Candidates for long-lived high-K isomers in even-even and odd-A superheavy nuclei

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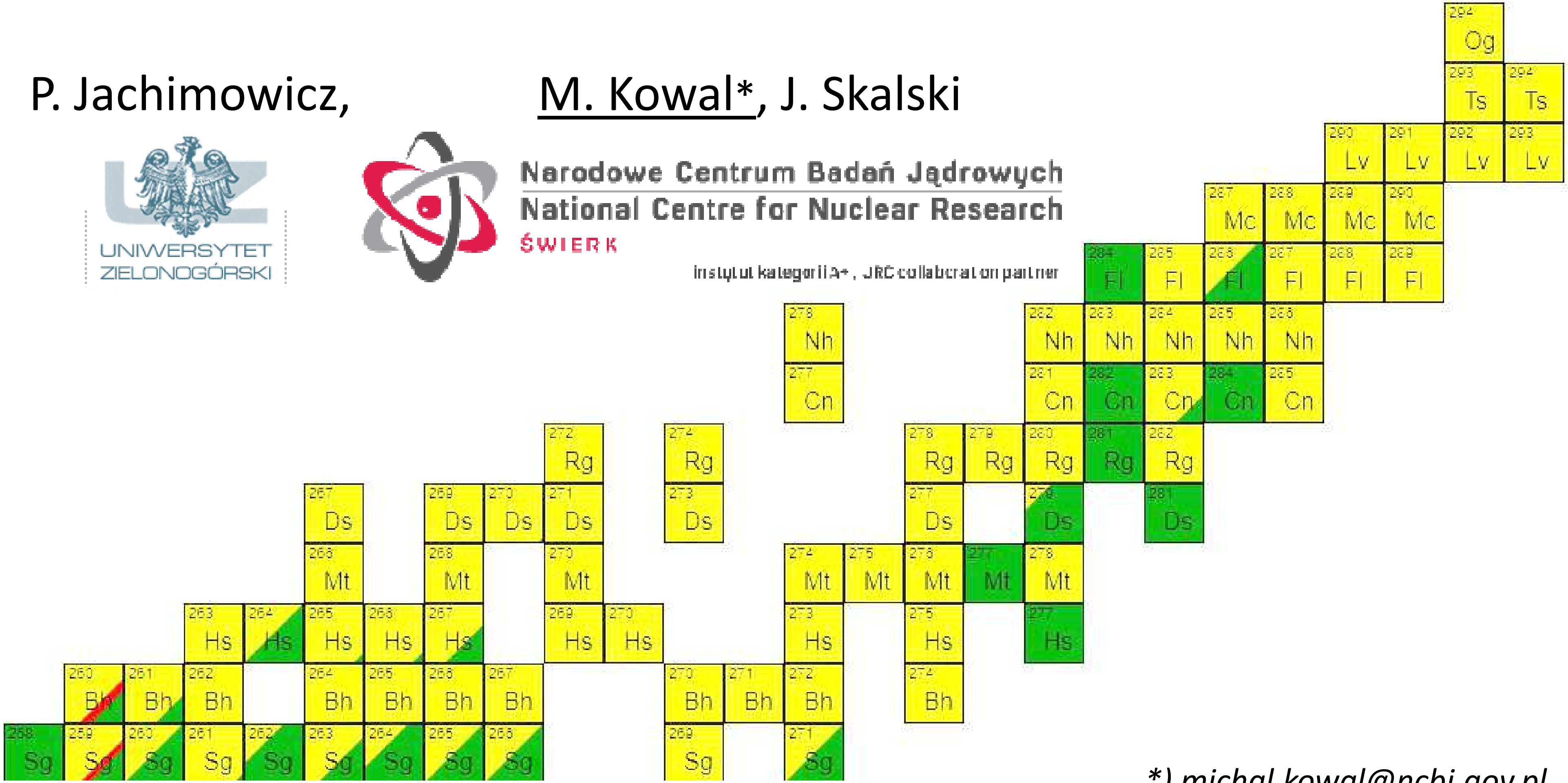

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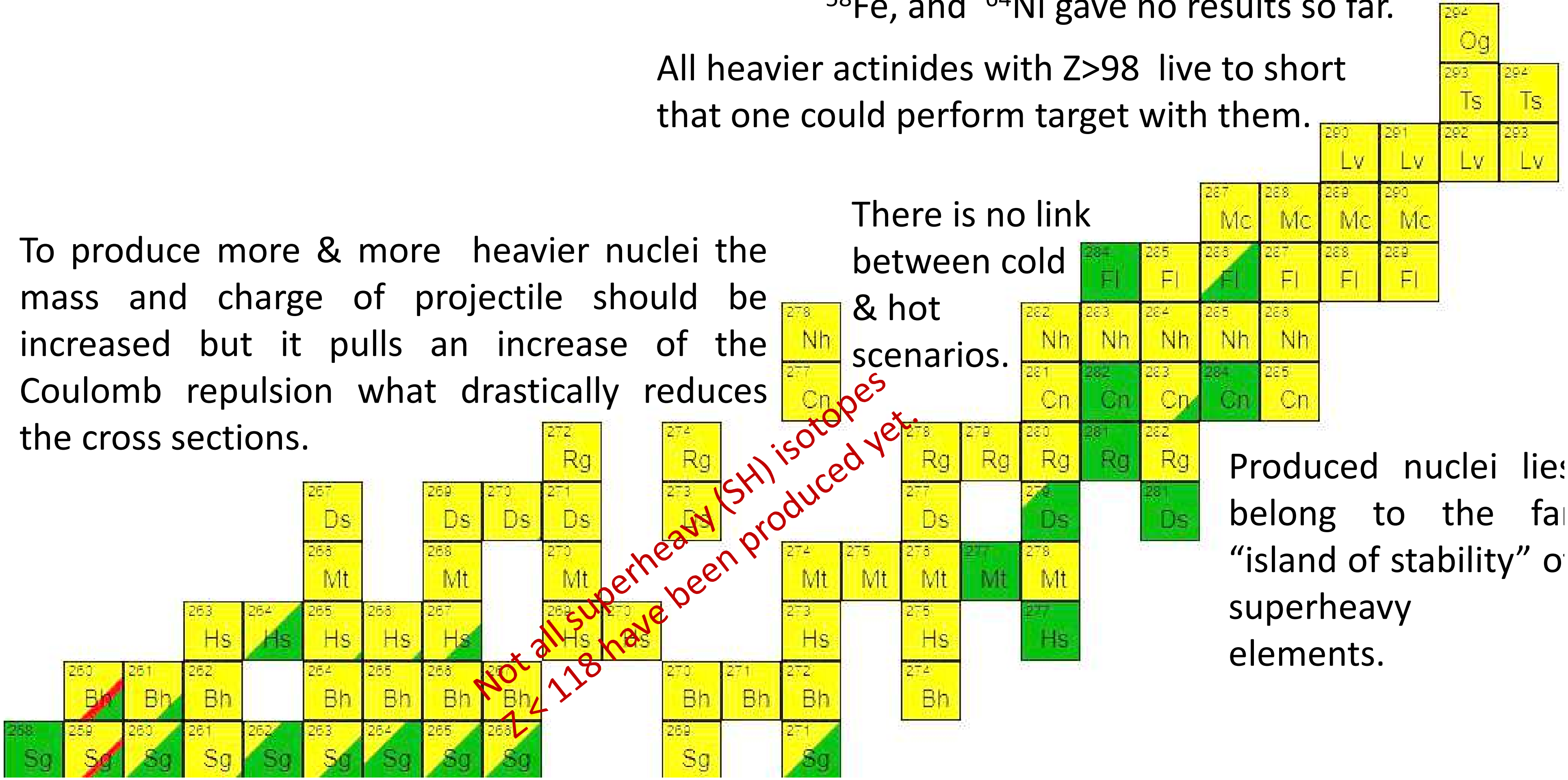
Candidates for long-lived high-K isomers in even-even and odd-A superheavy nuclei

Attempts of going beyond the reactions Act. + ^{48}Ca by using heavier projectiles like ^{50}Ti, ^{54}Cr, ^{58}Fe, and ^{64}Ni gave no results so far.

All heavier actinides with Z>98 live to short that one could perform target with them.

There is no link between cold & hot scenarios.

To produce more & more heavier nuclei the mass and charge of projectile should be increased but it pulls an increase of the Coulomb repulsion what drastically reduces the cross sections.

