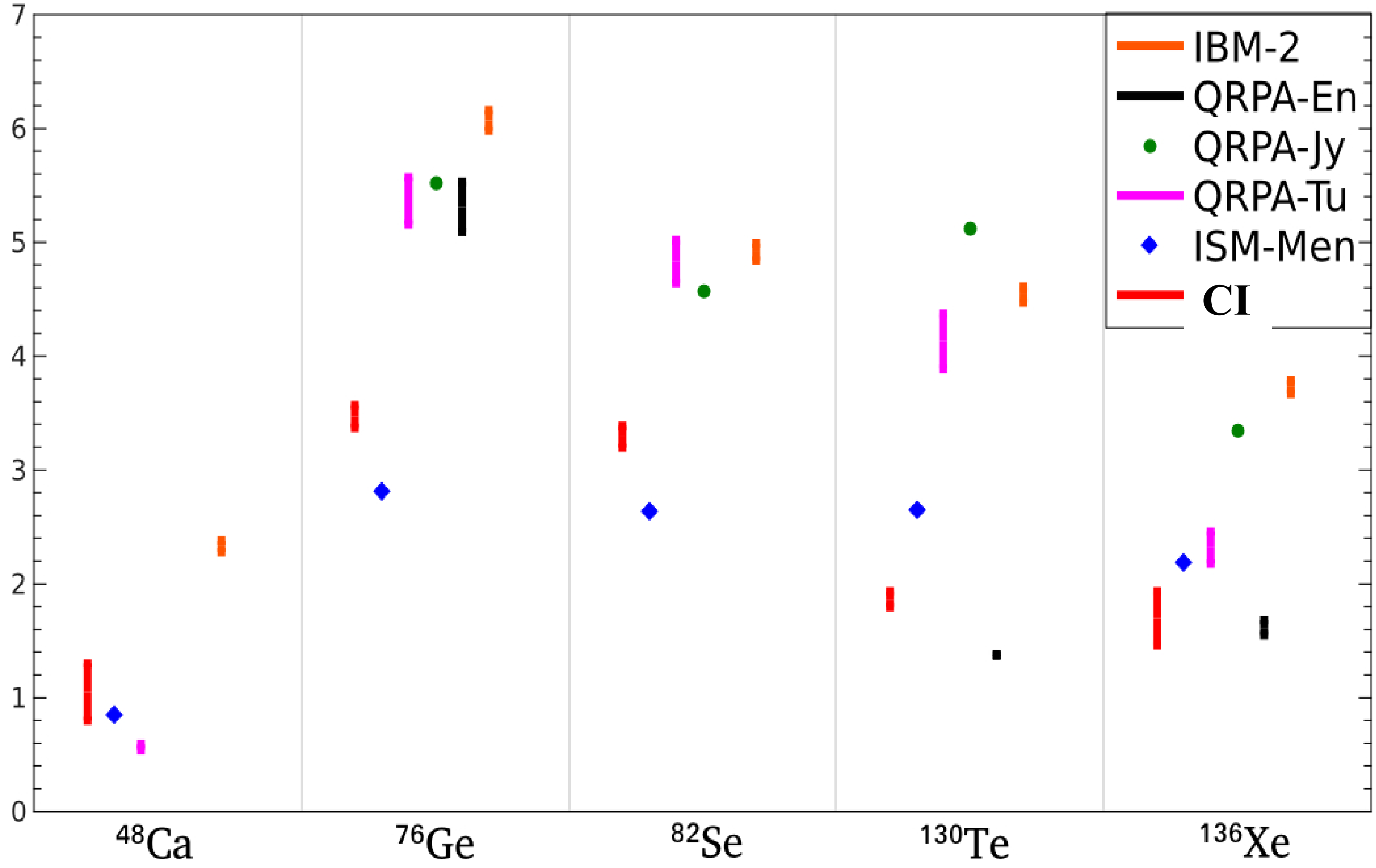
$$M = R_V \quad R_S \quad R_{GT} \quad M_{CI\text{-}GT}$$

