High-K ground states and isomers in superheavy nuclei

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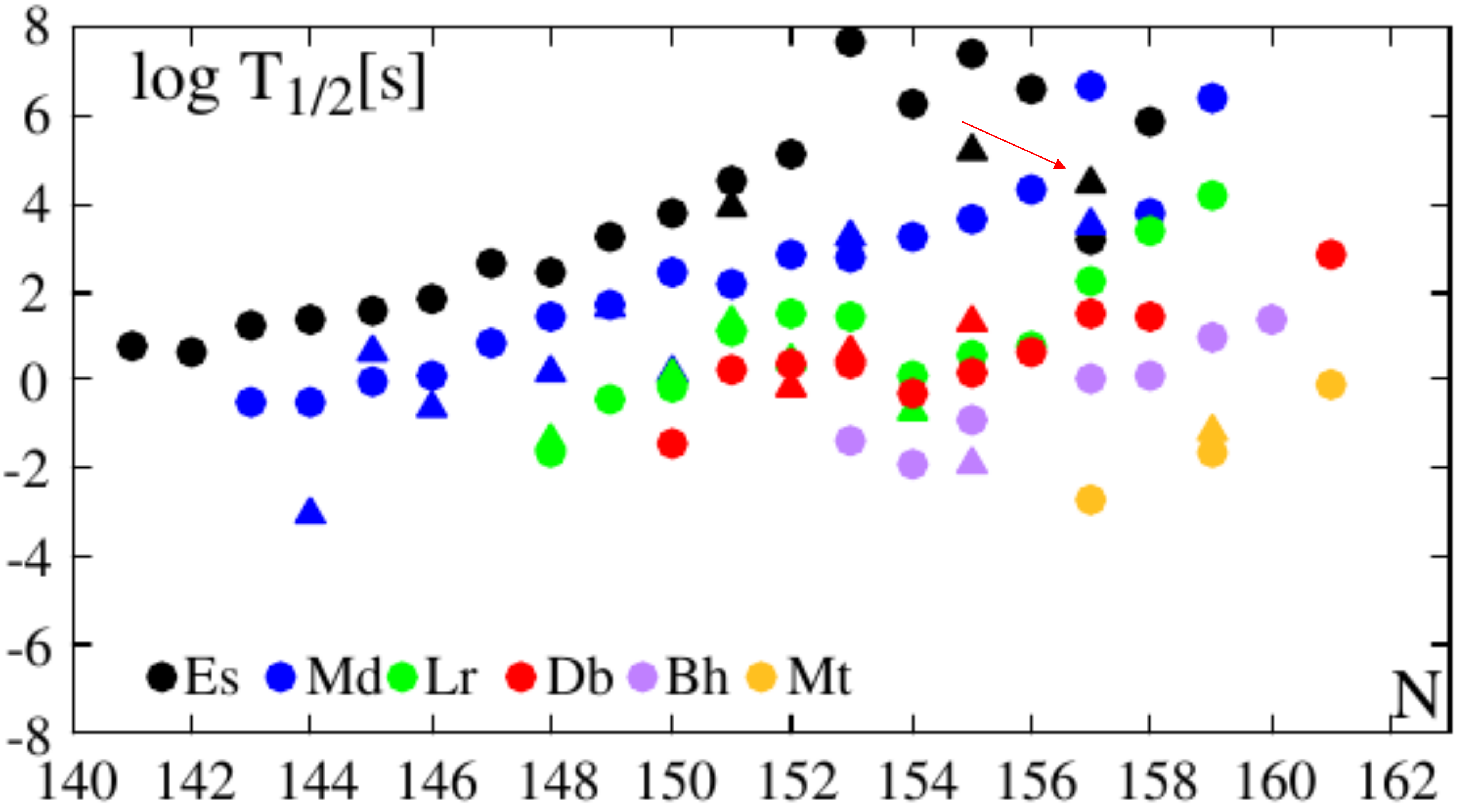
A. Motivation – how long-lived could be high-K (near) ground states and isomers in SHN?
B. Method
C. Candidates for high-K g.s. in (mostly) odd-odd nuclei
D. Candidates for 3qp K-isomers in odd-even Z=101-111, N=142-166
E. Candidates for 3qp K-isomers in even-odd Z=100-112, N=141-167

- K-isomers provide some information on the level scheme /deformation of nuclei.
- There is a hope that some SH K-isomers could be more stable than the g.s., especially if their structure, shape etc. would make fission and alpha decay less probable, e.g. F.R.Xu at al. Phys. Rev. Lett. 92 (2004) 252501, and others.

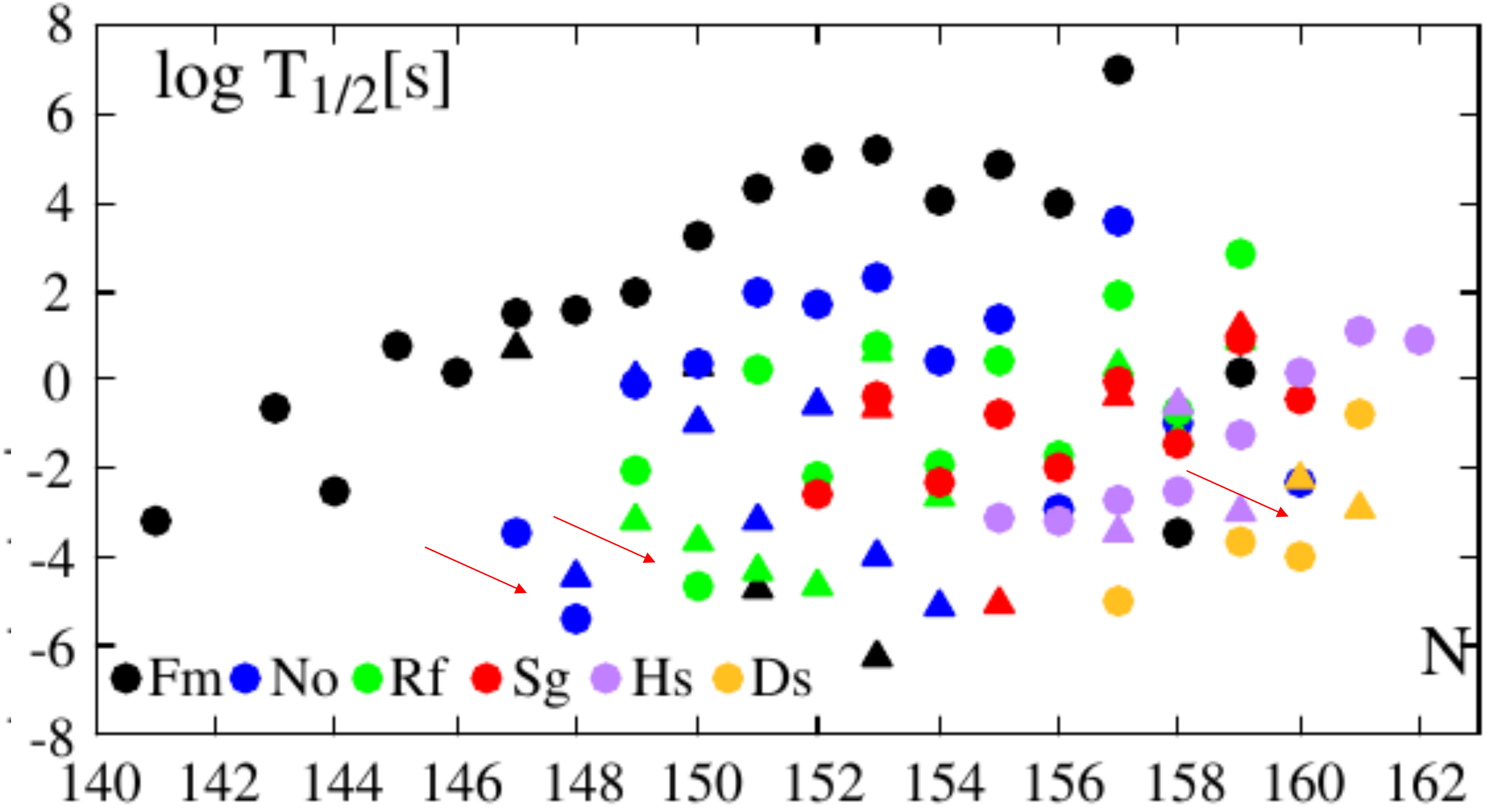
Heavy isomers living longer than the g.s. :

	g.s.			is.		
^{256}Es	$(1^+, 0^-)$	25.4 m	β^-	(8^+)	7.6 h	β^-
^{250}No	0^+	3.8 μs	sf	(6^+)	35 μs	IT
^{254}Rf	0^+	23.2 μs	sf	(16^+)	247 μs	IT
^{270}Ds	0^+	100 μs	α	(10^-)	6 ms	α/IT

Circles – g.s. ; triangles - isomers



Circles – g.s. ;   triangles - isomers



Conditions for an isomer with $T_{1/2} > T_{1/2}$(g.s.) in SHN are stringent: not only its EM (or converted) decay must be delayed, but also its SF and α–decay (β is less important for the heaviest SHN).

It seems that SF is indeed delayed for K-isomers (the examples of ^{250}No and ^{254}Rf). So the main question remains: can α–decay be sufficiently delayed for an isomer? The case of ^{270}Ds is encouraging (although it would be good to check it).

Two factors delaying α–decay:

- smaller Q_α – the excitation of the initial configuration in the parent is smaller than that of the final one in the daughter (~3 orders of magnitude increase in T_α /per 1 MeV drop in Q_α) ;
- configuration change – different I, π , or a spin flip – induce hindrance of α- transitions (up to >3 orders of magnitude for odd-A nuclei).

They counteract each other in a rather complicated way.

Microscopic-macroscopic method with a possibility of many various deformations

$$E_{tot}(\beta_{\lambda\mu}) = E_{macro}(\beta_{\lambda\mu}) + E_{micro}(\beta_{\lambda\mu})$$

- Calculated energy: $E = E_{tot}(\beta_{\lambda\mu}) - E_{macro}(\beta_{\lambda\mu} = 0)$
- $E_{macro}(\beta_{\lambda\mu}) = \text{Yukawa} + \text{exponential}$
- $E_{micro}(\beta_{\lambda\mu}) = \text{Woods-Saxon} + \text{pairing BCS}$

S. Cwiok, J. Dudek, W. Nazarewicz, J. Skalski and T. Werner, Comput. Phys. Commun. 46, 379 (1987).
H. J. Krappe, J. R. Nix and A. J. Sierk, Phys. Rev. C20, 992 (1979).
I. Muntian, Z. Patyk and A. Sobiczewski, Acta Phys. Pol. B 32, 691 (2001).

Extension to odd-A & odd-odd nuclei - a fit to exp. masses Z>82, N>126 (number of nuclei: 252)

P. Jachimowicz, M. Kowal, and J. Skalski, *Phys. Rev. C* **89**, 024304 (2014).

Results for 72 actinides & 1300 SHN: P. Jachimowicz, M. Kowal, J.Skalski, At. Data Nucl. DataTab. 138 (2021) 101393.

3qp K - isomers in odd-even Md – Rg nuclei: P. Jachimowicz, M. Kowal, J. Skalski, arXiv:2308.02893, Phys. Rev. C 108, 064309 (2023), 3qp K - isomers in even-odd Fm-Cn nuclei: preliminary results.

3qp excitations in odd-even nuclei:either 1p2n (>2500 conf.) or 3p (>500 conf.).

Excitation energies and corresponding deformations of various configurations are found by energy minimization with respect to deformation.

$$R(\vartheta,\varphi) = R_0 \{1 + \beta_{20} Y_{20} + \beta_{30} Y_{30} + \beta_{40} Y_{40} + \\ + \beta_{50} Y_{50} + \beta_{60} Y_{60} + \beta_{70} Y_{70} + \beta_{80} Y_{80}\}.$$

Four-dimensional minimization is performed using the gradient method.

Pairing was treated by three methods: BCS with blocking, in the quasiparticle scheme (sum of BCS qp energies added to the energy of the core) and with the particle number projection (PNP) for the lowest configurations.

