α clustering and neutron-skin thickness of carbon isotopes

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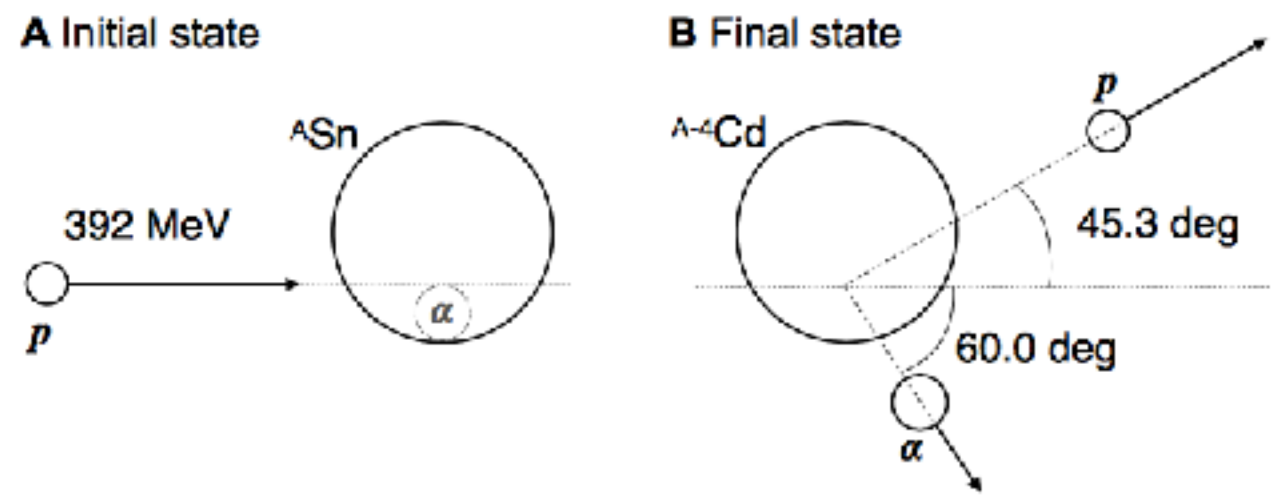
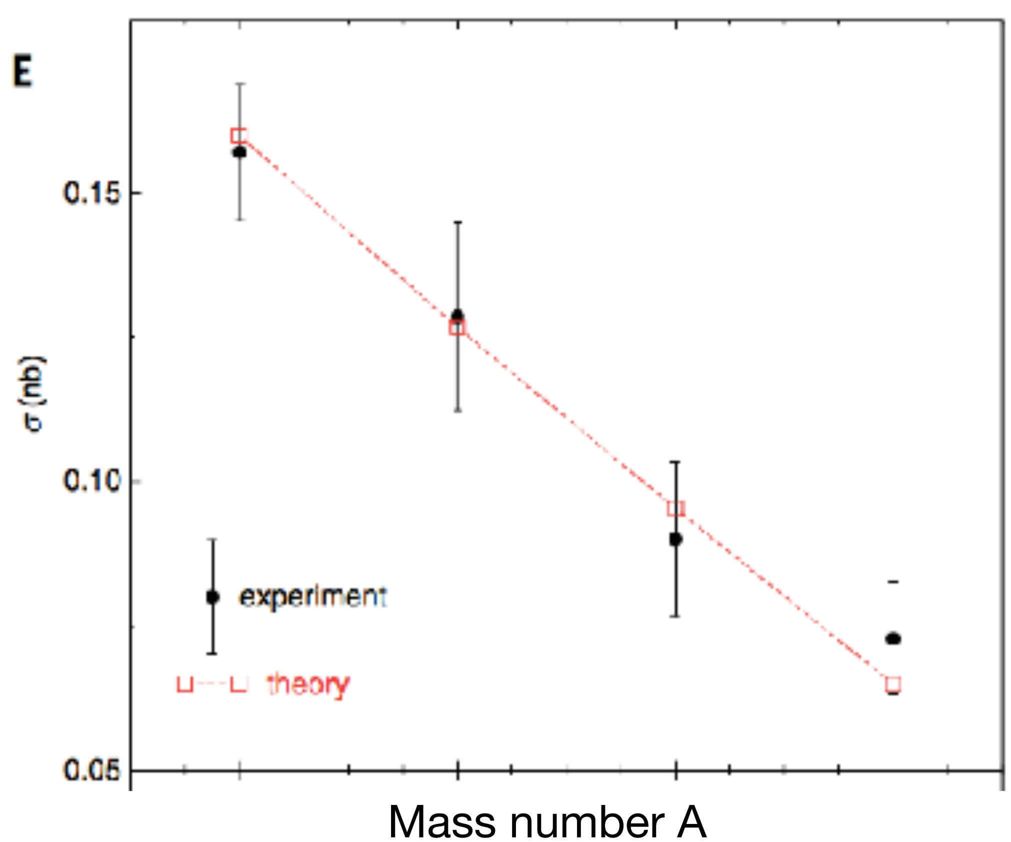
Background: α formation probability