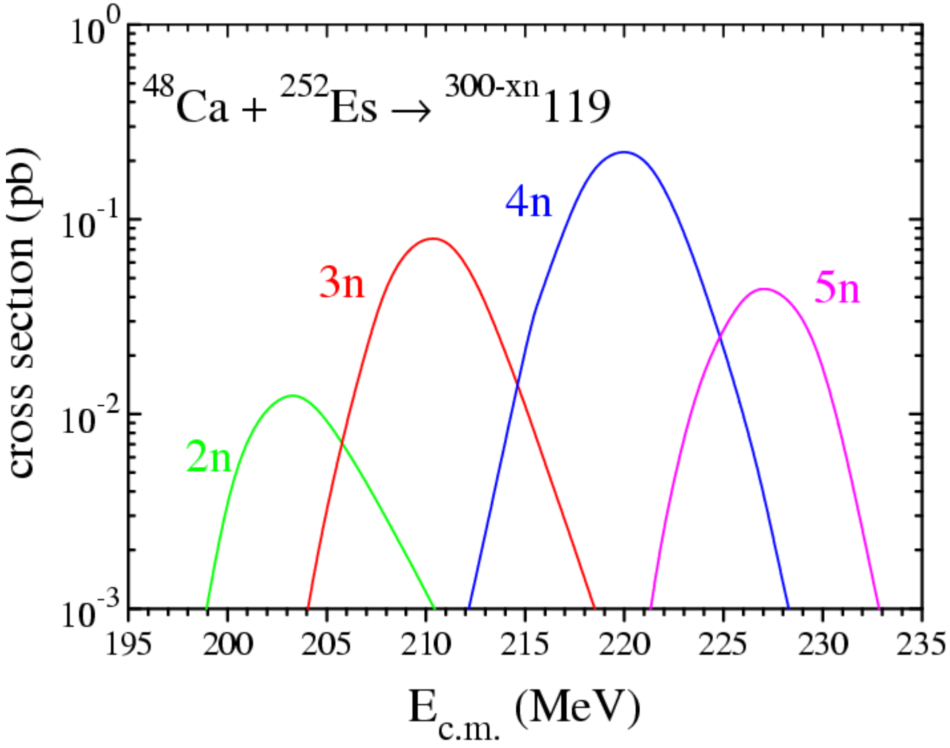


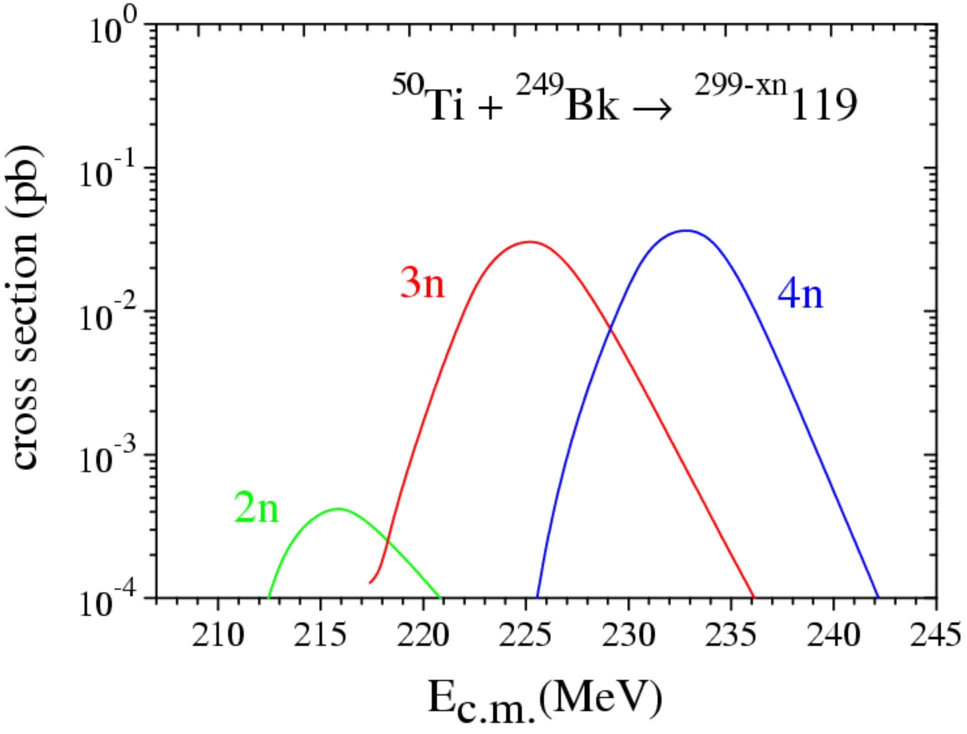
Not all superheavy (SH) isotopes Z< 118 have been produced yet.

Produced nuclei lie
belong to the fa
“island of stability” o
superheavy
elements.

motivation

Superheavy elements are highly unstable systems with extremely low production cross sections. As the creation of new ones is very difficult, as a parallel or additional line of study one could try a search for new, long-lived metastable states of already known nuclei. It is well known that an enhanced stability may result from the K-isomerism phenomenon





K. Siwek-Wilczynska, T. Cap, M. Kowal, A. Sobiczewski, and J. Wilczynski, Phys. Rev. C **86**, (2012).

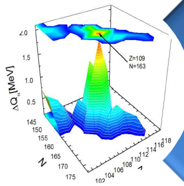
SERUM?

Candidates are high-K isomers or ground-states, for which increased stability is expected due to some specific hindrance mechanisms.

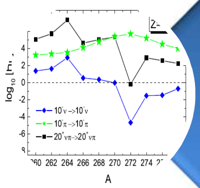
extreme properties:

Nuclide	Half-life	Spin (ħ)	Energy	Attribute
^{12}Be	~500 ns	0	2.2 MeV	low mass
^{94}Ag	300 ms	21	6 MeV	proton decay
^{152}Er	11 ns	~36	13 MeV	high spin and energy
^{180}Ta	>10^{16} y	9	75 keV	long half-life
^{229}Th	~5 h	3/2	~7.6 eV	low energy
^{270}Ds	~6 ms	~10	~1 MeV	high mass

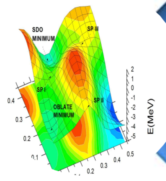
P. WALKER'S TABLE



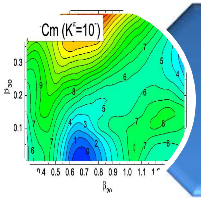
High-K g. s. in odd and odd-odd SHN



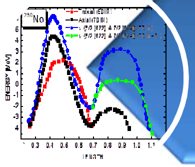
2qp & 4qp high-K isomers in even-even SHN



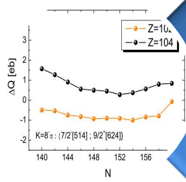
Super-Deformed Oblate (SDO) high-K isomers & g.s.



High-K isomers build at superdeformed minimum



Fission hindrance of high-K states in SHN



Sizes and shapes of high-K states in SHN

Method

Predictions for high-K multi-quasiparticle nuclear configurations require a model that

- satisfactorily describes well-known basic nuclear properties as: ground state masses, fission barriers, equilibrium deformations etc.
- gives sufficiently distinct energetic shell gaps: two of them in the proton spectrum, at around Z=100 and Z=108, and next two at N=152 and N=162 in the neutron spectrum.

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

I. Muntian, Z. Patyk and A. Sobiczewski, Acta Phys. Pol. B 32, 691 (2001).
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).

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).

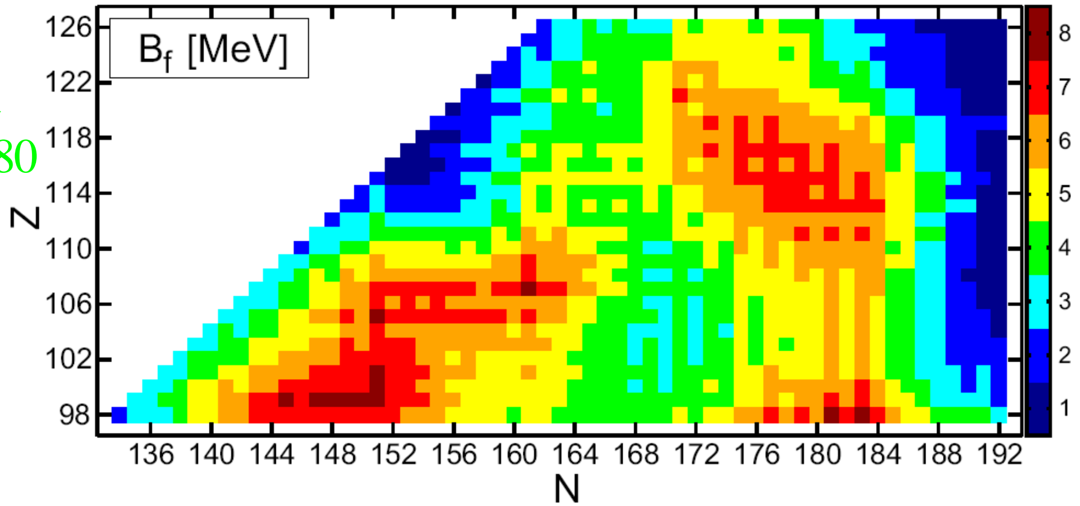
Shape parametrization:

$$R(\Theta,\Phi)=\{1+a_{20}Y_{20}+a_{40}Y_{40}+a_{60}Y_{60}+a_{80}Y_{80}$$

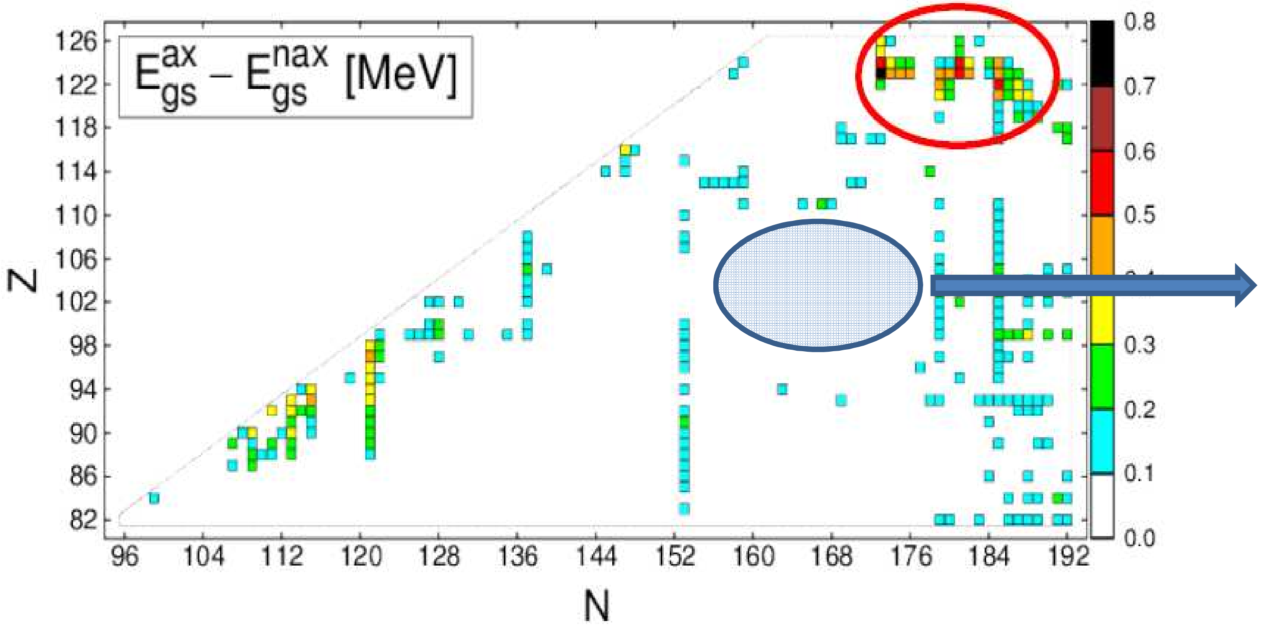
$$+a_{22}Y_{22}^{(+)}+a_{42}Y_{42}^{(+)}+a_{44}Y_{44}^{(+)}$$

