Enhanced monopole and dipole transitions in medium-heavy nuclei induced by α clusters

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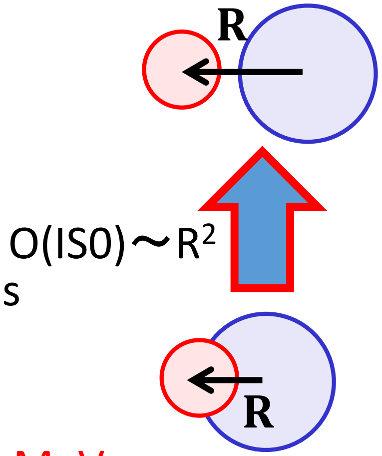
1. Background: Isoscalar transitions in light nuclei ($^{16,18}O$, ^{12}Be)
2. Our subjects: Monopole and dipole transitions in heavy nuclei
3. Framework: α potential model + complex boundary condition
4. Results(1): IS0 and IS1 transitions in $^{44}Ti = \alpha + {}^{40}Ca$
5. Results(2): IS1 in $^{104\sim110}Te = \alpha + {}^{100\sim106}Sn$ (E1 in $^{135}Cs = \alpha + {}^{131}I$)
5. Discussion and future studies: Improvement of calculations

α clustering phenomena and monopole transition



1. α clustering phenomena in nuclei

α cluster structures are well known in excited states of lighter systems

^{8}Be = 2α, ^{12}C = 3α, ^{16}O=α +^{12}C, … ⇒ Identified by $E_x(0_{ex}^+)$, Γ_α, etc

→ below ∼15 MeV

2. IS0 transition and α cluster structures

IS0 transition is strongly enhanced if α cluster structures are well developed

$$M(IS0) = \langle 0_f^+ | \sum_{i=1}^{A} r_i^2 | 0_1^+ \rangle$$

Discrete IS0 strength at E_x < 15 MeV is possible to be described by α cluster model

⇒ IS0 will be new (or modern) probe to assign α cluster structure

cf. E_x > 15 MeV in M.F. model

(2hw∼30 MeV)

3. Investigations on IS0 transition

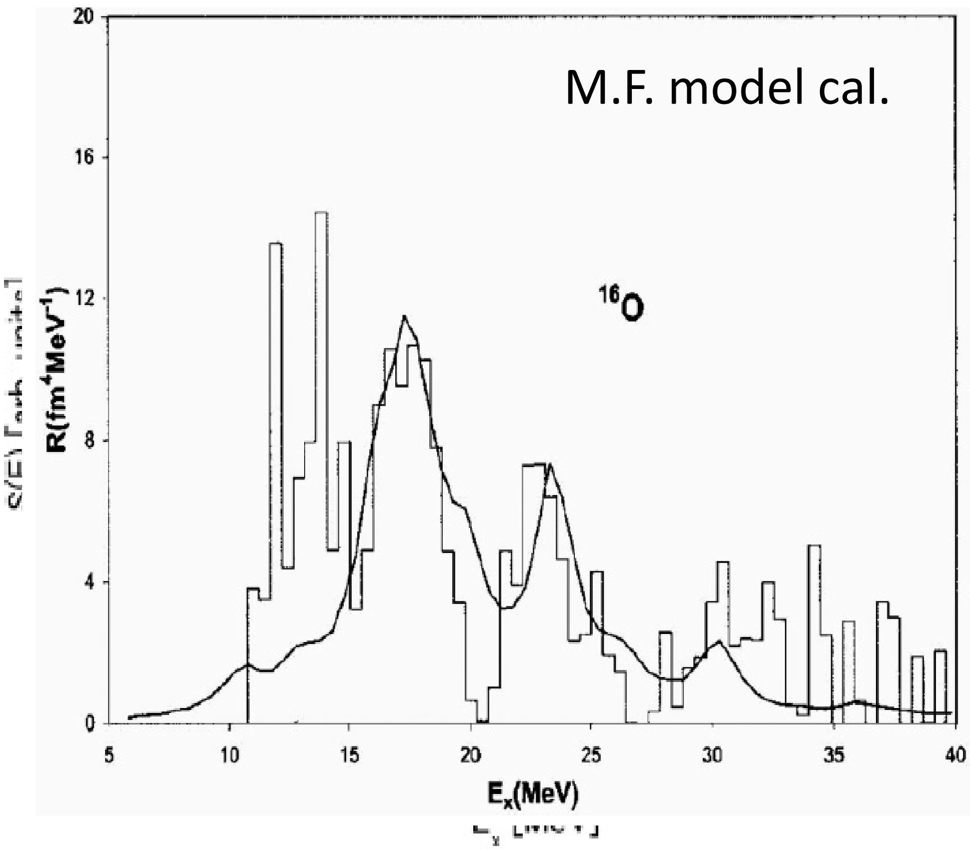
IS0 transitions are mainly investigated in lighter systems.

