Nuclear Clustering probed by Electron scattering

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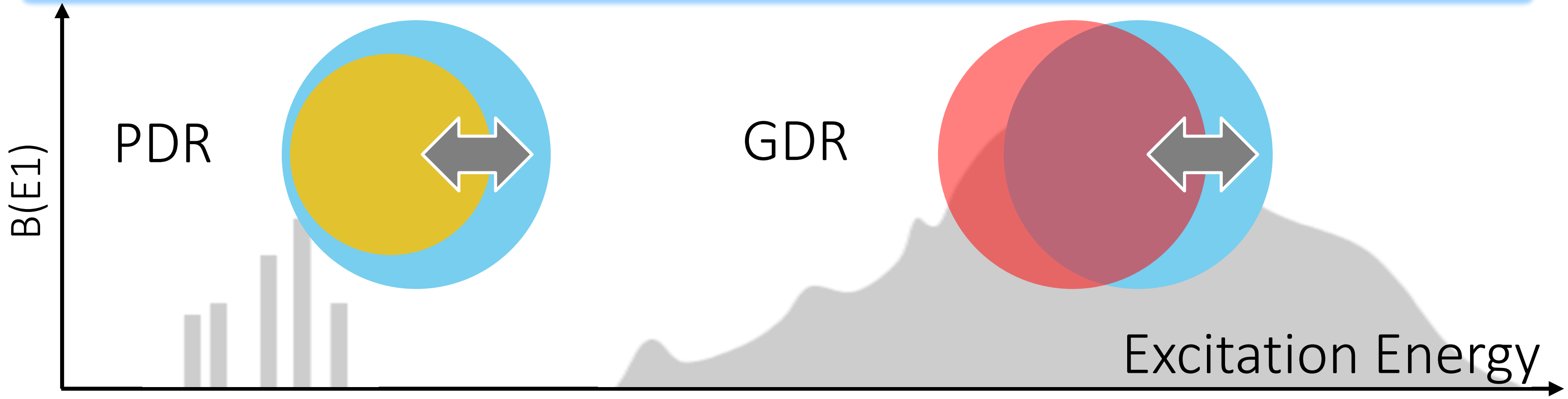
M. Kimura, T. Suhara and Y. Kanada-En'yo, EPJA 52, 373 (2016).

PART I : Structure and decay of
pygmy dipole resonances

PART II: Clusters in the ground states and
growth of charge radii toward neutron drip-line

Introduction: ^{26}Ne Puzzle



◎ Pygmy Dipole Resonances (PDR)

Low-lying E1 strength which locates well below the GDR

◎ Great 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).
- PDR can have the strong impact on the r-process abundance
  S. Goriely, PLB436, 10 (1998).
- PDR can be closely related to the neutron star matter properties
  A. Carbone PRC 81, 041301(R) (2010).

Introduction: ^{26}Ne Puzzle

◎ PDR of ^{26}Ne have been studied in detail

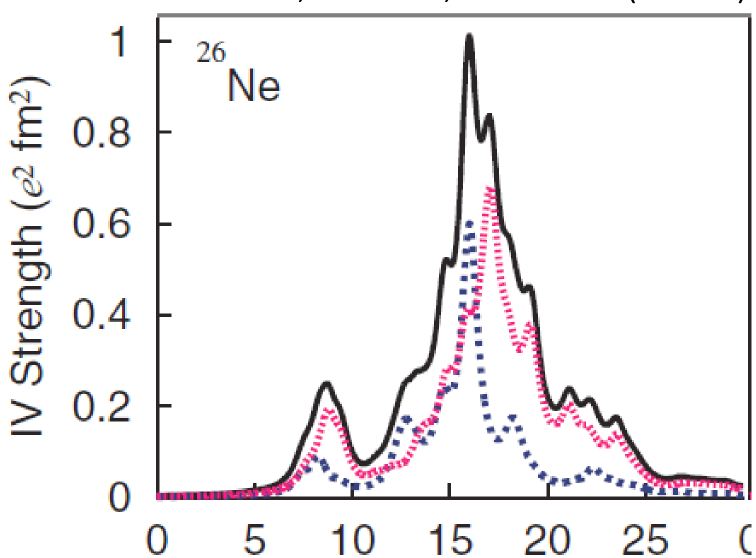
◎ Reasonable agreement between theory and experiment for the energy and strengths of PDR.

Theory: QRPAs

Energy: E_x = 6 - 10 MeV

Strength: 5 - 10 % of TRK sum

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

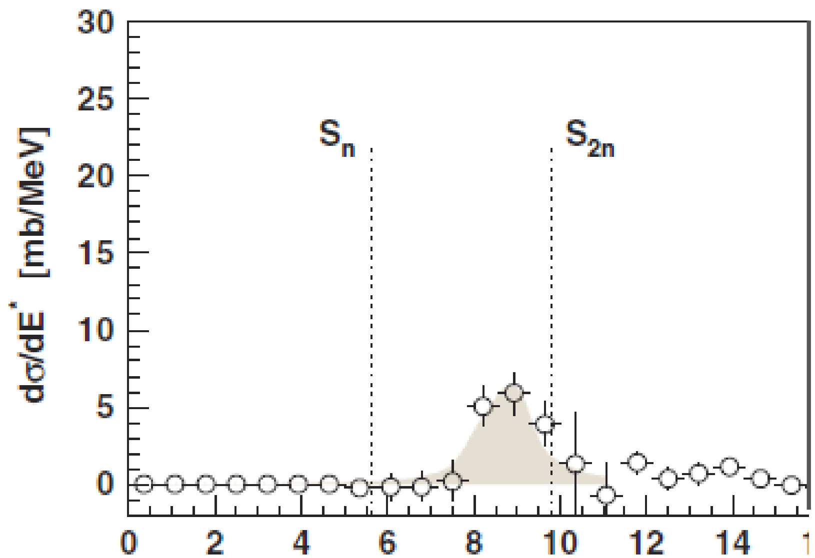


Experiment@RIKEN

Energy: E_x = 9 MeV

Strength: 5 % of TRK sum

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



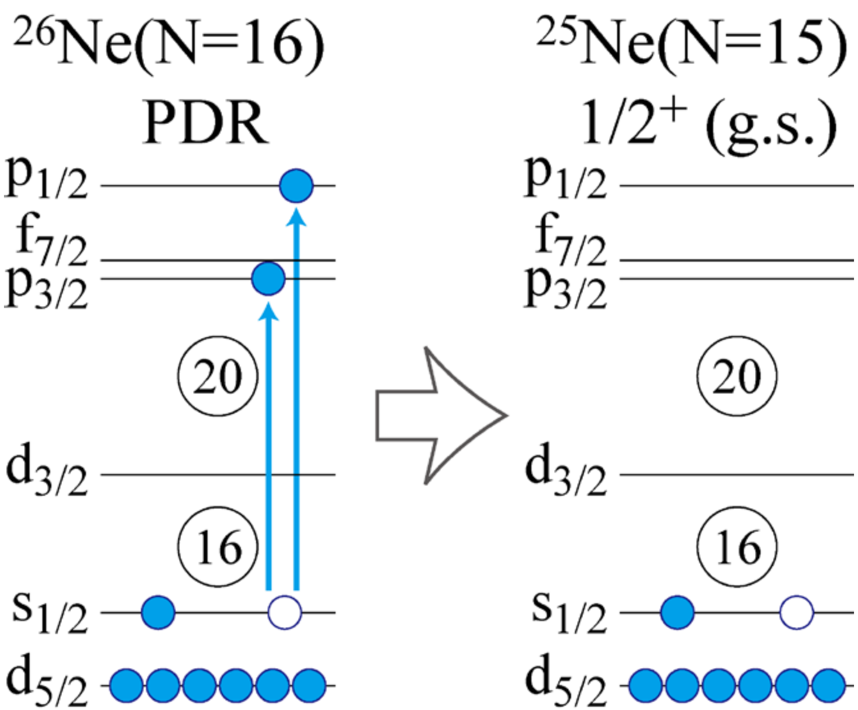
Introduction: ^{26}Ne Puzzle

◎ Unexpected decay pattern was observed

Theory: QRPAs

Leading configurations of PDR

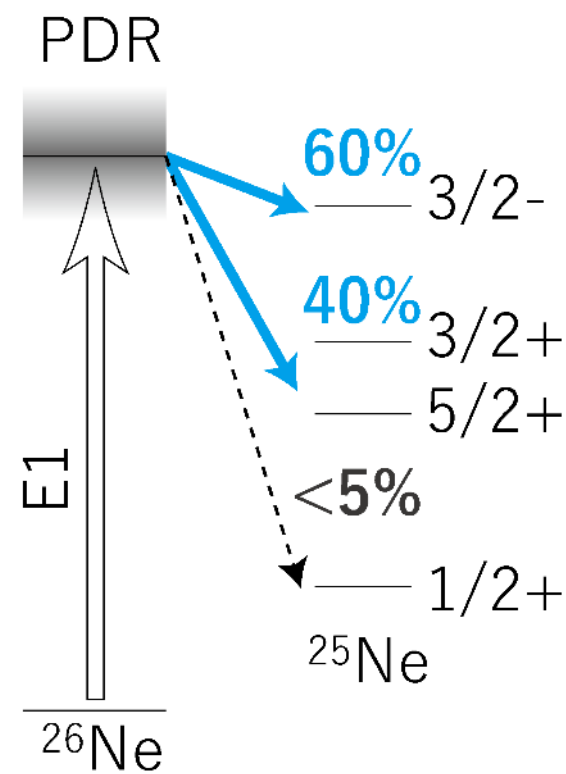
$\nu(s_{1/2})^{-1}(p_{3/2})^{1}$ and $\nu(s_{1/2})^{-1}(p_{1/2})^{1}$



Experiment: RIKEN

PDR decays to ^{25}**Ne***

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



Introduction: ^{26}Ne Puzzle

◎ ^{26}Ne Puzzle

○ Energy and strength are reasonably described by QRPA

○ Unexpected decay pattern of PDR

◎ How the puzzle can be solved ?

○ Decay to ^{25}Ne* implies the core excitation of PDR
(This is a theoretical challenge !)

⇒ Theoretical description beyond RPA is in need

・ Rob. & Vib. Coupling models

・ Second QRPA (higher orders of perturbation series)

I introduce a possible solution

"Real-time evolution method"

Model: Real-Time evolution method

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

- ○ Gogny D1S effective interaction
- ○ Center-of-mass motion is exactly removed $\Rightarrow$ No spurious modes

◎ Model wave function (time-dependent wave packets)

- ○ Slater determinant of wave packets for nucleons

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

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

- ○ 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)

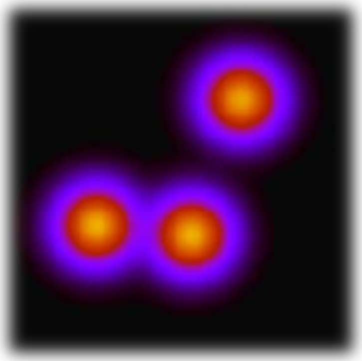
$\alpha_i(t)$ $\beta_i(t)$: Spin directions

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 nature
- 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)

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

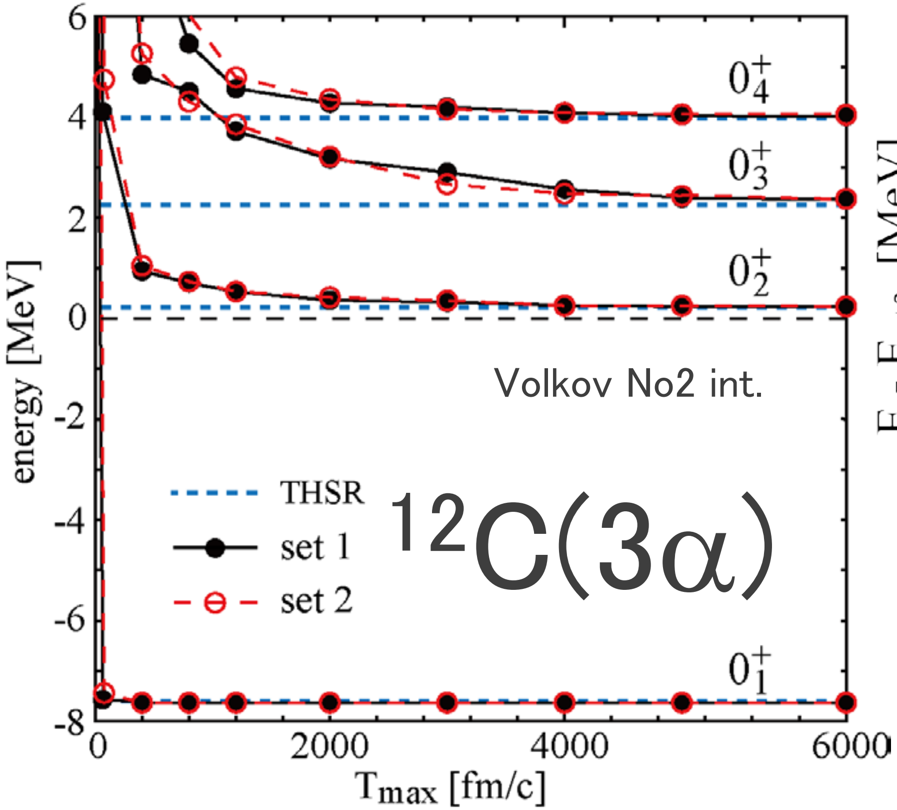
○ The result should be converged after the long-time propagation

