β-Decays of Isotones with N=126 and Nuclei nearby and R-Process Nucleosynthesis

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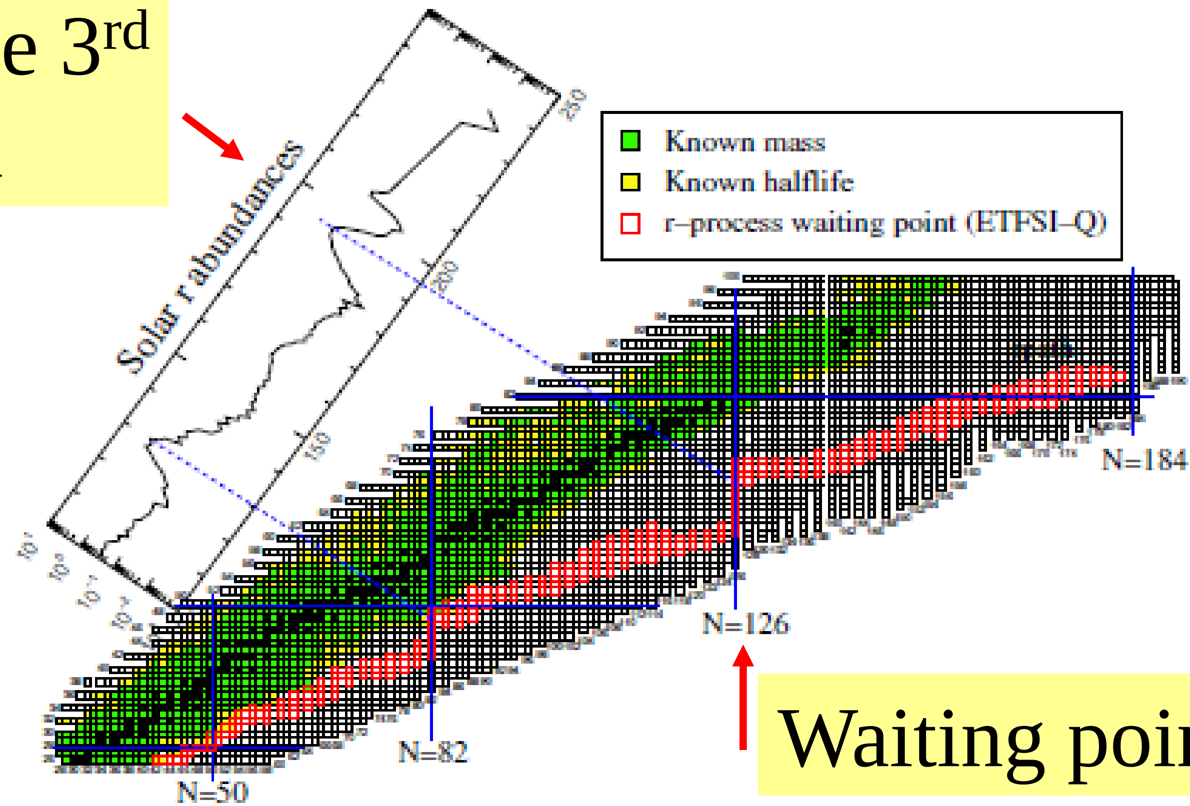
R-Process Nucleosynthesis and Beta Decays of N=126 Isotones

H Grawe *et al*

Focus on the 3rd peak region



Waiting point nuclei

Figure 18. The figure shows the range of r-process paths, defined by their waiting point nuclei. After decay to stability the abundance of the r-process progenitors produce the observed solar r-process abundance distribution. The r-process paths run generally through neutron-rich nuclei with experimentally unknown masses and half lives. In this calculation a mass formula based on the ETFSI model and special treatment of shell quenching [79] has been adopted (courtesy of Kratz and Schatz).

r-process

Mass formula -> waiting point nuclei

Beta decay rates at the waiting point nuclei, delayed n-emission probability

Other effects:

neutrino processes: $n(\nu,e^-)p$, $\alpha(\nu,e^-p)^3He$ -> less n -> Y_e increses -> suppression of the 3rd peak of the r-process (Meyer et al.)

reaction rates of α-processes in light nuclei (Kajino et al.) enhanced -> less n -> suppression of the 3rd peak

fission processes (Langanke-Pinedo)

Beta decay half-lives:

Decay rates, Mass

- GT vs GT+FF(first-forbidden)
- SM, QRPA

1. Beta-decays of N=126 isotones

- Gamow-Teller (GT) + First-forbidden (FF) transitions
- Shell-model calculation
- Short half-lives of the isotones compared to the standard ones by Moller

2. Effects on the r-process nucleosynthesis

- Element abundances at 3rd-peak region

3. Dependence of half-lives on quenching factors

Resuts thus far: SM (GT), QRPA, CQRPA etc.
Theoretical half-lives prediction: N=126 scattered

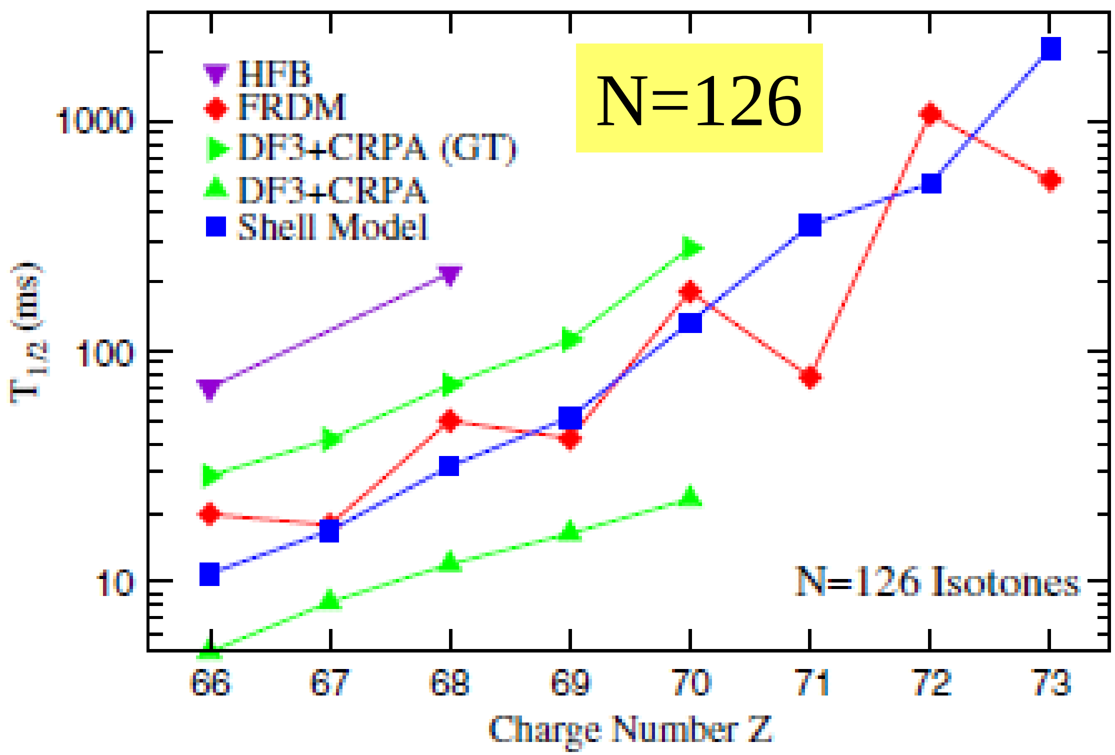


Figure 26. Theoretical half life predictions for $N = 126$ isotones in the shell model [299], the HFB [76], FRDM [57] and the DF3+CQRPA [77] approaches.

N=82

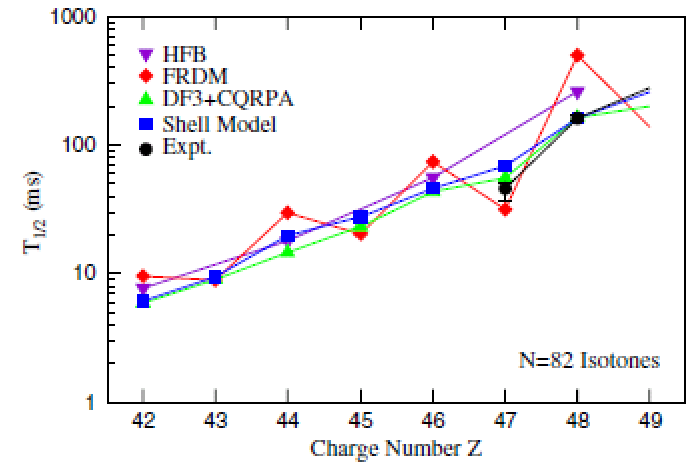


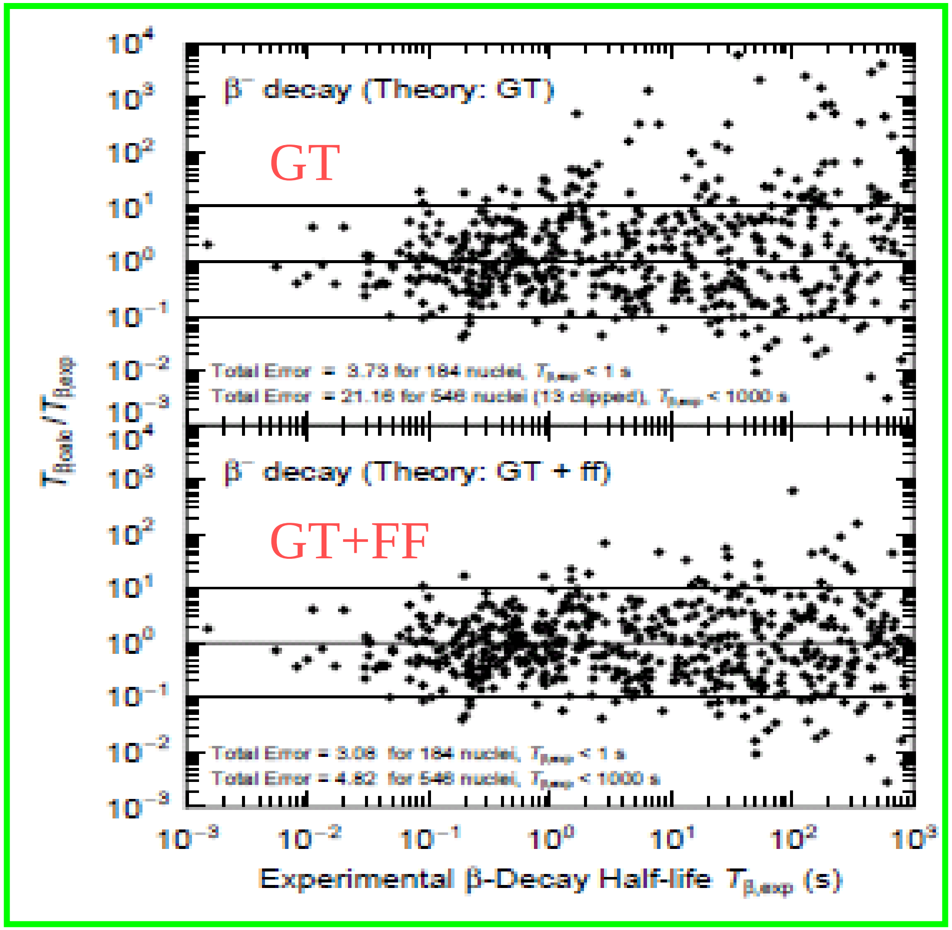
Figure 23. Half lives for $N = 82$ isotones in various approaches HFB [76 DF3+CQRPA [77] and shell model [296] in comparison with experimental data ^{130}Cd [16] and ^{131}In [8].

