Structure and Responses studied by time evolution method

Cluster resonances and PDR

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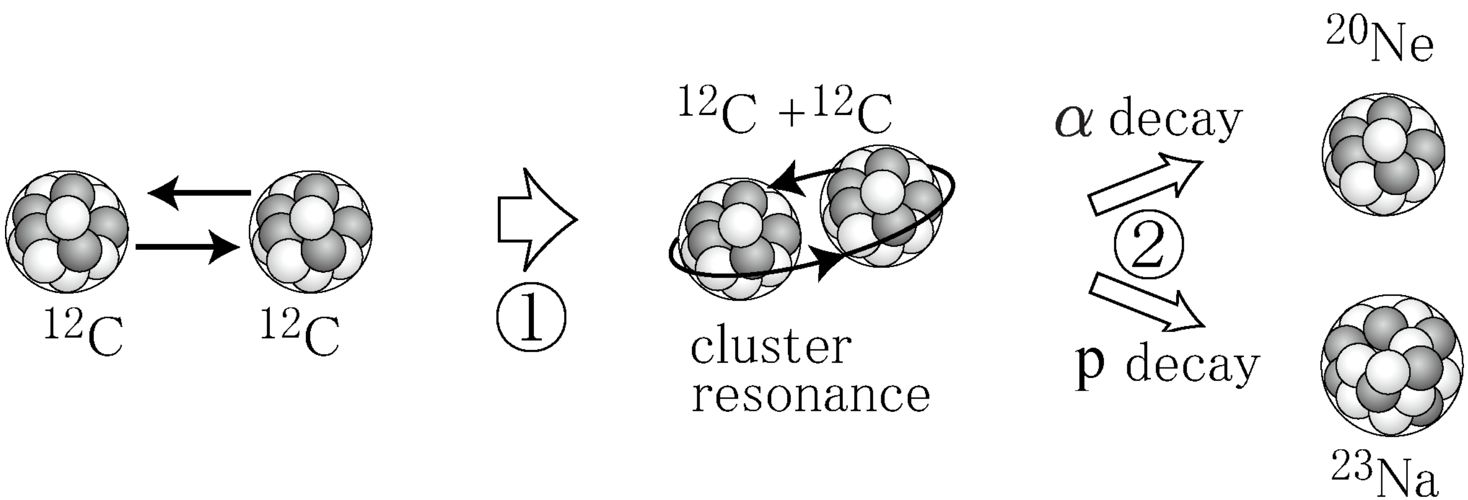
Collaborators: Y. Chiba and Y. Taniguchi

References

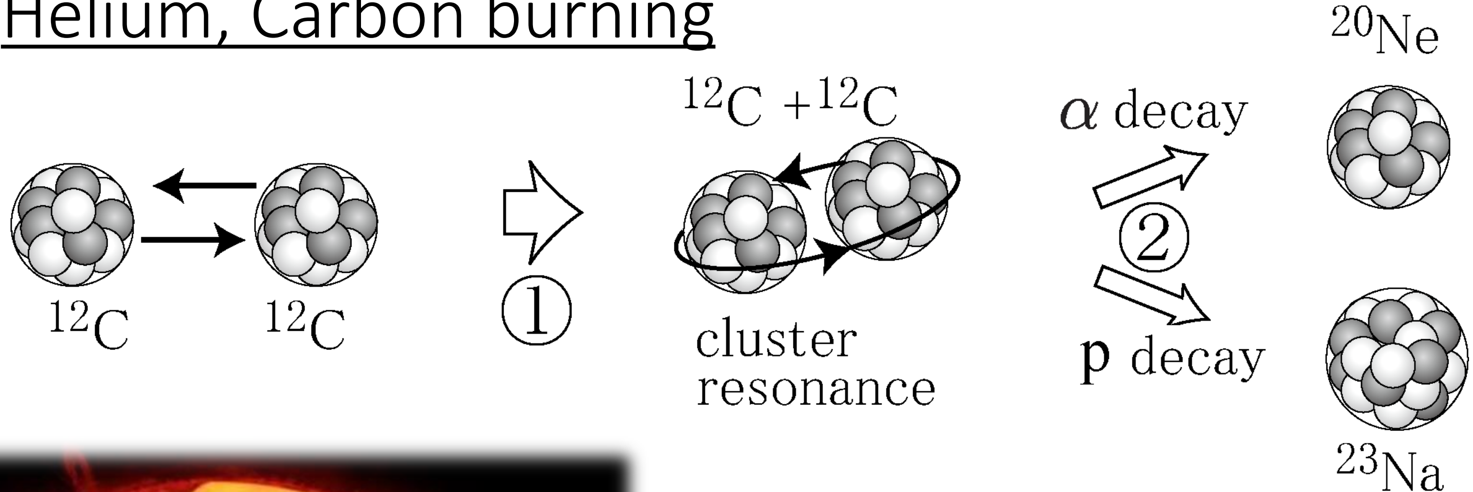
Y. Chiba, and M.K., PRC91, 061302(R) (2015).
Y. Chiba, M.K., and Y. Taniguchi, PRC93, 034319 (2016).
M.K., PRC95, 034331 (2017).
Y. Chiba, M.K., and Y. Taniguchi, PRC95, 044328 (2017).

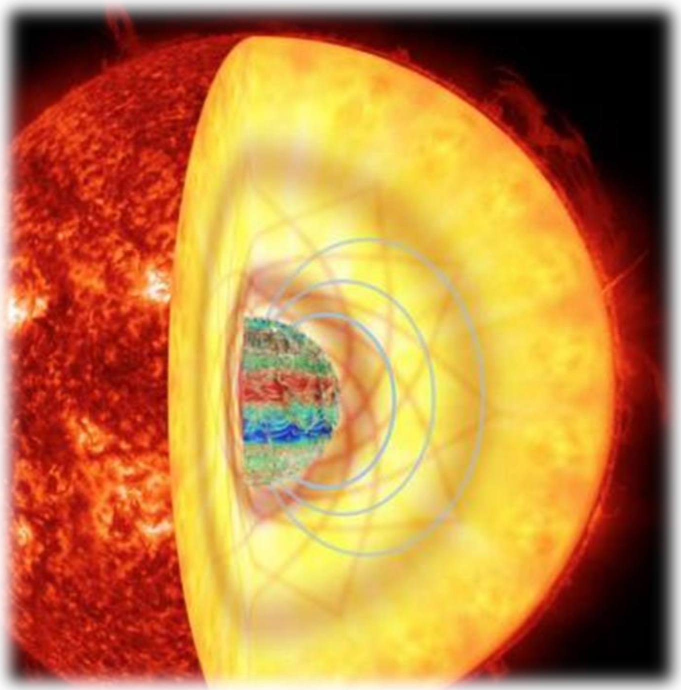
Cluster resonances probed by (α,α') reaction



He, C-burning process and Cluster resonances

Helium, Carbon burning





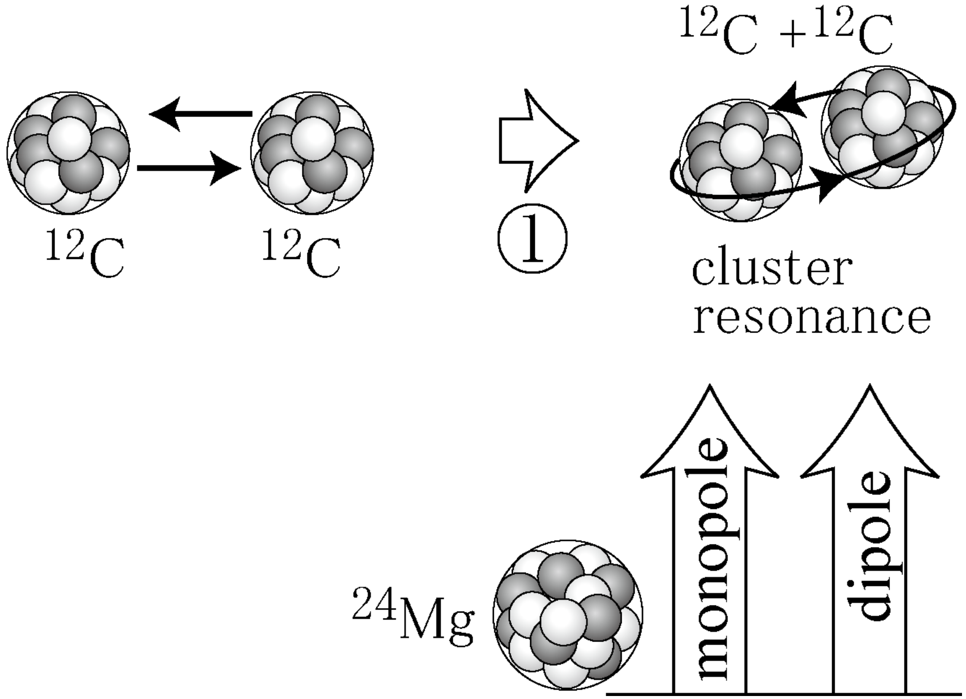
The cluster resonances have strong impact on the stellar processes

① The reaction rate becomes large in order of magnitude, if the cluster resonances locate in the Gamow window

② The final product of the reaction is determined by the decay mode of the cluster resonances