$$+a_{32}Y_{32}^{(+)}+a_{52}Y_{52}^{(+)}$$

$$+a_{30}Y_{30}+a_{50}Y_{50}+a_{70}Y_{70}\}$$



P. Jachimowicz, M. Kowal, and J. Skalski, *Phys. Rev. C* 95, 014303 (2017).



- *K* is a good quantum number

P. Jachimowicz, M. Kowal, J. Skalski, *Phys. Rev. C* 95, 034329 (2017).

- the intrinsic parity of states is well defined,

N	A	M^{gs}_{th} (MeV)	E^{gs}_{tot} (MeV)	E^{gs}_{mac} (MeV)	E^{gs}_{mic} (MeV)	β^{gs}_{20}	β^{gs}_{30}	β^{gs}_{40}	β^{gs}_{50}	β^{gs}_{60}	β^{gs}_{70}	β^{gs}_{80}
152	262	134.53	-3.94	0.66	-4.60	0.24	0.00	-0.02	0.00	-0.04	0.00	0.01
153	263	134.83	-3.40	1.65	-5.04	0.24	0.00	-0.03	0.00	-0.04	0.00	0.02
154	264	133.91	-4.22	0.87	-5.09	0.24	0.00	-0.03	0.00	-0.04	0.00	0.02
155	265	134.33	-3.84	2.02	-5.86	0.24	0.00	-0.04	0.00	-0.04	0.00	0.02
156	266	133.80	-4.53	1.09	-5.63	0.23	0.00	-0.04	0.00	-0.03	0.00	0.02
157	267	134.26	-4.37	2.31	-6.68	0.24	0.00	-0.05	0.00	-0.03	0.00	0.03
158	268	134.02	-5.04	1.34	-6.39	0.23	0.00	-0.06	0.00	-0.02	0.00	0.02
159	269	134.53	-5.09	2.34	-7.42	0.23	0.00	-0.07	0.00	-0.02	0.00	0.02
160	270	134.55	-5.74	1.60	-7.34	0.23	0.00	-0.07	0.00	-0.02	0.00	0.02
161	271	135.01	-6.09	2.65	-8.74	0.23	0.00	-0.07	0.00	-0.01	0.00	0.03
162	272	135.44	-6.60	1.89	-8.48	0.23	0.00	-0.08	0.00	-0.01	0.00	0.03
163	273	137.16	-5.93	2.73	-8.66	0.22	0.00	-0.08	0.00	0.00	0.00	0.02
164	274	138.15	-6.12	1.90	-8.01	0.22	0.00	-0.08	0.00	0.00	0.00	0.02
165	275	140.43	-5.12	2.79	-7.92	0.21	0.00	-0.09	0.00	0.01	0.00	0.01
166	276	141.44	-5.54	1.98	-7.52	0.21	0.00	-0.09	0.00	0.01	0.00	0.01
167	277	143.90	-4.61	3.19	-7.80	0.21	0.00	-0.09	0.00	0.02	0.00	0.01
168	278	145.19	-4.97	2.11	-7.08	0.20	0.00	-0.09	0.00	0.01	0.00	0.01
169	279	147.90	-4.03	2.49	-6.52	0.18	0.00	-0.08	0.00	0.01	0.00	0.01
170	280	149.22	-4.59	0.80	-5.40	0.15	0.00	-0.05	0.00	0.00	0.00	0.01
171	281	151.57	-4.25	1.68	-5.93	0.14	0.00	-0.06	0.00	0.01	0.00	0.00
172	282	153.11	-4.81	0.67	-5.49	0.13	0.00	-0.05	0.00	0.01	0.00	0.00
173	283	155.54	-4.61	1.37	-5.98	0.11	0.00	-0.04	0.00	0.01	0.00	0.00
174	284	157.32	-5.16	0.58	-5.74	0.10	0.00	-0.05	0.00	0.01	0.00	0.00
175	285	159.74	-5.18	1.55	-6.73	0.10	0.00	-0.05	0.00	0.01	0.00	0.00
176	286	161.95	-5.52	0.70	-6.22	0.09	0.00	-0.05	0.00	0.01	0.00	0.00
177	287	164.96	-5.17	0.99	-6.17	-0.09	0.00	-0.02	0.00	0.01	0.00	0.00
178	288	167.28	-5.62	0.17	-5.78	-0.09	0.00	-0.01	0.00	0.01	0.00	0.00
179	289	170.44	-5.33	0.90	-6.22	0.03	0.00	-0.02	0.00	0.00	0.00	0.00
180	290	172.87	-5.87	0.05	-5.92	-0.04	0.00	-0.01	0.00	0.00	0.00	0.00

Scheme of action:

- Four dimensional minimization is performed using the gradient method:

$$\begin{aligned} R(\vartheta, \varphi) = R_0\{1 \ &+\ \beta_{20}\mathrm{Y}_{20} + \cancel{\beta_{30}\mathrm{Y}_{30}} + \beta_{40}\mathrm{Y}_{40} + \\ &+\ \cancel{\beta_{50}\mathrm{Y}_{50}} + \beta_{60}\mathrm{Y}_{60} + \cancel{\beta_{70}\mathrm{Y}_{70}} + \beta_{80}\mathrm{Y}_{80}\}. \end{aligned}$$

- Certains states are blocked and minimization is served again.

excitation energies of particular states and corresponding to those states deformations be found.

Candidates for 2qp & 4qp K-isomeric states:

Favored configurations for four-quasiparticle K isomerism in the heaviest nuclei
H. L. Liu, P. M. Walker, and F. R. Xu Phys. Rev. C 89, 044304 (2014).

N=152 GAP

- KN=8-1 : 7/2+[624] & 9/2-[734]
- KN=8-2 : 7/2+[613] & 9/2-[734]

P=102 GAP

- KP=8-1 : 7/2-[514] & 9/2+[624]
- KP=8-2 : 5/2-[512] & 11/2+[615]

K=16+1 {KN=8-1 : 7/2+[624] & 9/2-[734]} & {KP=8-1 : 7/2-[514] & 9/2+[624]}
K=16+2 {KN=8-2 : 7/2+[613] & 9/2-[734]} & {KP=8-1 : 7/2-[514] & 9/2+[624]}

- KN=6+ : 5/2+[622] & 7/2+[624]
- KN=6- : 7/2-[743] & 5/2+[622]
- KN=7- : 7/2-[743] & 7/2+[624]

- KP=5- : 1/2-[521] & 9/2+[624]
- KP=7- : 7/2+[633] & 7/2-[514]

N=162 GAP

- KN=10- : 9/2+[615] & 11/2-[725]
- KN=9- : 7/2+[613] & 11/2-[725]

P=108 GAP

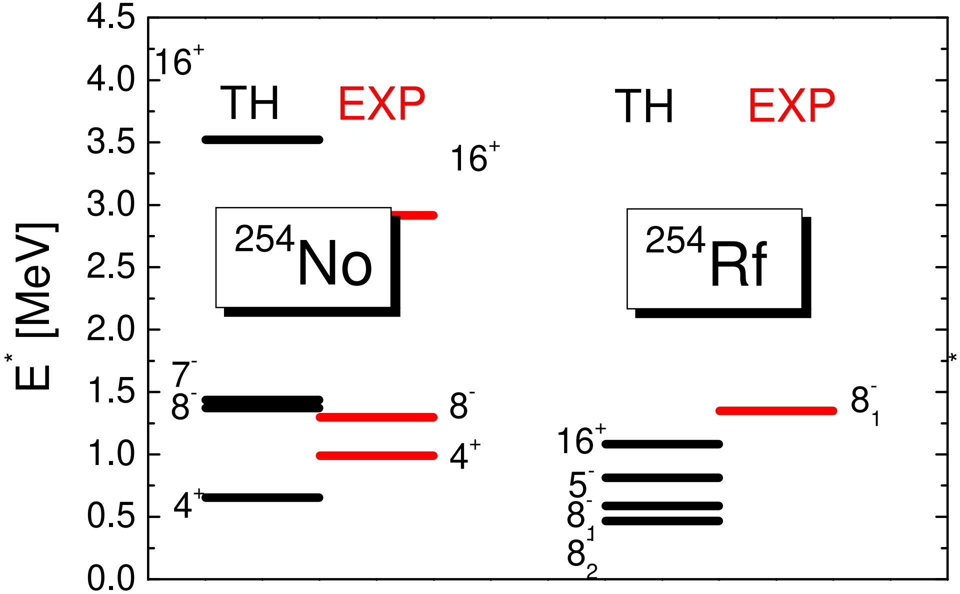
- KP=10- : 9/2-[505] & 11/2+[615]

