Low-lying $^{12}\mathrm{C} + ^{16}\mathrm{O}$ molecular resonance band in $^{28}\mathrm{Si}$

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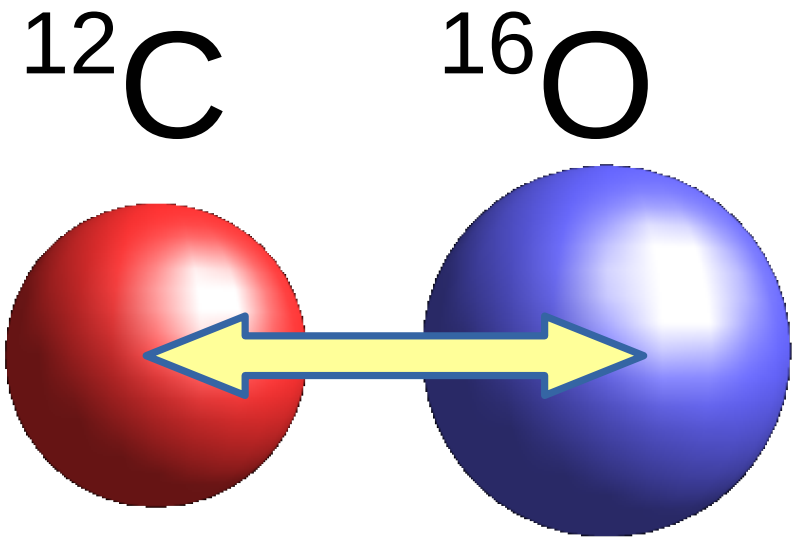
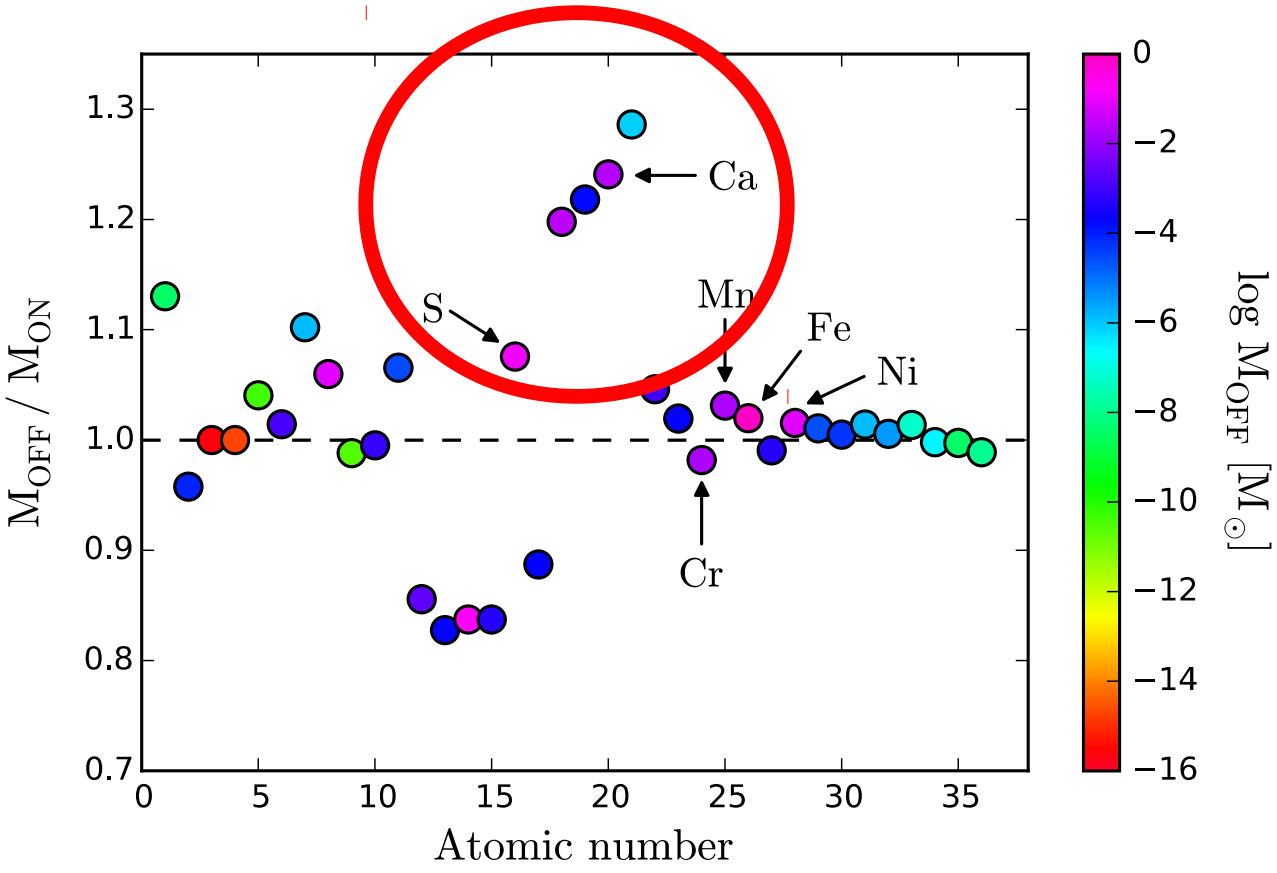
Nuclear fusion reaction rate and nucleosynthesis