$$= 1.20(20) \quad 0.97(3) \quad 1.12(7) \quad 3.0(3)$$

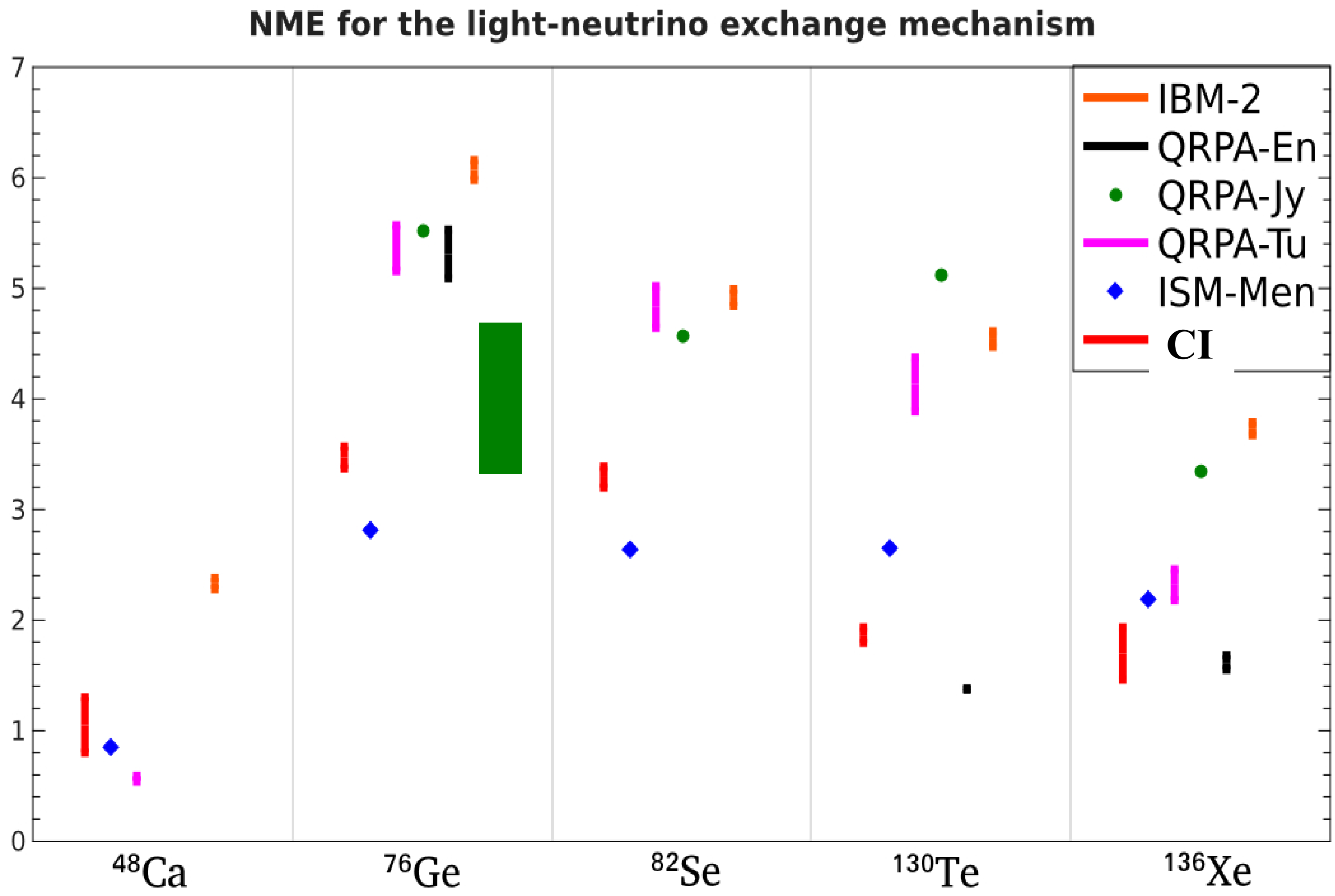
$$= 3.9(8)$$

NSCL

NME for the light-neutrino exchange mechanism



IBA-2 J. Barea, J. Kotila, and F. Iachello, Phys. Rev. C **87**, 014315 (2013).
QRPA-En M. T. Mustonen and J. Engel, Phys. Rev. C **87**, 064302 (2013).
QRPA-Jy J. Suhonen, O. Civitarese, Phys. NPA **847** 207–232 (2010).
QRPA-Tu A. Faessler, M. Gonzalez, S. Kovalenko, and F. Simkovic, arXiv:**1408.6077**
ISM-Men J. Menéndez, A. Poves, E. Caurier, F. Nowacki, NPA **818** 139–151 (2009).
SM M. Horoi et. al. PRC **88**, 064312 (2013), PRC **89**, 045502 (2014), PRC **90**, PRC **89**, 054304 (2014), in preparation, PRL **110**, 222502 (2013).



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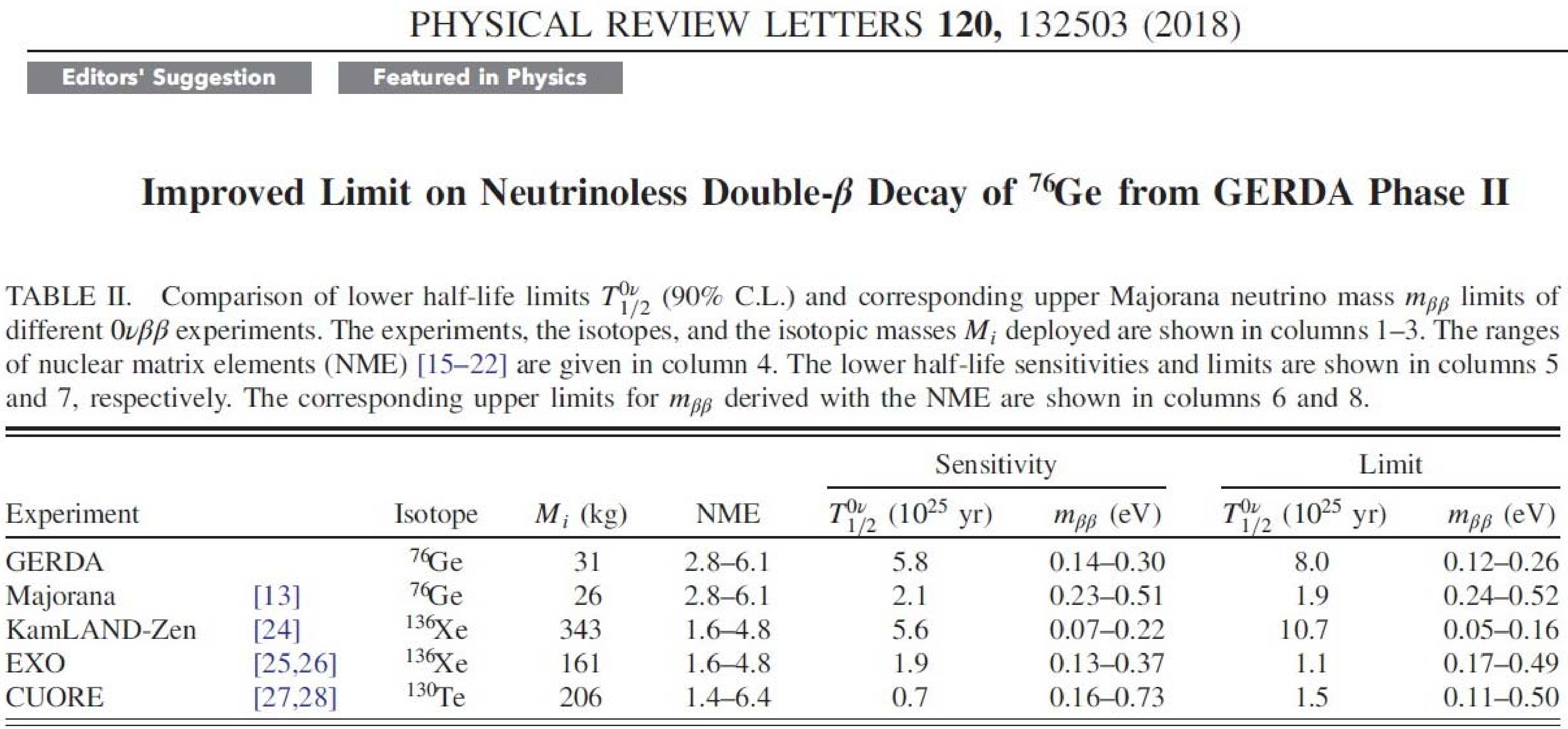


