Heavy neutron-rich nuclei: approaching the r-process path

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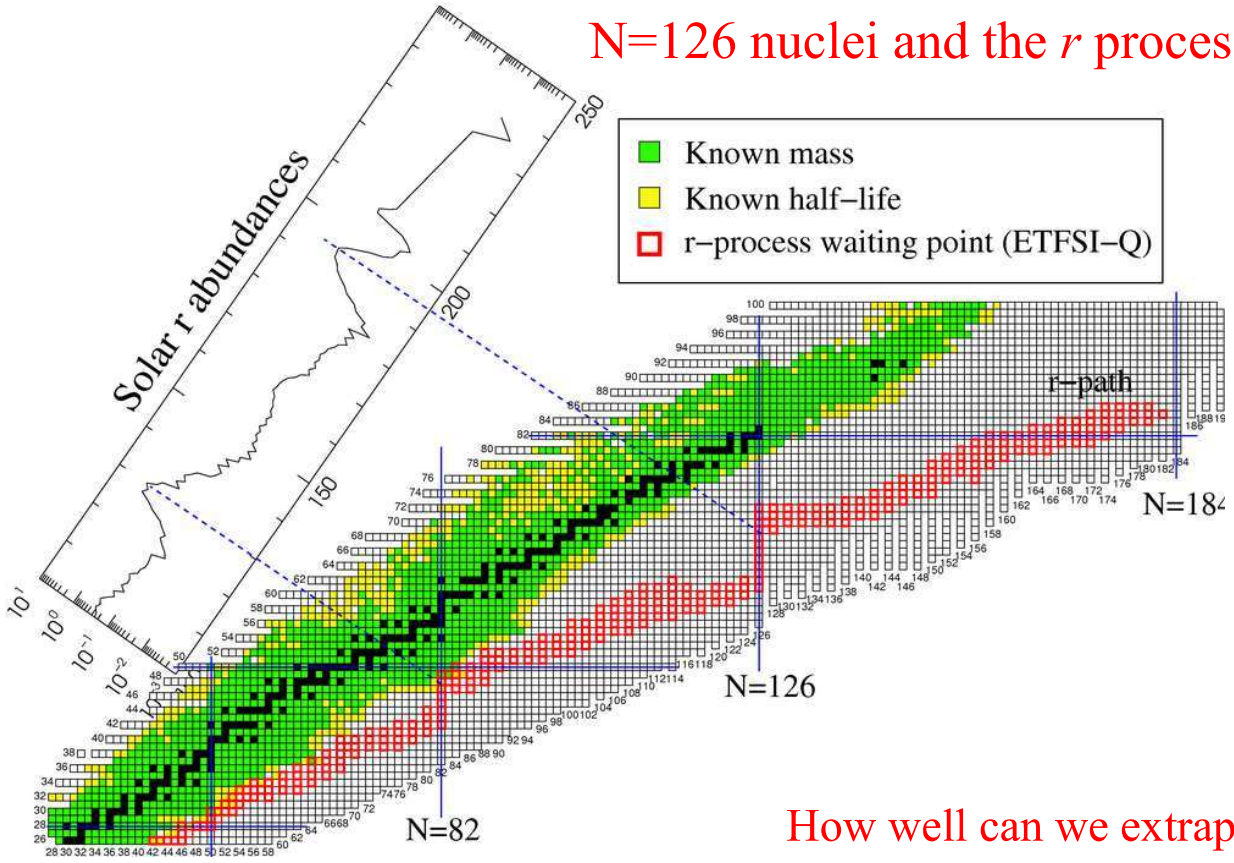
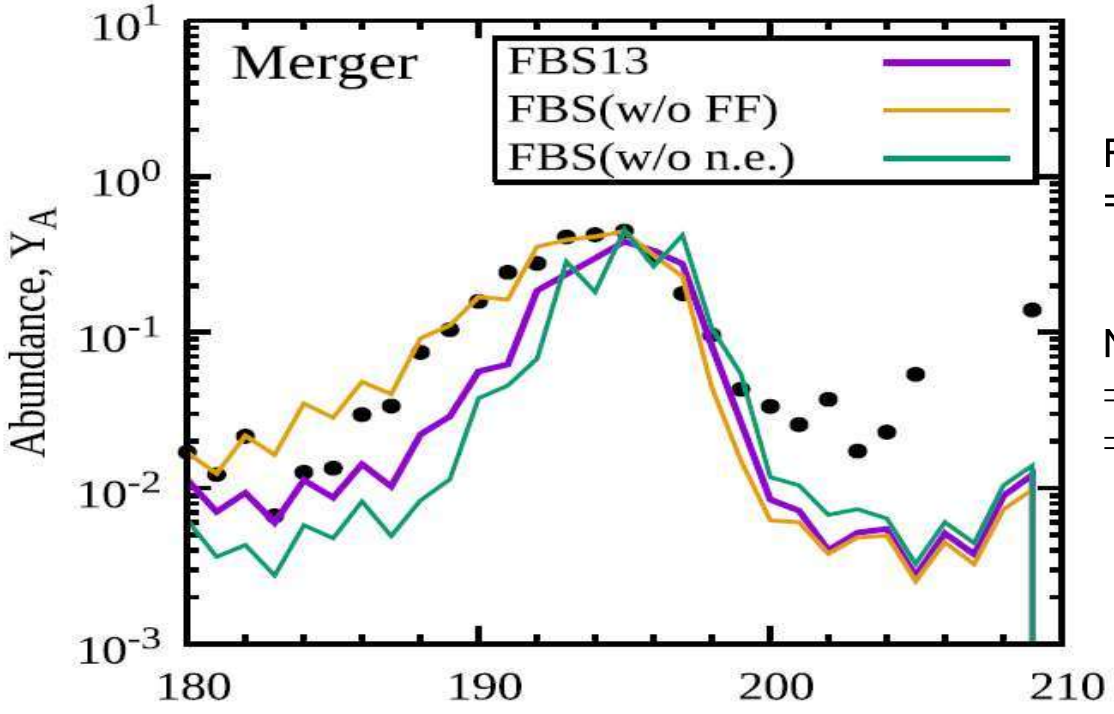
N=126 nuclei and the *r* process?



How well can we extrapolate?

