^{26}Ne PDR Problem and Nature of PDR

M. KIMURA

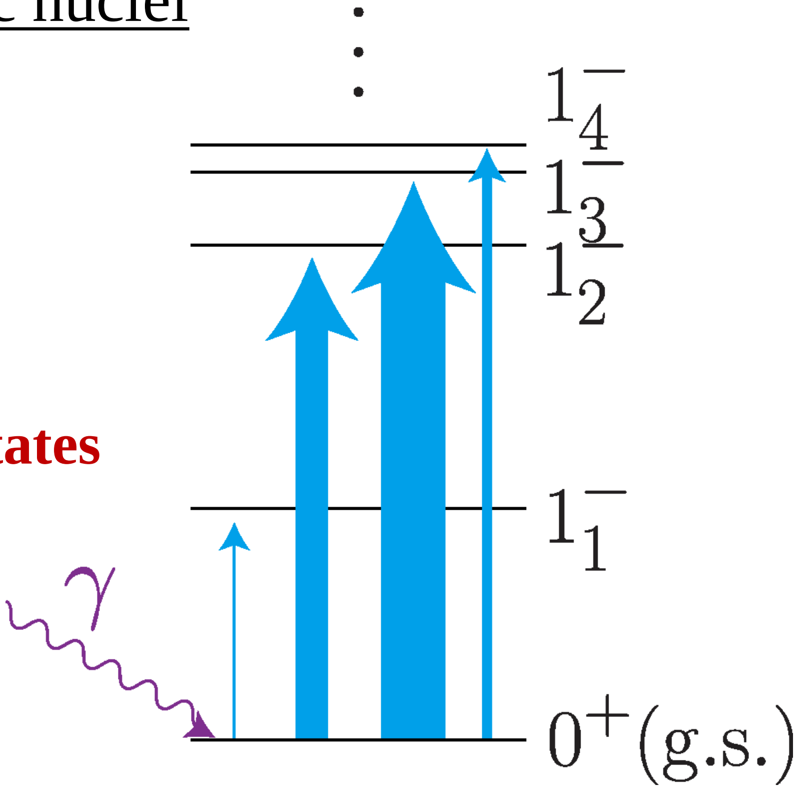
What is “^{26}Ne PDR Problem” ?

Electric dipole (E1) excitation of atomic nuclei

◎ Operator: Electric transition with $\Delta\ell = 1$

$$\mathcal{M}_\mu(E1) = \sum_{i\in proton} r_i' \, Y_{1\mu}(\hat{r}_i')$$

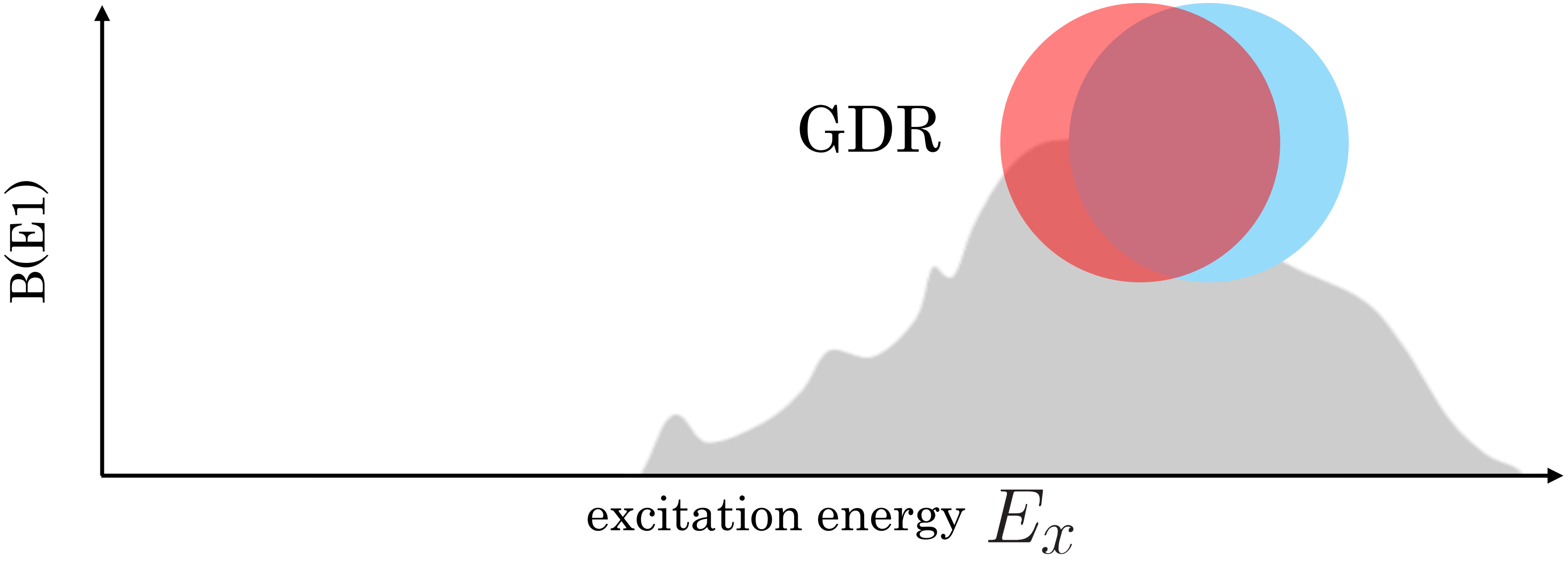
E1 excitation from 0+ state populates 1$^-$ states



◎ The (reduced) probability for the population of the nth 1- state is given as

$$B(E1) = \sum_\mu |\langle J^\pi = 1_n^-, \mu | \mathcal{M}_\mu(E1) | J^\pi = 0^+ \rangle|^2$$

What is “^{26}Ne PDR Problem” ?



Giant Dipole Resonance (GDR)

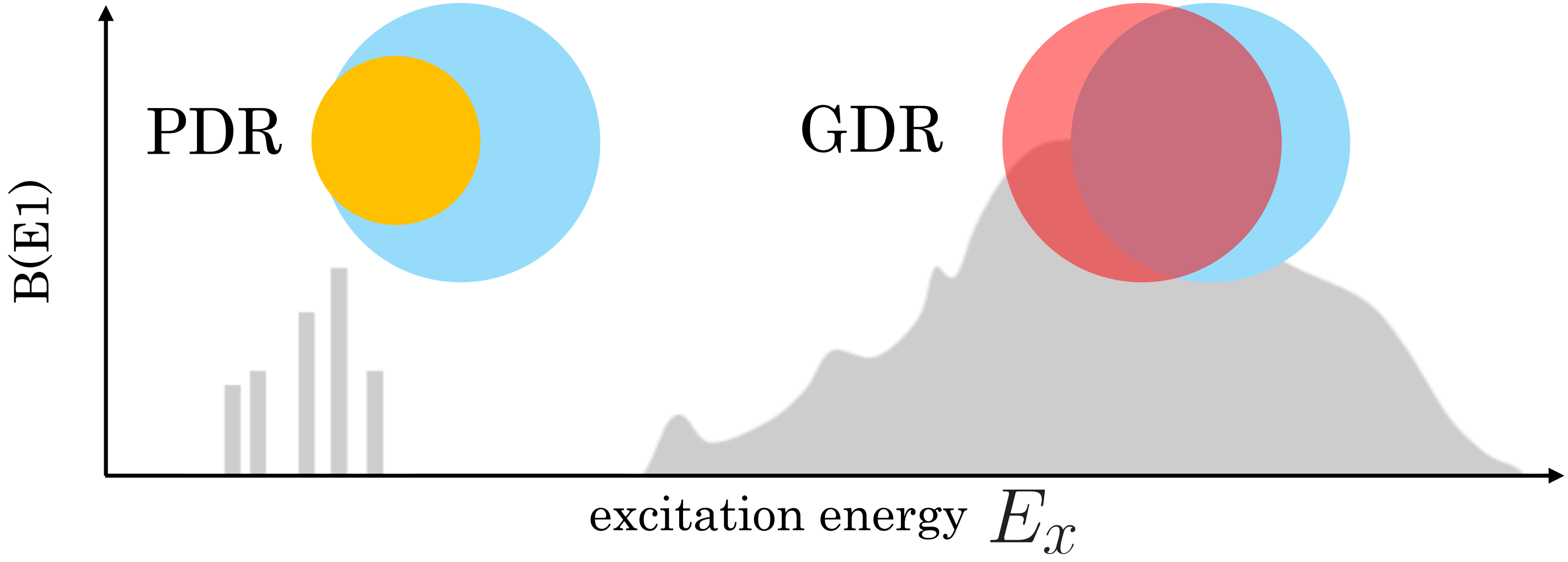
◎ An ordinary and famous vibrational mode of atomic nuclei

◎ Protons and neutrons oscillates in the opposite phase

$$|\mathrm{GDR}\rangle \propto M_\mu(E1)|J^\pi = 0^+\rangle = e \sum_{i\in proton} r_i' Y_{1\mu}(\hat{r}_i')|J^\pi = 0^+\rangle$$

$$= e\left(\frac{N}{A}\sum_{i\in proton} r_i Y_{1\mu}(\hat{r}_i) - \frac{Z}{A}\sum_{i\in neutron} r_i Y_{1\mu}(\hat{r}_i)\right)|J^\pi = 0^+\rangle$$

What is “^{26}Ne PDR Puzzle” ?



Pygmy Dipole Resonance (PDR)

◎ A small fraction of the B(E1) strength appears at small excitation energy

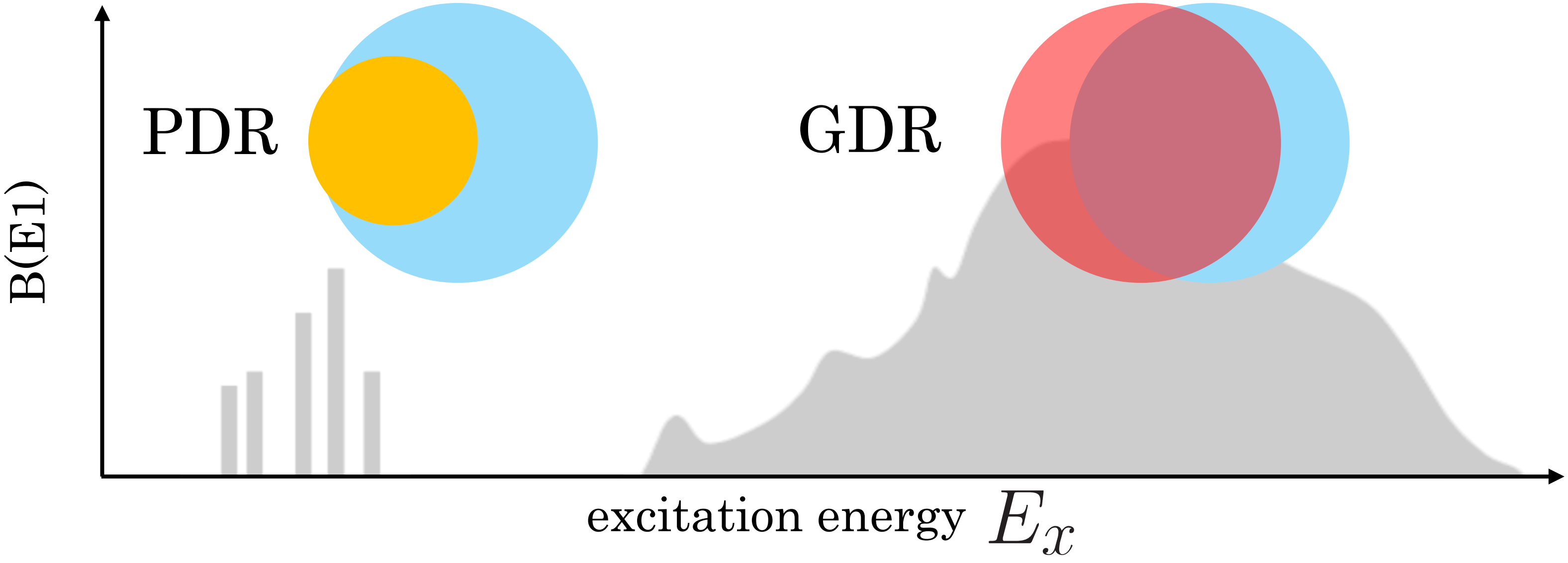
◎ A novel type of vibration mode different from GDR

  − Tightly bound inert core oscillates against the weakly bound neutrons

A.M. Lane, Ann. Phys. 63, 171 (1971)
K. Ikeda, INS Report JHP-7 (1988)

◎ Enhancement in unstable nuclei is expected

What is “^{26}Ne PDR Problem” ?