J. Tanaka et al, Science 371, 260 (2021)

Recently, the α knockout (p, pα) reaction has been established and the α cluster formation at the surface of Sn isotope chain has been measured for the first time.





It has been shown that the knockout cross section monotonically decreases in neutron-rich Sn isotopes

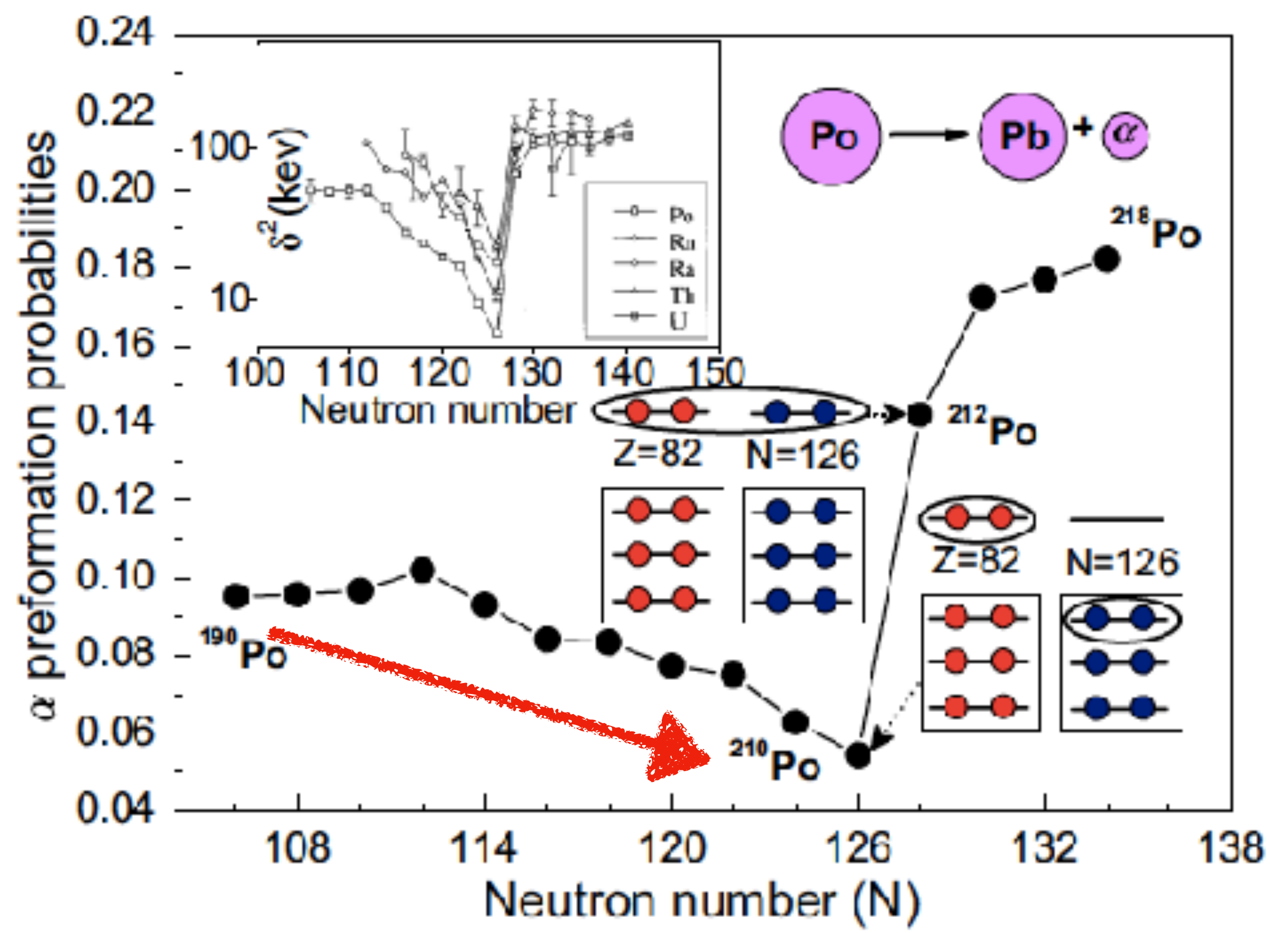
It indicates **the negative correlation between the neutron skin thickness and α cluster formation.**