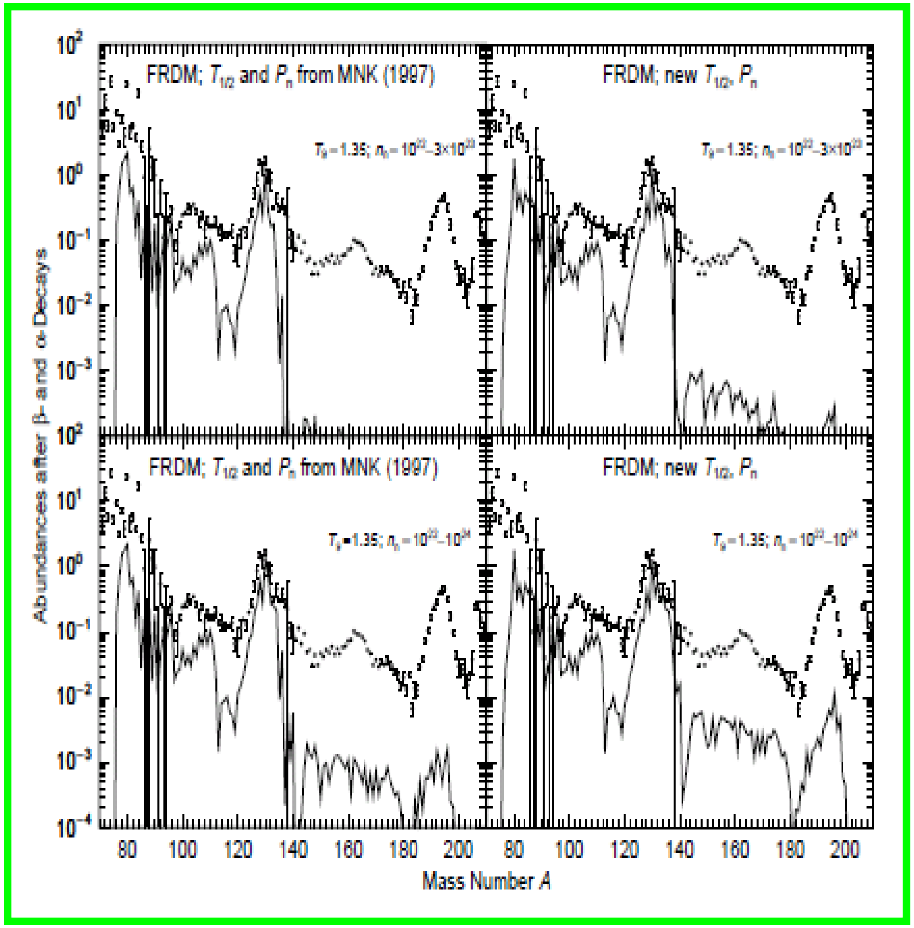
SM (GT): Langanke, Martinez-Pinedo, RMP 75, 819 (2003)
QRPA: Moller, Pfeiffer and Kratz, PR C67, 055802 (2003)
CQRPA: Borzov, PR C67, 025802 (2003)

Grawe, Langanke, Martinez-Pinedo, RPP 70, 1525 (2007)

QRPA

GT GT+FF





Moller, Pfeiffer, Kratz, PR C67, 055802 (2003)

Beta Decays of N=126 Isotones

Z=64-73 (A=190-199)

- **Shell-model calculations:**
  Kuo-Herling G + mod. Steer et al., PR C78, 061302 (2008)
  Ryndstrom et al., NP A512, 217 (1990)
  Energy levels of Z=77-81 nuclei well described

- **GT (1^+) + FF (first-forbidden: 0-, 1-, 2-) transitions**

$$O(1^+) = g_A \sigma t_-$$

$$O(0^-) = g_A [\frac{\sigma \cdot p}{m} + \frac{\alpha Z}{2R} i\sigma \cdot r] t_-$$

$$O(1^-) = [g_V \frac{p}{m} - \frac{\alpha Z}{2R}(g_A \sigma x r - i g_V r)] t_-$$

$$O(2^-) = i \frac{g_A}{\sqrt{3}} [\sigma x r]^2_\mu \sqrt{p_e^2 + q_\nu^2}\, t_-$$

$$\Lambda(s^{-1}) = \ln 2 / t = f / 8896(s)$$

$$f = \int_1^{w_0} C(w) F(Z,w) p w (w_0 - w)^2 dw$$

$$C(w) = K_0 + K_1 w + K_{-1}/w + K_2 w^2$$

$$K_N : \quad \vec{r}, \quad [\vec{r} \times \vec{\sigma}]^\lambda \quad (\lambda = 0,1,2)$$

$$\gamma_5, \quad \vec{\alpha}$$

Warburton et al., Ann.Phys. 187 (1988)

Structure of N=126 Isotones

- **Shell-model calculations of proton-hole states of 208Pb**
  Kuo-Herling G + mod.
  proton hole config.: 2s1/2, 1d3/2, 0h11/2, 1d5/2, 0g7/2

Energy levels of Z=77-81 nuclei well described

PHYSICAL REVIEW C 78, 061302(R) (2008)

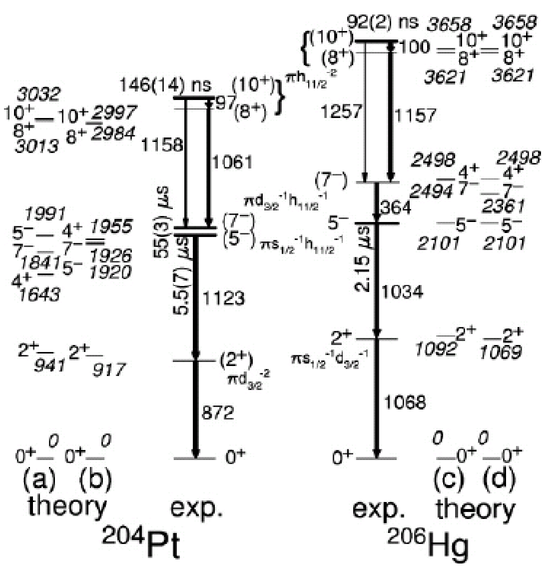


FIG. 3. Experimental and calculated partial level schemes of the $N = 126$ ^{204}Pt and ^{206}Hg [9] nuclei. Arrow widths denote relative intensities of parallel decay branches. The dominant state configurations are indicated. (a) and (d) are calculations using the Rydström matrix elements, while (b) and (c) are with the modified ones, as described in the text.

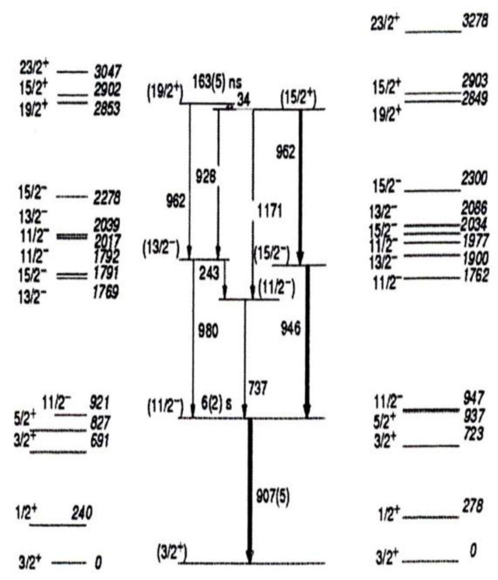


FIGURE 3. Experimental (middle) and calculated level schemes of ^{205}Au. Calculations using Rydsrtöm matrix elements are shown on the left, while calculations with the modified TBMEs are the right hand side.

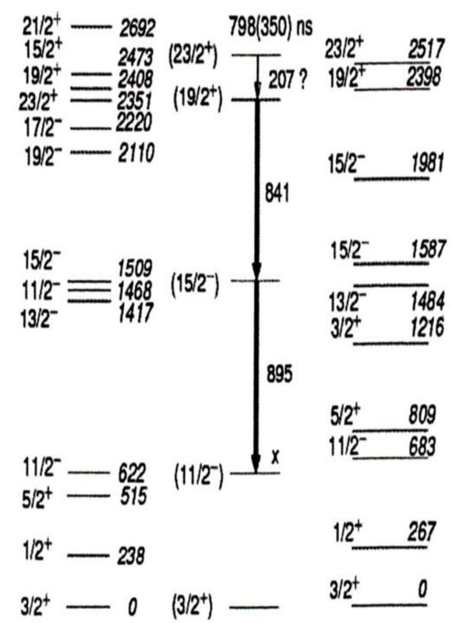


FIGURE 4. Same as figure 3, but for ^{203}Ir. The experimental level scheme is preliminary

$$\Lambda(s^{-1}) = \ln 2 / t = f / 8896(s)$$

$$f = \int_1^{w_0} C(w) F(Z, w) p w (w_0 - w)^2 dw$$

$$C(w) = K_0 + K_1 w + K_{-1} / w + K_2 w^2$$

$$K_N : \quad \vec{r}, \quad [\vec{r} \times \vec{\sigma}]^{\lambda} \quad (\lambda = 0, 1, 2)$$

$$\gamma_5, \quad \vec{\alpha}$$

Warburton et al., Ann.Phys.187 (1988)
Behrens and Buring, NP A162 (1971)
Schopper, (North-Holland, 1966)