^{12}C ⇒ 3α, ^{16,18}O ⇒ α +^{12,14}C, ^{12}Be ⇒ α + ^{8}He are compared with experiments

Monopole transition in $^{16,18}O$ with α cluster model

^{16}O: 4α model

$$M(IS0) = \langle 0_f^+ | \sum_{i=1}^{A} r_i^2 | 0_1^+ \rangle$$



^{18}O: α + ^{14}C coupled-ch.

$$M(E0) = \langle 0_f^+ | \sum_{i=1}^{A} \tau_i(p) r_i^2 | 0_1^+ \rangle$$

M. Nakao et al., PRC98 (2018)

	Theory	Exp. [27]
0_4^+ (Res.)	2.0	–
0_5^+ (Res.)	6.3	–

Ratio to weisskopf unit (W.U.)

Theory ($0_1^+ \Rightarrow 0_2^+$) = 1.1 W.U.

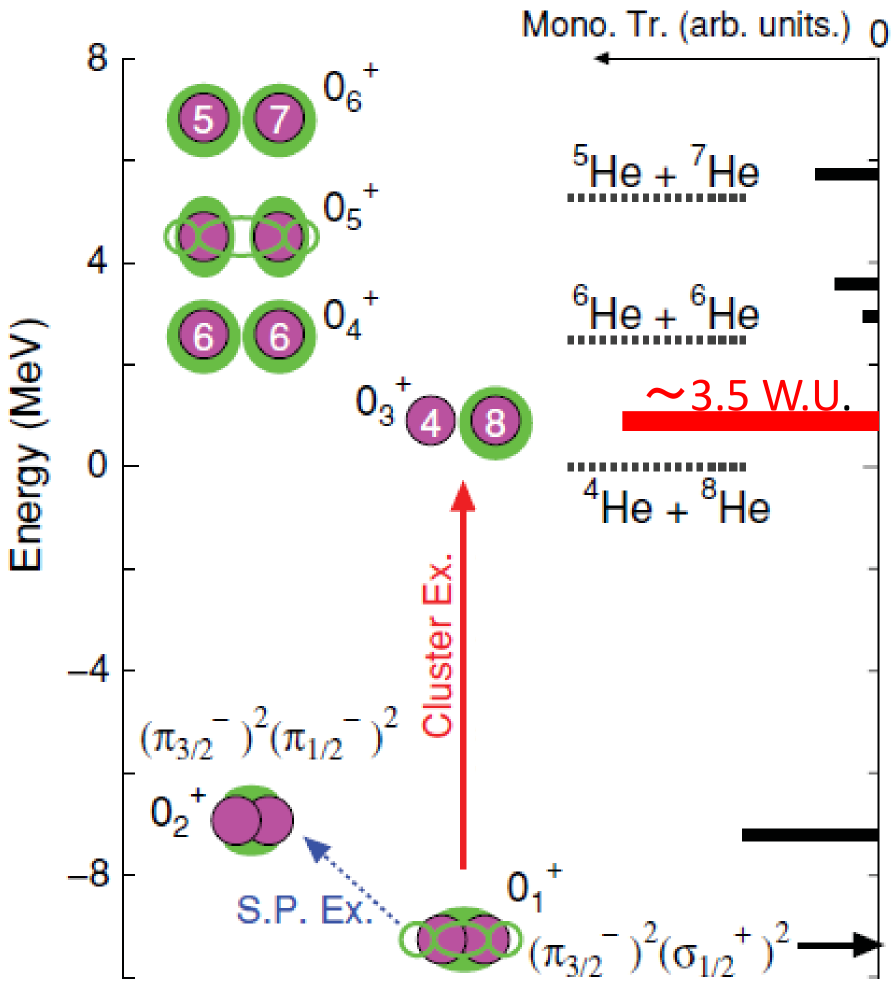
Experiment ($0_1^+ \Rightarrow 0_2^+$) = 1.5 W.U.

