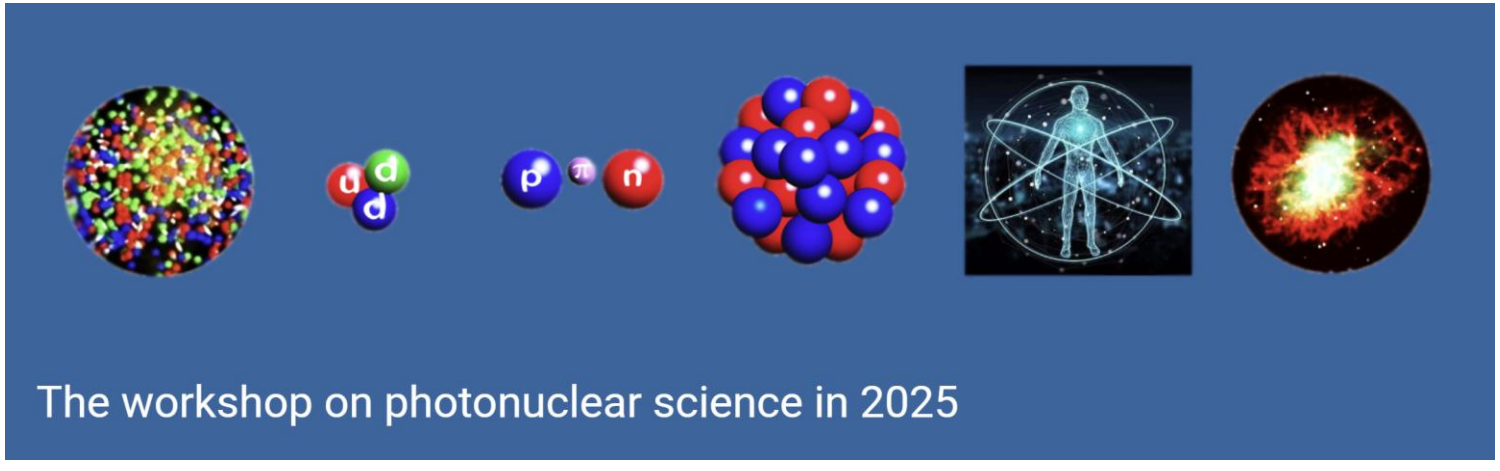
Study on the Collectivity of Particle-Hole Configurations and Spreading Width for Nuclear Resonances

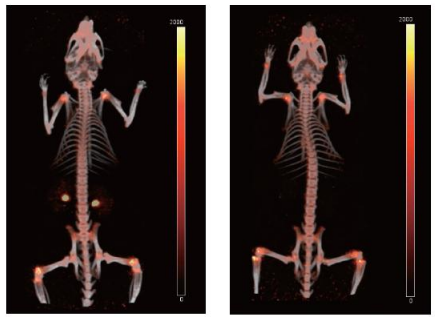
Futoshi Minato
Kyushu University

https://napp.fudan.edu.cn/event/322/



Applications of Nuclear Physics

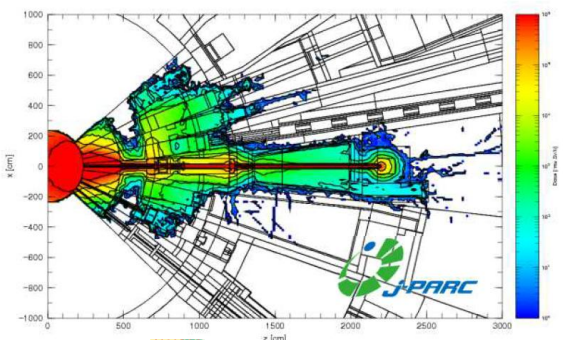
Medical Purpose/Radioactive protections



Medical RI Productions

K. Hashimoto et al., JPSJ84, 043202 (2015)

(figure from Univ. Tokyo)

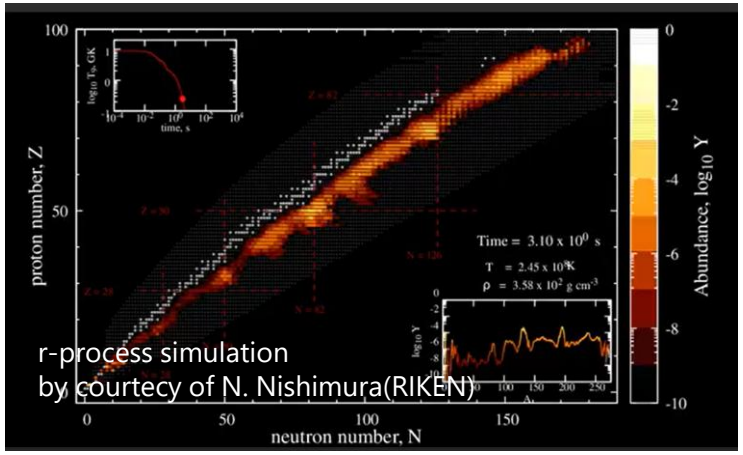


PHITS

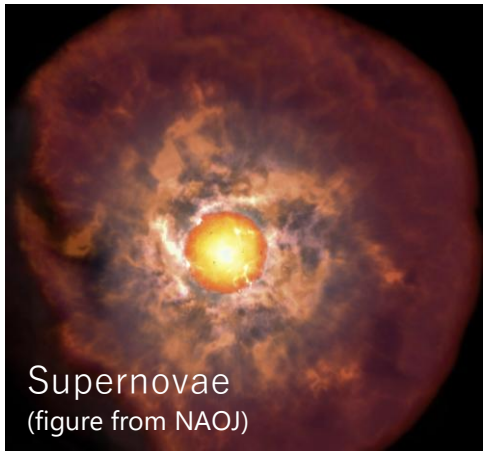
Energy & Decommissioning

(figure from TERRAPOWER)

Astrophysical Purpose



r-process simulation
by courtecy of N. Nishimura(RIKEN)

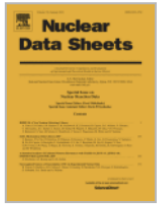


(figure from NAOJ)