PHYSICAL REVIEW LETTERS **120,** 132503 (2018)

Editors' Suggestion **Featured in Physics**

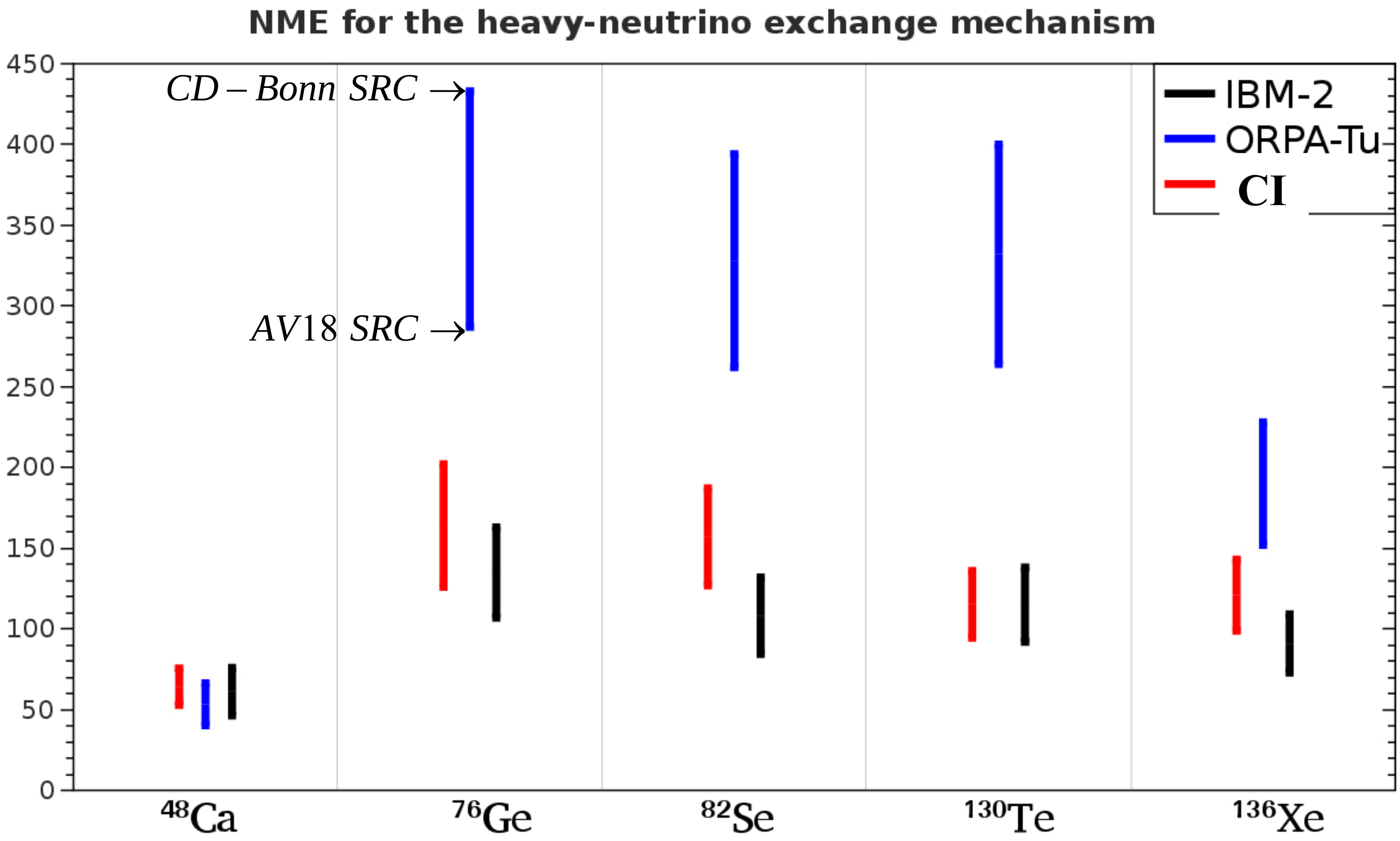
Improved Limit on Neutrinoless Double-β Decay of ^{76}Ge from GERDA Phase II

TABLE II. Comparison of lower half-life limits $T^{0\nu}_{1/2}$ (90% C.L.) and corresponding upper Majorana neutrino mass $m_{\beta\beta}$ limits of different $0\nu\beta\beta$ experiments. The experiments, the isotopes, and the isotopic masses M_i deployed are shown in columns 1–3. The ranges of nuclear matrix elements (NME) [15–22] are given in column 4. The lower half-life sensitivities and limits are shown in columns 5 and 7, respectively. The corresponding upper limits for $m_{\beta\beta}$ derived with the NME are shown in columns 6 and 8.