He, C-burning process and Cluster resonances

Helium, Carbon burning



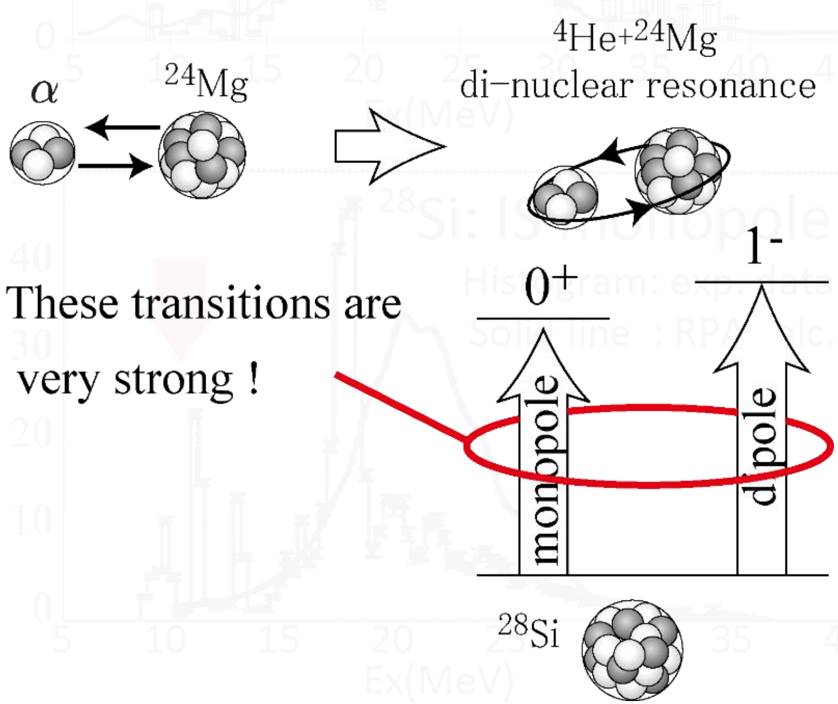
- The big problem is that the cross section is very small
- The IS monopole/dipole transitions strongly populate cluster resonances

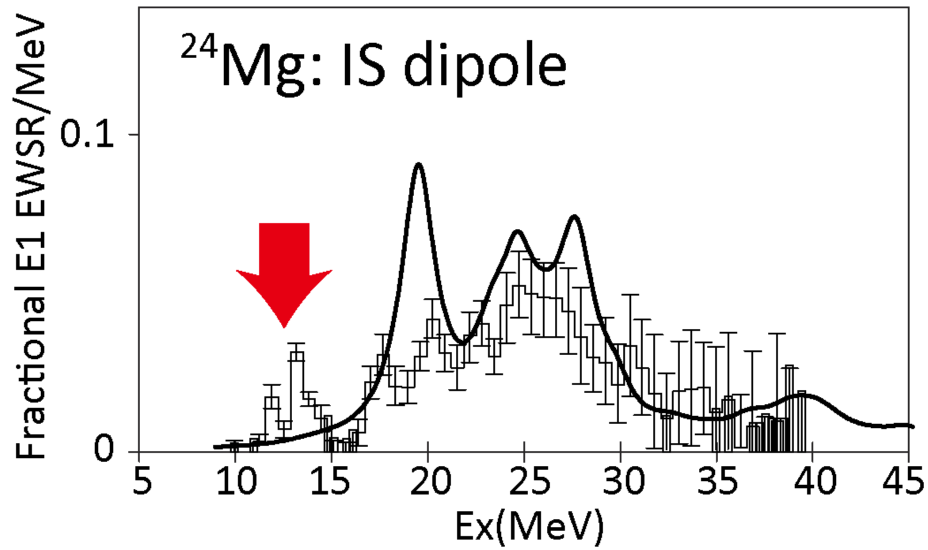
(α,α') reaction (IS monopole/dipole transitions) Is promising probe for the cluster resonances

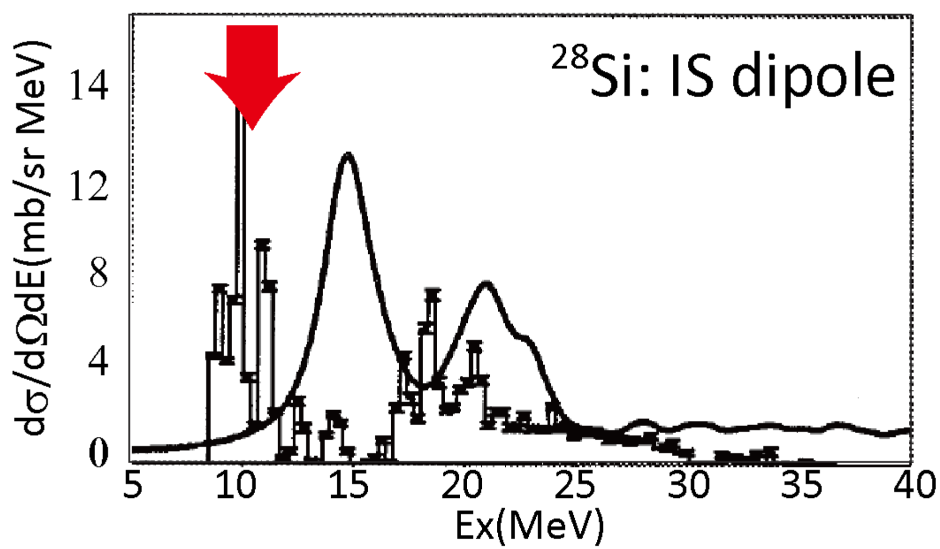
Introduction: IS monopole/dipole responses

X. Chen et al.,PRC80, 014312 (2009). D. H. Young-Blood et al.,PRC65, 034302 (2002).

- They are what we are looking for!
- They are the 0^+ and 1^- resonances having di-nuclear structure such as $\alpha+^{20}$Ne, $\alpha+^{24}$Mg,...







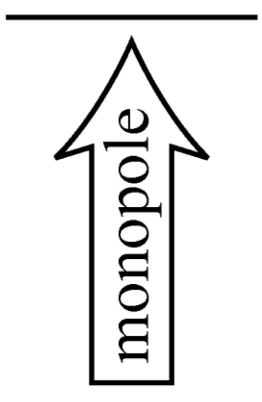
Part2. IS monopole/dipole transitions

T. Yamada et al., PTP120, 1139 (2008)

Monopole transition populates 0+ cluster resonances

$$\mathcal{M}_{\mu}^{IS0} = \sum_{i=1}^{A} (\boldsymbol{r}_i - \boldsymbol{r}_{\rm cm})^2 = \sum_{i \in C_1} \xi_i^2 + \sum_{i \in C_2} \xi_i^2 + \frac{C_1 C_2}{C_1 + C_2} r^2$$

$\Phi(0_{\rm ex}^+)$ cluster state



$\Phi(0_1^+)$ ground state
(harmonic oscillator)

Cluster estimate (analytical)

$$M^{IS0} = \langle \Phi(0_{\rm ex}^+) | \mathcal{M}^{IS0} | \Phi(0_1^+) \rangle$$
$$= f_{N_0+2} \sqrt{\frac{\mu_{N_0}}{\mu_{N_0+2}}} \langle R_{N_0 0} | r^2 | R_{N_0+2 0} \rangle$$
$$\simeq 5.5\ \mathrm{fm}^2 \quad (\text{for } ^{20}\mathrm{Ne})$$

Single-particle estimate

$$M_{WU}^{IS0} = \frac{3}{5}(1.2 A^{1/3})^2 \simeq 6.4\ \mathrm{fm}^2 \ (\text{for } ^{20}\mathrm{Ne})$$

Part2. IS monopole/dipole transitions

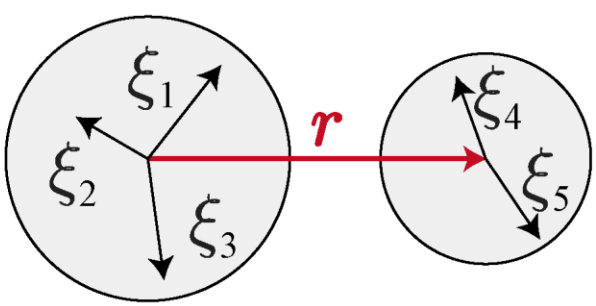
Dipole transition populates 1⁻ cluster resonances

Y. Chiba, M.K. and Y. Taniguchi, PRC93, 034319 (2016)

$$\mathcal{M}^{IS1}_{\mu} = \sum_{i=1}^{A} (\boldsymbol{r}_i - \boldsymbol{r}_{\rm cm})^3 Y_{1\mu}(\widehat{r_i - r_{\rm cm}})$$

$$= \frac{5}{3}\left(\frac{C_2}{A}\sum_{i\in C_1}\xi_i^2 - \frac{C_1}{A}\sum_{i\in C_2}\xi_i^2\right)\boldsymbol{r}\boldsymbol{Y}_{\boldsymbol{1\mu}}(\hat{\boldsymbol{r}}) - \frac{C_1C_2(C_1-C_2)}{A^2}\boldsymbol{r}^{\boldsymbol{3}}\boldsymbol{Y}_{\boldsymbol{1\mu}}(\hat{\boldsymbol{r}})$$

$$+\cdots$$



C_1, C_2 : masses of clusters

ξ_i : internal coordinates of clusters

r : relative coordinates of clusters

Part2. IS monopole/dipole transitions

Dipole transition populates 1^- cluster resonances

Y. Chiba, M.K. and Y. Taniguchi, PRC93, 034319 (2016)

Cluster estimate (analytical)

$$M^{IS1} = \langle \Phi(1^-_{\rm ex}) | \mathcal{M}^{IS1} | \Phi(0^+_1) \rangle$$

$$= \sqrt{\frac{3}{4\pi}\frac{C_1C_2}{A}} \Bigg[f_{N_0+1}\sqrt{\frac{\mu_{N_0}}{\mu_{N_0}}}\left\{\frac{5}{3}\left(\langle r^2\rangle_{C_1} - \langle r^2\rangle_{C_2}\right)\langle R_{N_00}|r|R_{N_0+11}\rangle\right.$$

$\Phi(1^-_{\rm ex})$ cluster state

(harmonic oscillator)