Pygmy Dipole Resonance (PDR) PDR attracts much interest today.

Nuclear Physics

◎ neutron skin thickness, nuclear symmetry energy

Astrophysics

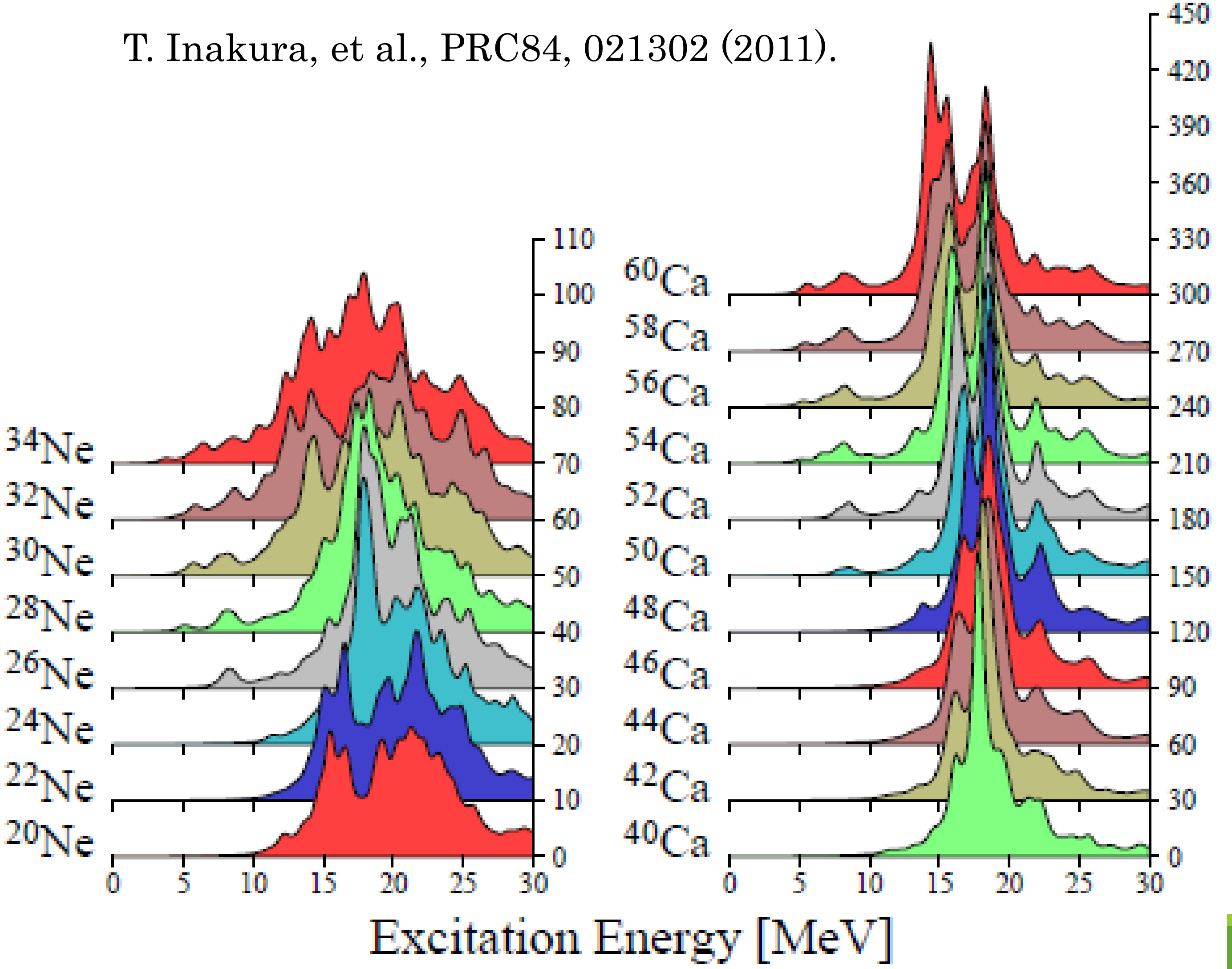
◎ neutron star properties, supernova explosion mechanism

◎ impact on production of r-process elements

What is “^{26}Ne PDR Problem” ?

Recent researches of PDR

T. Inakura, et al., PRC84, 021302 (2011).



What is “^{26}Ne PDR Problem” ?

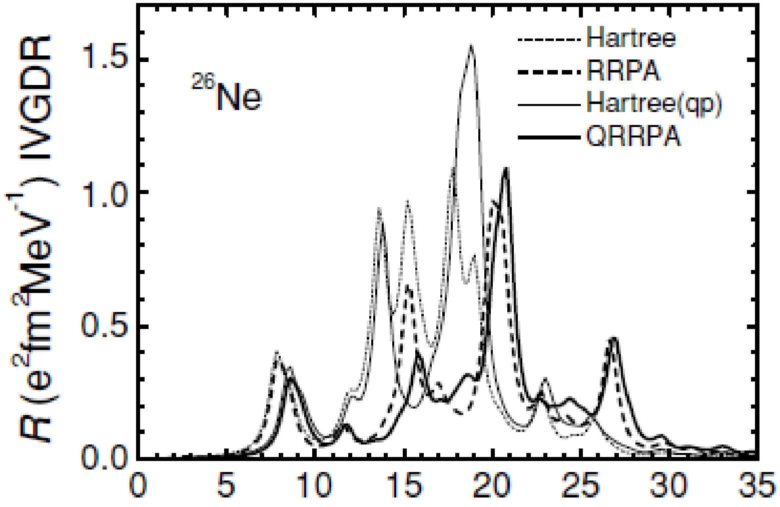
◎ PDR of ^{26}Ne have been studied experimentally and theoretically

◎ Reasonable agreement between theory and experiment
for the energy and B(E1) of ^{26}Ne PDR.

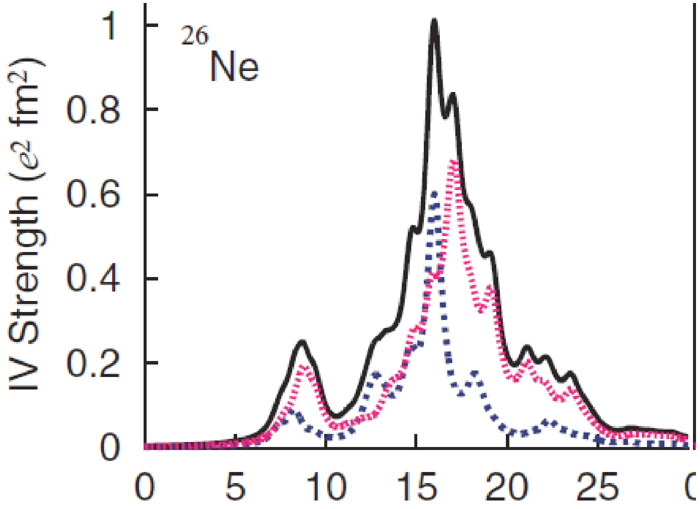
Theory: QRPA calculations

Theoretical studies predict ^{26}Ne PDR at E_x = 6 ~ 10 MeV
whose strength exhausts about 5~10 % of energy weighted sum

L. Cao et al., PRC71, 034305(2005).



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



What is “^{26}Ne PDR Problem” ?

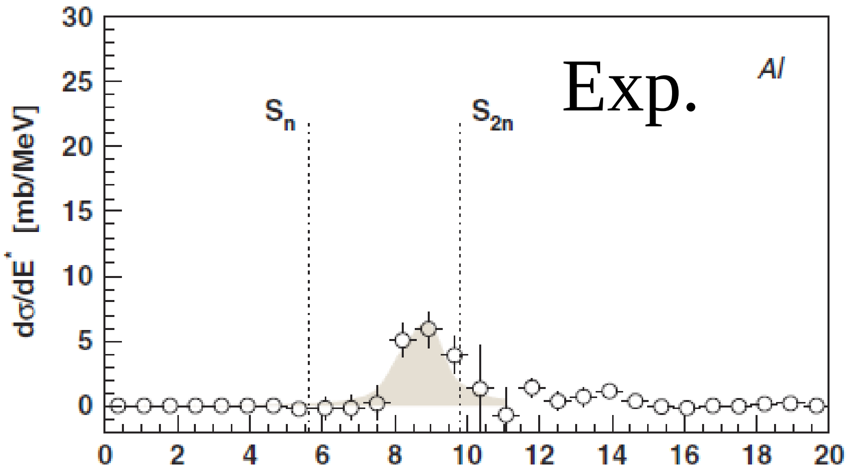
◎ PDR of ^{26}Ne have been studied experimentally and theoretically

◎ Reasonable agreement between theory and experiment for the energy and B(E1) of ^{26}Ne PDR.