$^{16,18}O$ → α + $^{12,14}C$ excitation nicely describe discrete strength below E_x < 15 MeV

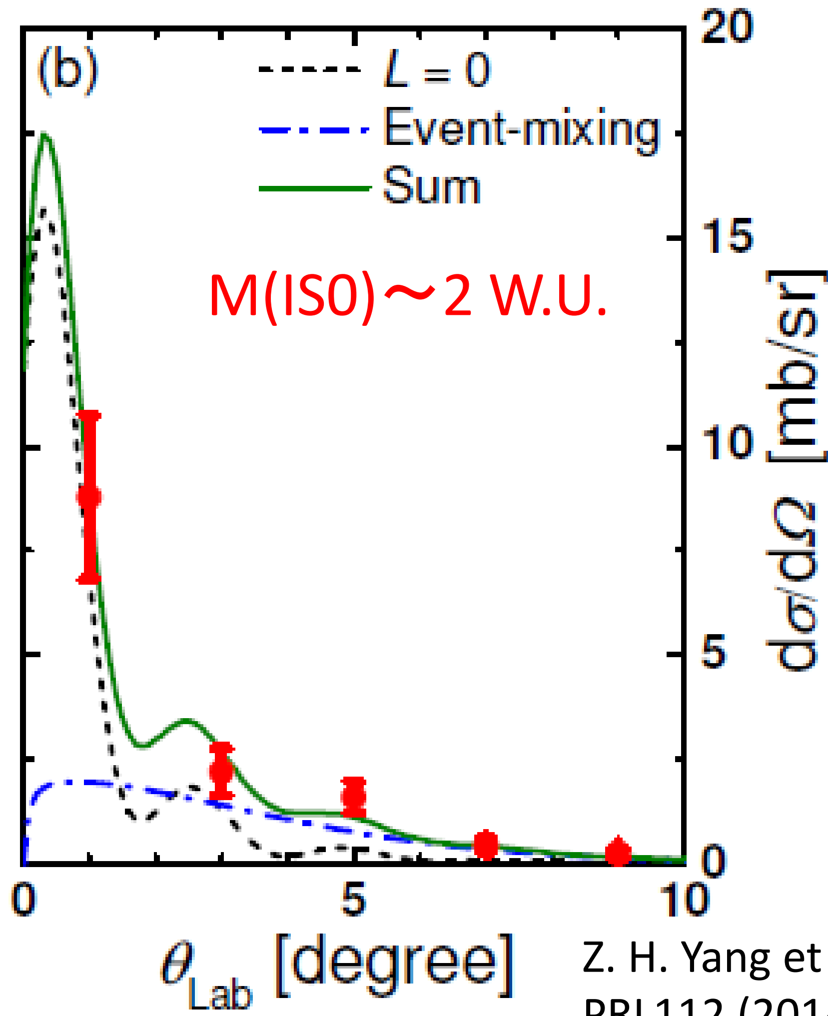
IS0 transitions in ^{12}Be

IS0 strength is enhanced for $^{12}Be \rightarrow \alpha + {}^{8}He$ excitation; M. Ito and K. Ikeda, RPP77 (2014)

Theoretical cal. of IS0 transition



Exp. of $^{12}C + {}^{12}Be$



Z. H. Yang et al. PRL112 (2014)

Our subject: Extension of IS transition to heavier systems

1. Studies of IS transition (A < 50)

① IS0 transition is effective probe to identify cluster structures $\hat{O}(IS0) = \sum_i r_i^2$

② IS1 transition is proposed as a new probe for asymmetric cluster with N=Z

Y. Chiba et al., PRC93, 034319 (2016)

α + ^{16}O in ^{20}Ne and α + ^{40}Ca in ^{44}Ti

$$\hat{O}(IS1) = \sum_i r_i^3 Y_{1,0}(\hat{r}_i)$$

2. Studies of cluster structure in heavy systems

^{44}Ti with α + ^{40}Ca is deeply studied by microscopic and potential models

Heavier systems (Actinide, rare-earth, …) are extensively studied by Potential model

Intensive contributions from B. Buck et al. → Ground and negative rot. band struture

Our subject: Studies on IS0 and IS1 transitions in heavier systems

3. Today's report

We discuss continuum strength of isoscalar transitions by potential model for

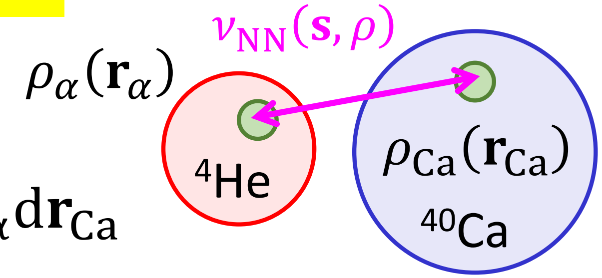
IS0 and IS1: ^{44}Ti with α + ^{40}Ca model