Background: α formation probability

C. Xu et al, Phys. Rev. C 95, 061306 (2017)

A microscopic calculation of α-cluster formation in heavy nuclei is performed by using the quartetting wave function approach.

Hence, the growth of neutron skin looks preventing the α clustering at the surface of heavy nuclei.



How about in light nuclei?

Motivated by this question, we investigate the relationship between the neutron-skin thickness and α clustering in C isotopes.

Framework: Antisymmetrized molecular dynamics

Single particle wave function:

$$\varphi_i(\boldsymbol{r}) = \exp\{-\sum_{\sigma=x,y,z} \nu_\sigma (r_\sigma - Z_{i\sigma})^2\} \chi_i \tau_i,$$

$$\chi_i = a_i \chi_\uparrow + b_i \chi_\downarrow, \quad \tau_i = \{\text{proton or neutron}\}.$$

AMD wave function:

$$\Phi^\pi = P^\pi \mathcal{A}\{\varphi_1 \varphi_2 \ldots \varphi_A\}$$

Frictional cooling method:

$$E(\beta) = \frac{\langle \Phi^\pi | H | \Phi^\pi \rangle}{\langle \Phi^\pi | \Phi^\pi \rangle} + v_\beta(\langle \beta \rangle - \beta)^2,$$

Deformation parameter: β

GCM wave function:

$$\Psi_\alpha^{J\pi} = \sum_{iK} g_{iK\alpha} \Phi_{MK}^{J\pi}(\beta_i).$$

Hamiltonian:

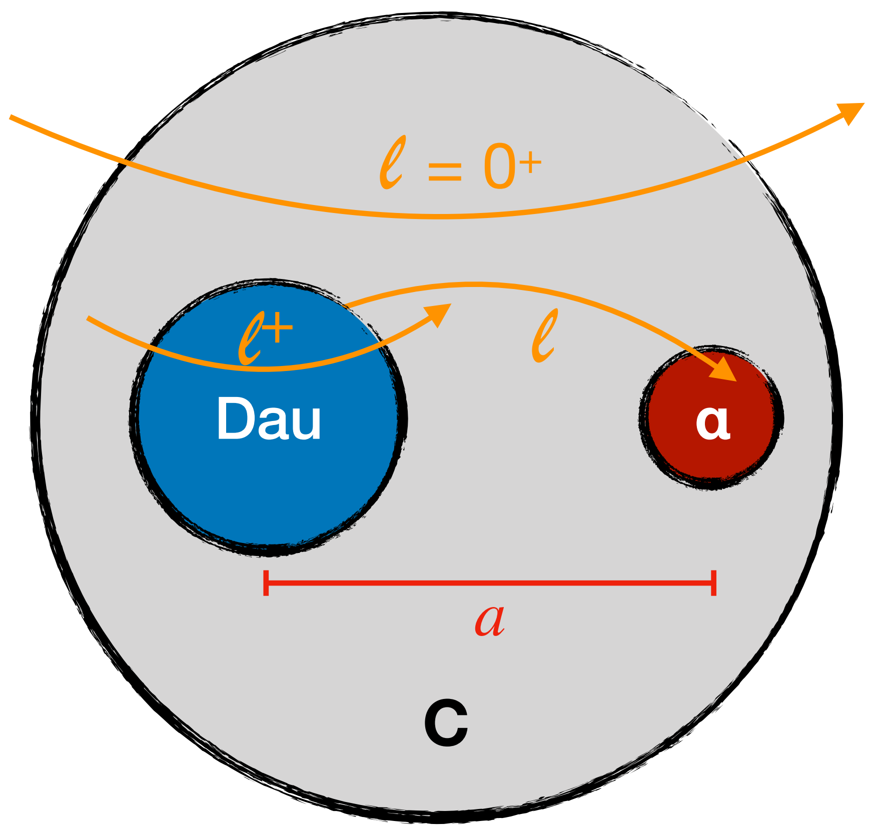
Gogny D1S interaction (→ v_{NN})