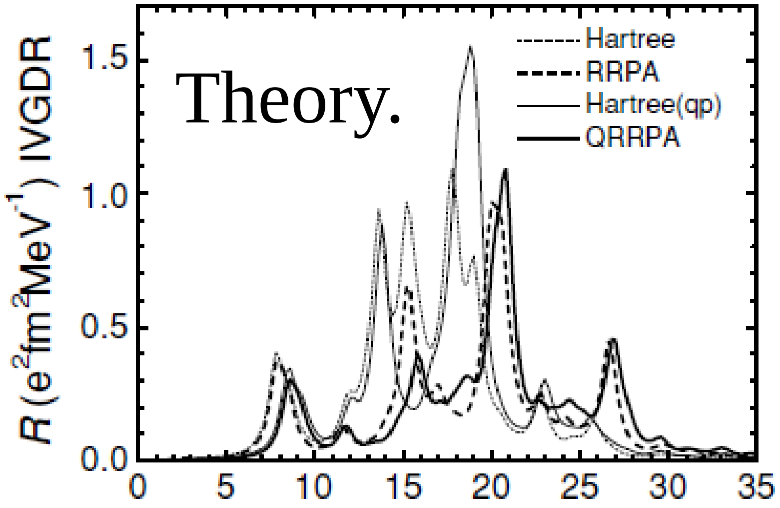
Experiment@RIKEN

PDR of ^{26}Ne is observed at E_x = 9 MeV with the strength of B(E1)=0.49 [e^2fm^2] which exhausts 5 % of energy weighted sum

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



L. Cao et al., PRC71, 034305(2005).

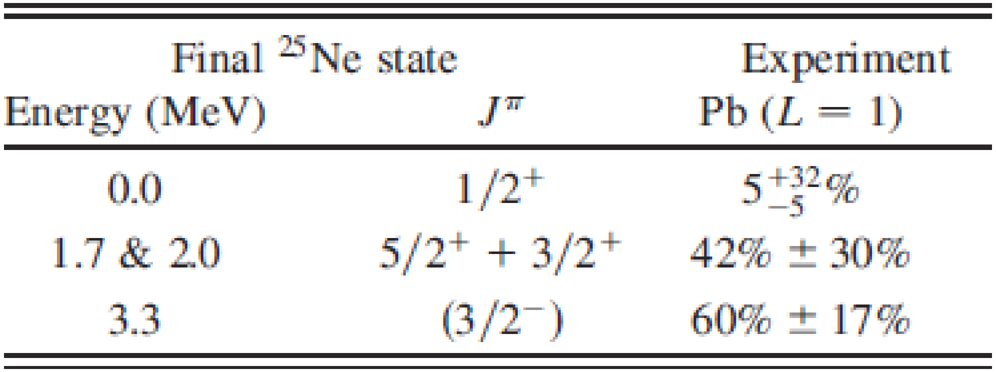


What is “^{26}Ne PDR Problem” ?

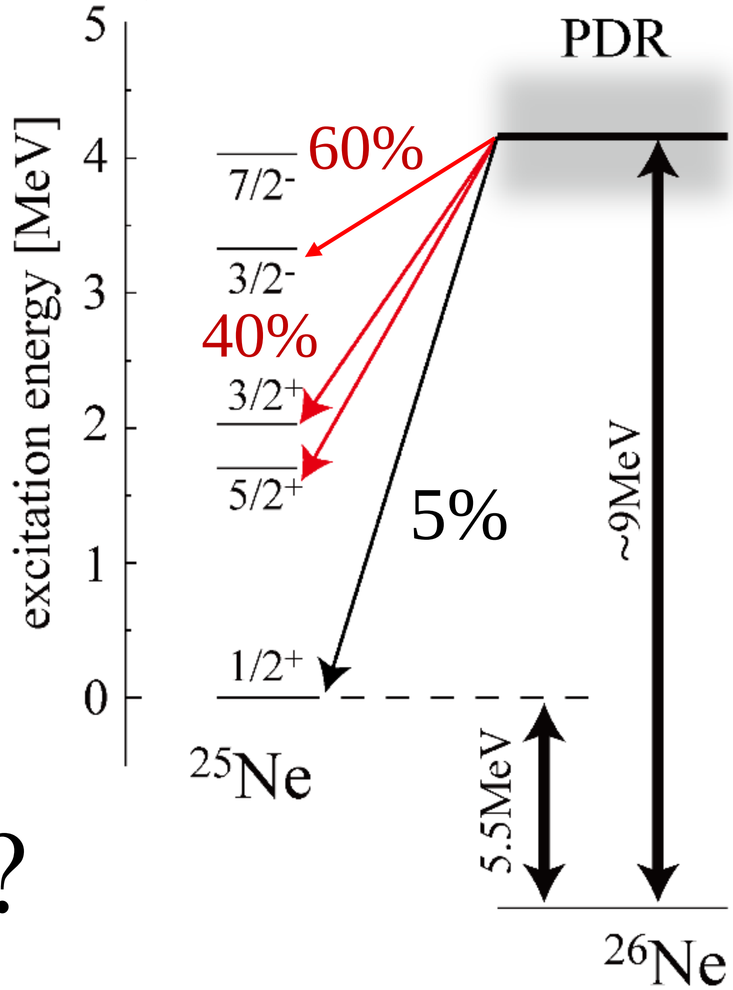
◎ Theory cannot explains the observed decay scheme

Experiment@RIKEN J. Gibelin et al., PRL101, 212503 (2008).

Observed decay pattern of PDR



Final ^{25}Ne state		Experiment
Energy (MeV)	J^{π}	Pb ($L = 1$)
0.0	$1/2^+$	$5^{+32}_{-5}\%$
1.7 & 2.0	$5/2^+ + 3/2^+$	42% ± 30%
3.3	$(3/2^-)$	60% ± 17%



^{26}Ne PDR does not decay to the ground state of ^{25}Ne, but decays to the excited states.

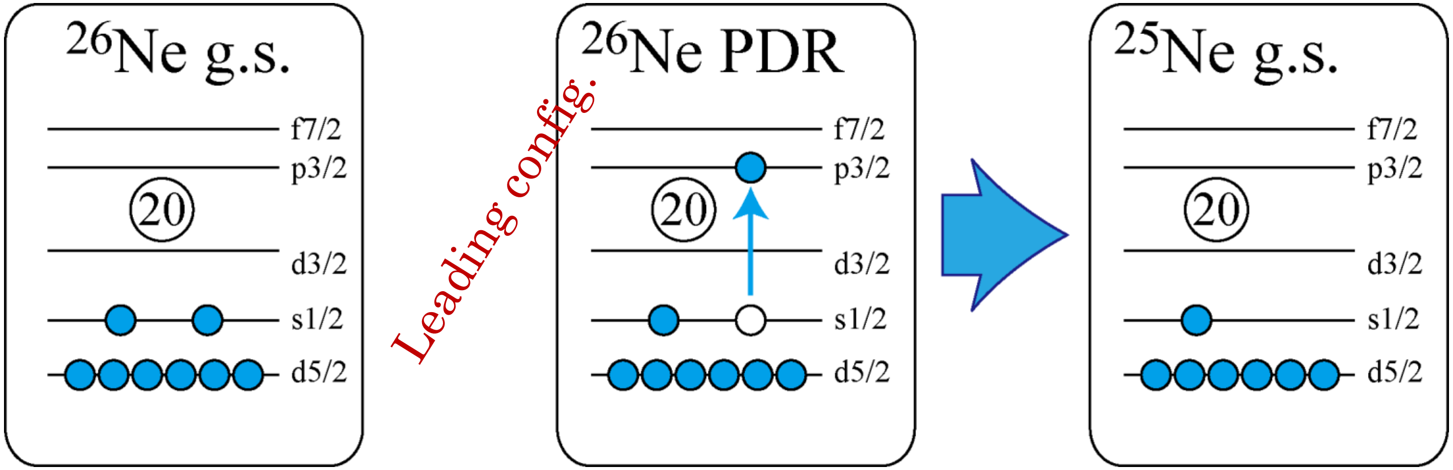
Why this is a problem?

What is “^{26}Ne PDR Problem” ?

◎ Theory cannot explains the observed decay scheme

QRPA calculations suggest that

the $(s_{1/2})^{-1}(p_{3/2})^{1}$ is the leading configuration of PDR



⇒ PDR should dominantly decay to the g.s. of ^{25}Ne

<u>PDR Problem</u>

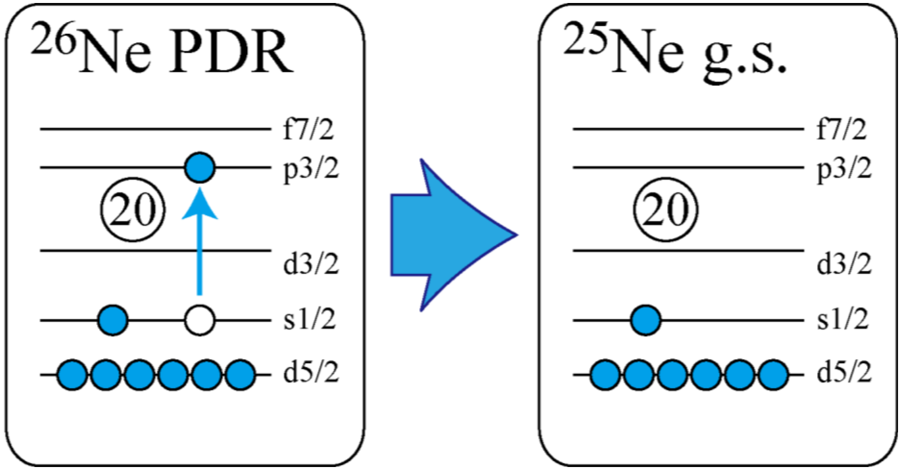
◎ Energy and strength of PDR are reasonably described by QRPA

◎ Decay pattern cannot be explained by QRPA

How the PDR problem can be solved ?

◎ PDR is a superposition of many configurations (collective state). Therefore, its decay pattern cannot be naively discussed by only the leading configuration of PDR.

?



○ Decay pattern should be estimated

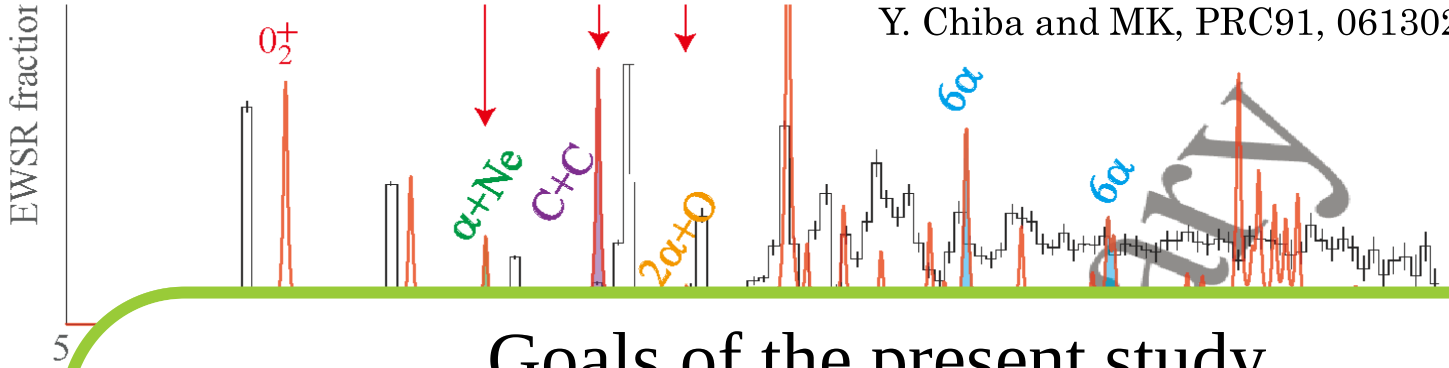
⇒ Structure of PDR must be understood based on spectroscopic observables such as S-factors

⇒ Reason for the decay to the excited states should be explained.