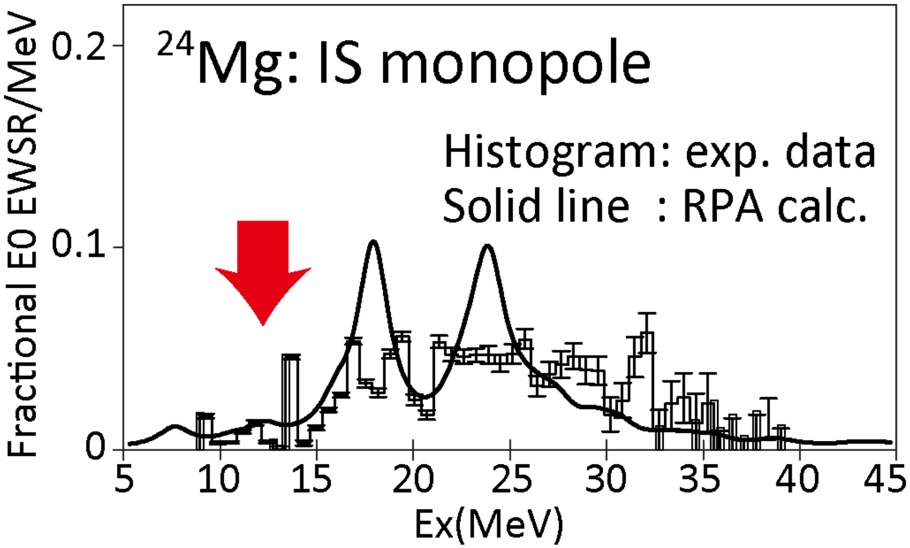
Even if the ground state is an ideal shell model state,
the IS dipole transition to the excited cluster resonances
is as strong as single-particle estimate

Single-particle estimate

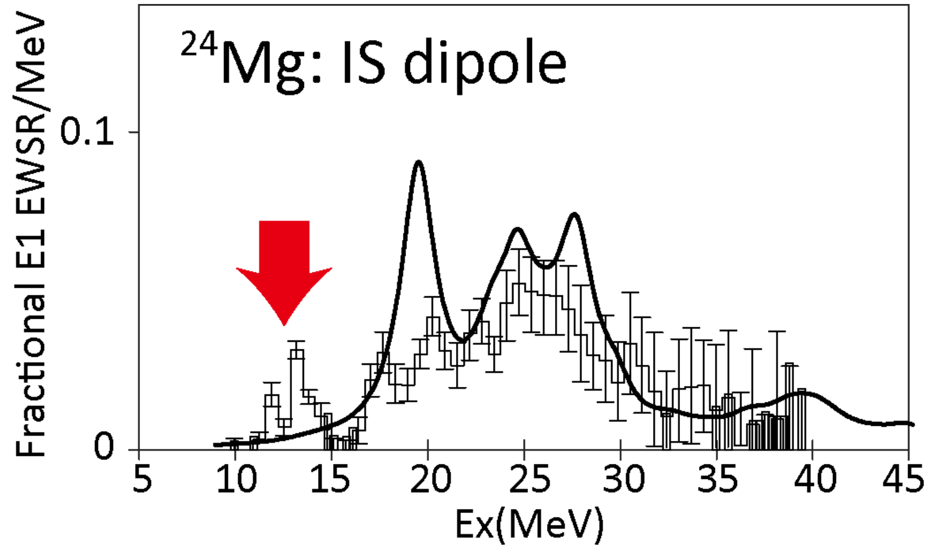
$$M^{IS1}_{WU} = \sqrt{\frac{3}{16\pi}}(1.2A^{1/3})^3 \simeq \mathbf{8.4\ fm^3} \quad \text{(for } ^{20}\text{Ne)}$$

Introduction: IS monopole/dipole responses

X. Chen et al.,PRC80, 014312 (2009).



D. H. Young-Blood et al.,PRC65, 034302 (2002).



We can explain
why narrow resonances exist well below the Giant Resonances

◎ Giant resonance: Stronger than s.p. estimate, E > 15 MeV

◎ Cluster resonance: Comparable with s.p. estimate,
They appear at thresholds (E < 15 MeV)

Real Time Evolution Method

Model: Real-Time evolution method

◎ Hamiltonian $H = \sum_{i=1}^{A} t(i) - t_{cm} + \sum_{i<j}^{A} v_{\rm Gogny}(ij) + \sum_{i<j}^{A} v_{\rm Coulomb}(ij)$

○ Gogny D1S effective interaction

○ Center-of-mass motion is exactly removed ⇒ No spurious modes

◎ Model wave function (time-dependent wave packets)

○ Slater determinant of wave packets for nucleons

$$\Phi_{AMD}(t) = \mathcal{A}\left\{\phi(\boldsymbol{Z}_1(t)), \ldots, \phi(\boldsymbol{Z}_A(t))\right\}$$

$$\phi(\boldsymbol{Z}_i(t)) = \exp\left\{-(\boldsymbol{r} - \boldsymbol{Z}_i(t))^T M(t)(\boldsymbol{r} - \boldsymbol{Z}_i(t))\right\}(\alpha_i(t)\chi_\uparrow + \beta_i(t)\chi_\downarrow)$$

○ Dynamical variables of the model

$\boldsymbol{Z}_i(t)$: Centroids of wave packets (positions and momentums)

$M(t)$: Size parameters of wave packets (3x3 matrix)

$\alpha_i(t)$ $\beta_i(t)$: Spin directions

Model: Real-Time evolution method

◎ Equation of Motion

$$\delta \int dt \frac{\langle \Phi | i\hbar \, d/dt - H | \Phi \rangle}{\langle \Phi | \Phi \rangle} = 0$$

$$\Rightarrow \quad i\hbar \frac{dX_i(t)}{dt} = \sum_j C_{ij}^{-1} \frac{\partial \mathcal{H}}{\partial X_j^*(t)}$$

○ By solving EOM, we obtain time-dependent wf.

◎ The ensemble of the time-dependent wave functions has beautiful nature

○ It has ergodic property

○ It follows quantum statistics (micro canonical ensemble)

J. Schnack and H. Feldmeier, NPA601, 181 (1996).

A. Ono and H. Horiuchi, PRC53, 845 (1996), PRC53, 2341 (1996).

Model: Real-Time evolution method

◎ This means that the superposition of the time-dependent wave functions describes the quantum state very well

○ All possible quantum states will appear after long-time propagation

○ More important states appear more frequently, if the excitation energy is properly chosen

Time dependent wave function must be a good basis for the generator coordinate method (GCM)

$$\Psi_M^{J\pi}(T) = \int_0^T dt \sum_{K=-J}^{J} \hat{P}_{MK}^{J\pi} \, f_K(t)\Phi(\mathbf{Z}_1(t), ..., \mathbf{Z}_N(t))$$

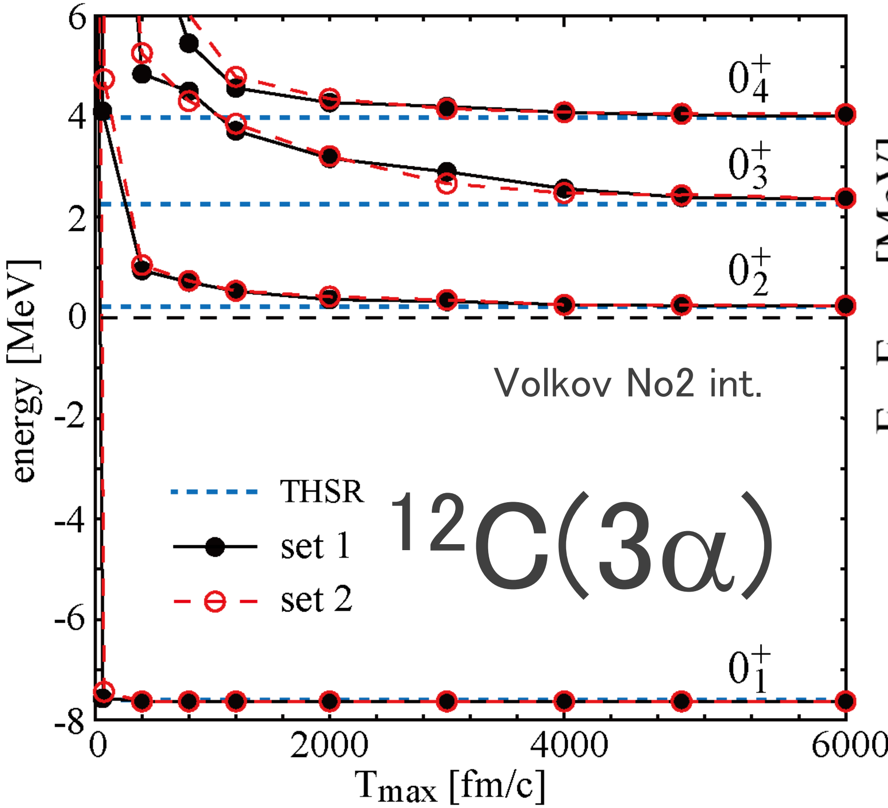
○ The result should be converged after the long-time propagation