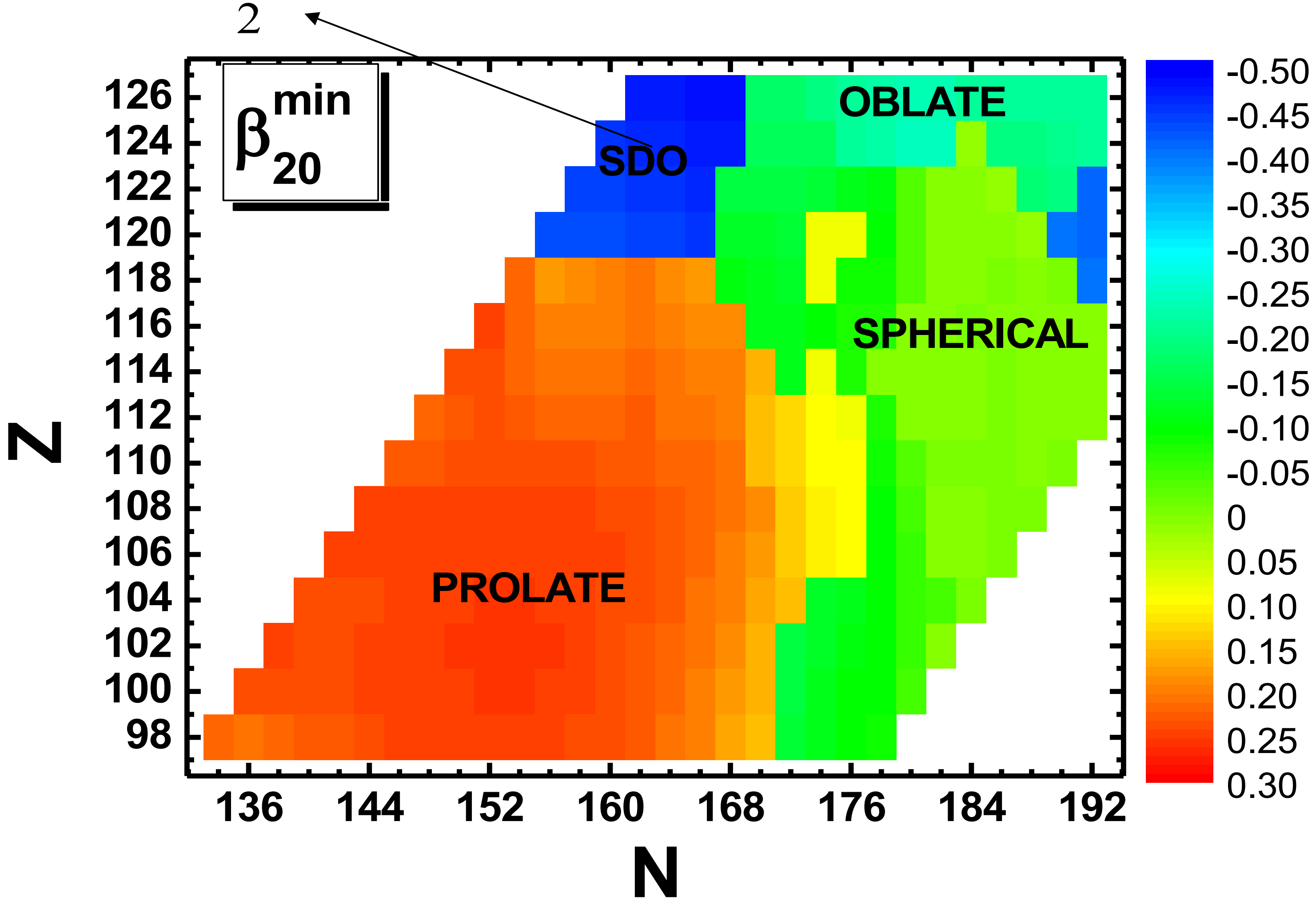
Ground state shapes

$SDO:$

$\beta_{20} \approx -0.5$

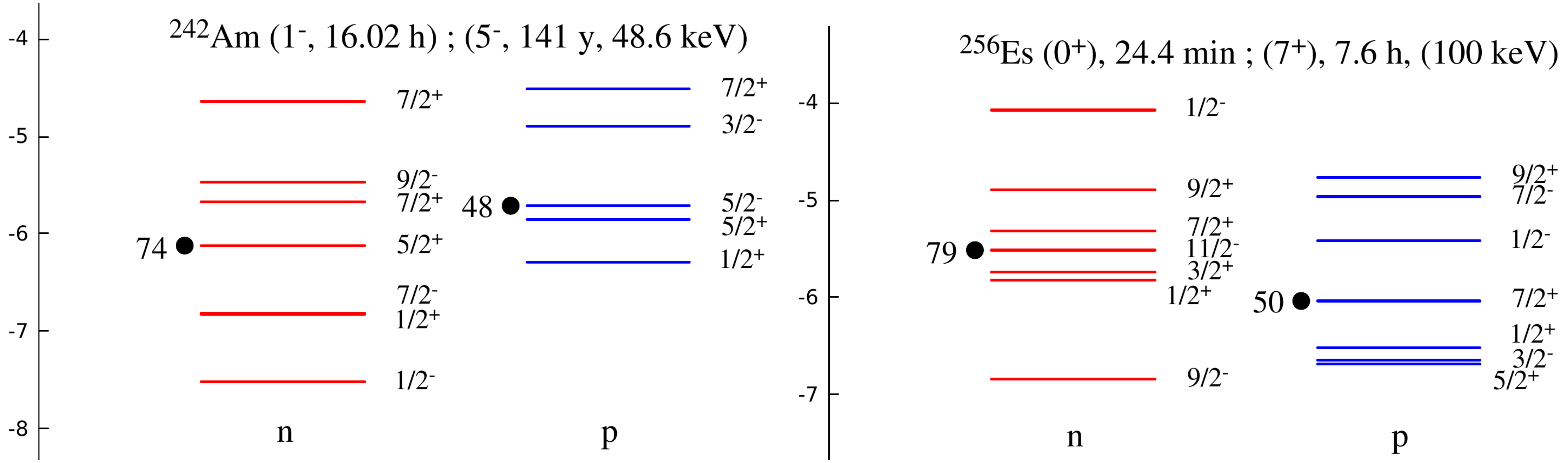
$Axis.ratio \approx \frac{3}{2}$

Micro-macro results; mostly four - dimensional minimization

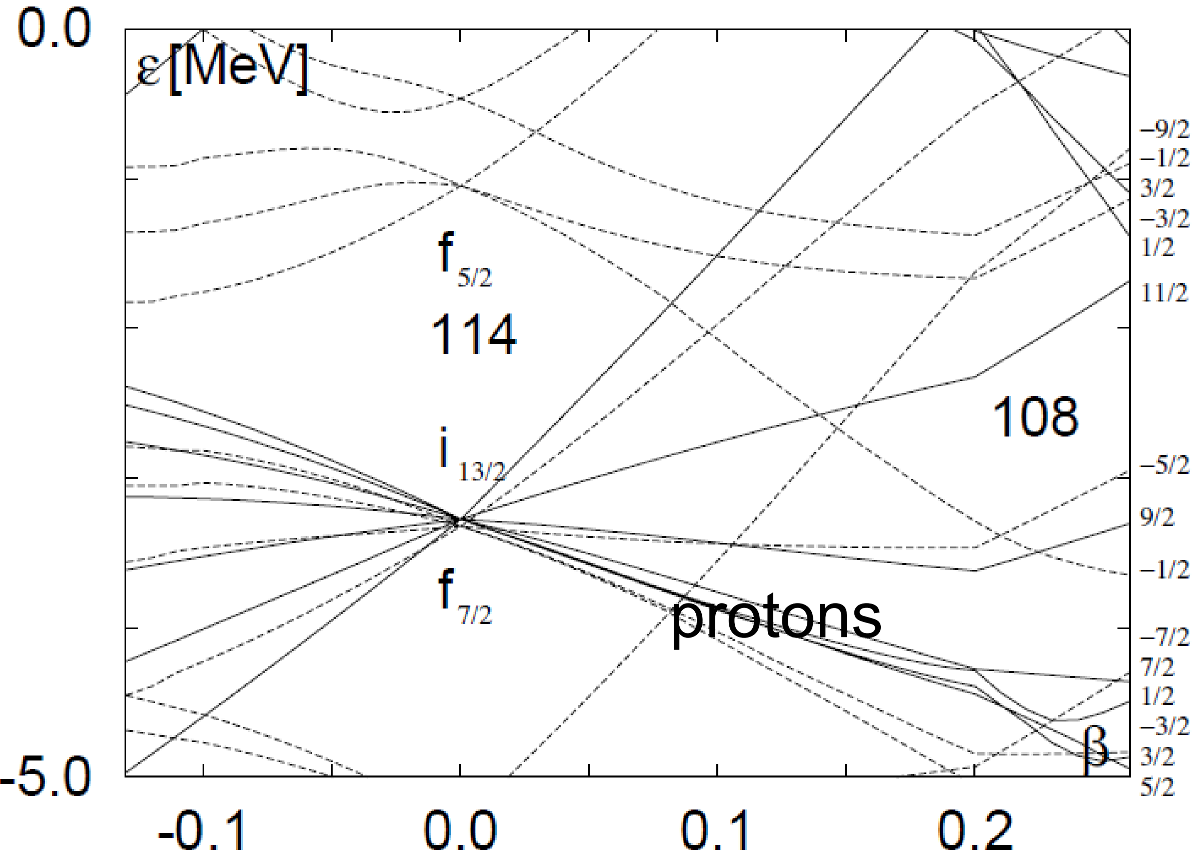


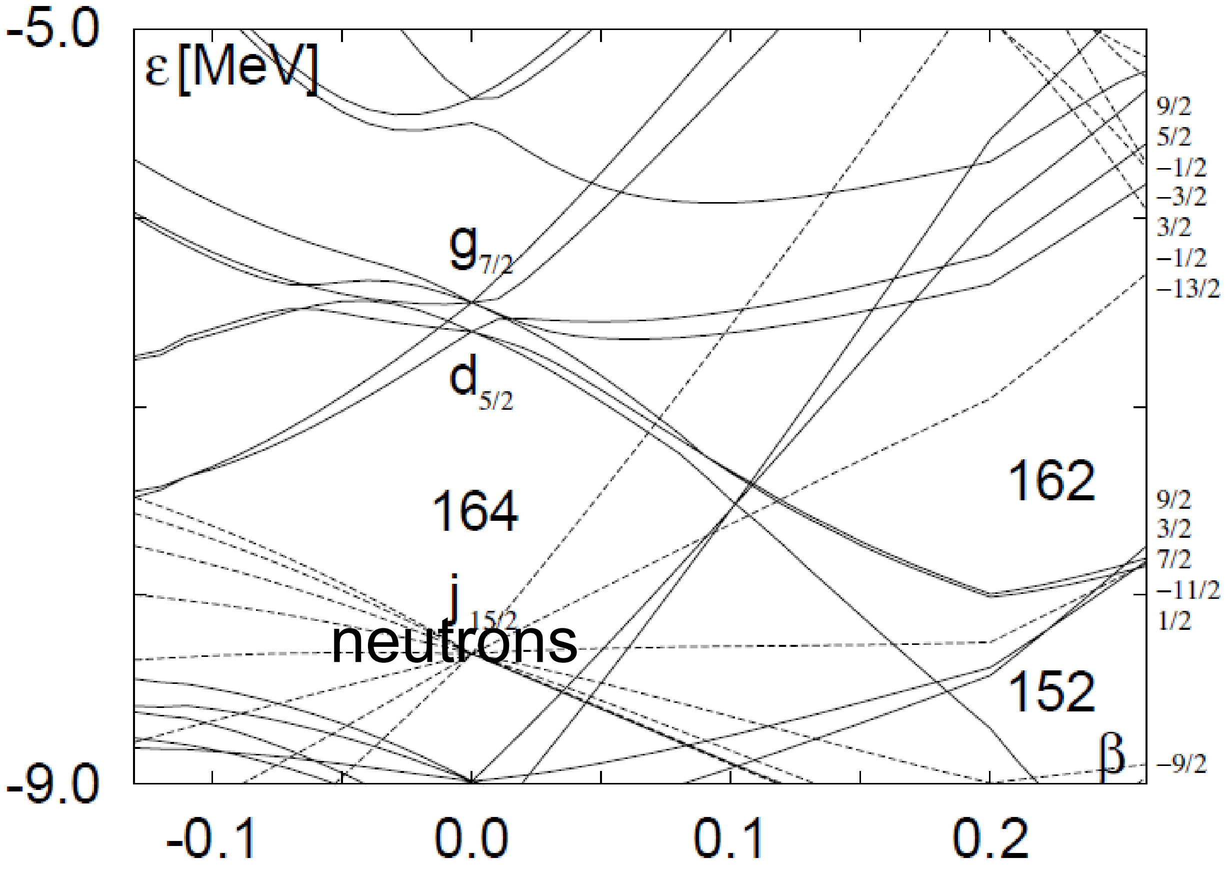
In contrast to many Skyrme forces, Woods-Saxon micro-macro model gives lower barriers and mostly oblate ground states for Z>=124,126 (no magic gap for 126 protons).

WS spectrum vs data – an example of odd-odd nuclei (dot designates the last occupied level with its number given):



High-K g. s. in odd and odd-odd SHN





The effect of intruder states lying sclose to the Fermi level is most apparent in heavier nuclei

Predicted high-K g.s. or near-ground states.