Research by Antisymmetrized Molecular Dynamics

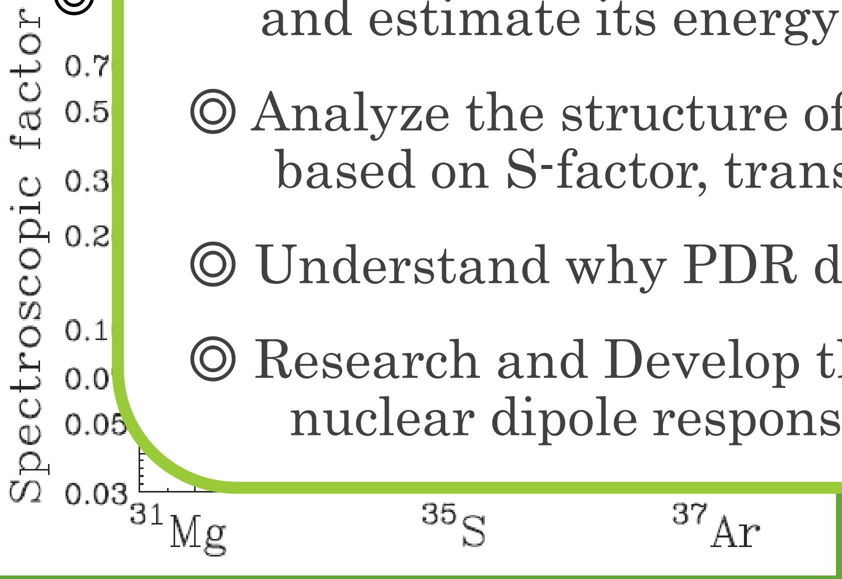
Response function

◎ Monopole response of ^{24}Mg has been successfully described by AMD



Y. Chiba and MK, PRC91, 061302.

◎



Goals of the present study

◎ Theoretically investigate the ^{26}Ne PDR (and GDR) and estimate its energy and strength

◎ Analyze the structure of PDR based on S-factor, transition density, etc.

◎ Understand why PDR decays to the excited state of ^{25}Ne

◎ Research and Develop the methodology to describe nuclear dipole response by AMD

Theoretical Framework

◎ Microscopic Hamiltonian: Gogny D1S, D1M, D1N interactions

$$H=\sum_{i=1}^{A} t_i - t_{\mathrm{c.m.}} + \sum_{i<j}^{A} v_{\mathrm{NN}}(r_{ij}) + \sum_{i<j}^{Z} v_{\mathrm{Coul}}(r_{ij})$$

◎ Variational wave function: Gaussian wave packets

$$\Phi^{\pi}=\frac{1+\pi P_r}{2}\mathcal{A}\left\{\varphi_1\varphi_2\cdots\varphi_A\right\}$$

$$\varphi_i(\boldsymbol{r})=\exp\left\{-\nu_x\left(x-Z_{ix}\right)^2-\nu_y\left(y-Z_{iy}\right)^2-\nu_z\left(z-Z_{iz}\right)^2\right\}$$
$$\otimes\left\{a_i|\uparrow\rangle+b_i|\downarrow\rangle\right\}\otimes\left\{|n\rangle \text{ or } |p\rangle\right\}$$

Variational parameters: $\underline{\boldsymbol{Z}_1,\ldots,\boldsymbol{Z}_A},\ \underline{a_1,\ldots,a_A,b_1,\ldots,b_A},\ \underline{\nu_x,\nu_y,\nu_z}$

Ganssian centroids in phase space

spin orientation

size and shape of wave packets

Theoretical Framework

◎ Angular momentum projection and Superposition of the wave functions

- ○ variational wave functions Φ^{π} are projected to the eigenstates of J and superposed to describe the ground and excited states

$$\Psi_{\alpha}^{J\pi} = \sum_{i} c_{\alpha i} P_{MK}^{J} \Phi_{i}^{\pi}$$

P_{MK}^{J}: angular momentum projector

Φ_{i}^{π} : variational wave functions with different structure, configurations etc…

- ○ Coefficients $c_{\alpha i}$ of the wave function is determined by the diagonalization of the Hamiltonian

$$\sum_{j} (H_{ij} - E_{\alpha} N_{ij}) c_{j\alpha} = 0$$

$$H_{ij} = \langle P_{MK}^{J} \Phi_i | H | P_{MK'}^{J} \Phi_j \rangle$$
$$N_{ij} = \langle P_{MK}^{J} \Phi_i | P_{MK'}^{J} \Phi_j \rangle$$

It is essential to prepare basis wave functions Φ_i in an efficient way for the description of dipole response

Theoretical Framework & Results

◎How to prepare Φ_i ?

① Energy variation with constraint on nuclear deformation

- Minimize the energy for each given value of nuclear deformation
- Wave functions with different deformation are generated
- Efficient for the description of the low-lying states

$$E' = \underbrace{\frac{\langle \Phi^\pi | H | \Phi^\pi \rangle}{\langle \Phi^\pi | \Phi^\pi \rangle}}_{\text{energy}} + \underbrace{v_\beta \left(\frac{\langle \Phi^\pi | \beta | \Phi^\pi \rangle}{\langle \Phi^\pi | \Phi^\pi \rangle} - \beta_0 \right)^2}_{\text{constraint on nuclear deformation}}, \quad v_\beta \gg 1$$

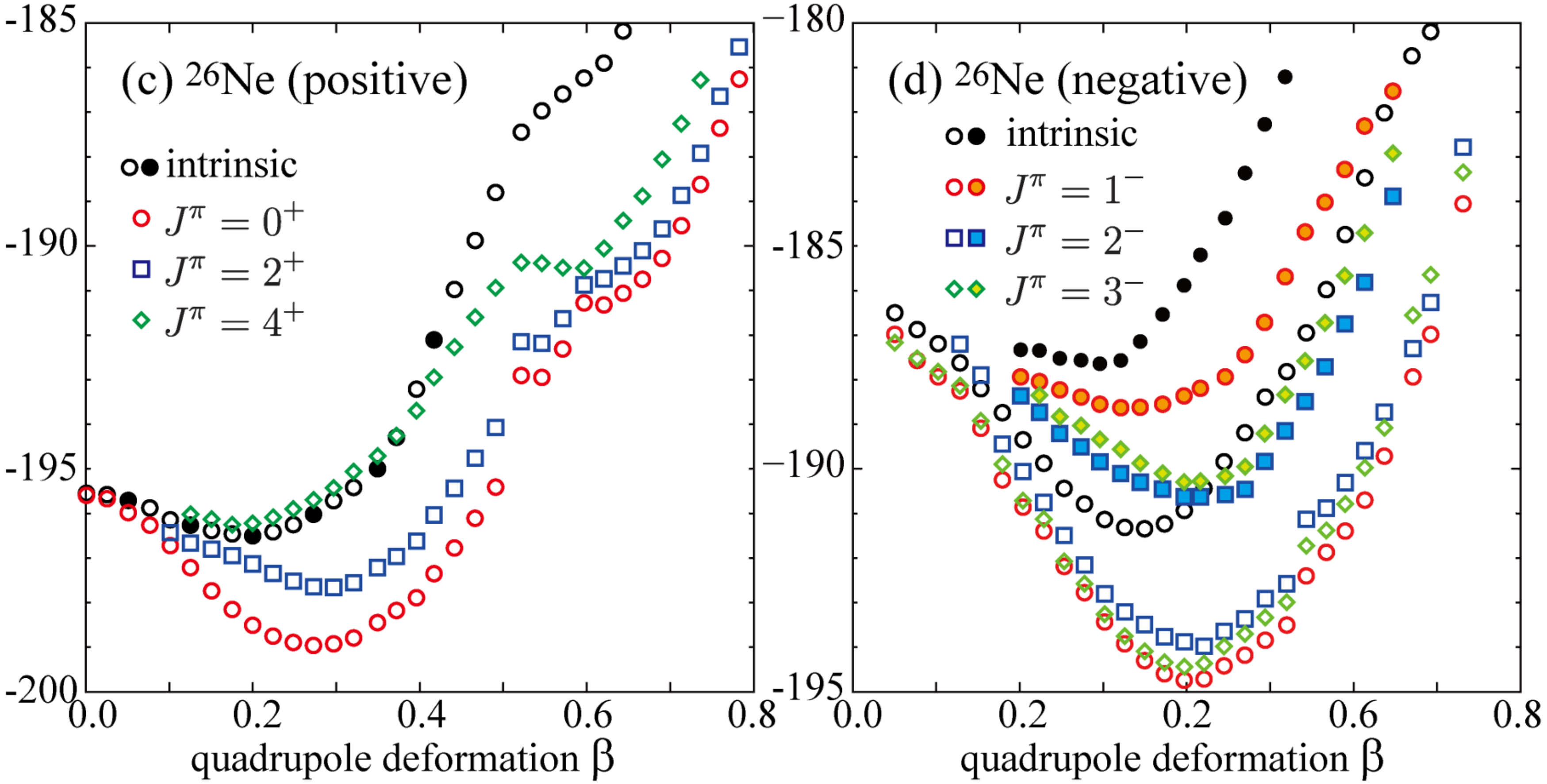
Imaginary time development e.q.

$$\frac{d}{d\tau} X_i = \mu \frac{\partial E'}{\partial X_i^*}, \qquad X_i \in \boldsymbol{Z}_1, \ldots, \boldsymbol{Z}_A, a_1, \ldots, a_A, b_1, \ldots, b_A, \nu_x, \nu_y, \nu_z$$

Theoretical Framework & Results

◎How to prepare Φ_i ?