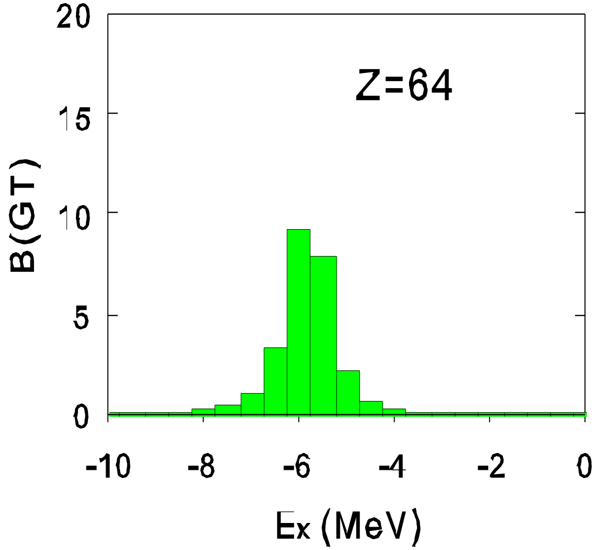
- **GT (1^+)**

$$K_0 = \frac{1}{2J_i + 1} |\langle f \| g_A \sigma t_- \| i \rangle|^2$$

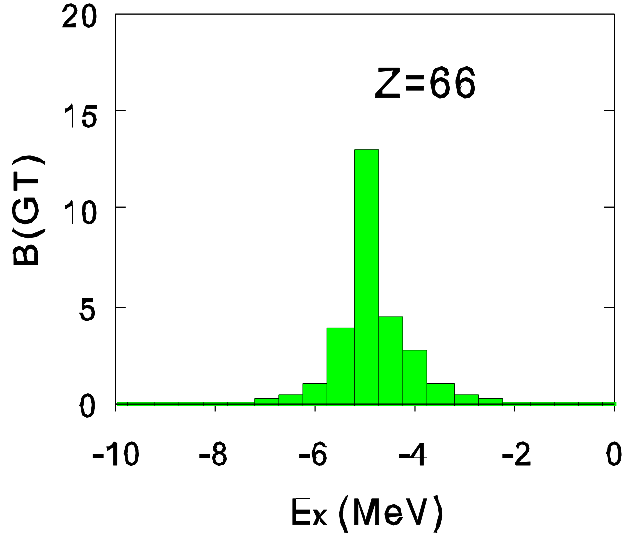
$$q = g_A^{eff} / g_A < 1$$

$$\nu 0h9/2 \rightarrow \pi 0h11/2$$

GT strengths



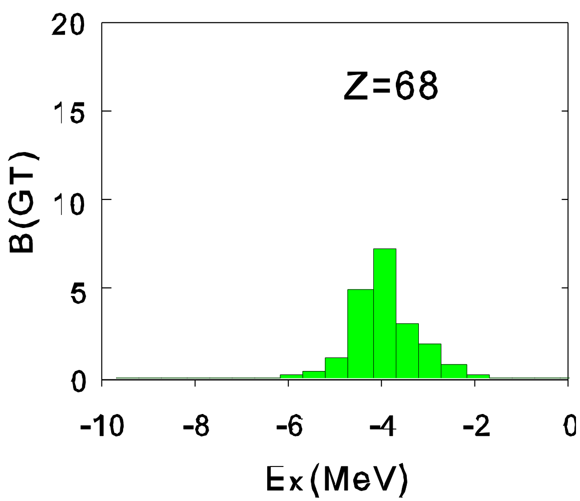
∑B(GT)=14.4



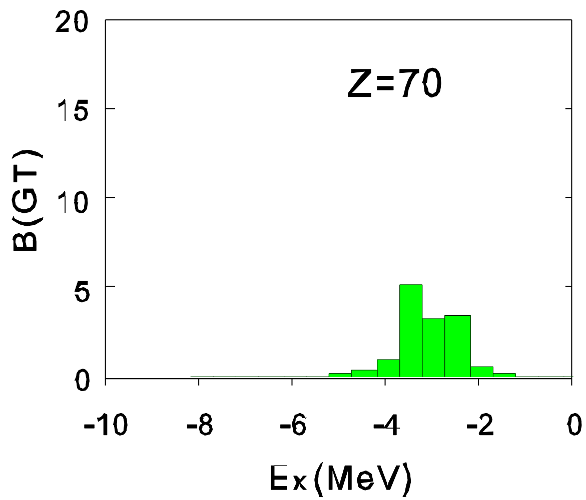
∑B(GT)=14.6

$Q = g_A^{eff}/g_A = 0.7$

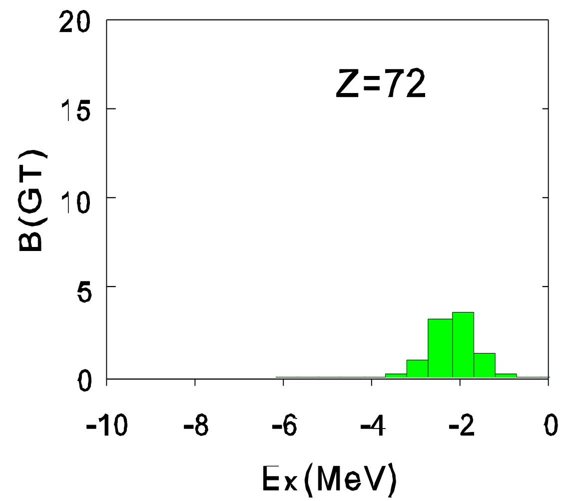
$E_x = 0 \longleftrightarrow$ g.s. of the parent nuclei



∑B(GT)=11.7



∑B(GT)=8.5



∑B(GT)=5.6

0^- Expansions in (p_eR), (WR), (αZ), $(q_\nu R)$, (m_eR), (P_N/M_N)

$$M_0^S = -g_A\sqrt{3} < J_f T_f \| i[r\cdot\sigma]^0 t_- \| J_i T_i > C \quad \leftrightarrow \quad g_A i\sigma\cdot r$$

$$M_0^T = -g_A < J_f T_f \| \gamma_5 t_- \| J_i T_i > C \quad \leftrightarrow \quad g_A \frac{\sigma\cdot p}{m}$$

$$C = 1/\hat{J}_i$$

$$\varepsilon = g_A^{eff}/g_A = 1.5-2.0 \quad \text{in} \quad M_0^T(\gamma_5): \quad \text{MEC}$$

Warburton, PR C44, 233 (1991), Warburton, Towner, Brown, PR C49, 824 (1994)

$$O(0^-) = g_A\left[\frac{\sigma\cdot p}{m} + \frac{\alpha Z}{2R} i\sigma\cdot r\right]t_-$$

$$K_0 = \varsigma_0^2 + \frac{1}{9}(M_0^S)^2$$

$$K_{-1} = -\frac{2}{3}\mu_1\gamma_1\varsigma_0 M_0^S$$

$$\varsigma_0 = V + \frac{1}{3}M_0^S W_0, \quad V = M_0^T + \varsigma M_0^S$$

: finite nuclear charge distribution effect

$$\varsigma = \frac{\alpha Z}{2R}, \quad \gamma_1 = \sqrt{1-(\alpha Z)^2}, \quad \mu_1 \approx 1 \ \ (1.0-0.9)$$

(Calculations are done with all the K_0, K_{-1} terms)

▪ 1^-

$$x = < J_f T_f \| irt_- \| J_i T_i > C \quad \leftrightarrow \quad g_V ir$$

$$u = -g_A \sqrt{2} < J_f T_f \| i[rx\sigma]^1 t_- \| J_i T_i > C \quad \leftrightarrow \quad g_A rx\sigma$$

$$\varsigma' y = - < J_f T_f \| \alpha t_- \| J_i T_i > C \quad \leftrightarrow \quad g_V \frac{p}{m}$$

$$q = g_A^{eff} / g_A < 1$$

$$K_0 = \varsigma_1^2 + \frac{1}{9}(x+u)^2 - \frac{4}{9}\mu_1\gamma_1 u(x+u) + \frac{1}{18}W_0^2(2x+u)^2 - \frac{1}{18}\lambda_2(2x-u)^2$$

$$K_1 = -\frac{4}{3}uY - \frac{1}{9}W_0(4x^2+5u^2)$$

$$K_{-1} = \frac{2}{3}\mu_1\gamma_1\varsigma_1(x+u)$$

$$K_2 = \frac{1}{18}(8u^2 + (2x+u)^2 + \lambda_2(2x-u)^2$$

$$\varsigma_1 = Y + \frac{1}{3}(u-x)W_0, \quad Y = \varsigma' y - \varsigma(u' + x')$$

$$\lambda_2 \approx 0.7 - 1.0 \quad (p > 0.5)$$

$$O(1^-) = [g_V \frac{p}{m} - \frac{\alpha Z}{2R}(g_A \sigma xr - ig_V r)]t_-$$

' :finite nuclear charge distribution effect

(Calculations are done with all theK_0, K_1, K_{-1},K_2 terms)