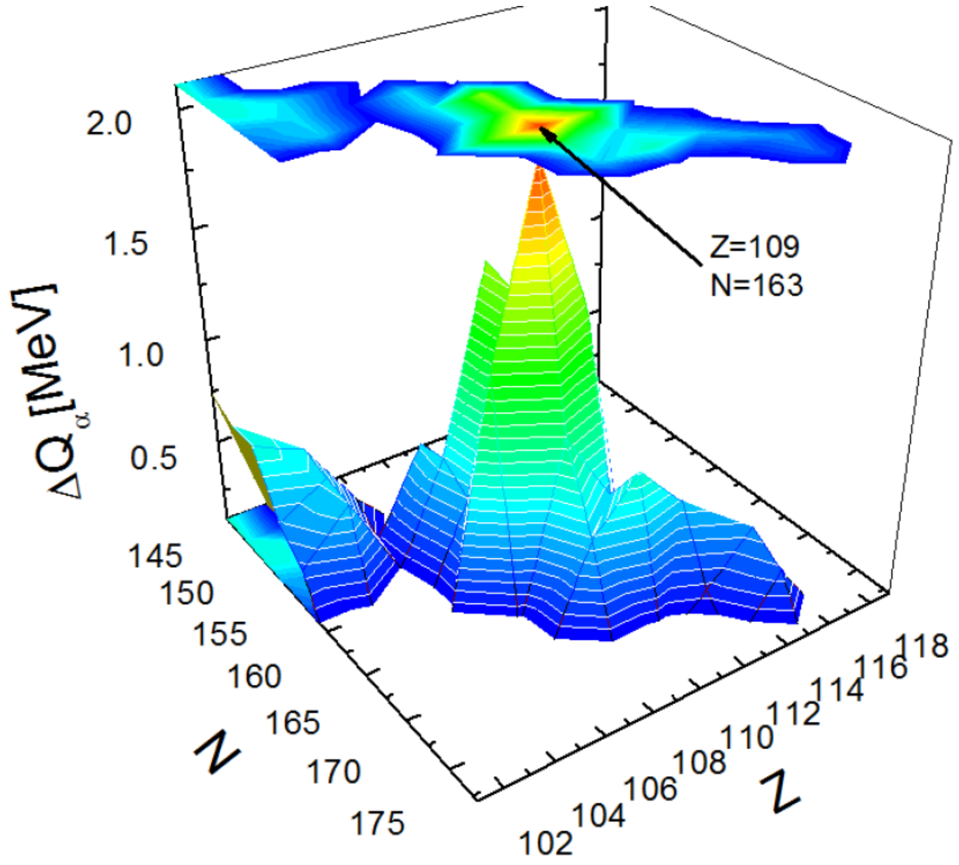
Z	N	p	n	K
101	151	1/2-	9/2-	5+
	157	„	11/2-	6+
103	149	7/2-	7/2+	7-
	151	„	9/2-	8+
	157	„	11/2-	9+
105	151	9/2+	9/2-	9-
	155	„	3/2+	6+
	157	„	11/2-	10-
107	157	5/2-	11/2-	8+
	159	„	7/2+	6-
	161	„	9/2+	7-
	163	„	13/2-	9+

Z	N	p	n	K
109	157	11/2+	3/2+	7+
	159	„	9/2+	10+
	161	„	9/2+	10+
	163	„	13/2-	12-
	165	„	3/2+	7+
	167	„	5/2+	8+
	169	„	9/2+	10+
111	163	3/2-	13/2-	8+
	169	9/2-	5/2+	8+
	157	„	11/2-	7+
112	173	x	15/2-	15/2-
113	173	7/2-	5/2+	6-

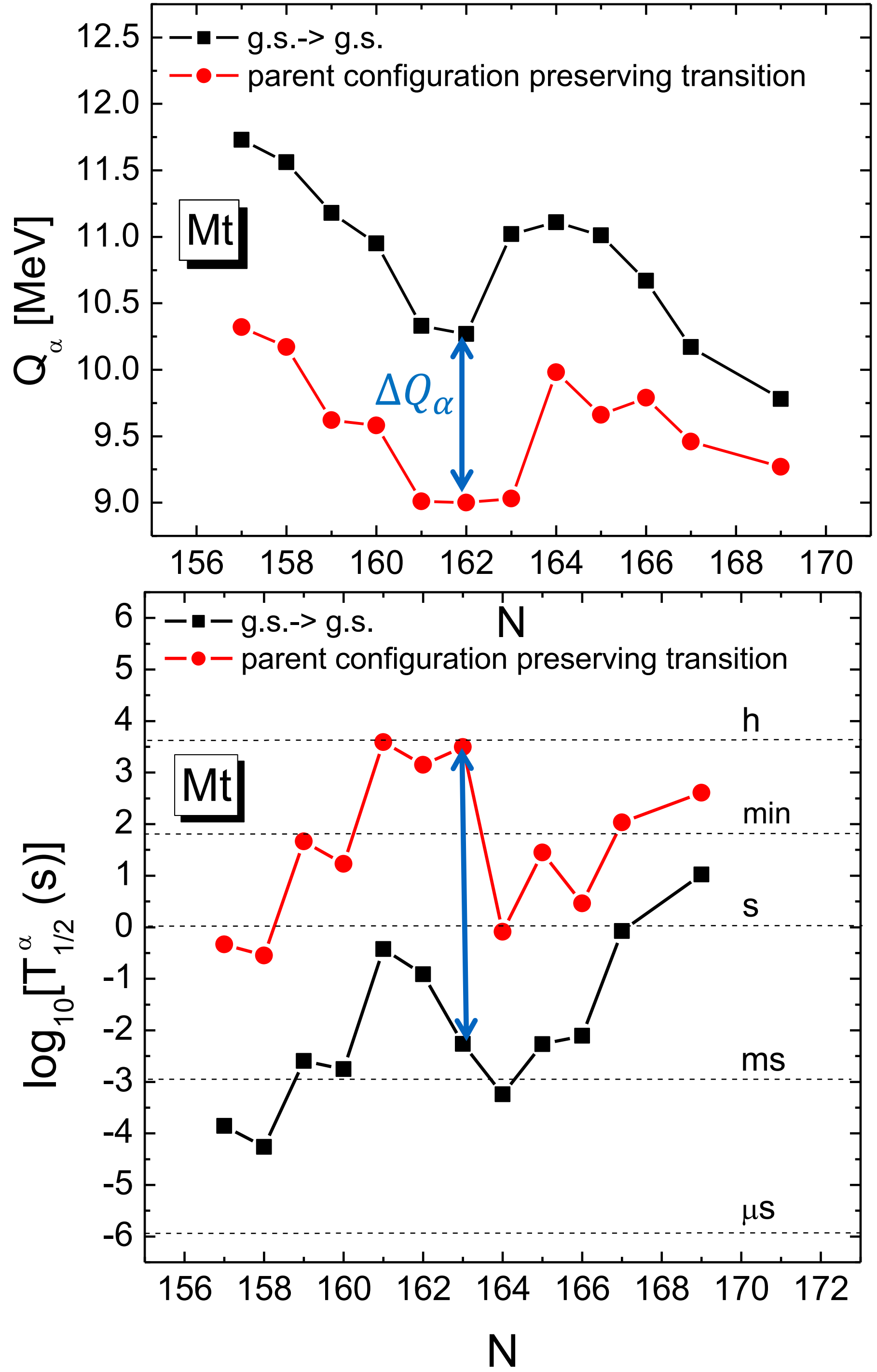
High-K states: a chance for longer half-lives.

P. Jachimowicz, M. Kowal, and J. Skalski, *Phys. Rev. C* **92**, 044306 (2015).

For candidates for high-K ground states in odd and odd-odd SHN one can calculate within the W-S model a reduction in Qα for configuration-preserving alpha transitions.



The results show the maximal effect around Z=109, N=163 (^{272}Mt) which may point to a hindrance of alpha-decay.

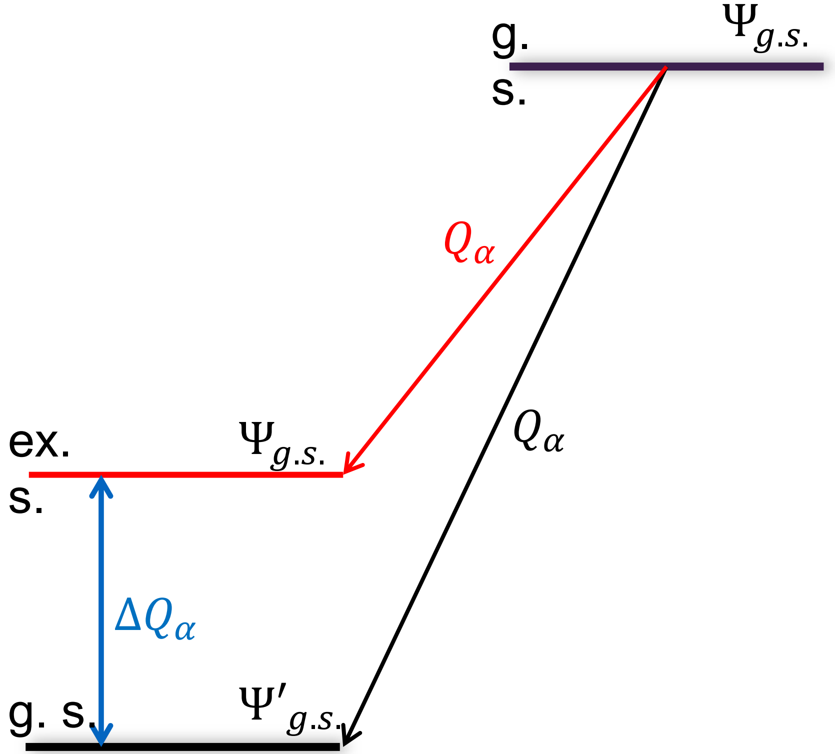


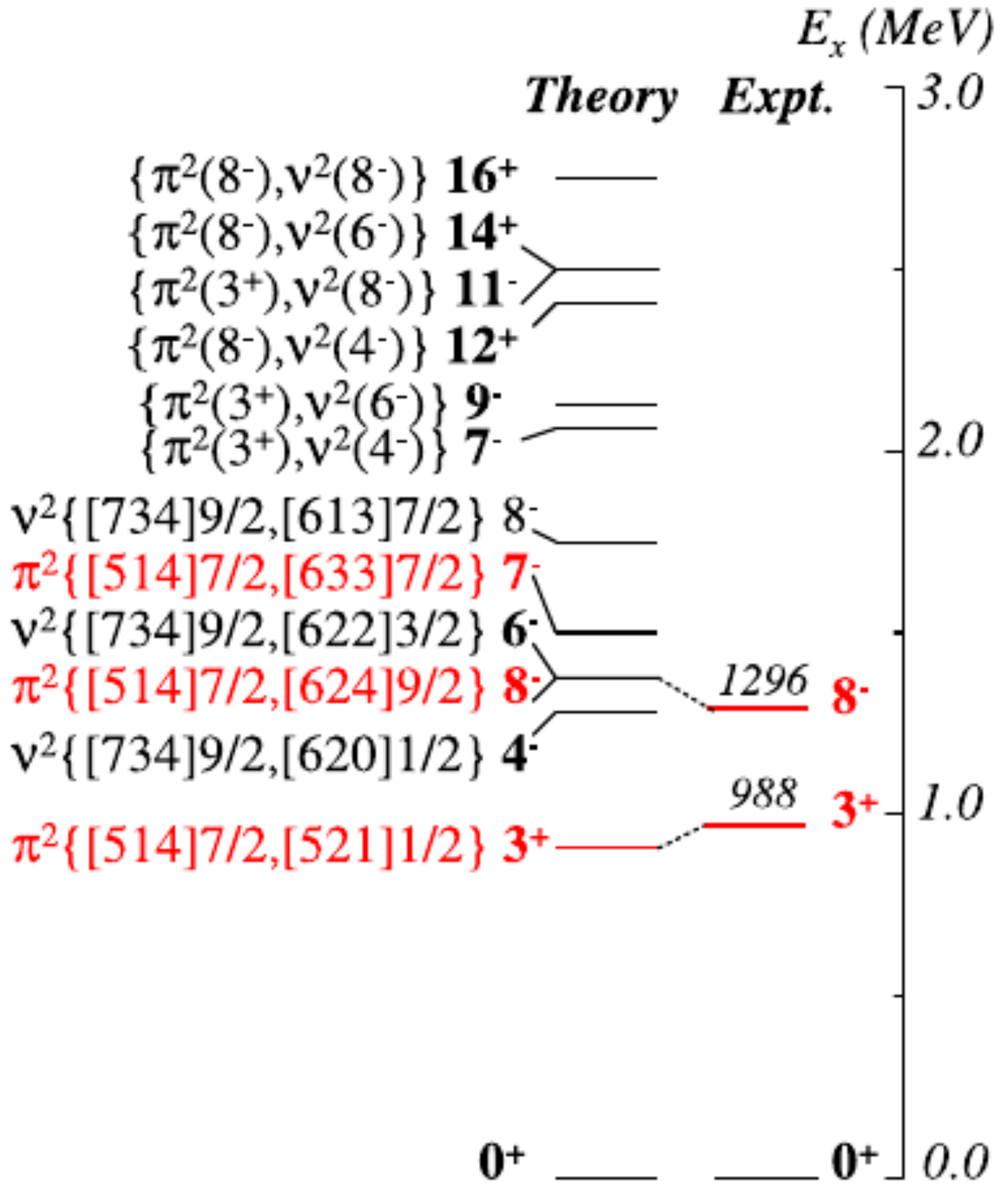
P. Jachimowicz, M. Kowal, and J. Skalski, *Phys. Rev. C* **92**, 044306 (2015).

Unique blocked orbitals may hinder alpha transitions.
The effect of a reduced Q alpha for g.s. -> excited state (top panel) on the life-times (below)

according to the formula by Royer.

A particular situation occurs above double closed subshells $N = 162$ and $Z = 108$ where two intruder orbitals, neutron $13/2^-$ from $j_{15/2}$ and proton $11/2^+$ from $i_{13/2}$ spherical subshells, are predicted. These orbitals combine to the 12^- g.s. in $Z = 109$, $N = 163$,





Interpretation of experimental results is often induced by models. Two candidates for the 8^- isomer in ^{254}No, either a proton or a neutron 2qp configuration, are predicted by the Woods-Saxon model.