K=20+ {KN=10- : 9/2+[615] & 11/2-[725]} & {KP=10- : 9/2-[505] & 11/2+[615]}
K=19+ {KN=9- : 7/2+[613] & 11/2-[725]} & {KP=10- : 9/2-[505] & 11/2+[615]}
K=18+ {KN=10- : 9/2+[615] & 11/2-[725]} & {KP=8- : 5/2-[512] & 11/2+[615]}
K=17+ {KN=9- : 7/2+[613] & 11/2-[725]} & {KP=8- : 5/2-[512] & 11/2+[615]}

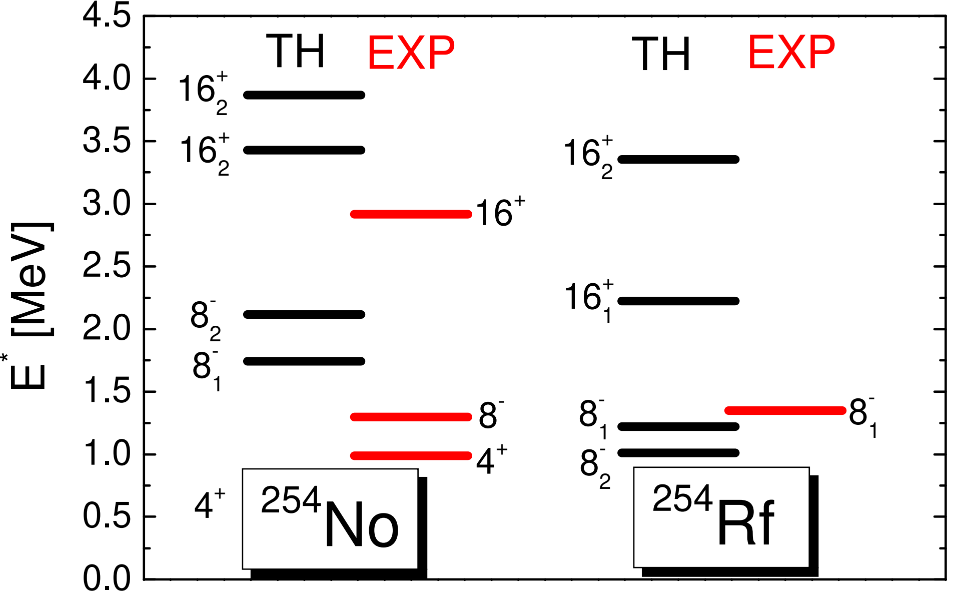
Theory vs. experiment for No and Rf.

The blocking procedure often causes an excessive reduction of the pairing gap in 2qp and particulary in 4qp systems. One device to avoid was to assume a stronger (typically by ~5% or 10%) pairing interaction.

Gp(n)



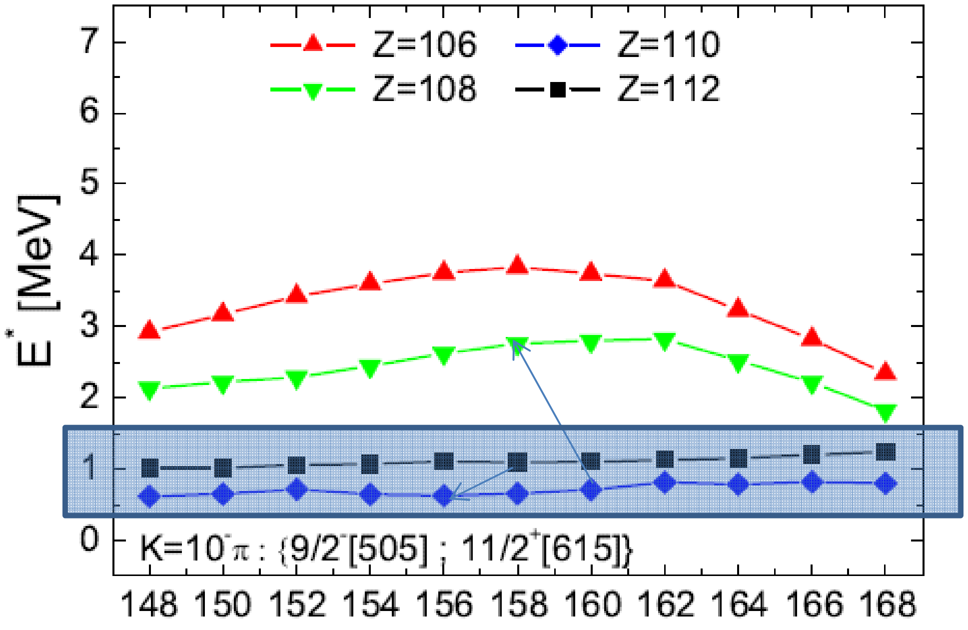
1.1Gp(n)

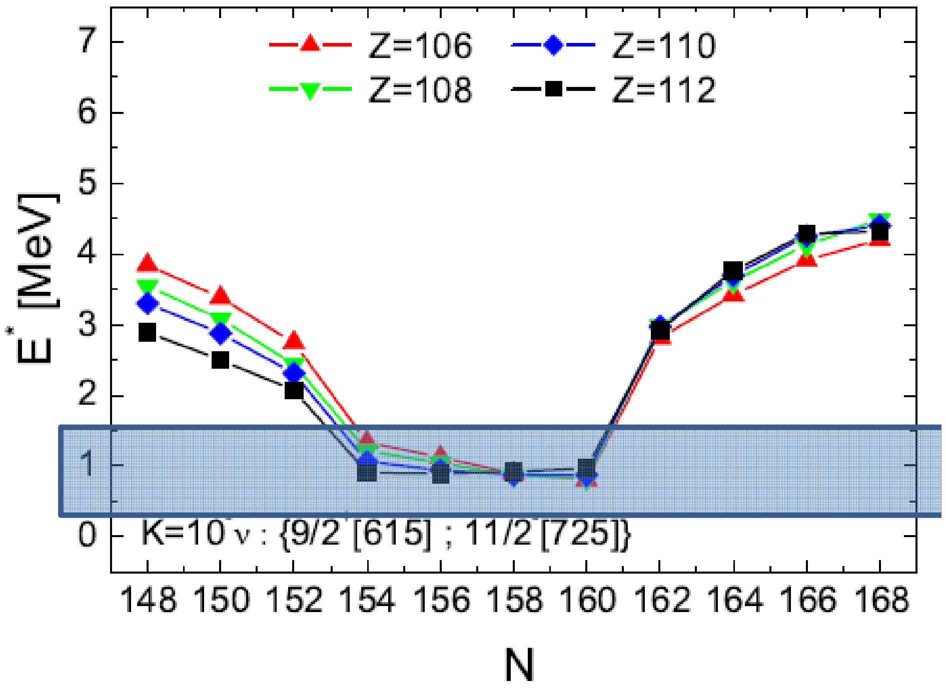


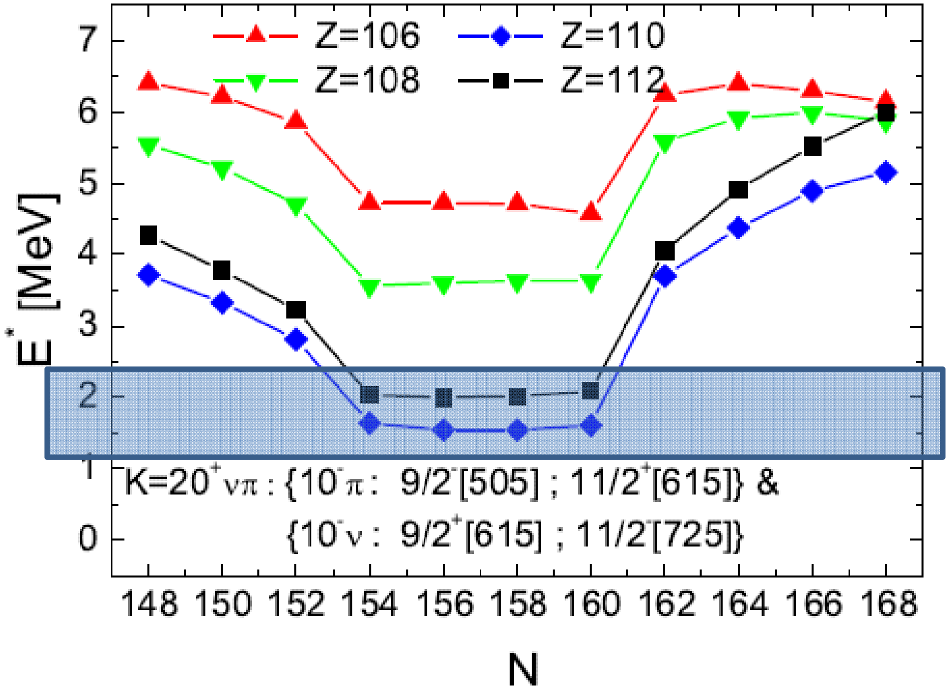
2qp & 4qp high-K isomers in even-even SHN

Stability of high-spin isomers against alpha decay is determined mainly by three factors:

- the overlap between final and initial states wherein a similar structure of states favors the transition between them;
- change in angular momentum - a significant change is associated with a large centrifugal barrier which blocks a decay;
- transition energy, which we shall also call *Q* for a given decay, that follows from the *Q* value for the g.s.->g.s. transition and the difference in the excitation energies of the initial and final state in, respectively, mother and daughter nucleus.