$$H = \sum_i^A t_i - t_{cm} + \frac{1}{2}\sum_{ij}^A v_{NN}(ij) + \frac{1}{2}\sum_{ij \in \text{proton}}^Z v_C(ij)$$

Framework: Reduced width amplitude

Reduced width amplitude (RWA) :

$$ay_\ell(a) = \sqrt{\binom{A}{4}} \langle \delta(r-a)\Phi_\alpha[\Phi_{\mathrm{Be}(\ell+)} Y_\ell(\hat{r})]_0 | \Phi_{\mathrm{C}} \rangle$$



The probability amplitude to find the α cluster at distance **a** from the daughter nucleus.

α spectroscopic factor:

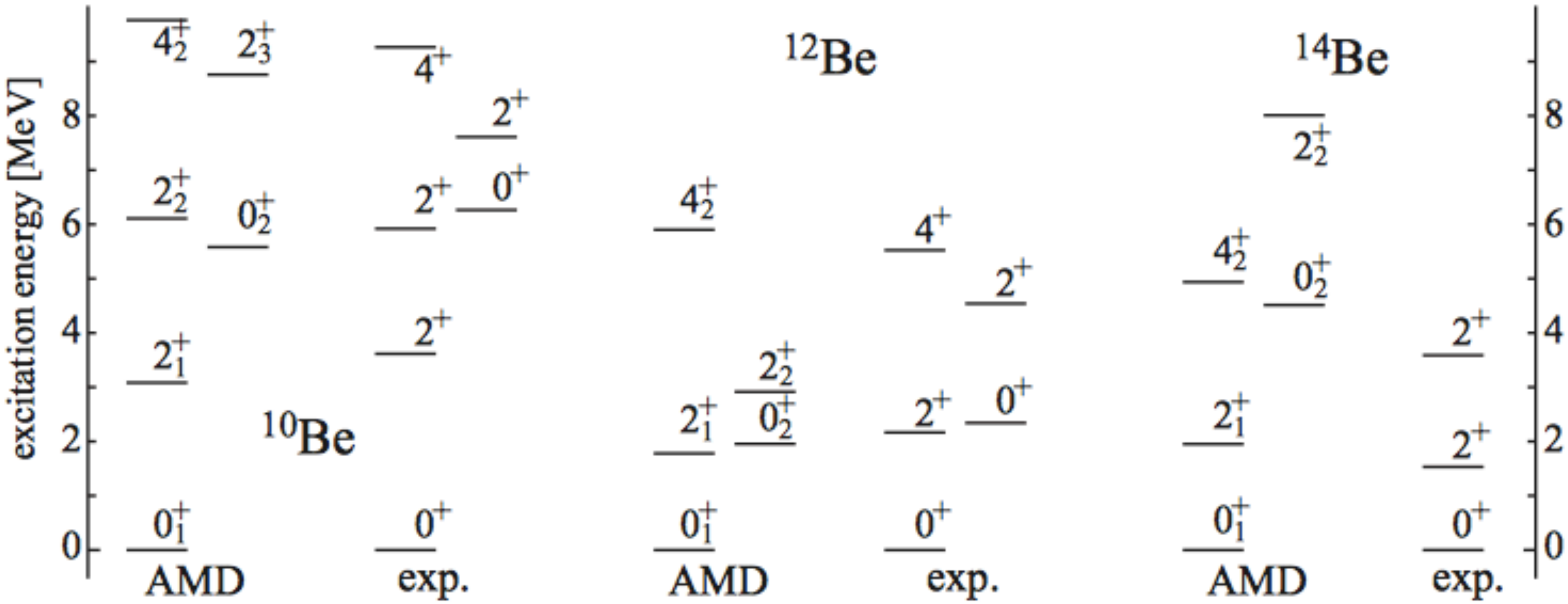
$$S_\alpha(\ell^+ \times \ell) = \int_0^\infty r^2 dr \; y_\ell^2(r).$$