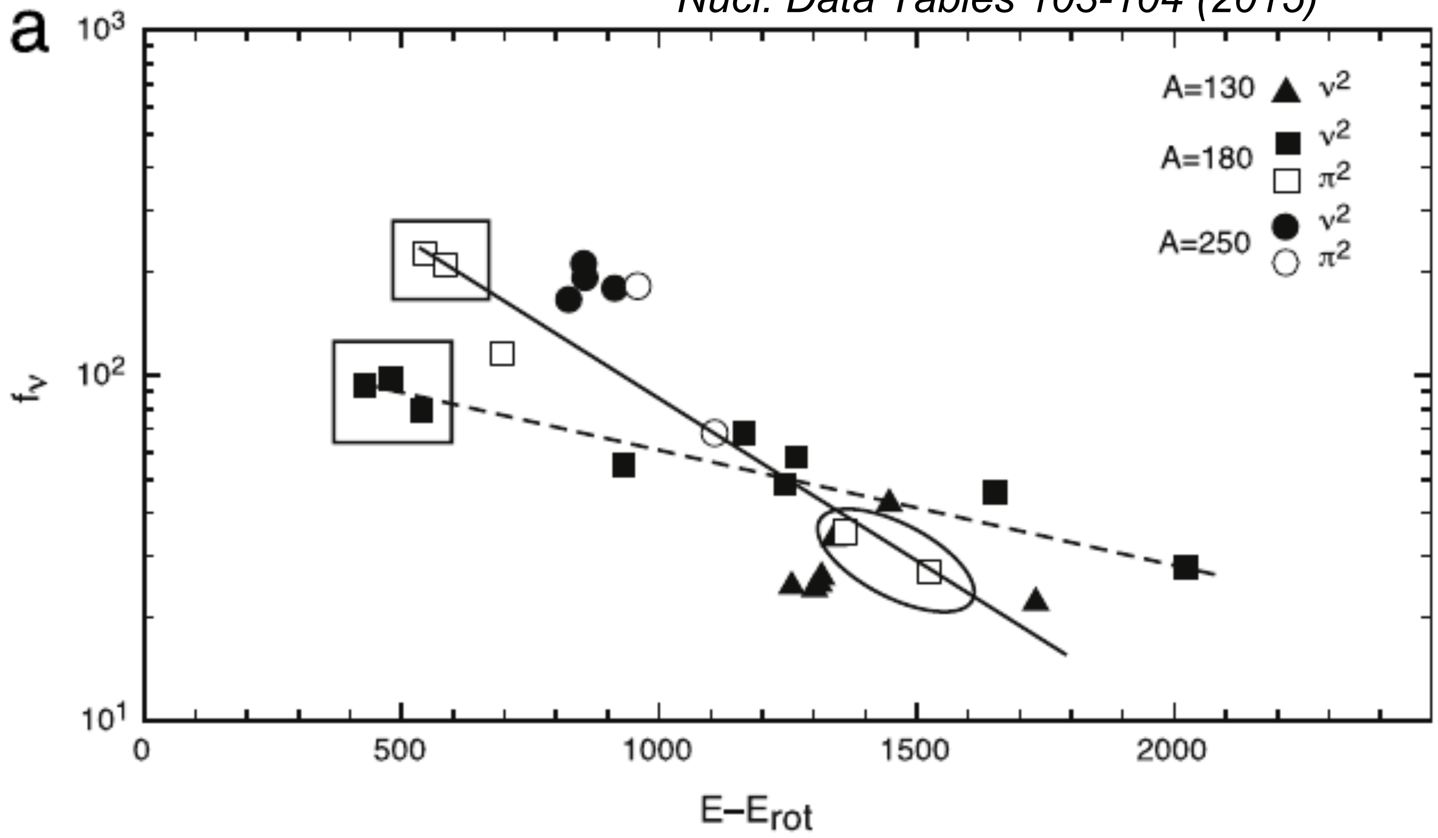
Although g_K factors for two configurations are very different, $|g_K-g_R|$ controlling intraband transitions are probably similar. (hyperfine structure splitting measurement will decide?)

This assignment is related to isomer assignments in Md, Lr and Db nuclei.

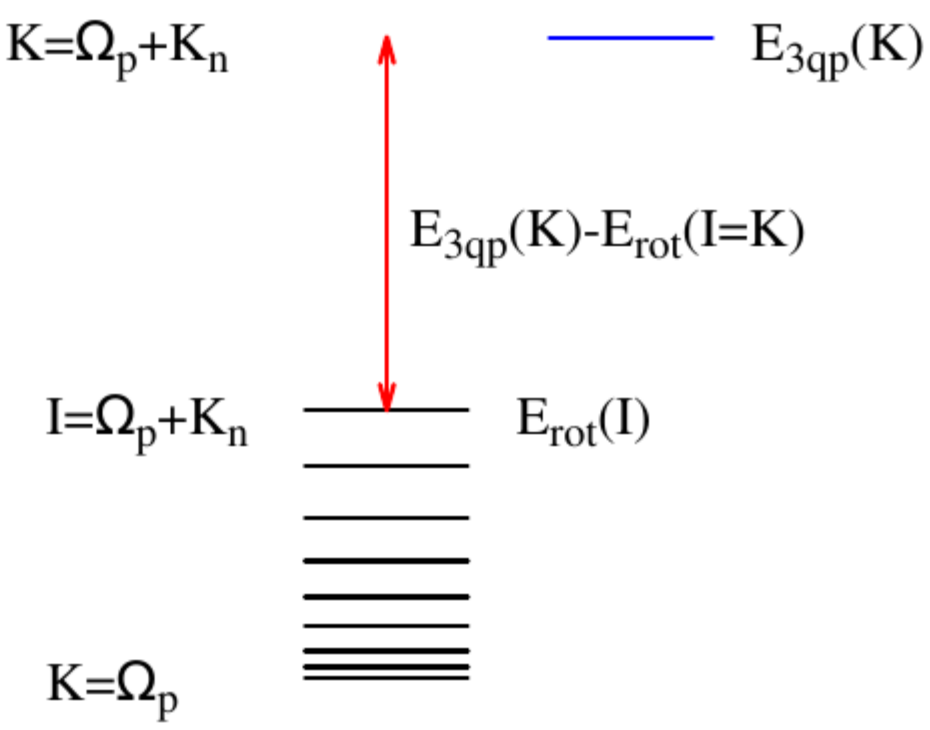
S. K. Tandel et al., Phys. Rev. Lett. 97, 082502 (2006)

F.G. Kondev et al. / Atomic Data and

Nucl. Data Tables 103-104 (2015)

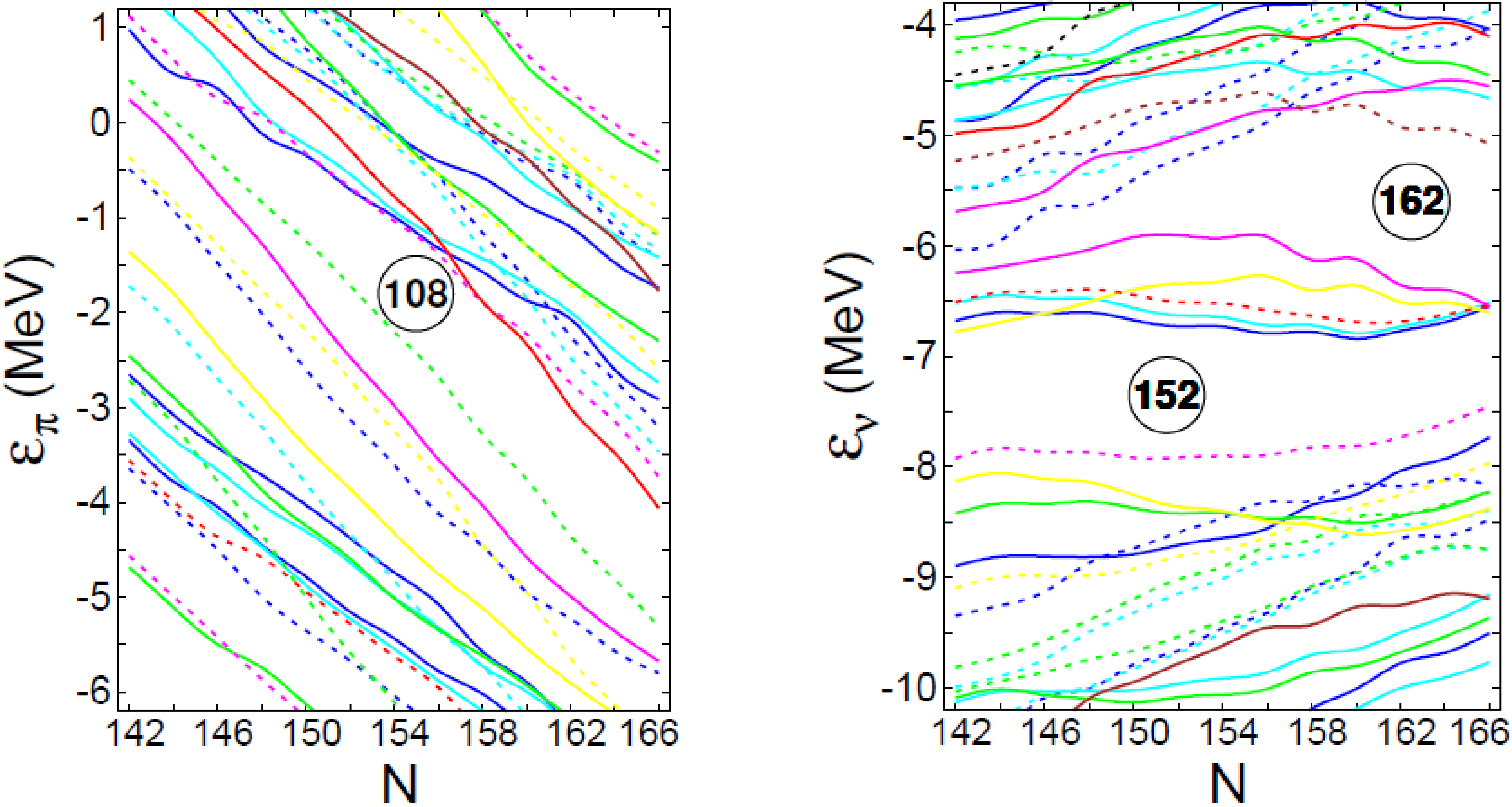


The reduced hindrance for 8⁻ isomers in deformed regions



Smaller $E_{3qp}(K)$-$E_{rot}(I=K)$ –
a better candidate for isomer.

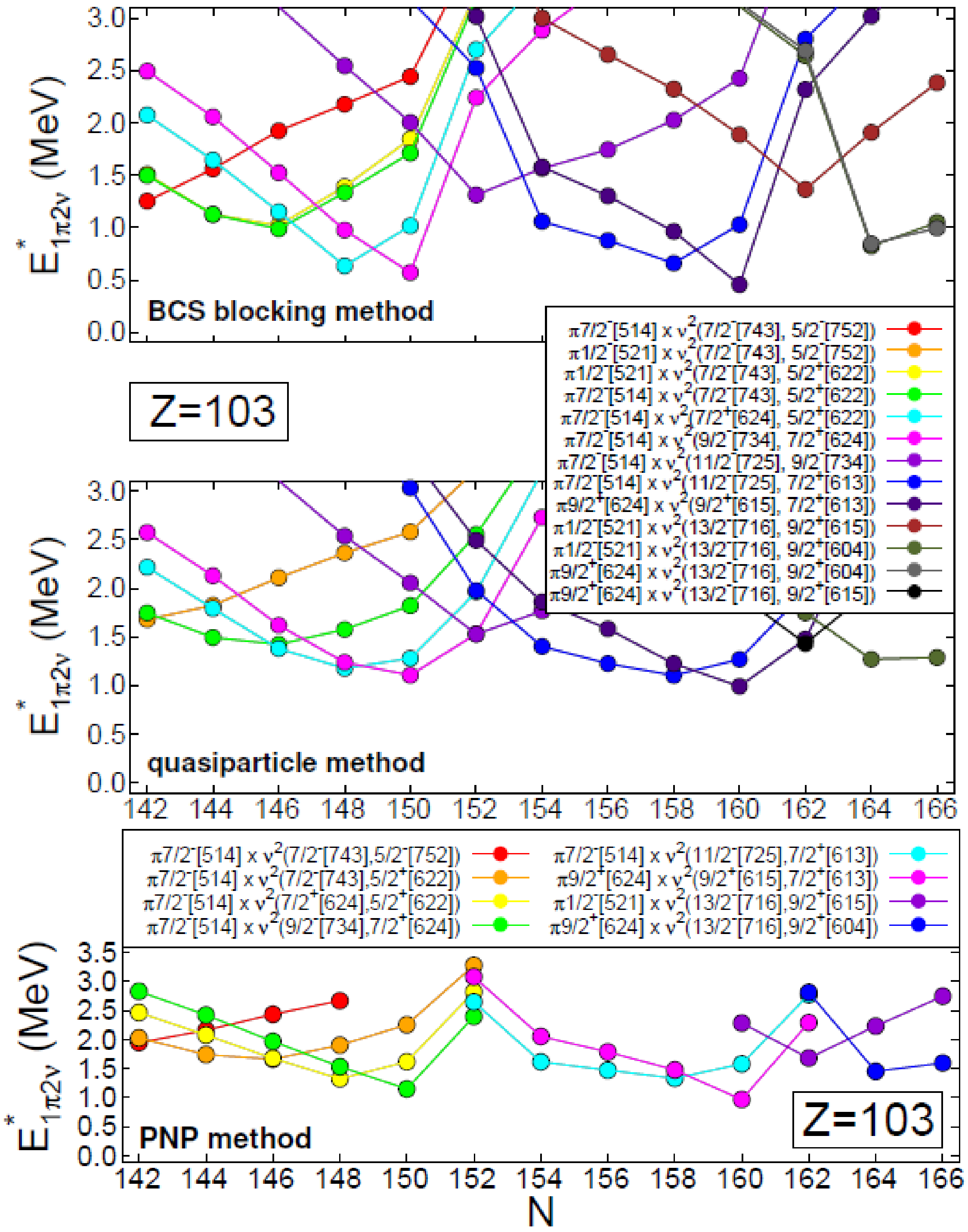
s.p. levels along g.s. deformations for Lr isotopes