					Sensitivity		Limit	
Experiment		Isotope	M_i (kg)	NME	$T^{0\nu}_{1/2}$ (10^{25} yr)	$m_{\beta\beta}$ (eV)	$T^{0\nu}_{1/2}$ (10^{25} yr)	$m_{\beta\beta}$ (eV)
GERDA		^{76}Ge	31	2.8–6.1	5.8	0.14–0.30	8.0	0.12–0.26
Majorana	[13]	^{76}Ge	26	2.8–6.1	2.1	0.23–0.51	1.9	0.24–0.52
KamLAND-Zen	[24]	^{136}Xe	343	1.6–4.8	5.6	0.07–0.22	10.7	0.05–0.16
EXO	[25,26]	^{136}Xe	161	1.6–4.8	1.9	0.13–0.37	1.1	0.17–0.49
CUORE	[27,28]	^{130}Te	206	1.4–6.4	0.7	0.16–0.73	1.5	0.11–0.50

^{76}Ge 3.1 - 4.7 0.18 – 0.25

NSCL



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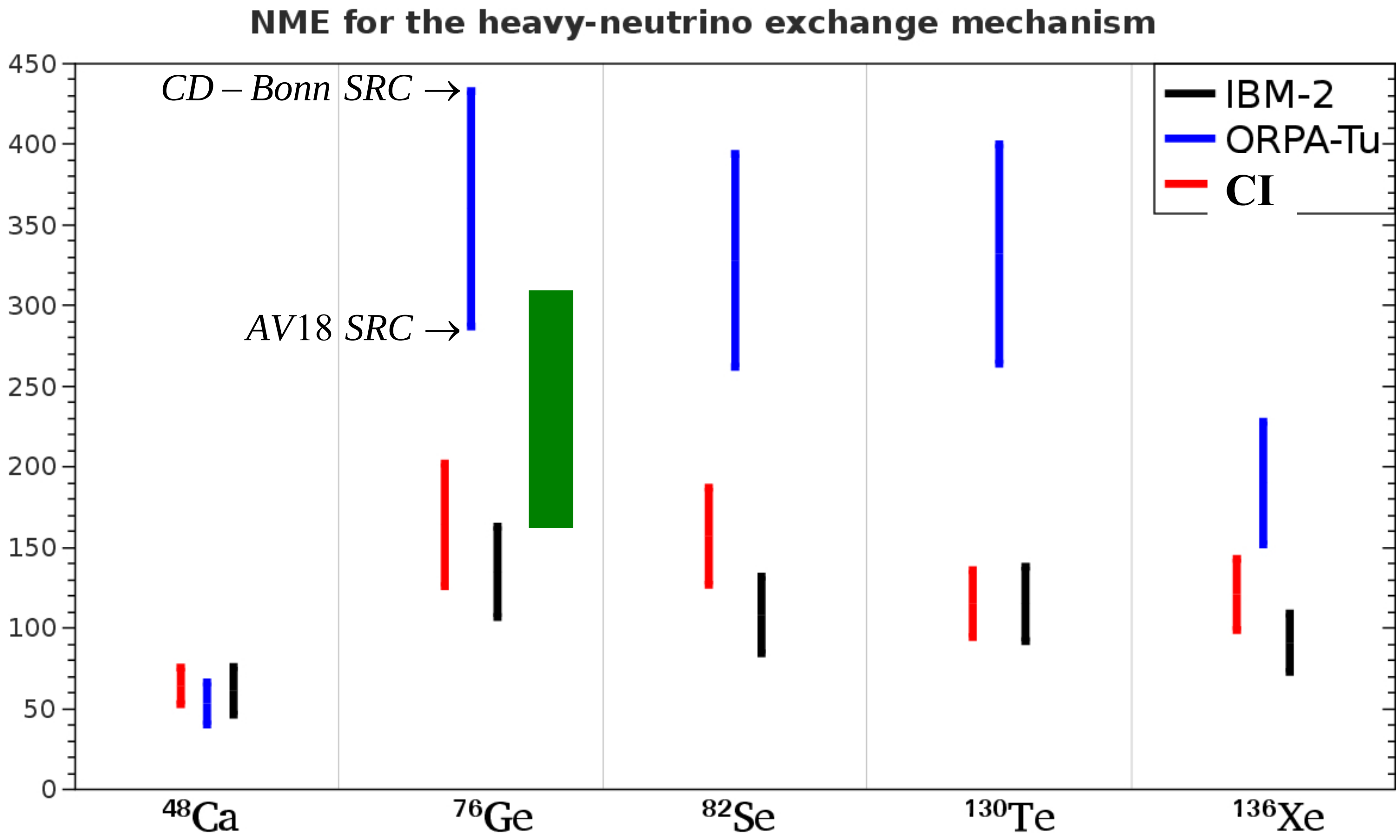

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SM M. Horoi et. al. PRC **88**, 064312 (2013), PRC **90**, PRC **89**, 054304 (2014), in preparation, PRL **110**, 222502 (2013).

Next

1) Check the jj44 CI Hamiltonian for the A=76 region by making more comparisons to known spectroscopy including two nucleon transfer and other transfer reactions.

2) Understand the horizontal – vertical division with ab-initio and no core calculations for lighter nuclei.

3) Check and improve the corrections beyond jj44 with MBPT and other methods like coupled cluster (CC) for all relevant operators including B(GT).

4) Reduce the error on the short range correlations – using for example the techniques being developed by Bogner et al for in-medium similarity renormalization group (IM-SRG)

5) Make a similar evaluation for other cases of interest.