Impact of the first-forbidden β decay on the A~195 r-process peak



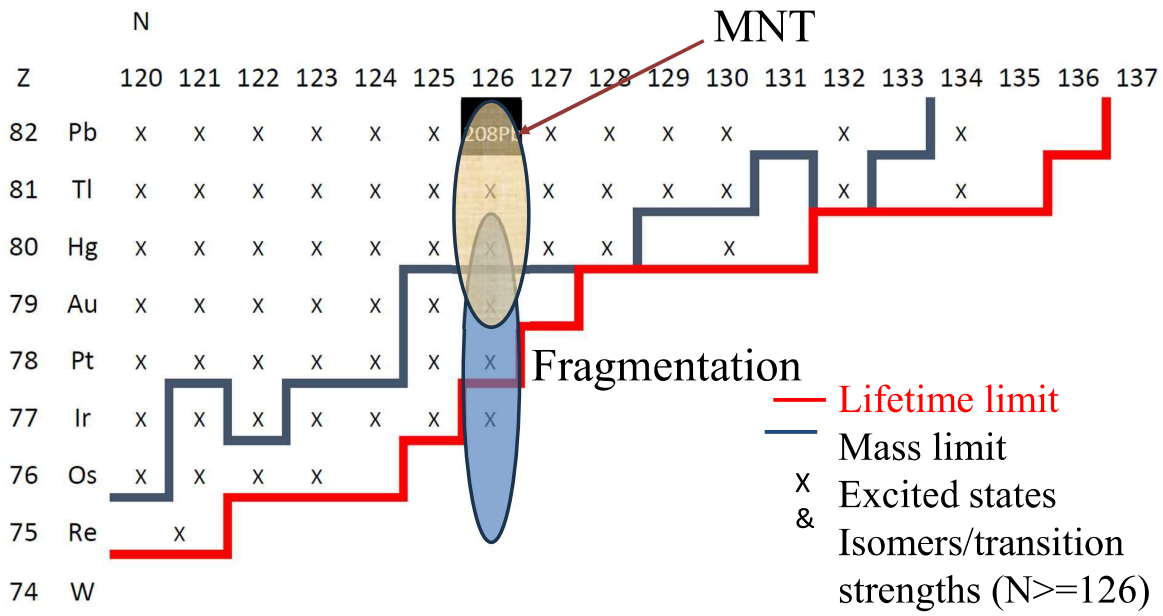
FF transitions:
=>peak moves →

Neutron decay:
⇒ Peak moves ←
⇒ Peak smoother

Neutron-star merger

N. Nishimura et al., Phys. Lett. B 756, 273 (2016)

The N~126 region



MNT

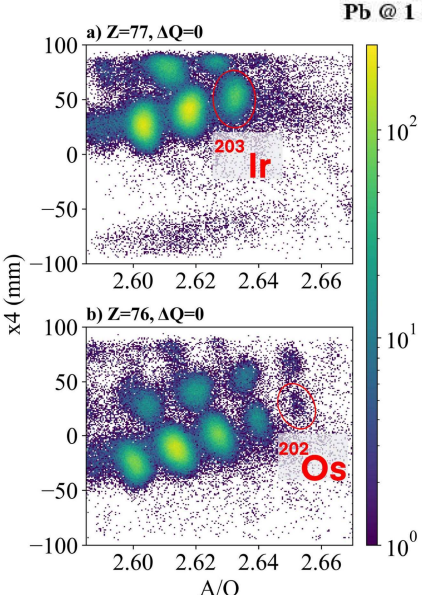
^{205}Au: Ch. Wennemann et al., Z. Phys. A 347, 185 (1994) ^{208}Pb on ^{nat}W ; new isotope

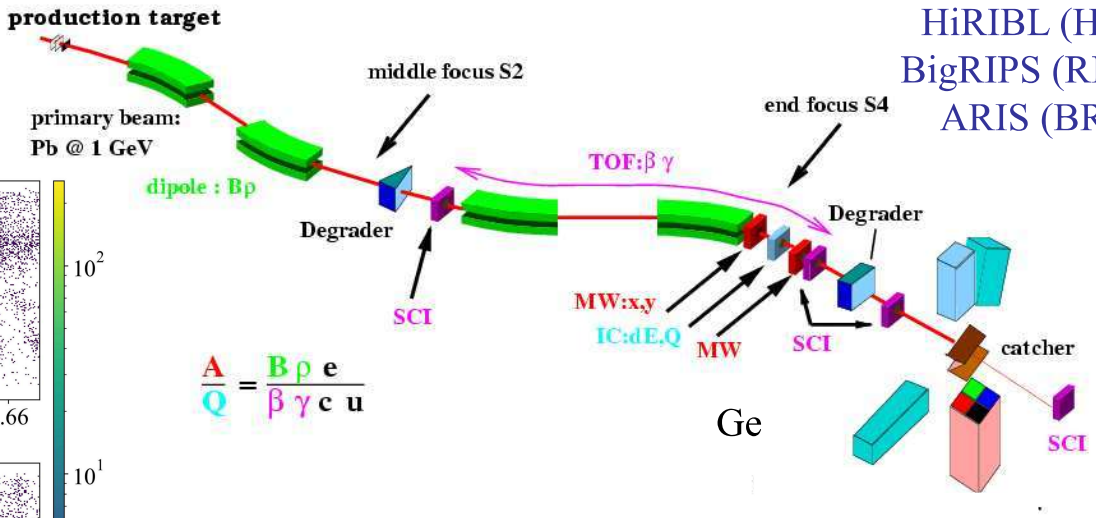
^{206}Hg: B. Fornal et al., Phys. Rev. Lett. 87, 212501 (2001) ^{208}Pb + ^{238}U GS

^{207}Tl: E. Wilson et al., Phys. Lett. B 747, 88 (2015) ^{208}Pb + ^{208}Pb GS

Production of neutron-rich nuclei: fragemtnation (and projectile fission)

Fragment Separator (GSI)
HiRIBL (HIAF)
BigRIPS (RIKEN)
ARIS (BRIB)





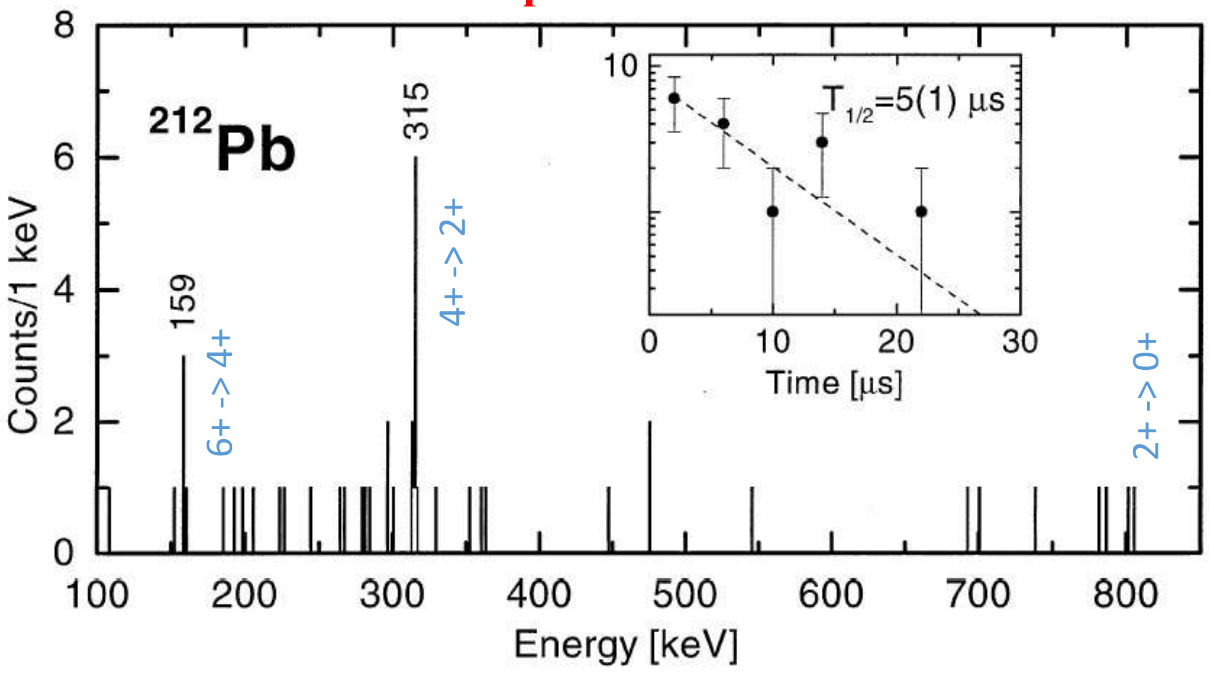
Relativistic energy fragmentation: => heavy ions

Decay (**internal** and β, α) spectroscopy:
- decay correlated with the fragment
- ***very sensitive*** (ion beams > 1 ion/hour)