○ The results should not depend on the initial condition

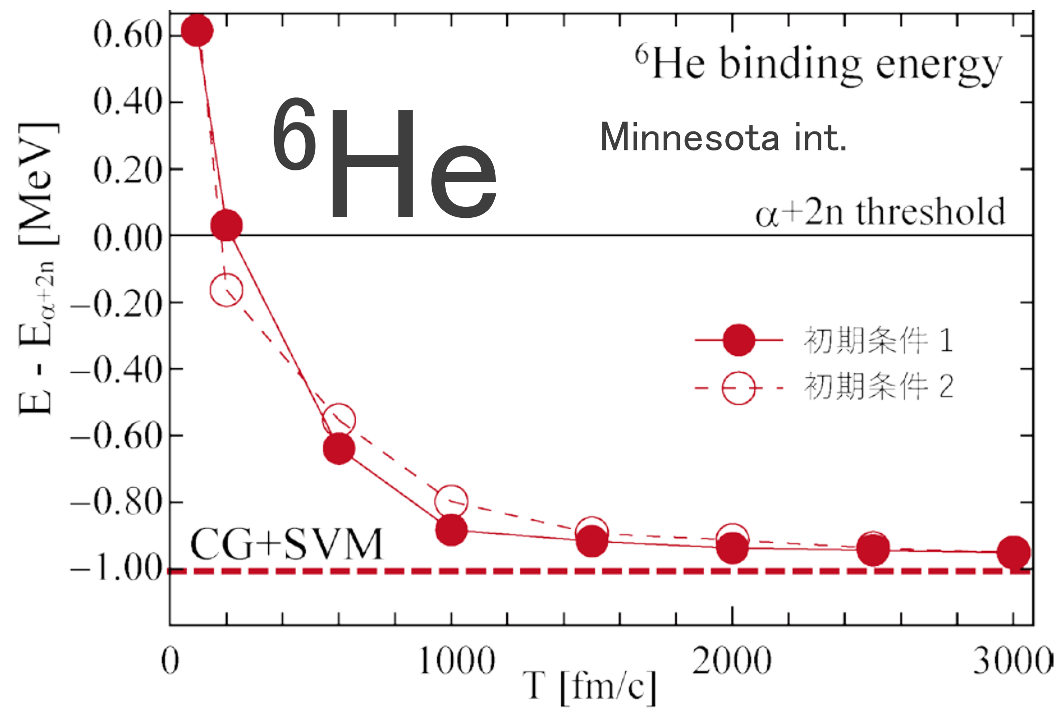
Model: Real-Time evolution method

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

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



M.K. in preparation

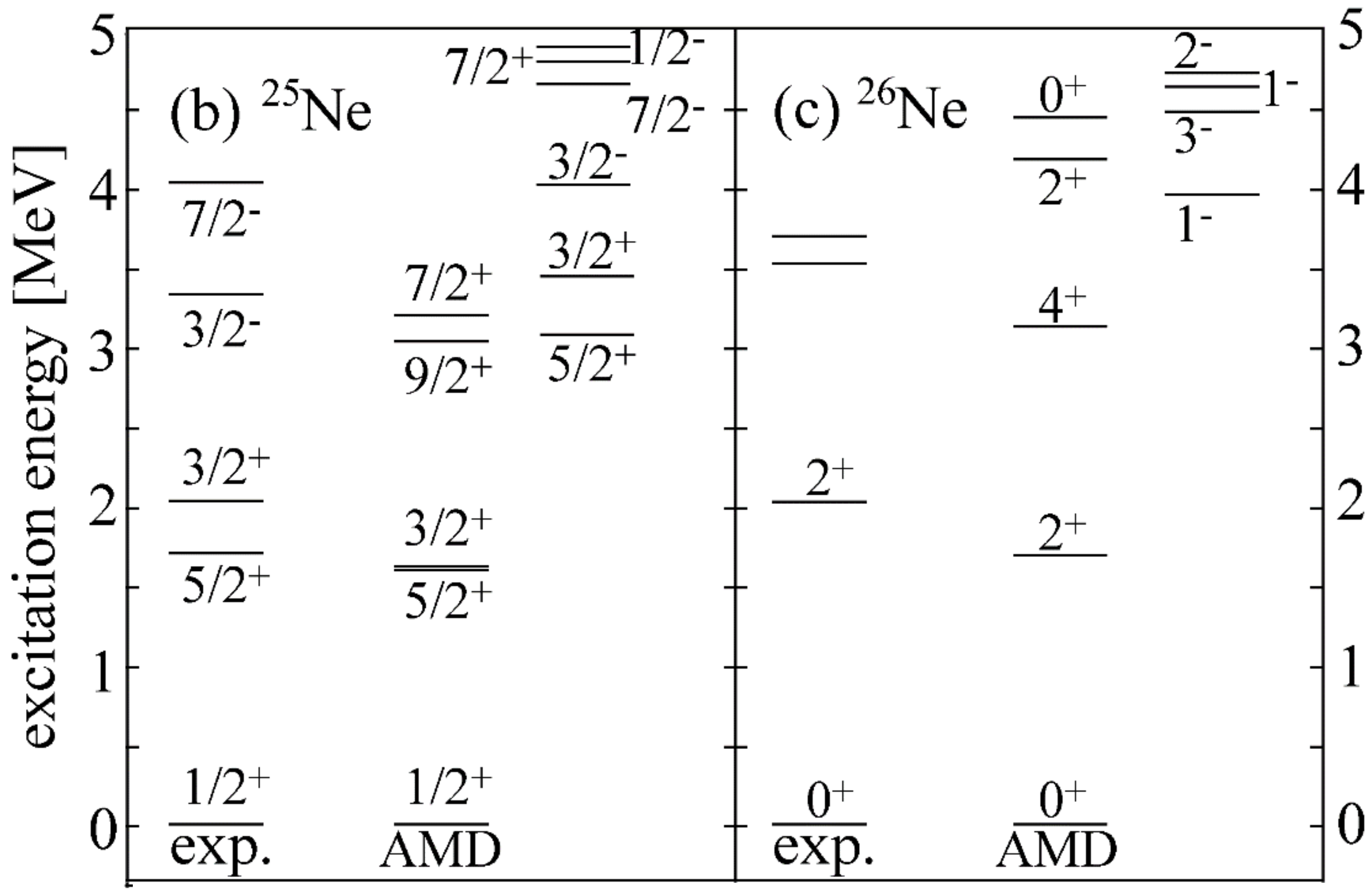


◎ A long time propagation brings us to the very accurate description of quantum many-body system

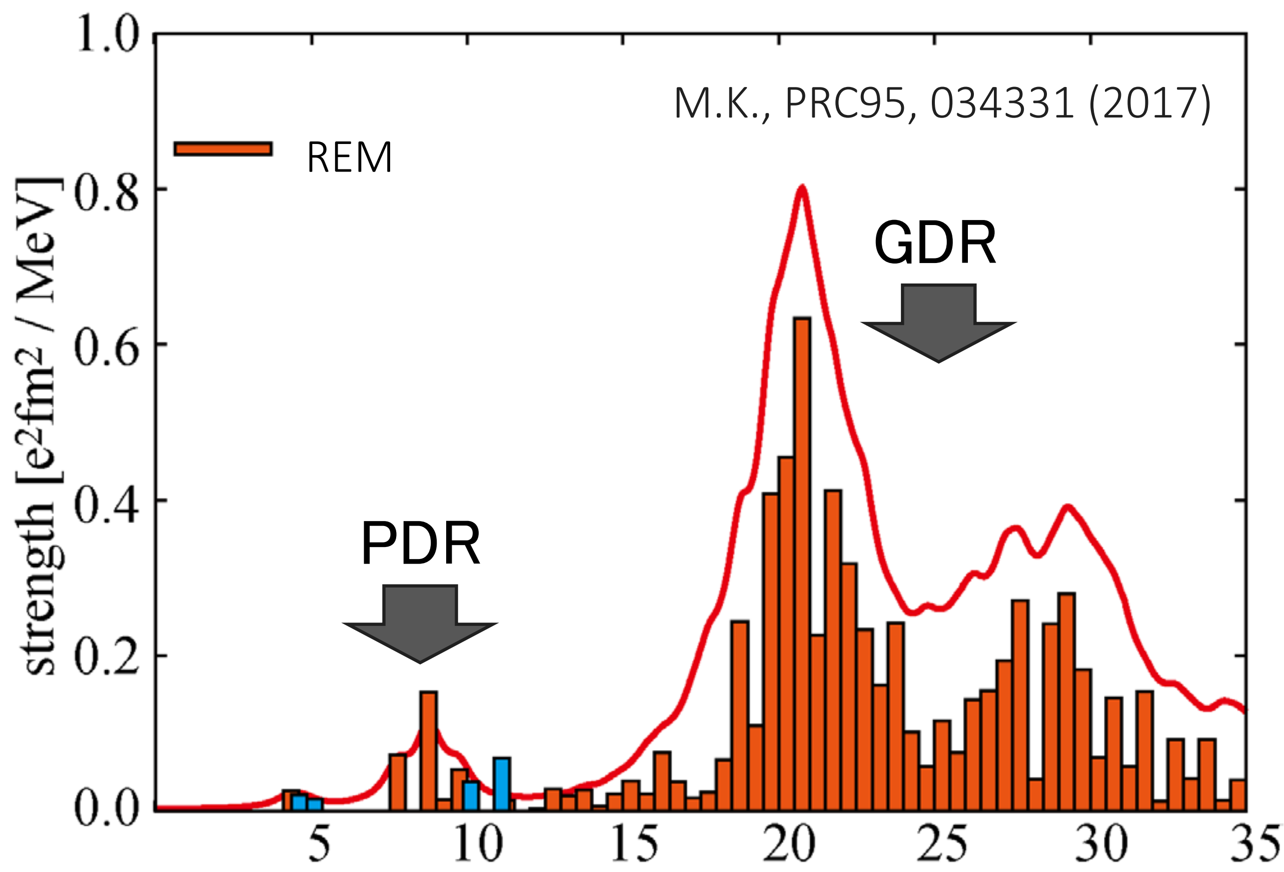
Results: Spectrum obtained by REM

REM yields reasonable description of low-lying stats

M.K., PRC95, 034331 (2017)