▪ 2^-

$$z = 2g_A < J_f T_f \| i[rx\sigma]^2 t_- \| J_i T_i > C \quad \leftrightarrow \quad g_A[rx\sigma]^2$$

$$q = g_A^{eff} / g_A < 1$$

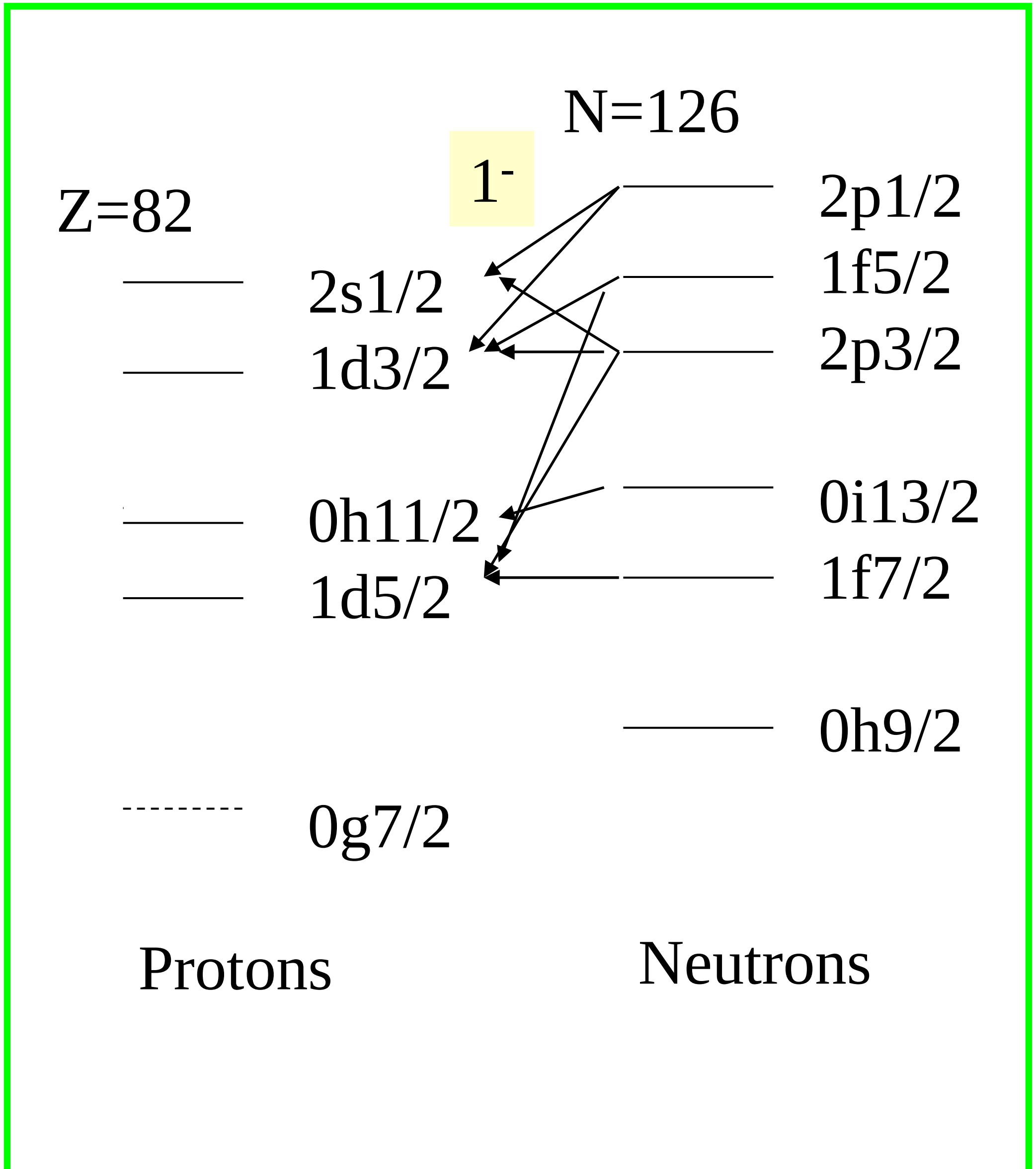
$$K_0 = \frac{1}{12} z^2 (W_0^2 - \lambda_2)$$

$$K_1 = -\frac{1}{6} z^2 W_0$$

$$K_2 = \frac{1}{12} z^2 (1 + \lambda_2)$$

$$O(2^-) = i \frac{g_A}{\sqrt{3}} [\sigma x r]^2_\mu \sqrt{p_e^2 + q_\nu^2}\, t_-$$

(Calculations are done with all the K_0, K_1, K_2 terms)



e.g.

Z=64 (18 proton-holes)

orbit	number of holes
2s1/2	0-2
1d3/2	2-4
0h11/2	10-12
1d5/2	0-2
0g7/2	0
sum	18

0p-0h+2p-2h

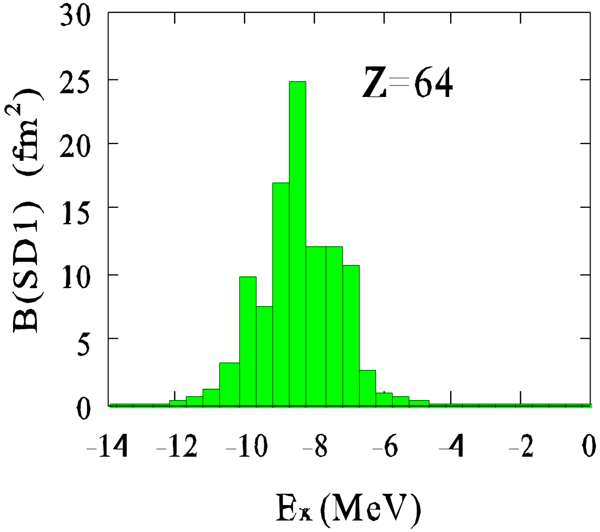
Z=68 (14 proton-holes)

orbit	number of holes
2s1/2	0-2
1d3/2	2-4
0h11/2	8-10
sum	14

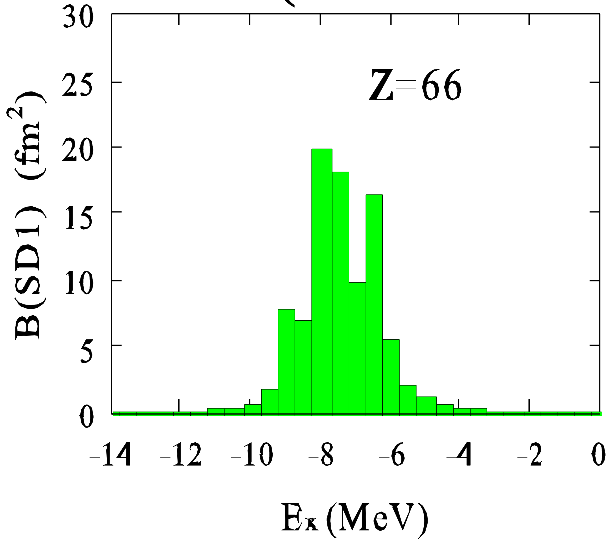
8 10

0p-8h+2p-10h

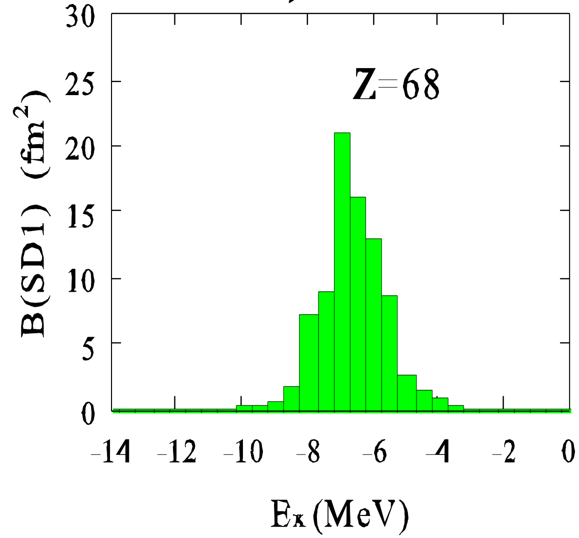
SD (1^-) strengths (folded over a Lorenzian)