G. Bartram, Zs.P. et al., Phys. Lett. B 880, 140790 (2026)

Very sensitive

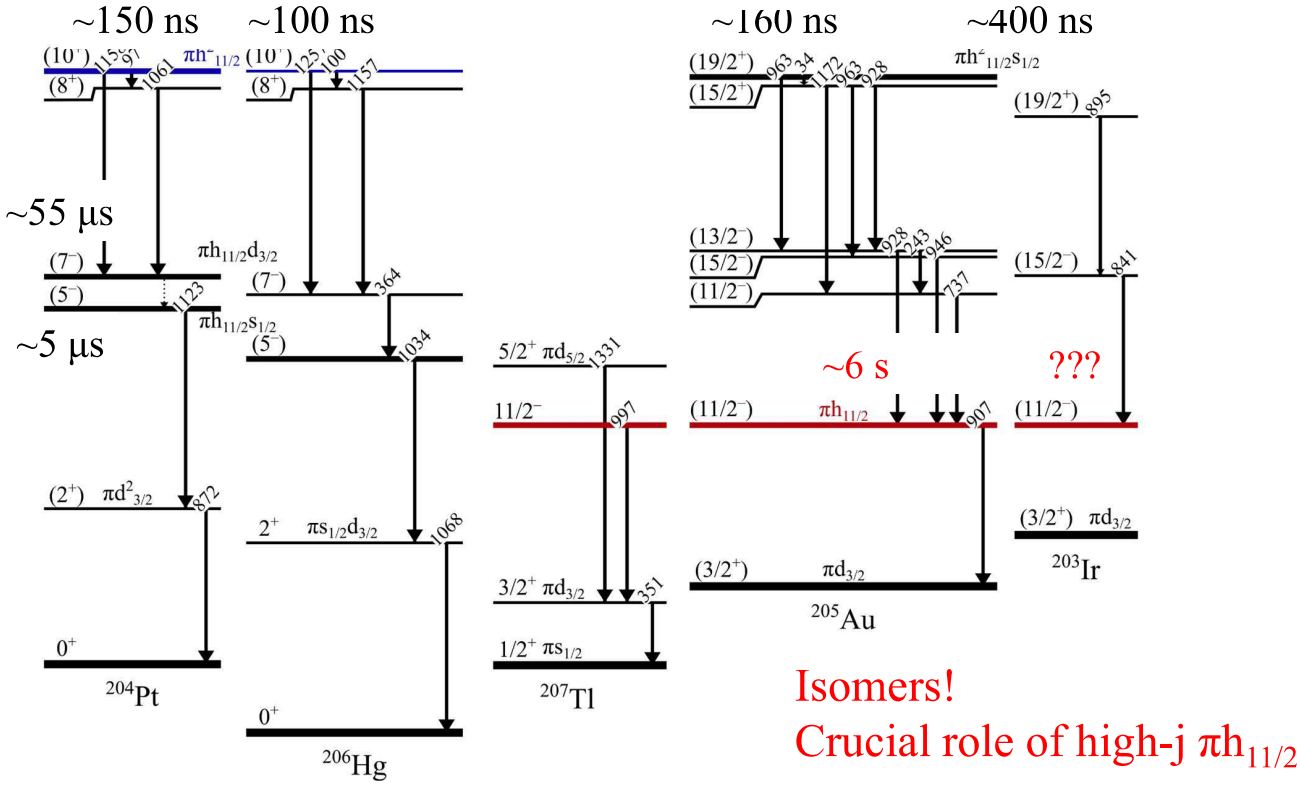
370 implanted ^{212}Pb ions!



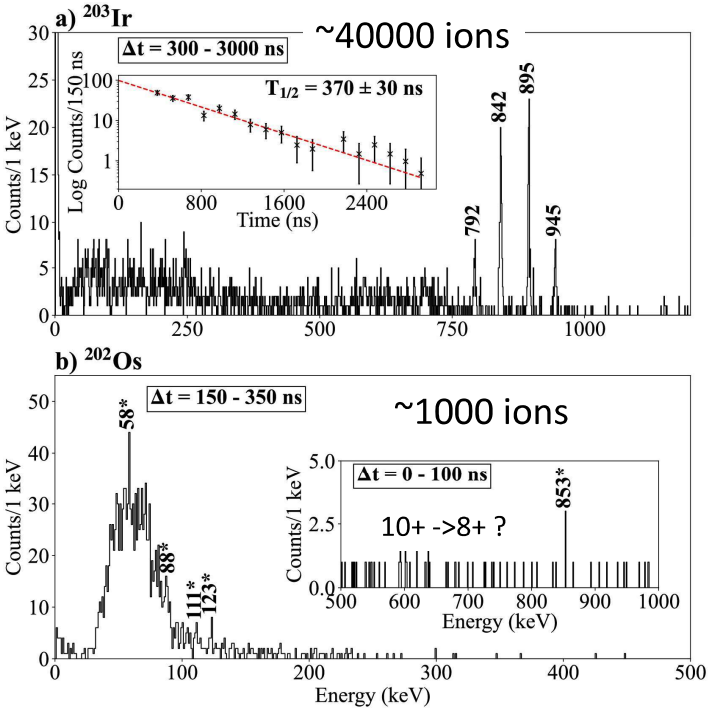
decay of the $\nu g_{9/2}^2$ 8^+ seniority isomer