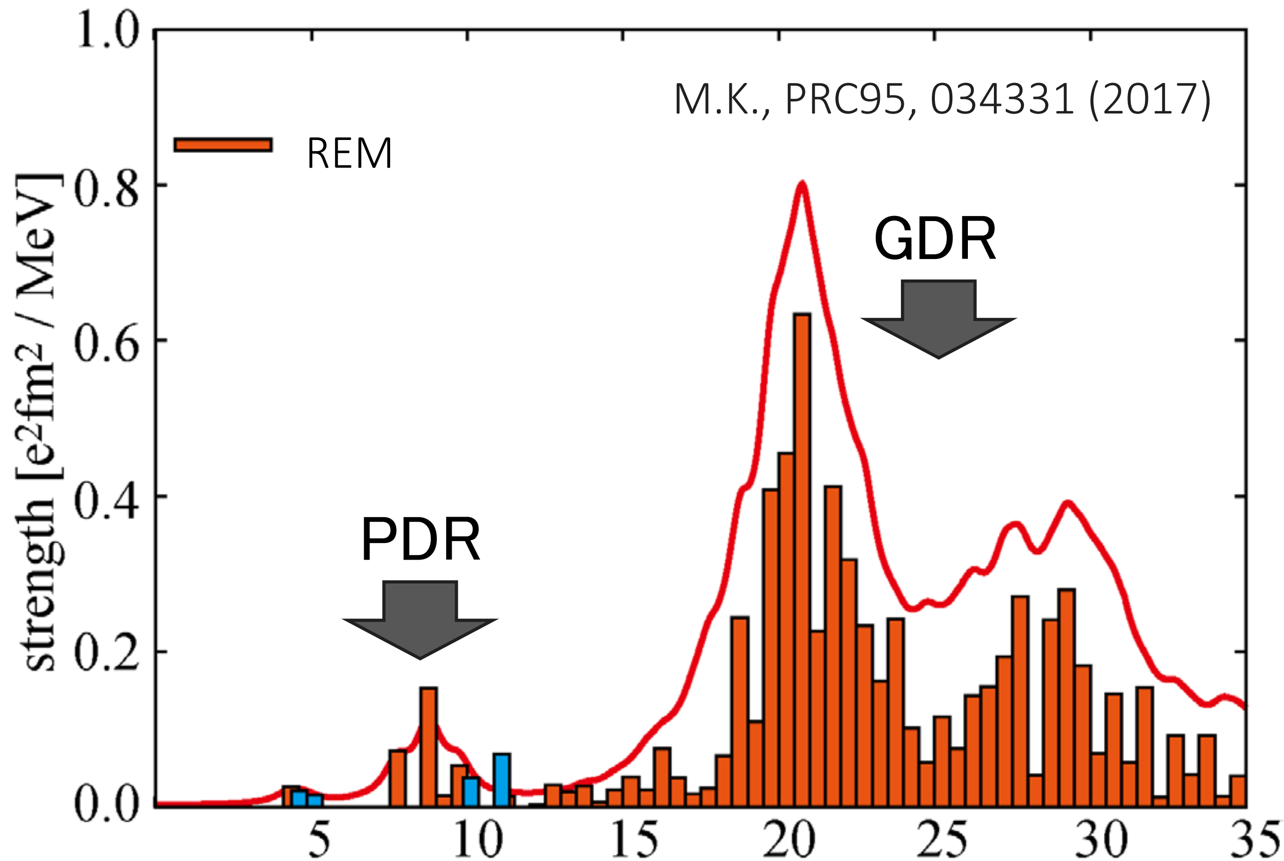
Results: E1 strengths



◎ PDR and GDR are reasonably described

◎ Global properties looks consistent with QRPAs with Gogny

Results: E1 strengths

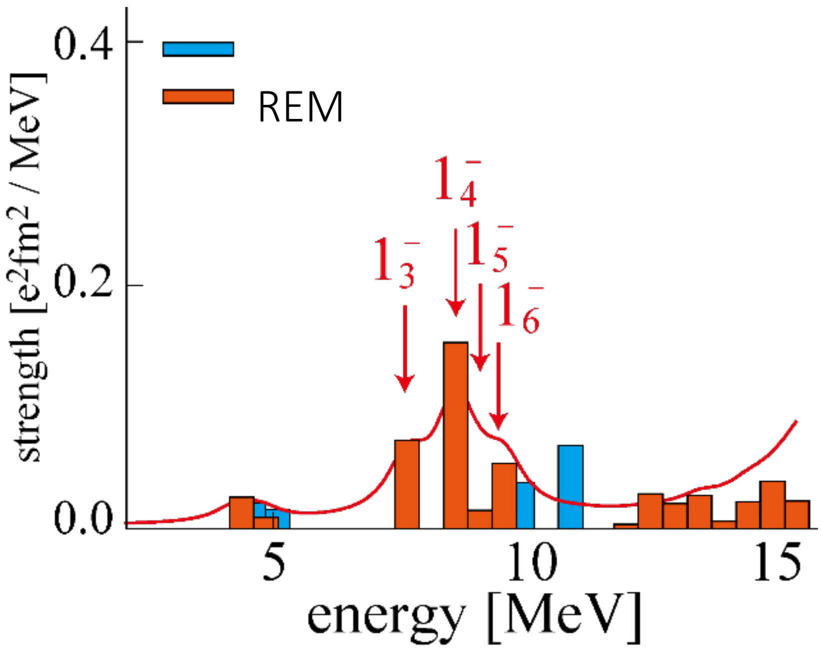


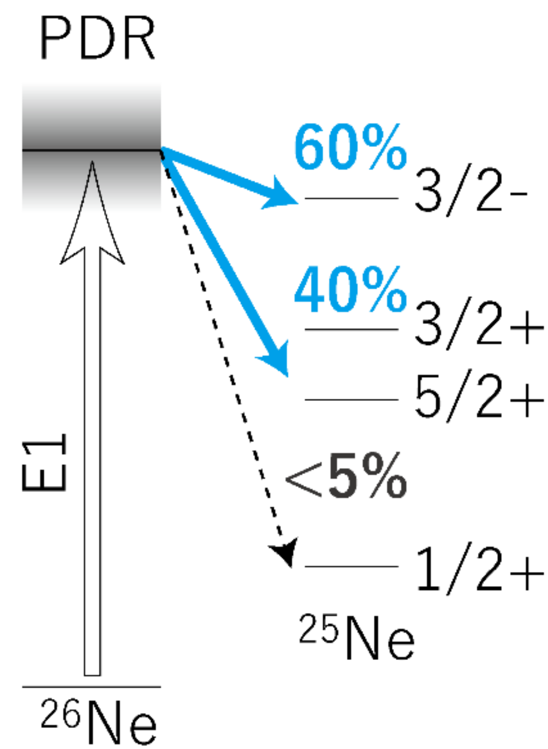
◎ PDR strength and energy are consistent with exp.

◎ 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.

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

Discussion: Isoscalar component of PDR

A conjecture: Why PDR are 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

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

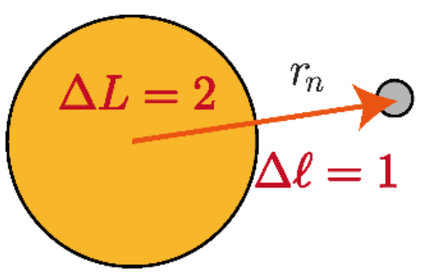
② Isoscalar component induces strong core excitation

$$\mathcal{M}(IS1) = \sum_i r_i^3 Y_{1\mu}(\hat{r}_i) = \sum_{i\in\mathrm{Core}} \xi_i^3 Y_{1\mu}(\hat{\xi}_i) - \frac{(A-1)(A-2)}{A^2} r_n^3 Y_{1\mu}(\hat{r}_n)$$

$$+\frac{5}{3A}\left(\sum_{i\in\mathrm{Core}} \xi_i^2\right) r_n Y_{1\mu}(\hat{r}_n) - \frac{4\sqrt{2\pi}}{3A}\left[\left(\sum_{i\in\mathrm{Core}} \xi_i^2 Y_2(\hat{\xi}_i)\right)\otimes r_n Y_1(\hat{r}_n)\right]_{1\mu}$$

ξ_i : internal coordinate of the core

r_n : relative coordinate between core-neutron



dipole excitation of the core-neutron motion coupled to the core quadrupole

⇒ Very large when the core has strong low-lying quadrupole collectivity

Discussion: Isoscalar component of PDR

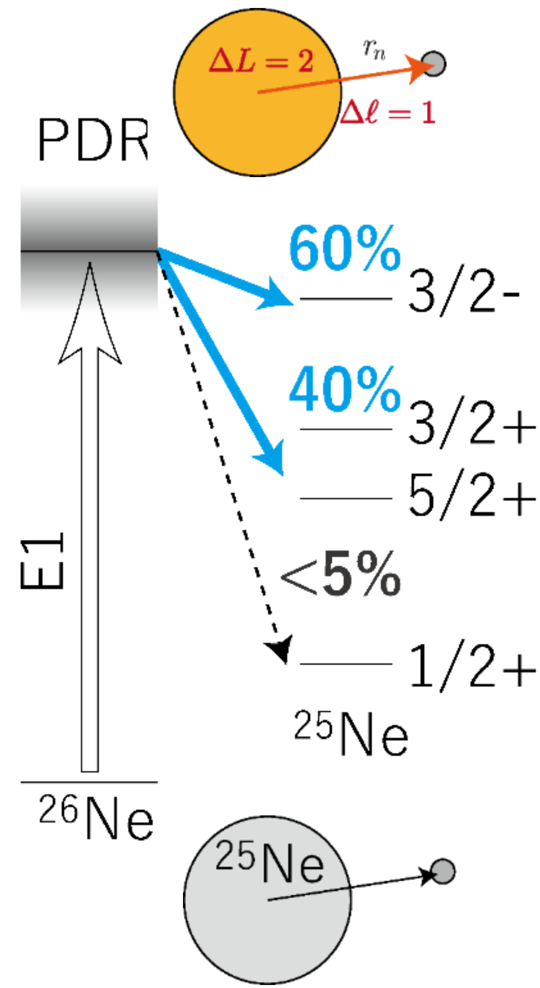
Summary of the conjecture

① PDR is admixture of IV and is components

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

② IS component induces quadrupole core excitation

$$\mathcal{M}(IS1) \simeq -\frac{4\sqrt{2\pi}}{3A}\left[\left(\sum_{i\in \mathrm{Core}} \xi_i^2 Y_2(\hat{\xi}_i)\right)\otimes r_n Y_1(\hat{r}_n)\right]_{1\mu}$$



◎ If this conjecture is true,

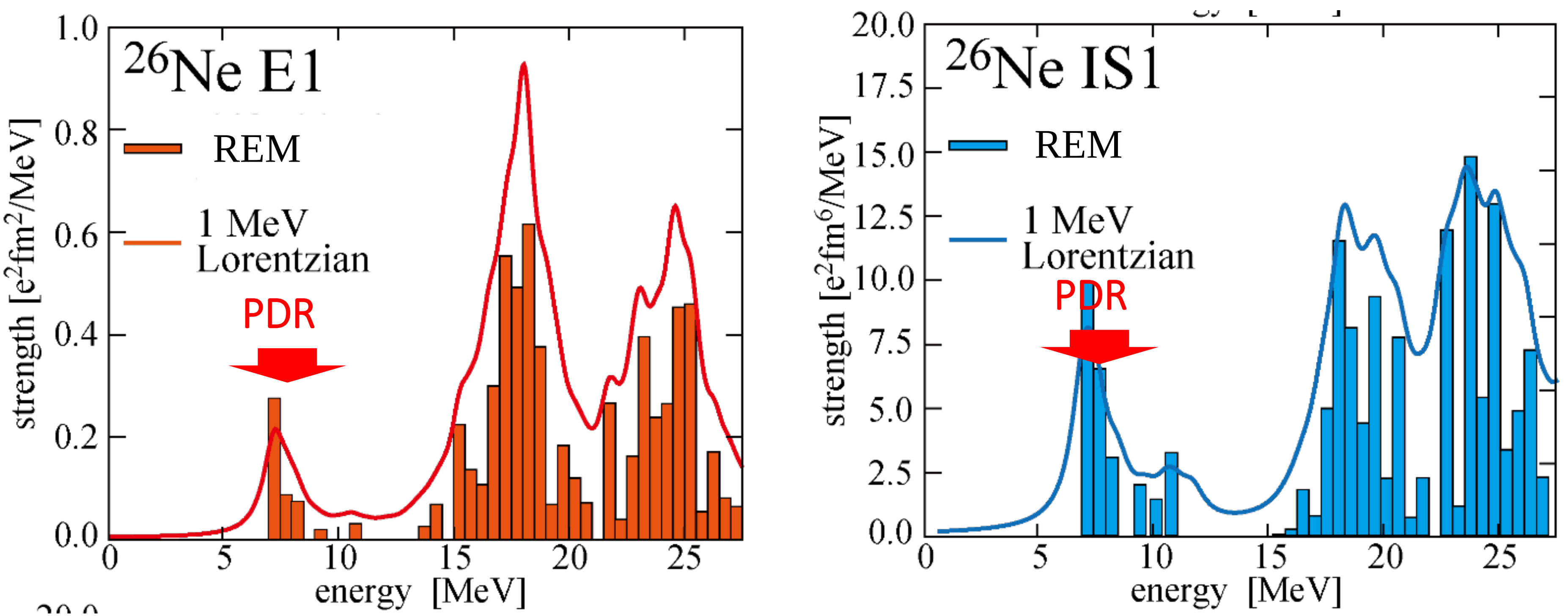
- ○ PDR should have IS dipole strength
- ○ Ne isotopes in the Island of Inversion should have stronger core excitations