ELSEVIER

Nuclear Data Sheets

Volume 163, January 2020, Pages 109-162

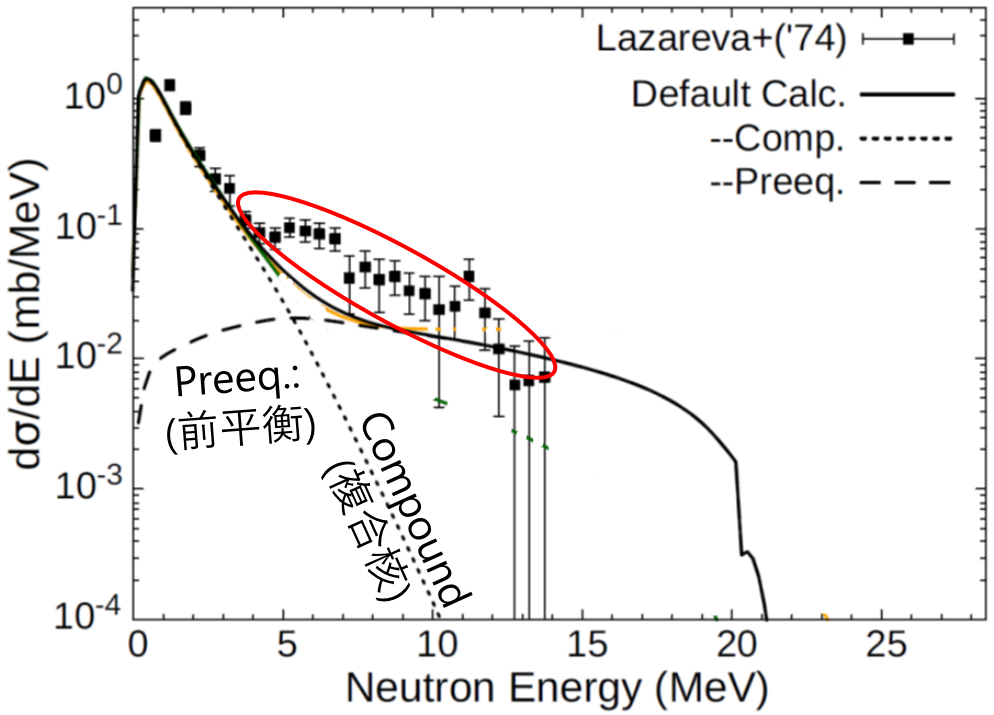


IAEA Photonuclear Data Library 2019

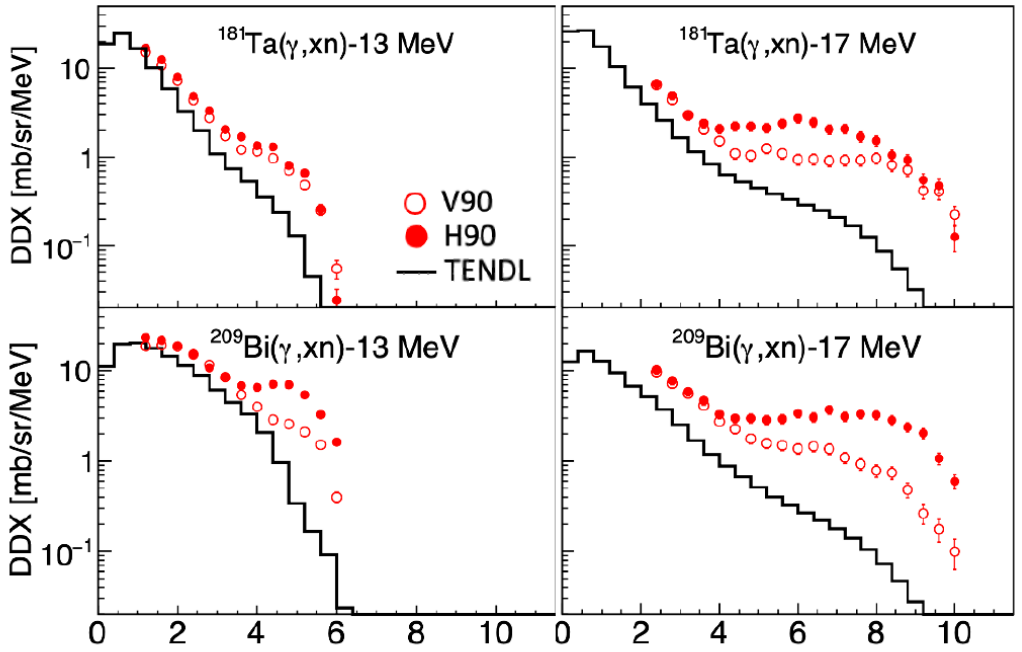
T. Kawano [a], Y.S. Cho [b], P. Dimitriou [c], D. Filipescu [d], N. Iwamoto [e], V. Plujko [f], X. Tao [g], H. Utsunomiya [h], V. Varlamov [i], R. Xu [g], R. Capote [c], I. Gheorghe [d], O. Gorbachenko [f], Y.L. Jin [g], T. Renstrøm [j], M. Sin [k], K. Stopani [i], Y. Tian [g], G.M. Tveten [j], J.M. Wang [g], T. Belgya [l], R. Firestone [m], S. Goriely [n], J. Kopecky [o], M. Krtička [p], R. Schwengner [q], S. Siem [j], M. Wiedeking [r]

Photodisintegration

$^{181}\mathrm{Ta}(\gamma, xn)@E_\gamma = 28.5$ MeV



T.H. Nguyen et al. EPJ Web of Conf. **292**, 07004 (2024)