IS1: ^{104}Te with α + ^{100}Sn and Te isotopes

^{104}Te Exp. K. Auren et al., PRL121 (2018)

Framework (1): Potential and boundary condition

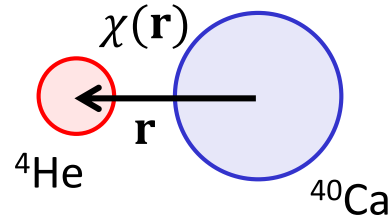
1. Double folding model



$$U_{\rm DF} = \iint \underline{\rho_\alpha(\mathbf{r}_\alpha)}\,\underline{\rho_{\rm Ca}(\mathbf{r}_{\rm Ca})}\,v_{\rm NN}^{\rm DDM3Y}(\mathbf{s},\rho)\,d\mathbf{r}_\alpha d\mathbf{r}_{\rm Ca}$$

Exp. Charge F.F. M.F. model (by S. Ebata)

2. Schrödinger equation



$$(T + V(r) - E)\,\chi(\mathbf{r}) = 0$$

Nuclear interaction

$$V(r) = N_{\rm r}\cdot U_{\rm DF}(r) + V_{\rm C}(r) + V^{\rm PF}$$

Double Folding pot. (N_r is optimized)

Coulomb pot. (Uniform charge)

Pseudo pot. (Pauli's principle of α + ^{40}Ca)

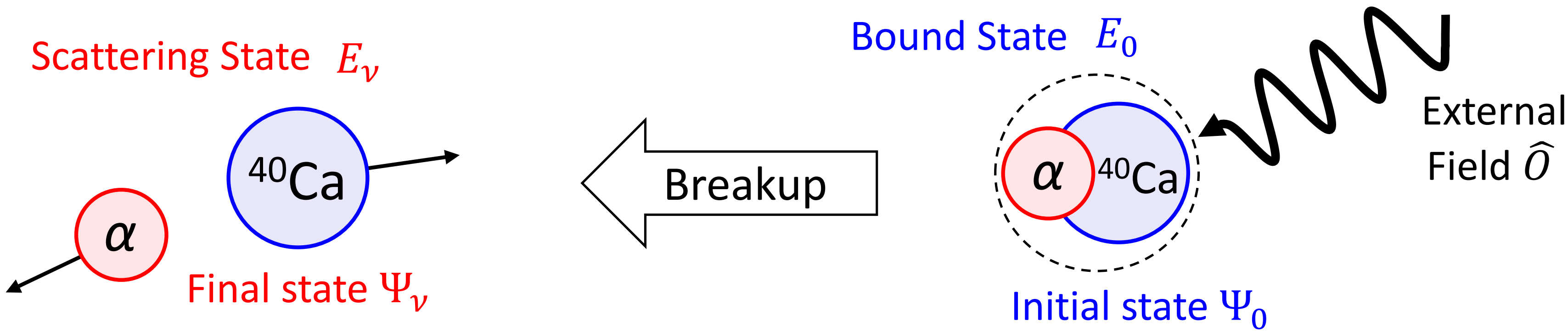
3. Boundary condition for continuum strength

We apply absorbing boundary condition (ABC) or complex scaling method (CSM)

ABC: M. Iwasaki et al., PTEP2015

CSM: S. Aoyama et al., PTPS116, 1 (2006).

Framework (2) : Calculation of Strength function



$$S_\lambda(E) = \sum_\nu \left| \langle \Psi_\nu | \widehat{O_\lambda} | \Psi_0 \rangle \right|^2 \delta(E - E_\nu)$$