- Nuclear fusion reaction rate is important for nucleosynthesis.
- Nuclear fusion reaction rate is sensitive to energy of molecular resonant (MR) states.



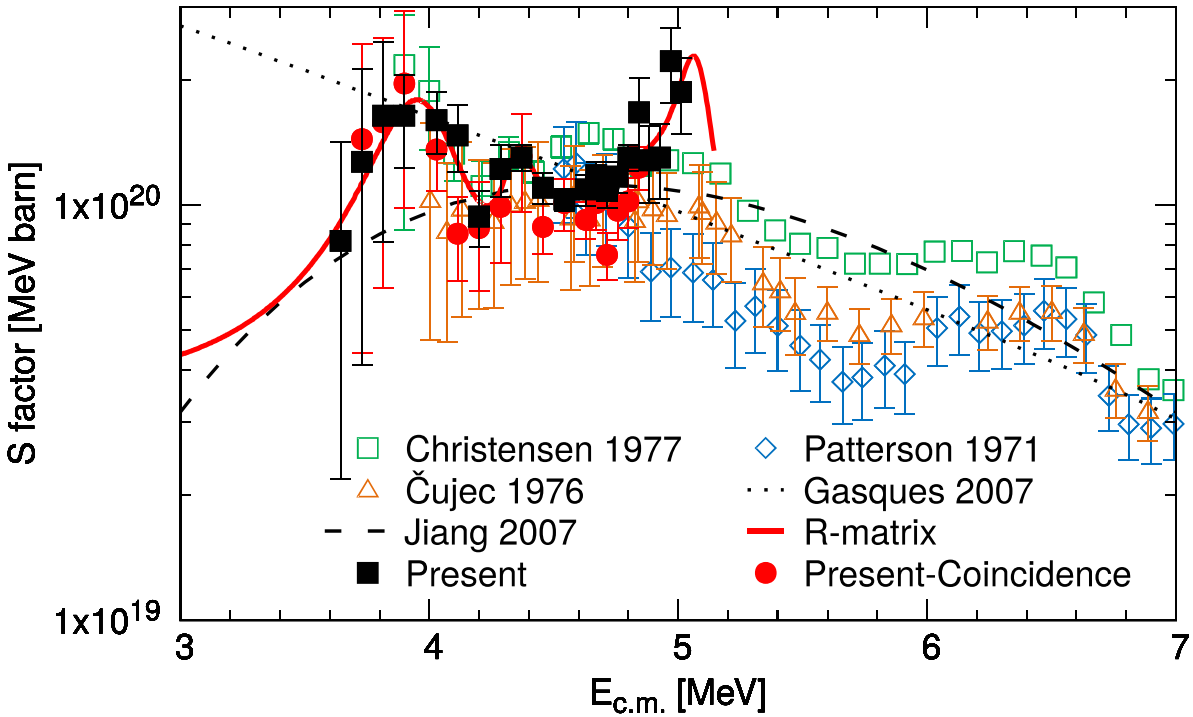
$^{12}\mathrm{C} + {}^{16}\mathrm{O}$ fusion reaction rate and abundance of S–Ca



[H. Martínez-Rodríguez et al, ApJ**843**, 35 (2017)]

- S–Ca abundances are sensitive to $^{12}\mathrm{C} + {}^{16}\mathrm{O}$ fusion reaction rate in type Ia SN.