M. Pfützner et al., Phys. Lett. B 444 (1998) 32

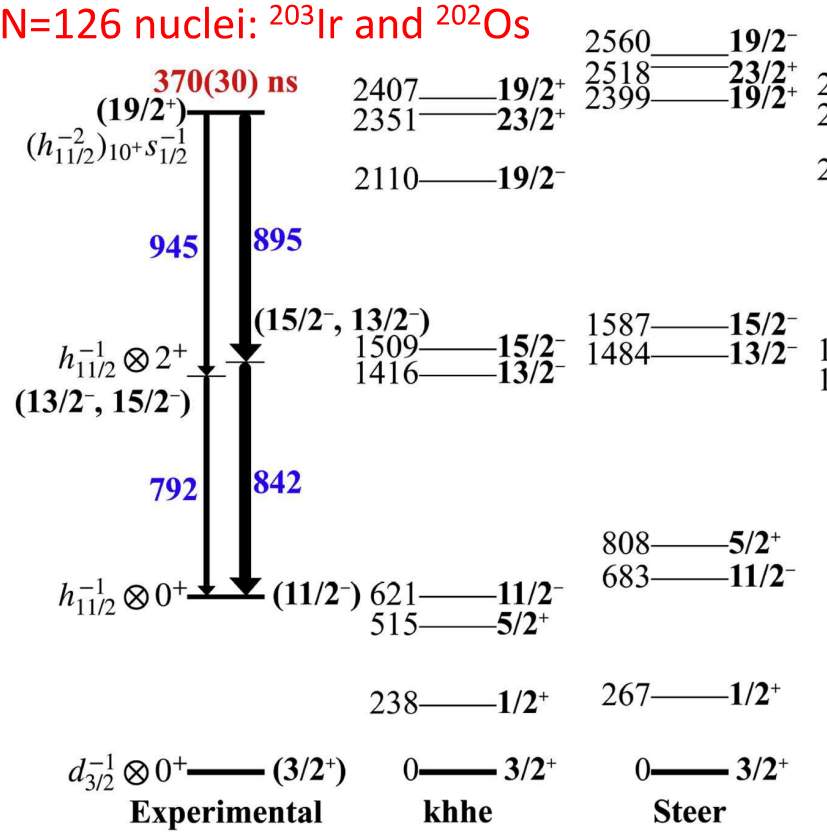
Structure of N=126 nuclei



The most neutron-rich N=126 nuclei: ^{203}Ir and ^{202}Os

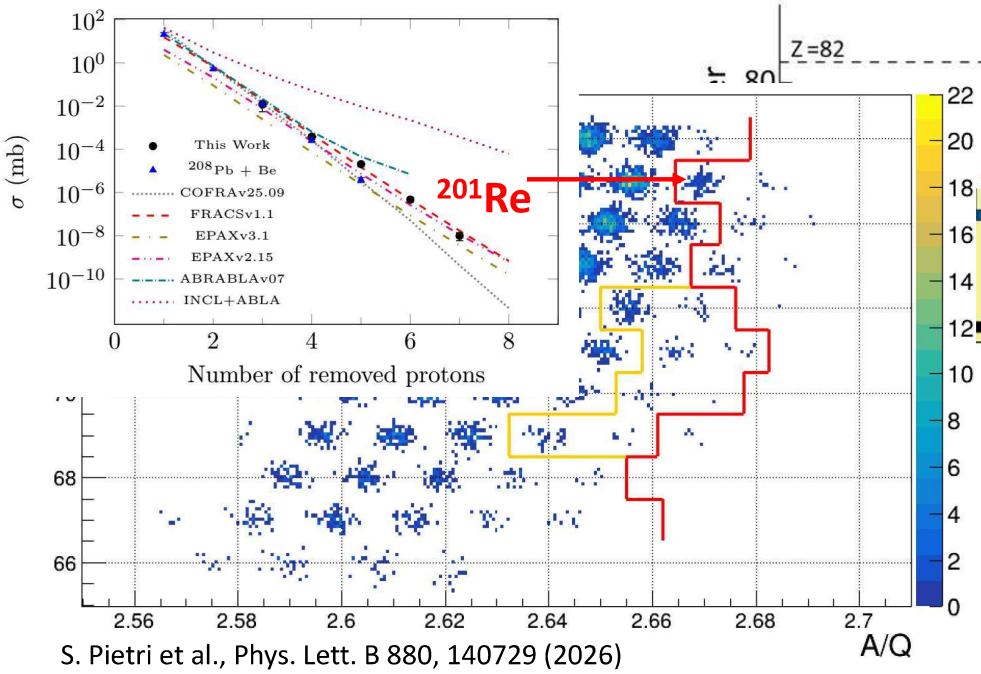


G. Bartram, Zs.P. et al., Phys. Lett. B 880, 140790 (2026)



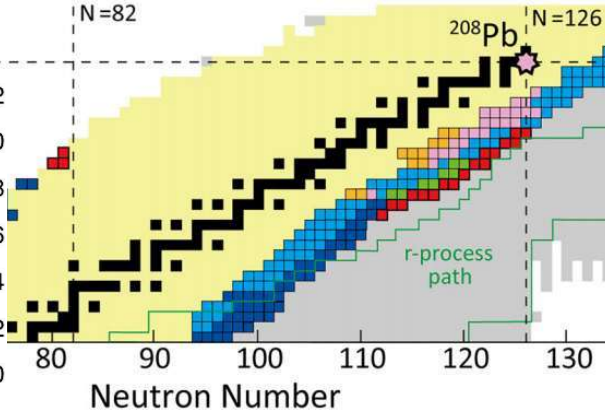
Future of N=126: ^{202}Os, ^{201}Re, …

GSI (1 GeV/u) RIKEN (345 MeV/u) FRIB (~200 MeV/u)



S. Pietri et al., Phys. Lett. B 880, 140729 (2026)

S.K. Singh et al., Phys. Rev. C, in press



N. Fukuda et al., Prog. The. and Exp. Phys. 061D01 (2026)

What can we learn about r-process path nuclei from studying N=126 isotones close to stability?

r-process waiting point nuclei 11/2- ground-state (h11/2)
the same h11/2 is responsible for the isomeric structures observed!



Will refined models, based on data, be better in predicting exotic nuclei?

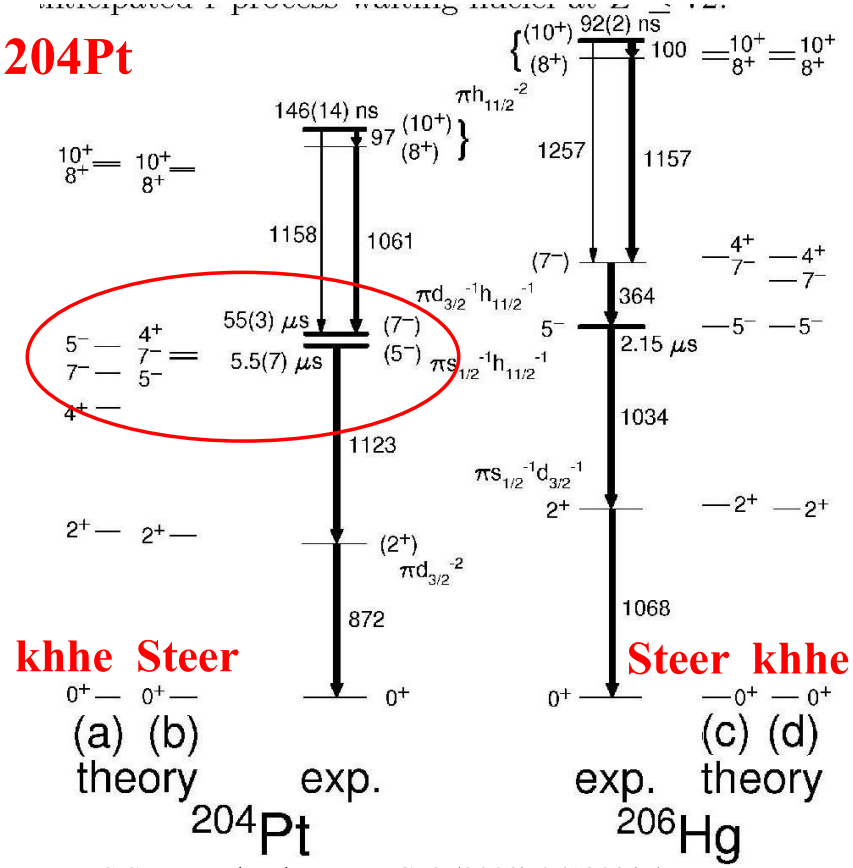
changes made to the shell model to describe ^{204}Pt,
reproduces ^{203}Ir data

Will refined models, based on data, be better in predicting exotic nuclei?

