

Clustering in nuclei: perspectives on the spectroscopy of light nuclei

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Caen, France

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Clustering in nuclei

A phenomenon across the nuclear chart

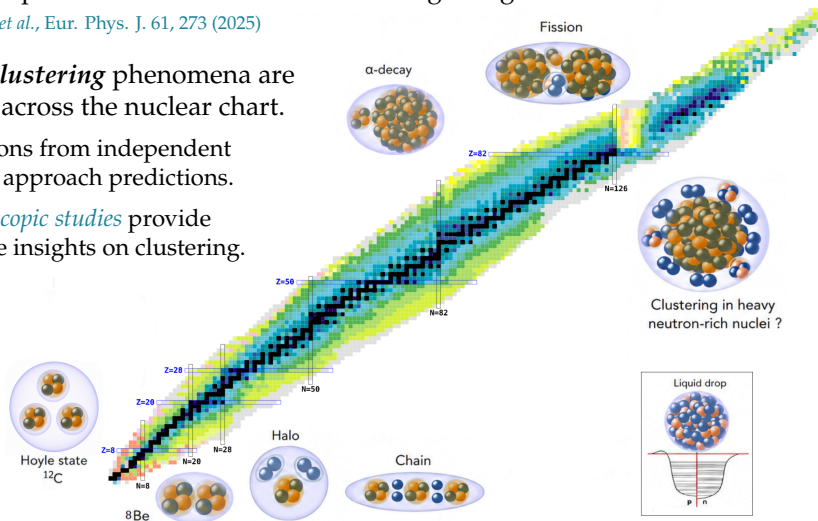
Clustering: tendency of many-body systems to form correlated structures, ubiquitous phenomenon in nature across a large range of scales.

T. Nakamura *et al.*, Eur. Phys. J. 61, 273 (2025)

Nuclear clustering phenomena are observed across the nuclear chart.

→ Deviations from independent particle approach predictions.

→ *Spectroscopic studies* provide valuable insights on clustering.



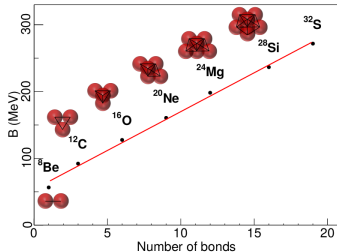
Clustering in α -conjugate nuclei

First descriptions in the nuclear landscape

Alpha-conjugate nuclei show the strongest evidences of clustering:

- Early description: binding energy in terms of number of interactions between the alpha constituents N_{α} -interactions.

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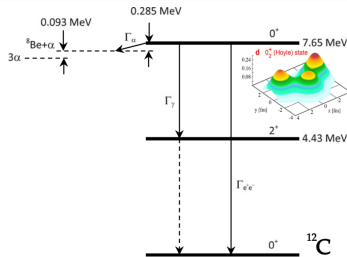
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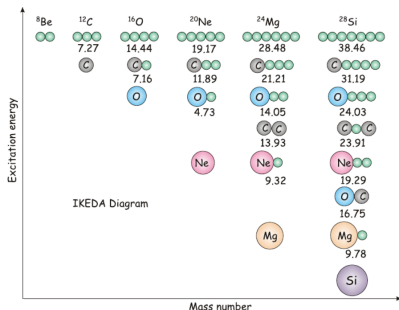
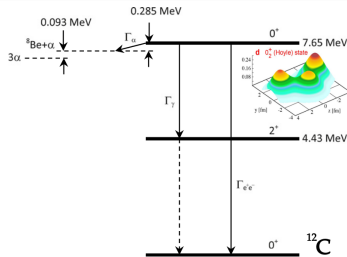
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- **Ikeda conjecture:**
cluster nature $\leftrightarrow$ cluster decay threshold

K. Ikeda *et al.*, *Prog. Theor. Phys. Suppl.* E 68, 464 (1968).



Clustering in non- α conjugate nuclei

Beyond the original Ikeda diagram: more exotic manifestations of clustering

Clustering phenomena also appear in **non- α -conjugate nuclei**:
the description extends to **nuclear molecules** and **generalized clusters**.