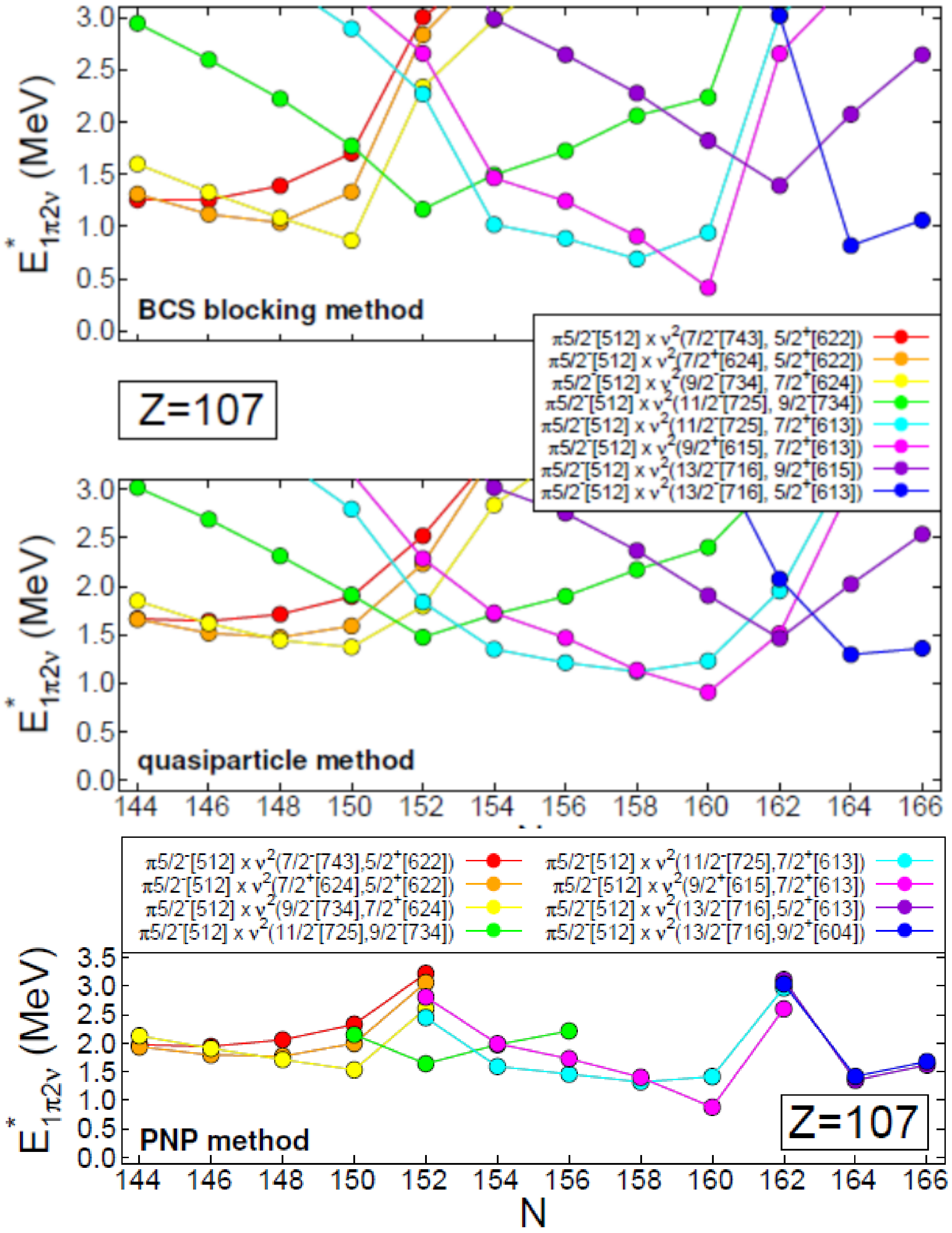


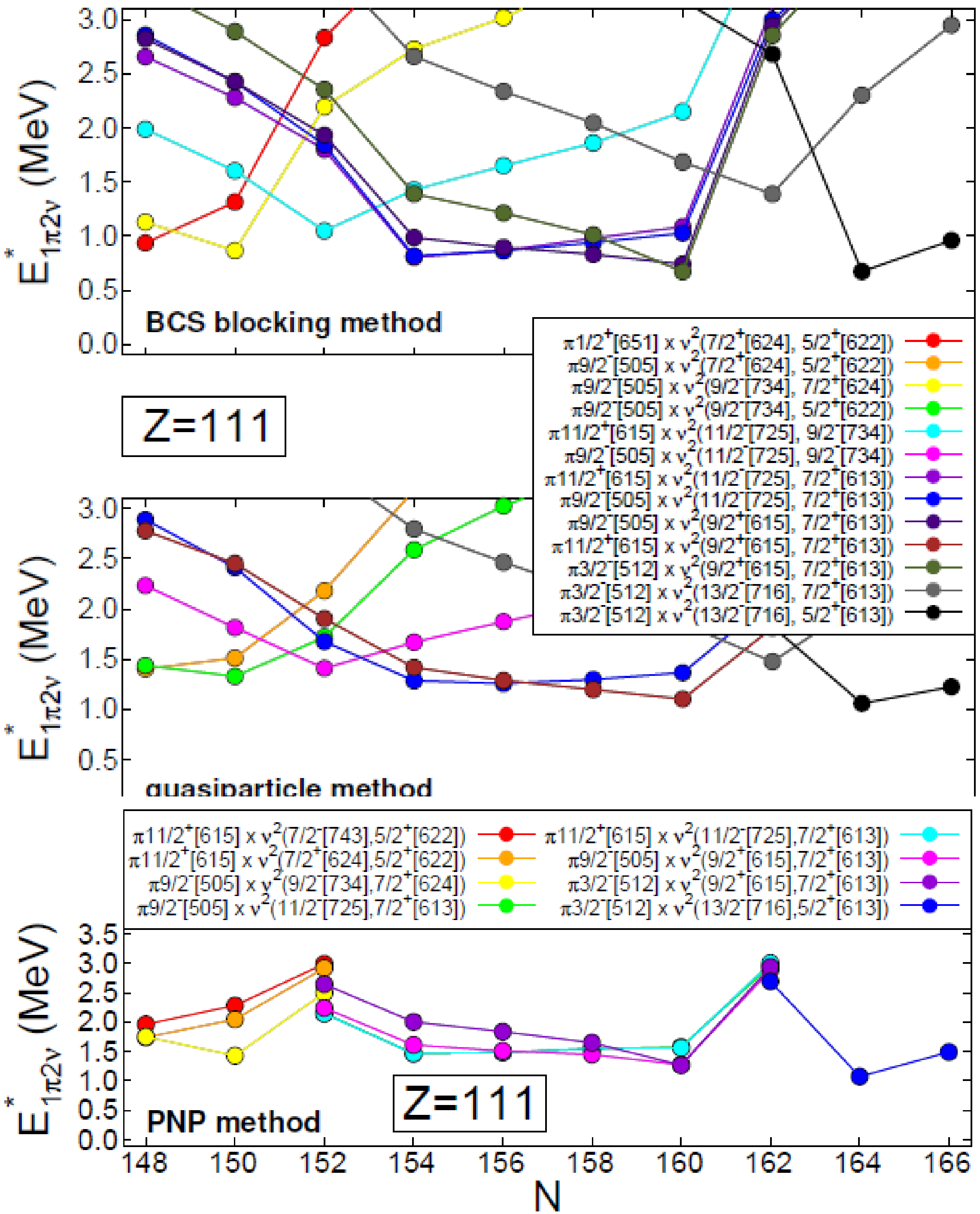
π - dashed; 1/2 - blue, 3/2 - cyan, 5/2 - green, 7/2 - yellow, 9/2 - magenta, 11/2 - red, 13/2 - brown, 15/2 - black

Odd-even systems N=142-166;

1p2n results

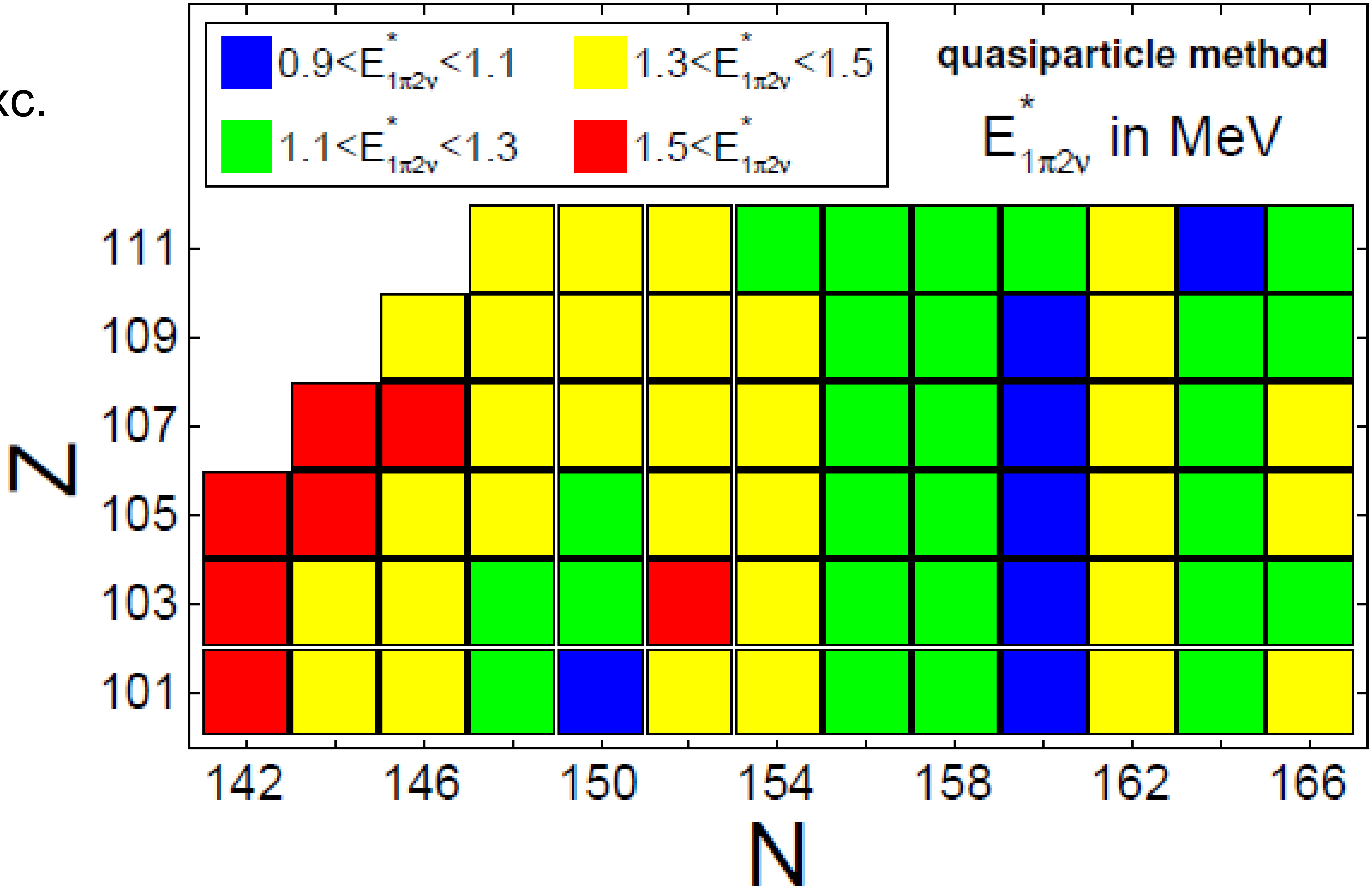



BCS blocking method
Z=107
quasiparticle method
PNP method
Z=107
N
E*1π2ν (MeV)
π5/2-[512] x ν2(7/2-[743], 5/2+[622])
π5/2-[512] x ν2(7/2+[624], 5/2+[622])
π5/2-[512] x ν2(9/2-[734], 7/2+[624])
π5/2-[512] x ν2(11/2-[725], 9/2-[734])
π5/2-[512] x ν2(11/2-[725], 7/2+[613])
π5/2-[512] x ν2(9/2+[615], 7/2+[613])
π5/2-[512] x ν2(13/2-[716], 9/2+[615])
π5/2-[512] x ν2(13/2-[716], 5/2+[613])
π5/2-[512] x ν2(13/2-[716],5/2+[613])
π5/2-[512] x ν2(13/2-[716],9/2+[604])

