Alpha-decay of superheavy nuclei with odd particle numbers

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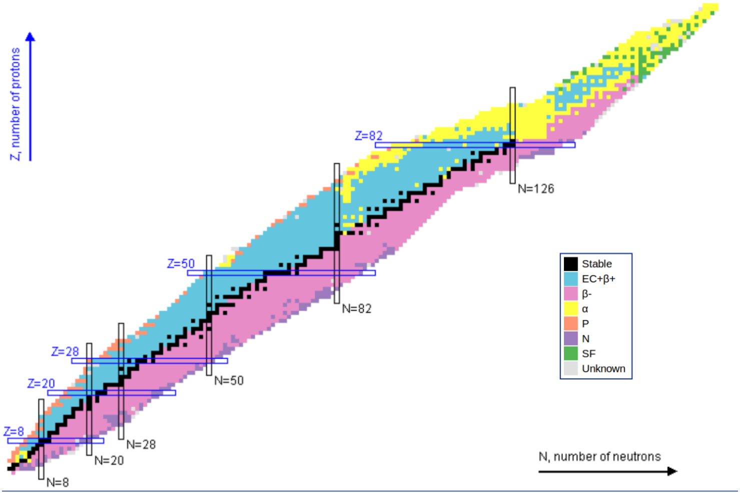
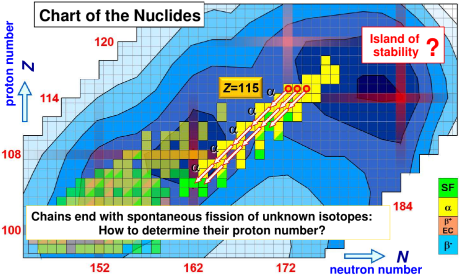
Outline

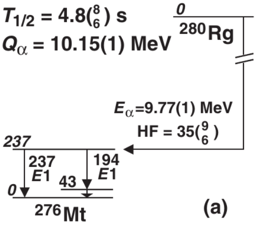
Nuclear chart



α-decay

- Important decay mode for heavy nuclei.
- Decay to excited states useful for spectroscopy, X-ray fingerprinting.
- First observation of excited states in the decay chain of Z=115.[1]





[1] D. Rudolph, PRL 111, 112502 (2013)

Theoretical goals

From the theoretical side we would like to:

- Predict α-decay lifetimes
- Calculate chance of α-decay to different excited states

Nuclear structure model II

We assume the effective $\tilde{H}$ can be approximated as

$$\tilde{H} \simeq \hat{T} + \hat{V}[\rho]$$

where $\hat{V}[\rho]$ is the effective interaction
EDF approach, so average correlations and three-body parts are mimicked by density-dependence

2 methods:

1. Try to derive it from bare interactions [1]
2. Fit to experimental data (rms=0.58 MeV) [2]

[1] J.W. Negele and D. Vautherin, PRC 5 , 1472 (1972)
[2] S. Goriely, N. Chamel, and J. M. Pearson, Phys. Rev. C 82, 035804, (2010)

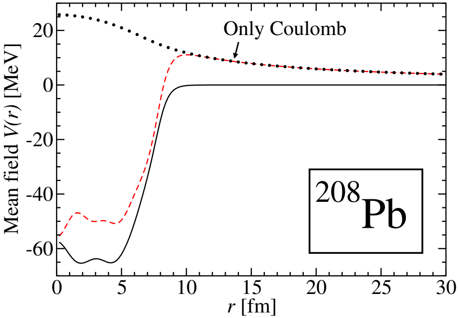
Nuclear structure model III

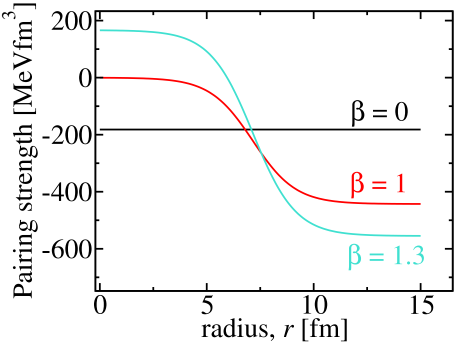
The effective interaction is taken as the Skyrme functional:

$$
\begin{aligned}
\hat{V}^{ph}[\rho] &= \frac{t_3}{6}\left(1 + x_3 P^{\sigma}\right)\rho\left(\vec{r}\right)^{\alpha} \\
&+ t_0\left(1 + x_0 P^{\sigma}\right) + \frac{t_1}{2}\left(1 + x_0 P^{\sigma}\right)\left(\hat{k}'^2 + \hat{k}^2\right) \\
&+ t_2\left(1 + x_0 P^{\sigma}\right)\hat{k}' \cdot \hat{k} + i w_0\left(\vec{\sigma}_1 + \vec{\sigma}_2\right) \cdot \hat{k}' \times \vec{k} \\
&+ \hat{v}_{coul} \\
\hat{V}^{pp}[\rho] &= v_q\left(1 - \beta\frac{\rho\left(\vec{r}\right)}{\rho_0}\right)
\end{aligned}
$$