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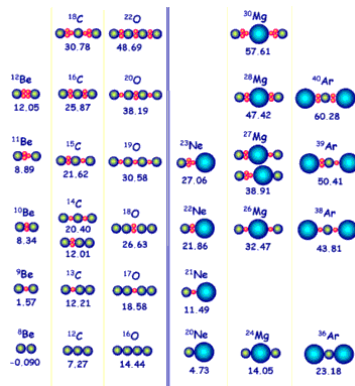
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→ *extended Ikeda diagram*

W. von Oertzen *et al.*, Phys. Rep. 432, 43-113 (2006)



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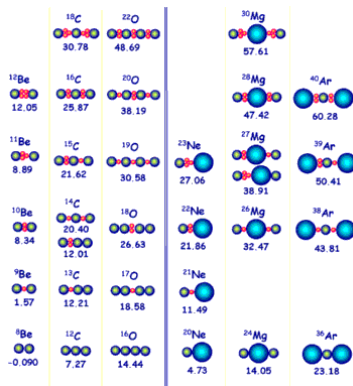
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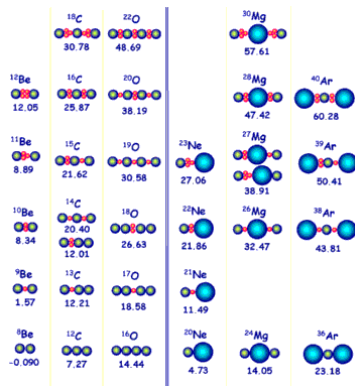
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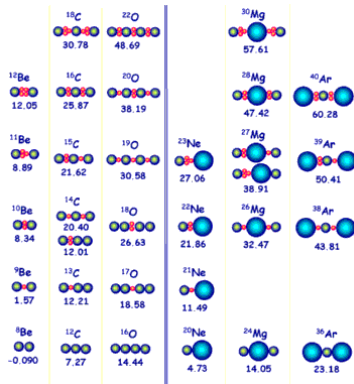
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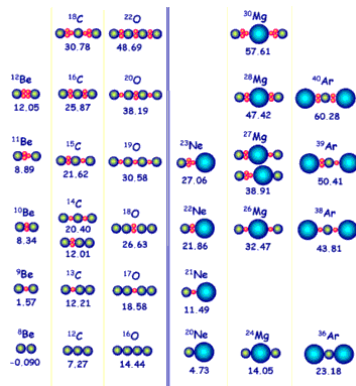
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Generalized clusters: Description introducing clusters more weakly bound than α in the proposed molecular structure, such as d, t, ³He.

Signatures of cluster states

Deformation and rotational bands E_x vs $J(J+1)$

Cluster structures $\leftrightarrow$ Pronounced deformations $\rightarrow$ *Rotational bands*.

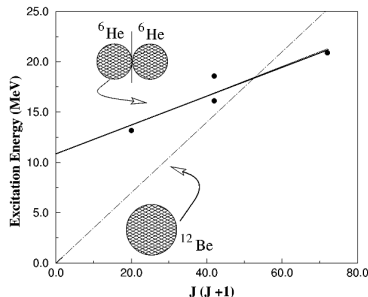
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Slope $\hbar^2/2I$ compatible with moment of inertia of two touching ^6He .
Band intercept close to decay threshold.



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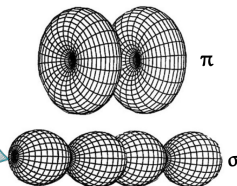
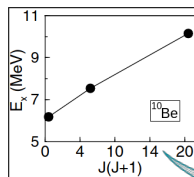
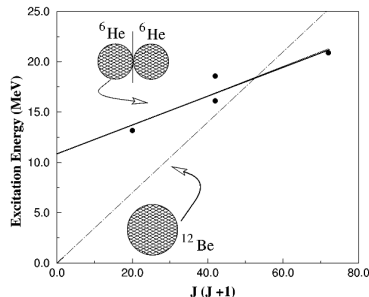
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- ^{10}Be : M. Freer *et al.*, Phys. Rev. Lett. 96, 042501 (2006)
 $\alpha:2n:\alpha$ probed via resonant $^6\text{He}+^4\text{He}$ elastic scattering.
 $J^\pi = 4^+$ member of rotational band built on the 0_2^+ , predicted by AMD as associated with σ -orbital, the most deformed molecular picture.



Signatures of cluster states

Geometrical configurations and decay paths

Increasing the number of α -cores opens the possibility of *different geometries*.