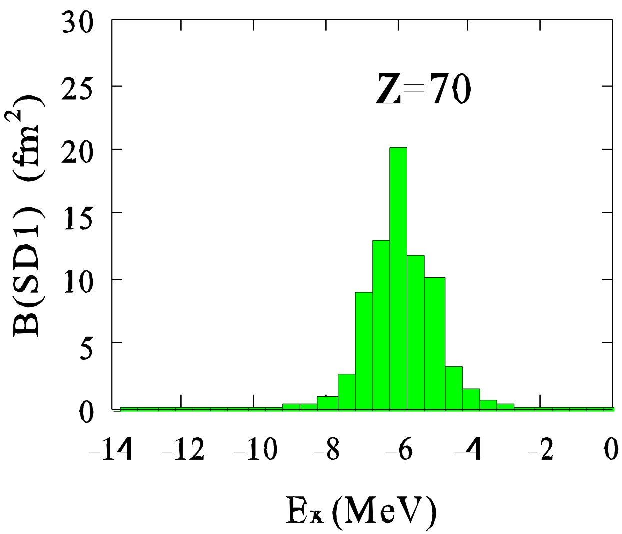
ΣSD1=55.5 fm^2



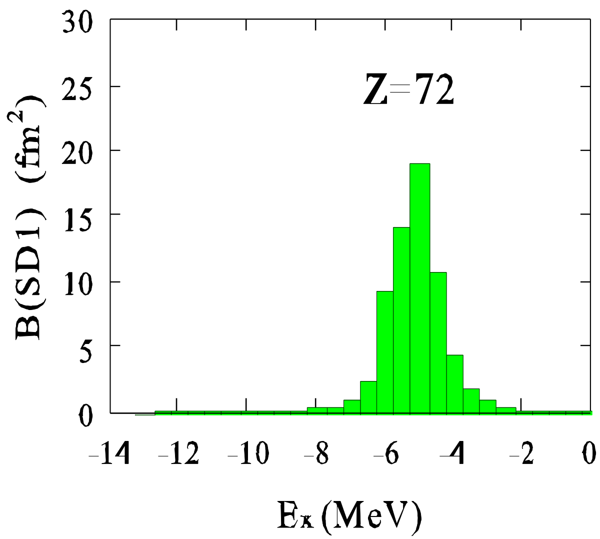
ΣSD1=49.2 fm^2



ΣSD1=43.9 fm^2



ΣSD1=40.1 fm^2



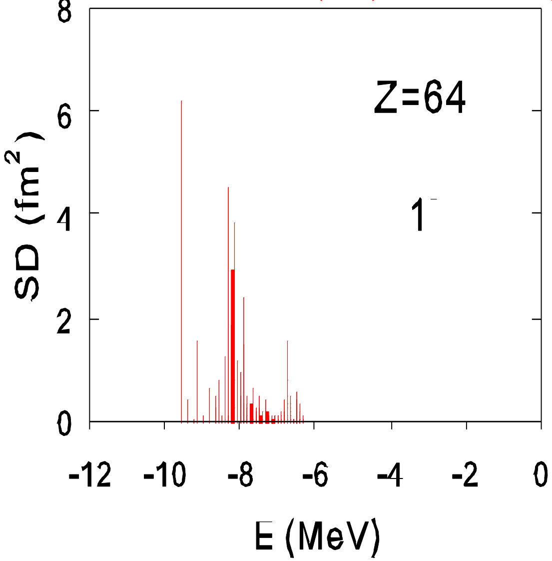
ΣSD1=35.1 fm^2

SD 1^-

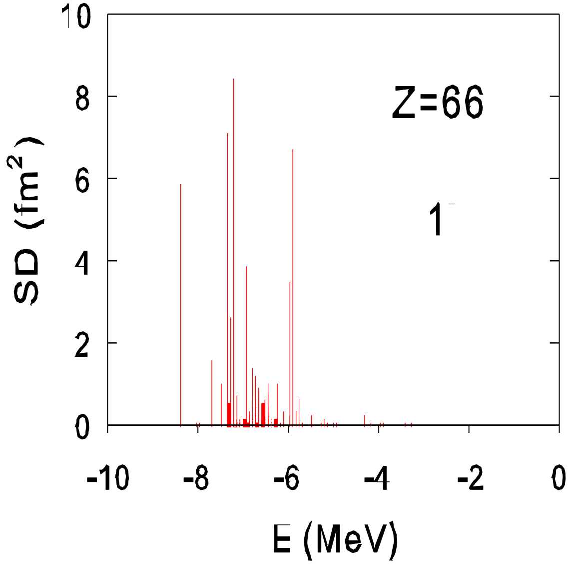
$O=r[Y_1 x \boldsymbol{\sigma}]^1 t_-$

E=0: g.s. of the parent nuclei

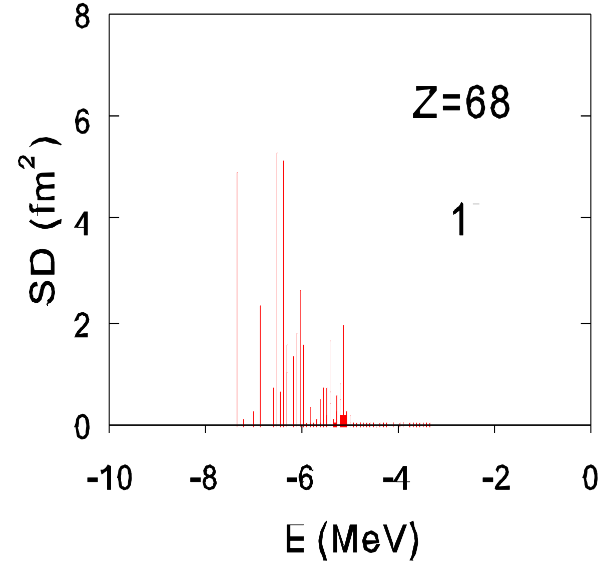
SD (1^-) strengths



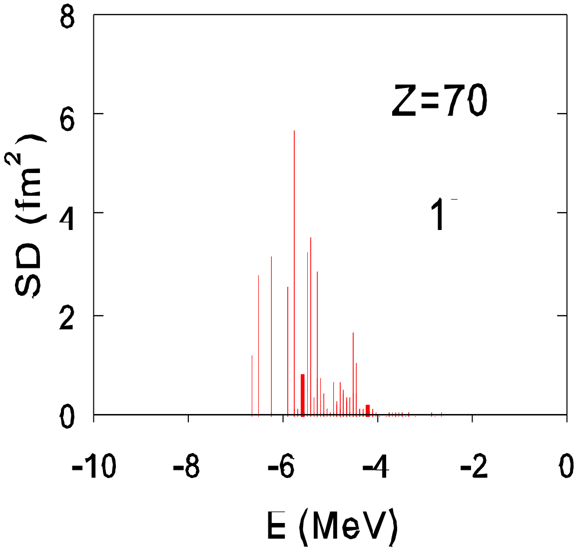
ΣSD1=55.5 fm²



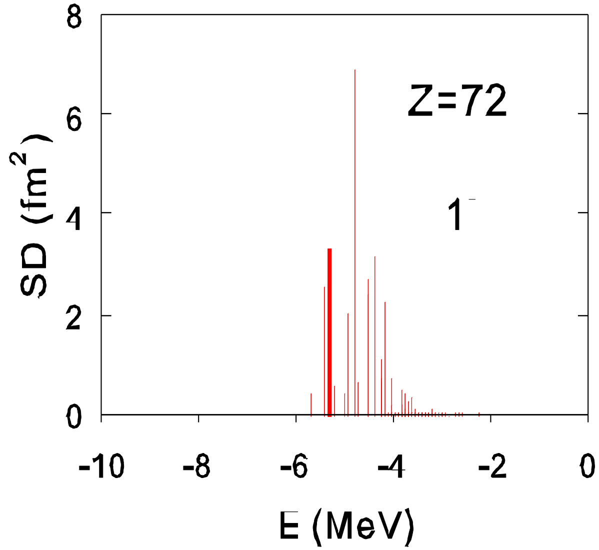
ΣSD1=49.2 fm²



ΣSD1=43.9 fm²



ΣSD1=40.1 fm²



ΣSD1=35.1 fm²

SD 1^-

$r[Y_1 x \boldsymbol{\sigma}]^1$

E=0: g.s. of the parent nuclei

SD+E1 (1^-) strengths

spin part only

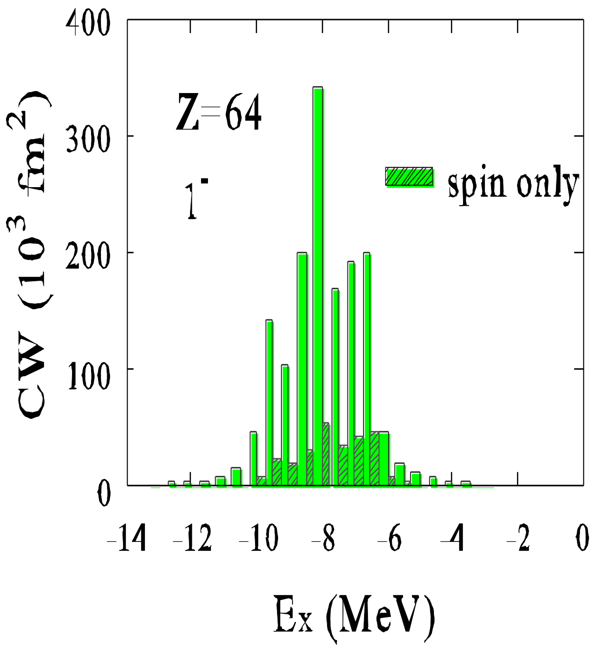
$$\overline{C(w)} = f/f_0$$

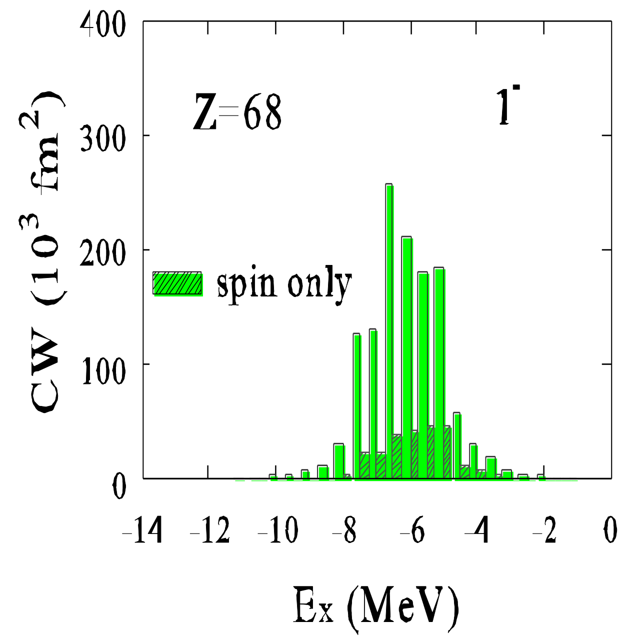
$$f_0 = \int_1^{w_0} F(Z,w)pw(w_0-w)^2 dw$$

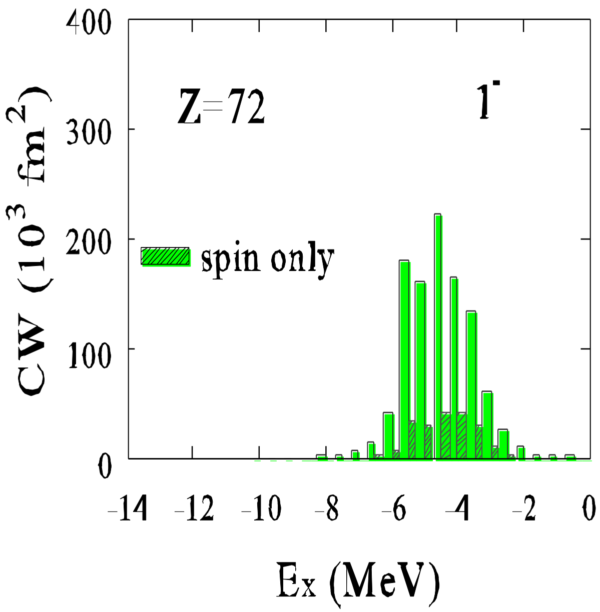
$$f = \int_1^{w_0} C(w)F(Z,w)pw(w_0-w)^2 dw$$