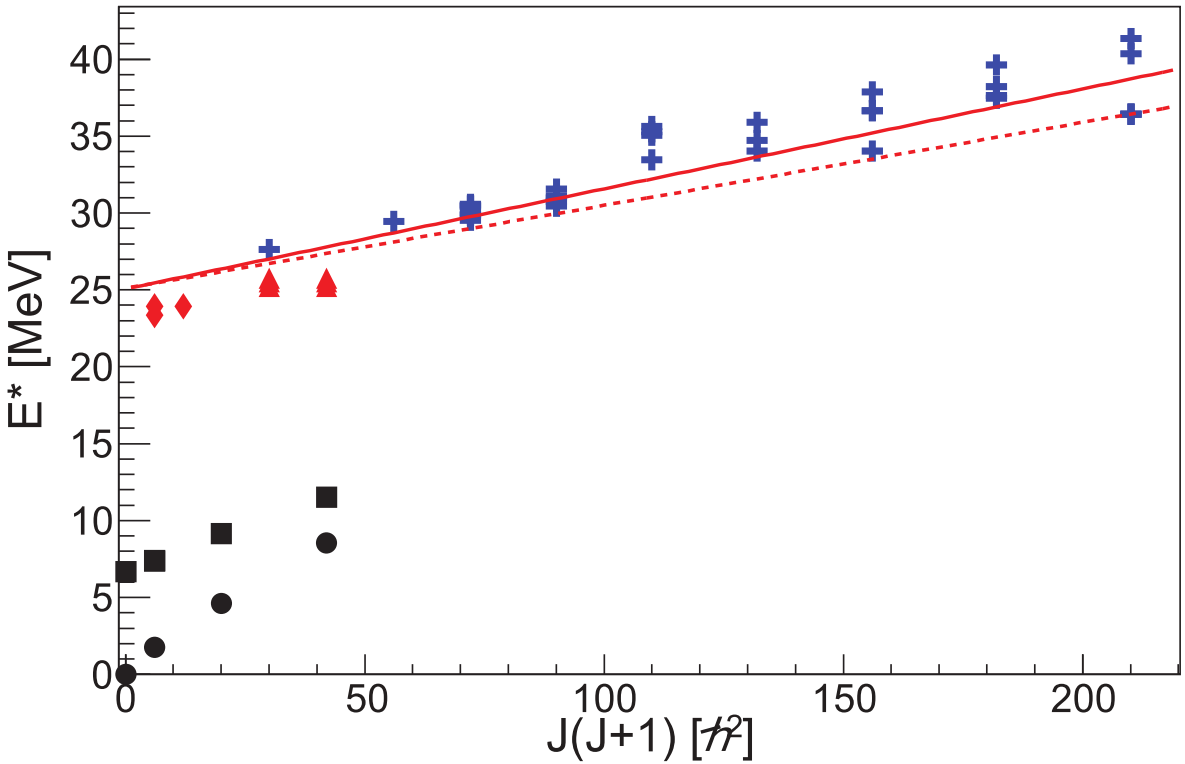
Low-energy $^{12}\mathrm{C} + {}^{16}\mathrm{O}$ fusion reaction



[X. Fang et al, PRC**96**, 045804 (2017)]

- Resonant states are observed around $\gtrsim 4$ MeV.
- Theoretical calculations of $^{12}\mathrm{C} + {}^{16}\mathrm{O}$ resonant states around the threshold energy are necessary.