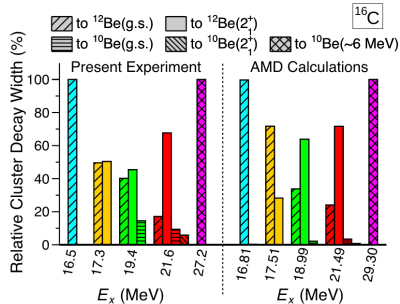
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C isotopes: formation of triangular structures or 3α linear chains.

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Cluster $^{12,10}\text{Be}-^{4,6}\text{He}$ decays following inelastic scattering of ^{16}C on CD_2 .
 0^+ band-head observed, selective decay path analysis carried out on higher members, agrees well with AMD $\pi^2\sigma^2$ linear-chain prediction.



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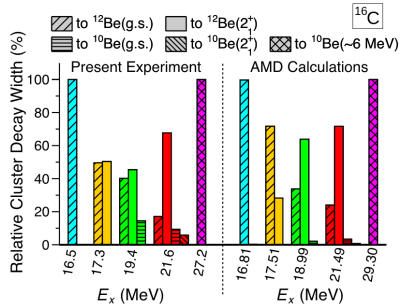
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Debated result: Mirror ^{14}O study does not support the 4^+ member.



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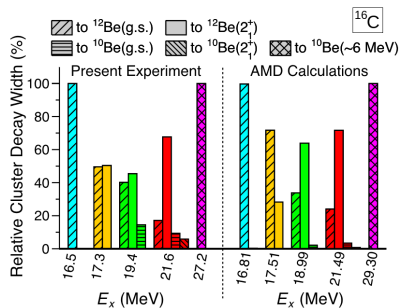
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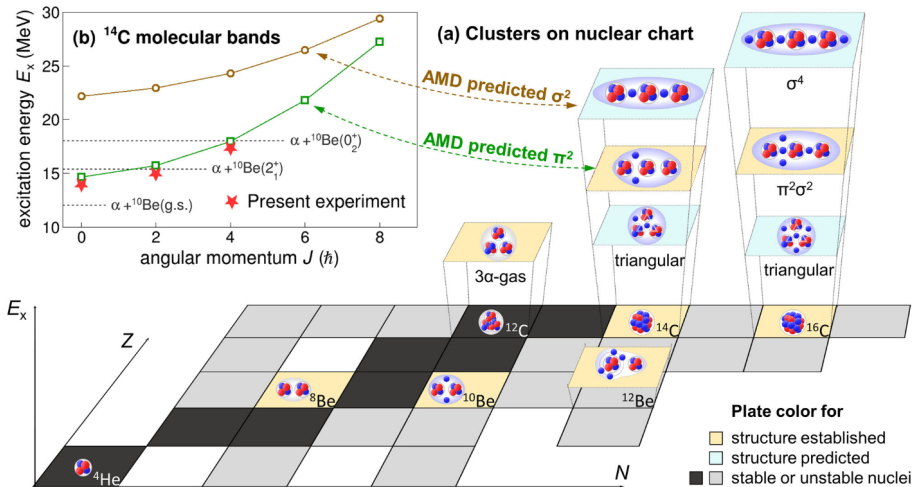
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Decay paths are a fingerprint of the internal configuration of a given cluster state, reflecting its α geometry and valence-nucleons orbitals.

E_x and J^π are not sufficient to discriminate between similar structures.

Signatures of cluster states

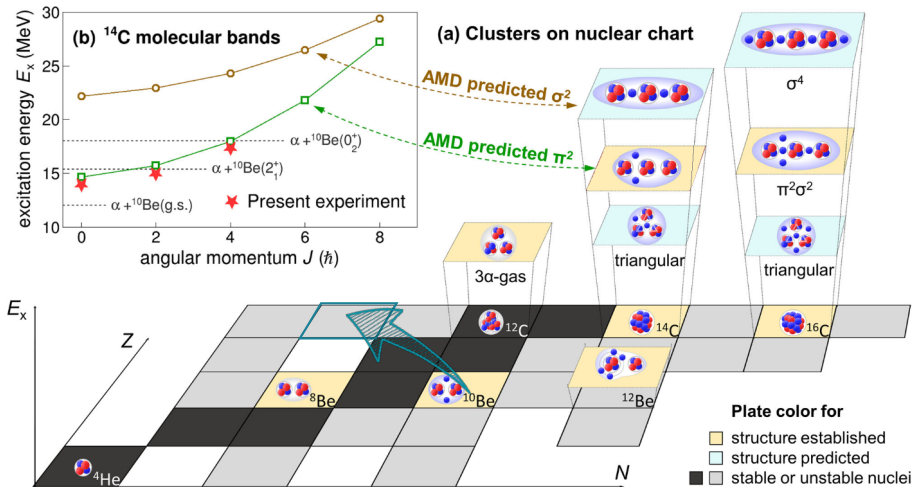
Different configurations across the nuclear chart