$$C(w) = K_0 + K_1 w + K_{-1}/w + K_2 w^2,$$

$$\overline{C(w)} = \frac{9195 \times 10^5}{fot} \quad (\mathrm{fm}^2).$$





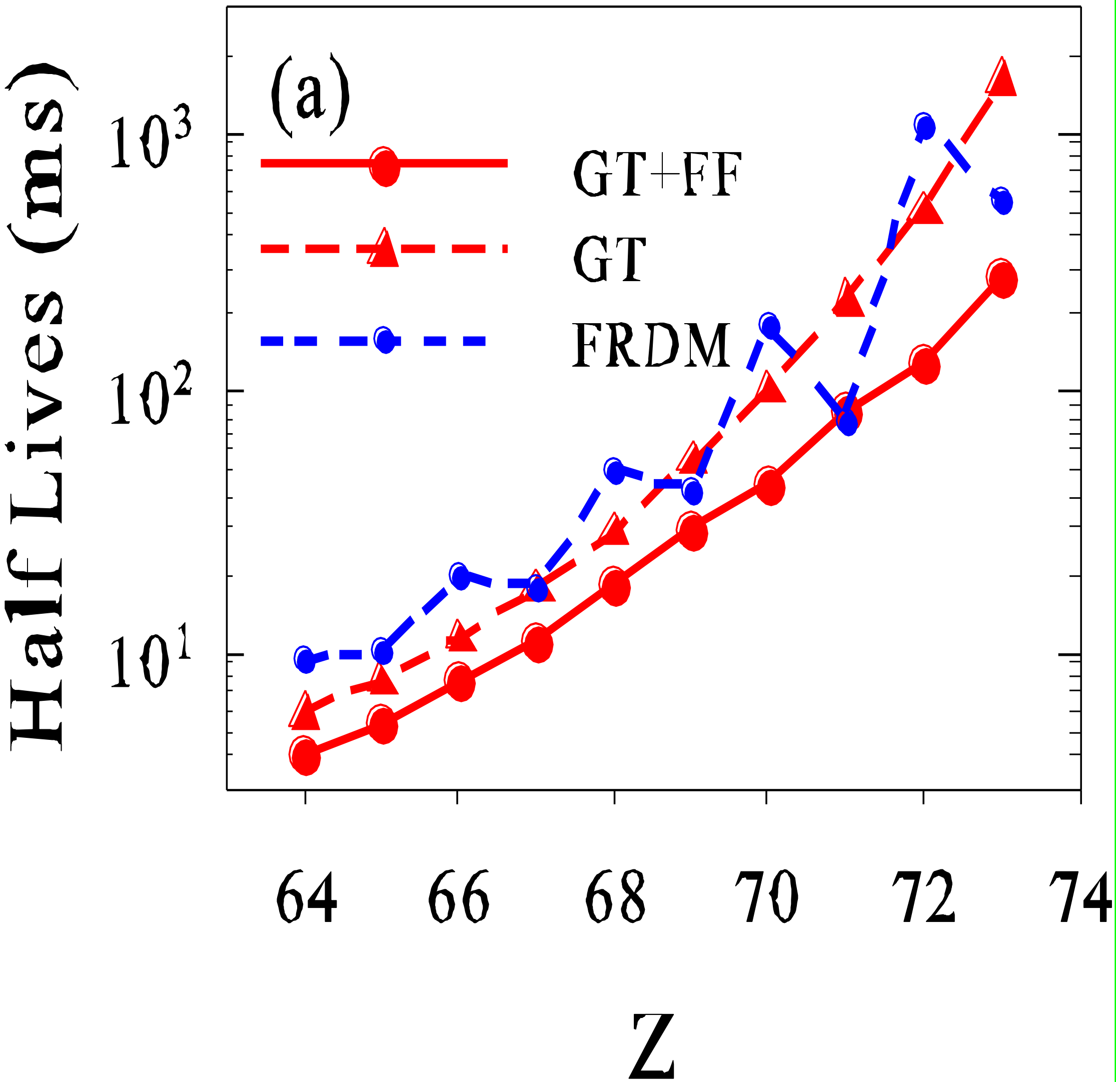


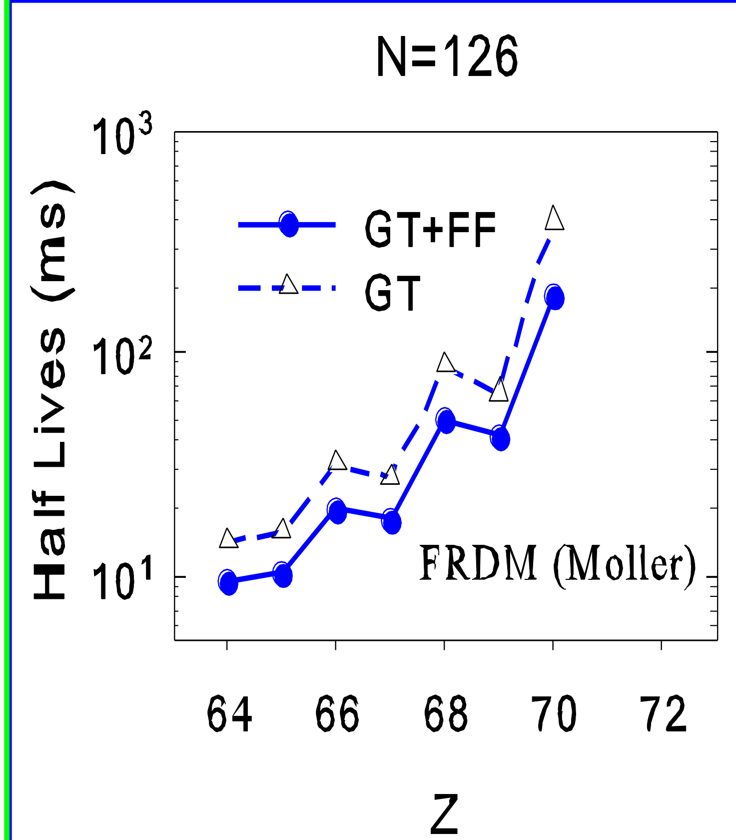
$Q = g_A^{eff}/g_A = 0.7$

E=0: g.s. of the parent nuclei

Shell Model calculations

cf.

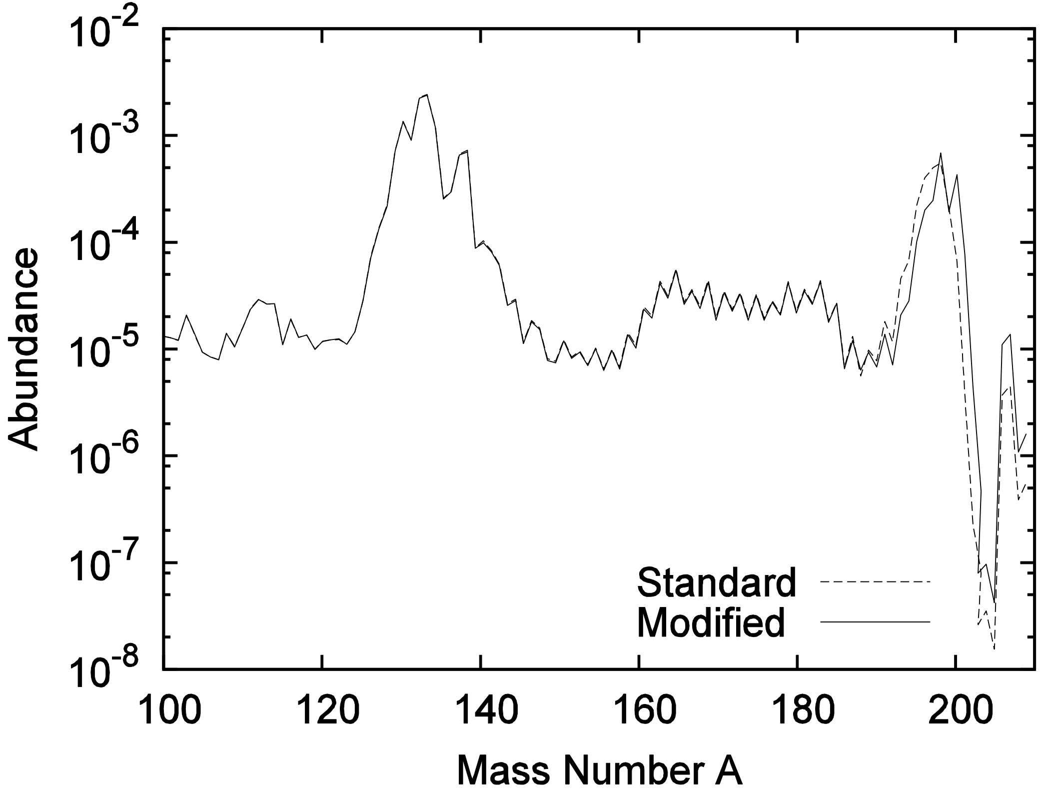




Moller, Pfeiffer, Kratz,
PR C 67, 055802 (2003)

$Q=g_A^{eff}/g_A=0.7$, ε =2.0 (0^-)

Neumann-Cosel et al, PRL 82 (1999)
$Q=g_s^{eff}/g_s=0.64$: 2- in ^{90}Zr (e-scatt.)

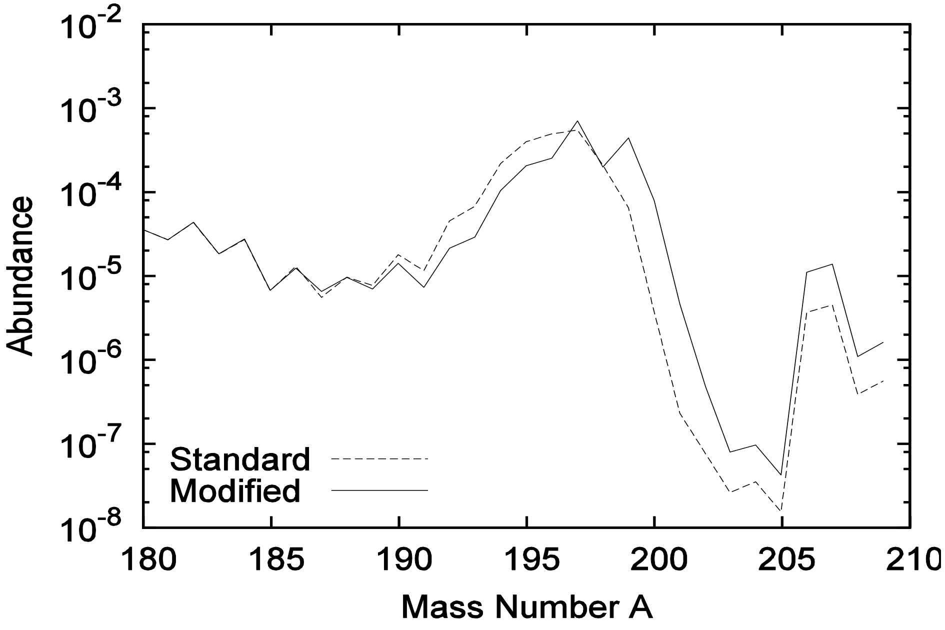


r-process nucleosynthesis

Constant Entropy Wind Model
$L_\nu = 0.5 \times 10^{51}$ erg/s
$S = 133\ k_B\ (\gamma, e^-, e^+)$
$dm/dt = 2.34 \times 10^{-6}\ M_{sun}$

$\tau = 5.60$ ms for $T_9 = 5 \rightarrow T_9 = 2$
$T_{9f} = 0.8$

Neutrino processes on n, p and ^{4}He are included



Half-lives:
- - - Standard (Moller et al.)
—— Modified

Large quenchings are favored in A =206

$(g_A^{eff}/g_A,\ g_V^{eff}/g_V)=(0.34,\ 0.67)$

$(0.51,\ 0.30)$

$(0.47,\ 0.64)$

Warburton, PR C 44, 233 (1991)

PR C42, 2479 (1990)