Collaborators:

Dong-Liang Fang	Jilin University, Changchun, China
Mihai Horoi	Central Michigan University
Bill Rae	Garsington, England

Input from:

Jose Barea (Chile)
Mark Caprio (Notre Dame)
Alfredos Poves (Madrid)
Fedor Šimkovic (Dubna)

Germanium detectors – detector is its own source of decay

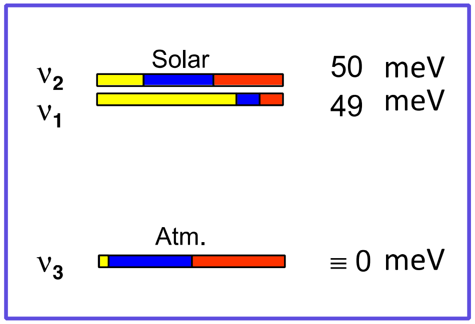
$T_{1/2} > 3 \times 10^{25}$ yr (90% C.L.) $\langle m_\nu \rangle < 0.30$ eV

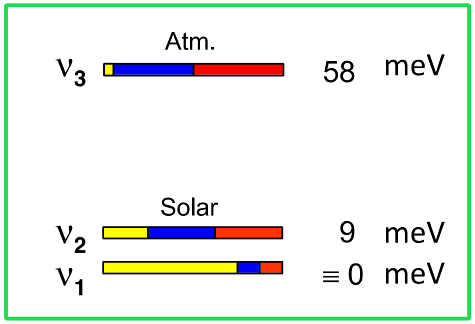
GERDA

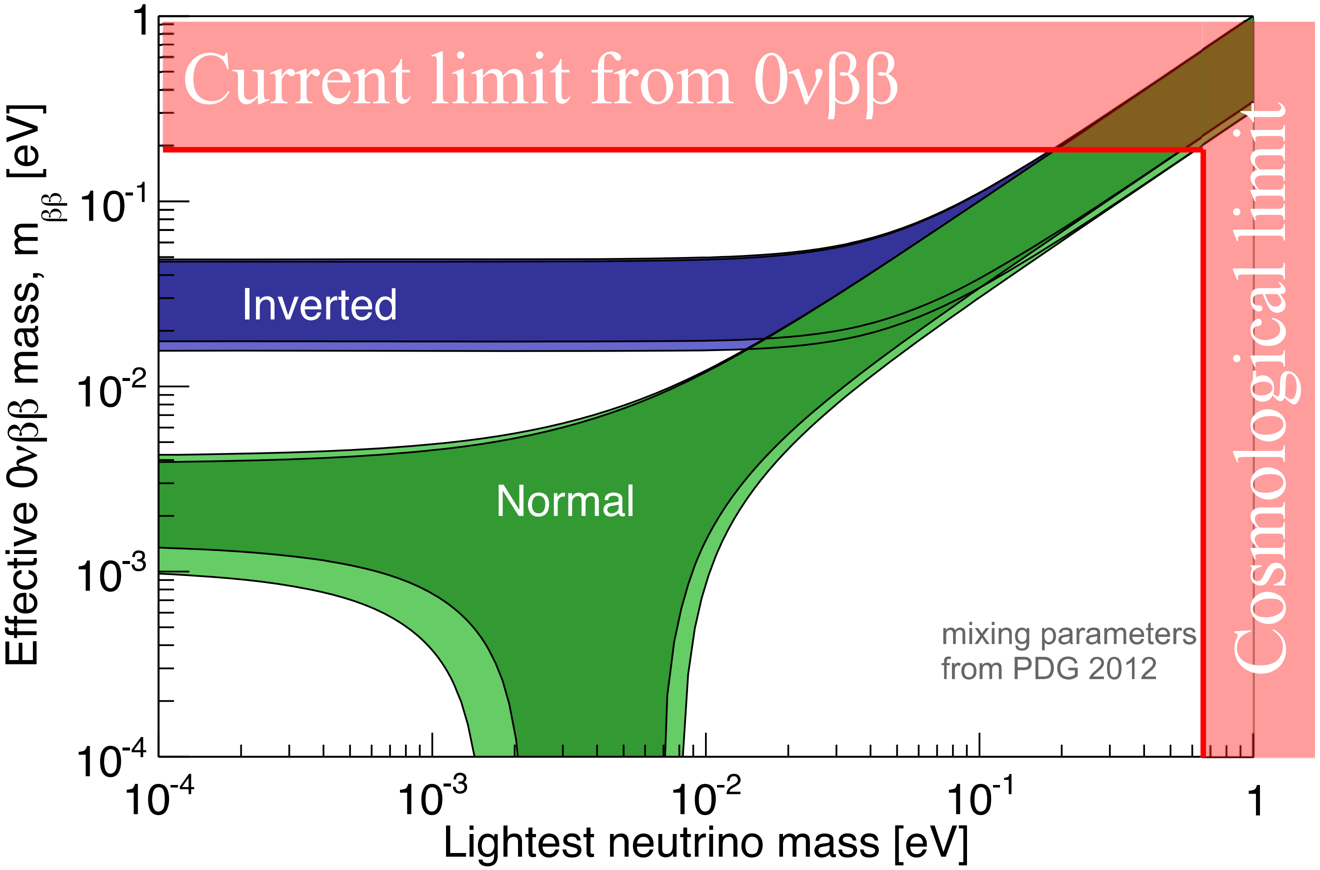
The GERmanium Detector Array

for the search of neutrinoless double beta decay in Ge-76
at the Laboratori Nazionali del Gran Sasso (LNGS)