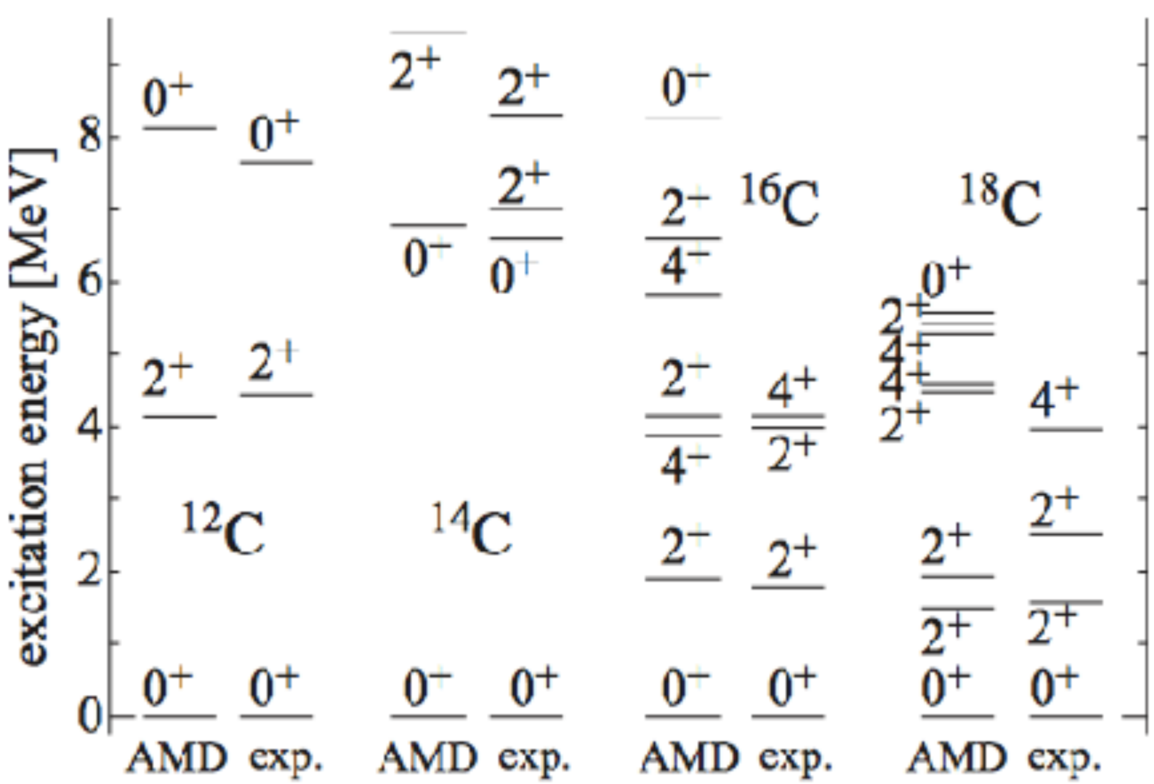
Only in the exterior region

$$S_\alpha^>(\ell^+ \times \ell) = \int_{\sqrt{\langle r_m^2 \rangle}}^\infty r^2 dr \; y_\ell^2(r).$$