S. Hofmann et al. , "The new isotope ^{270}110 and its decay products ^{266}Hs and ^{262}Sg" . Eur. Phys. J. A. ***10*** *(1): 5–10, 2001*

^{207}Pb(^{64}Ni,n) ^{270}Ds

$\sigma = (13 \pm 5)$ pb

$$HF \;=\; [T_{1/2}^{a \rightarrowtail b} / T_{1/2}^{gs \rightarrowtail gs}]$$

a – initial state; b - final state

(structural) (tunneling)

$$HF = HF_S * HF_\Gamma$$

(difference in Q) (centrifugal)

$$HF_\Gamma \simeq HF_Q * HF_L$$

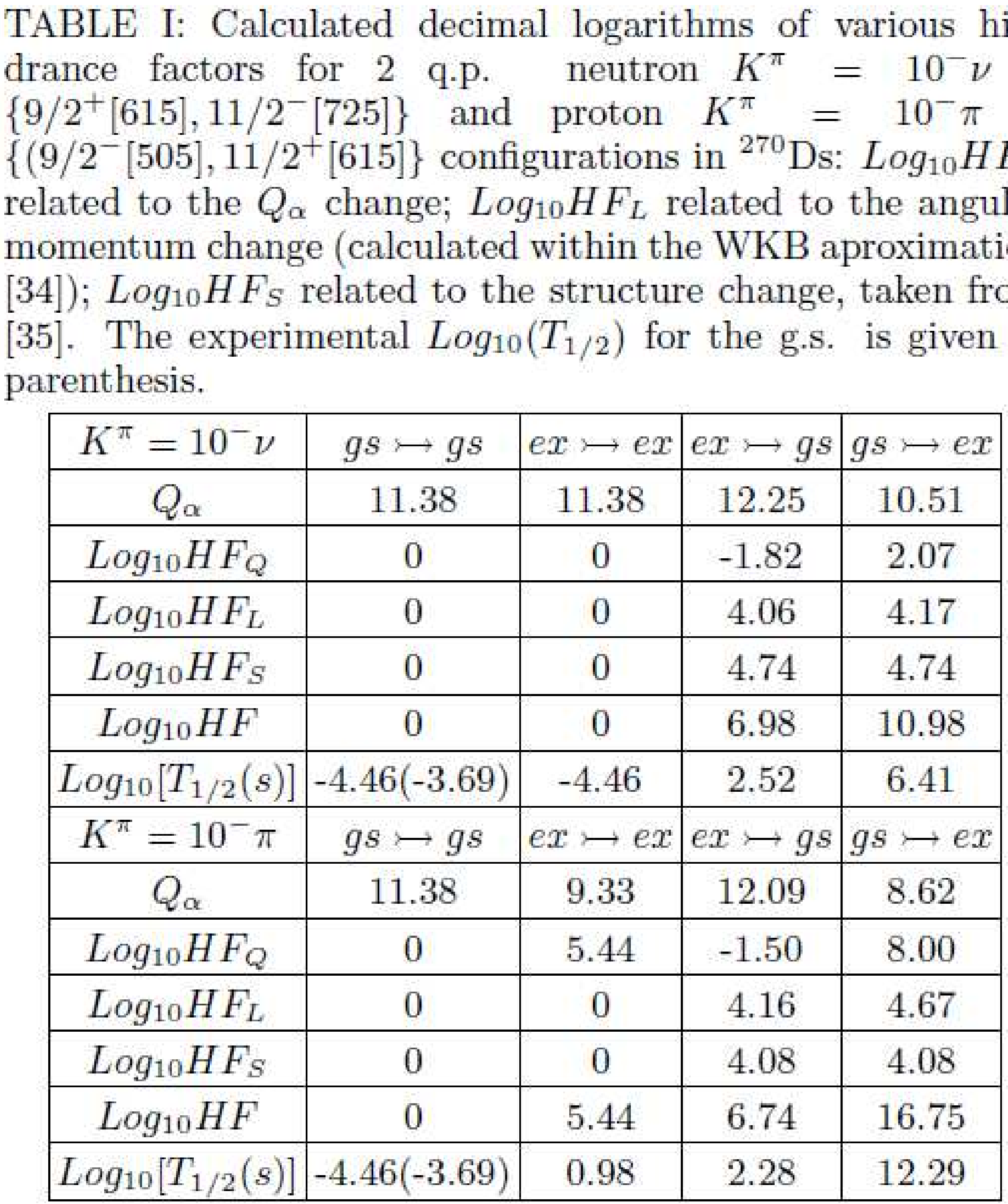


TABLE I: Calculated decimal logarithms of various hindrance factors for 2 q.p. neutron $K^{\pi} = 10^{-}\nu$: $\{9/2^{+}[615], 11/2^{-}[725]\}$ and proton $K^{\pi} = 10^{-}\pi$: $\{(9/2^{-}[505], 11/2^{+}[615]\}$ configurations in ^{270}Ds: $Log_{10}HF_{Q}$ related to the Q_{α} change; $Log_{10}HF_{L}$ related to the angular momentum change (calculated within the WKB aproximation [34]); $Log_{10}HF_{S}$ related to the structure change, taken from [35]. The experimental $Log_{10}(T_{1/2})$ for the g.s. is given in parenthesis.

$K^{\pi} = 10^{-}\nu$	$gs \rightarrowtail gs$	$ex \rightarrowtail ex$	$ex \rightarrowtail gs$	$gs \rightarrowtail ex$
Q_{α}	11.38	11.38	12.25	10.51
$Log_{10}HF_{Q}$	0	0	-1.82	2.07
$Log_{10}HF_{L}$	0	0	4.06	4.17
$Log_{10}HF_{S}$	0	0	4.74	4.74
$Log_{10}HF$	0	0	6.98	10.98
$Log_{10}[T_{1/2}(s)]$	-4.46(-3.69)	-4.46	2.52	6.41
$K^{\pi} = 10^{-}\pi$	$gs \rightarrowtail gs$	$ex \rightarrowtail ex$	$ex \rightarrowtail gs$	$gs \rightarrowtail ex$
Q_{α}	11.38	9.33	12.09	8.62
$Log_{10}HF_{Q}$	0	5.44	-1.50	8.00
$Log_{10}HF_{L}$	0	0	4.16	4.67
$Log_{10}HF_{S}$	0	0	4.08	4.08
$Log_{10}HF$	0	5.44	6.74	16.75
$Log_{10}[T_{1/2}(s)]$	-4.46(-3.69)	0.98	2.28	12.29

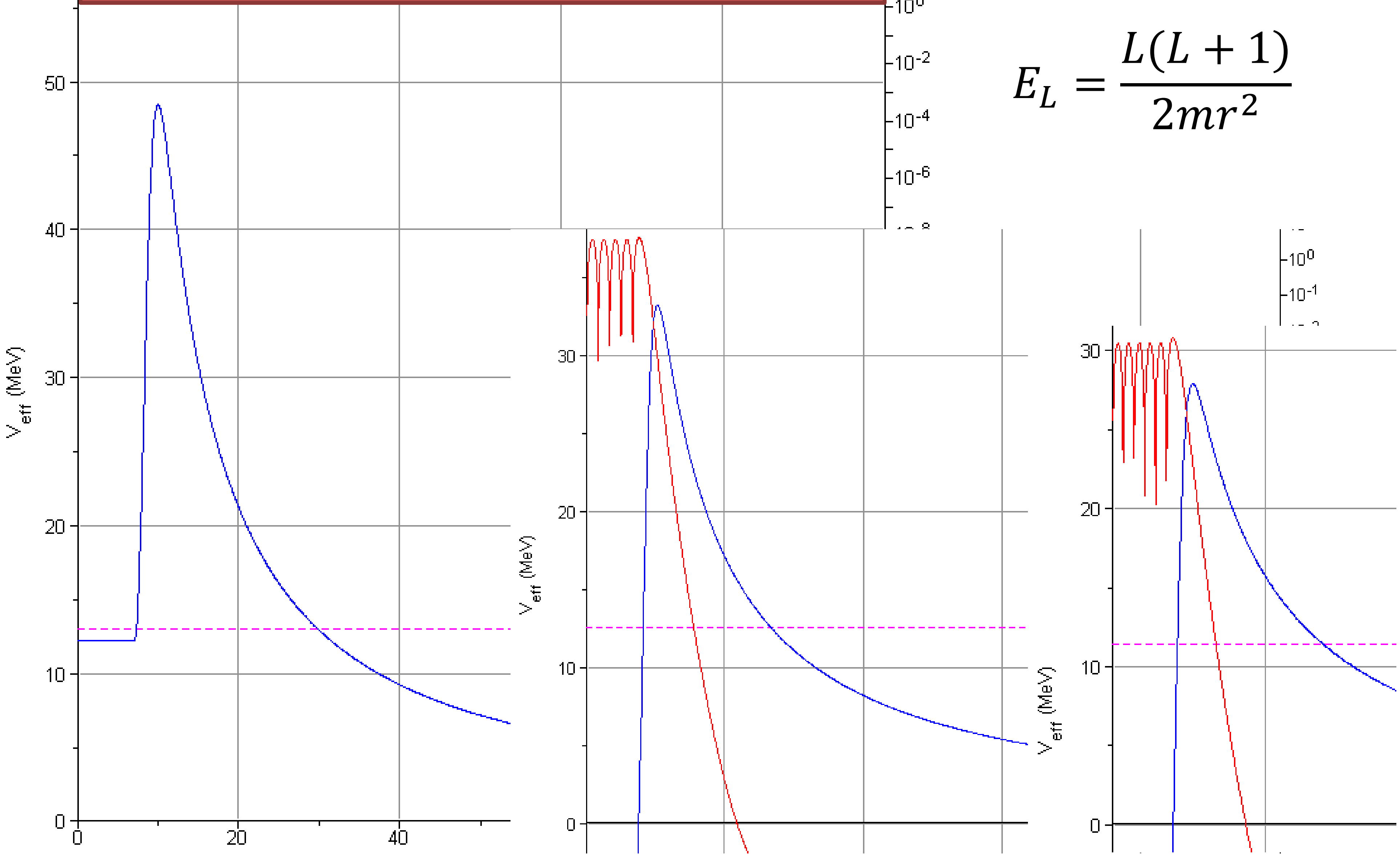
[34] V.I. Zagrebaev, A.S. Denikin, A.V. Karpov, A.P. Alekseev, M.A. Naumenko, V.A. Rachkov, V.V. Samarin, V.V. Saiko, NRV web knowledge base on low-energy nuclear physics

http://nrv.jinr.ru/nrv/webnrv/alphadecay/index.php

[35] D. S. Delion, R. J. Liota, R. Wyss, *Phys. Rev. C*, **76** 044301 (2007).