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

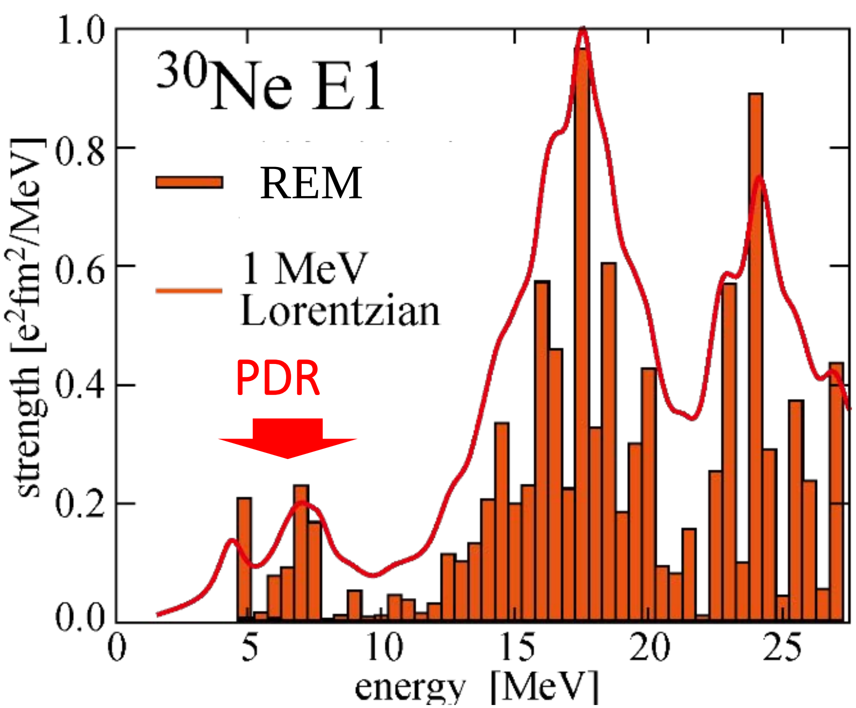


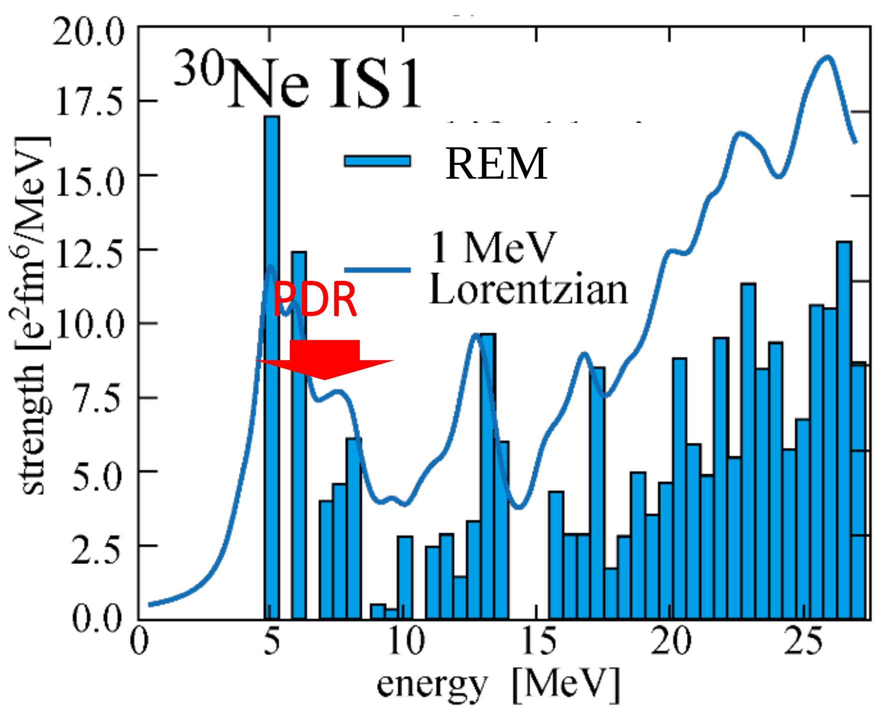
Discussion: Isoscalar component of PDR

② IS component induces quadrupole core excitation

$$\mathcal{M}(IS1) \simeq -\frac{4\sqrt{2\pi}}{3A}\left[\left(\sum_{i\in\text{Core}}\xi_i^2 Y_2(\hat{\xi}_i)\right)\otimes r_n Y_1(\hat{r}_n)\right]_{1\mu}$$

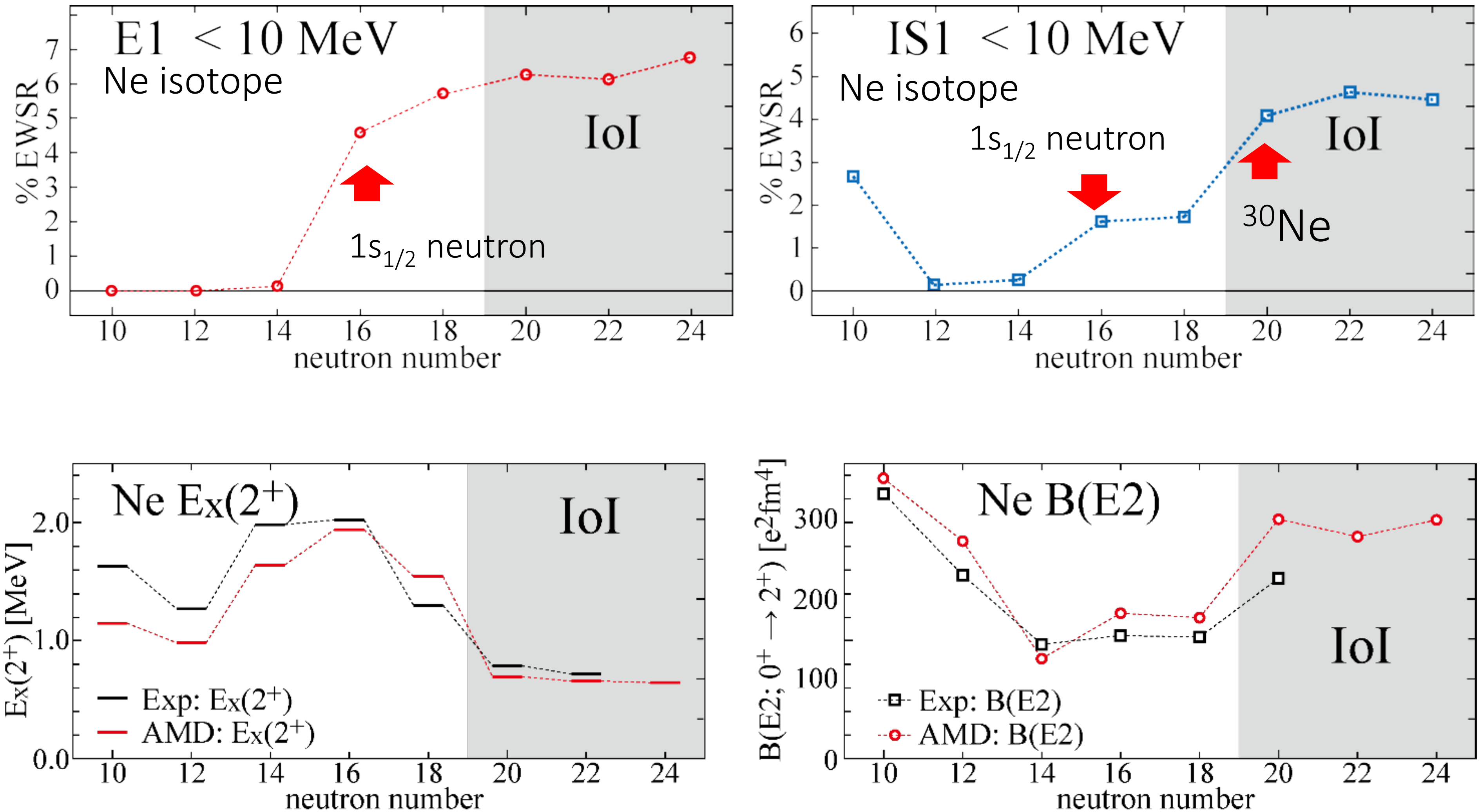
⇒ The isoscalar component should be enhanced in the Island of Inversion





Discussion: Isoscalar component of PDR

◎ IS dipole strength is correlated the quadrupole collectivity



Summary

◎ ^{26}Ne puzzle has been discussed

◎ A new model "Real-Time evolution method" (REM)

◎ REM described ^{26}Ne PDR reasonably

◎ The importance of the IS dipole mode has been emphasized

◎ And the scenario has tested in neutron-rich Ne isotopes.

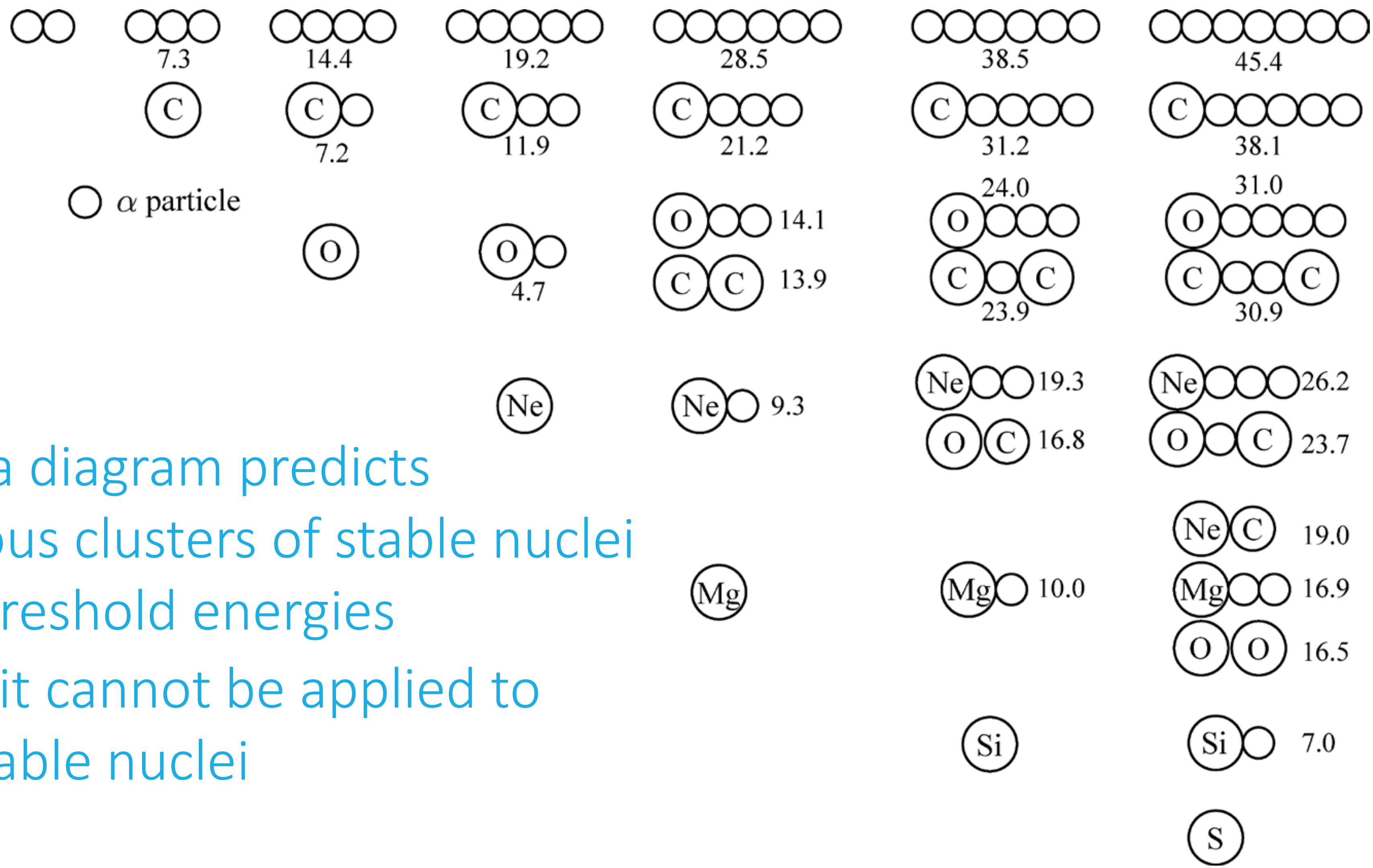
◎ The discussion is also applicable to the Cluster physics such as ^{12}C+^{12}C fusion problem.

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).
Y. Chiba and M.K, arXiv:1801.00562 (2018).