Shaded areas shows what we know from neutrino oscillations

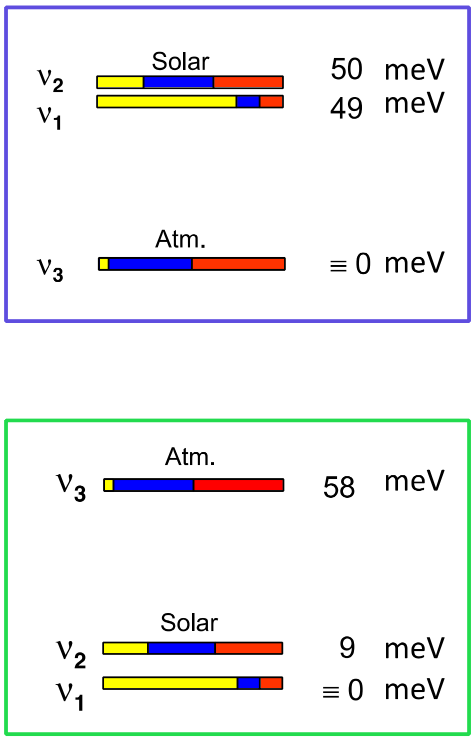


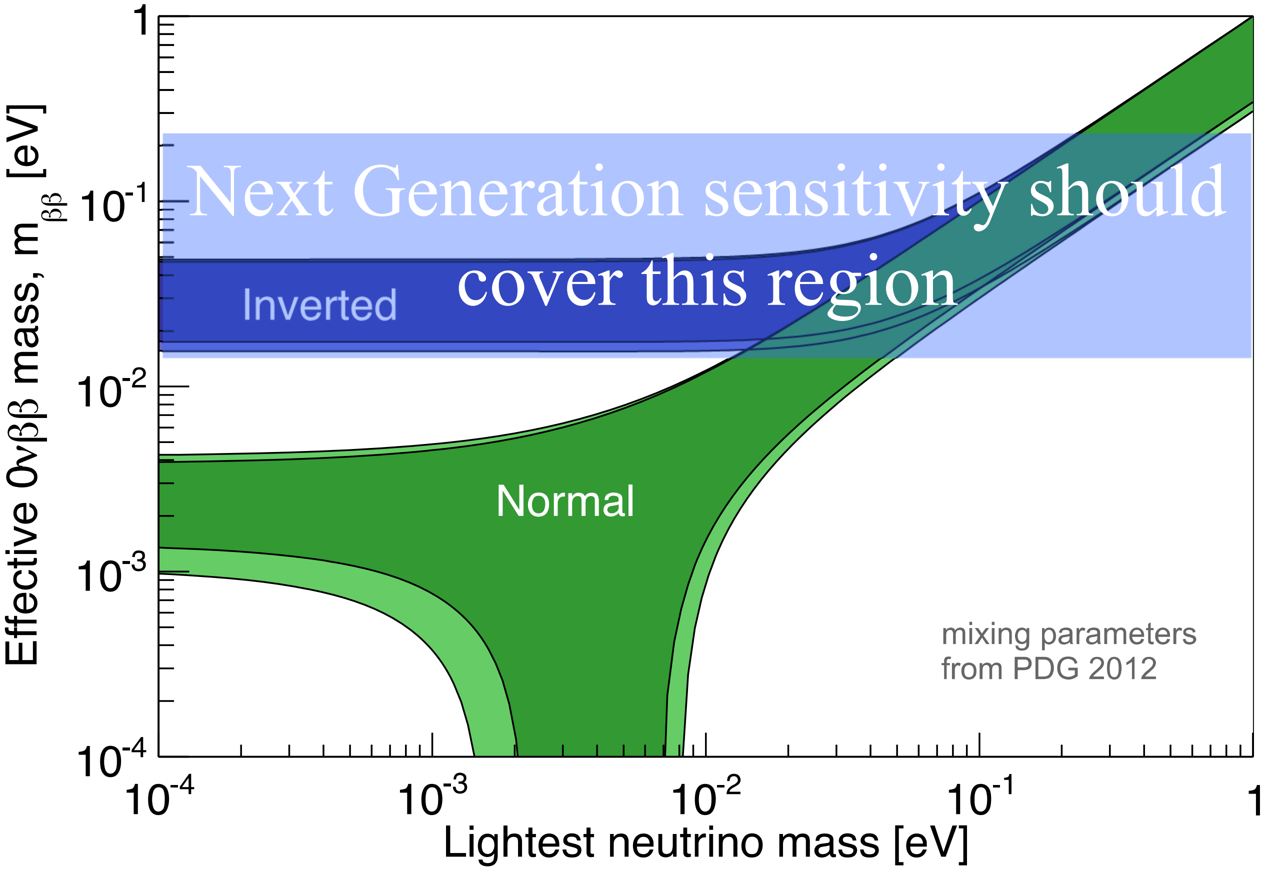




Alex Brown, INT, March 28, 2018

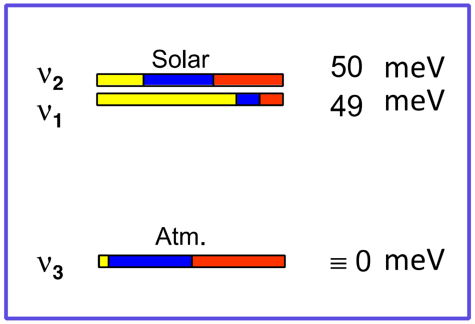
- Covering the inverted hierarchy region (<m> ~ 15 meV) requires sensitivity to half-lives of $10^{27} – 10^{28}$ years.
- Corresponds to one decay per year for a tonne of material