Nuclear structure model IV

HFB+LN. Mean-field + pairing correlations





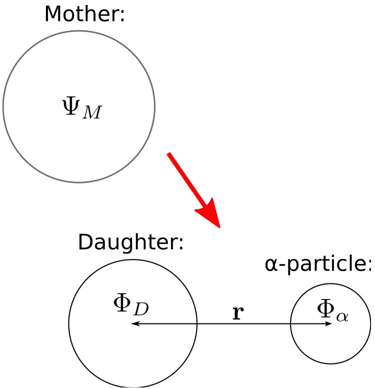
α-decay, theoretical description I

Calculation procedure:

- Solve HFB+LN => get mother nucleus $|\Phi^{(M)}\rangle$
- Solve HFB+LN => get daughter nucleus $|\Phi^{(D)}\rangle$
- α-particle:

$$\Phi^{(\alpha)}_{00} = \left(\frac{4}{b_\alpha^3\sqrt{\pi}}\right)^{3/2} e^{-\frac{r_\pi^2+r_\nu^2+r_\alpha^2}{2b_\alpha^2}}[\chi_{\frac{1}{2}}(s_1),\chi_{\frac{1}{2}}(s_2)]_{00}[\chi_{\frac{1}{2}}(s_3),\chi_{\frac{1}{2}}(s_4)]_{00}$$

α-decay, theoretical description II



- Find the relative wavefunction of the α-particle

$$g_L(r) = \langle \Phi^{(D)} \Phi^{(\alpha)};\ r | \Phi^{(M)} \rangle$$

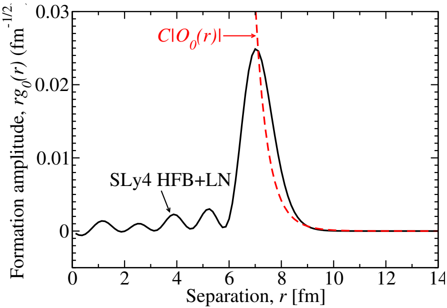
α-decay, theoretical description III

- $\Phi^{(M)}$ assumed to be a decaying Gamow state
- The formation amplitude:

$$g_L(r)$$

is matched to the analytical solution of an outgoing Coulomb wave function:

$$O_L(Q_\alpha; r).$$



- Matched at the touching radius: $r_c = 1.2\left[(A-4)^{1/3} + 4^{1/3}\right]$ fm.

α-decay, theoretical description IV

Enclosing the nucleus with a sphere and calculating the flow of α particles through the surface one finds the lifetime.

- Lifetime: $T = \frac{\hbar \ln 2}{\Gamma}$
- Decay width:
  $\Gamma(r_c) = \hbar \sqrt{\frac{2Q_\alpha}{\mu}} \left| \frac{r g_0(r_c)}{O_0(Q_\alpha; r_c)} \right|^2 = 2\gamma_0^2(r_c) P_0(Q_\alpha, r_c)$
- Penetrability: $P_0(Q_\alpha, r_c)$ (depends on Q_α)
- Reduced decay width: $\gamma_0^2(r_c)$

α-decay, theoretical description V

- For electromagnetic transitions

$$T(E2) = 1.223 \cdot 10^9 E_\gamma^5 \cdot B(E2)$$

  reduced transition probabilities $B(E2)$ tell us about nuclear deformations
- Reduced decay widths γ_0^2 tells us about α-particle correlations

α-decay, theoretical description VI

New things in the current approach:

- Self-consistent Skyrme-HFB wave functions.
- Large basis ensures convergence
- Test different pairing functionals

sofar:

- Even-even spherical α-emitters [1]
- New results for α-emitters with odd particle numbers [2]

[1] D.E. Ward, B.G. Carlsson, S. Åberg PRC 88, 064316 (2013)
[2] D.E. Ward, B.G. Carlsson, S. Åberg, to be published

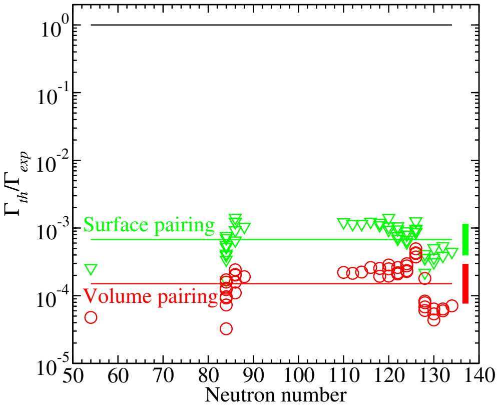
First results

even-even nuclei

α decay of even nuclei - decay rate

Compare with all available data for even spherical nuclei

- Skyrme force SLy4.
- α-clustering underestimated with HFB+LN.
- Relative values are well described.
- Scale formation amplitude with single constant C. Mean $\Gamma_{th}/\Gamma_{exp} = 1$.