○ The results should not depend on the initial condition

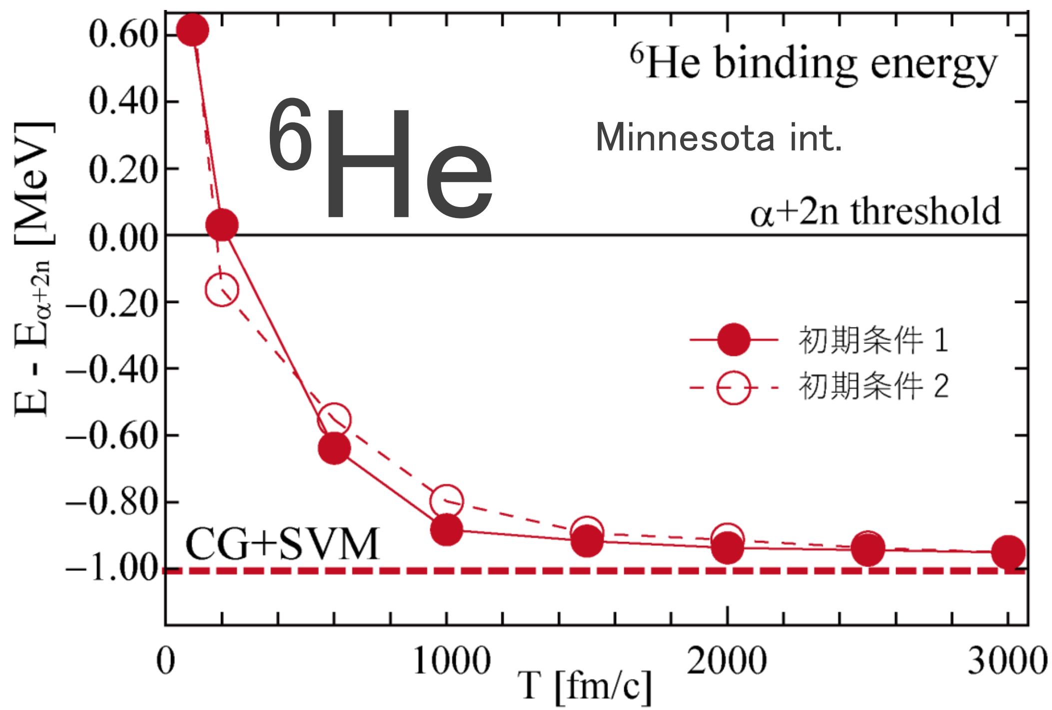
Model: Real-Time evolution method

◎ Benchmark calculations for ^{12}C and ^{6}He

R. Imai, T. Tada and M.K., arXiv:1802.03523



M.K. in preparation

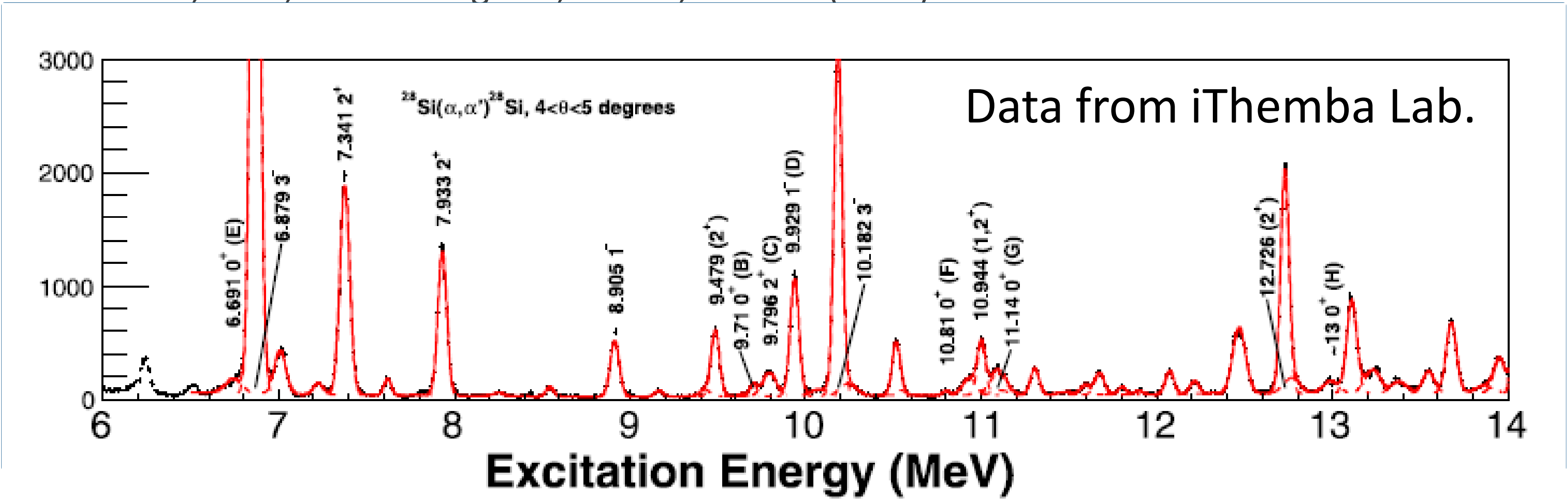


◎ A long time propagation brings us to the very accurate description of quantum many-body system

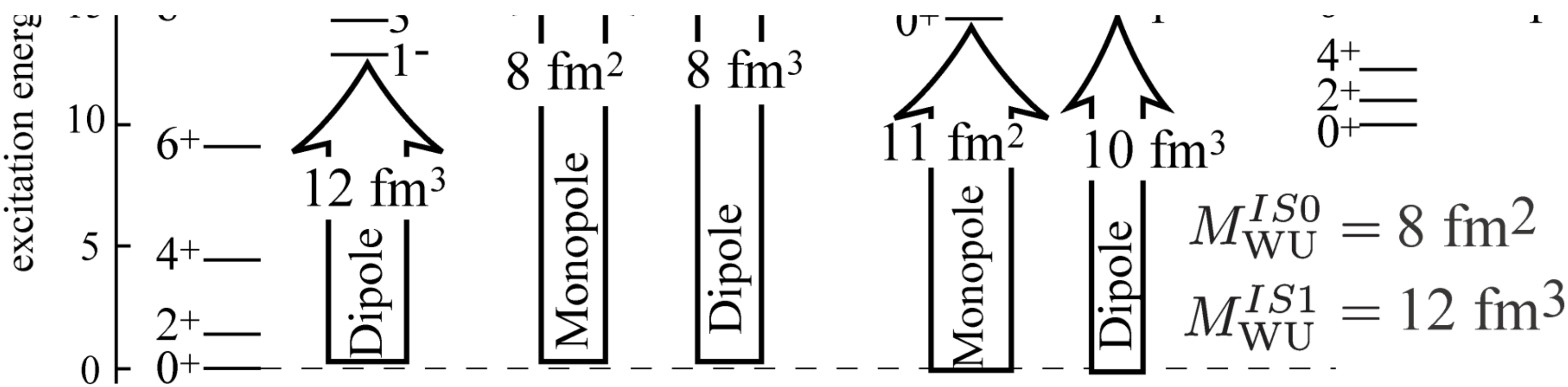
3.2 Result for ^{28}Si (α+^{24}Mg and ^{8}Be+^{20}Ne resonances)

Y. Taniguchi, Y. Kanada-En'yo and M.K. PRC80, 044316 (2009).

Y. Chiba, M.K., and Y. Taniguchi, PRC95, 044328 (2017)



P. Adsley, et al., PRC95, 024319 (2017).

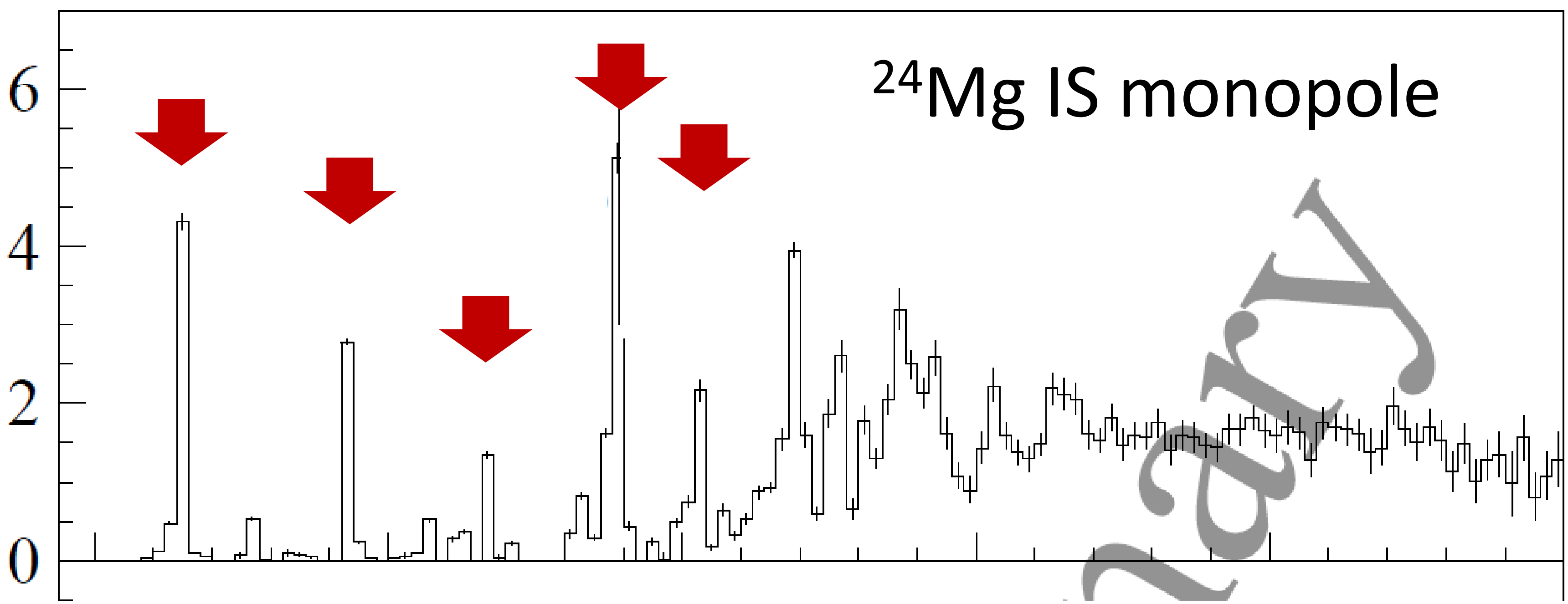


3.2 Result for ^{24}Mg (^{12}C+^{12}C and α+^{20}Ne resonances)

High resolution data from RCNP(Osaka)

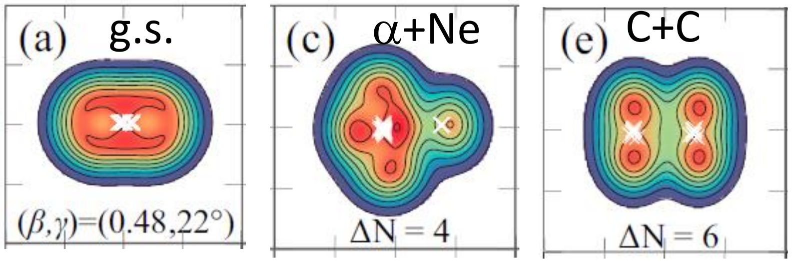
Strong peaks appear well blow the Giant resonance

