Cluster formation in low- and high-lying states

—Cluser structures in ^{35}Cl—

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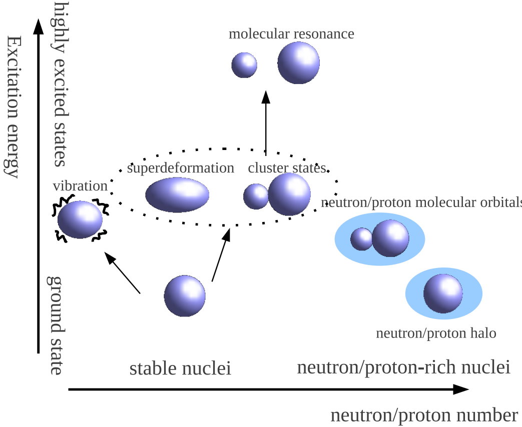
Cluster structures in nuclei



- Cluster structure is important in nuclei.
- Cluster transfer/capture/decay reactions, and so on.
- Nucleosynthesis.

- What kind of cluster structures develop?
- What are excitation energies of cluster states?

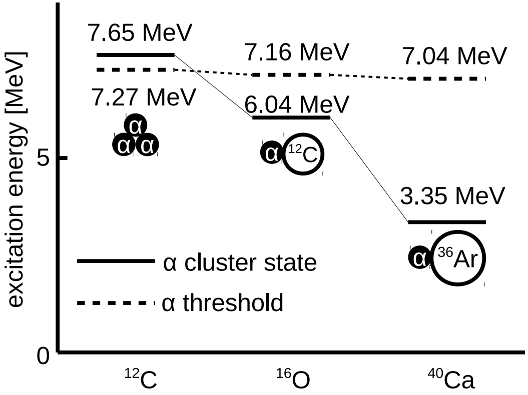
Threshold energy rule

Ikeda diagram (1968)

Threshold energy rule

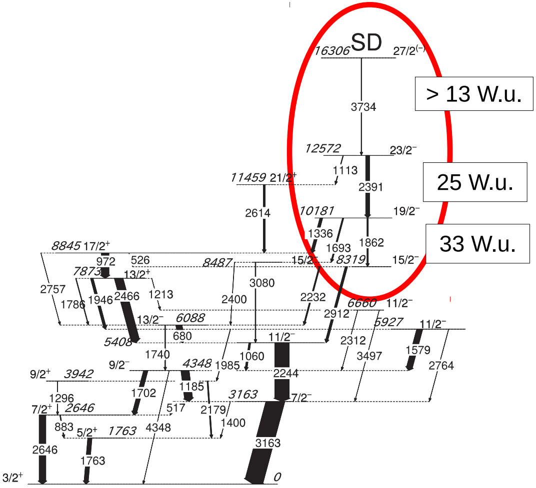
Cluster structures develop in excited states whose excitation energies are similar to threshold energies of the cluster decay.

Violation of the threshold energy rule



- In p-shell region, the threshold energy rule works well.
- In ^{40}Ca, excitation energy of the lowest α-cluster state are lower than α-threshold energy.

Deformed states in ^{35}Cl



[A. Bisoi et al, Phys. Rev. C 88, 034303 (2013)]

- A negative-parity deformed band was observed by a γ-spectroscopy experiment.
- It is suggested that this deformed states have α-^{31}P cluster structure with no direct evidence or theoretical calculation about α-clustering.

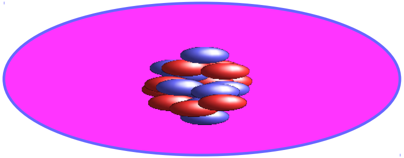
- Structure of the negative-parity deformed band.
- α-^{31}P and t-^{32}S clustering in low- and high-lying states.

Wave function

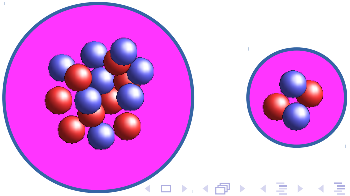
Deformed-basis antisymmetrized molecular dynamics (AMD) wave function $|\Phi\rangle$:
Slater determinant of Gaussian wave packets that can deform.

$$
\begin{aligned}
|\Phi\rangle &= \hat{\mathcal{A}}\,|\varphi_1,\ \varphi_2, \cdots, \varphi_A\rangle\,, \\
\varphi_i &\propto \exp\left[-(\mathbf{r}-\mathbf{Z}_i)\cdot \mathrm{M}(\mathbf{r}-\mathbf{Z}_i)\right]\sigma_i\tau_i.
\end{aligned}
$$

Deformed structure



Cluster structure



Framework

Energy variation

Energy variational calculation with a constraint potential

Parameters in wave functions are determined by energy variational calculations with a constraint potential V_{cnst}.