High-lying $^{12}\mathrm{C} + {}^{16}\mathrm{O}$ resonant states

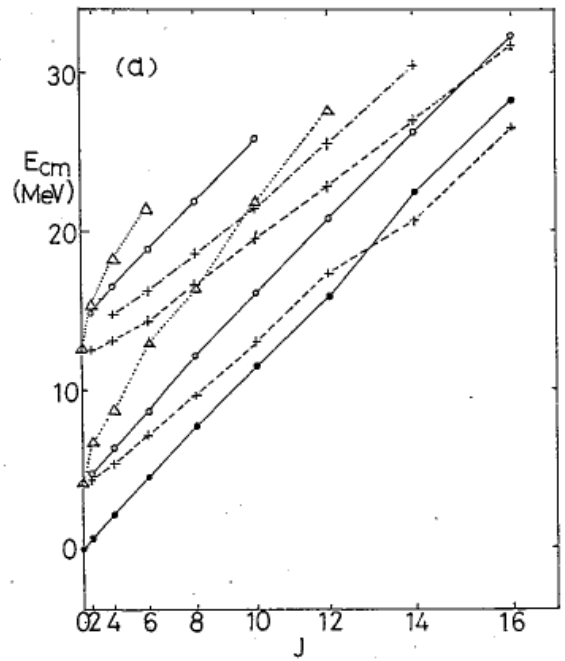


[A. Goasduff et al, PRC**89**, 014305 (2014)]

- Many $^{12}\mathrm{C} + {}^{16}\mathrm{O}$ resonant states are observed around the Coulomb barrier top. ($E_{\mathrm{th}}^{\mathrm{CO}} = 16.75$ MeV).

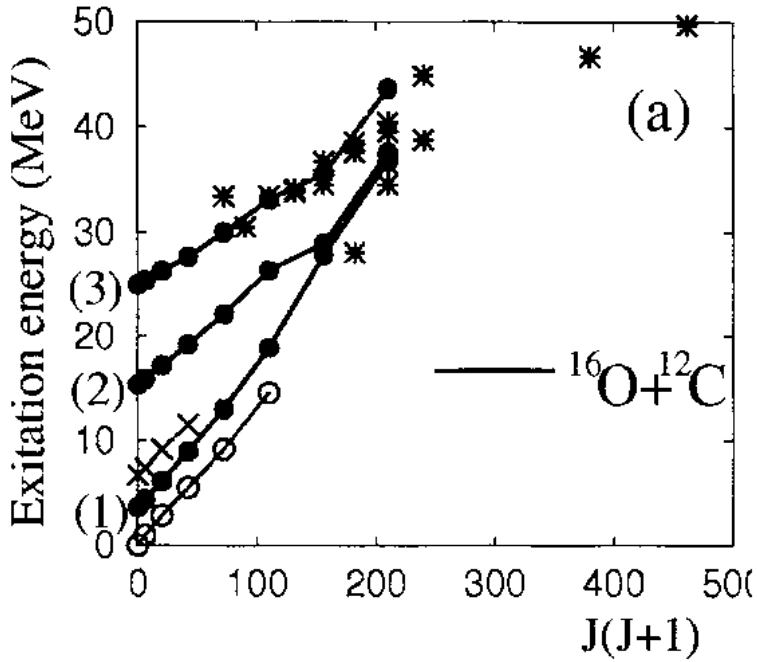
Theoretical studies of $^{12}\mathrm{C} + ^{16}\mathrm{O}$ MR states

Semi-micro. (OCM)



[K. Katō, S. Okabe, and Y. Abe, PTP**74**, 1053 (1985)]