T. Kawabata, Reported at the last Cluster conf. in 2012

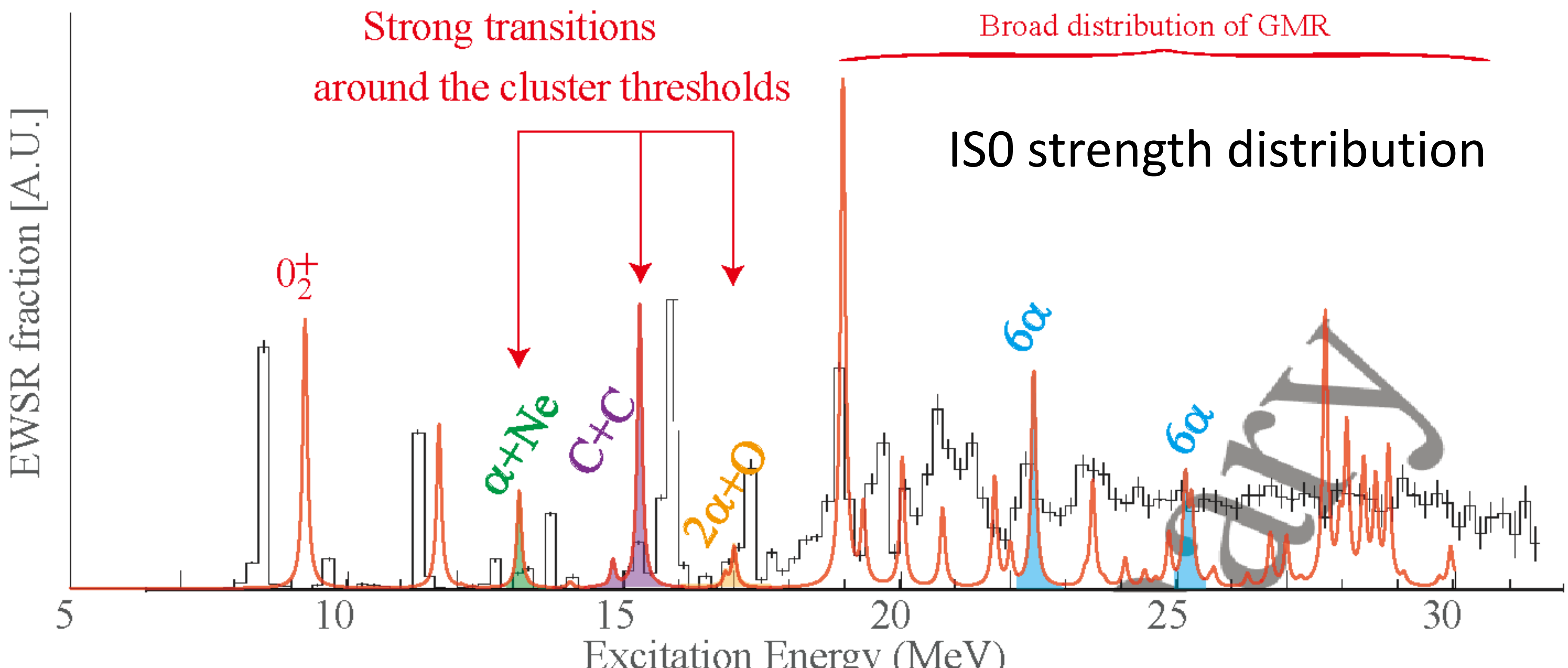


3.2 Result for ^{24}Mg (^{12}C+^{12}C and α+^{20}Ne resonances)

IS monopole/dipole transitions of ^{24}Mg strongly populate α+^{20}Ne/^{12}C+^{12}C resonances



M.K, R. Yoshida and M. Isaka, PTP127, 287 (2012)
Y. Chiba, and M.K., PRC91, 061302(R) (2015)



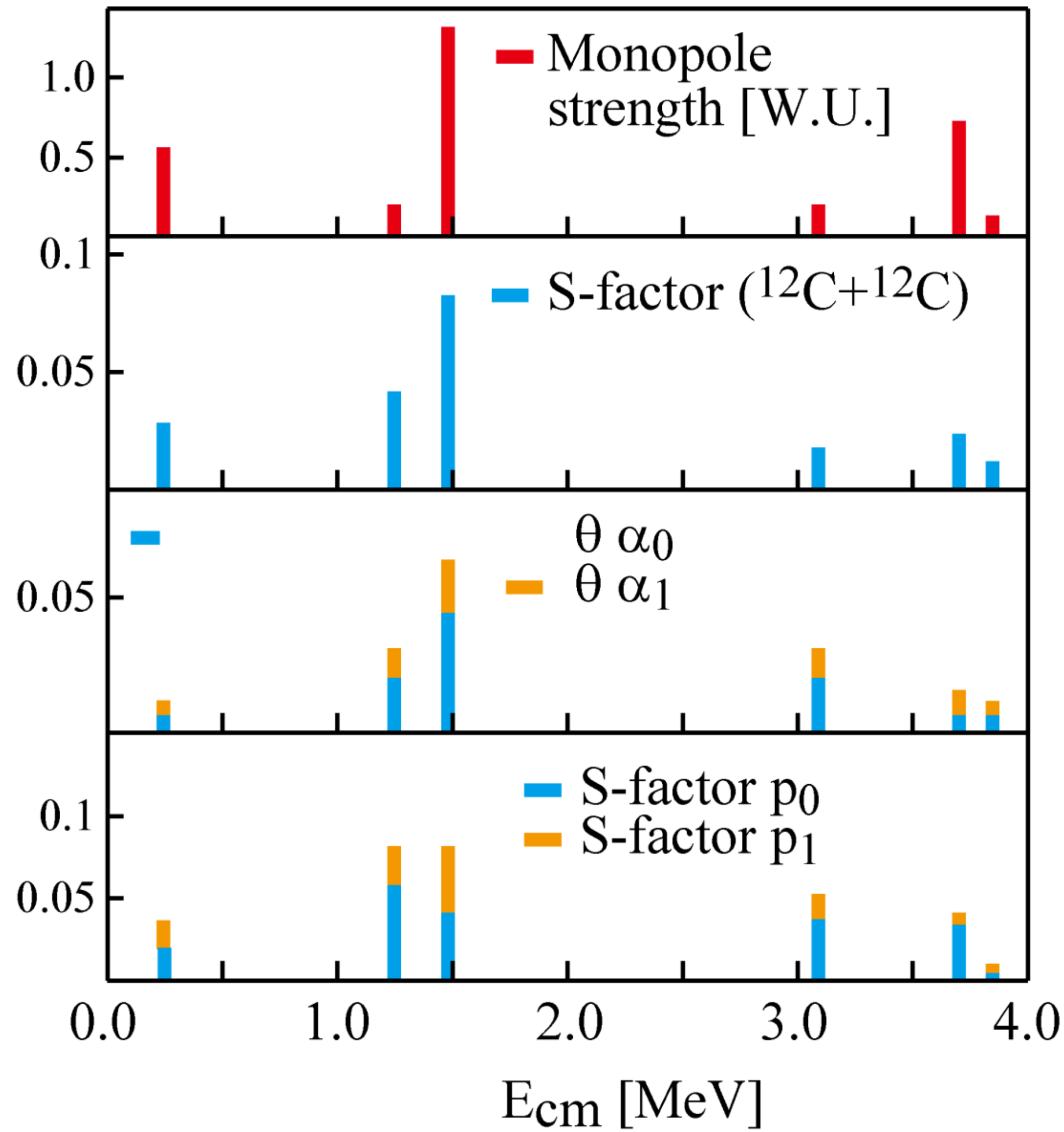
Resonance parameters

- A couple of resonances in the Gamow window
- They have monopole transition strenghts
- They have S-factors in the C+C, α+Ne, p+Na channels

  ⇒ $^{12}C(^{12}C, \alpha)^{20}Ne$

  $^{12}C(^{12}C, p)^{23}Na$

0^+ resonances



What we can describe and learn ?

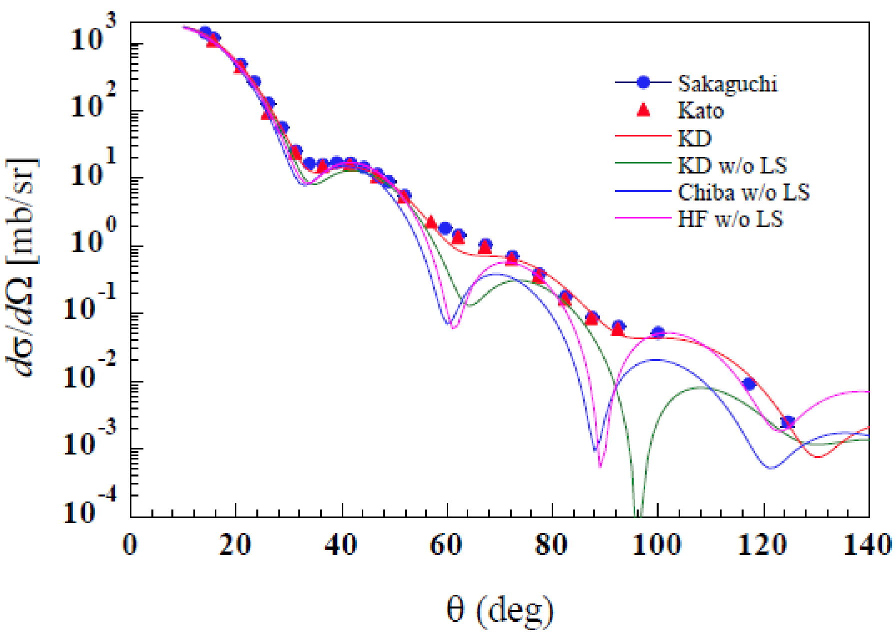
○ Partial cross sections for (p,p') and (α,α')