① Energy variation with constraint on nuclear deformation

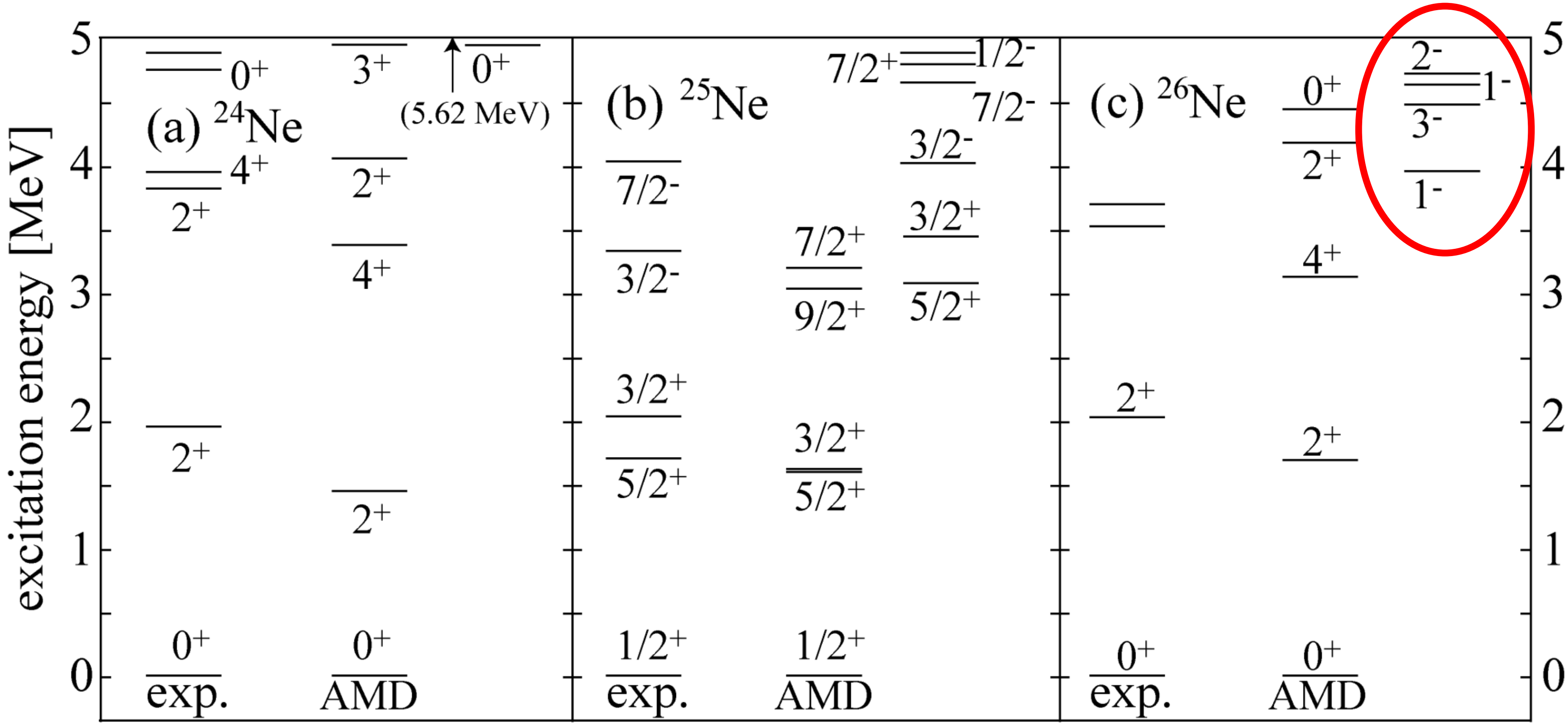


Theoretical Framework & Results

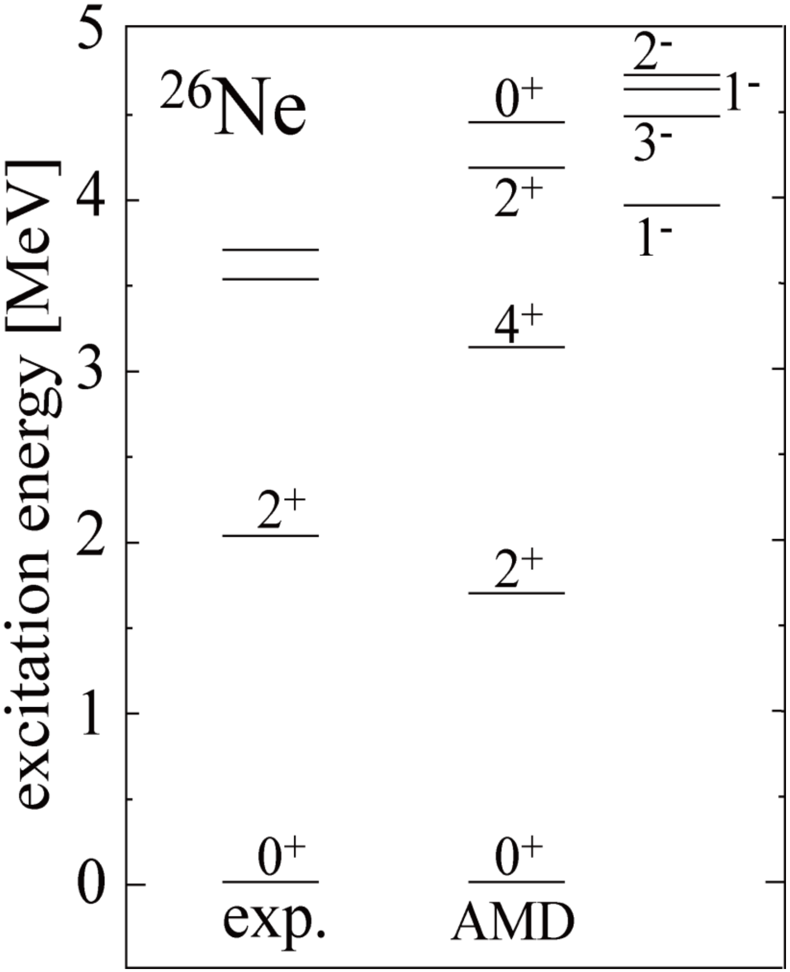
◎How to prepare Φ_i ?

① Energy variation with constraint on nuclear deformation

neutron ex.
$(sd)^{-1}(pf)^{1}$



Discussions: S-factor of ^{26}Ne G.S.



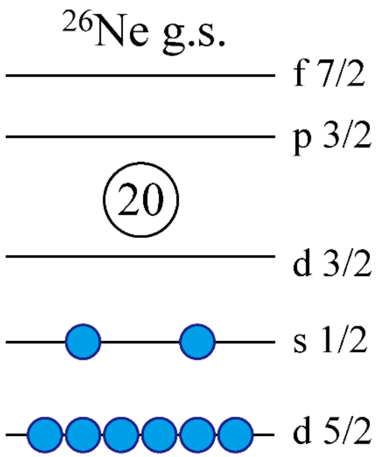
◎ Reasonable reproduction of the low-lying spectrum

◎ Configuration of the ground state looks OK.

Spectroscopic Factor of the ^{26}Ne g.s.

$\langle {}^{25}\mathrm{Ne}(J) | {}^{26}\mathrm{Ne}(0^+) \rangle$

	${}^{25}\mathrm{Ne}(1/2^+) \otimes s_{1/2}$	${}^{25}\mathrm{Ne}(3/2^+) \otimes d_{3/2}$	${}^{25}\mathrm{Ne}(5/2^+) \otimes d_{5/2}$
Exp.	1.4	0.5	1.3
Calc.	1.1	0.5	1.4



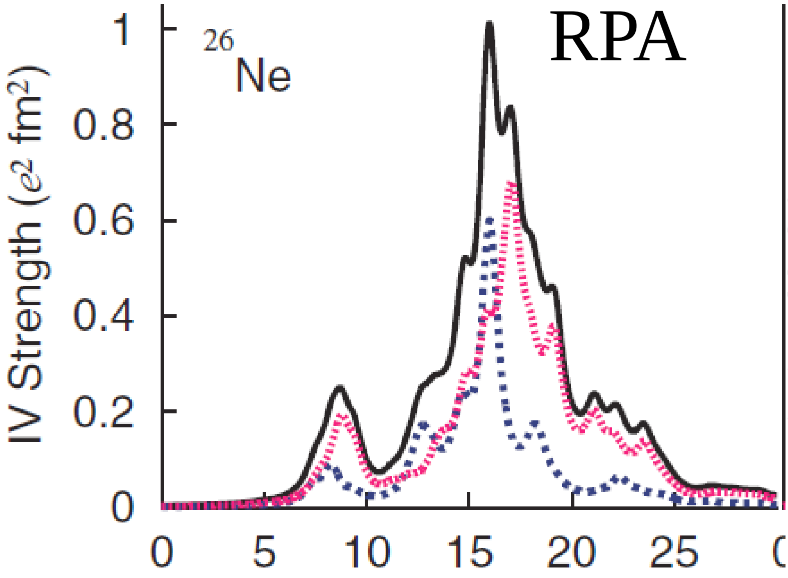
Theoretical Framework & Results

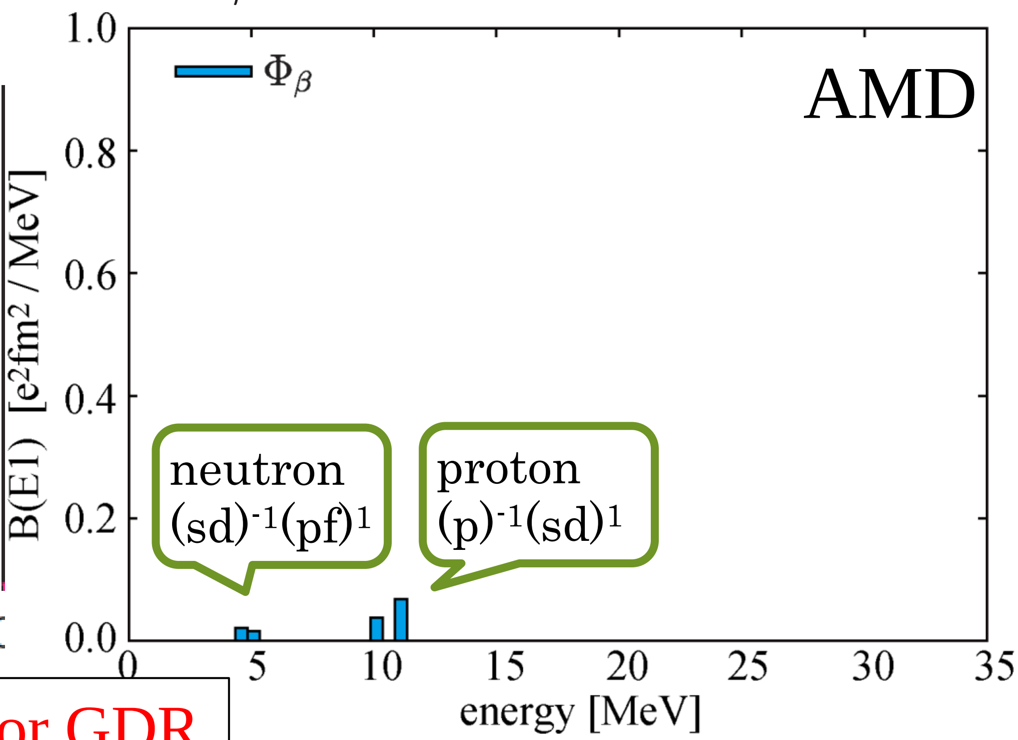
◎How to prepare Φ_i ?

① Energy variation with constraint on nuclear deformation

$$B(E1) = \sum_{\mu} |\langle J^{\pi} = 1^{-}_{n}, \mu | \mathcal{M}_{\mu}(E1) | J^{\pi} = 0^{+} \rangle|^2$$

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





This method does not work for GDR

Theoretical Framework & Results

◎How to prepare Φ_i ?