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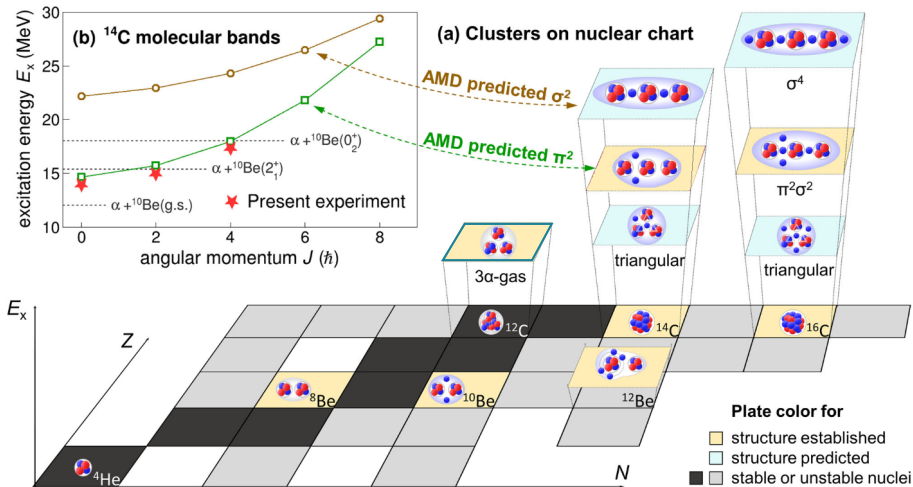
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Extending the picture to non- α clusters

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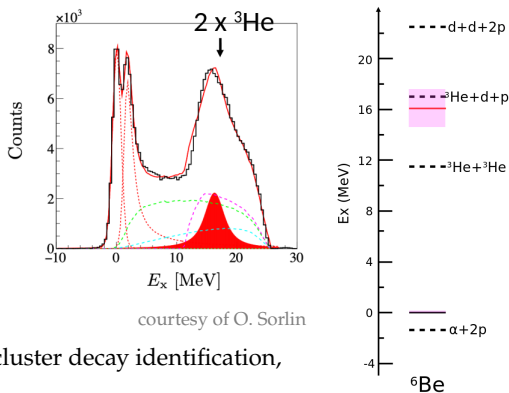
e.g. (p,d) reactions on $N = 3$ isotones studied with MUST2 at LISE.

Resonances around 17 MeV in $N = 2$ isotones, above $^3\text{He}+x$ threshold.

e.g. in ^6Be , it tends to decay by $^3\text{He}+^3\text{He}$ despite being unbound by about 16 MeV with respect to $\alpha+2p$ threshold.

Incomplete information on decay partition for other isotones (*higher multiplicity*).

$\Rightarrow$ Improve detection performance for cluster decay identification, also for high decay multiplicities.



courtesy of O. Sorlin

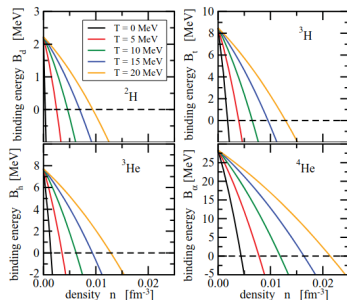
Clustering phenomena in nuclear matter

A necessary ingredient for describing low-density nuclear matter

Description of **infinite nuclear matter** at low density and finite temperature:

- Need to account for **light cluster** formation and the in-medium effects on their properties
- Clusters are bound only below a density threshold (Mott density)