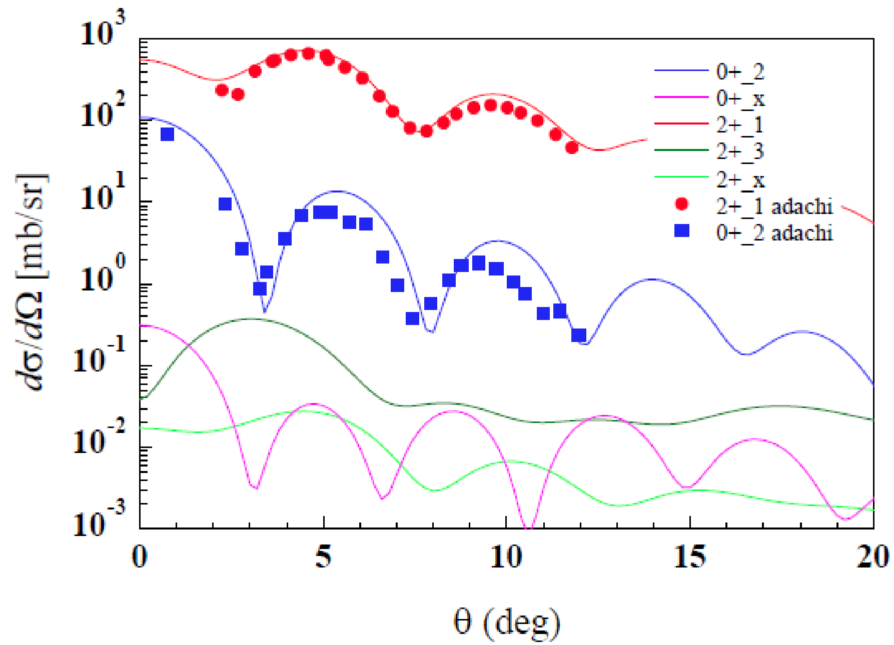
(p,p) reaction 65MeV

H. Sakaguchi et al.,
Prog.Part.Nucl.Phys. 97, 1 (2017)

(α,α') reaction 386MeV

S. Adachi et al.,
PRC97, 014601 (2018)

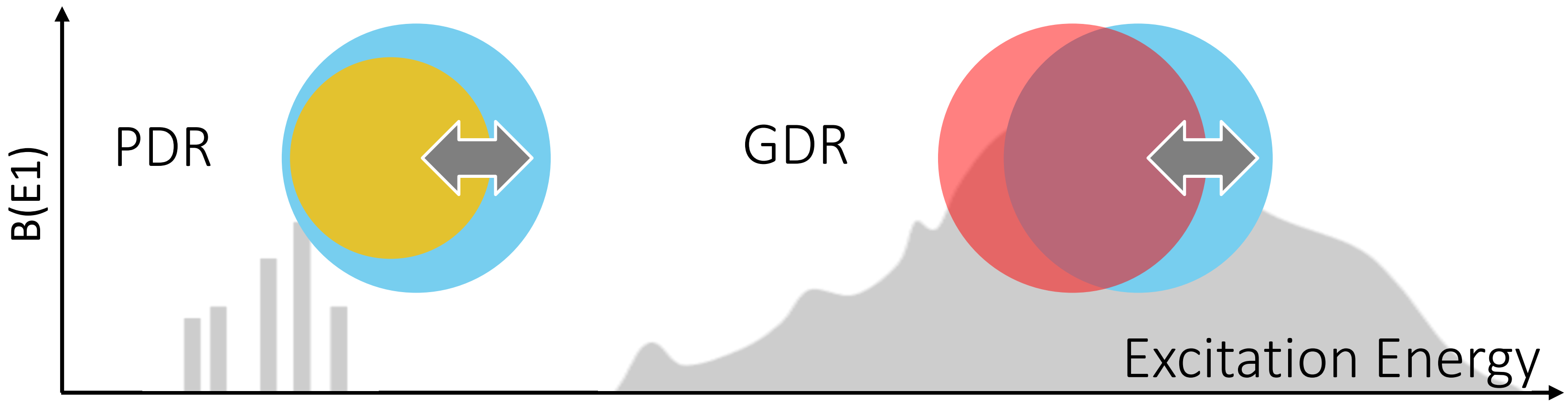




◎ A realistic calculation by the real time evolution method showed many resonances and their properties

Application to PDR

Introduction: ^{26}Ne Puzzle



◎ Pygmy Dipole Resonances (PDR)

Low-lying E1 strength which locates well below the GDR

◎ Scientific Impact

- A new excitation mode in which the core and neutron-skin oscillates in the opposite phase

  K. Ikeda, INS Report JHP-7 (1988). T. Nomura, S. Kubono, INS Report JHP-7 (1988).

- PDR can have the strong impact on the r-process abundance
- PDR can be closely related to the neutron star matter properties

  A. Carbone PRC 81, 041301(R) (2010). S. Goriely, PLB436, 10 (1998).

Introduction: ^{26}Ne Puzzle

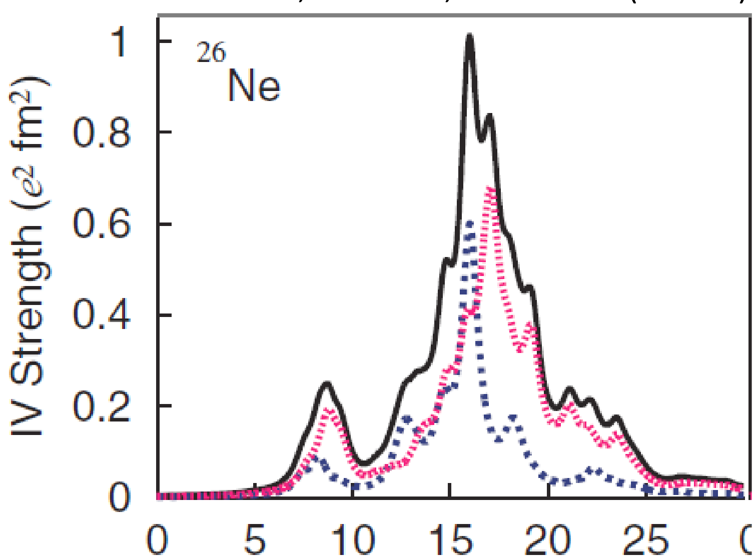
- ◎ PDR of ^{26}Ne have been studied in detail
- ◎ Reasonable agreement between theory and experiment for the energy and strengths of PDR.

Theory: QRPAs

Energy: E_x = 6 - 10 MeV

Strength: 5 - 10 % of TRK sum

K. Yoshida et al., PRC78, 014305 (2008).

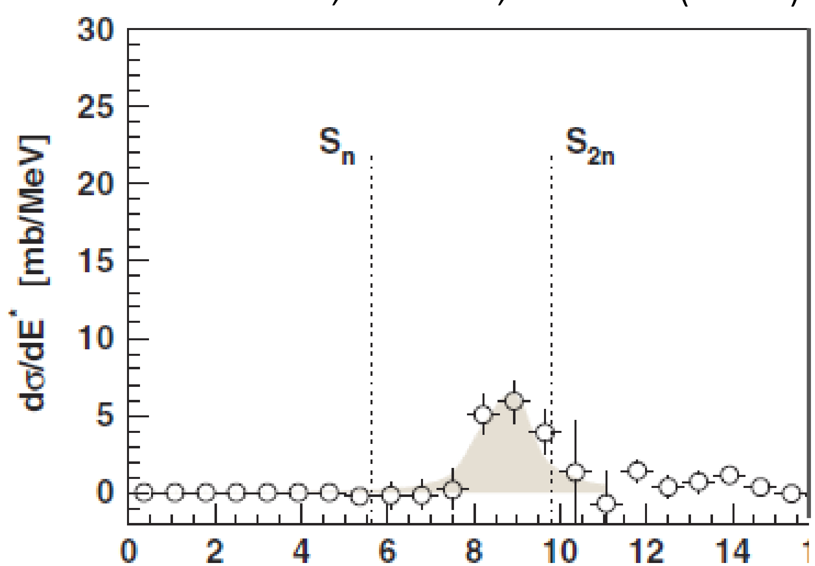


Experiment@RIKEN

Energy: E_x = 9 MeV

Strength: 5 % of TRK sum

J. Gibelin et al., PRL101, 212503 (2008)



Introduction: ^{26}Ne Puzzle

◎ Unexpected decay pattern was observed

Theory: QRPAs

Leading configurations of PDR

$\nu(s_{1/2})^{-1}(p_{3/2})^{1}$ and $\nu(s_{1/2})^{-1}(p_{1/2})^{1}$

^{26}Ne(N=16) ^{25}Ne(N=15)

Experiment: RIKEN

PDR decays to ^{25}Ne*

not to ^{25}Ne(g.s.)