http://nrv.jinr.ru/nrv/webnrv/alphadecay/index.php

$$E_L = \frac{L(L+1)}{2mr^2}$$



$\Delta L[\hbar]$	$20\hbar$	$10\hbar$	$0\hbar$
Turning Points [fm]:	7.27; 29.70	8.21; 27.15	8.45;27.33

K=20+ {KN=10- : 9/2+[615] & 11/2-[725]}
& {KP=10- : 9/2-[505] & 11/2+[615]}

Crucial is the hindrance in the fastest channel, between two identical configurations. This is especially true for four quasi-particle states!

significant increase in the centrifugal barrier.
With $L = \Delta K = 20h$

$$HF_L \simeq 10^{12}$$

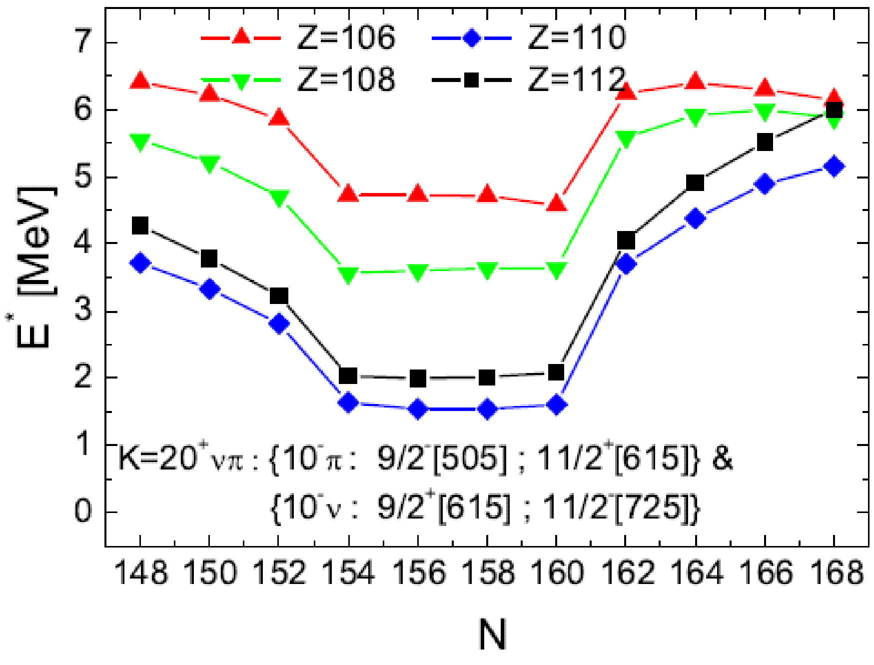
A structural hindrance for 4 q.p. isomers must be also substantial. If one assumes that it is a product of the hindrance factors for protons and neutrons

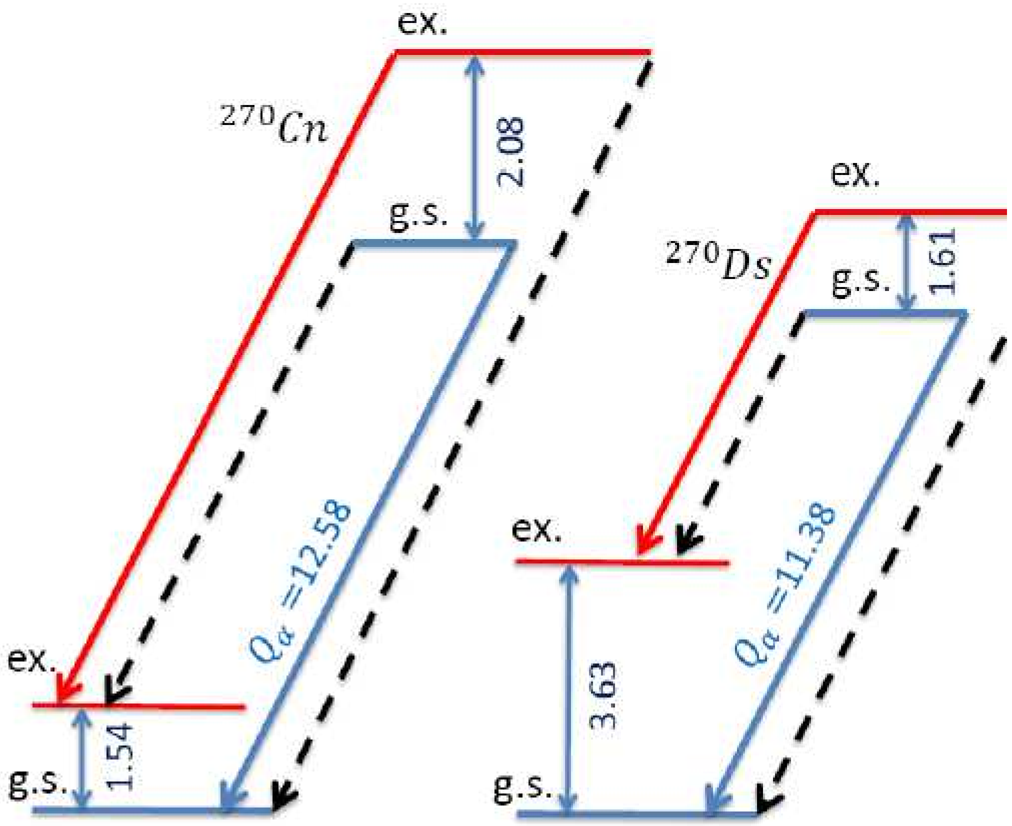
$$HF_S = 10^9$$

Taken together, this leads to the conclusion that transitions *ex* -> *gs* or *gs* -> *ex* are excluded.

TABLE II: Q_α-values (in MeV) and hindrance factors corresponding to the change $\Delta Q_\alpha = Q_\alpha^{ex\to ex} - Q_\alpha^{gs\to gs}$ for the $K^\pi = 20^+\nu\pi : (10^-\nu : \{(9/2^+[615], 11/2^-[725]\} \otimes 10^-\pi : \{(9/2^-[505], 11/2^+[615]\})$ configuration in ^{270}Cn and ^{270}Ds, calculated using: WKB method (WKB) [34], the formula of Royer [36] (ROY), and the Viola-Seaborg-type formula by Parkhomenko and Sobiczewski (PS) [39].

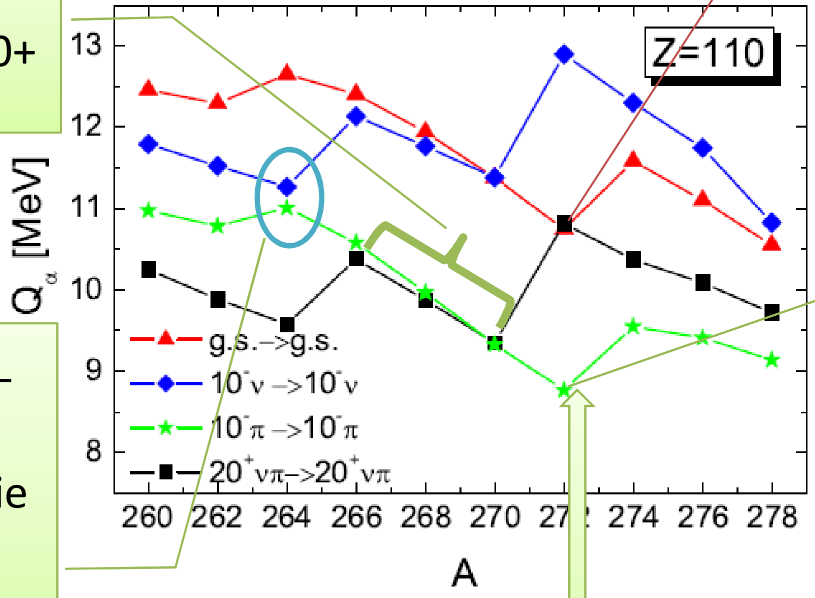
	Q_α	ΔQ_α	$Log^{WKB}[HF]$	$Log^{ROY}[HF]$	$Log^{PS}[HF]$
^{270}Cn	13.06	0.48	-0.87	-0.92	-0.88
^{270}Ds	9.36	-2.02	6.75	5.42	5.13





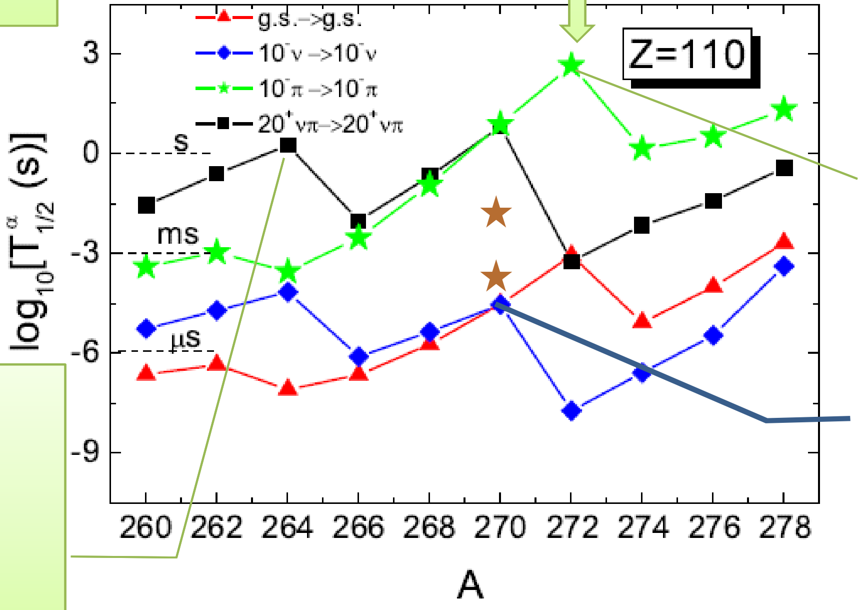
the proton character of states with delayed alpha-decay 20+-> 20+

semi-magic gap predicted at N=162 is clearly visible.