$$\sum_m |\Psi_m\rangle\langle\tilde{\Psi}_m| = 1$$

Extended Completeness Relation of ABC or CSM solutions

ABC or CSM Solution

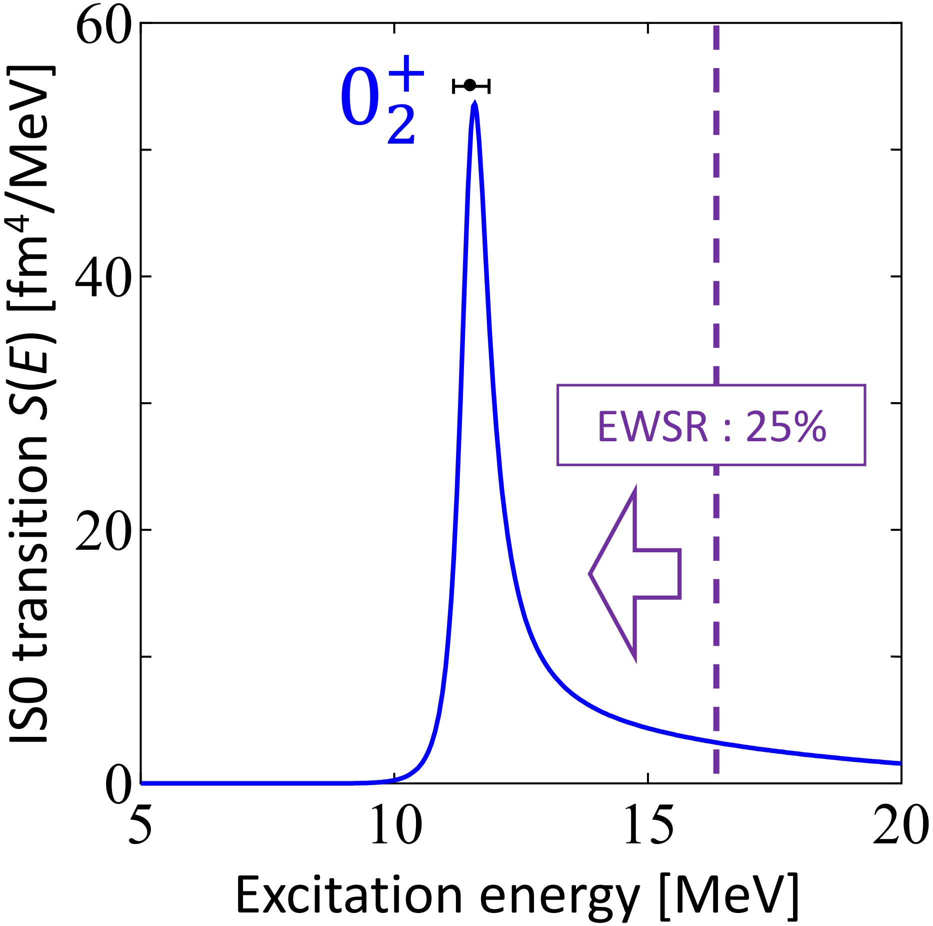
$$S_\lambda(E) = -\frac{1}{\pi} \sum_m \mathrm{Im}\left[\frac{\langle \Psi_0 | \widehat{O_\lambda}^\dagger | \Psi_m \rangle \langle \tilde{\Psi}_m | \widehat{O_\lambda} | \Psi_0 \rangle}{E - E_m} \right]$$