PDR

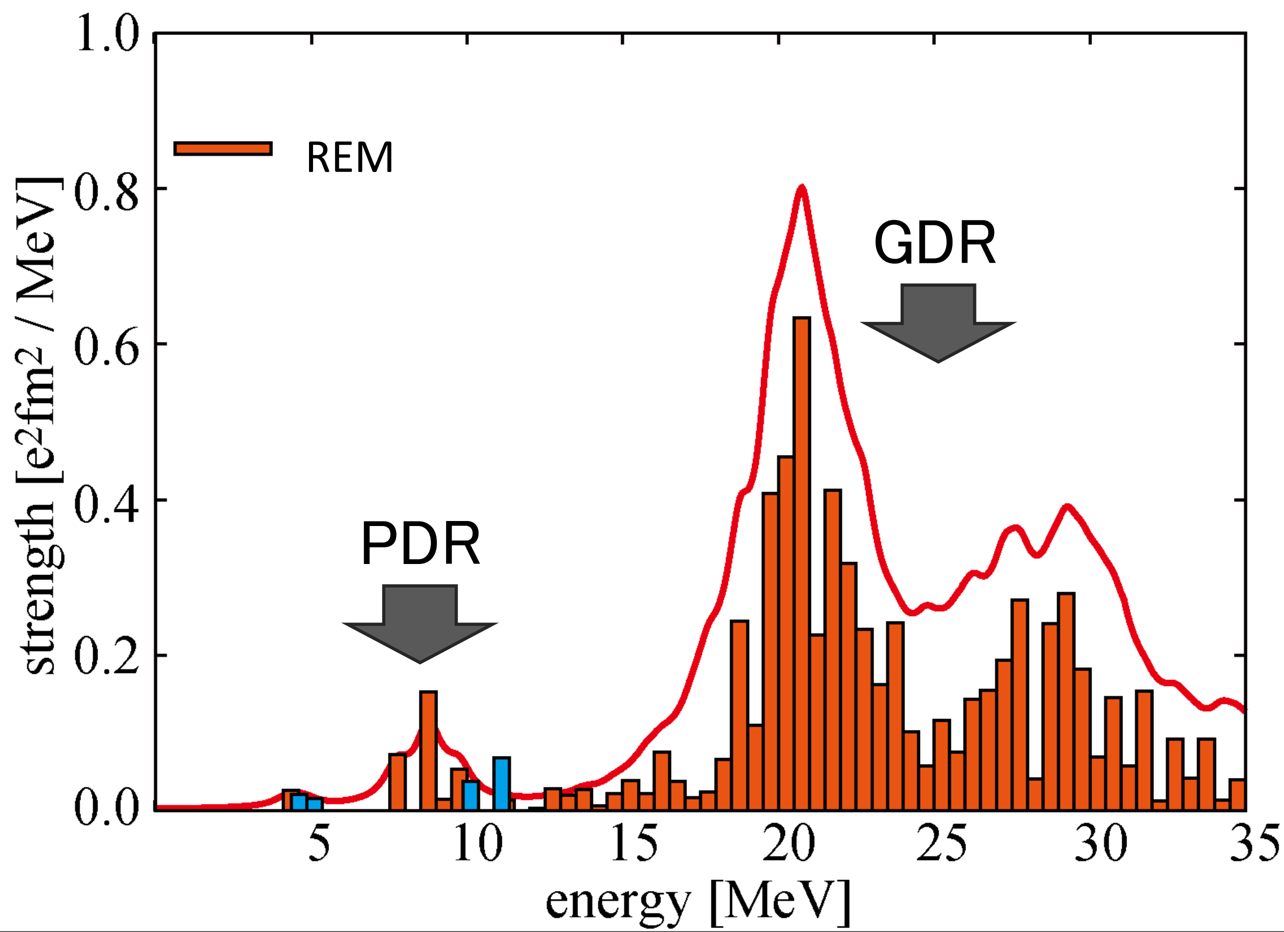
◎ ^{26}Ne Puzzle

- ○ Energy and strength are reasonably described by QRPA
- ○ Unexpected decay pattern of PDR

◎ Decay to ^{25}Ne* implies the core excitation of PDR

⇒ "Real-time evolution method" has been applied

Results: E1 strengths

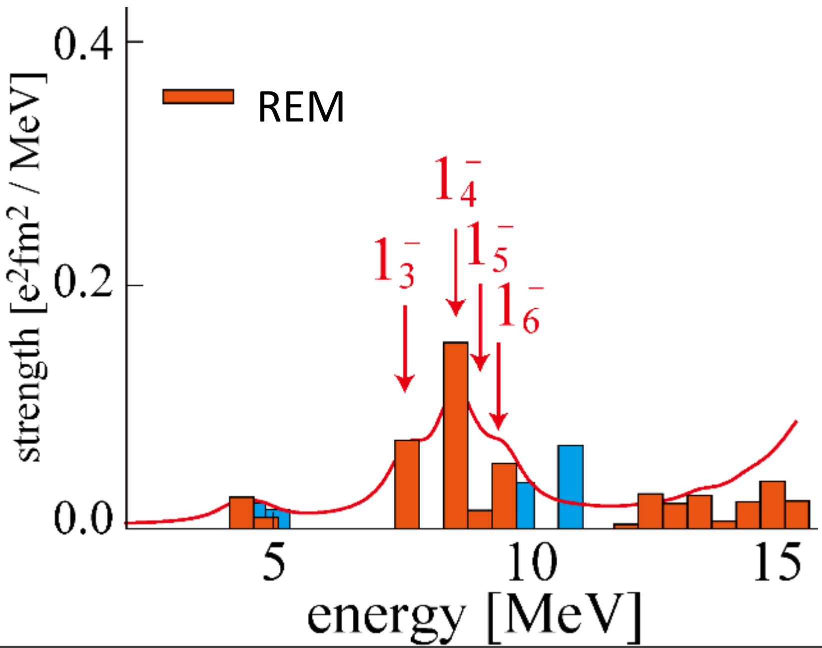


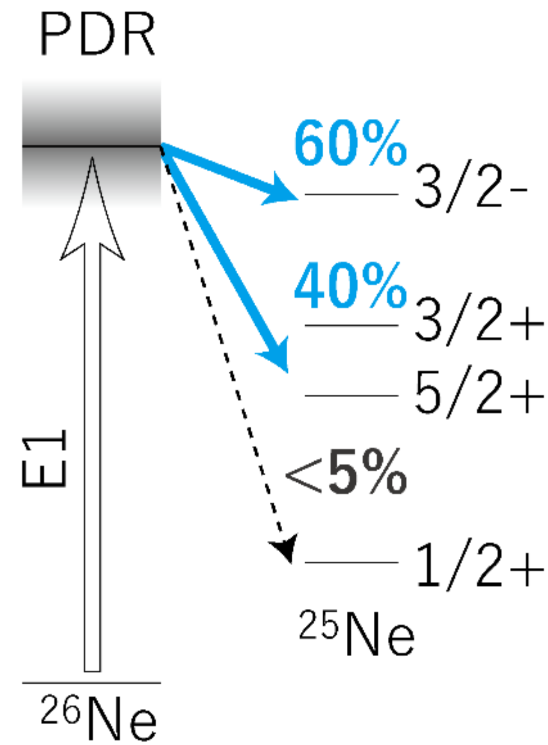
◎ PDR strength and energy are consistent with exp.

and also consistent with QPRAs

Results: Structure of PDR

◎ S-factors of PDR





◎ Not only the energy & strength, but also the structure (core excitation) looks consistent with exp.

◎ Everything look fine, but why the core is excited in the PDR?

Discussion: Isoscalar component of PDR

Question : Why PDR is dominated by the core excitation ?

① PDR is dominated by neutron excitation

⇒ It is not an eigenmode of isospin, but an admixture of IV and IS

$$|\mathrm{PDR}\rangle \simeq \underbrace{\mathcal{M}(E1)\,|\mathrm{g.s.}\rangle}_{\text{isovector}} + \underbrace{\mathcal{M}(IS1)\,|\mathrm{g.s.}\rangle}_{\text{isoscalar}}$$

② Isoscalar component induces strong core excitation

$$\mathcal{M}(IS1) = \sum_i r_i^3 Y_{1\mu}(\hat{r}_i) = \sum_{i\in\mathrm{core}} x_i^3 Y_{1\mu}(\hat{x}_i) - \frac{(A-1)(A-2)}{A^2} R^3 Y_{1\mu}(\hat{R})$$

◎ If this conjecture is true,

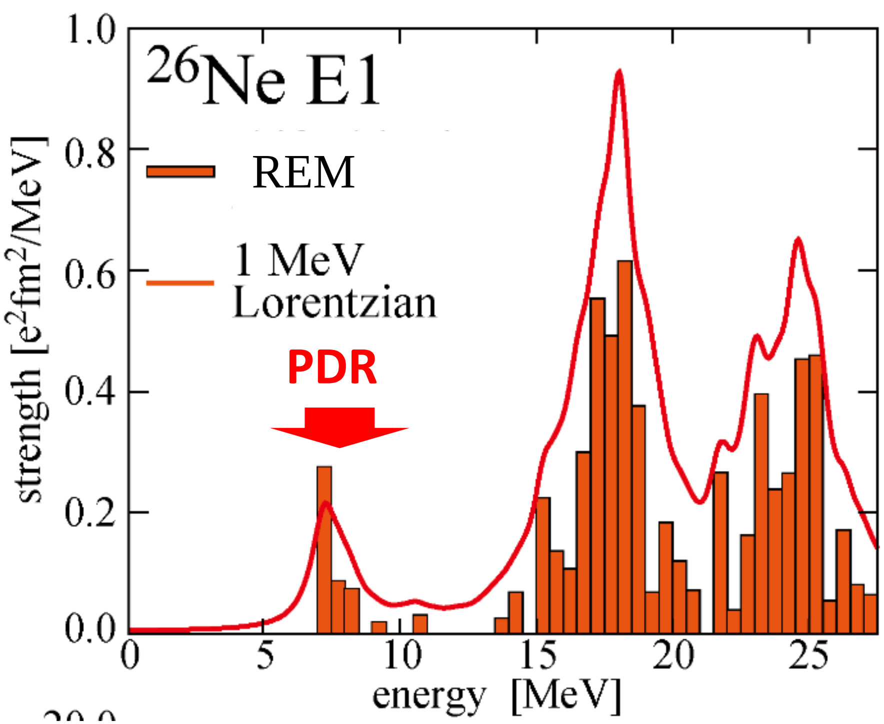
- ○ PDR should have IS dipole strength
- ○ Ne isotopes in the Island of Inversion should have large core excited components

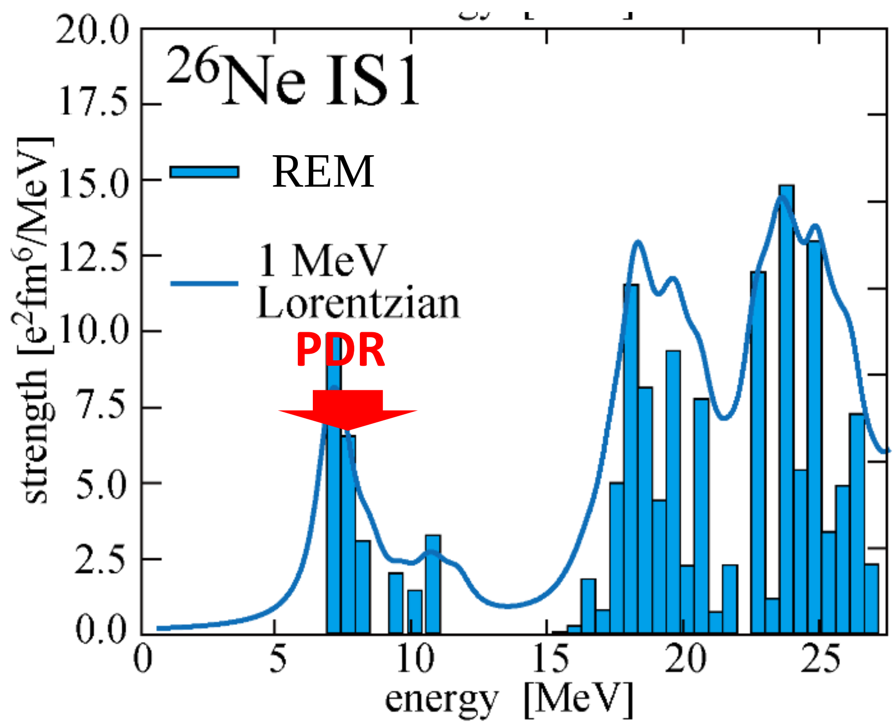
Discussion: Isoscalar component of PDR

① PDR is admixture of IV and is components

$$|\mathrm{PDR}\rangle \simeq \mathcal{M}(E1)\,|\mathrm{g.s.}\rangle + \mathcal{M}(IS1)\,|\mathrm{g.s.}\rangle$$