signal then an extra stable nuclear state;

two-neutron and two-proton congurations are similar and both lie signicantly below the energy for the *gs=>gs*



The most stable system (T~h)

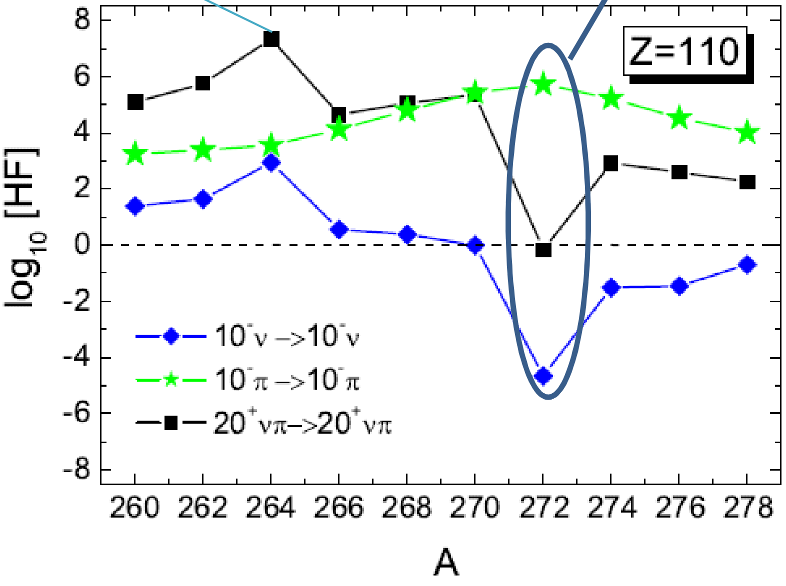
energy of states is quite low => suggest their isomeric character.

These transitions will be therefore much slower (10-4) than that between the ground states.

a two-neutron isomeric state in 270Ds does not live longer than the ground state,

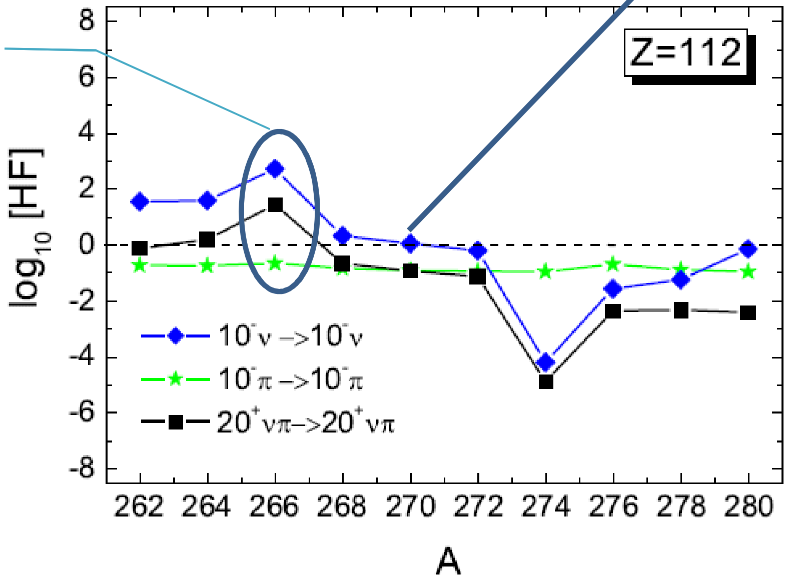
P. Jachimowicz, M. Kowal, J. Skalski, PRC 98, 014320 (2018).

The most prominent hindrance of the alpha decay among the four quasi-particle (*K* = 20+) states 10^8 – is predicted for 264Ds. However, due to the short g.s. half-life, the total half- life for this particular isomer will be practically on the same level as for 270Ds.



the decay of the two-neutron quasi-particle (10n) state is not at all hindered, while the decay of the proton two quasi-particle state (10p) is strongly forbidden: *Log*10*HFQ* = 5*:*42.

some hindrance of the alpha decay from the isomer built on the neutron excitation. The predicted hindrance is not very large (≃10^3)



the energies of these high-K states are sufficiently low to make them candidates for high-K isomers, but as follows from the discussion of excitations in 270Cn we do not expect any hindrance here. On the contrary, a decay from the isomeric states should be faster than from the ground states.

P. Jachimowicz, M. Kowal, J. Skalski, PRC 98, 014320 (2018).

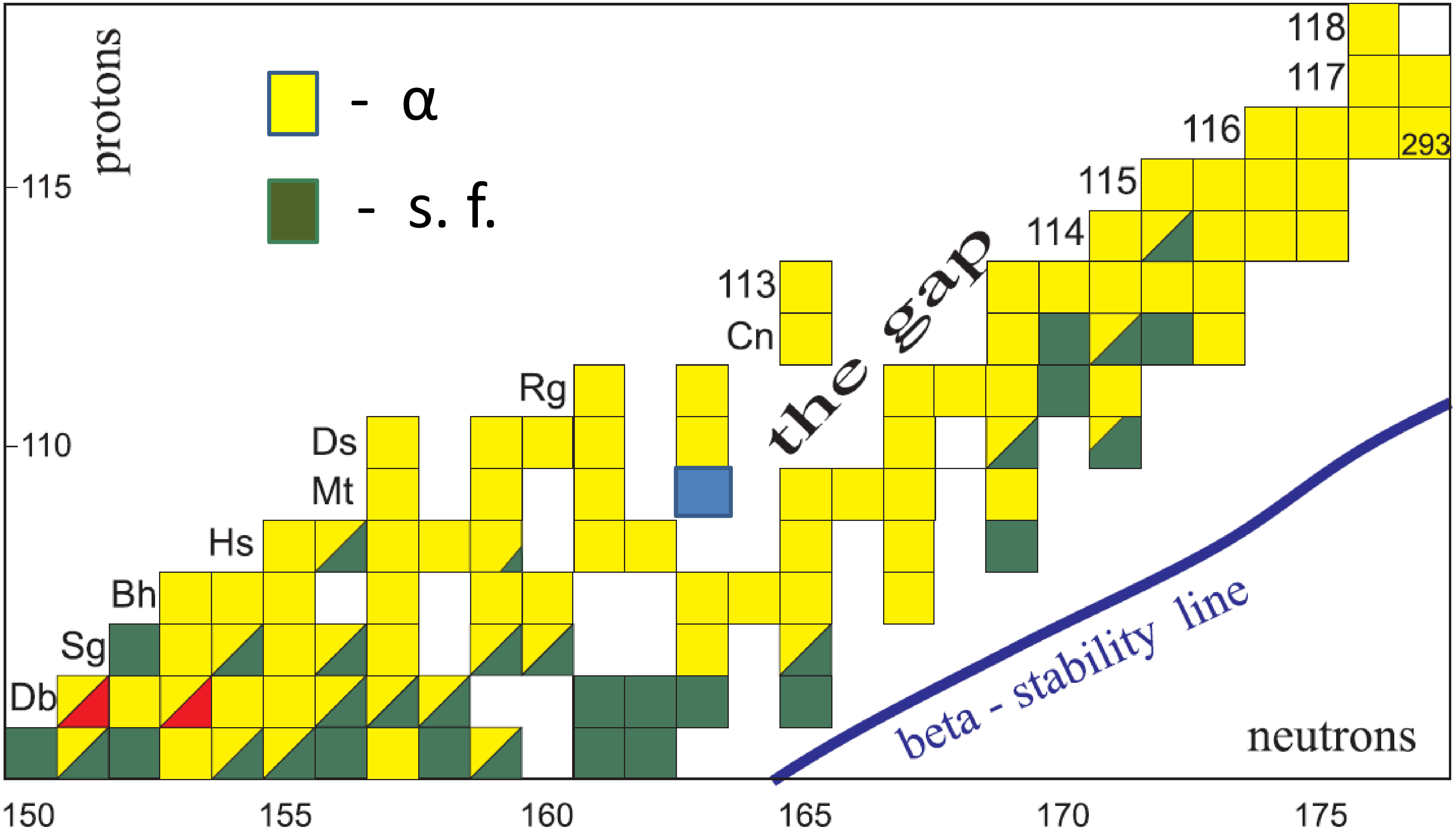
Finally, one should mention that our argument based on *HFQ* for structure-preserving transitions may overestimate hindrances - as it does for 270Ds. In principle, one should analyse hindrances for all possible final states in daughter.

Summary:

- We have found a quite strong hindrance against alpha decay for four quasi-particle states: *K* = 20+ and/or 19+. This, together with their relatively low excitation suggests a possibility that they could be isomers with an extra stability - five and more orders of magnitute longer-lived than the ground states.
- This would mean that chemical studies of such exotic high-K sates would be more likely than for quite unstable ground states.
- Among all tested nuclei, the best candidates for long- lived high-K isomers are predicted in 264Ds-270Ds.
- Except a moderate (about 3 orders of magnitude) alpha-decay hindrance in 266Cn for a 2 q.p. neutron state, there are no more candidates for an enhanced stability against alpha decay in Cn nuclei.
- Contrary to what has been recognized so far, our analysis indicates that the alpha-decay hindrance results mainly from the proton 2q.p. component.
- The most prominent hindrance of the α decay among the two-quasiproton $\boldsymbol{\pi^2 10^-}$ states is predicted for ^{272}***Ds***.