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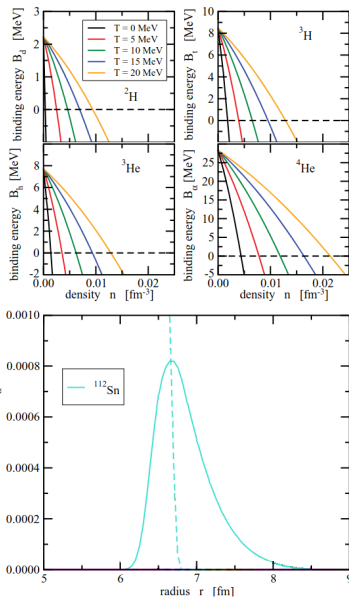
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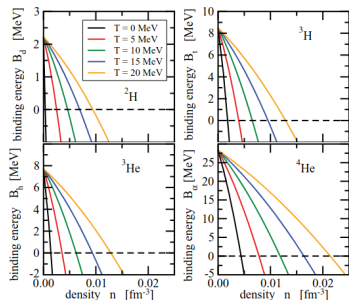
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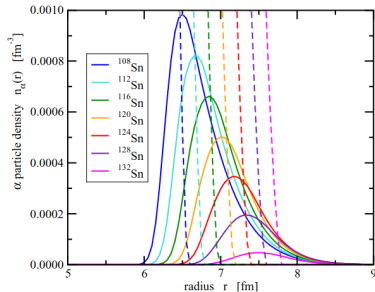
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- The effect evolves with the isospin content
→ theoretical study along the Sn isotopic chain

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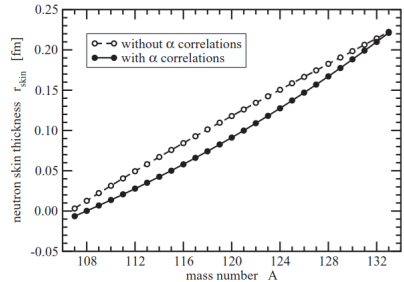


Clustering phenomena in nuclear matter

Interplay between clustering and neutron skin formation

Effect of surface α -clustering on finite nuclei:

- Including α -clustering reduces the predicted n-skin thickness along the Sn isotopic chain
- Largest effect at mid-chain, vanishes at both ends (low $A \rightarrow$ no n-skin, high $A \rightarrow$ no efficient α formation)



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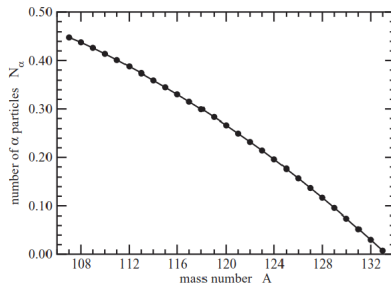
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More n-rich $\rightarrow$ harder to correlate p and n into α .

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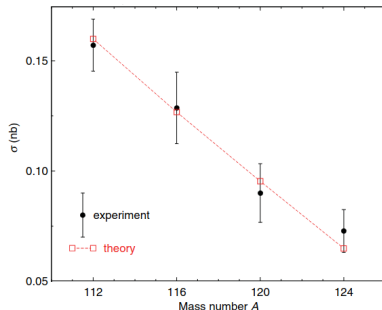
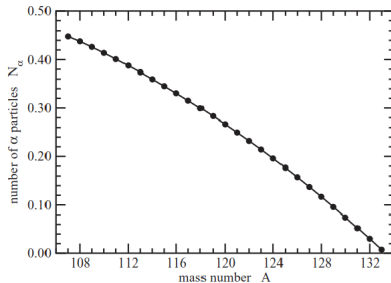
S. Typel et al., Phys. Rev. C 89, 064321 (2014)

Experimental test at RNCP (Osaka):

quasi-free α -knockout reactions $^A\text{Sn}(p, p\alpha)$

- $(p, p\alpha)$ cross-section decreases smoothly with A
 $\rightarrow$ direct evidence of decreasing N_α
- Excellent agreement with gRDF prediction

J. Tanaka et al., Science 371, 260-264 (2021).



Clustering phenomena in nuclear matter

Upcoming INDRA-FAZIA experiment E894: α -clustering in neutron-rich oxygen isotopes

“ α -clustering in neutron-rich oxygen isotopes”

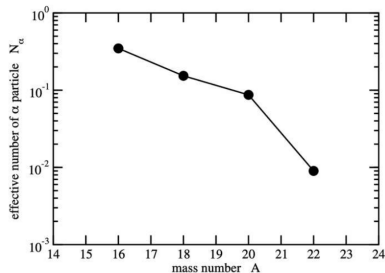
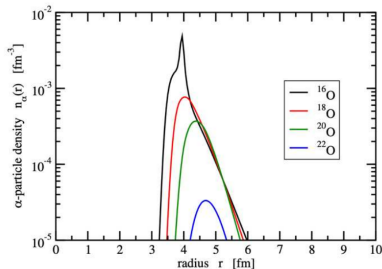
J. Benlliure, A. Chbihi *et al.*, E894 proposal, GANIL PAC 2024