Objects: 12C > 8Be + α
14C > 10Be + α
16C > 12Be + α
18C > 14Be + α

Results: Energy spectra

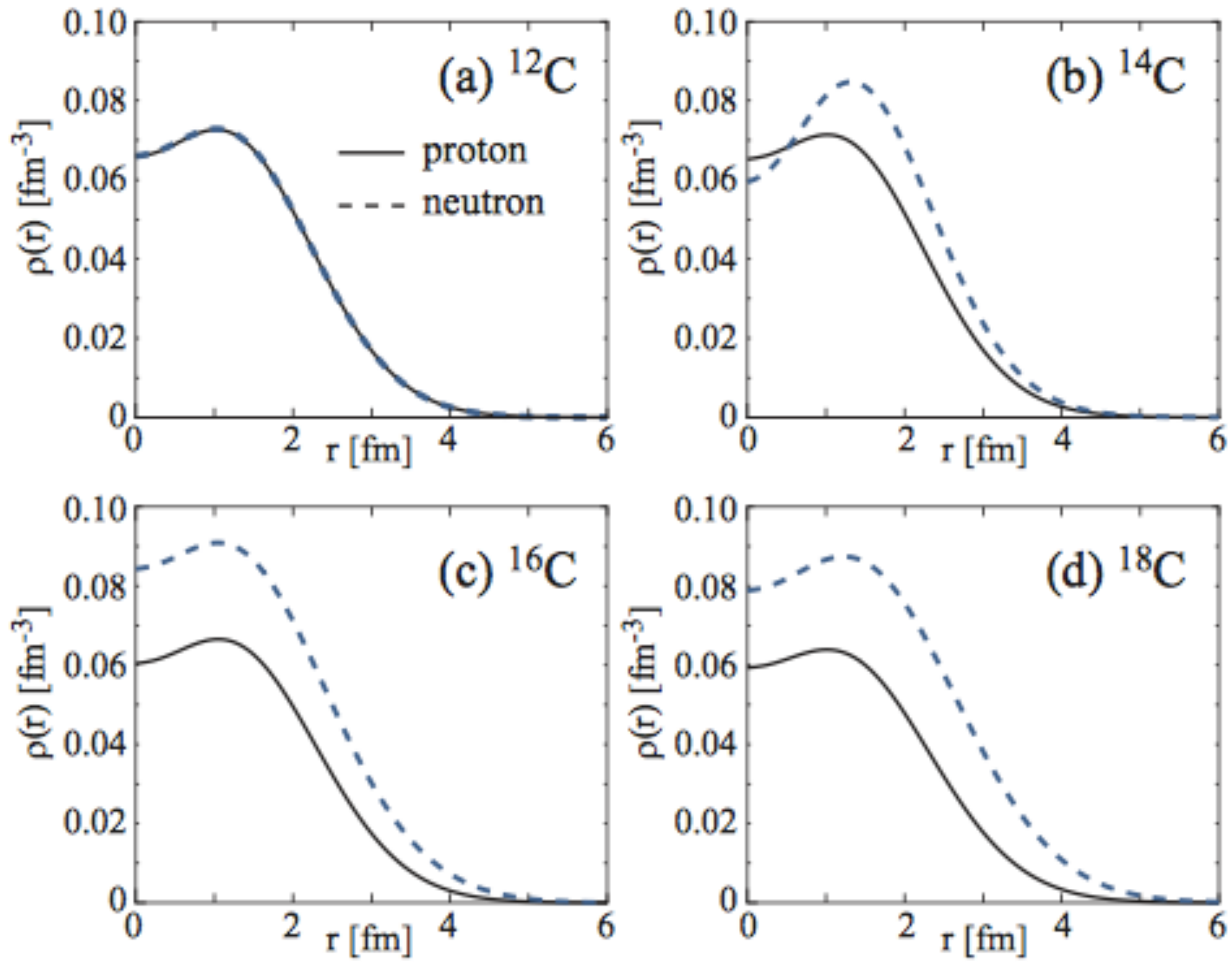




The calculated low-lying spectra of Be and C isotopes compared with the experimental data. Only the positive-parity states are shown.

We have gotten very nice wave functions of Be and C isotopes.