Ikeda diagram

K. Ikeda et al., PTPS Ex. 464(1968)



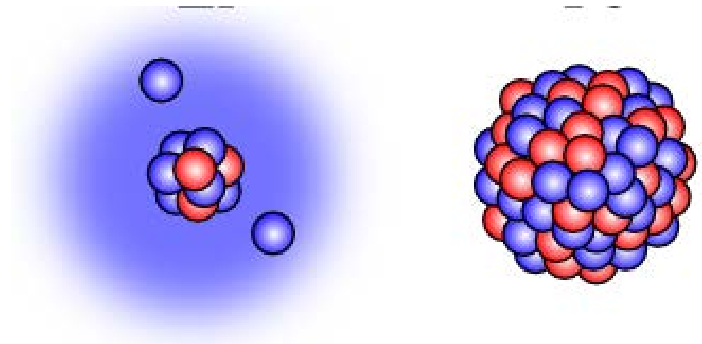
Ikeda diagram predicts various clusters of stable nuclei at threshold energies

But, it cannot be applied to unstable nuclei

What will happen in neutron-rich nuclei?

- Ikeda diagram is based on the fundamental nuclear properties, saturation of energy/matter density
- But saturation property is lost in neutron-rich nuclei. Hence, Ikeda diagram cannot be applied straightforwardly

^{11}Li



^{208}Pb

So, what will happen?

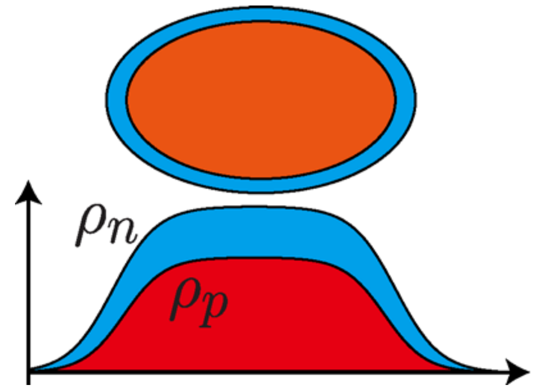
- Energy/Matter density should be kept constant
- Symmetry energy should be minimized

“MF with neutron skin” v.s. “Clustering”

There are two solutions

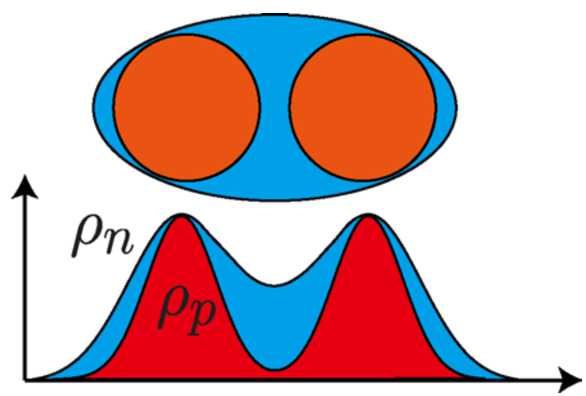
1. Mean-field with neutron skin

- ○ Densities are globally kept almost constant
- ○ Symmetry energy is globally minimized



2. Clusters with valence neutrons

- ○ Densities are locally kept constant
- ○ Symmetry energy is locally minimized

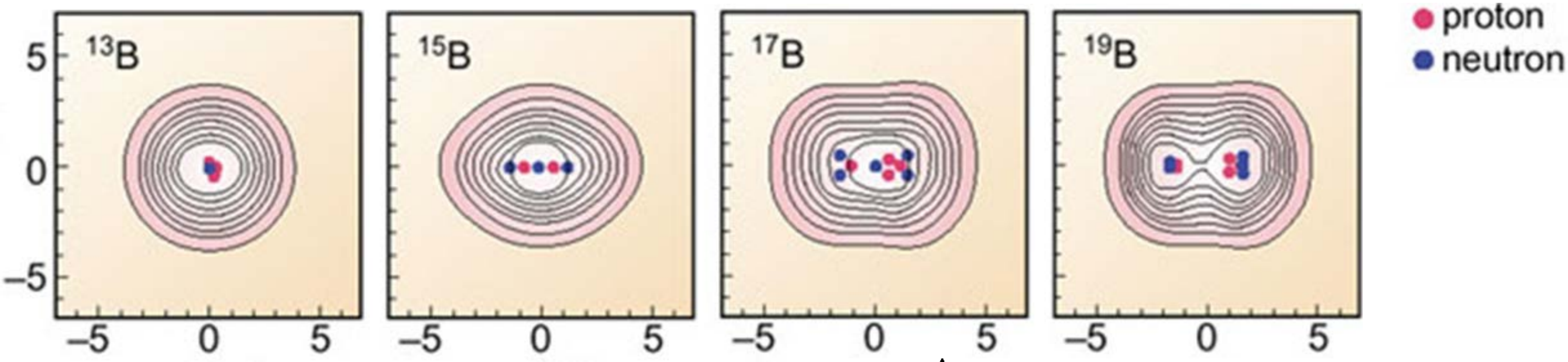


Which is better for deeper binding?

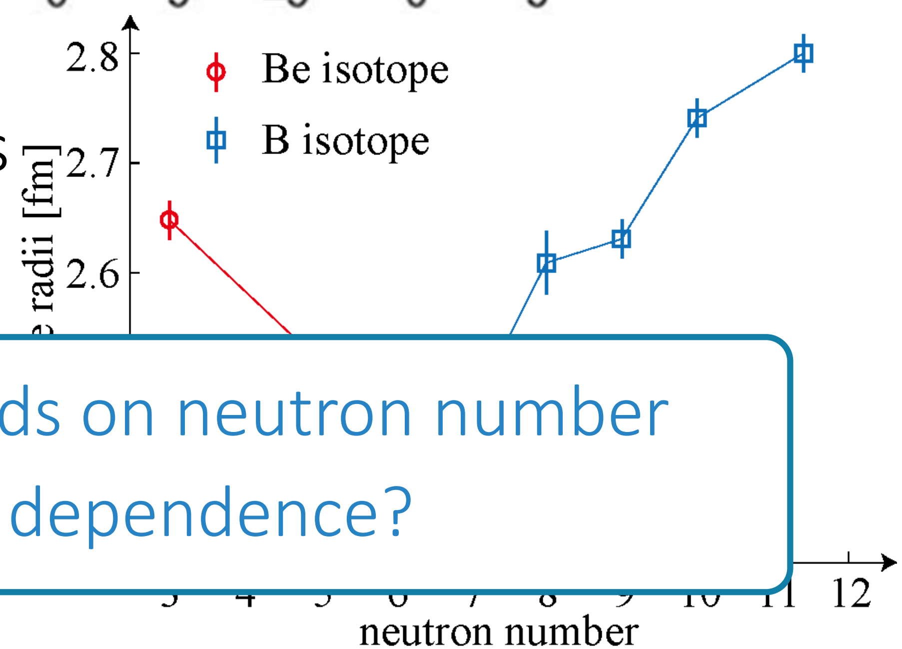
“MF with neutron skin” v.s. “Clustering”

A possible answer in light nuclei: mean-field ⇒ cluster

Y. Kanada-En’yo and H. Horiuchi, PRC52, 647(1995).



Charge radii of Be and B isotopes can be a signature of clustering



A. Kr

A. Es

Clustering sharply depends on neutron number

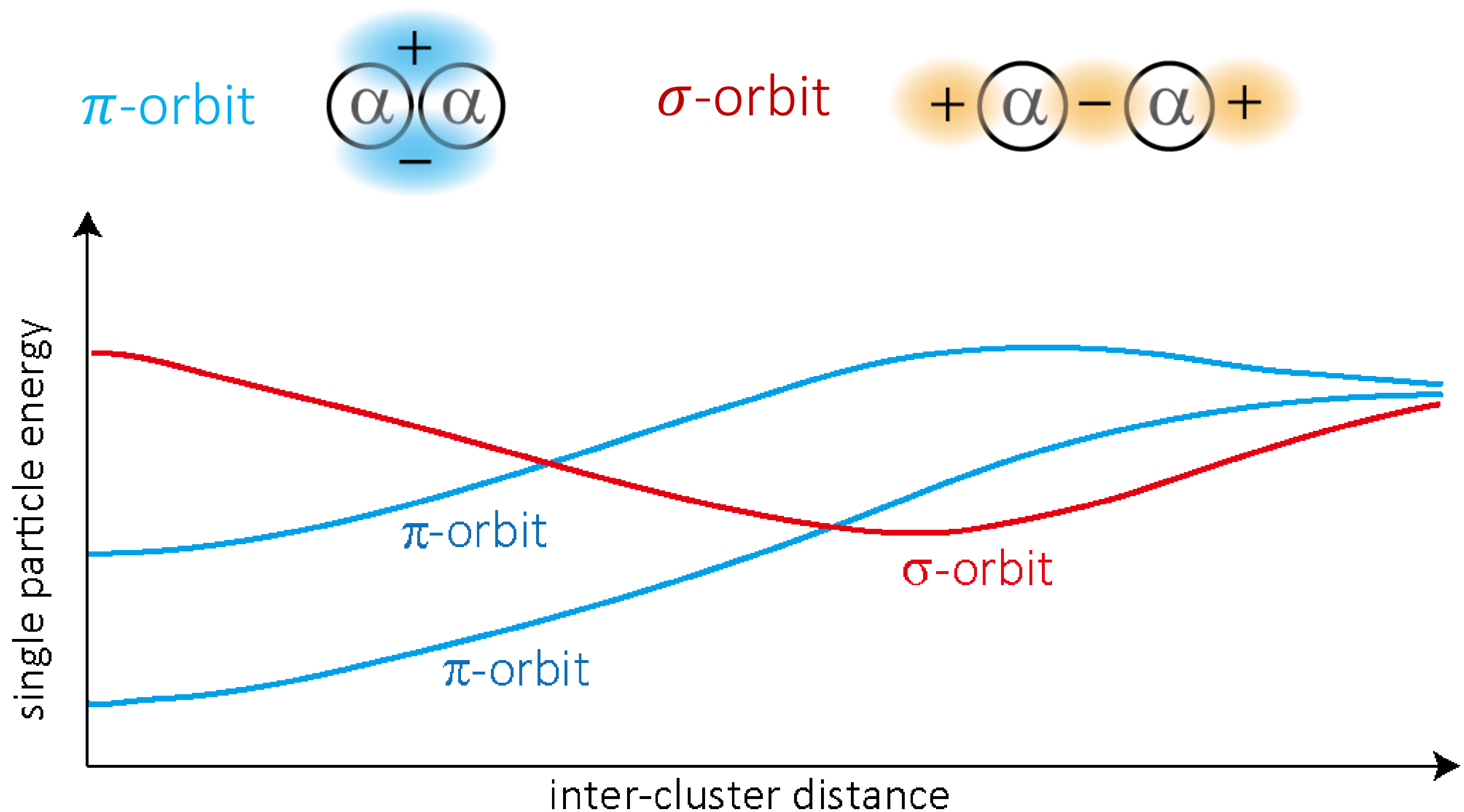
What is the origin of this dependence?