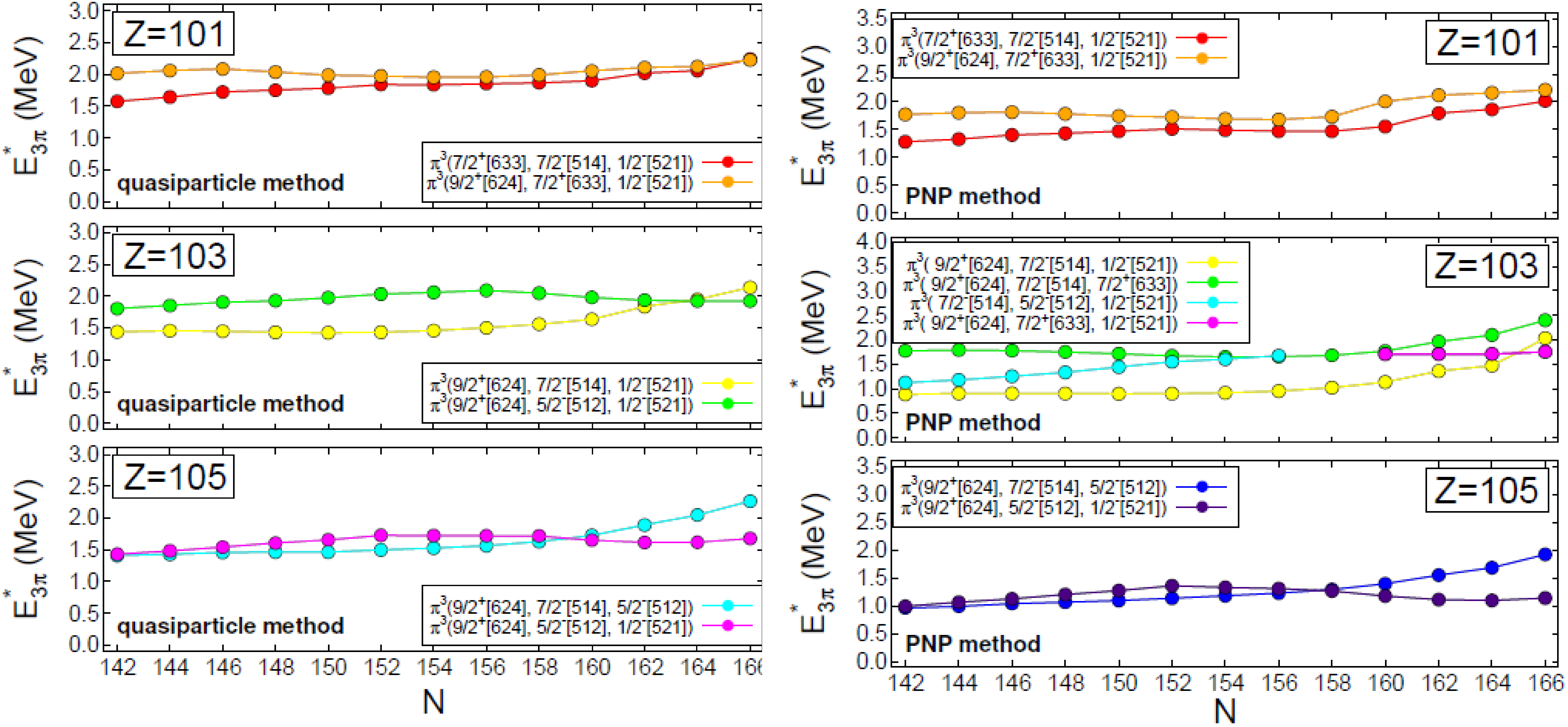


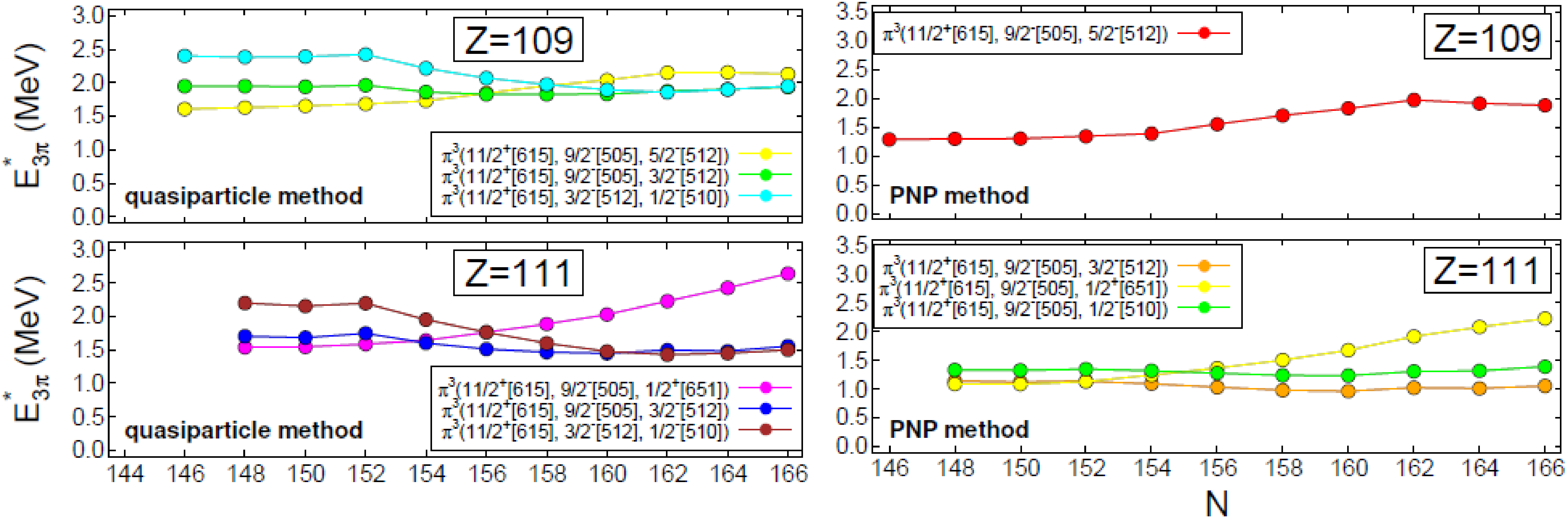
BCS blocking method
Z=111
π1/2+[651] x ν2(7/2+[624], 5/2+[622])
π9/2-[505] x ν2(7/2+[624], 5/2+[622])
π9/2-[505] x ν2(9/2-[734], 7/2+[624])
π9/2-[505] x ν2(9/2-[734], 5/2+[622])
π11/2+[615] x ν2(11/2-[725], 9/2-[734])
π9/2-[505] x ν2(11/2-[725], 9/2-[734])
π11/2+[615] x ν2(11/2-[725], 7/2+[613])
π9/2-[505] x ν2(11/2-[725], 7/2+[613])
π9/2-[505] x ν2(9/2+[615], 7/2+[613])
π11/2+[615] x ν2(9/2+[615], 7/2+[613])
π3/2-[512] x ν2(9/2+[615], 7/2+[613])
π3/2-[512] x ν2(13/2-[716], 7/2+[613])
π3/2-[512] x ν2(13/2-[716], 5/2+[613])
quasiparticle method
π11/2+[615] x ν2(7/2-[743],5/2+[622])
π11/2+[615] x ν2(7/2+[624],5/2+[622])
π9/2-[505] x ν2(9/2-[734],7/2+[624])
π9/2-[505] x ν2(11/2-[725],7/2+[613])
π11/2+[615] x ν2(11/2-[725],7/2+[613])
π9/2-[505] x ν2(9/2+[615],7/2+[613])
π3/2-[512] x ν2(9/2+[615],7/2+[613])
π3/2-[512] x ν2(13/2-[716],5/2+[613])
PNP method
Z=111
E*1π2ν (MeV)
N
148 150 152 154 156 158 160 162 164 166

Lowest exc. energies



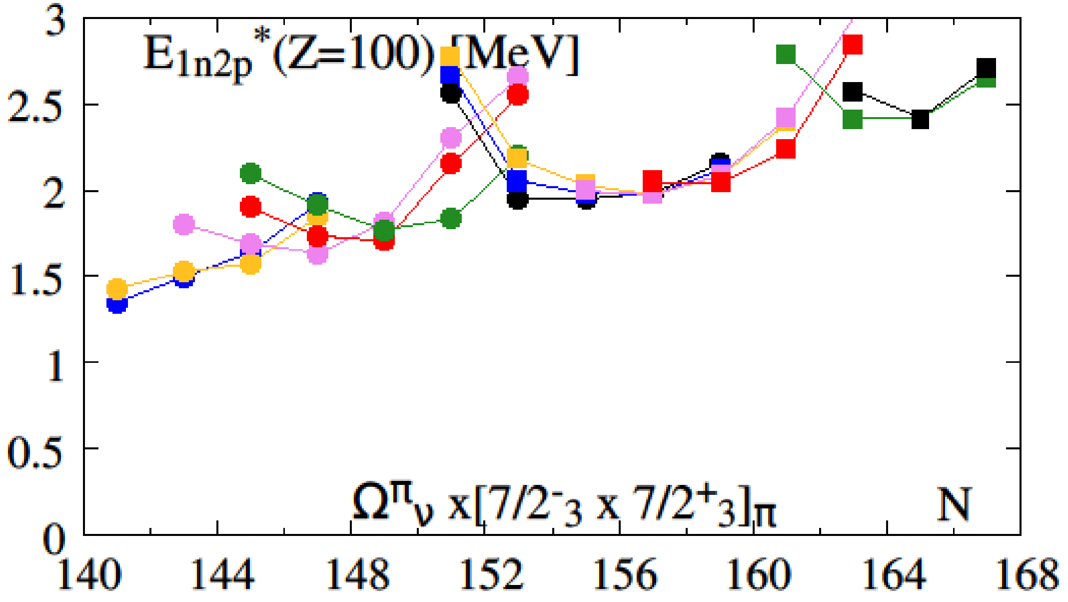
3p excitations

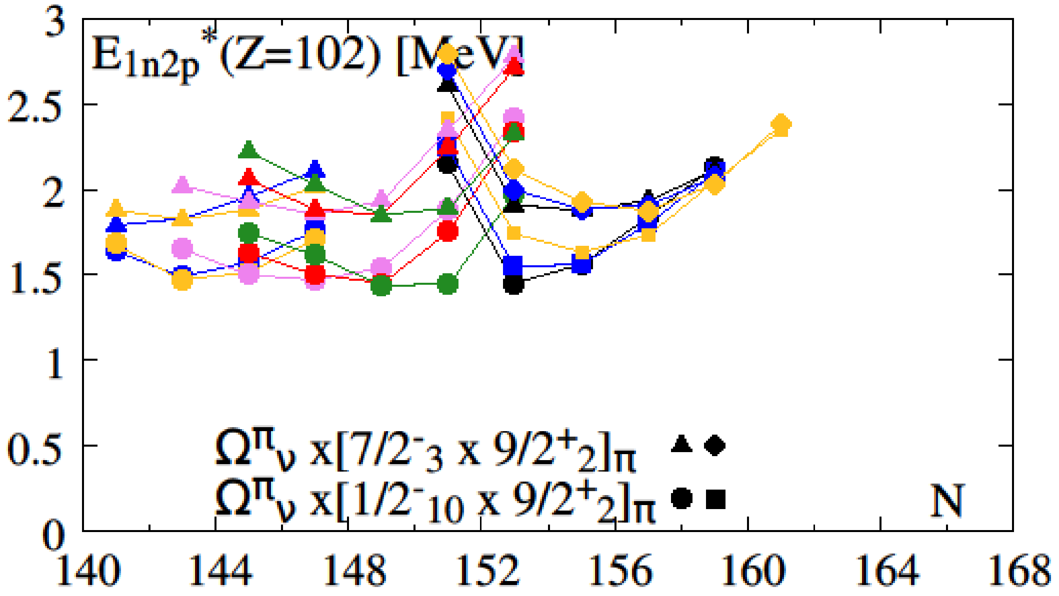


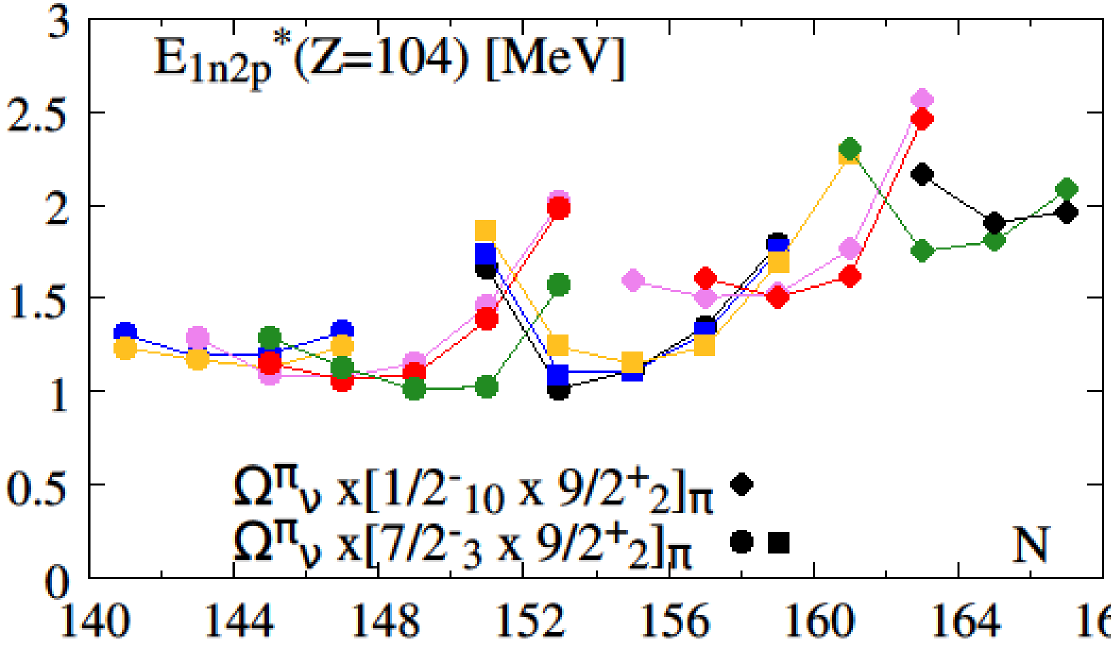

Z=109
quasiparticle method
π^3(11/2$^+$[615], 9/2$^-$[505], 5/2$^-$[512])
π^3(11/2$^+$[615], 9/2$^-$[505], 3/2$^-$[512])
π^3(11/2$^+$[615], 3/2$^-$[512], 1/2$^-$[510])
Z=111
quasiparticle method
π^3(11/2$^+$[615], 9/2$^-$[505], 1/2$^+$[651])
π^3(11/2$^+$[615], 9/2$^-$[505], 3/2$^-$[512])
π^3(11/2$^+$[615], 3/2$^-$[512], 1/2$^-$[510])
$E^*_{3\pi}$ (MeV)
Z=109
PNP method
π^3(11/2$^+$[615], 9/2$^-$[505], 5/2$^-$[512])
Z=111
PNP method
π^3(11/2$^+$[615], 9/2$^-$[505], 3/2$^-$[512])
π^3(11/2$^+$[615], 9/2$^-$[505], 1/2$^+$[651])
π^3(11/2$^+$[615], 9/2$^-$[505], 1/2$^-$[510])
N