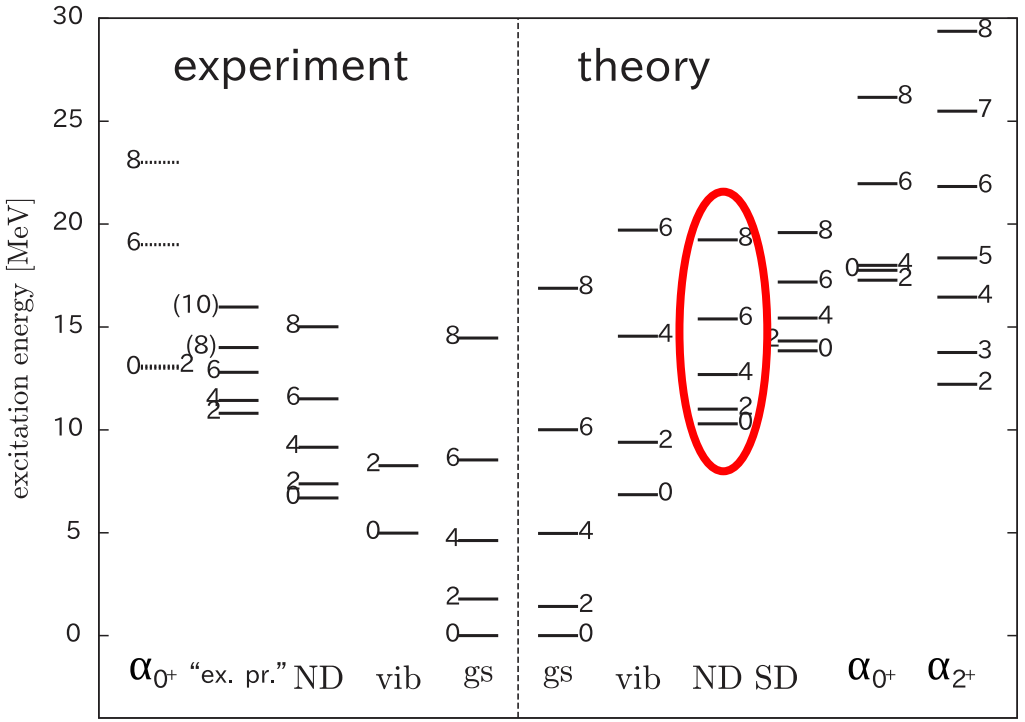
Full micro. (AMD)



[Y. Kanada-En'yo et al, NPA**738**, 3 (2004)]

- $^{12}\mathrm{C} + ^{16}\mathrm{O}$ resonant states close to the threshold energy are predicted by semi- and full microscopic calculations.
- No full microscopic study treating $^{12}\mathrm{C}$-$^{16}\mathrm{O}$ and α-$^{24}\mathrm{Mg}$ relative motion. $\Rightarrow$ α- and p-decay cannot be evaluated.

^{12}C-^{16}O cluster correlations in low-lying states



[Y. Taniguchi, Y. Kanada-En'yo, M. Kimura, PRC**80**, 044316 (2009)]

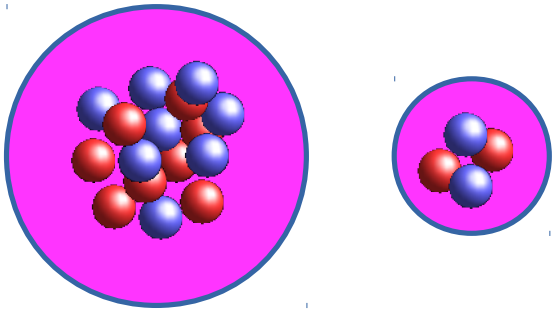
- Low-lying states are well reproduced by the antisymmetrized molecular dynamics (AMD).
- The ND states contain large amount of ^{12}C-^{16}O cluster structure components.

Wave function

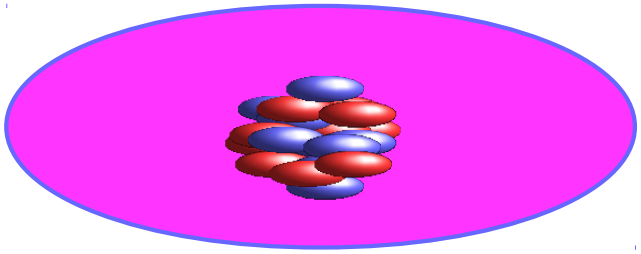
Deformed-basis antisymmetrized molecular dynamics (AMD) wave function $|\Phi\rangle$:
Slater determinant of Gaussian wave packets that can deform.