② Multiply dipole operator on Φ_β obtained by the method ①

- Method ① works fine for g.s. of ^{26}Ne
- $|\mathrm{GDR}\rangle \propto M_\mu(E1)|J^\pi = 0^+\rangle = e \sum_{i\in proton} r'_i Y_{1\mu}(\hat{r}'_i)|J^\pi = 0^+\rangle$

New basis wave functions are generated

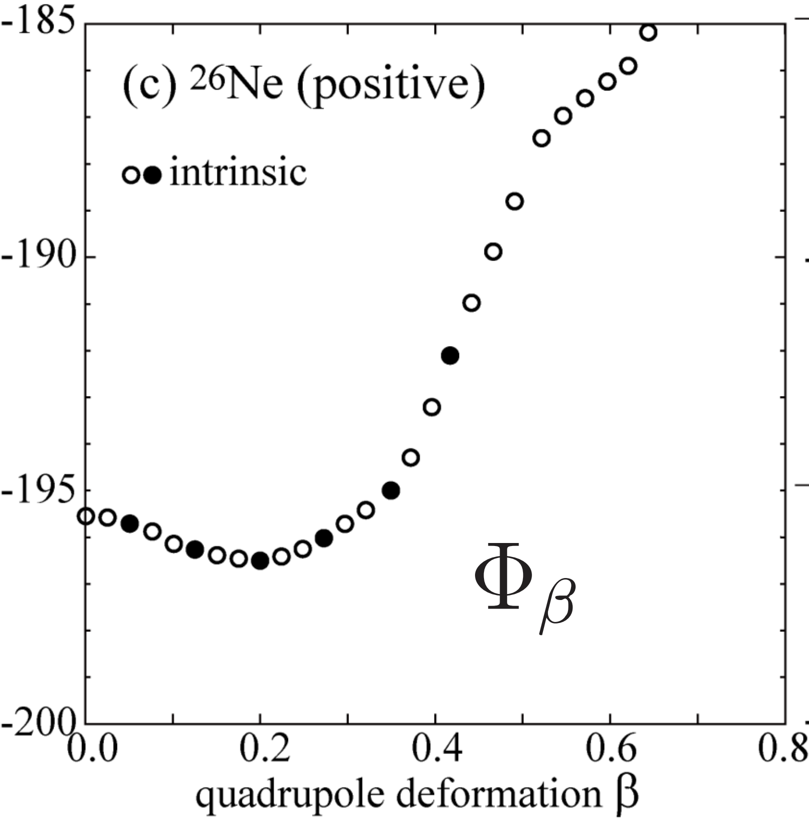
$$\Phi_{\Delta Z} = (e^{\alpha\mathcal{M}_\mu(E1)} - 1)\Phi_\beta$$

$$\simeq \alpha\mathcal{M}_\mu(E1)\Phi_\beta \quad \text{for } \alpha \ll 1$$

$$e^{\alpha\mathcal{M}_\mu(E1)}\Phi_\beta(\boldsymbol{Z}_1, ..., \boldsymbol{Z}_A)$$

$$= \sum_i^A \Phi_\beta(\boldsymbol{Z}_1, ..., \boldsymbol{Z}_i + \Delta Z_i, ..., \boldsymbol{Z}_A)$$

$$\Delta Z_i = \alpha(\tau_z)_i \frac{e_\mu}{\nu_\mu}$$

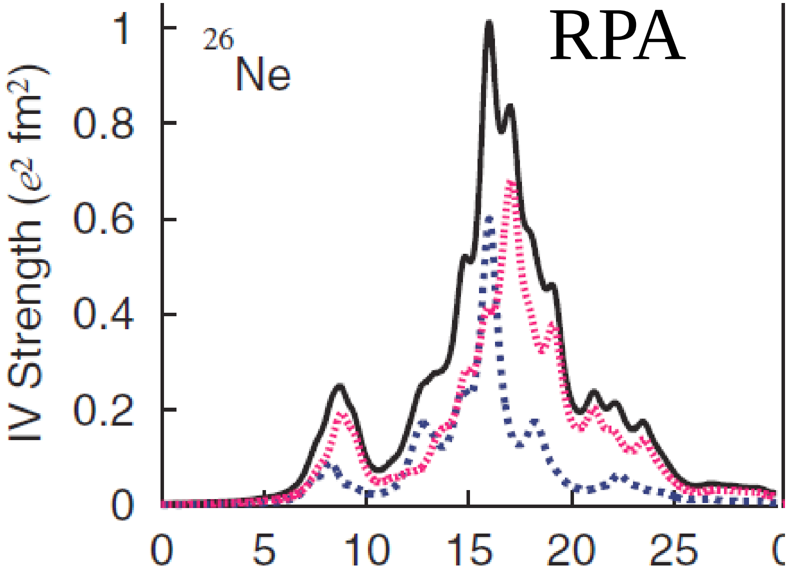


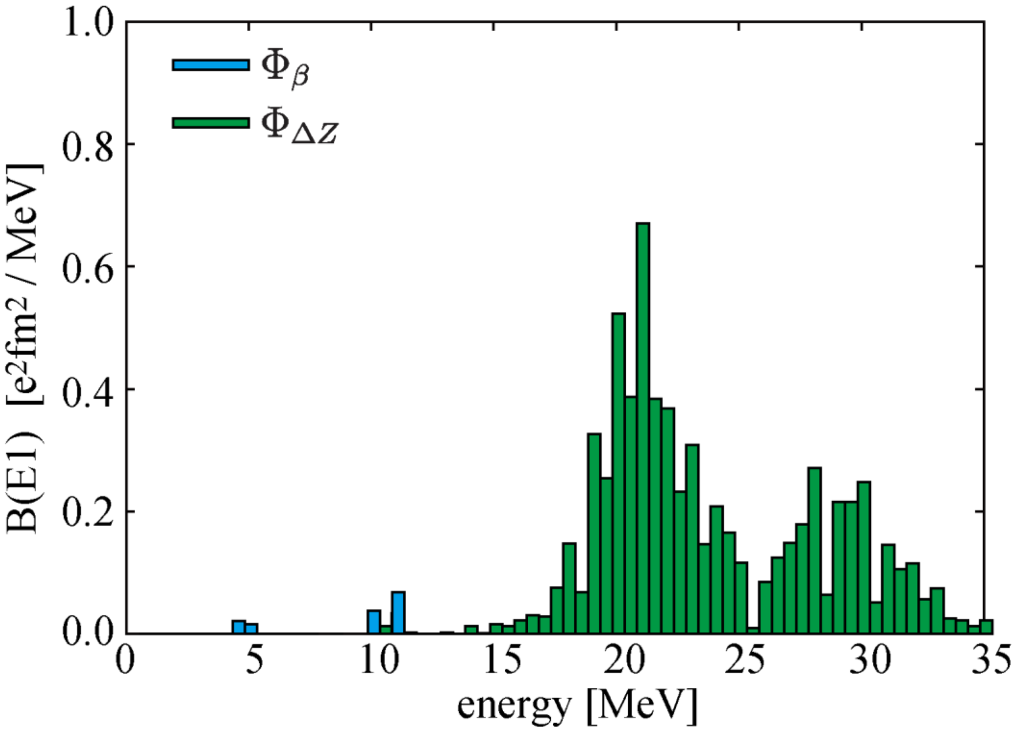
Theoretical Framework & Results

◎How to prepare Φ_i ?

② Multiply dipole operator on Φ_β obtained by the method ①

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





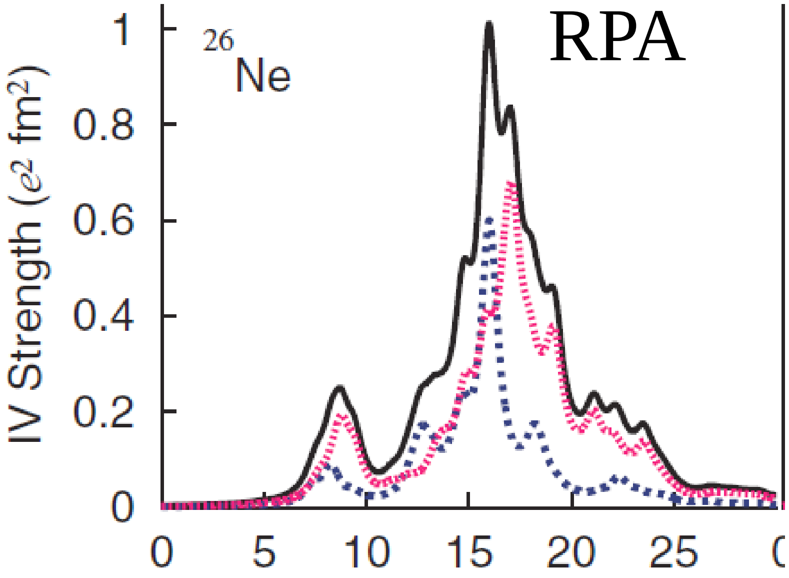
Theoretical Framework & Results

◎How to prepare Φ_i ?