Study of α -transfer reaction cross section along the oxygen isotopic chain:

- $(d, {}^6\text{Li})$ reactions induced by ${}^{16,18,20}\text{O}$ beams at 7.5 MeV/nucleon.
- Unambiguous determination of reaction channel thanks to multi-hit identification capability
→ study of cluster configurations of unbound states of O isotopes populated by inelastic reactions

Aimed at understanding the interplay between α -cluster formation and n-skin:

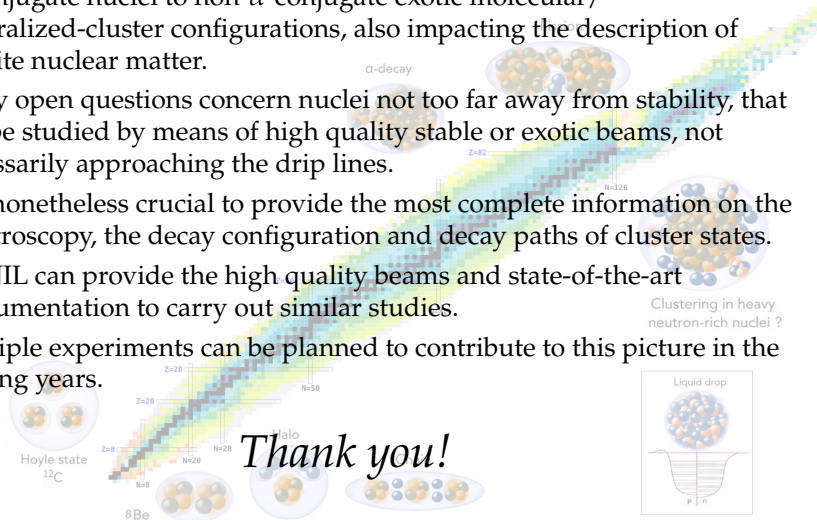
- Role of clustering in the relationship between the neutron-skin thickness and the L_{sym} parameter of the symmetry energy.



S. Typel, private communication

Conclusions and perspectives

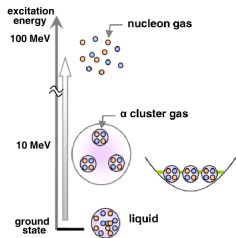
- Clustering is a *transversal phenomenon*: from the structure of light α -conjugate nuclei to non- α -conjugate exotic molecular/generalized-cluster configurations, also impacting the description of infinite nuclear matter.
- Many open questions concern nuclei not too far away from stability, that can be studied by means of high quality stable or exotic beams, not necessarily approaching the drip lines.
- It is nonetheless crucial to provide the most complete information on the spectroscopy, the decay configuration and decay paths of cluster states.
- GANIL can provide the high quality beams and state-of-the-art instrumentation to carry out similar studies.
- Multiple experiments can be planned to contribute to this picture in the coming years.



Backup slides

Signatures of cluster states

BEC-like interpretation and decay paths



Bose-Einstein-condensate-like states in $N\alpha$ nuclei

Interpretation of Hoyle-like states, associated with their large radius and low density $\rightarrow$ THSR wave function

A. Tohsaki *et al.*, Phys. Rev. Lett. 87, 192501 (2001)

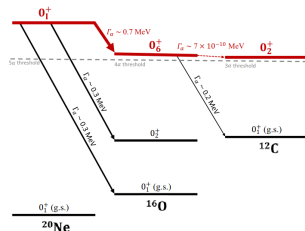
Good description of ^8Be and ^{12}C , while indications but no conclusive evidence for ^{16}O , ^{20}Ne , ^{24}Mg .

J. Chen *et al.*, Sci. Bull. 68, 1119 (2023), S. Adachi *et al.*, Phys. Lett. B 819, 136411 (2021)

Experimental search for BEC-like states in $N\alpha$ nuclei:

- Enhanced yield α for cluster emission
- Low kinetic energy of the decay products
- Decay path through α -condensate subsystems

Precision break-up measurements with complete detection of multi- α decay products
 $\rightarrow$ clean reconstruction of the decay path



B. Zhou *et al.*, Nat. Comm. 14, 8206 (2023)