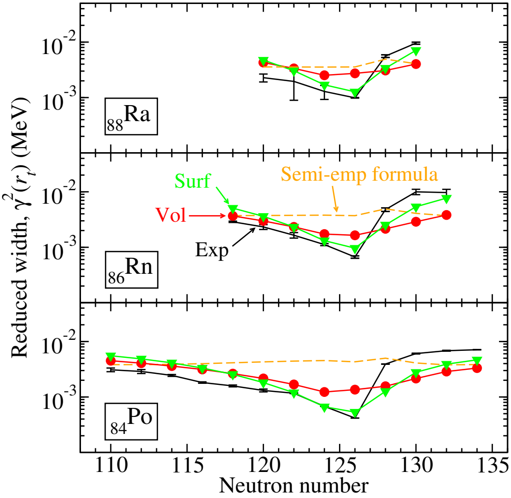


α decay of even nuclei - effect of structure

Remove Q_α dependence $\rightarrow$ Reduced widths

- Scaling leads to better results than empirical formulas
- From approximate formulas we expect [1]:

$$\gamma^2 \sim (\Delta_\pi \Delta_\nu)^2$$

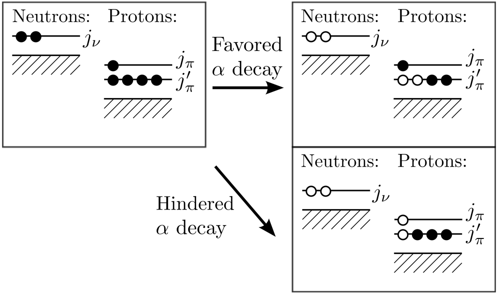


[1] J.K. Poggenburg, H.J. Mang, J.O. Rasmussen, Phys. Rev. 181, 1697 (1969)

First results

odd nuclei

Odd nuclei, competing decay channels



- Odd nucleon remains in same orbital - Favored
- Odd nucleon changes orbital - Unfavored/Hindered
  - Spin flip, $j_i = l_i \pm \frac{1}{2}$ to $j_f = l_f \mp \frac{1}{2}$.
  - Changes parity.
- Rule-of-thumb estimates, Fav ∼3, Change Parity ∼100, Spin Flip ∼1000 slower decay rate than even-even.[2]

[2] G.T. Seaborg, W.D. Loveland, *The Elements Beyond Uranium*, Wiley-Interscience (1990)

Odd nuclei

Formation amplitude, Favored and Hindered components

- *M*other and *D*aughter states,

$$|M; k_i\rangle = \beta^{\dagger}_{k_i}|M_{ee}\rangle,$$

$$|D; k_f\rangle = \beta^{\dagger}_{k_f}|D_{ee}\rangle.$$

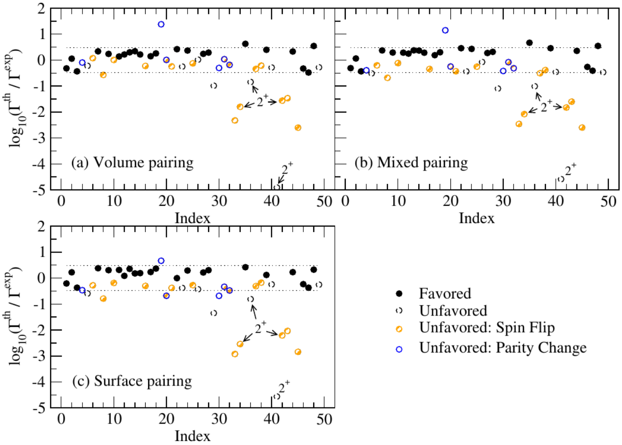
- Formation amplitude, partial wave L_α,

$$g_{L_\alpha}(r) = \delta_{I_M,I_D}\delta_{L_\alpha,0}F^{\pi}_{k_f,k_i}g^{ee}_0(r) - \frac{1}{2}\left(1 + (-1)^{I_M+I_D-L_\alpha}\right) g^{H}_{L_\alpha}(r).$$

  - F-part - odd particle acts as spectator. Factor $F^{\pi}_{k_f,k_i} \approx 1$.
  - H-part - orbitals k_i, k_f involved in formation of α particle.