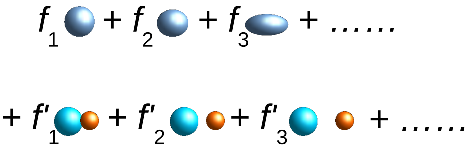
$$\delta \left[\left\langle \hat{P}^{\pi}\Phi \middle| \hat{H} \middle| \hat{P}^{\pi}\Phi \right\rangle + V_{\text{cnst}} \right] = 0$$

- V_{cnst}: quadrupole deformation parameter β (deformed structure)
  intercluster distance (α- and t-cluster structure)
- Effective interaction $\hat{H}$: Gogny D1S
- Conjugate gradient method.

Generator coordinate method (GCM)

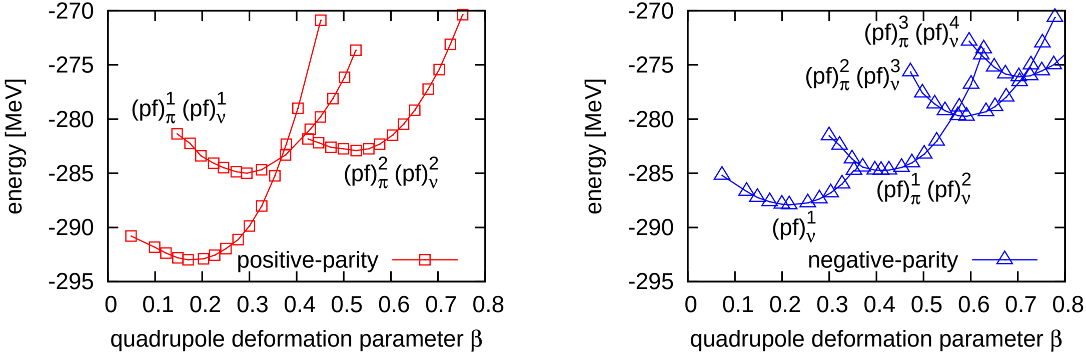
$$\left|\Phi_n^{J\pi M}\right\rangle = \sum_i f_{ni} \hat{P}^J_{MK_i} \hat{P}^\pi \left|\Phi_i\right\rangle$$

$$\left\langle \Phi_n^{J\pi M} \middle| \begin{Bmatrix} 1 \\ \hat{H} \end{Bmatrix} \middle| \Phi_{n'}^{J\pi M} \right\rangle = \begin{Bmatrix} 1 \\ E_n \end{Bmatrix} \delta_{nn'}$$



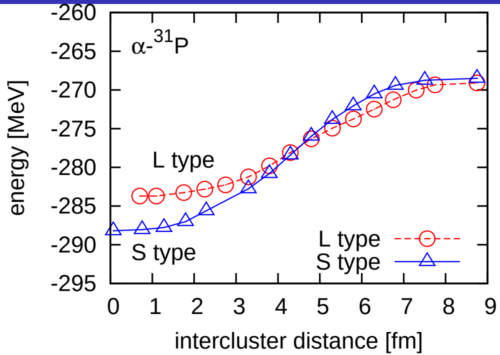
Various correlations are taken into account such as intercluster motion, coupling of cluster and deformed structures, and so on.

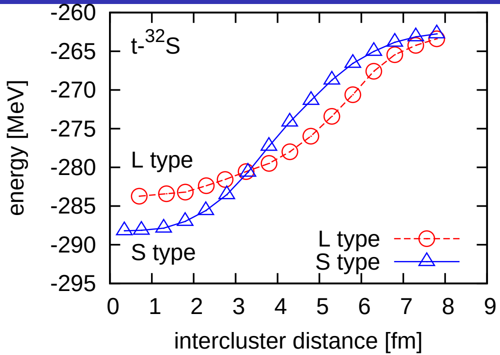
β-energy curves



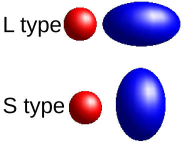
- In negative-parity states, a local minimum with $3\hbar\omega$ excited configurations exists at $\beta \sim 0.4$.

Energies of negative-parity α-^{31}P and t-^{32}S cluster structures.