"original" shell model interaction
(khhe interaction)

changes made to the shell model
to describe ^{204}Pt and 206Hg,
(Steer interaction)





Shell-model calculations (H.Grawe)

(a)and (d): TBME from L.Rydstrom et al, NPA512(1990)217 (based on Kuo-Brown interaction)

(b) and (c): three TBMEs modified

$\Delta(d_{3/2}\ h_{11/2};\ d_{3/2}\ h_{11/2})_{7-}$ = +135 keV

$\Delta(s_{1/2}\ d_{5/2};\ s_{1/2}\ d_{5/2})_{2+,3+}$ =+230 keV (monopole only)

$\Delta(d_{3/2}\ h_{11/2};\ s_{1/2}\ h_{11/2})_{6-}$ changed to +0.160 MeV (fit for B(E2)

Good description of energies and B(EL)s

Key:
Ordering of 4+ and 5-

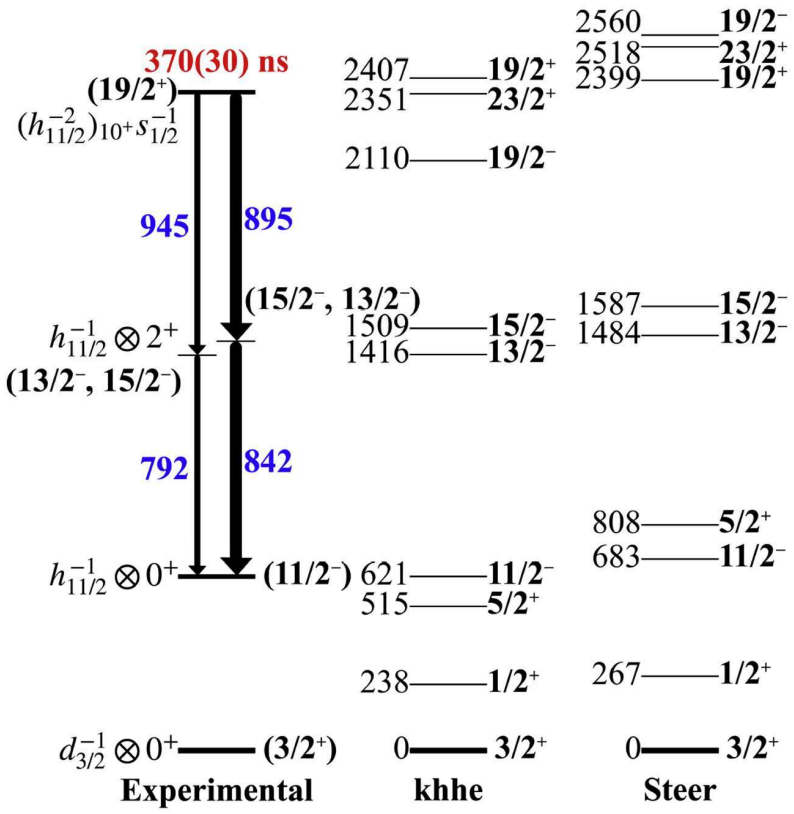
d5/2 <-> h11/2

S.Steer et al., Phys. Rev C78 (2008) 061302(R); 206Hg: B. Fornal et al., PRL 87, 212501 (2001)

^{203}Ir

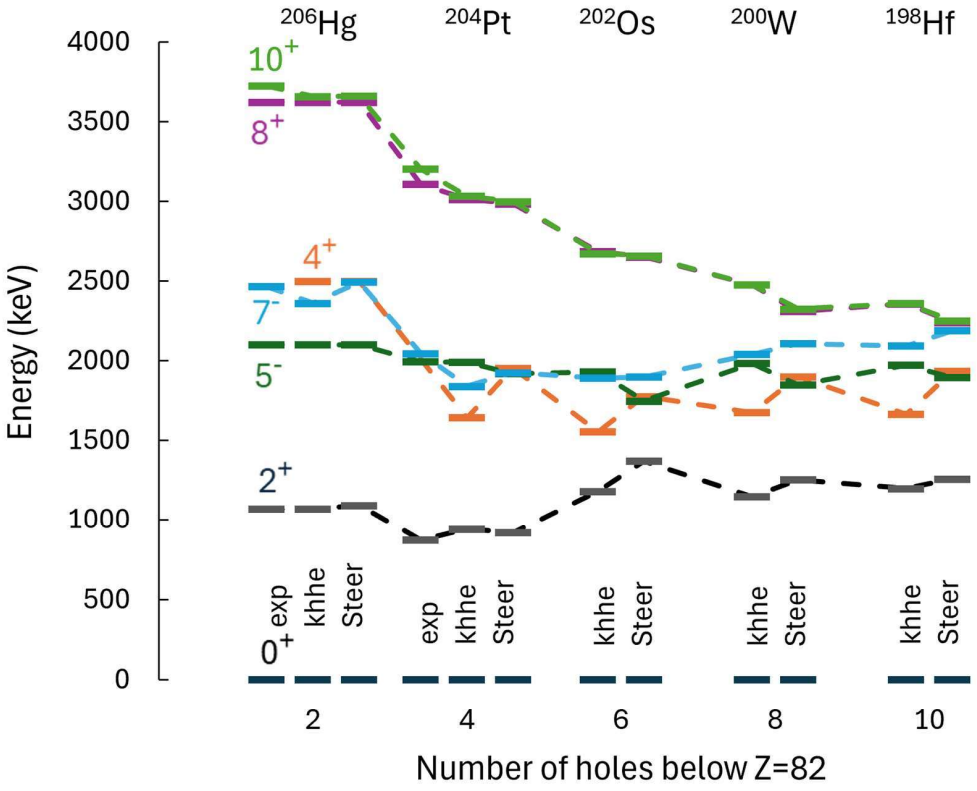
203Ir describe by Steer,
but not by khhe

(isomerism of 19/2+)
(ordering of 19/2+ and 19/2-!)



G. Bartram, Zs.P. et al., Phys. Lett. B 880, 140790 (2026)

Predictions: even-mass N=126 isotones



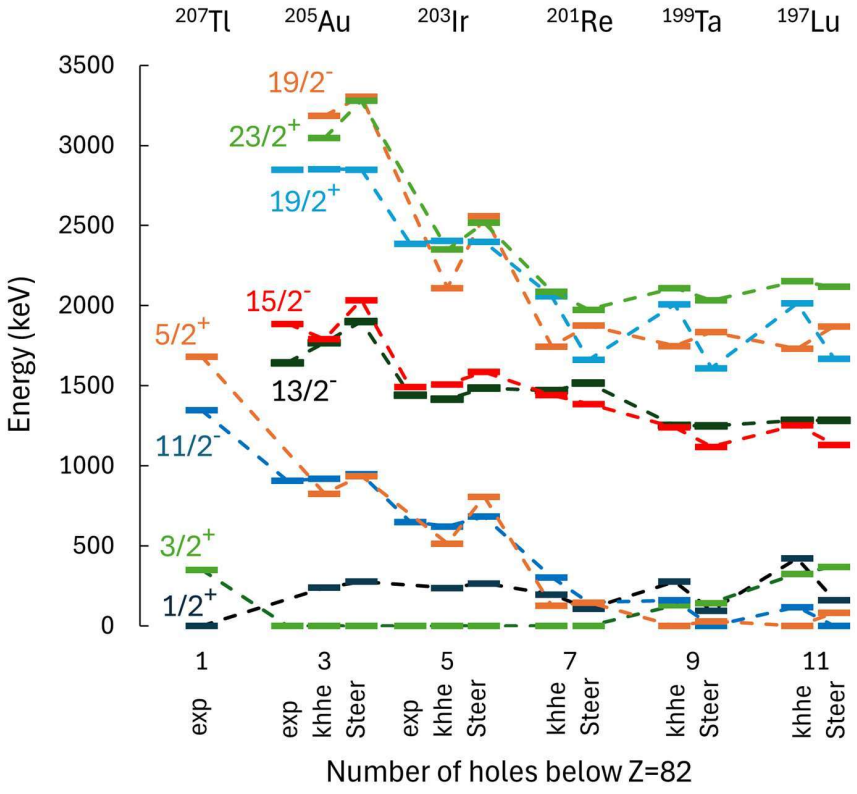
Predictions:

10+ isomeric
~100 ns

5- isomeric in “Steer”
but not in khhe

Zs. Podolyák, C.J. Wilson, in press

Predictions: odd-mass N=126 isotones

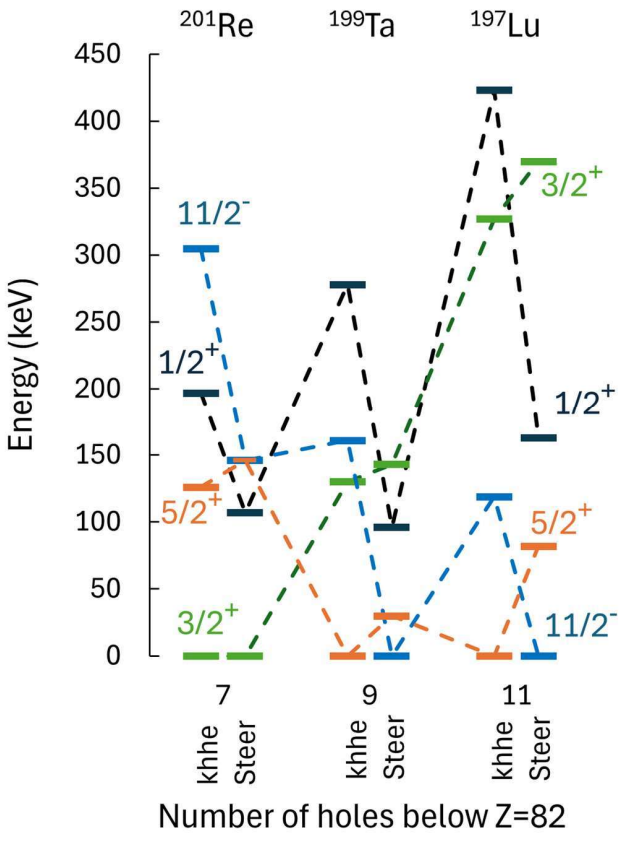


Predictions:

19/2+ isomeric in "Steer" but not in khhe

"single-particle" isomers

Zs. Podolyák, C.J. Wilson, PRC, in press



Odd-mass N=126 isotones

(single-particle dominated states)

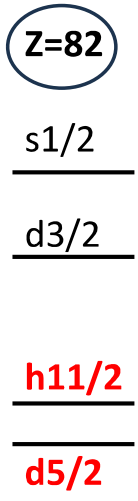
Predictions:

19/2+ isomeric in "Steer"

"single-particle" isomers
d5/2 <-> h11/2

d5/2 and h11/2 are linked:
role of octupole vibration!
Parametrisation is trying to deal with it

But very little info on d5/2



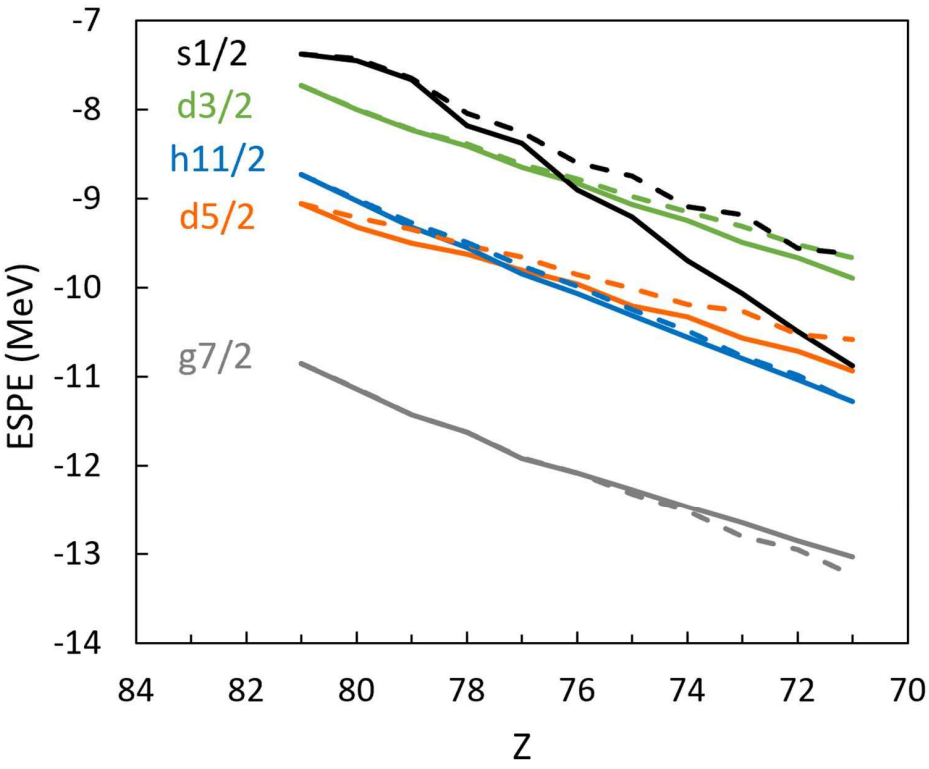
h press

(Shell model) predictions for N=126 isotones

Effective single proton-hole energies

– – – khhe

——— Steer (modified)

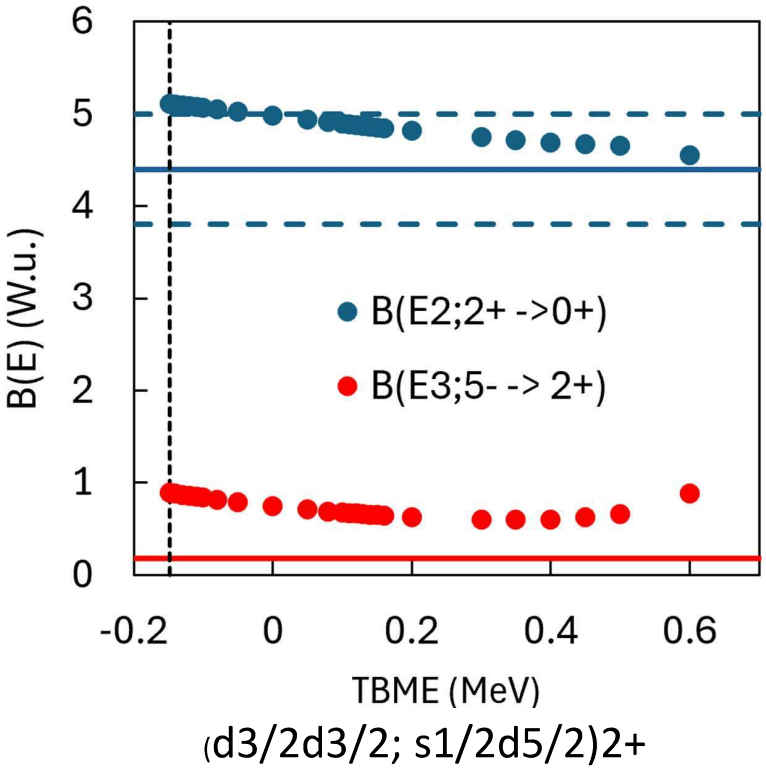


d5/2 and h11/2 are linked: role of octupole vibration!

For d5/2 one needs to study non-yrast states

Zs. Podolyák, C.J. Wilson, PRC, in press

(Shell model) predictions for N=126 isotones



(d3/2d3/2; s1/2d5/2)2+

Info on d5/2?