Rydstrom, NP A512, 217 (1990)

$$\overline{C(w)} = f/f_0$$

$$f_0 = \int_1^{w_0} F(Z,w)pw(w_0-w)^2 dw$$

$$f = \int_1^{w_0} C(w)F(Z,w)pw(w_0-w)^2 dw$$

$$C(w) = K_0 + K_1 w + K_{-1}/w + K_2 w^2,$$

$$\overline{C(w)} = \frac{9195 \times 10^5}{f_0 t} \quad (\mathrm{fm}^2).$$

Transitions		Values of g_A and g_V		$\log f_0 t$	$\sqrt{\overline{C(w)}}$ (fm)
Initial	Final	ϵ for 0^-	$(g_A/g_A^{free}, g_V/g_V^{free})$ for 1^-		
^{206}Hg (0^+)	^{206}Tl (0^- g.s.)	2.0		5.199 (5.087)	76.3 (86.8)
		1.8		5.432 (5.320)	58.3 (66.3)
		Ref. [21]		5.173	78.6
	Expt. [28]			5.41	59.8
^{206}Hg (0^+)	^{206}Tl (1^-, 0.3049 MeV)		(a) (0.34, 0.67)	5.017 (4.929)	94.0 (104.1)
			(b) (0.51, 0.30)	5.157 (5.127)	80.0 (82.9)
			(c) (0.47, 0.64)	4.921 (4.832)	105.0 (116.4)
			(0.34, 0.40)	5.267 (5.178)	70.5 (78.2)
			Ref.[21]	5.181	77.9
	Expt.[28]			5.24	72.7

A=205

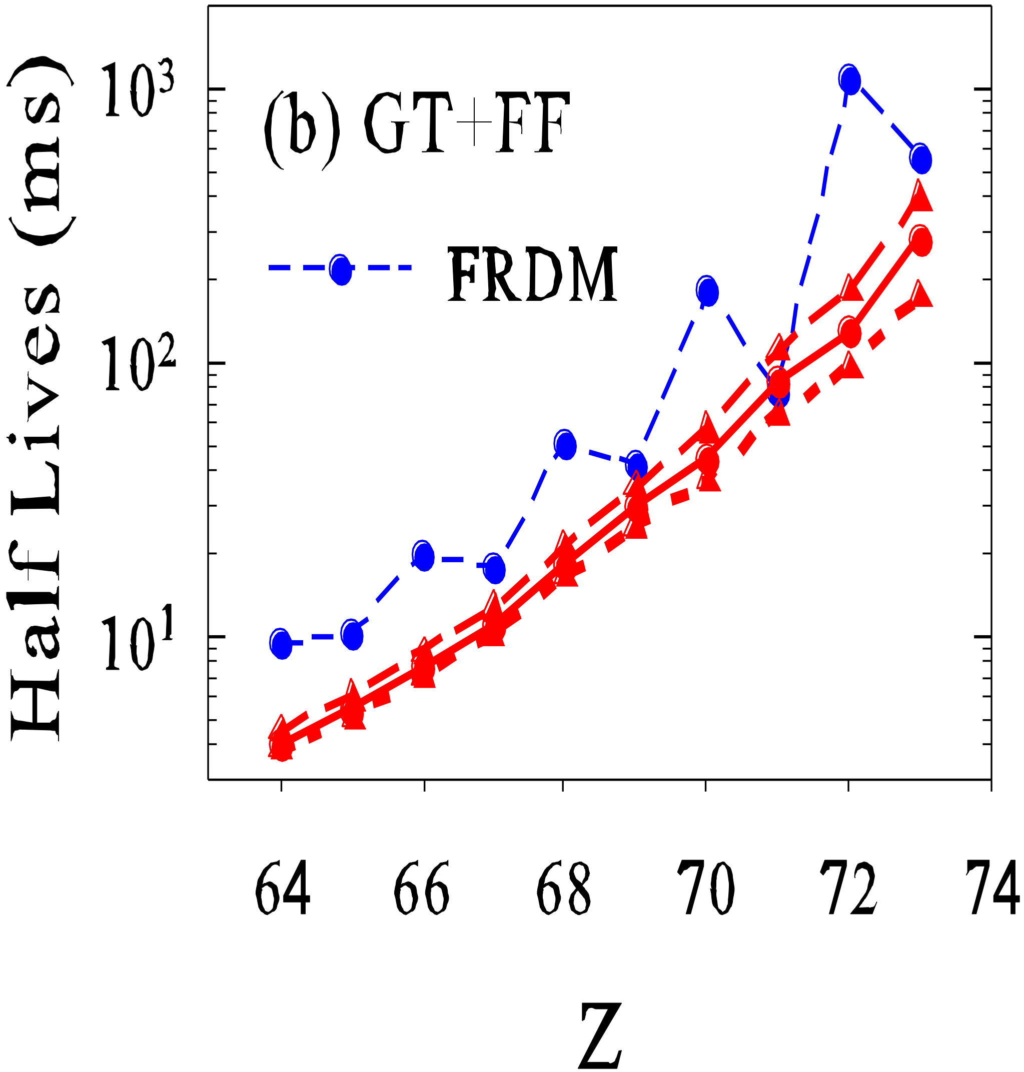
^{205}Au ($3/2^+$)	^{205}Hg ($1/2_1^-$)		(a) (0.34, 0.67)	6.197 (6.116)	24.2 (26.5)
			(b) (0.51, 0.30)	8.171 (7.834)	2.49 (3.67)
			(c) (0.47, 0.64)	6.412 (6.326)	18.9 (20.8)
			(0.34, 0.94)	5.793 (5.726)	38.7 (41.6)
	Expt.[28]			5.79	38.6
^{205}Au ($3/2^+$)	^{205}Hg ($3/2_1^-$, 0.4675 MeV)				
	0^-	2.0		5.674 (5.541)	44.1 (51.5)
		1.45		6.832 (6.699)	11.6 (13.6)
	$0^- + 1^-$	1.45	(a) (0.34, 0.67)	6.502 (6.247)	17.0 (22.8)
		1.45	(b) (0.51, 0.30)	6.000 (5.870)	30.3 (35.2)
		1.45	(c) (0.47, 0.64)	6.266 (6.073)	22.3 (27.9)
		1.45	(0.34, 0.94)	6.425 (6.173)	18.6 (24.9)
	Expt.[28]			6.43	18.5

A=204

Transitions		Values of g_A and g_V		Half-life (s)
Initial	Final	ϵ for 0^-	$(g_A/g_A^{free}, g_V/g_V^{free})$ for 1^-	
^{204}Pt (0^+)	^{204}Au (0^-)	2.0		65.1 (62.0)
^{204}Pt (0^+)	^{204}Au ($0^- + 1^-$)	2.0	(a) (0.34, 0.67)	22.8 (18.6)
		2.0	(b) (0.51, 0.30)	31.8 (26.9)
		2.0	(c) (0.47, 0.64)	21.1 (17.1)
		2.0	(0.7, 1.0)	10.9 (8.6)
		2.0	(0.34, 1.0)	14.4 (11.3)
		2.0	(0.51, 1.0)	12.7 (10.0)
	Expt.[28]			10.3±1.4

$$\overline{C(w)} = \frac{9195 \times 10^5}{f_0 t} \quad (\mathrm{fm}^2).$$

$$f_0 = \int_1^{w_0} F(Z,w) p w (w_0 - w)^2 dw$$

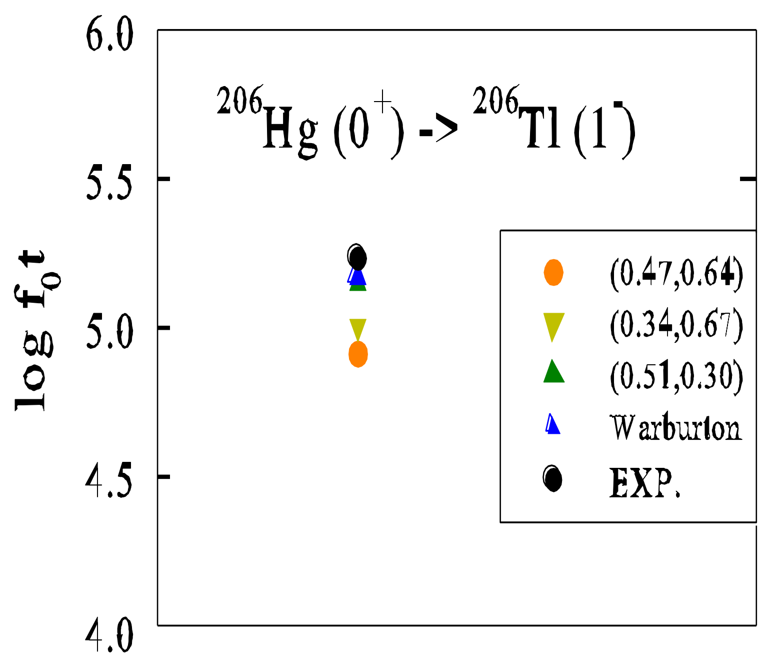


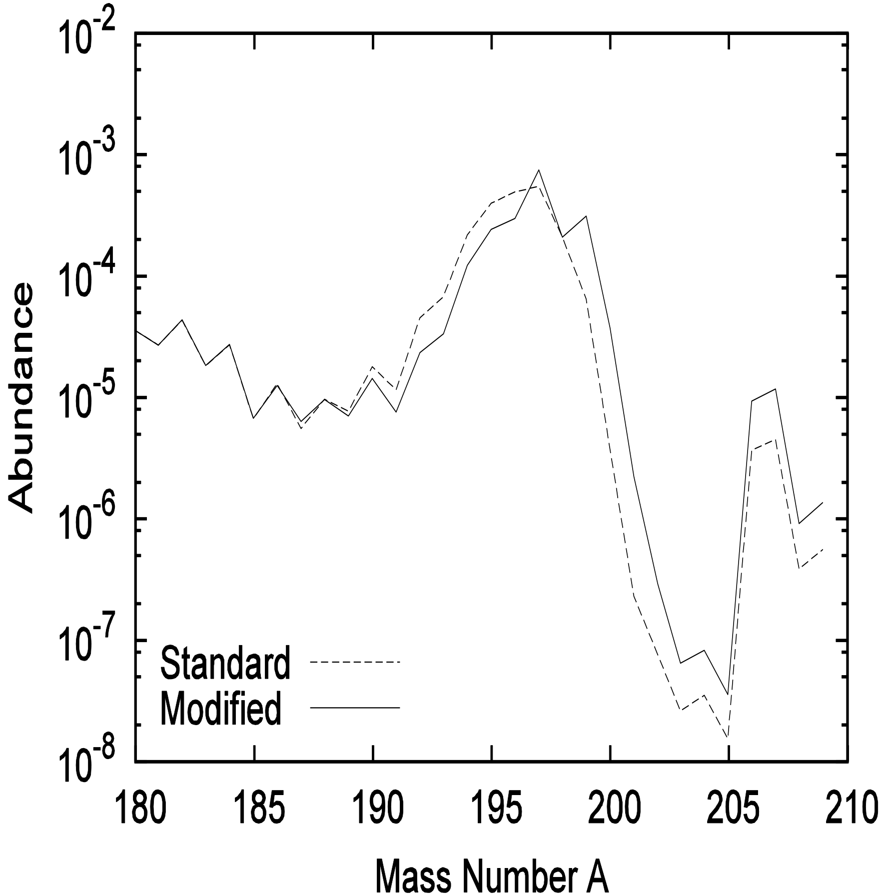
$g_A^{eff}/g_A = 0.34$, $g_V^{eff}/g_V = 0.67$