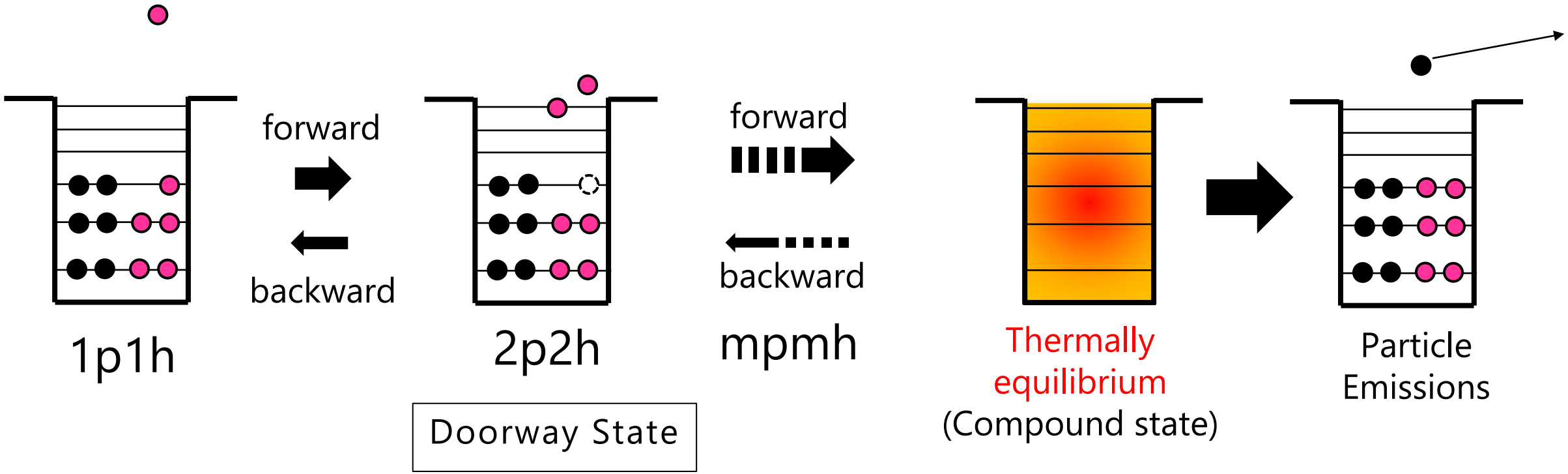


Issues are found in particle emissions of some nuclei

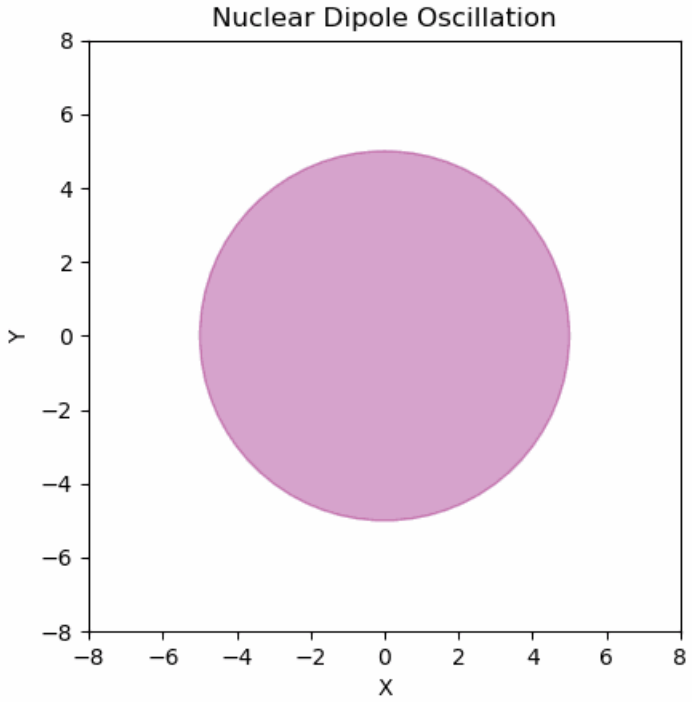
The origin may be in direct & preequilibrium process

Three Stages in Nuclear Reactions

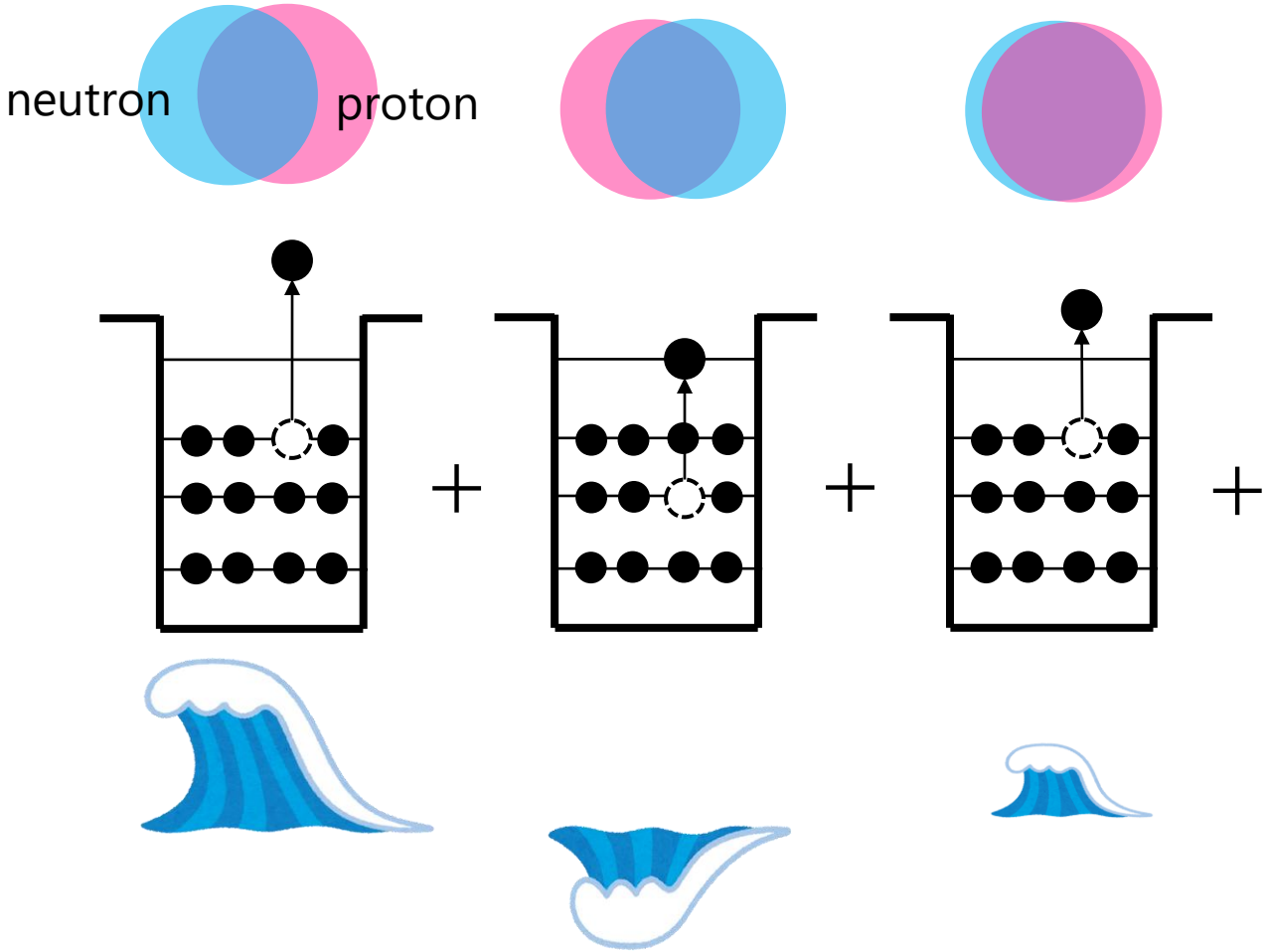
1.Direct Process 2.Preequilibrium Process 3. Compound Process



Origin of Giant Resonance -Collective Excitations-



Collective Excitations are essential for Many-Body Systems!



Many 1 particle-1 hole states are excited coherently
→ Nuclear Collective Excitation

Random Phase Approximation (RPA)

Annihilate particle below ε_F, Create particle above ε_F.