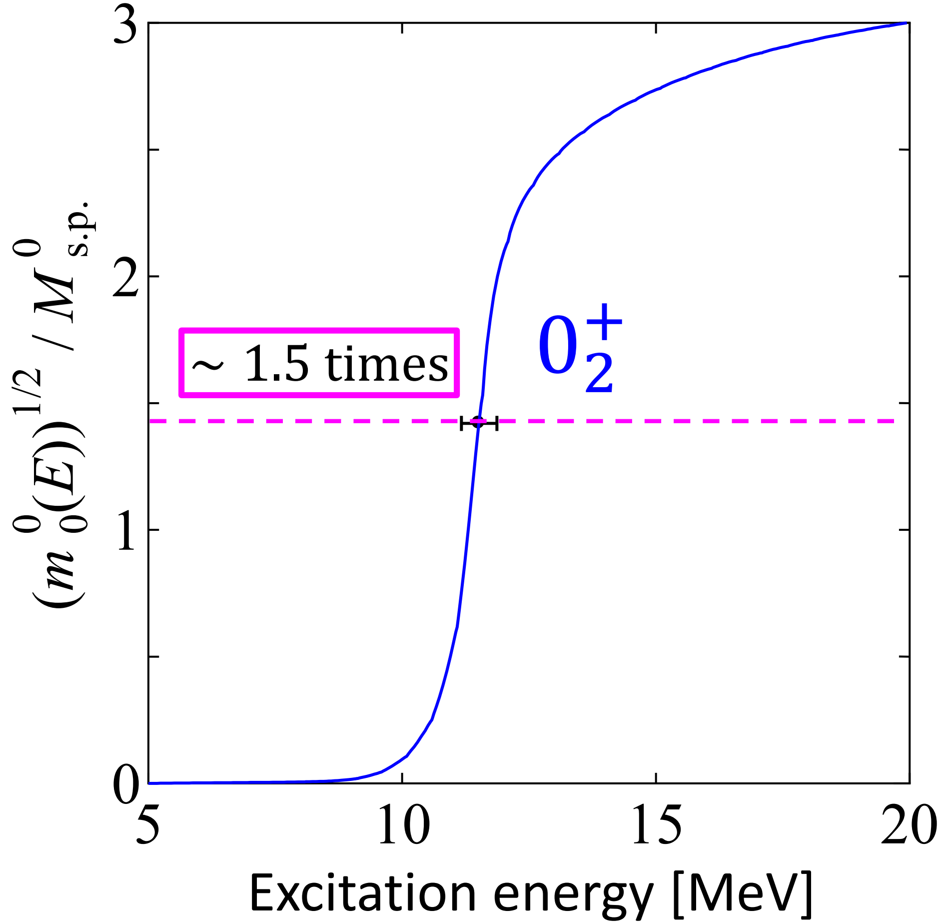
Complex Energy

→ Smooth continuum strength function is possible to calculate

Result of α + ^{40}Ca : IS0 strength function

※ Naïve M.F. $E_x > 2hw = 30$ MeV



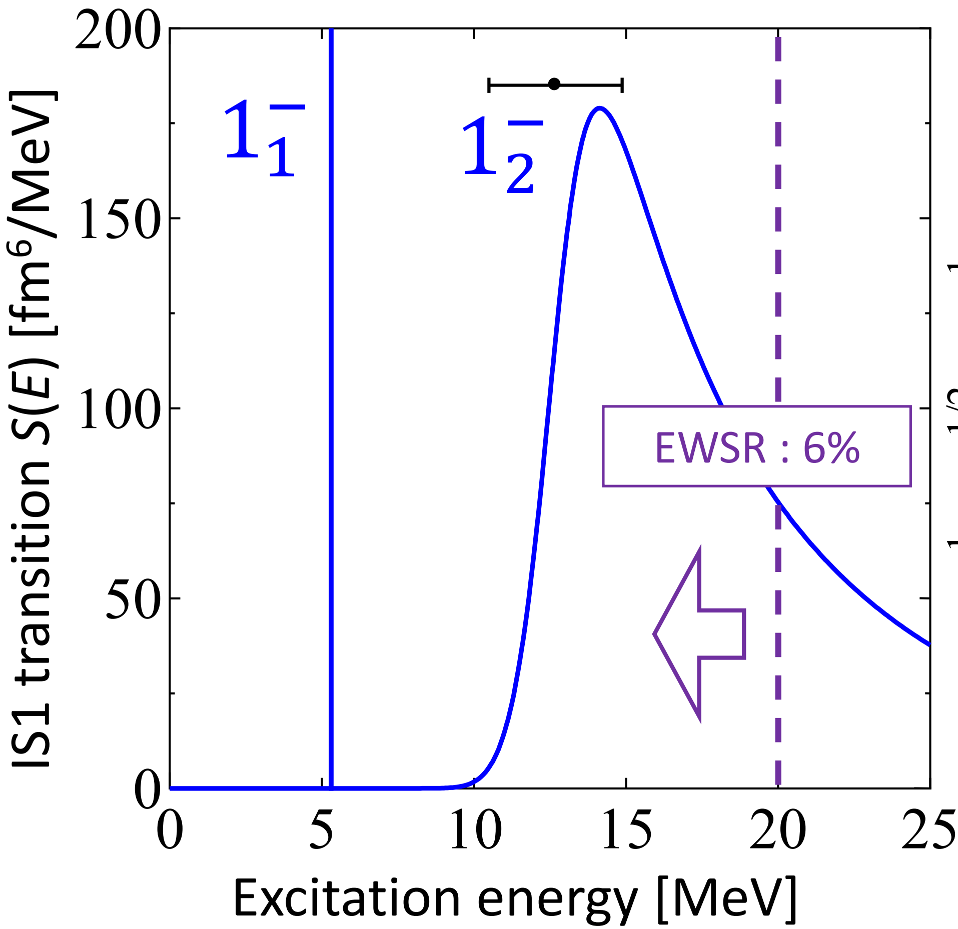