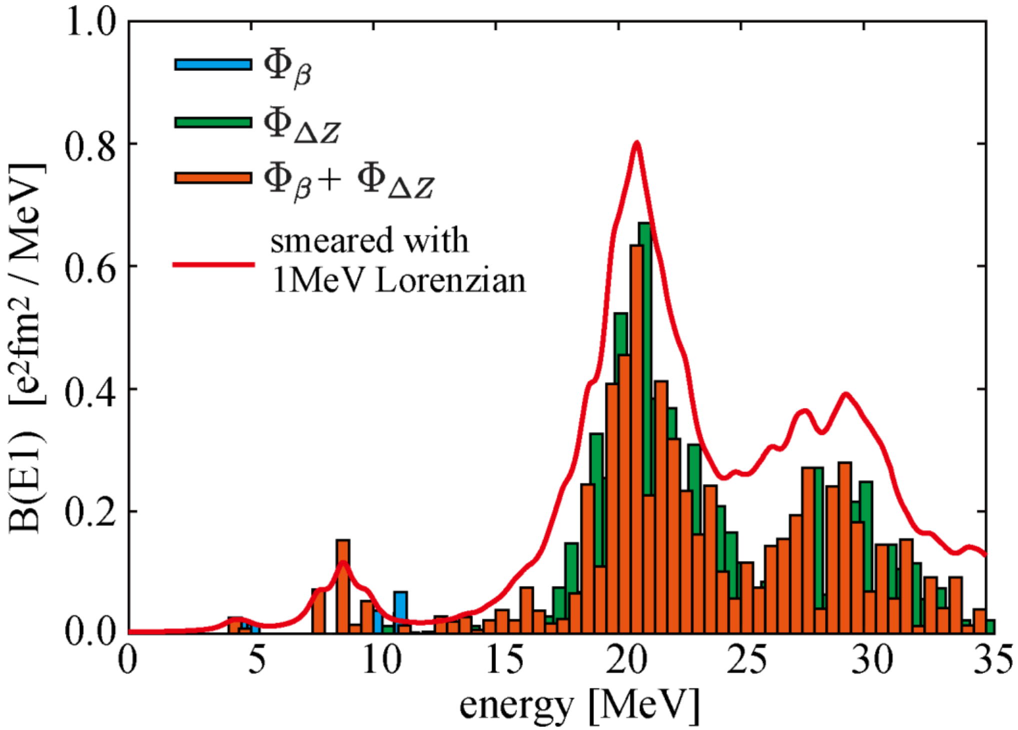
Combine both methods ① and ②

① Energy variation with constraint on nuclear deformation Φ_β

② Multiply dipole operator on Φ_i^π obtained by the method $\Phi_{\Delta Z}$



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



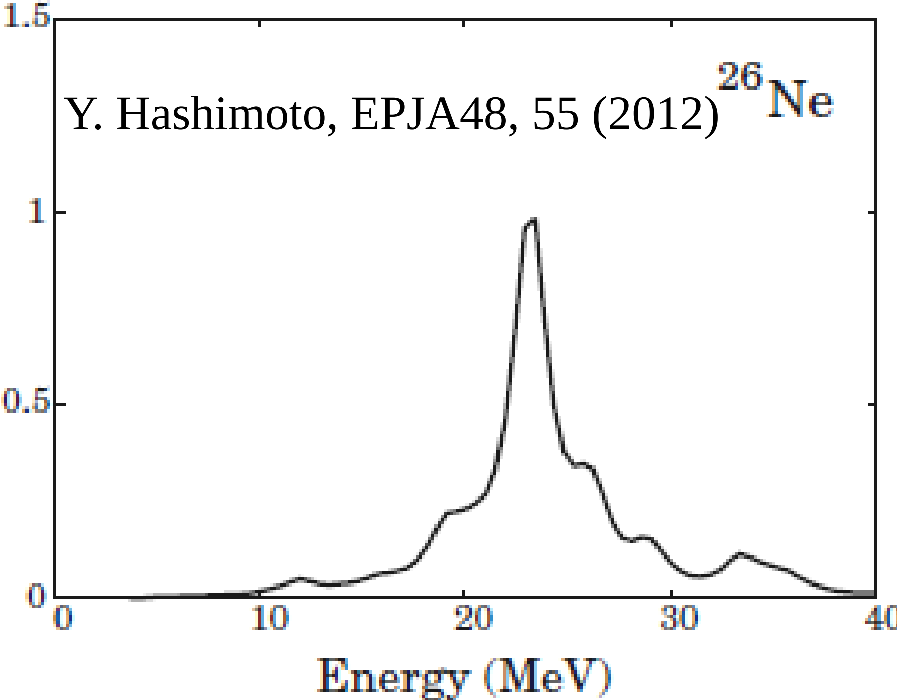
Results: Sum rules

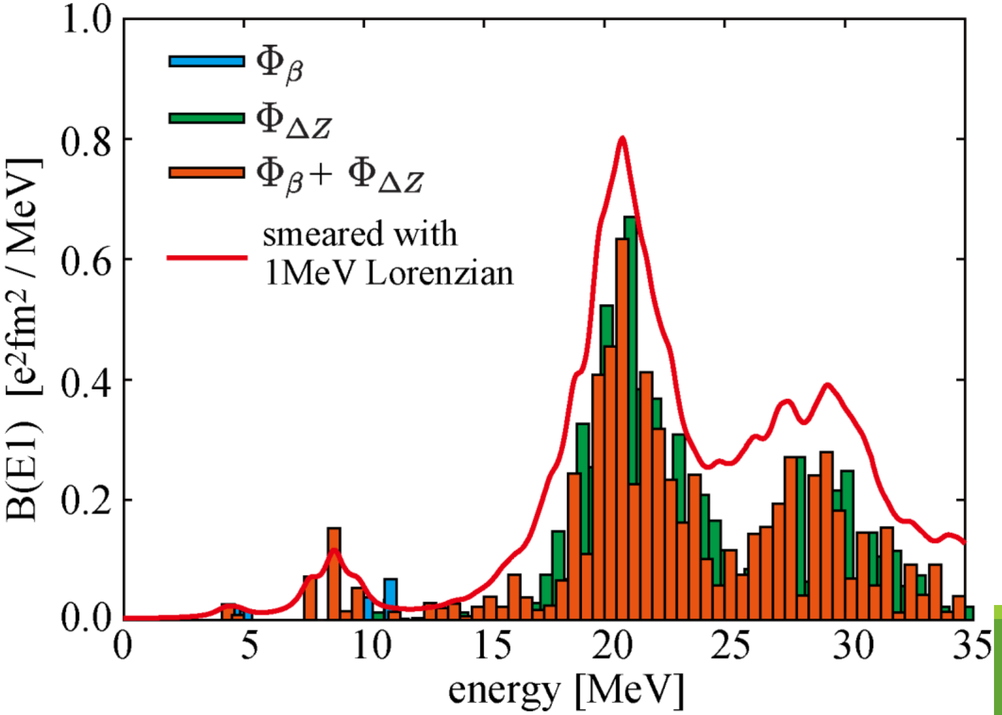
$$m_n = \int_0^{40\mathrm{MeV}} dE\ E^n B(E1;E)$$

	m_1 (EWSR) [e^2fm^2MeV]	GDR peak position	m_1/m_0
present result	183.3	21.5 MeV	23.4 MeV
Peru et al	−	21.9 MeV	−
Hashimoto	181.3	22.5 MeV	24.5 MeV

m_{TRK} = 127 e^2fm^2MeV

$m_{TRK}(1+\kappa)$ = 175 e^2fm^2MeV


Y. Hashimoto, EPJA48, 55 (2012)



Discussions: Structure of ^{26}Ne PDR

PDR properties

◎ Neutron and proton single-particle excited states exist around 5 and 10 MeV

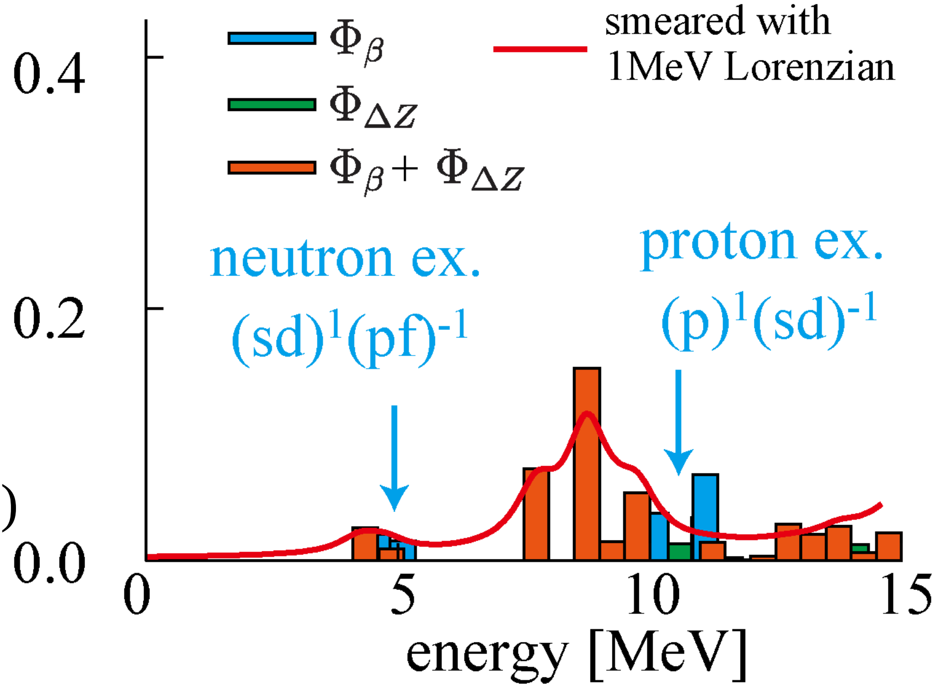
◎ Those single particle excitations are coupled with many other excited states and gain collectivity.

	Ex (MeV)	B(E1) e^2fm^2
3rd 1-	7.6 MeV	0.09
4th 1-	8.4 MeV	0.19
5th 1-	8.9	0.02
6th 1-	9.4 MeV	0.07

B(E1)=0.49±0.16 [e^2fm^2]

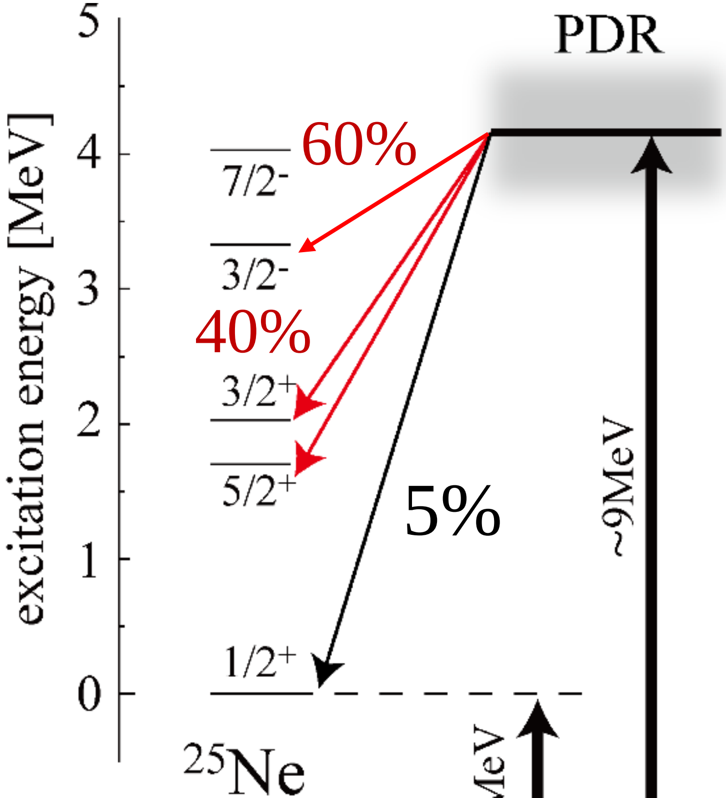
◎ PDR energy is 8.5 MeV (EXP: 9 MeV)

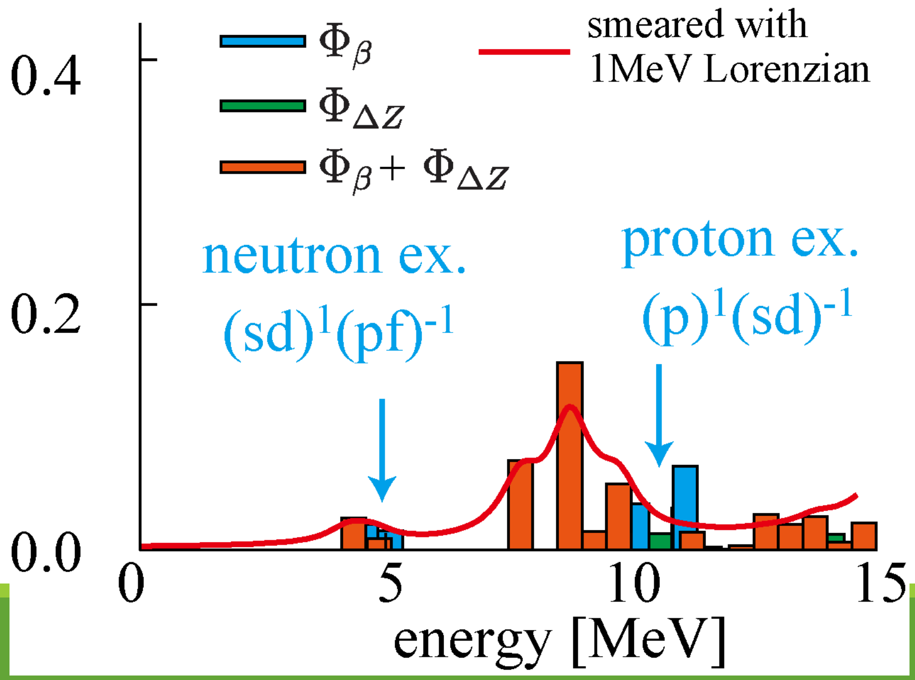
◎ PDR exhausts about 4% of TRK (EXP: 5%)