P. Jachimowicz, M. Kowal, J. Skalski, PRC 98, 014320 (2018).

V. I. Zagrebaev, A. V. Karpov, and W. Greiner PHYSICAL REVIEW C **85**, 014608 (2012).



37Cl+238U->272(109),3n

35Cl+238U->272(109),1n

37Cl+237Np->272(109),1p,2n

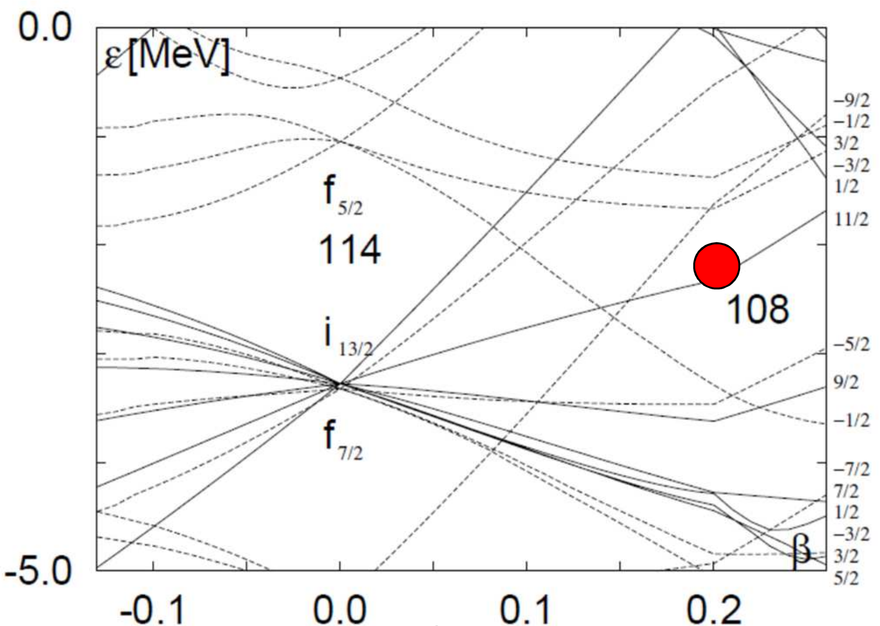
36S+237Np->272(109),1n

44Ca+232Th->272(109),1p,4n

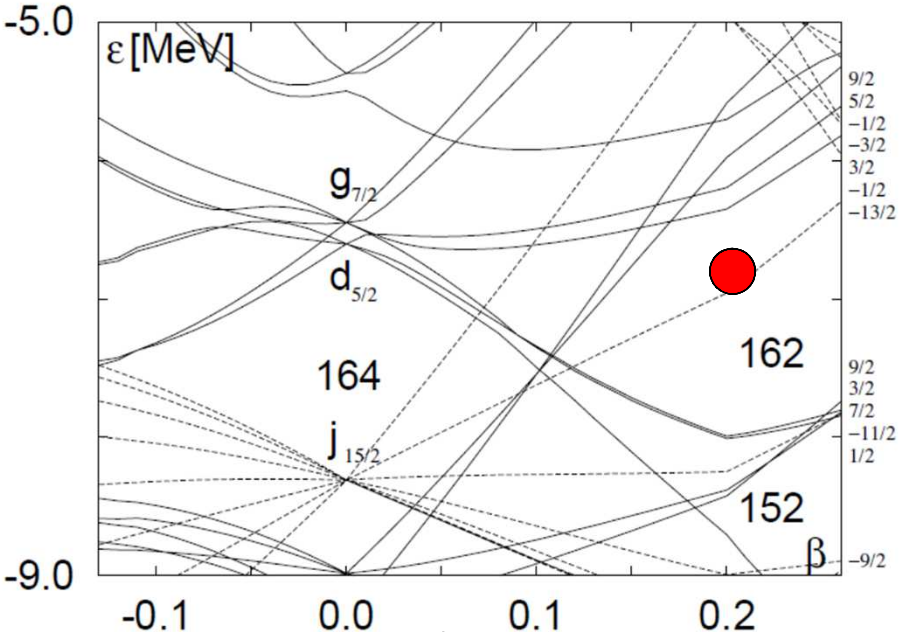
42Ca+232Th->272(109),1p,2n

32S+244Pu->272(109),1p,3n

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



protons



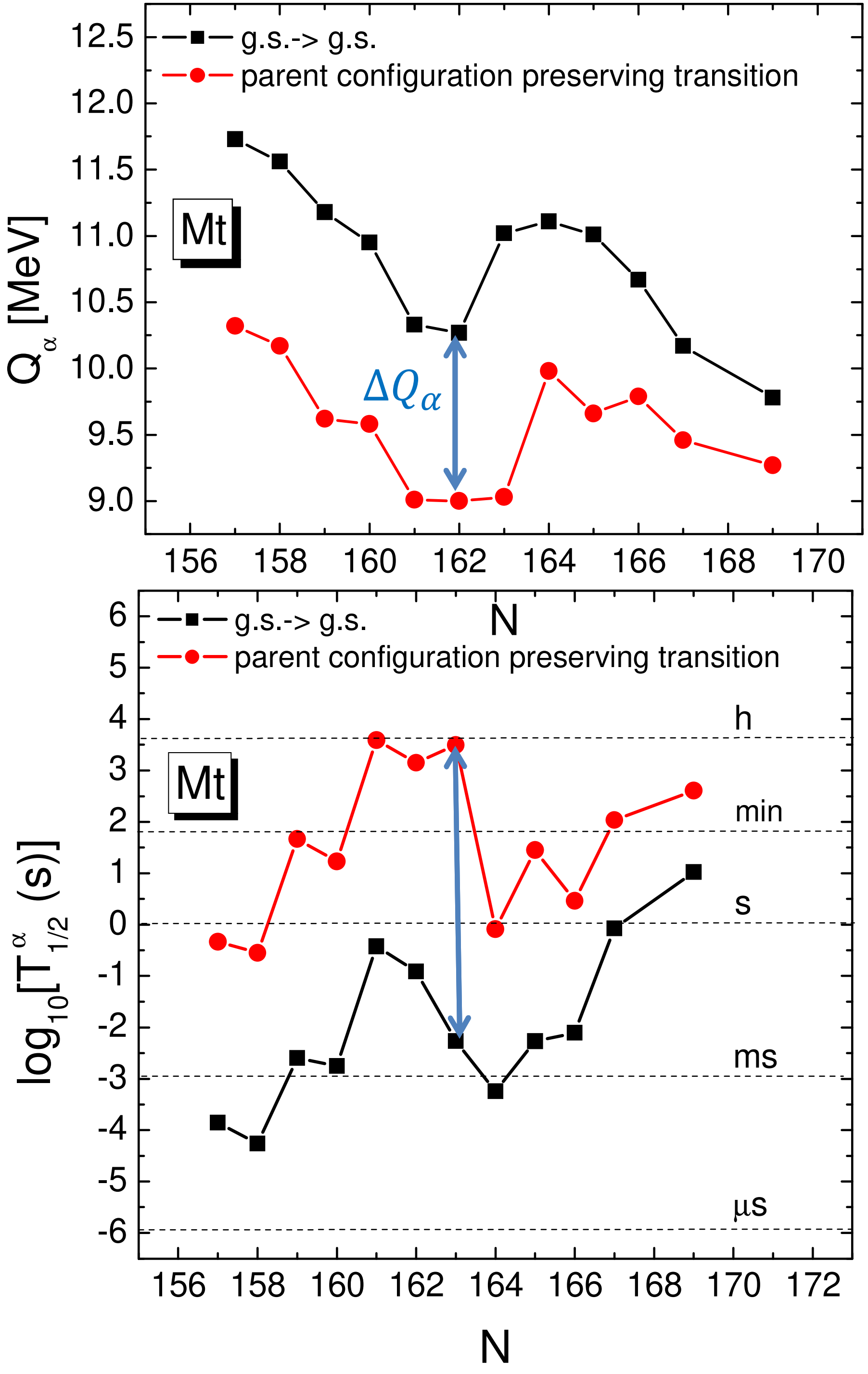
neutrons

$$(l,s,j,j_z||\mathbf{L^{\circ}s}||l,s,j,j_z) = \frac{1}{2}(j(j+1) - l(l+1) - s(s+1))$$

$|\delta E|$ - energy spliting

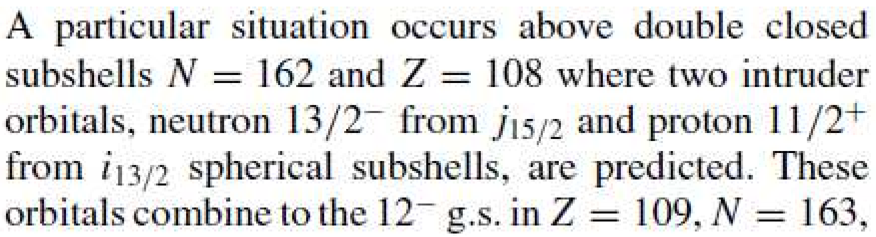
$$\left\{\begin{matrix}\frac{1}{2}l & if\ \ j = l + \frac{1}{2} \\ \frac{-1}{2}(l+1) & if\ \ j = l - \frac{1}{2}\end{matrix}\right\} \Rightarrow |\delta E| \sim L \Rightarrow \sim R \Rightarrow \sim A$$

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



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 $Z = 109$, $N = 163$,