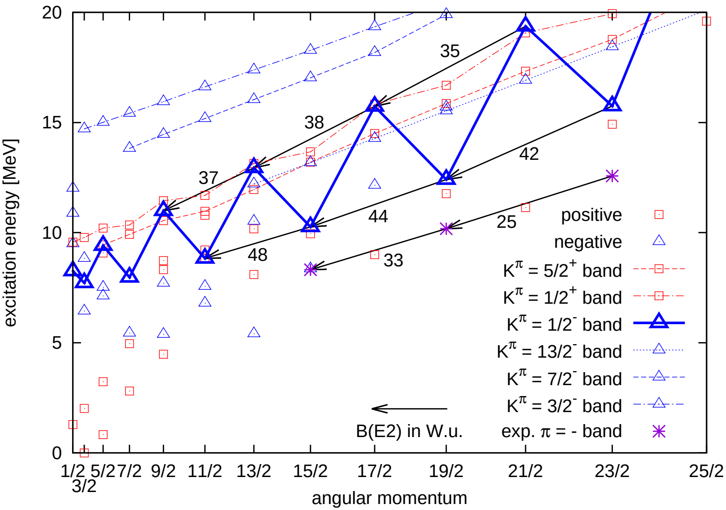




- A smaller cluster exists on the long/short-axis for L/S-type.
- Short intercluster distance: Reflecting particle-hole configurations (L: $3\hbar\omega$, S: $1\hbar\omega$), same type states have similar energies.
- Long intercluster distance: Reflecting threshold energies ($E_\alpha = 7$ MeV, $E_t = 18$ MeV), α-cluster states have lower energy.

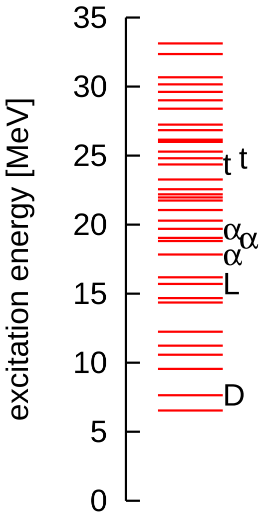


Level scheme of ^{35}Cl



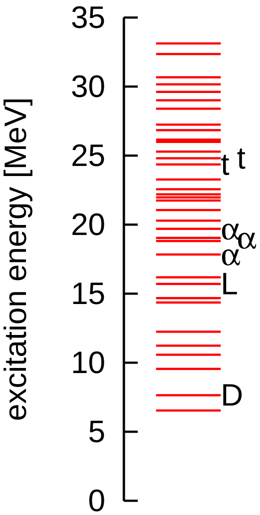
- The $K^\pi = \frac{1}{2}^-$ band corresponds to the observed negative-parity deformed band.
  (MoI, B(E2), yrast)
- It has $3\hbar\omega$ excited deformed structure.

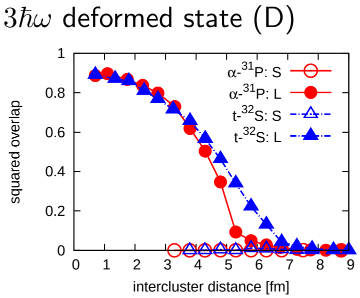
α- and t-cluster structure components ($J^\pi = \frac{3}{2}^-$)

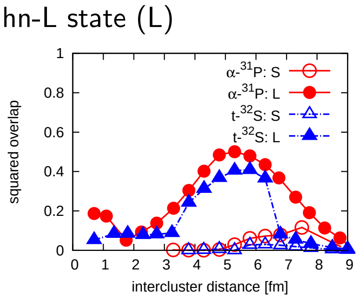


- Some states contain large amounts of cluster components.
  D: $K^\pi = \frac{1}{2}^-$ $3\hbar\omega$ excited deformed state
  L: hn-L state
  α: hn-α states
  t: hn-t states
  (hn = higher-nodal)
- The hn-L/α/t states do not contain deformed structure components.
  $\Rightarrow$ cluster states

α- and t-cluster structure components ($J^\pi = \frac{3}{2}^-$)

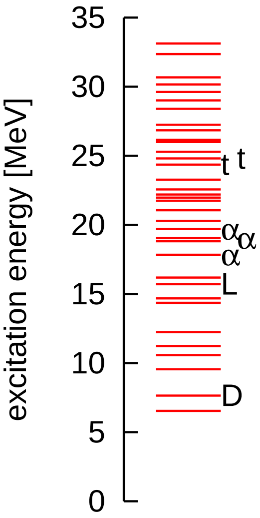




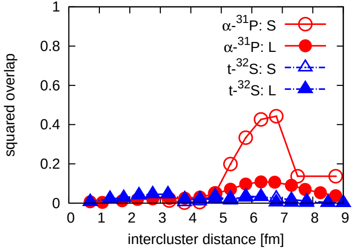


- The $3\hbar\omega$ deformed state contains similar amounts of L-type α- and t-cluster components.
- Short distance components are dominant.
  ⇒particle-hole configurations
- The hn-L states appear by excitation of intercluster motion in the $3\hbar\omega$ deformed state.