Phonon Creation Operator

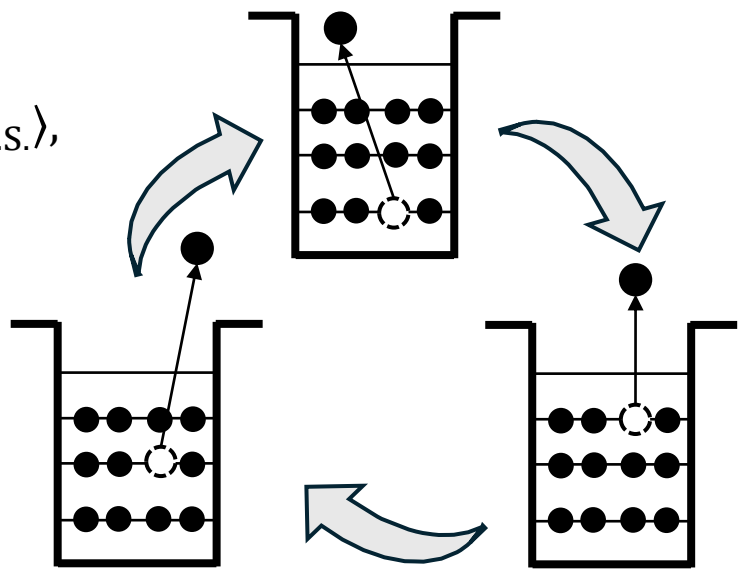
$$Q_\nu^\dagger = \sum_{ph} X_{ph}^{(\nu)} a_p^\dagger a_h - Y_{ph}^{(\nu)} a_h^\dagger a_p$$ ←superposition of 1p1h state

Excited state $|\nu\rangle = Q_\nu^\dagger |\Psi_{\text{G.S.}}\rangle$,

Amplitudes that ph state contributes to resonance state, ν

$$\Rightarrow P_{ph}^{(\nu)}(E) = \left[\left(X_{ph}^{(\nu)}\right)^2 - \left(Y_{ph}^{(\nu)}\right)^2\right] \delta\left(E - \left(\varepsilon_p - \varepsilon_h\right)\right)$$

Coherent Excitation



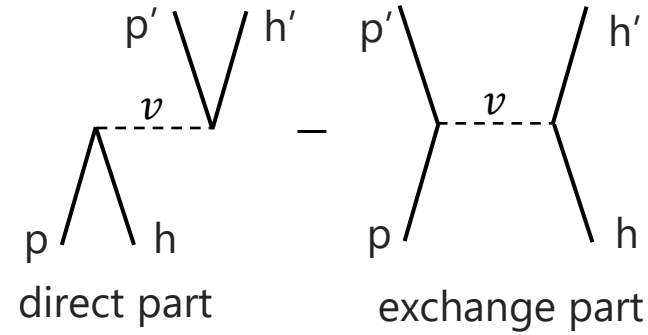
RPA Equation

$$\begin{pmatrix} A_{11} & B_{11} \\ -B_{11} & -A_{11} \end{pmatrix} \begin{pmatrix} X^{(\nu)} \\ Y^{(\nu)} \end{pmatrix} = \hbar\omega \begin{pmatrix} X^{(\nu)} \\ Y^{(\nu)} \end{pmatrix}$$

$$A_{11} = (\varepsilon_p - \varepsilon_h)\delta_{pp'}\delta_{hh'} + \bar{v}'_{ph'hp'} \qquad B_{11} = \bar{v}'_{pp'hh'}$$