Even-odd systems Z=100-112, N=141-167; PNP results, 1n2p

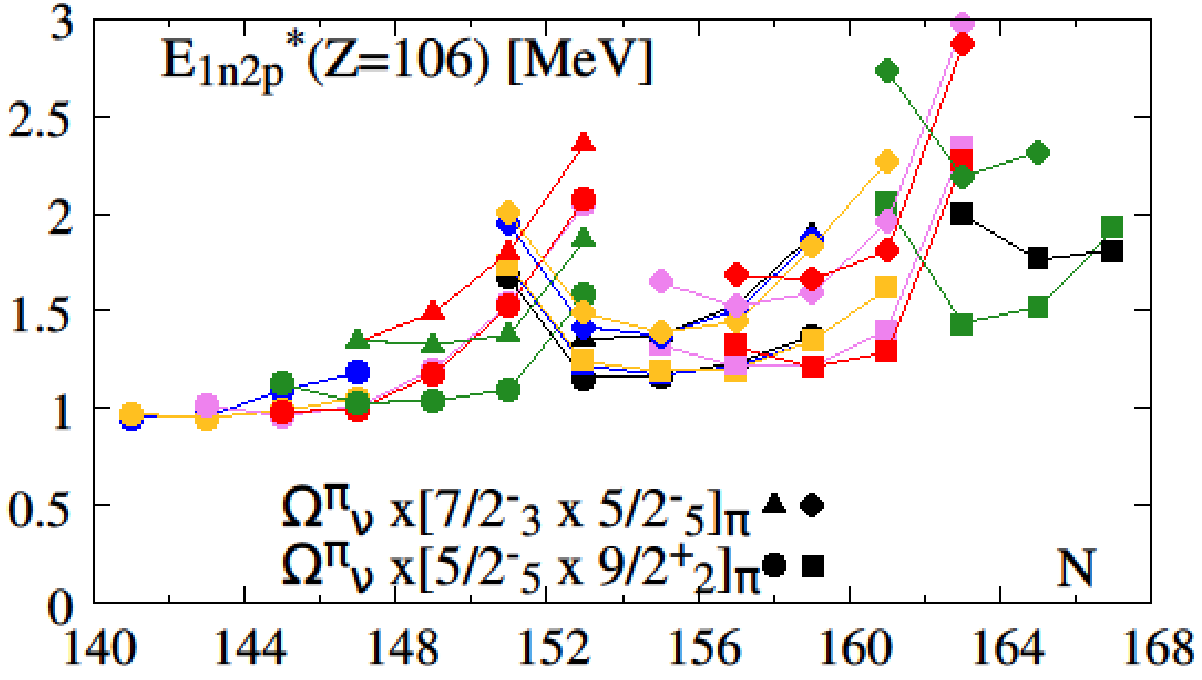
The lowest 2p configuration coupled to the lowest 1-neutron one (changing with N, depicted by a colour and shape of points)



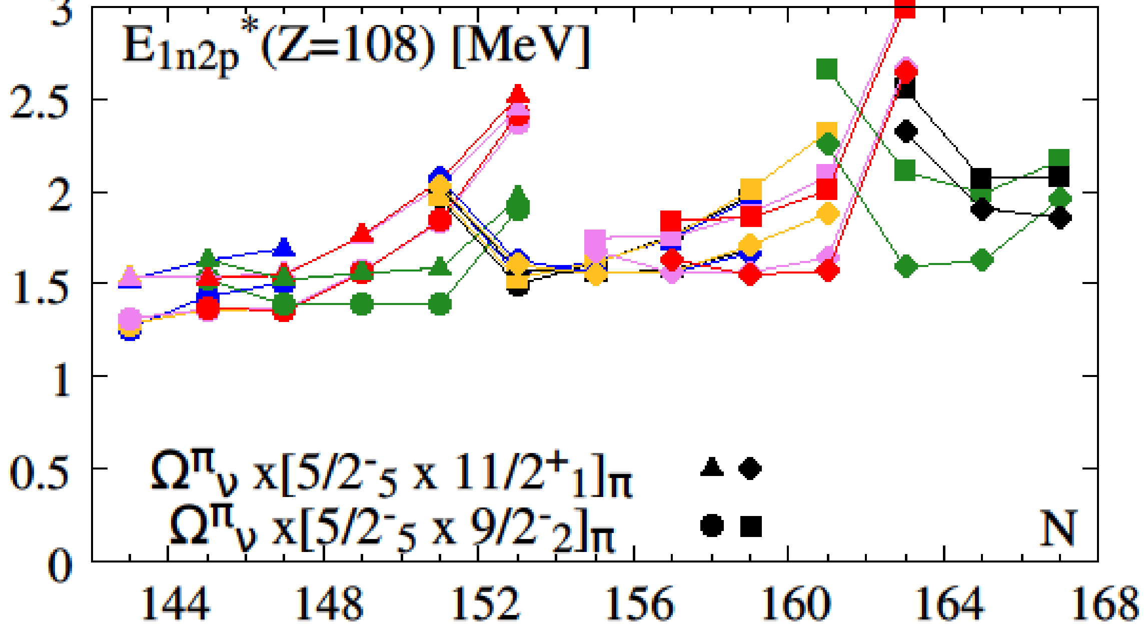


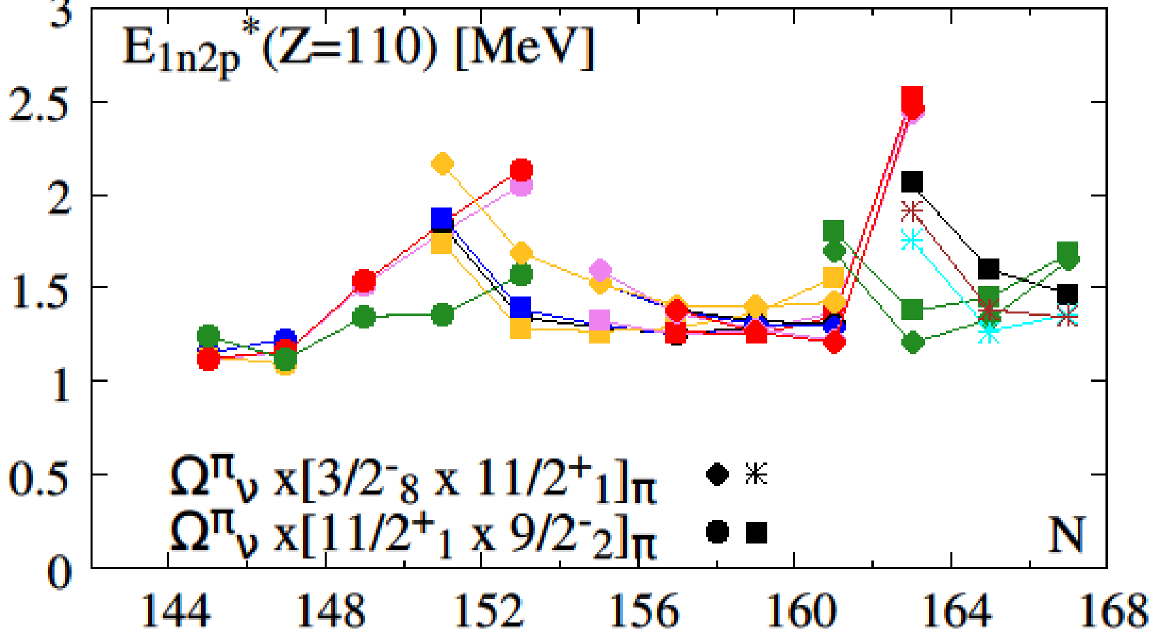


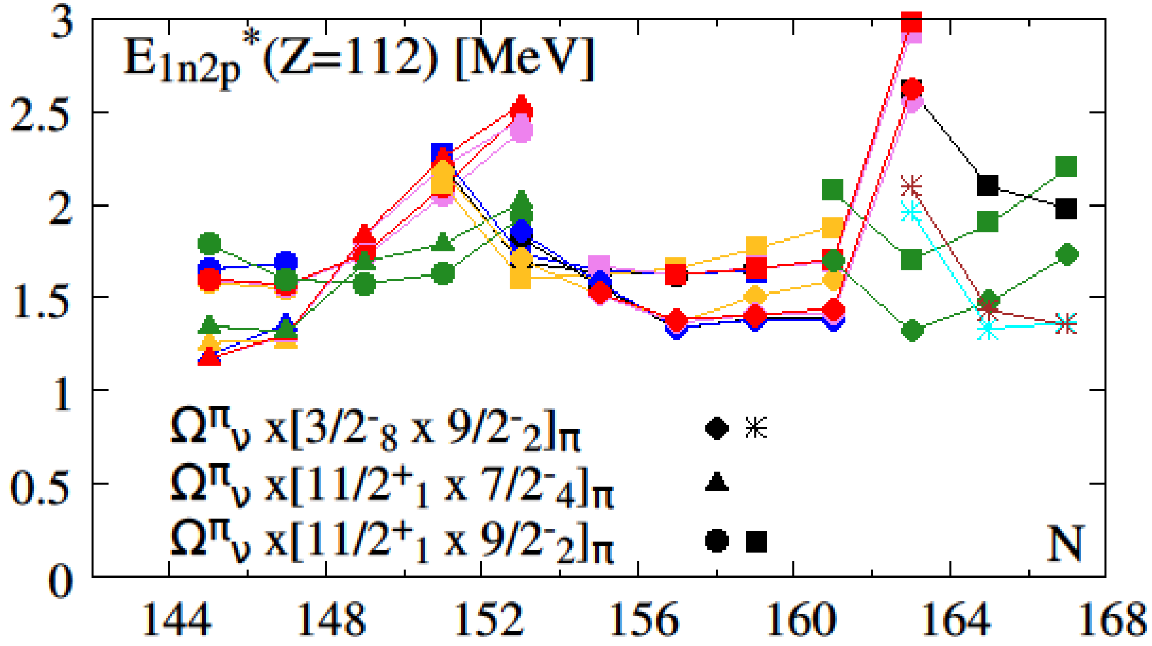
E1n2p*(Z=104) [MeV]
Ωπν x[1/2-10 x 9/2+2]π
Ωπν x[7/2-3 x 9/2+2]π
N



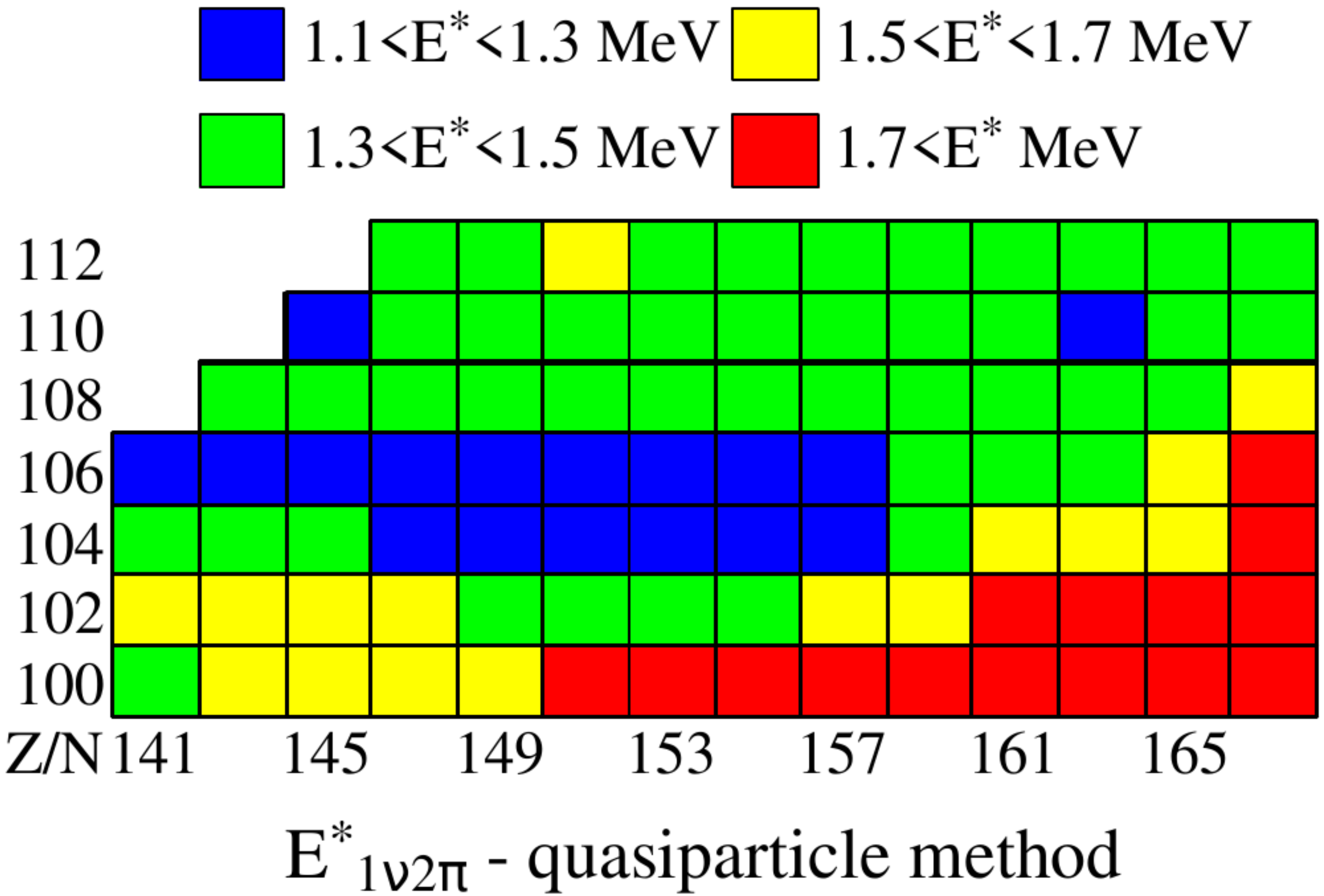
E1n2p*(Z=106) [MeV]
Ωπν x[7/2-3 x 5/2-5]π
Ωπν x[5/2-5 x 9/2+2]π
N