E3 via h11/2-> d5/2

2+ has s1/2d5/2 component

In both cases small admixtures

Needs the study of (non yrast) states dominated by d5/2

Zs. Podolyak, C.J. Wilson, PRC, in press

Physics in the N=126 region

Competition between first-forbidden and allowed beta

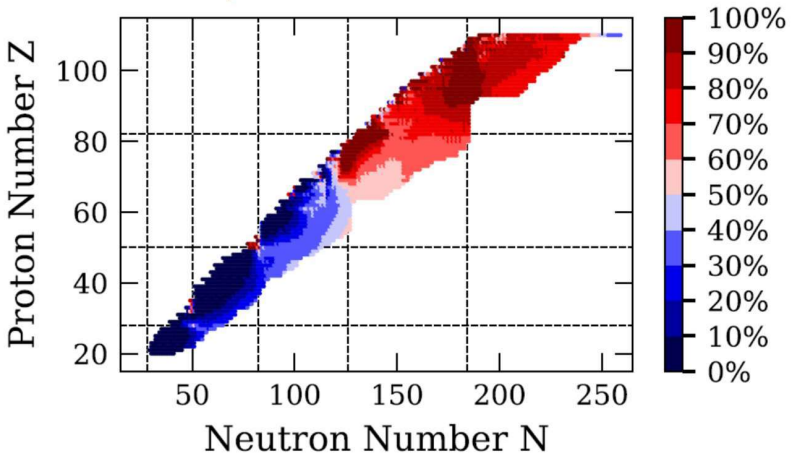
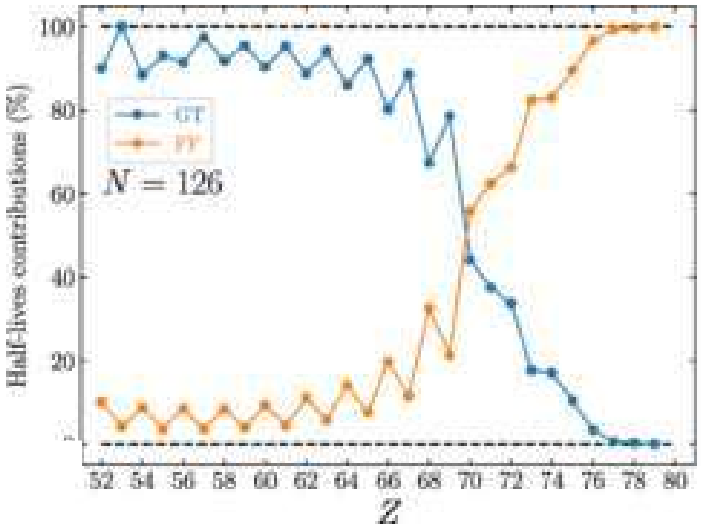


FIG. 5. First-forbidden contribution to the rates.

E.M. Ney, J. Engel, T.Li. N. Schunck,
Phys. Rev. C 102,034326 (2020)

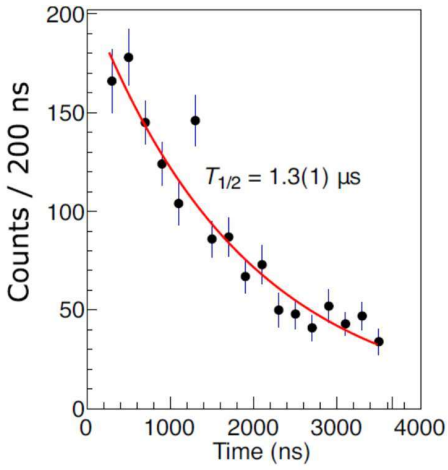


GT: νh9/2 -> **πh11/2**

A.Kumar, N. Shimizu, Y. Utsuno, C.Yuan,
P. C. Srivastava, Phys. Rev. C 109, 064319 (2024)

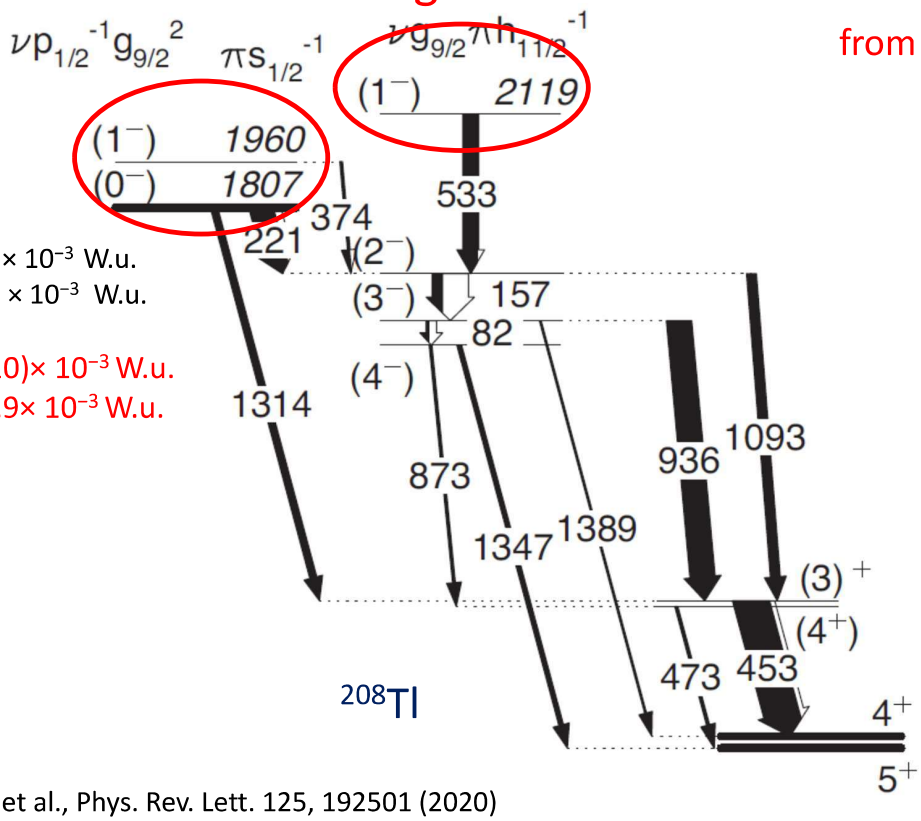
208Hg -> ^{208}Tl

from beta decay at IDS/ISOLDE



B(E2)=6.8(12) × 10^{-3} W.u.
SM: B(E2)=1.8 × 10^{-3} W.u.

B(E3)=11.5(20)× 10^{-3} W.u.
SM: B(E3)=7.9× 10^{-3} W.u.

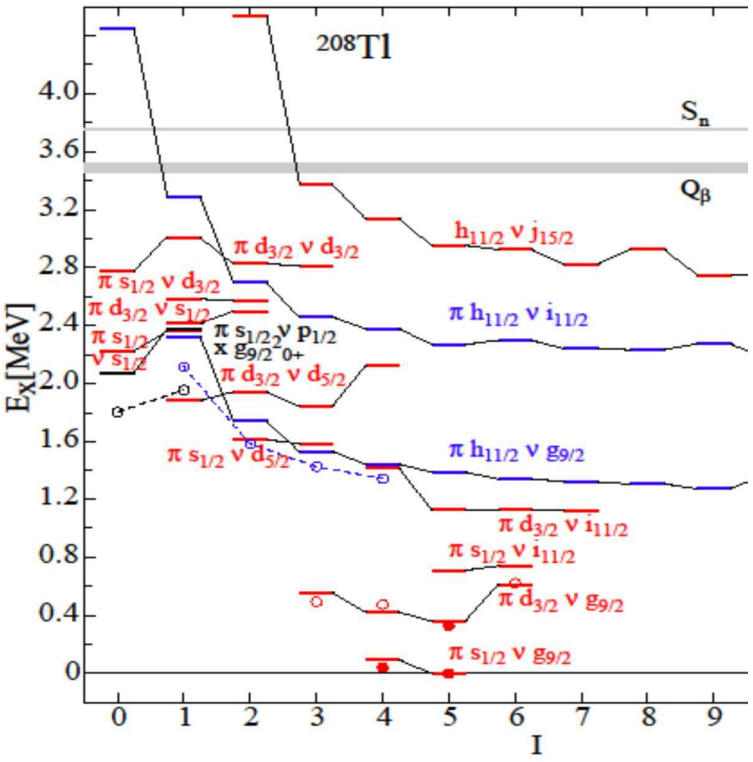


$\nu g_{9/2} \pi d_{3/2}^{-1}$

$\nu g_{9/2} \pi s_{1/2}^{-1}$

R.J. Carroll et al., Phys. Rev. Lett. 125, 192501 (2020)