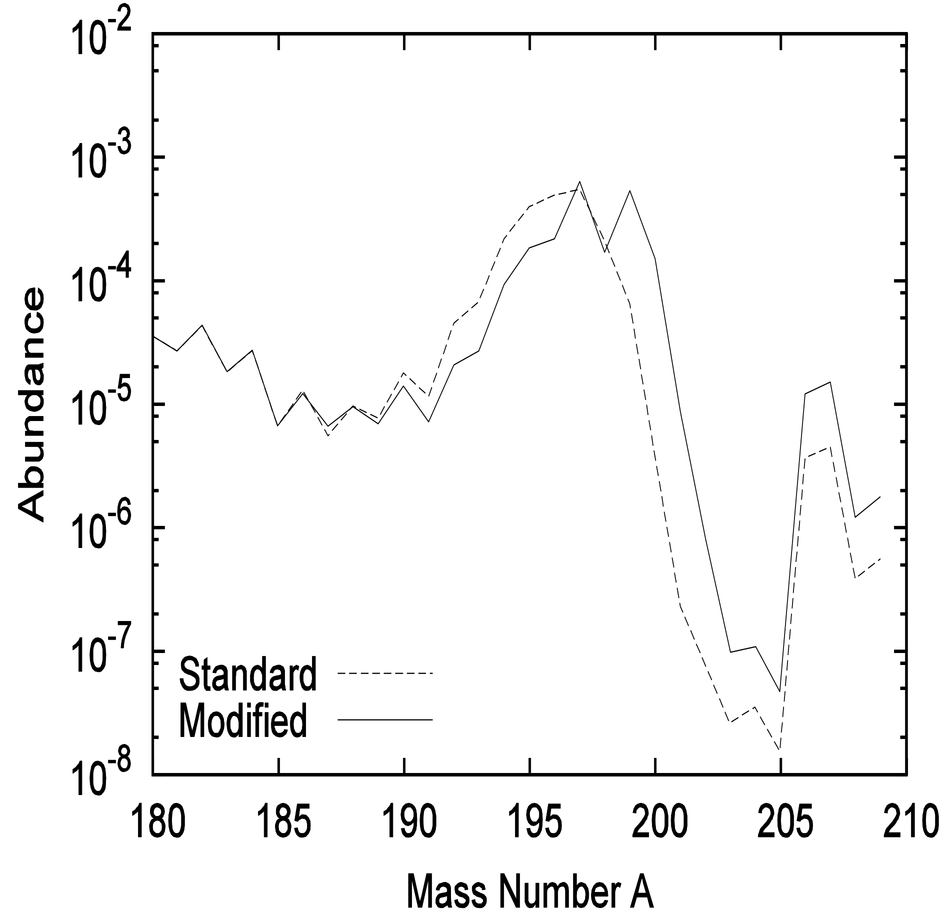
$+ \Delta Q = 1.0$ MeV

Large quenchings are favored in A =206
$(g_A^{eff}/g_A, g_V^{eff}/g_V) = (0.34, 0.67)$, $(0.51, 0.30)$, $(0.47, 0.64)$

Warburton, PR C 44, 233 (1991)
PR C42, 2479 (1990)
Rydstrom, NP A512, 217 (1990)







$g_A^{eff}/g_A = 0.34$, $g_V^{eff}/g_V = 0.67$

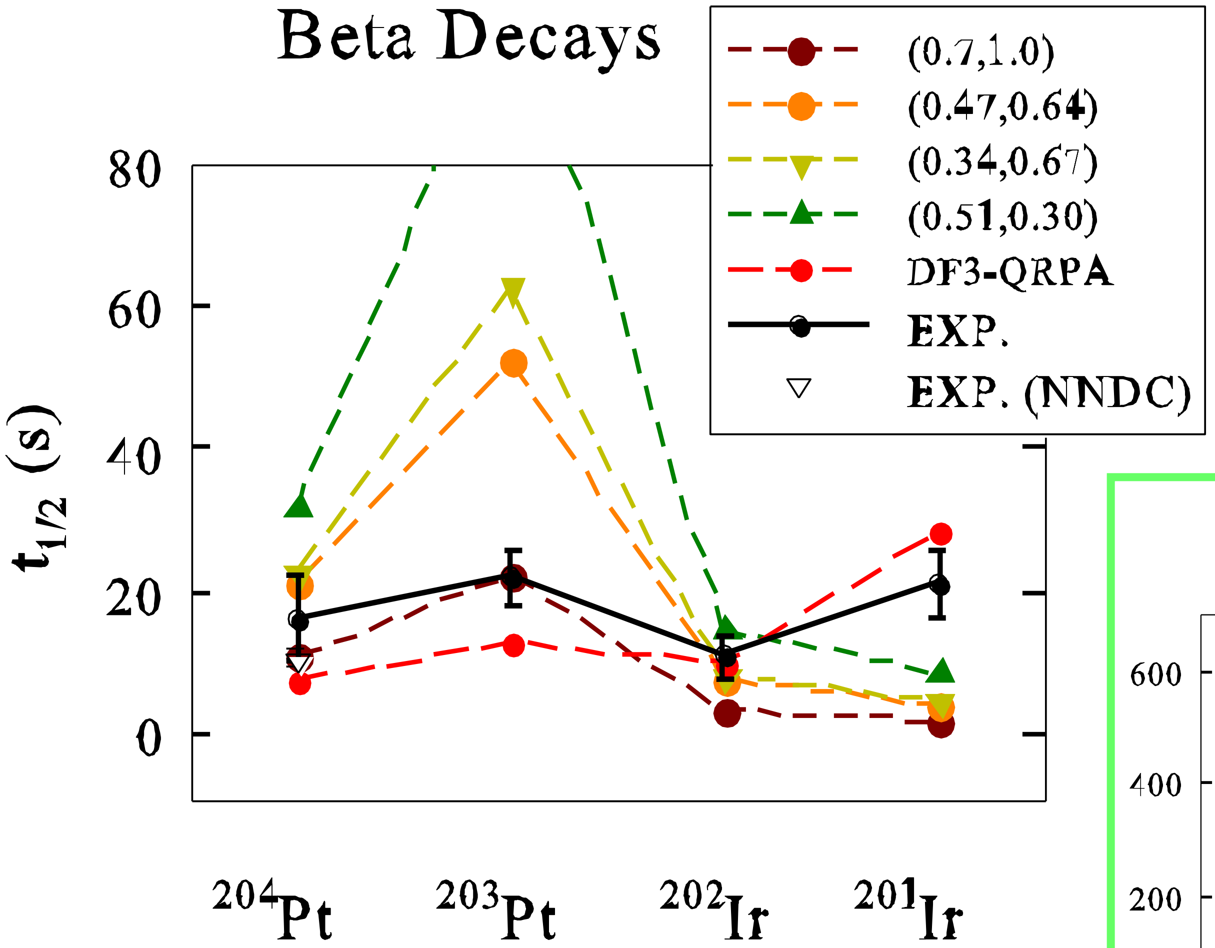
$+\,\Delta Q = 1.0$ MeV

Half-lives:

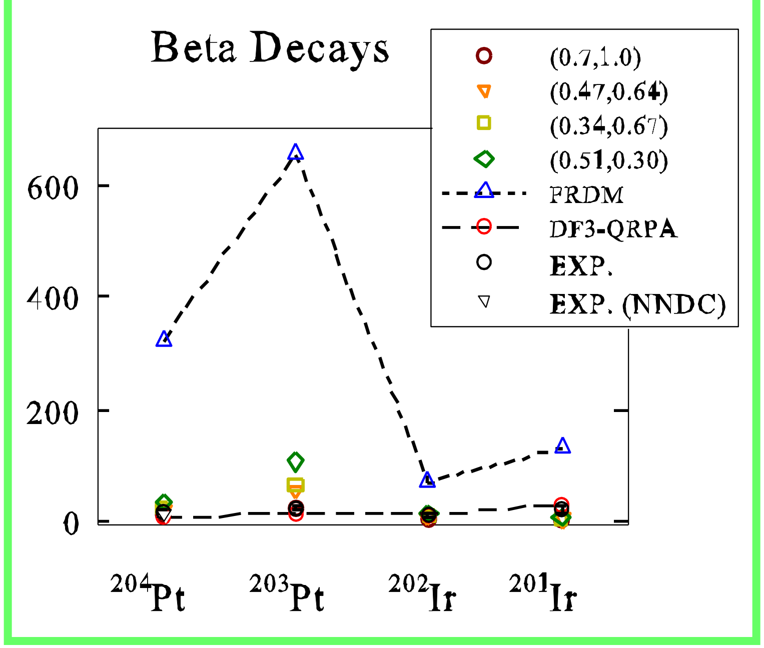
- - - Standard (Moller et al.)

—— Modified

Dependence on (g_A^{eff}/g_A, g_V^{eff}/g_V)



Exp: Benlliure et al.



Summary

· **Shell model calculations for beta-decay half-lives including both GT and FF transitions**
→ Short half-lives for beta decays of N=126 isotones (waiting point nuclei for the r-process) compared to a standard model (FRDM)

→ The 3rd peak of the r-process element abundances is shifted toward larger mass number region.

Quenchings of g_A and g_V in FF need further study

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Suzuki, Yoshida, Kajino, Otsuka, PR C85, 015802 (2012)