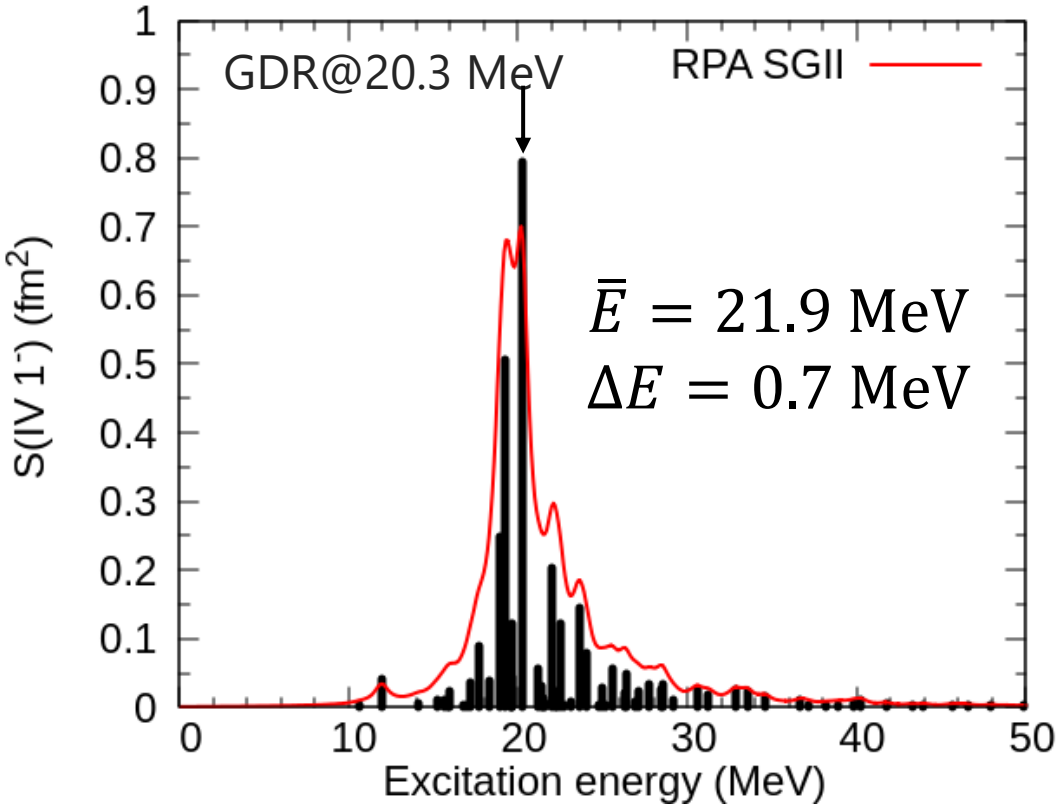
key role for collective excitation

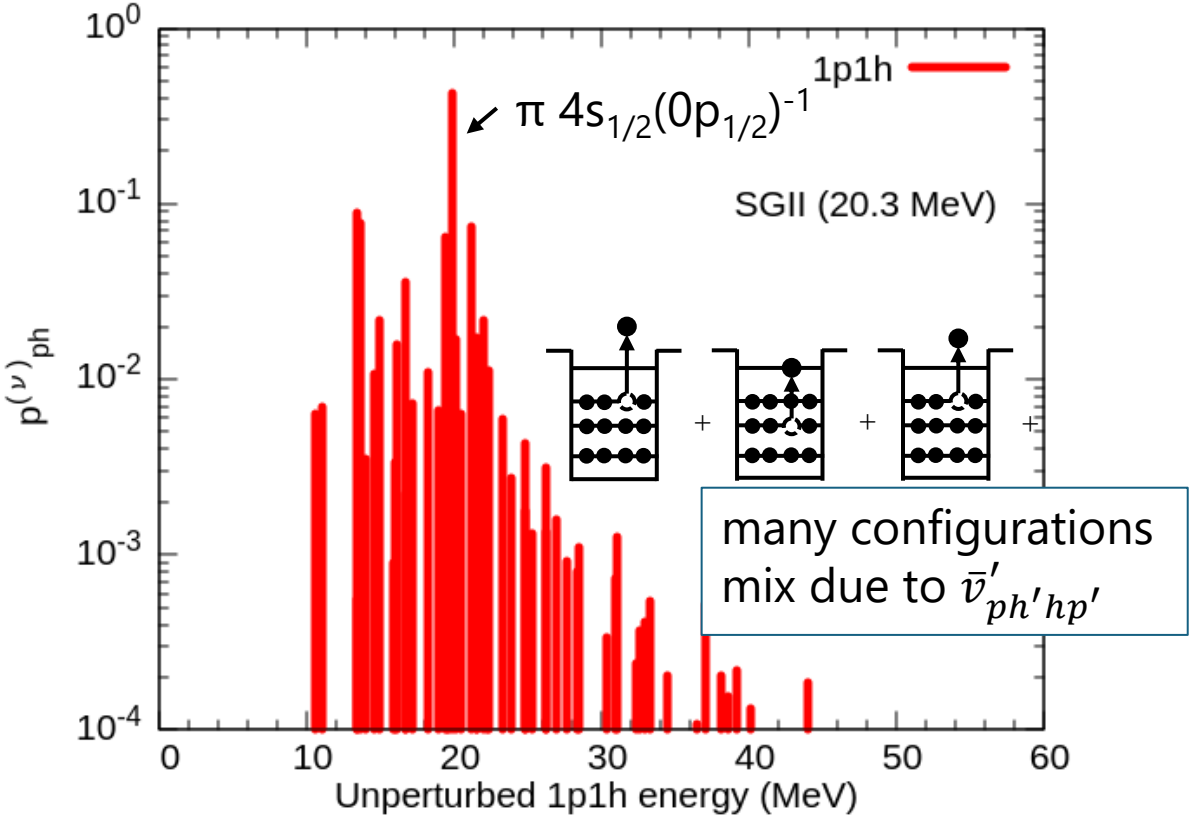
$\bar{v}_{ph'hp'} =$



direct part exchange part

Isovector Dipole Excitations of ^{16}O





Mean Energy

$$\bar{E} = \frac{m_1}{m_0}$$

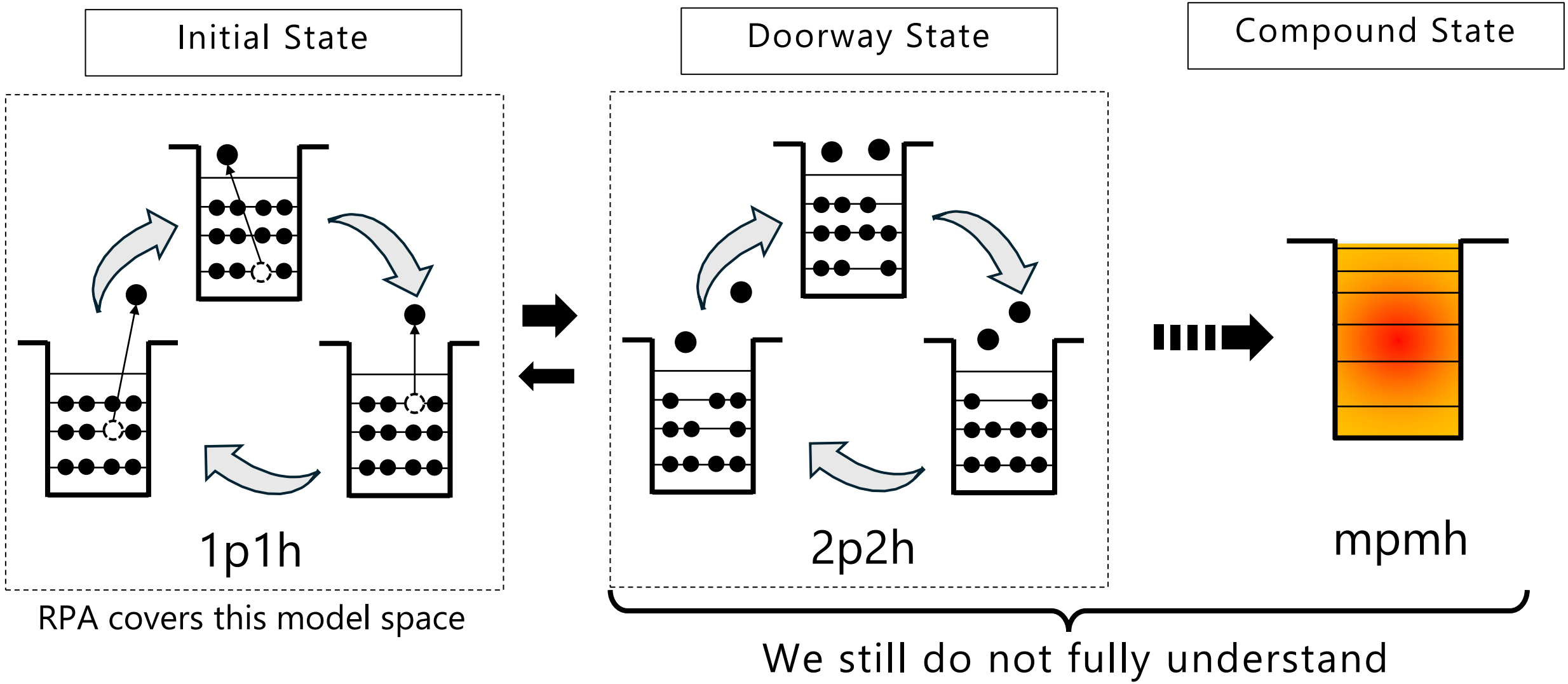
Width of Strength

$$\Delta E = \sqrt{\frac{m_2}{m_0} - \bar{E}^2}$$

※Energy Weighted Sum

$$m_k = \sum_\nu E_\nu^k S_\nu$$

Higher-order configuration mixing



Second Random Phase Approximation (SRPA)

J. Da. Providencia, NP 64, 87 (1965).
C. Yannouleas, PRC 35, 1159 (1987).

$$Q_\nu^\dagger = \sum_{ph} X_{ph}^{(\nu)} a_p^\dagger a_h - \sum_{ph} Y_{ph}^{(\nu)} a_h^\dagger a_p + \sum_{php'h'} \mathcal{X}_{php'h'}^{(\nu)} a_p^\dagger a_{p'}^\dagger a_h a_{h'} - \sum_{php'h'} \mathcal{Y}_{php'h'}^{(\nu)} a_h^\dagger a_{h'}^\dagger a_p a_{p'}$$