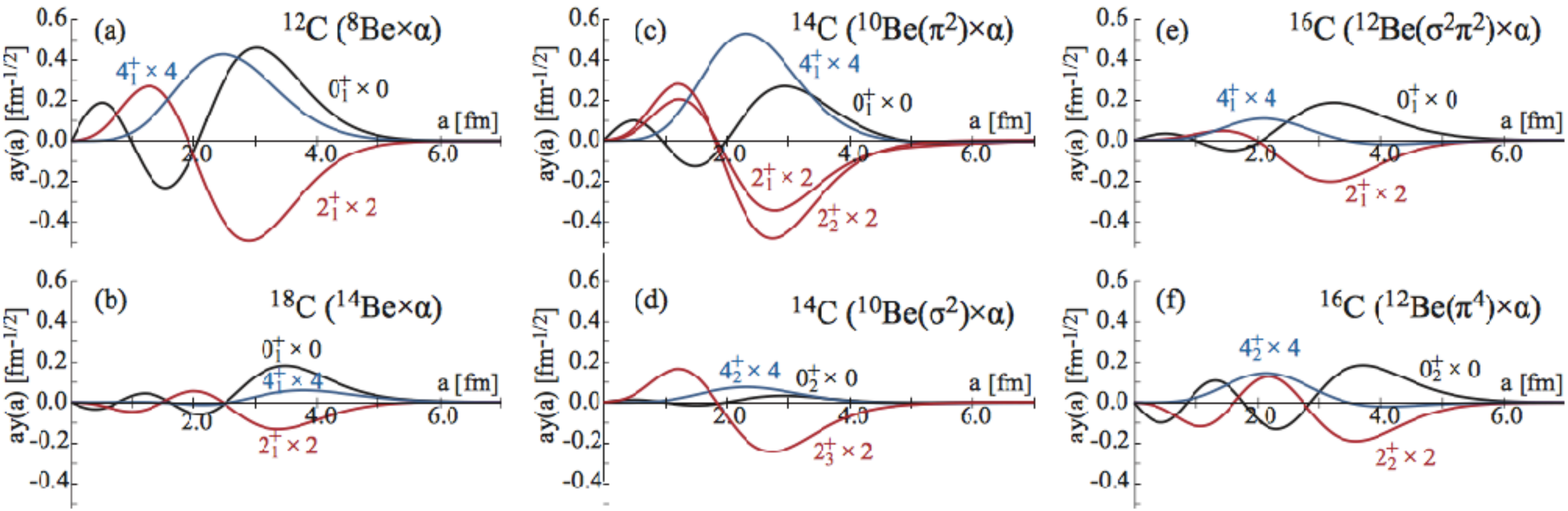
Results: Density distributions



The calculated point proton and neutron density distributions of the ground states of C isotopes. The densities are normalized to the particle numbers.