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

Cluster structure



Deformed structure



Energy variational calculation with a constraint potential

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

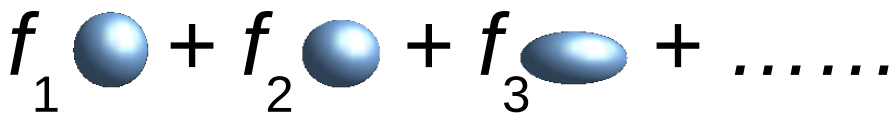
$$\delta \left[\left\langle \hat{P}^{\pi} \Phi \middle| \hat{H} \middle| \hat{P}^{\pi} \Phi \right\rangle + V_{\rm cnst} \right] = 0$$

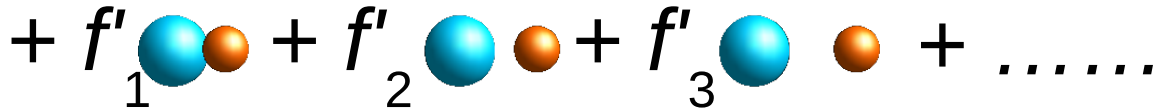
- $V_{\rm cnst}$: quadrupole deformation parameter β (deformed structure)
  intercluster distance (^{12}C-^{16}O and α-^{24}Mg cluster structures)
- Effective interaction $\hat{H}$: Gogny D1S
- Conjugate gradient method.

Generator coordinate method (GCM)

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

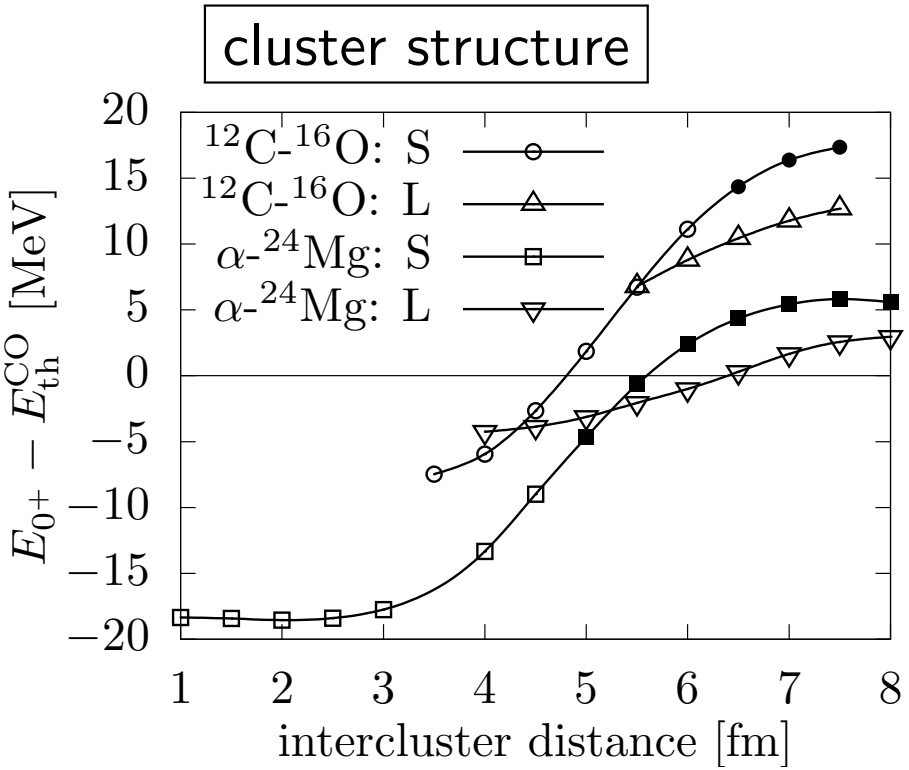
$$\left\langle \Phi_n^{J\pi M} \middle| \left\{ \begin{array}{c} 1 \\ \hat{H} \end{array} \right\} \middle| \Phi_{n'}^{J\pi M} \right\rangle = \left\{ \begin{array}{c} 1 \\ E_n \end{array} \right\} \delta_{nn'}$$