Discussions: S-factor of ^{26}Ne PDR

	$^{25}\mathrm{Ne}(g.s.)$ $\otimes p_{3/2}$	$^{25}\mathrm{Ne}(3/2^{+})$ $\otimes p_{3/2}$	$^{25}\mathrm{Ne}(5/2^{+})$ $\otimes p_{3/2}$	$^{25}\mathrm{Ne}(3/2^{-})$ $\otimes s_{1/2}$
3rd 1-	0.1	0.4	**1.2**	0.3
4th 1-	0.3	0.3	**1.1**	0.3
5th 1-	0.2	0.2	0.3	**0.7**
6th 1-	0.1	**1.1**	0.2	0.5





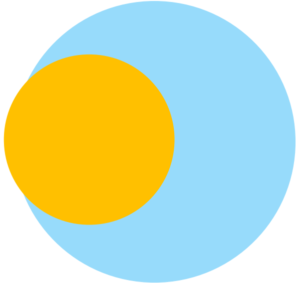
Discussions: Why PDR is dominated by $^{25}\mathrm{Ne}^*$

◎ PDR is a linear combination of M(E1) and M(IS1)

$$|GDR\rangle \simeq M(E1)|0^+\rangle$$

$$|PDR\rangle \simeq \alpha M(E1)|0^+\rangle + \beta M(IS1)0^+\rangle$$

PDR



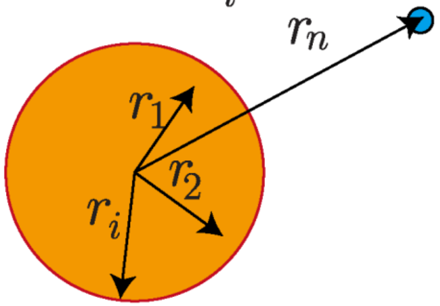
$$M(IS1) = \sum_i r_i'^3 Y_{1\mu}(\hat{r}_i')$$

◎ M(IS1) involves $\Delta\ell = 2^+$ excitation of core nuclei

$$M(IS1) = \sum_i r_i'^3 Y_{1\mu}(\hat{r}_i') = \underbrace{\sum_{i\in {}^{25}\mathrm{Ne}} r_i^3 Y_{1\mu}(\hat{r}_i)}_{^{25}\text{Ne IS dipole}} + \underbrace{\frac{5}{3A}\left(\sum_{i\in {}^{25}\mathrm{Ne}} r_i^2\right) r_n Y_{1\mu}(\hat{r}_n)}_{^{25}\text{Ne monopole} \otimes {}^{25}\text{Ne - } n \text{ dipole}}$$

$$\underbrace{-\frac{(A-1)(A-2)}{A^2} r_n^3 Y_{1\mu}(\hat{r}_n)}_{^{25}\text{Ne - } n \text{ compressional dipole}}$$

$$\underbrace{-\frac{4\sqrt{2\pi}}{3A}\left[\left(\sum_{i\in {}^{25}\mathrm{Ne}} r_i^2 Y_2(\hat{r}_i)\right) \otimes r_n Y_1(\hat{r}_n)\right]_{2\mu}}_{^{25}\text{Ne quadrupole} \otimes {}^{25}\text{Ne - } n \text{ dipole}}$$



r_i' : nucleon coordinate from c.m.

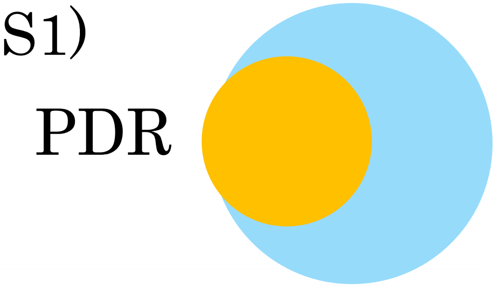
r_n : ^{25}Ne- n relative coordinate

r_i : ^{25}Ne intrinsic coordinate

Discussions: Why PDR is dominated by ^{25}Ne*

◎ PDR is a linear combination of M(E1) and M(IS1)

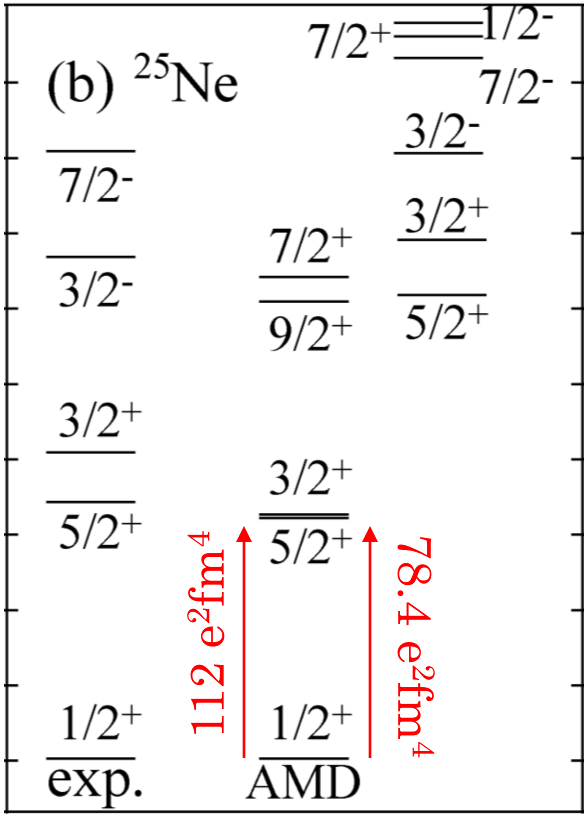
$$|PDR\rangle \simeq \alpha M(E1)|0^+\rangle + \beta M(IS1)0^+\rangle$$



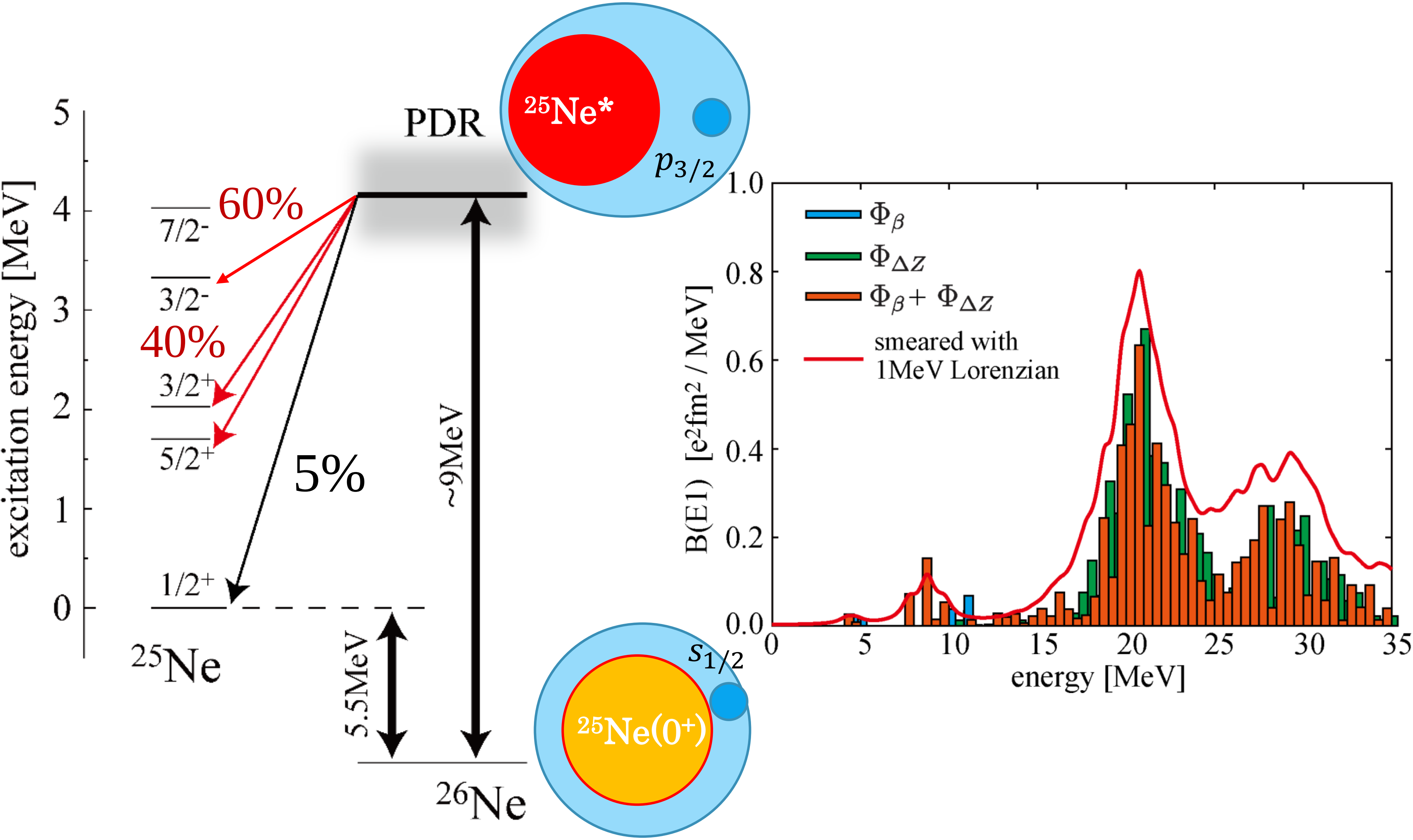
◎ M(IS1) involves $\Delta\ell = 2^+$ excitation of core nuclei

$$M(IS1) = \underbrace{-\frac{4\sqrt{2\pi}}{3A}\left[\left(\sum_{i\in{}^{25}\mathrm{Ne}} r_i^2 Y_2(\hat{r}_i)\right)\otimes r_n Y_1(\hat{r}_n)\right]_{2\mu}}_{^{25}\mathrm{Ne}\text{ quadrupole }\otimes{}^{25}\mathrm{Ne}\text{ - }n\text{ dipole}} + \ldots$$

⇒ [Conjecture] If PDR has IS component and the core nucleus has low-lying large B(E2), the core excitation with $\Delta\ell = 2^+$ occurs



Core excitation in ^{26}Ne PDF



Summary & Perspective

Summary

◎ Campaign on monopole strengths and clusters is in progress
AMD looks working well and promising

- ○ Monopole strength and Clusters in ^{24}Mg, ^{28}Si
- ○ IV dipole strength, PDR in ^{26}Ne

Perspective

◎ Campaign on monopole strengths and clusters is in progress
AMD looks working well and promising

- ○ Monopole strength in the island of inversion (^{30}Ne and ^{32}Mg)
- ○ GT response function and cluster states in ^{22}Ne and ^{22}Na