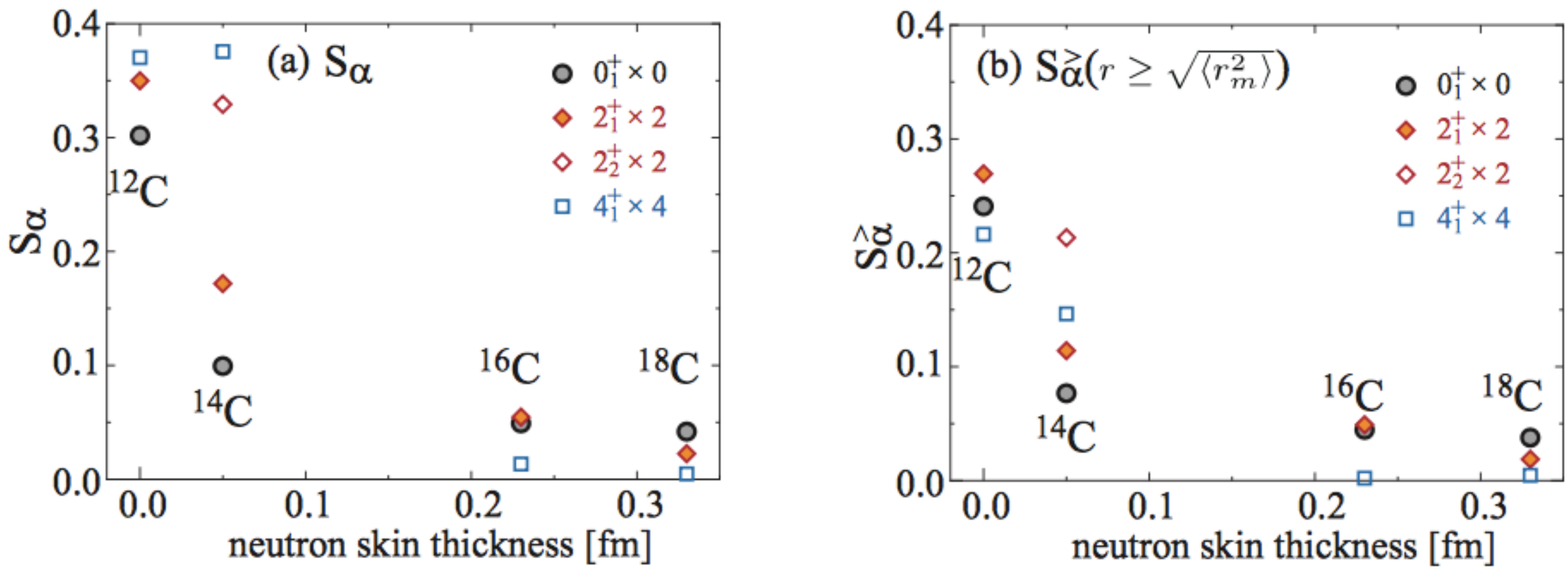
	β	$B(E2\uparrow)$	$\sqrt{\langle r_p^2\rangle}$	$\sqrt{\langle r_n^2\rangle}$	$\sqrt{\langle r_m^2\rangle}$	Δr	$S_\alpha(0_1^+\times 0)$	$S_\alpha^{\geq}(0_1^+\times 0)$
^{10}Be	0.56	11.2	2.43	2.50	2.47	0.07		
^{12}Be	0.60	14.3	2.63	2.91	2.82	0.28		
^{14}Be	0.59	12.8	2.63	3.03	2.92	0.40		
^{12}C	0.50	11.2	2.52	2.52	2.52	0.00	0.30	0.24
^{14}C	0.34	1.4	2.54	2.59	2.57	0.05	0.10	0.08
^{16}C	0.39	5.6	2.60	2.83	2.74	0.23	0.05	0.04
^{18}C	0.45	4.7	2.65	2.98	2.87	0.33	0.04	0.04

Results: Reduced width amplitudes



The calculated α RWA of carbon isotopes, where ℓ^+ denotes the spin-parity of Be and ℓ denotes orbital angular momentum between α and the Be. The panels (d) and (f) show the RWAs of 14C and 16C in the α + Be* channels where Be isotopes are excited to the non-yrast states.

Results: α spectroscopic factor



(letf) The calculated α spectroscopic factors as function of the neutron-skin thickness.

(right) Same with the panel (left), but the RWAs are integrated in the nuclear exterior ($r \geq \sqrt{\langle r_m^2 \rangle}$).

Summary

Q. Zhao et al. arXiv:2102.11733

- We have investigated the relationship between the neutron-skin thickness and α clustering of C isotopes to elucidate the possible clustering suppression by neutron skin.

- The AMD framework has successfully described the low-lying spectra of both isotope chains simultaneously.

- Using the obtained wave functions, we have evaluated the neutron-skin thickness and α clustering. It has been shown that 16C and 18C have thick neutron skin, while 12C and 14C do not.

- The calculated α spectroscopic factors show the negative correlation with the neutron-skin thickness. Namely, α clustering is considerably suppressed in 16 C and 18 C. Thus, the growth of the neutron skin seems to suppress the α clustering of C isotopes similarly to those observed in Sn isotopes.

- However, we also point out that neutron shell effect may also play the crucial role and can be the real cause of the α clustering suppression. This will be clarified by investigating the trends in the neighboring isotopes chains.

Thank you for attention