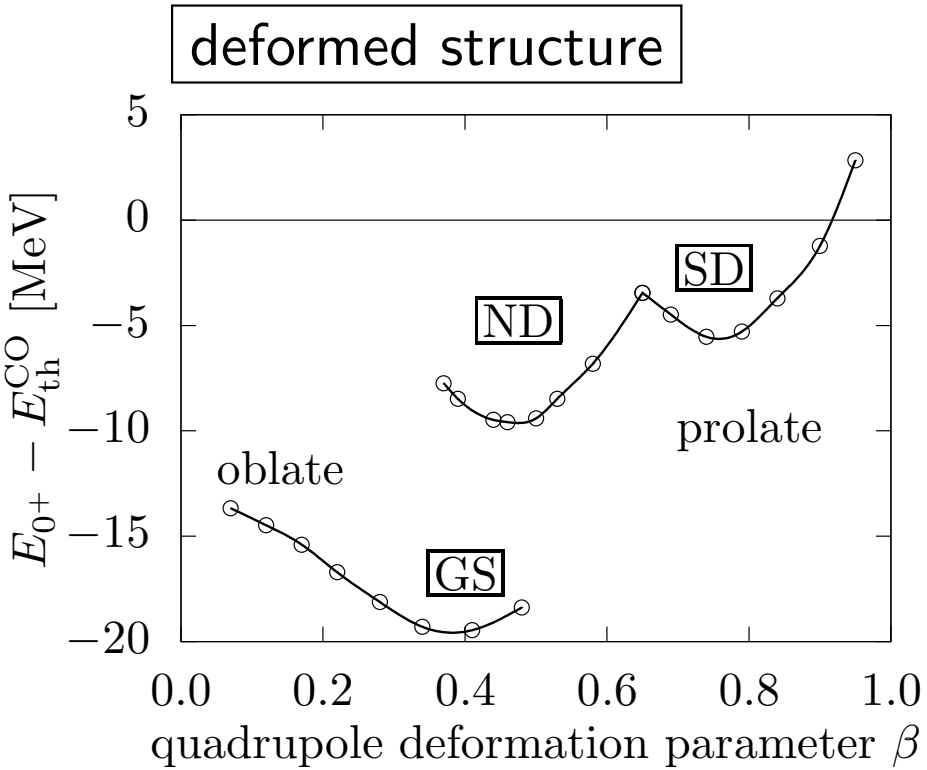




Intercluster motion is taken into account by superposition of basis wave functions.

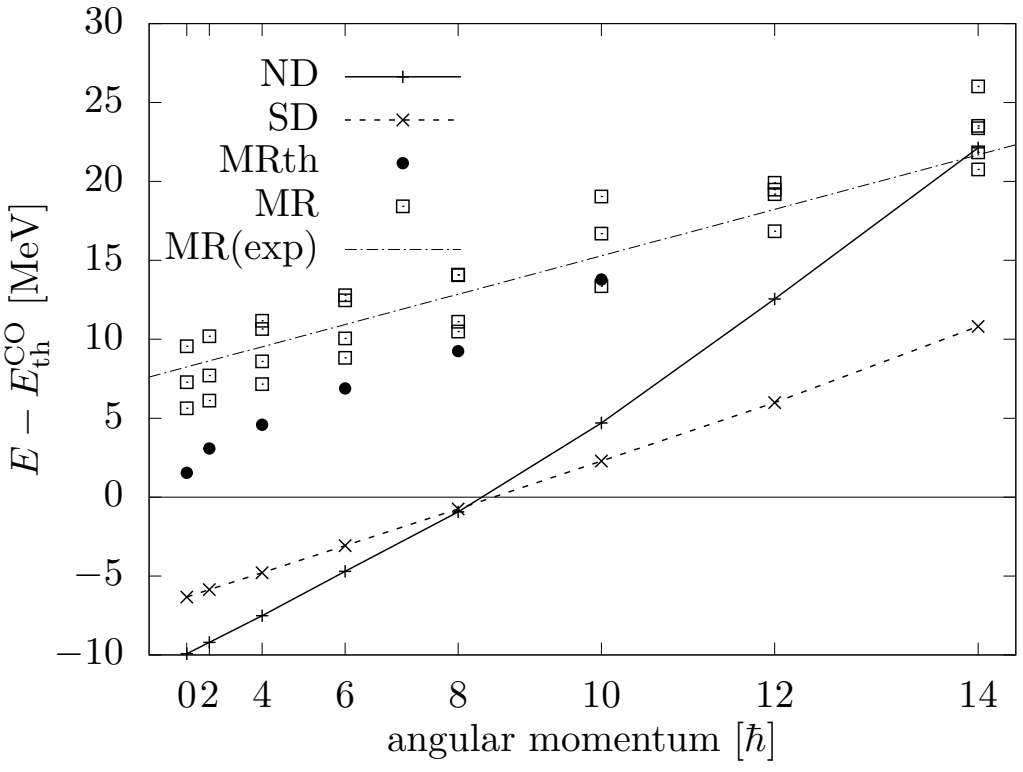
Energy curves





- Spherical clusters (^{16}O/α) locate on the short and long axes of deformed clusters (^{12}C/^{24}Mg) in S and L types, respectively.
- Oblate and prolate shapes coexist on the β-energy curve.