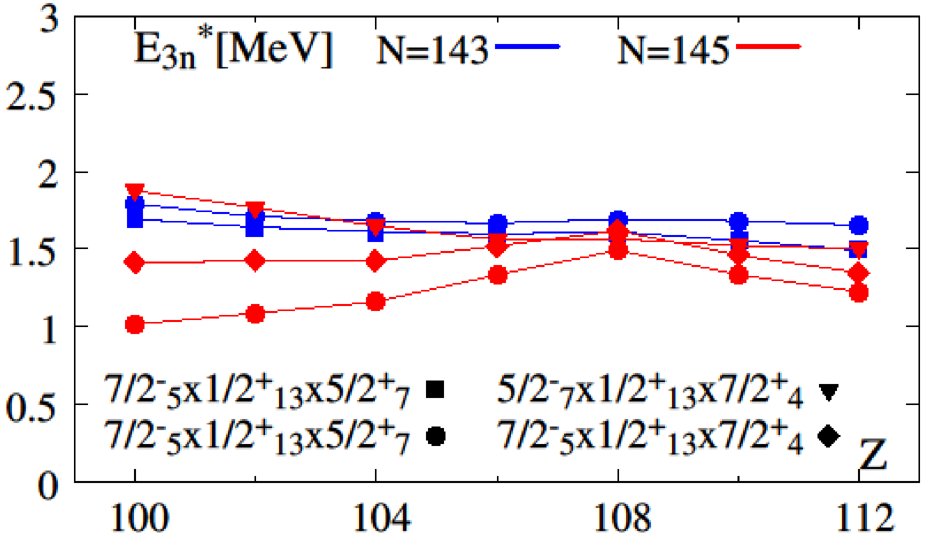

E1n2p*(Z=108) [MeV]
Ωπν x[5/2-5 x 11/2+1]π
Ωπν x[5/2-5 x 9/2-2]π
N
0
0.5
1
1.5
2
2.5
3
144
148
152
156
160
164
168

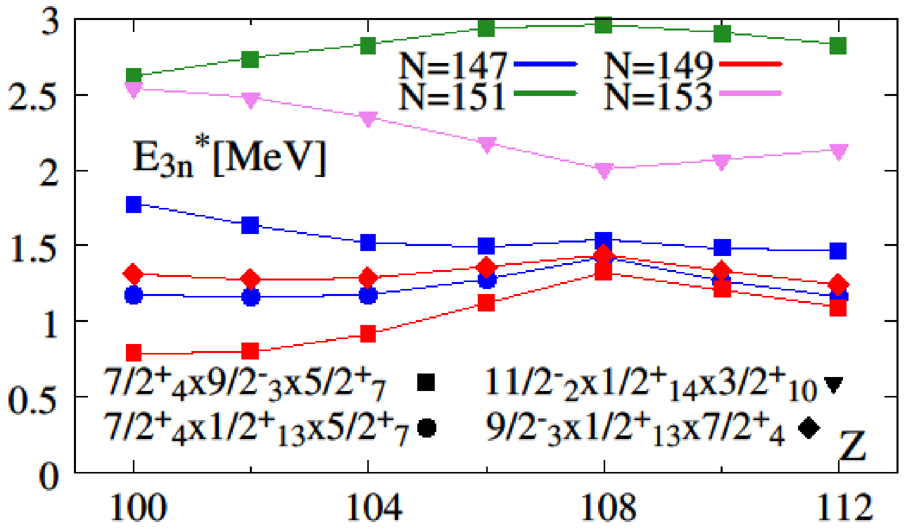

E1n2p*(Z=110) [MeV]
Ωπν x[3/2-8 x 11/2+1]π
Ωπν x[11/2+1 x 9/2-2]π
N
0
0.5
1
1.5
2
2.5
3
144
148
152
156
160
164
168

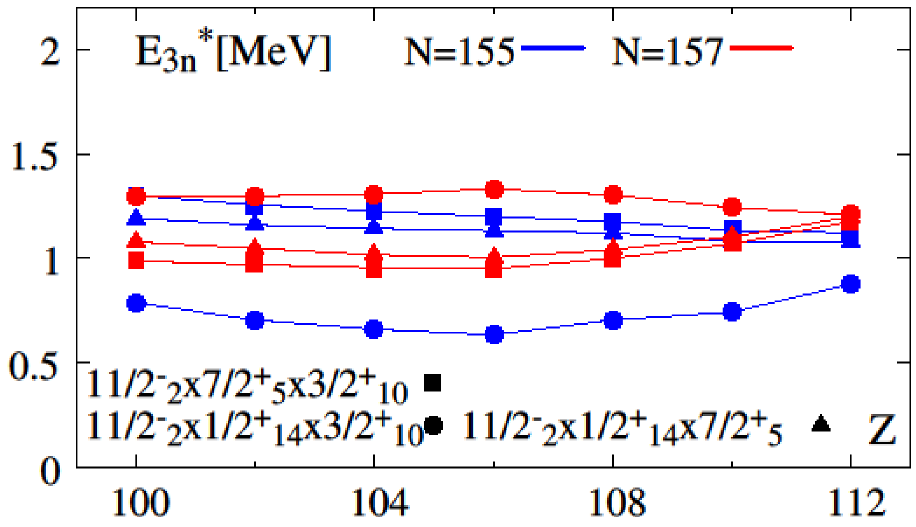

E1n2p*(Z=112) [MeV]
Ωπν x[3/2-8 x 9/2-2]π
Ωπν x[11/2+1 x 7/2-4]π
Ωπν x[11/2+1 x 9/2-2]π
N
0
0.5
1
1.5
2
2.5
3
144
148
152
156
160
164
168

Lowest exc. energies

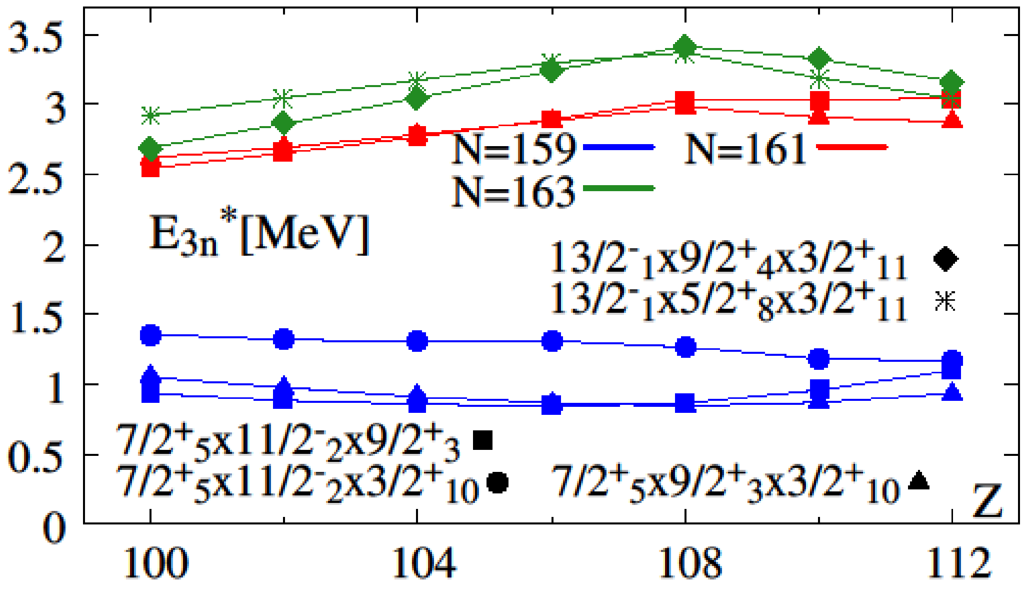


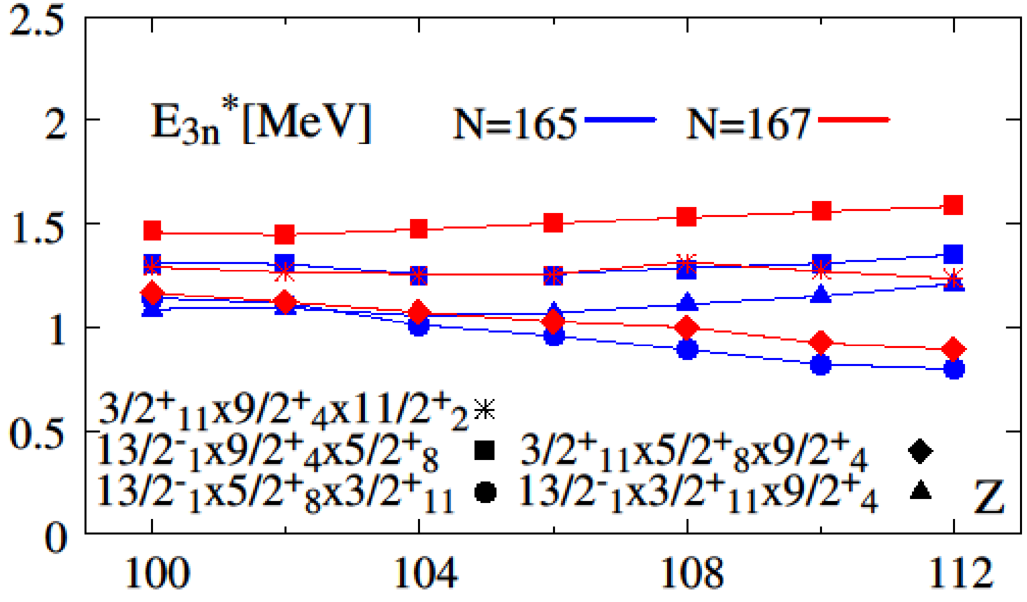






3n – PNP results


3.5
3
2.5
2
1.5
1
0.5
0
100
104
108
112
N=159
N=161
N=163
E3n*[MeV]
13/2-1x9/2+4x3/2+11
13/2-1x5/2+8x3/2+11
7/2+5x11/2-2x9/2+3
7/2+5x11/2-2x3/2+10
7/2+5x9/2+3x3/2+10
Z


2.5
2
1.5
1
0.5
0
100
104
108
112
E3n*[MeV]
N=165
N=167
3/2+11x9/2+4x11/2+2
13/2-1x9/2+4x5/2+8
3/2+11x5/2+8x9/2+4
13/2-1x5/2+8x3/2+11
13/2-1x3/2+11x9/2+4
Z

Conclusions:

- The WS s.p. scheme is reflected in a specific high-K structure for low-lying states in odd and odd-odd SH nuclei, and low-lying high-K 3qp states in odd-even and even-odd SH nuclei (which could be, in principle, tested experimentally).

- The treatment of pairing may change exctitation energies but not the candidate configurations.

- Promising candidates for 3qp isomers in odd-Z nuclei are predicted particularly for some N=148,150 (the lowest E* in Md), 158, 160 (the lowest E* in Bh), and 164 (the lowest E* in Rg) isotones (1p2n); and Z=103, 111, and some Z=105 isotopes (3p).

- Our results are consistent with the interpretation of 3qp isomers as 1p2n in N=148, 150 Md and Lr isotones; for ^{255}Lr they rather suggest a 3p high-K state.

- Promising candidates for 1n2p K-isomers in odd-N nuclei are predicted particularly for isotopes of Rf and Sg, up to N<158, and in Ds; energies of 1n2p excitations sharply rise with N in Fm.

  The smallest energies of 3n high- K states occur for N=155 and 159, lighter N=149 and heavier N=165, 167 isotones.
  3n energies are rather large around neutron gaps N=152, 162 in the PNP method.
  The quasiparticle method smoothes the energy variation with N.

- Energies of known isomers in odd No and Rf agree roughly with the calculated ones, but the attribution of configurations is too uncertain to decide on the quality of predictions.

- More data are required to assess the models.