Molecular Orbits

Underlying quantum shell effect; "Molecular Orbits (MO)"

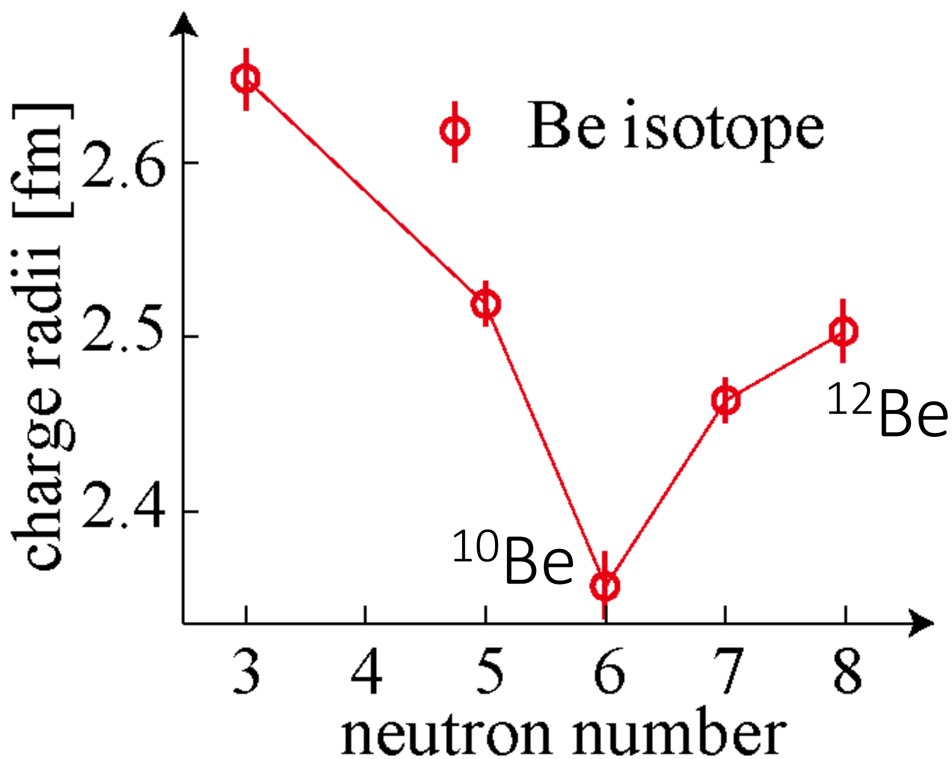
A special class of neutron orbits (MO) are formed around the clustered core

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

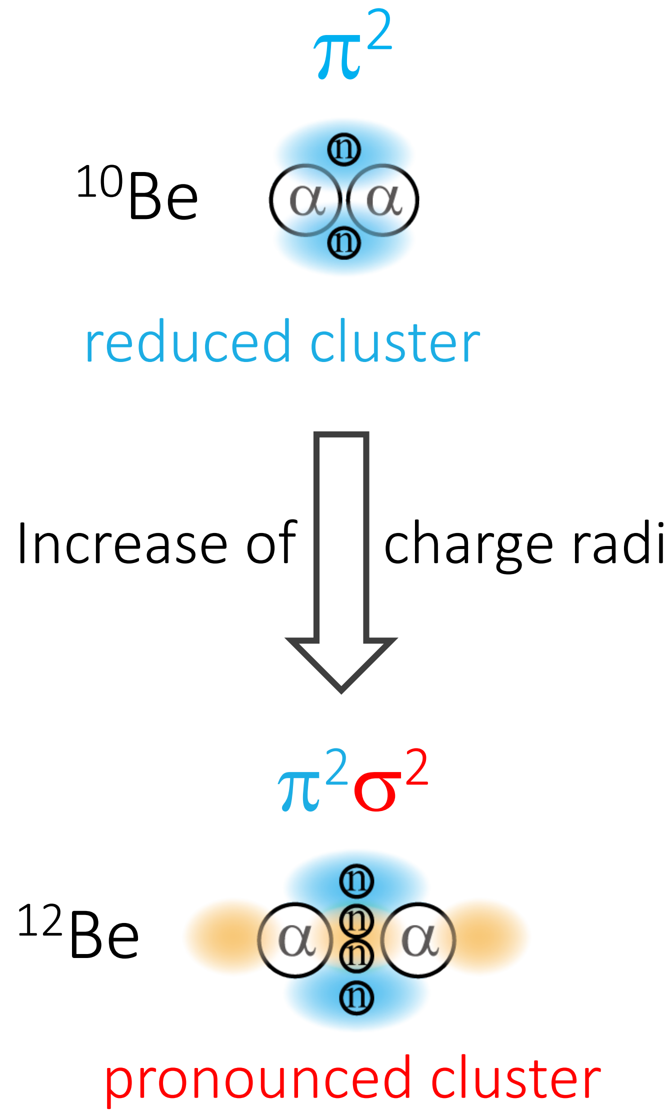


MO in Be isotopes

MO explains the increase of charge radii in ^{12}Be



A. Krieger, et al., PRL108, 142501 (2012)



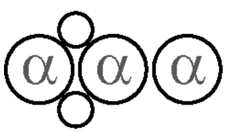
MO in p-shell nuclei

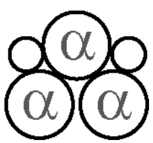
What we learned from light neutron-rich nuclei

- MO is a new binding mechanism of clusters
  It stabilizes clusters by its glue-like role
- MO generates a new types of clustering (covalent, ionic, ...)
  which do not follow ordinary Ikeda diagram
  ⇒ "extended Ikeda diagram" by von Oertzen

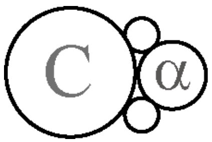
Molecular Orbits Today

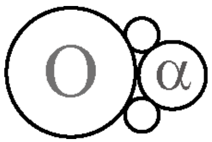
- Three center systems (Chains and Triangles)





- Parity asymmetric MO and its impact on astrophysics



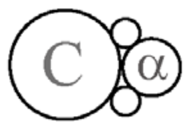


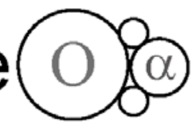
Reflection asymmetric clusters with MO

Discussion of MO can be extended to heavier systems

◎ An interesting target is O and Ne isotopes

- Clustering of ^{16}O and ^{20}Ne is well known (reflection asymmetric)

^{18}O 

^{22}Ne 

- Some of them are related to the astrophysical processes

  ^{14}C(α,γ)^{18}O, ^{18}O(α,γ)^{22}Ne, …

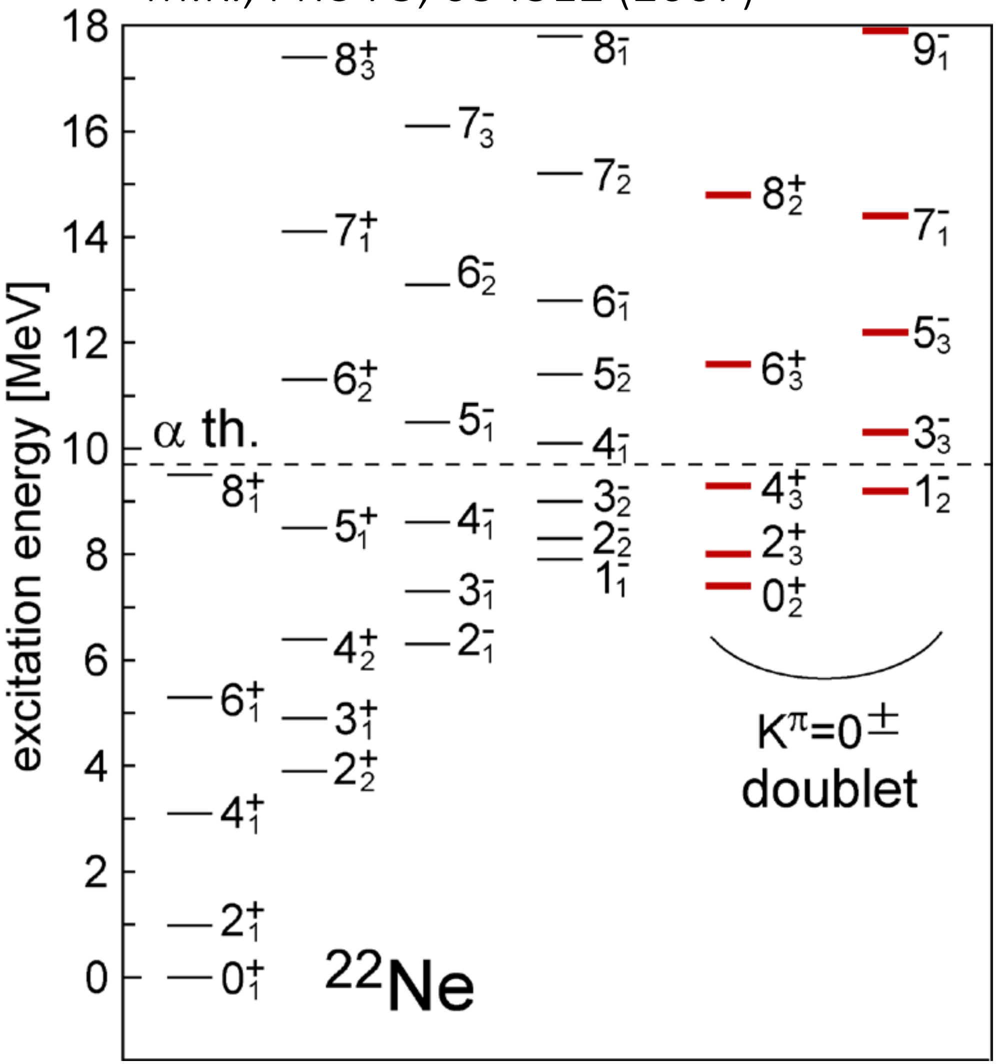
  Reflection asymmetric clusters may have strong impact on the astrophysical processes

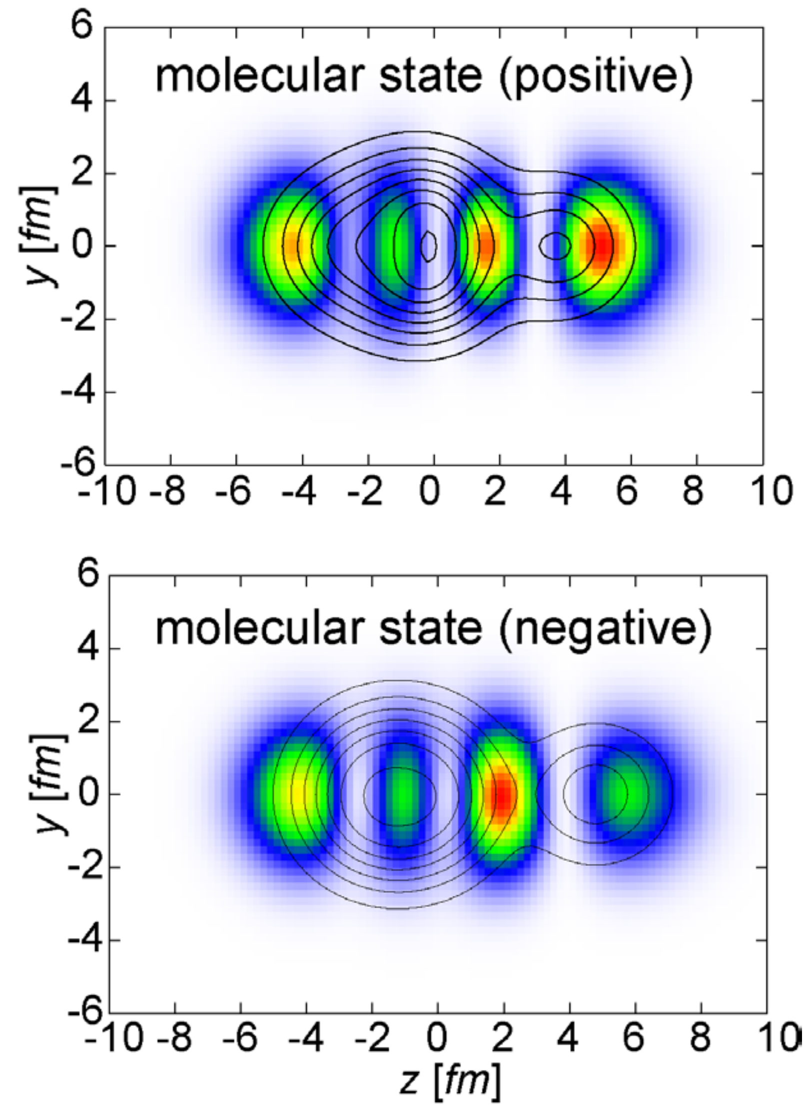
- They have much longer isotope chain than Be isotopes

MO in ^{22}Ne

A pair of cluster bands (positive & negative) in ^{22}Ne

M.K., PRC 75, 034312 (2007)