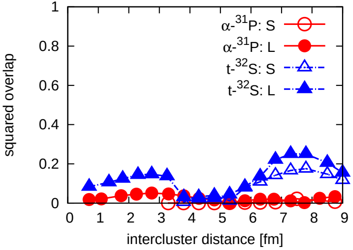
α- and t-cluster structure components ($J^\pi = \frac{3}{2}^-$)



hn-α states (α)



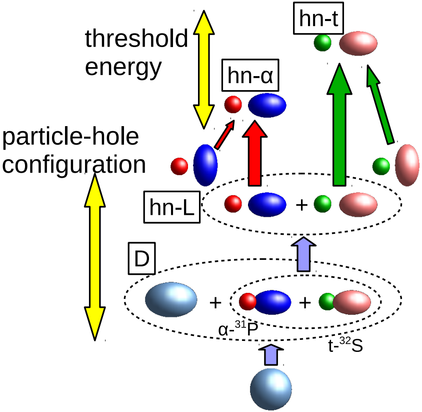
hn-t states (t)



- The hn-α and hn-t states have α- and t-cluster structures, respectively.
- Both of L- and S-type are contained.⇒Weak coupling
- Threshold energies are important for excitation energies.
  - $E_\mathrm{x}(\text{hn-}\alpha) < E_\mathrm{x}(\text{hn-t})$
  - Dominant components are around Coulomb barrier.

Conclusions

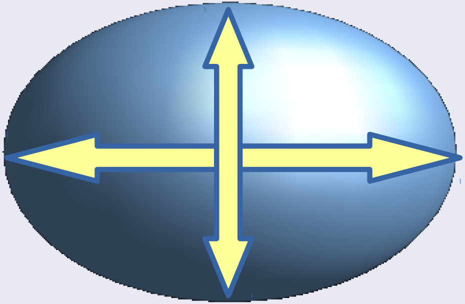
- Structures in ^{35}Cl are investigated focusing on α- and t-cluster structures.
- The observed deformed band is reproduced in which α- and t- cluster structures are coupled.
- By excitation of intercluster motion, higher-nodal cluster states appear.
- Particle-hole configurations and threshold energy are important for clustering structure in low- and high-lying states, respectively.



Back Up

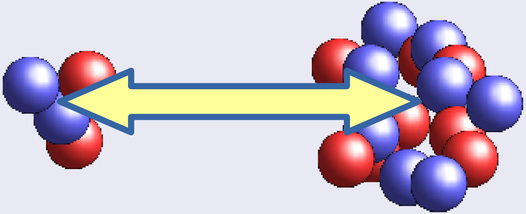
Framework
Constraint potentials

Deformation parameter β



- Deformed structures are obtained.

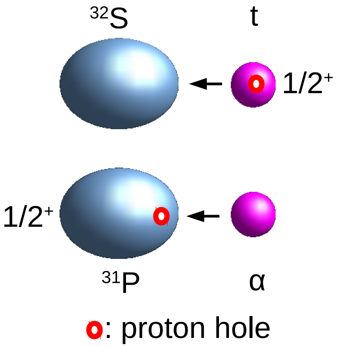
Intercluster distance



[Y. Taniguchi, M. Kimura, H. Horiuchi, PTP112, 475 (2004)]

- α-^{31}P and t-^{32}S cluster structures.

Particle-hole configurations of L-type α-^{31}P and t-^{32}S cluster structure



- L type α- and t-cluster structure become $\underline{3\hbar\omega}$ excited configurations in small intercluster distance.
- sd-shell orbits in a ^{32}S cluster are fully occupied in the direction of the long axis.
- A ^{31}P cluster has a proton hole at a sd-shell orbit in the direction of the long axis.
- Three nucleons in α and t clusters go into pf-shell when they are approaching to larger clusters.
  $\Rightarrow$ $3\hbar\omega$ excited configurations