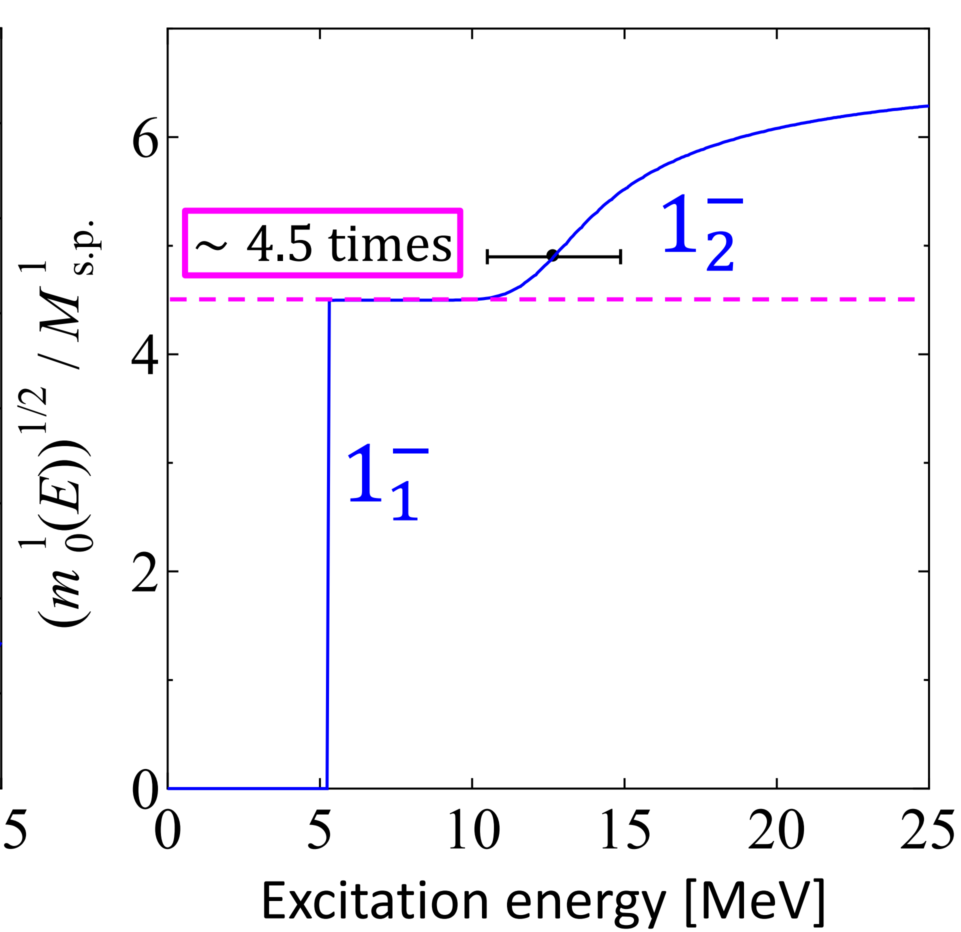
This strength appears below 15MeV which is lower than M.F. model

Fraction of EWSR $\int_0^E \varepsilon S_{\lambda=0}(\varepsilon)\mathrm{d}\varepsilon / M_{\mathrm{sum}}^{\lambda=0}$