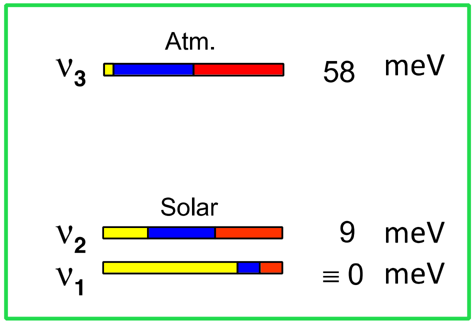


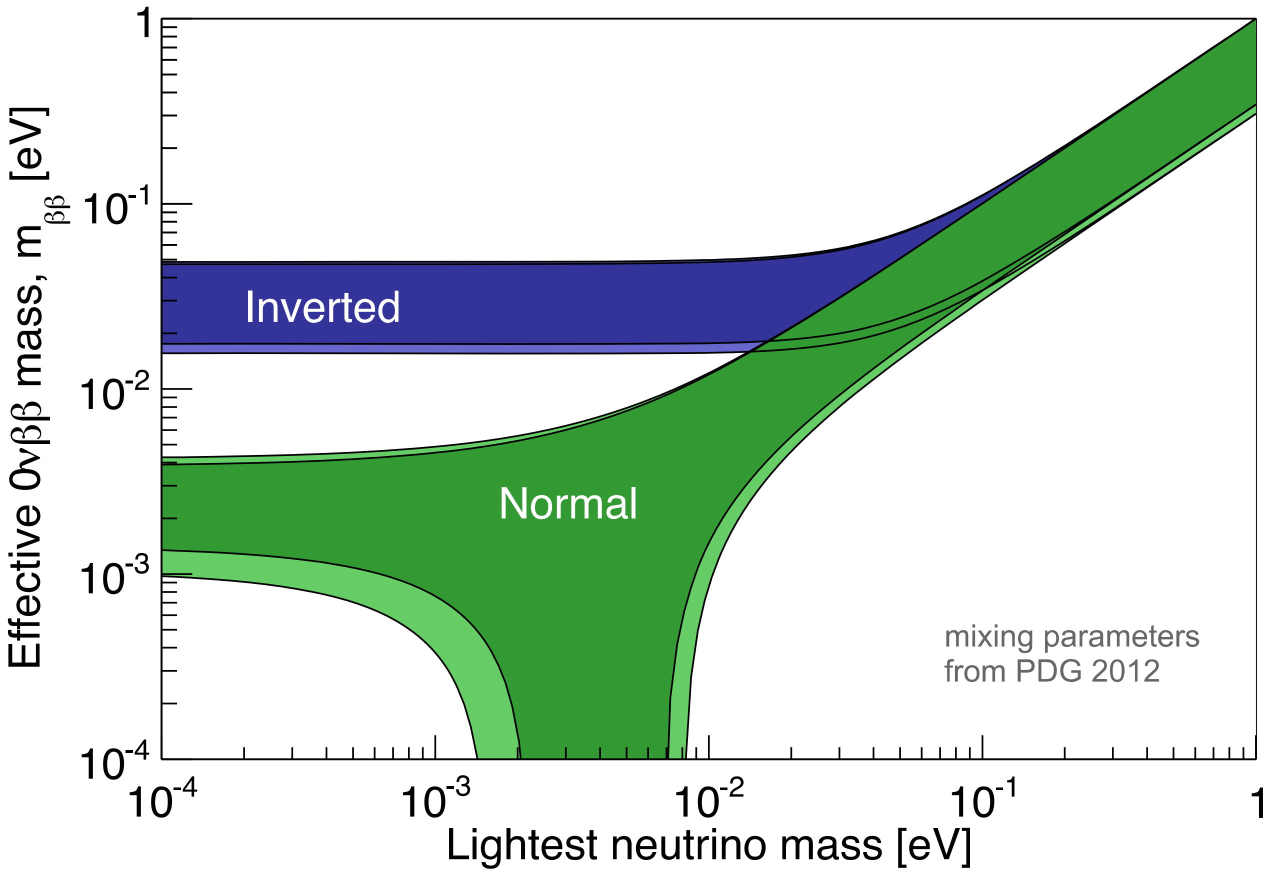


Next Generation sensitivity should cover this region

Shaded areas show what is allowed from neutrino oscillations







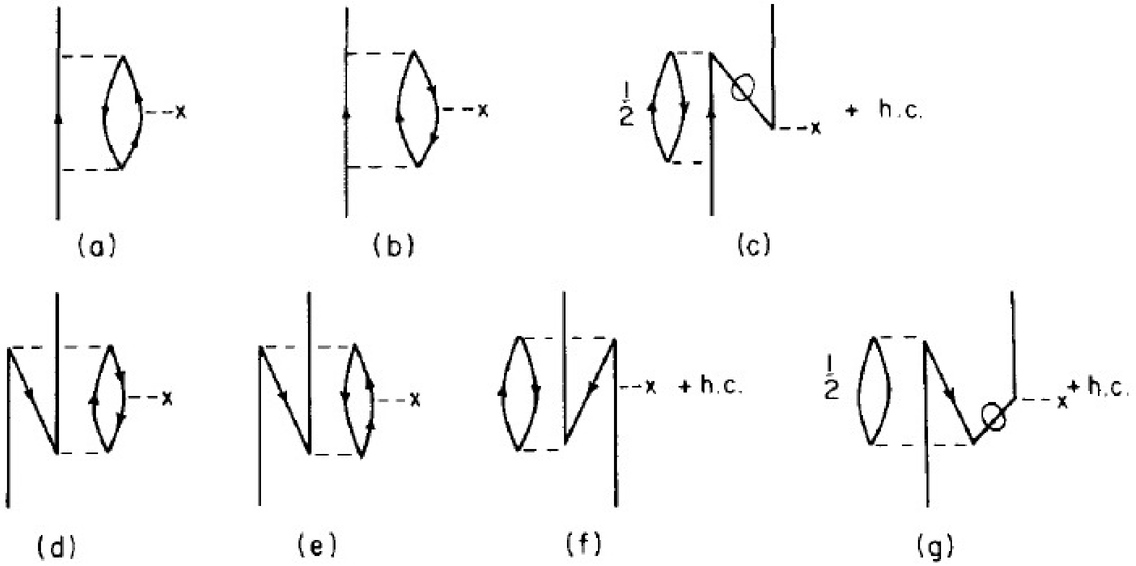


Fig. 10. Second-order core-polarisation graphs that give a correction to the magnetic moment of a closed-*LS*-shell-plus-one nucleus. Graphs (a), (b), (c) involve 2p–1h intermediate states, graphs (d), (e), (f) and (g) involve 3p–2h intermediate states. Graphs (c) and (g) are 'folded' graphs that correct (to second order) the normalization of the single-particle state.