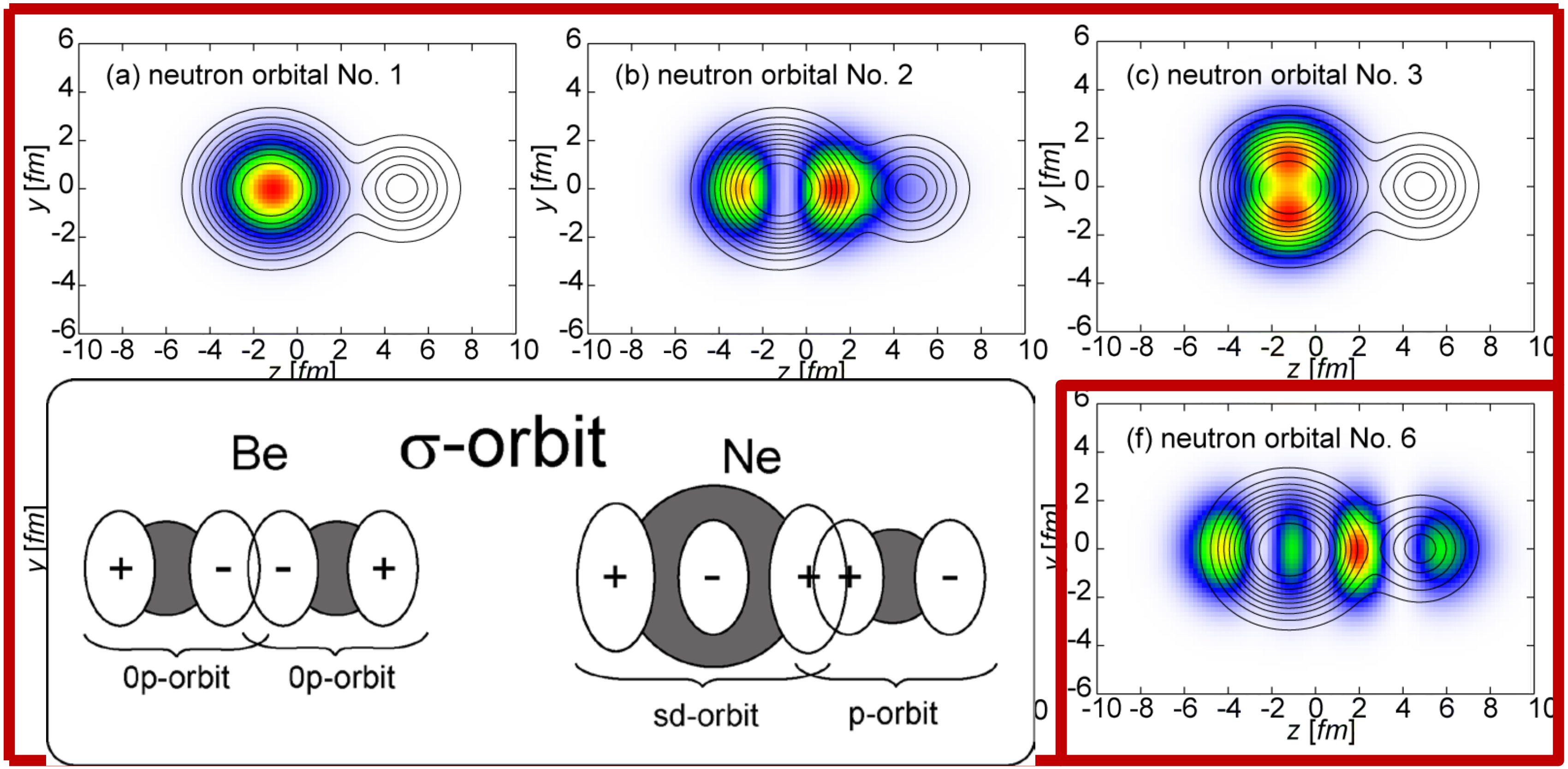




MO in ^{22}Ne

Neutron single-particle orbits

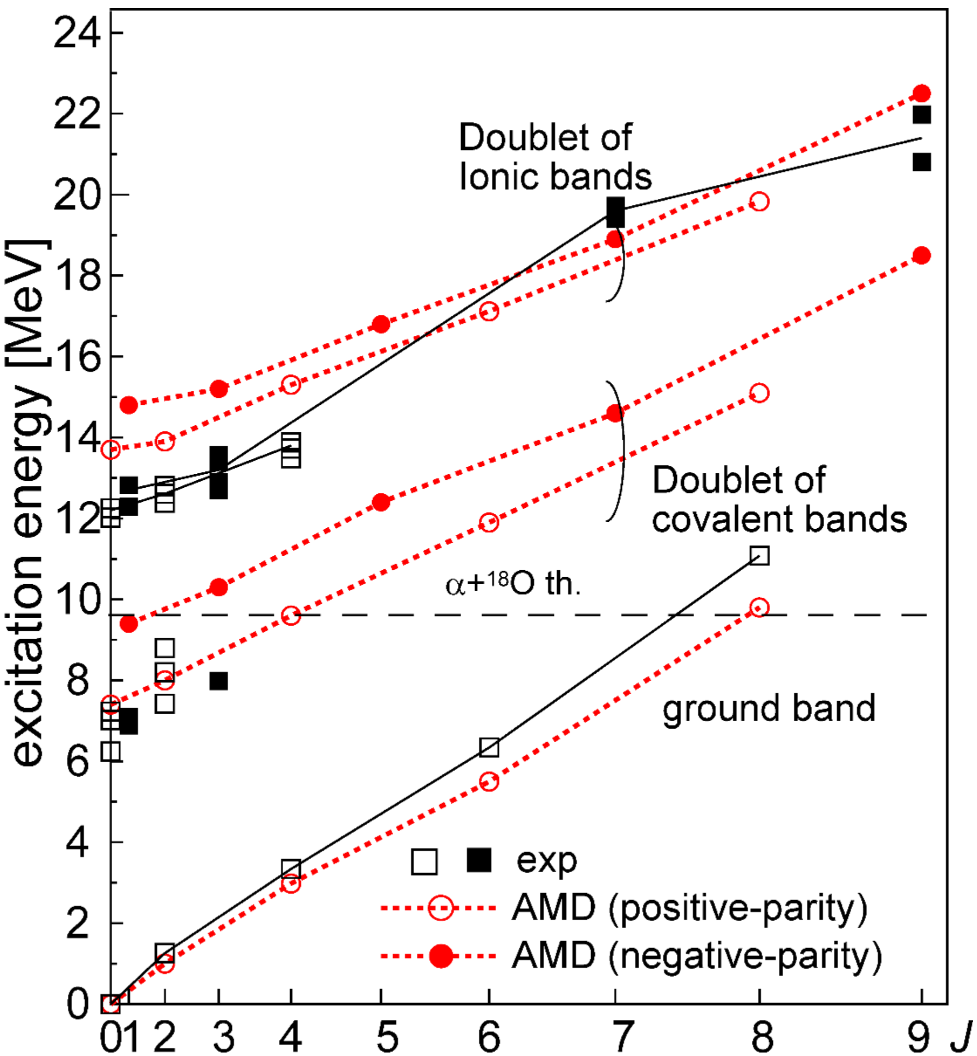
M.K., PRC 75, 034312 (2007)



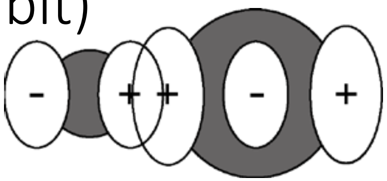
- Neutrons are confined within clusters
- Two valence neutrons occupy MO (σ-orbit, covalent)
- Two valence neutrons bound weakly interacting clusters (α, ^{16}O)

Covalent and Ionic bonding in ^{22}Ne

Theory predicts two cluster doublets



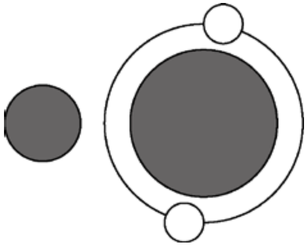
○ Doublet of covalent bands
(α + ^{16}O+ σ-orbit)



Candidate

W. Scholz, et al.,
PRL 22, 949 (1969), PRC 6, 893 (1972).

○ Doublet of ionic bands
(α + ^{18}O)

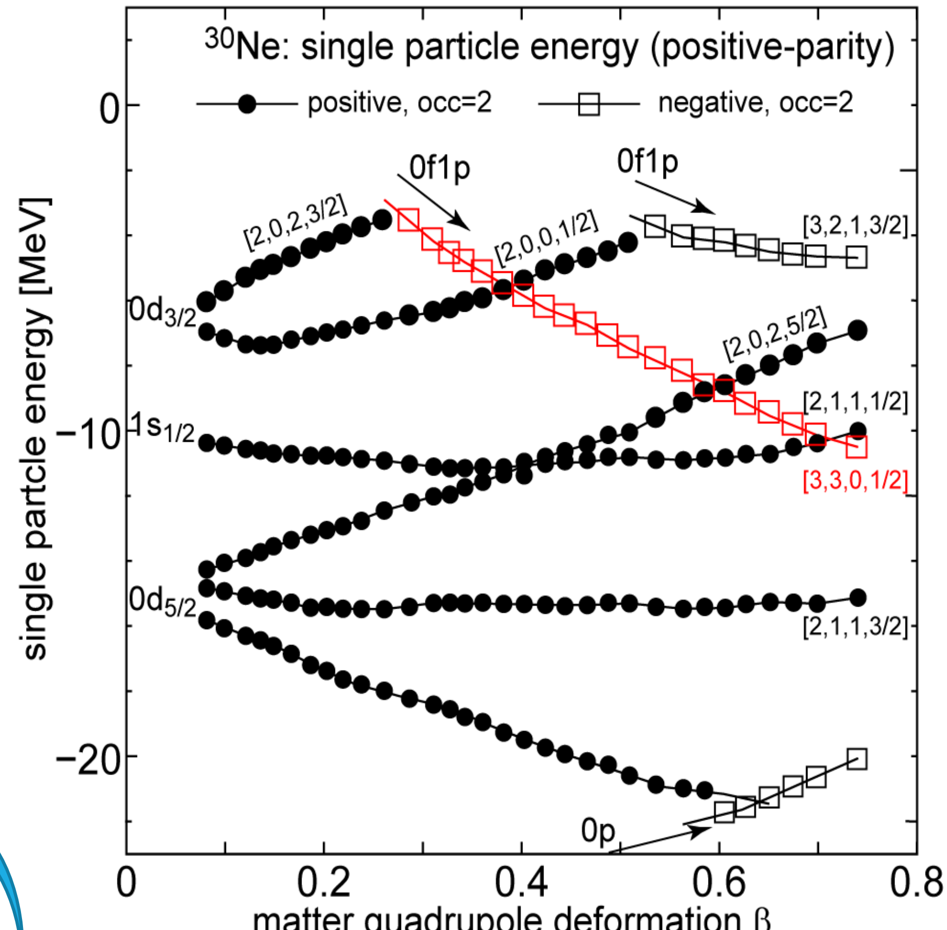


Identified by exp.

G. V. Rogachev, et al., PRC 64 051302 (2001).
N. Curtis, et al., PRC66 024315 (2002).
V.Z.Goldberg, et al., PRC 69, 024602 (2004).

Evolution of MO toward drip-line

- σ-orbit has the same quantum number with a Nilsson orbit [3,3,0, 1/2] that is an intruder orbit in the "Island of Inversion"
- This means that σ-orbit is occupied by the neutrons in the ground band and it induces strong deformation
- A pair of 0+ and 1- should exist

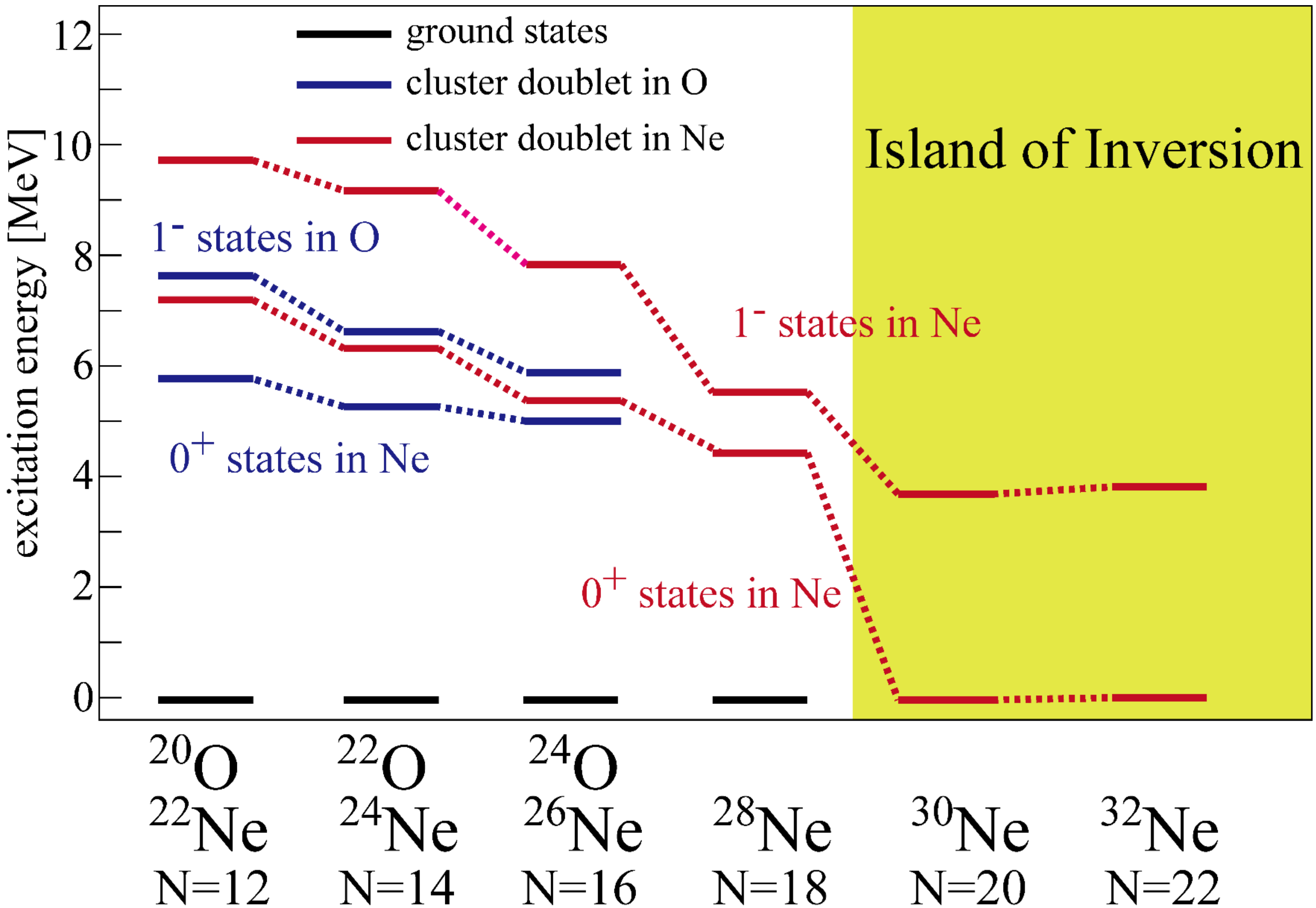


Occupation of σ-orbit
(breakdown of N=20 magic #)