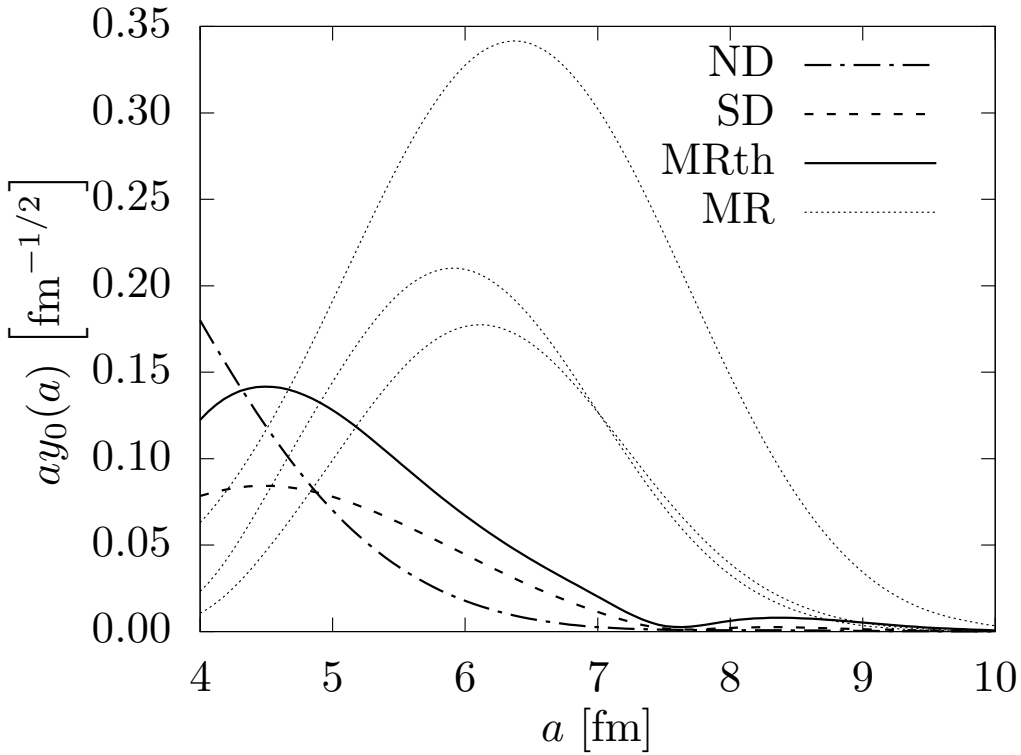
Level scheme



- ^{12}C-^{16}O resonant states (MRth and MR) are obtained.
- The band head energy of the MRth states is just above the $^{12}\mathrm{C} + {}^{16}\mathrm{O}$ threshold energy.

  $\Rightarrow$ Enhancement of fusion reaction rate at low temperature?

^{12}C-^{16}O reduced width amplitude (RWA)



- ^{12}C-^{16}O RWA are obtained.
- p-^{27}Al and α-^{24}Mg RWAs can be obtained.
  $\Rightarrow$ Branching ratio of α and p decay.

Summary

- By AMD + GCM, $^{12}\mathrm{C} + ^{16}\mathrm{O}$ molecular resonant states are investigated in $^{28}\mathrm{Si}$.
- $^{12}\mathrm{C} + ^{16}\mathrm{O}$ molecular resonant states exist just above the threshold energy. The molecular resonant states may be important for nucleosynthesis.
- Future works
  - Fusion reaction rate at low temperature. (with reaction theorists)
  - Branching ratio of α and p decay for the $^{12}\mathrm{C} + ^{16}\mathrm{O}$ molecular resonant states.