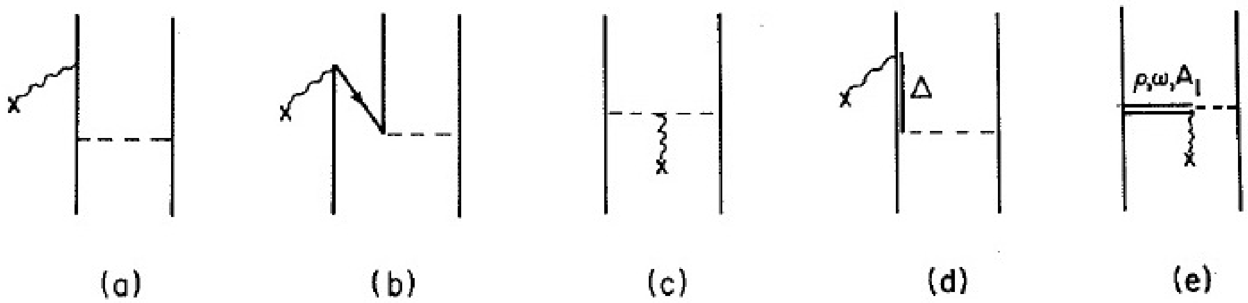
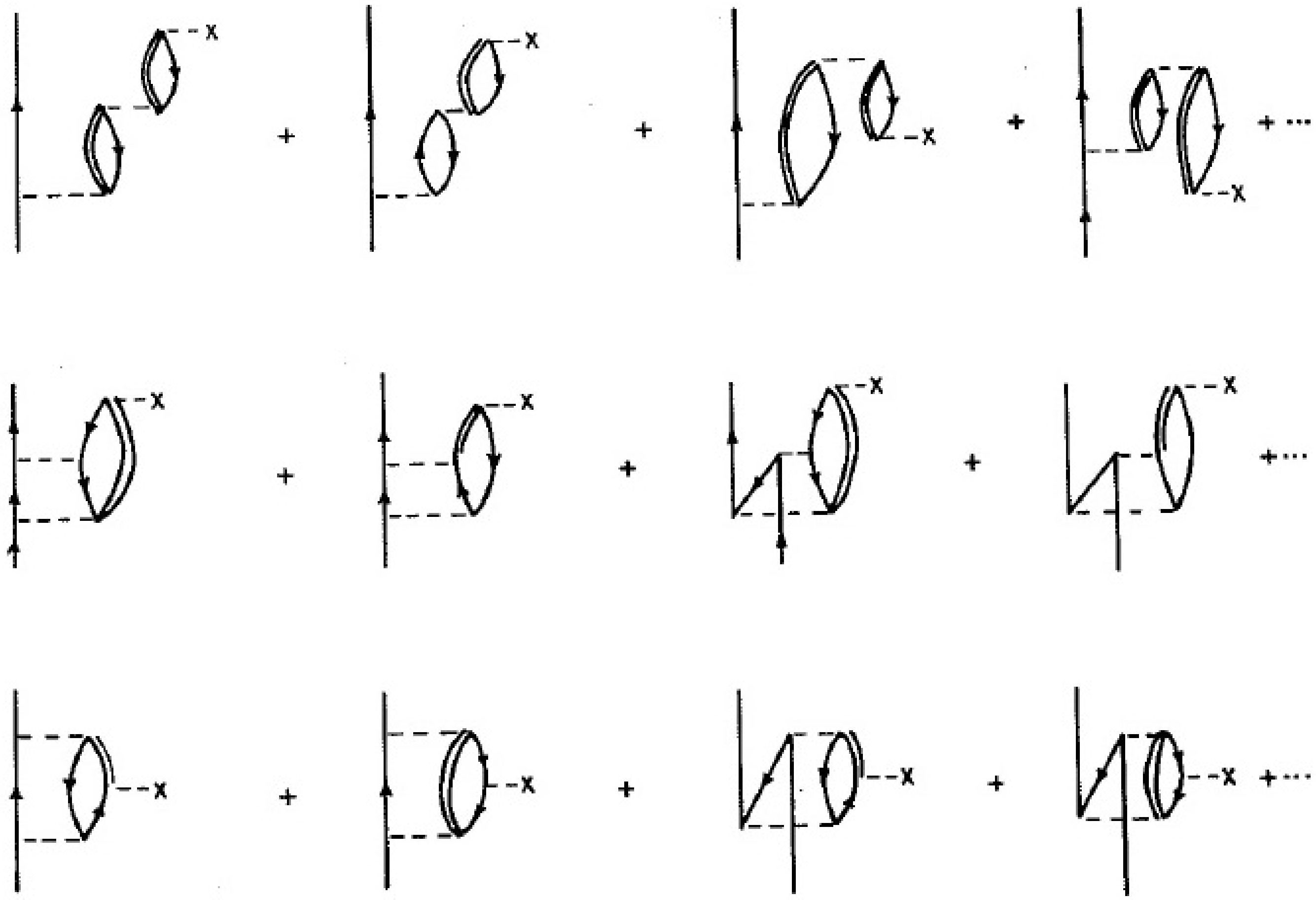


Fig. 13. Meson-exchange graphs of pion range: (a) nucleon intermediate states, (b) antinucleon intermediate states, pair graph, (c) pionic-current graph, (d) isobar intermediate states, and (e) heavy-meson current graph.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