Clustering
(strong deformation)

Evolution of MO toward drip-line

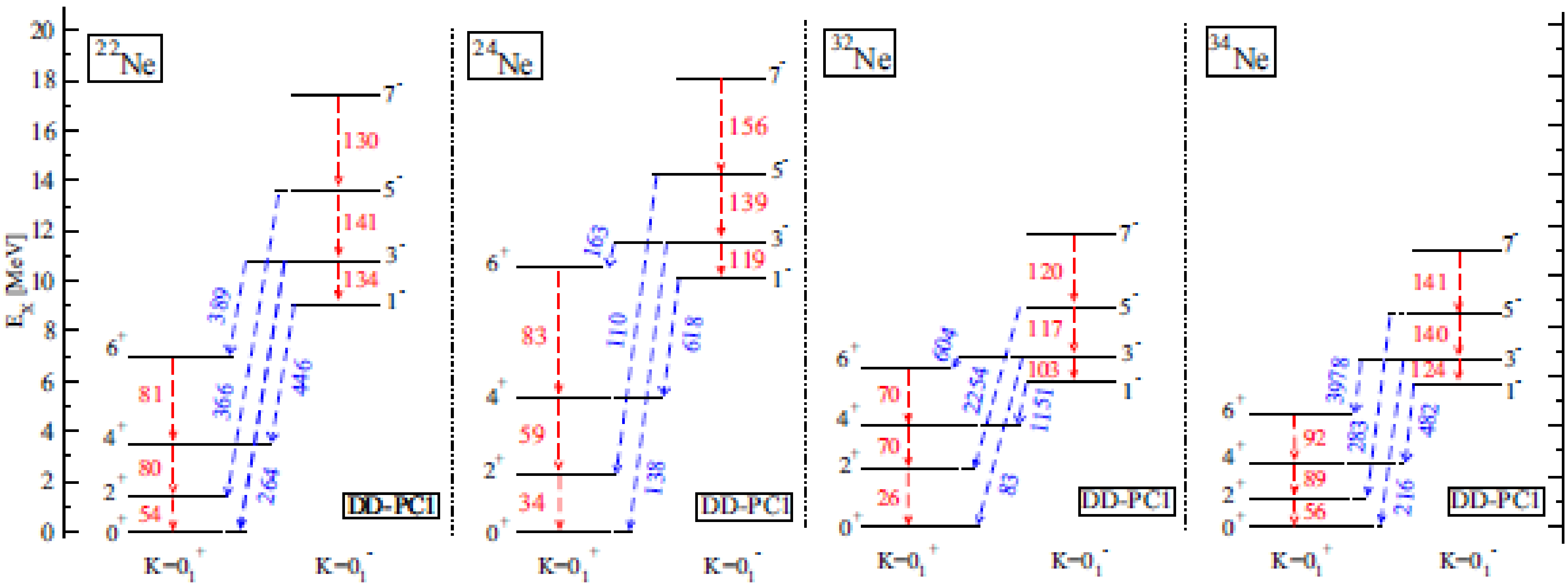
- 0+ and 1- doublet exists in all isotopes, and its energy is actually lowered in IOI



Evolution of MO toward drip-line

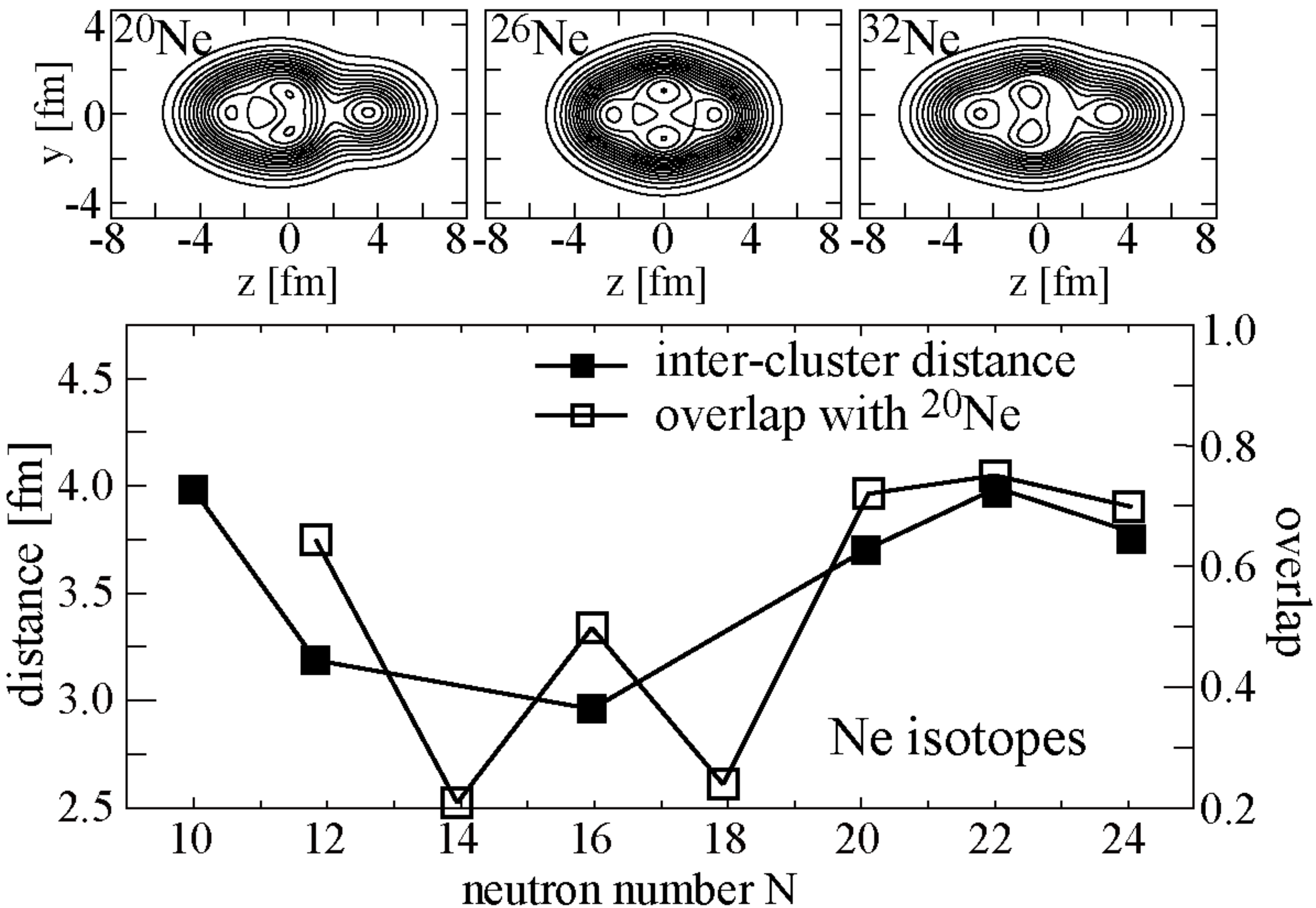
- A similar result was also reported by a DFT calculation

  P. Marevic et al., PRC97 024334 (2018).



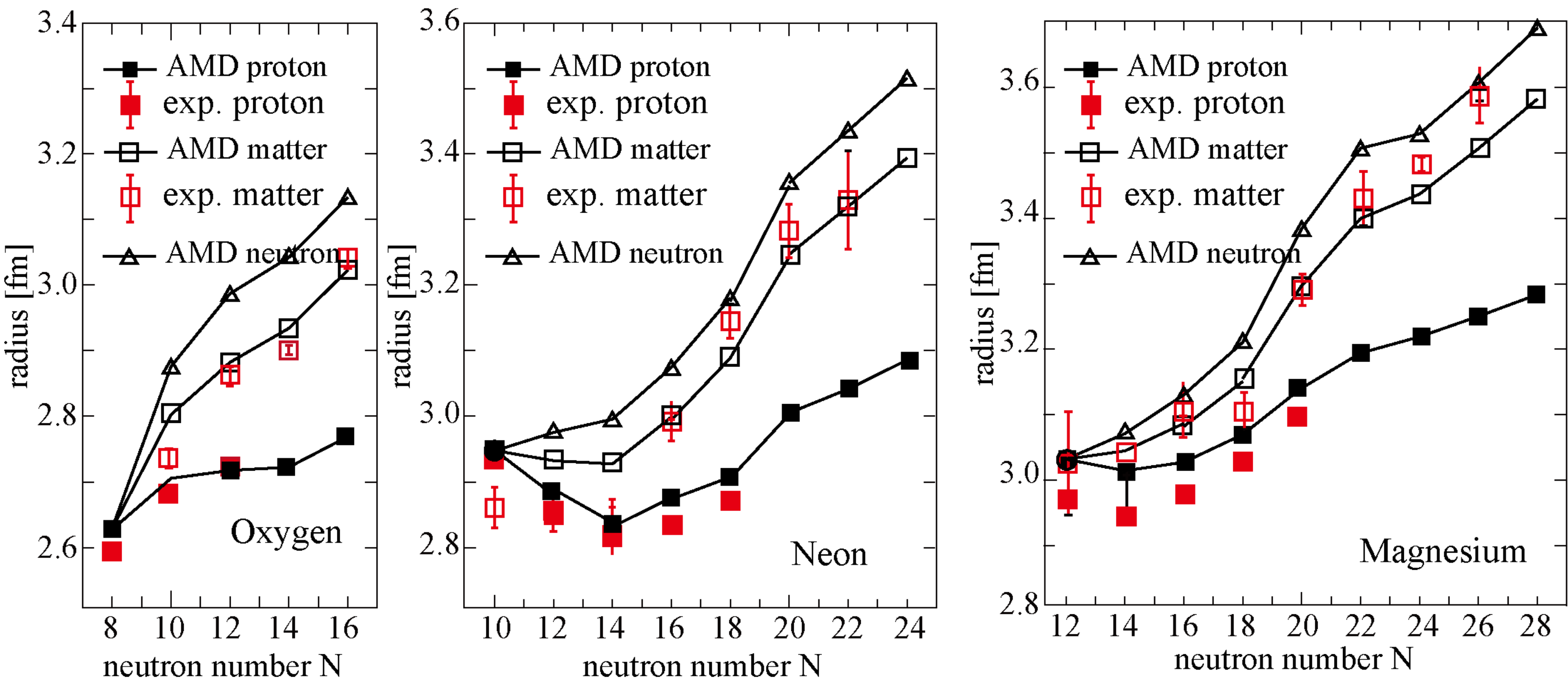
Evolution of MO toward drip-line

○ Strong deformation and clustering are induced in IOI



How we can observe it?

- charge radii (electron scat. Isotope shift etc.) and matter radii (reaction cross sec.) are indirect probes.



Summary and Perspective

- MO is a novel type of clustering and binding mechanism in neutron-rich nuclei
- Study of MO is extending to C, O and Ne isotopes exploring "new Ikeda diagram" in neutron-rich nuclei
- Reflection asymmetric MO is predicted in O and Ne isotopes Their impact on astrophysical processes is expected
- Charge radii can be a good signature of the clustering

Thank you for your attention