Result of α + ^{40}Ca : IS1 sttrength function

※ Naïve M.F. $E_x > 1hw = 15$ MeV

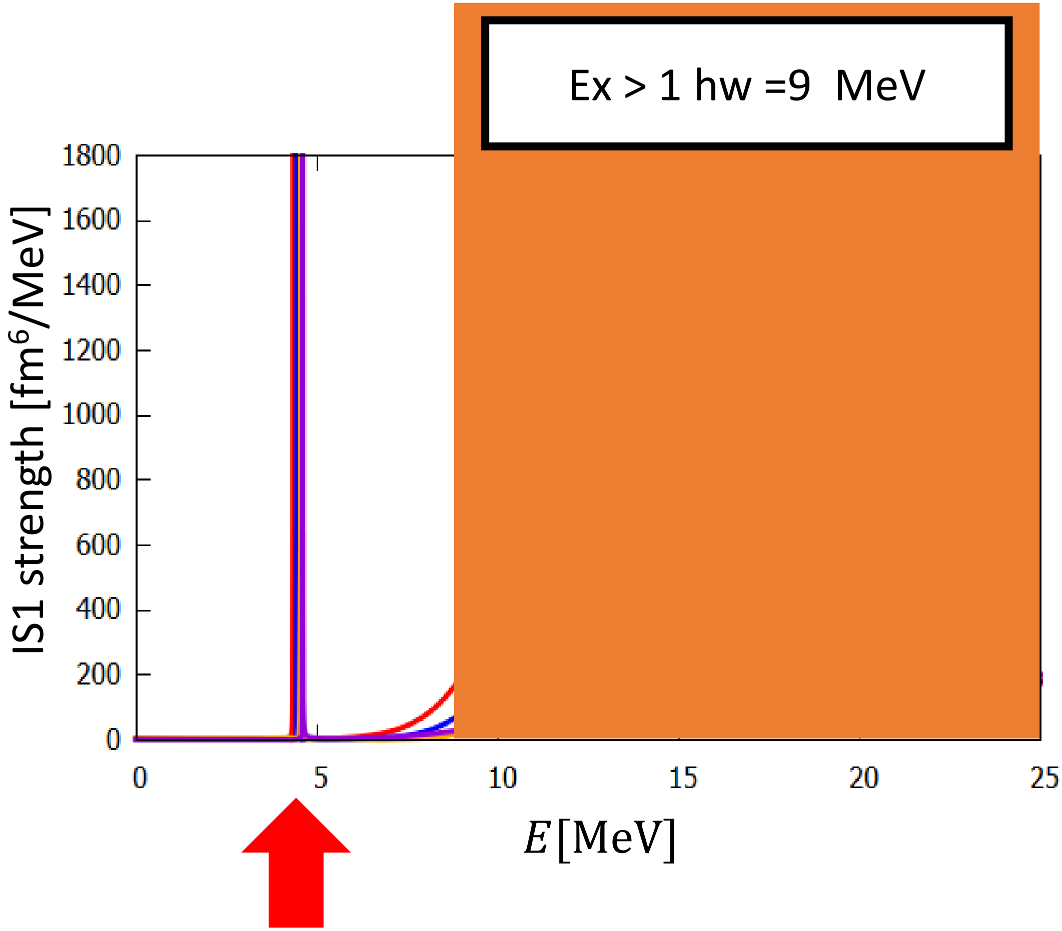


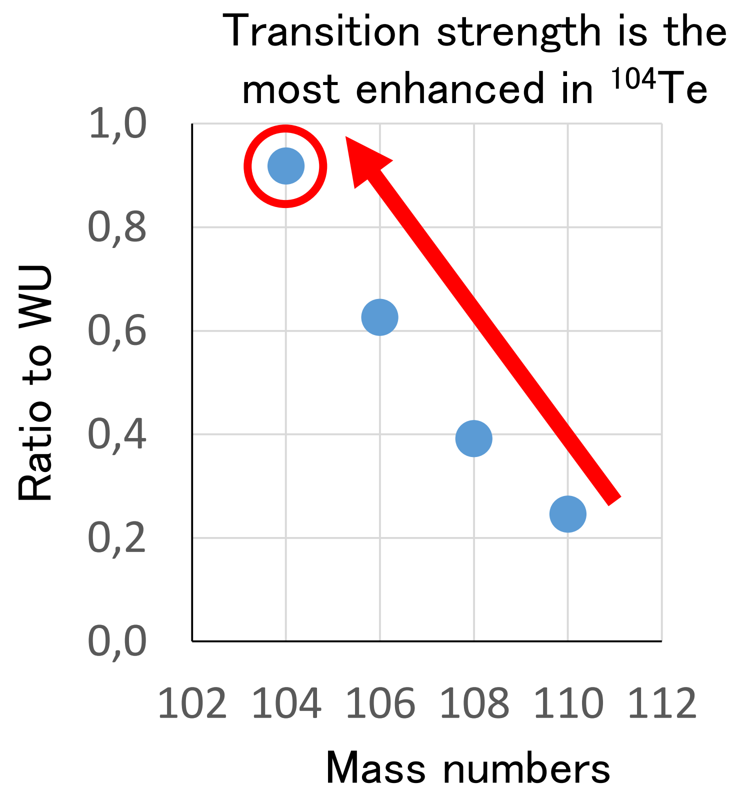


This strength appears around 5MeV which is lower than M.F. model

Fraction of EWSR $\int_0^E \varepsilon S_{\lambda=1}(\varepsilon) d\varepsilon / M_{\text{sum}}^{\lambda=1}$

Result of α + Sn: IS1 strength function





Peak at Ex～5 MeV appear in even Te isotopes

Peak Energy is lower than 1hw = 9 MeV for nucleon excitation

Strength in ^{104}Te is the most enhanced of all other systems

Summary

1. Features of clustering phenomena

① Spatial extension is induced by the development of cluster structure

② Cluster structure appears in low excited region of Ex <15 MeV

2. Importance of IS0 and IS1 transition

IS0 and IS1 are naturally enhanced when cluster structures are developed

⇒ Important probe to identify the cluster deg. of freedom

Important subject: Extension of analyses on IS0 and IS1 to heavier systems

Results

Enhanced IS transition appears at low energy region with EWSR fraction of 25 % for IS0 and 6 % for IS1 (α + ^{40}Ca, α + ^{100}Sn)

⇒ These strengths are a little difficult to explain in a simple M.F. picture

Low-lying and discrete IS strength due to clusters will be valid in heavy systems

Improvement of theory: Ground state correlation, Spreading width for continuum, etc…