Odd nuclei: reduced widths

- Same scaling factor C from the fit to even-even.



- Mean hindrance:

	Favored	Spin Flip	Parity Change
Exp	2.6	163	462
Th	1.7	625	335

Scaling with pairing

Approximate formulas BCS case, c.f.[4],

Favored Reduced width scales with both pairing gaps,

$$\gamma^2 \sim (\Delta_\pi \Delta_\nu)^2.$$

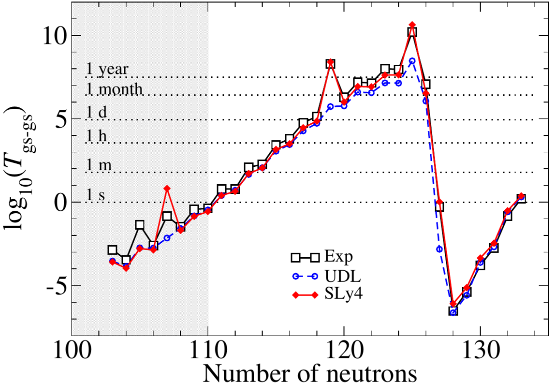
Hindered Scales with occupation of odd particle and even pairing gap,

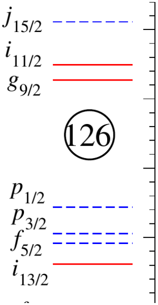
$$\gamma^2 \sim (U^D_{k_i} V^M_{k_f} \Delta_\nu)^2/(2j_M + 1).$$

In addition non-trivial dependence on the involved orbitals

[4] J.K. Poggenburg, H.J. Mang, J.O. Rasmussen, Phys. Rev. 181, 1697 (1969)

Results for the Po chain

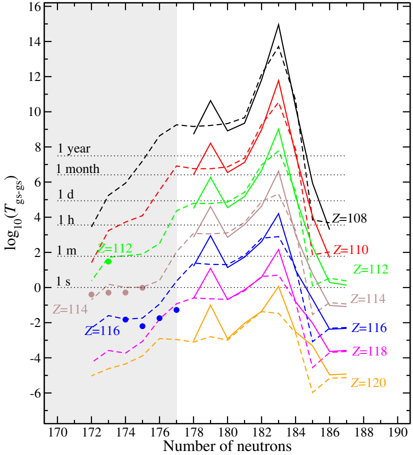


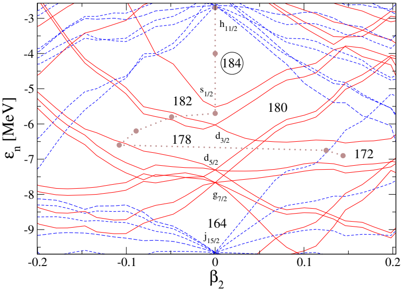


$$T = \frac{\hbar \ln 2}{\Gamma_{\text{gs-gs}}(Q_{\text{gs-gs}}) + \sum_i \Gamma_{\text{gs-}i}(Q_{\text{gs-gs}} - E_i)},$$

Results for the Superheavy region

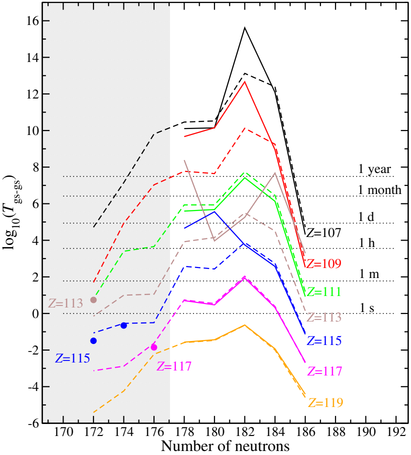
Odd neutron numbers

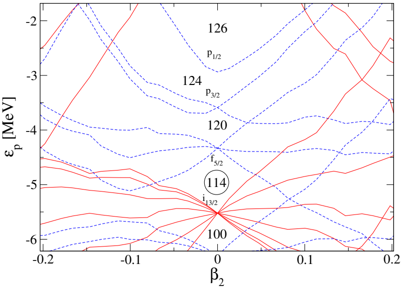




Results for the Superheavy region

Odd proton numbers





Summary

- Practical approach with one free parameter fitted to even-even nuclei describes decay widths of both even and odd nuclei.
- Provides predictions for α-gamma spectroscopy experiments.
- Predicts which odd super heavy nuclei can be identified by α + X-ray.

D.E. Ward, B.G. Carlsson, S. Åberg PRC 88, 064316 (2013)
D.E. Ward, B.G. Carlsson, S. Åberg, to be published

Thank you for your attention!