⇒ PDR should have strong IS dipole strengths
as well as IV strengths



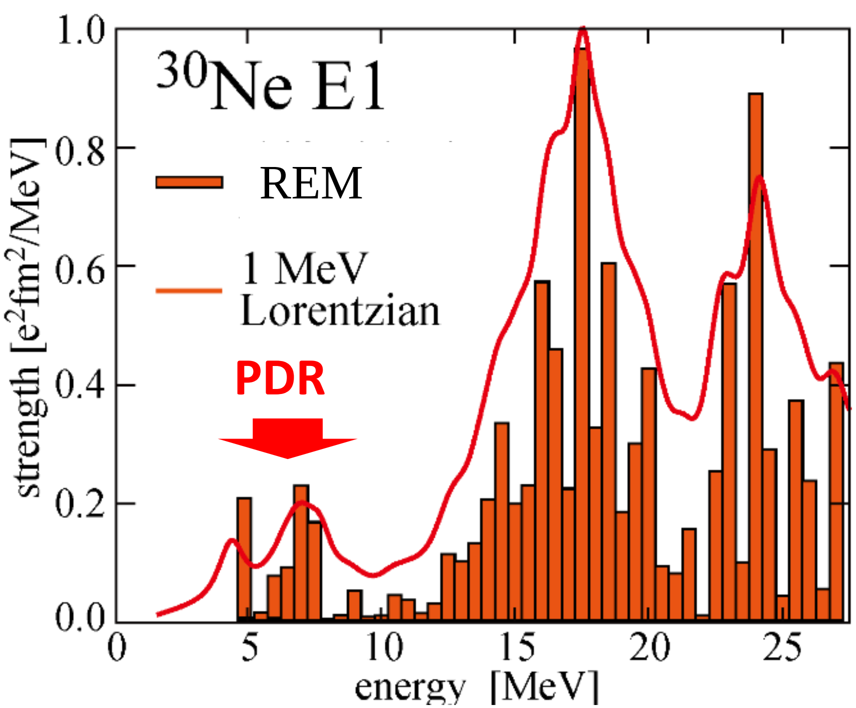


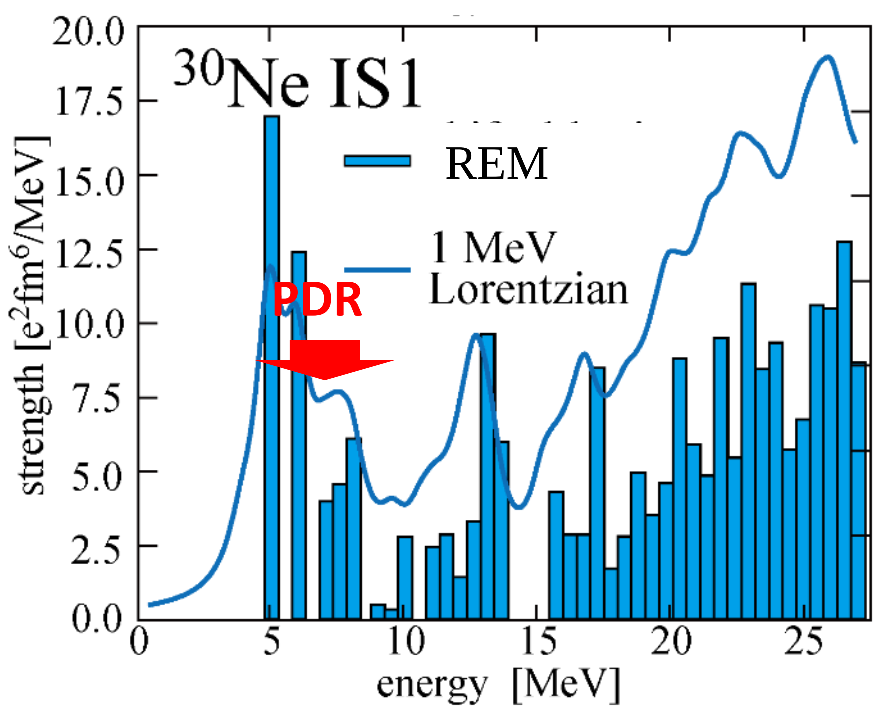
Discussion: Isoscalar component of PDR

② IS component induces quadrupole core excitation

$$\mathcal{M}(IS1) \simeq \frac{4\sqrt{2\pi}}{3A}\left[\left(\sum_{i\in\mathrm{core}} x_i^2 Y_2(\hat{x}_i)\right)\otimes RY_1(\hat{R})\right]_{1\mu}$$

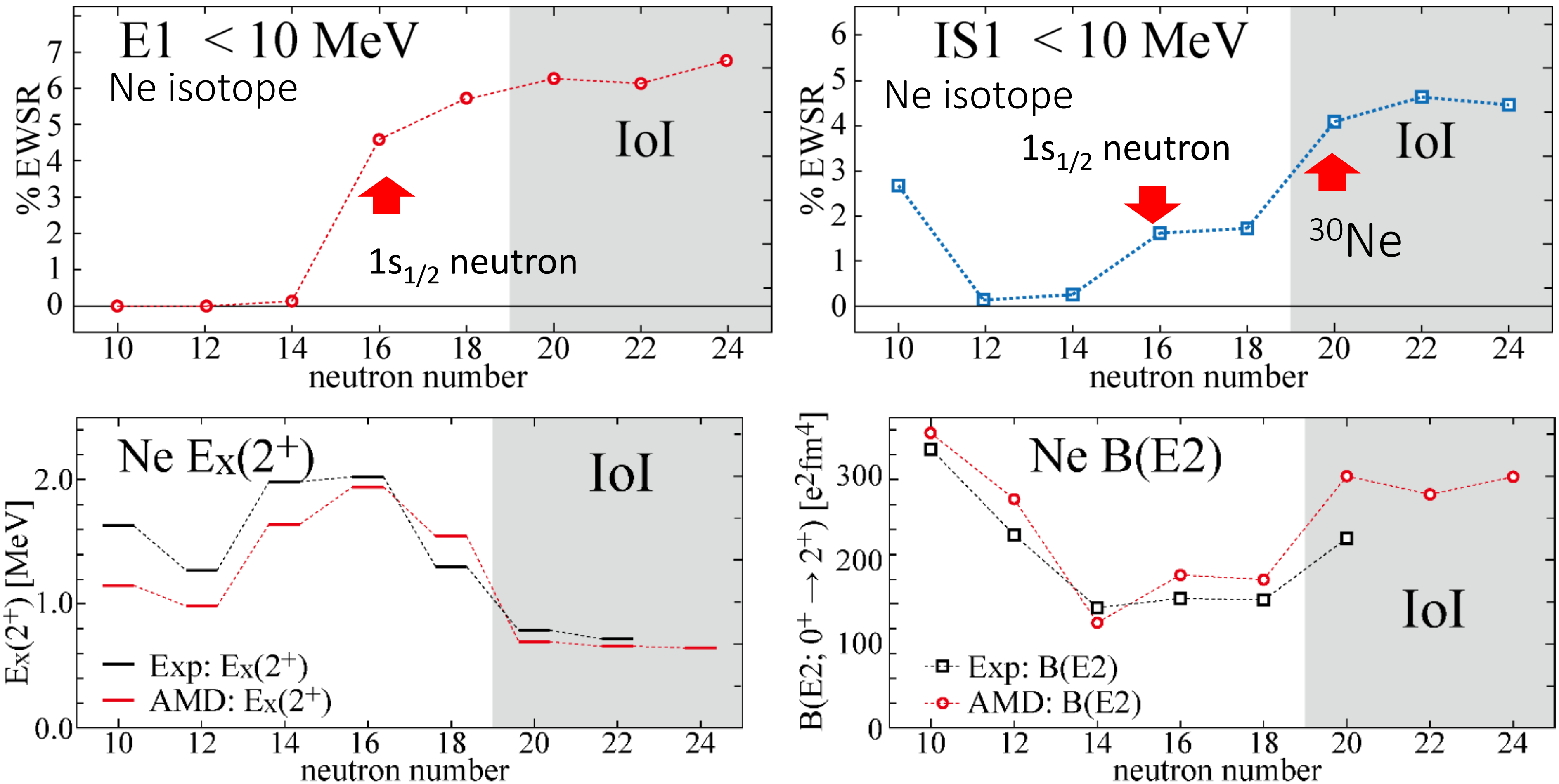
⇒ The isoscalar component should be enhanced in the Island of Inversion





Discussion: Isoscalar component of PDR

◎ IS dipole strength is correlated the quadrupole collectivity



- Coupling of dipole and octupole modes in neutron-rich deformed nuclei, K. Yoshida, PRC80, 044324 (2009)

Summary

○ (α,α') reaction is a promising probe for the cluster resonances

◎ An analytical estimate of the transition matrix showed that IS monopole/dipole transitions populates cluster resonances

◎ A realistic calculation by the real time evolution method showed many resonances and their properties

◎ More detailed analysis will pin down the resonance parameters

○ PDR; its IS component and core excitation

◎ Unique decay pattern of 26Ne PDR has been discussed

◎ The importance of the IS dipole mode has been emphasized

- Importance of pn interaction, I.Hamamoto and H.Sagawa, PRC96, 064312 (2017).

◎ Enhancement in neutron-rich Ne isotopes was numerically confirmed