First-forbidden vs allowed beta decay



Beta decay via FF:

$\nu g_{9/2} \rightarrow \pi h_{11/2}$

$\nu i_{11/2} \rightarrow \pi h_{11/2}$

$\nu p_{1/2} \rightarrow \pi s_{1/2}$

OR

~~Allowed transitions~~
~~($\nu 2g_{9/2} \rightarrow \pi 1g_{7/2}$)~~

Allowed $\nu i_{11/2} \rightarrow \pi i_{13/2}$:
Via ***small mixing*** of
$\pi^{-2}\, \pi i_{13/2}\, \nu i_{11/2}$ into
the low-lying 1^+ states

β decay:
nucleon decays

not the

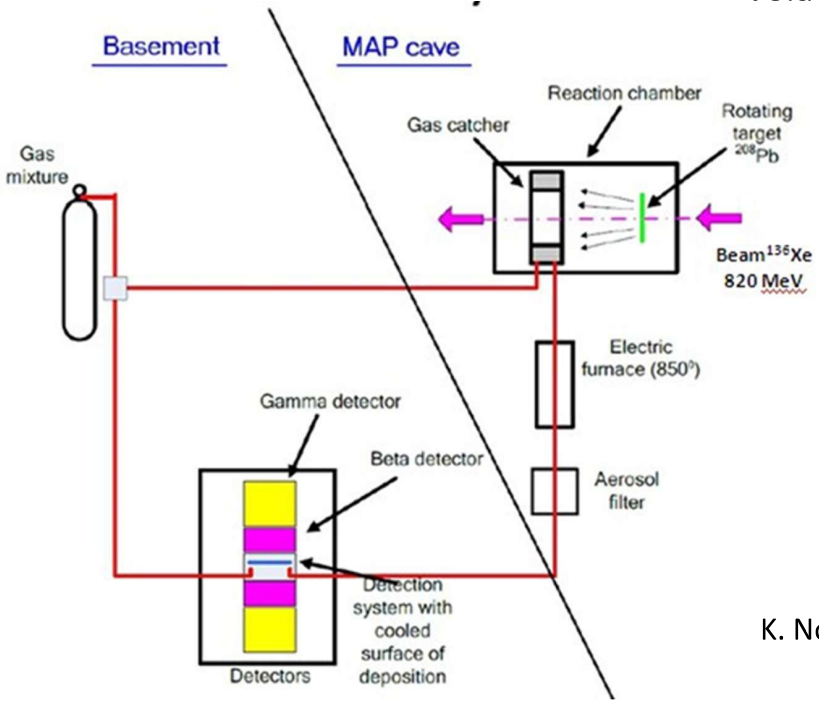
the nucleus

From super heavies to super-heavies

Chemistry for N=126?

Os homologue of Hs (Z=108)

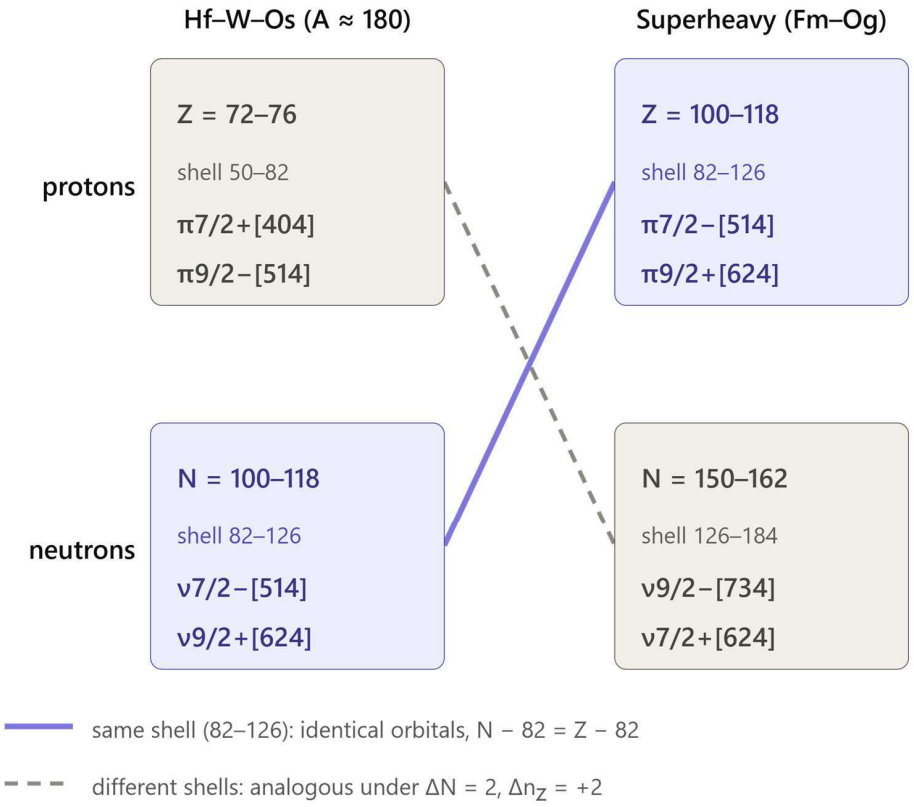
Volatile OsO_4



Eduard Kozulin et al., tried it in Jyvaskyla.

K. Novikov et al., J. Phys.: Conf. Ser. 515, 012016 (2014)

Deformed Er-Hf-Os region and the super-heavies



Example: 8- isomers

^{180}Hf is ν7/2−[514] ⊗ ν9/2+[624]

^{254}No is π7/2−[514] ⊗ π9/2+[624] or not!

Deformed Er-Hf-Os region and the superheavies

Transferable (?):

-residual interactions: Gallagher–Moszkowski splittings between the two-quasiparticle doublet depend on the orbital wavefunctions rather than on the mean field, and are approximately mass-independent

-Nilsson asymptotic selection rules for electromagnetic transitions

Non-transferable:

-single-particle energies,
-rotational response: alignment frequencies, band crossings, decoupling parameters and magnetic moments

Conclusions

-most neutron-rich nuclei studied (GSI)
isomers till 203Ir, gs.lifetimes, masses till 204Pt,
cross section till 201Re
-prediction for more neutron-rich N=126
-predictions strongly depend whether the parametrisation was modified to reproduce available data (spin-parity of g.s; isomer properties)
-real validation needs info on the d5/2 orbital! ***h11/2 <-> d5/2***
-first-forbidden vs allowed beta decay
-future: higher primary beam intensities (RIKEN, FRIB, FAIR)
-role of MNT reactions?
use of “super-heavy chemistry” at N=126?

-can we learn from the neutron-rich (deformed) Hf-Os region about super-heavy nuclei?