RPA Phonon Creation Operators

Additional Phonon Creation Operators

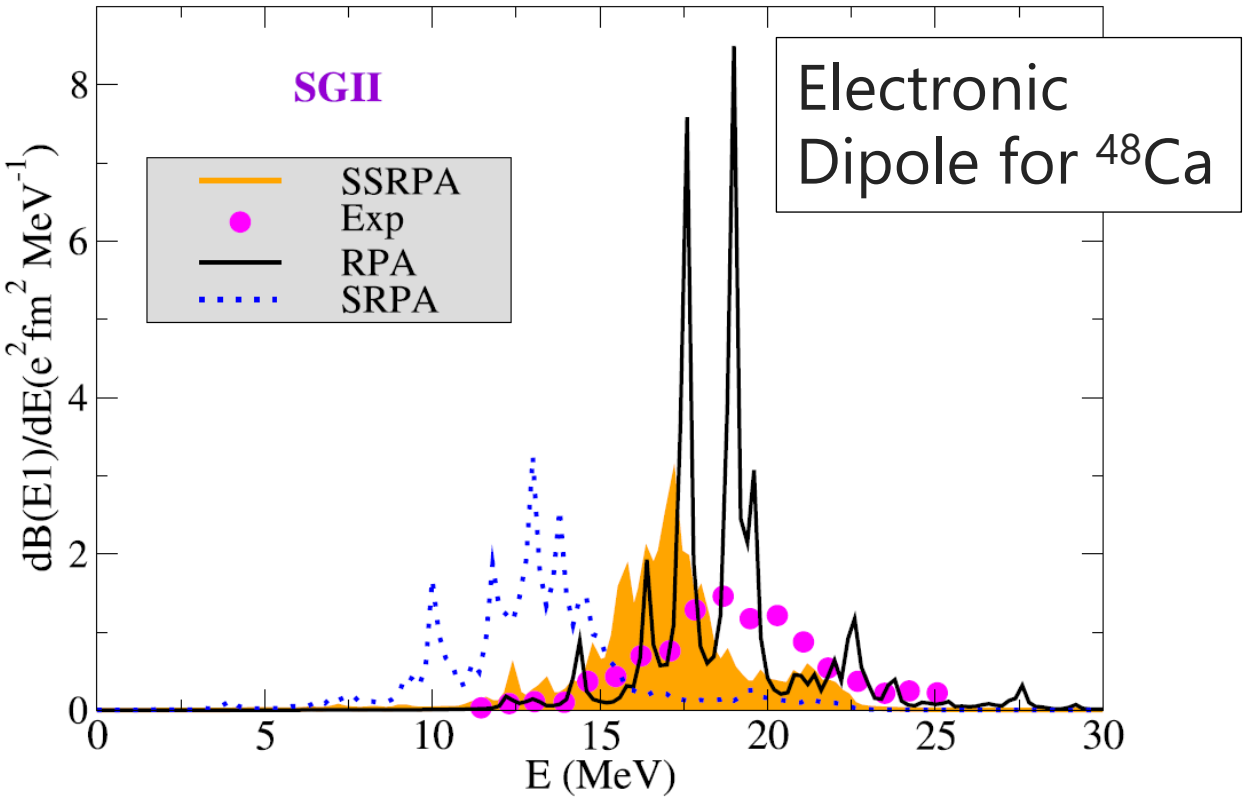
Amplitude for a 2p2h ($php'h'$) states contribute to resonance (ν)

$$P_{php'h'}^{(\nu)} = \left[\left(\mathcal{X}_{php'h'}^{(\nu)}\right)^2 - \left(\mathcal{Y}_{php'h'}^{(\nu)}\right)^2\right] \delta\left(E - \left(\varepsilon_p + \varepsilon_{p'} - \varepsilon_h - \varepsilon_{h'}\right)\right)$$

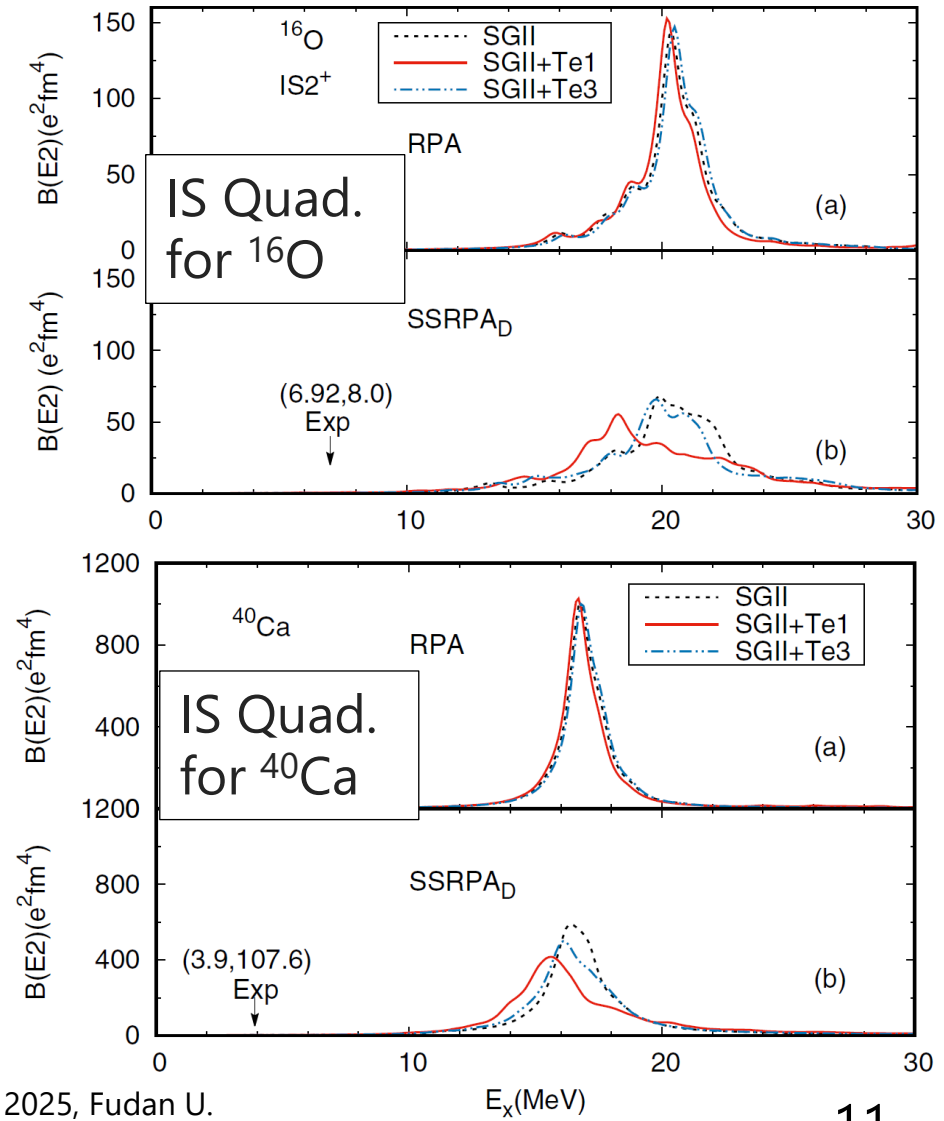
Second RPA can contribute the better understanding of nuclear excitations including GDR

Multipole Excitations by Subtracted SRPA (SSRPA)

D. Gambacurta et al. PLB 777, 163 (2018)



M. J. Yang, C. L. Bai, H. Sagawa, and H. Q. Zhang PRC **103**, 054308 (2021)



Energy-Weighted sum-rule m_1 is overestimated, But Inversed Energy-Weighted sum-rule m_{-1} is conserved.

SSRPA & Self-Energy

RPA Equation

$$\begin{pmatrix} A_{11} & B_{11} \\ B_{11} & A_{22} \end{pmatrix}\begin{pmatrix} X \\ Y \end{pmatrix} = \hbar\omega \begin{pmatrix} X \\ Y \end{pmatrix}$$

SRPA Equation

D. Gambacurta, M. Grasso, J. Engel, PRC **92**, 034303 (2015)

ω is resonance energy

$$\begin{pmatrix} A_{11}(\omega) & B_{11}(\omega) \\ B_{11}(\omega) & A_{22}(\omega) \end{pmatrix}\begin{pmatrix} X \\ Y \end{pmatrix} = \hbar\omega \begin{pmatrix} X \\ Y \end{pmatrix}$$

SRPA Matrix Element

$$A_{php'h'}(\omega) = A_{php'h'} + \Sigma_{php'h'}(\omega)$$
$$B_{php'h'}(\omega) = B_{php'h'}$$

Self-Energy

account for couplings between 1p1h & 2p2h states

$$\Sigma_{php'h'}(\omega) = \sum_{\substack{p_1p_2h_1h_2 \\ p_1'p_2'h_1'h_2'}} A_{ph,p_1p_2h_1h_2} \frac{1}{\omega - A_{p_1p_2h_1h_2,p_1'p_2'h_1'h_2'} + i\eta} A_{p_1'p_2'h_1'h_2',p'h'}$$

SSRPA matrix element

$$A^{(S)}_{php'h'}(\omega) = A_{php'h'}(\omega) - \Sigma_{php'h'}(\omega = 0) \qquad B^{(S)}_{php'h'} = B_{php'h'}$$

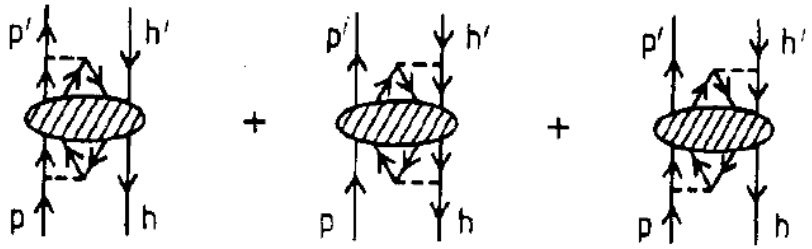
These ensure $A^{(S)}_{php'h'}(0) = A_{php'h'}$

Details on SRPA Self-Energy

J. Wambach, Rep. Prog. Phys. **51** (1988) 989-1046

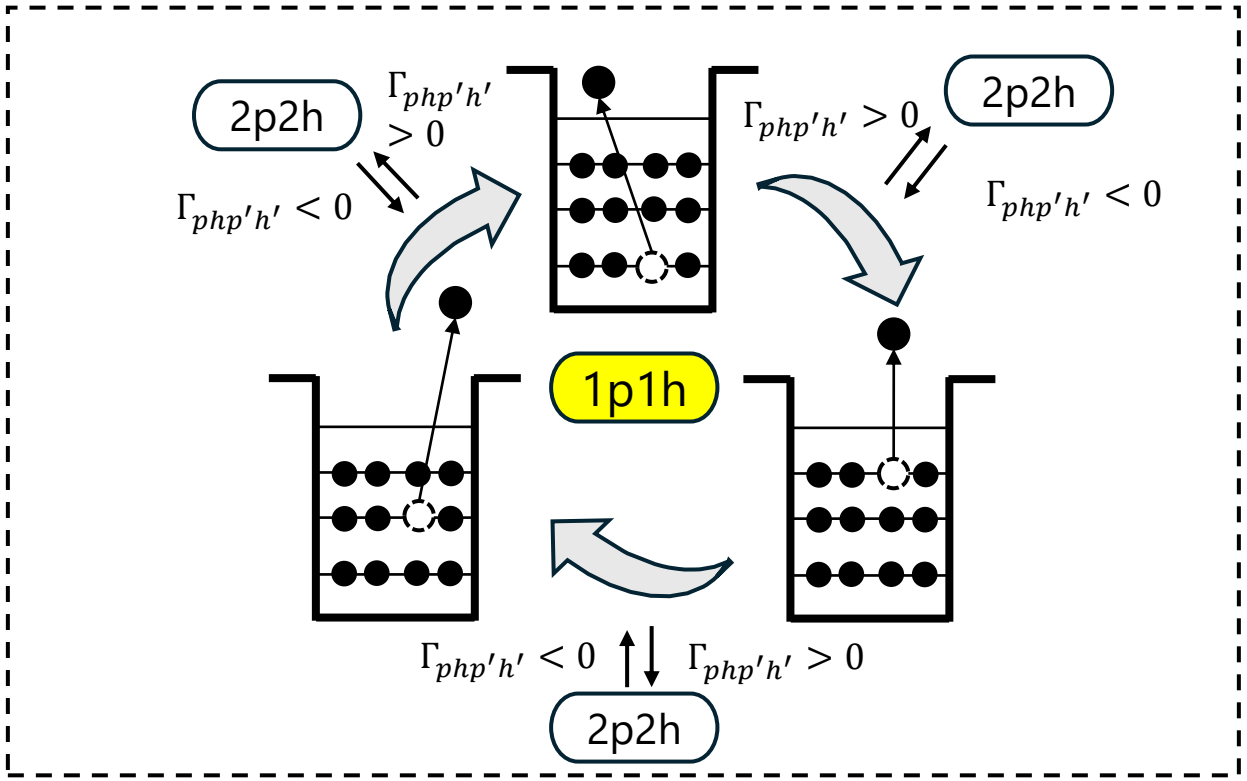
$$\Sigma_{php'h'}(\omega) = \Delta_{php'h'} - i\frac{\Gamma_{php'h'}}{2} =$$

Energy shift　　Width

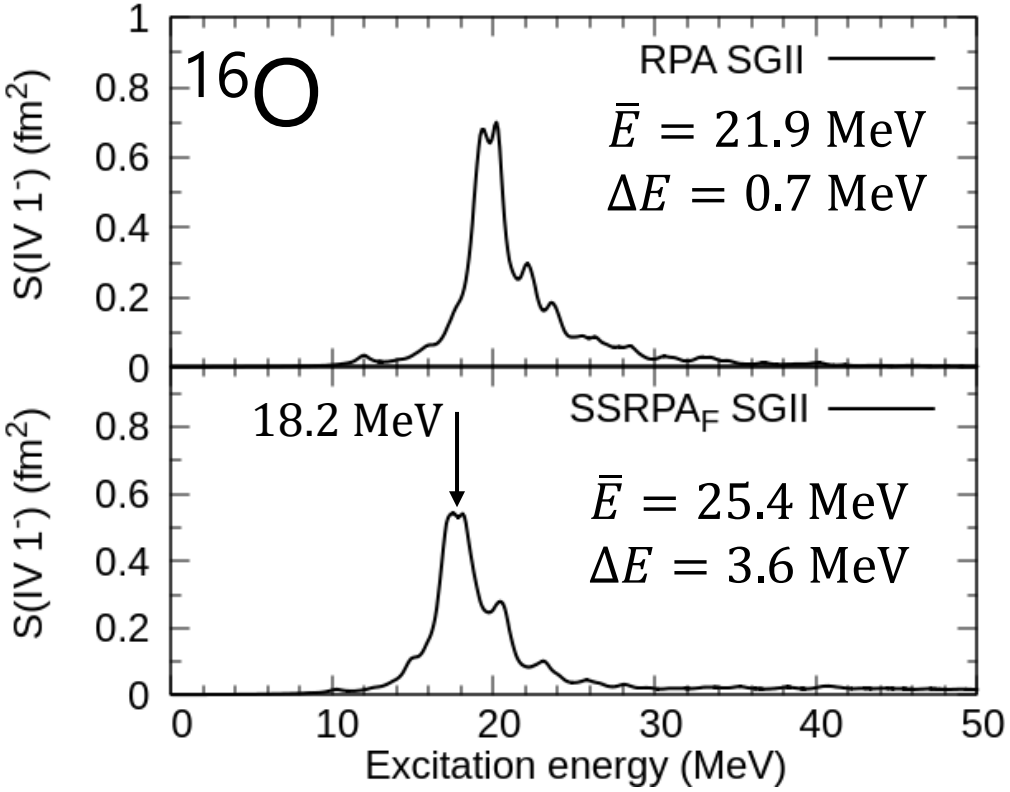


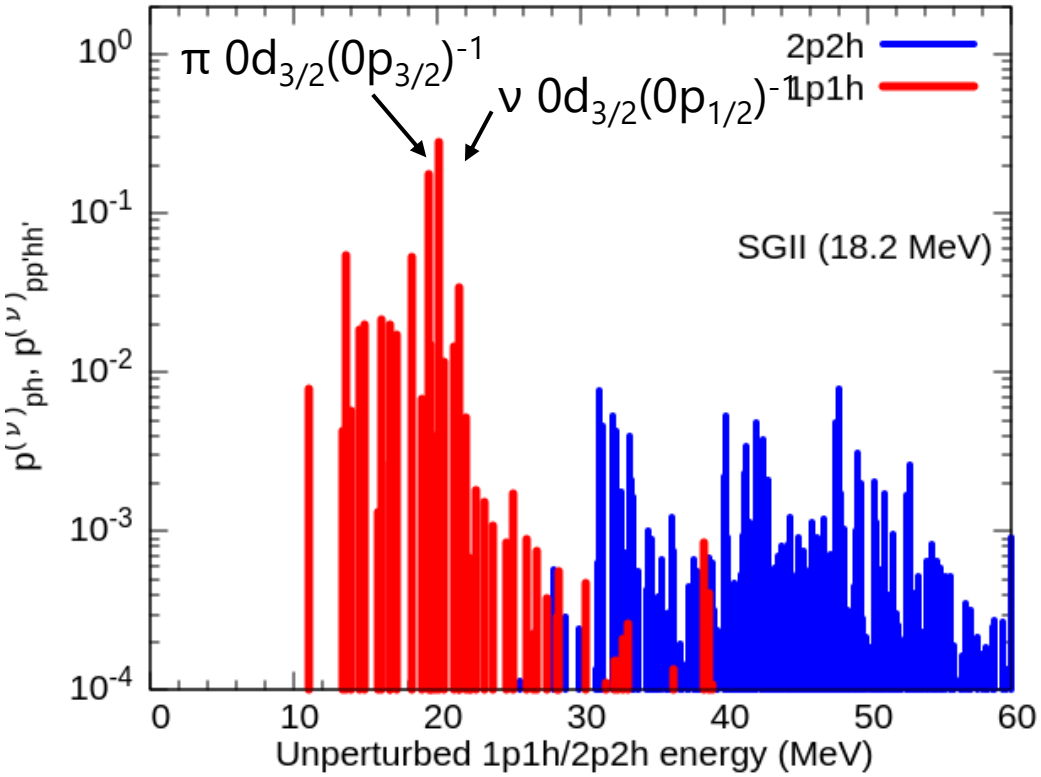
$\Gamma_{php'h'} > 0$　Amplitude of transition from $ph(p'h')$ state to $p'h'(ph)$ state escapes to 2p2h states

$\Gamma_{php'h'} < 0$　Amplitude of transition from $ph(p'h')$ state to $p'h'(ph)$ is reverted from 2p2h states



^{16}O Isovector dipole Transition (IV 1$^-$)



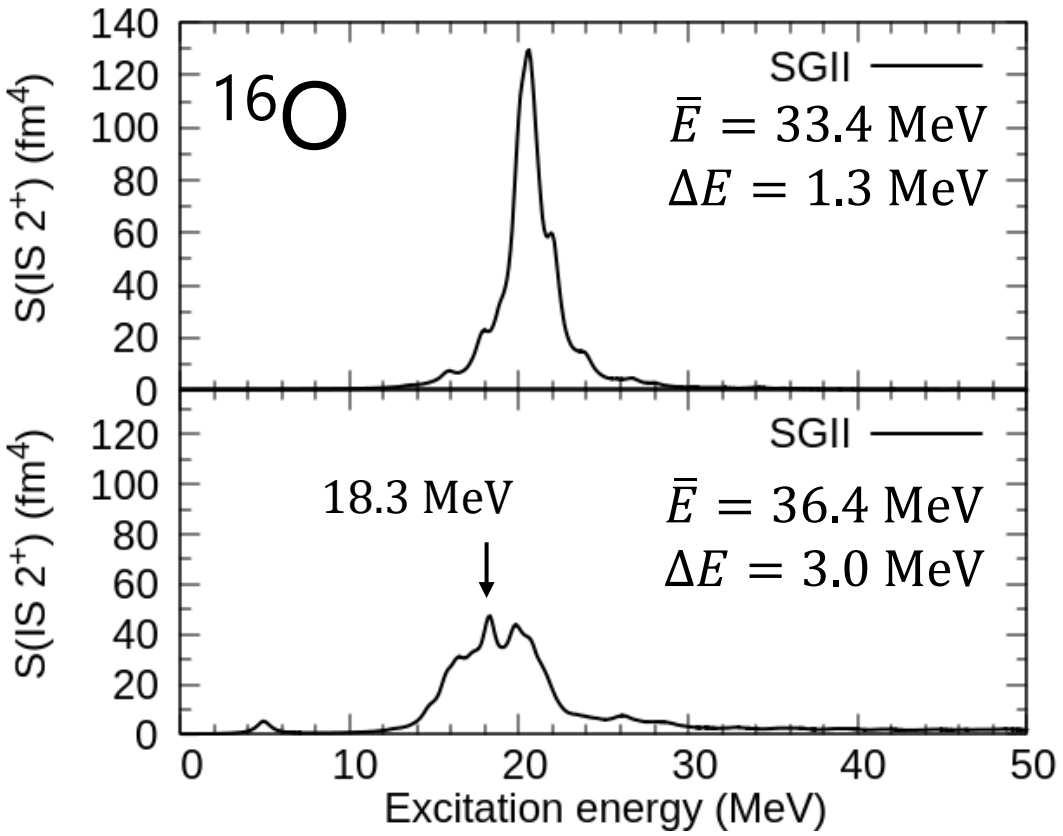


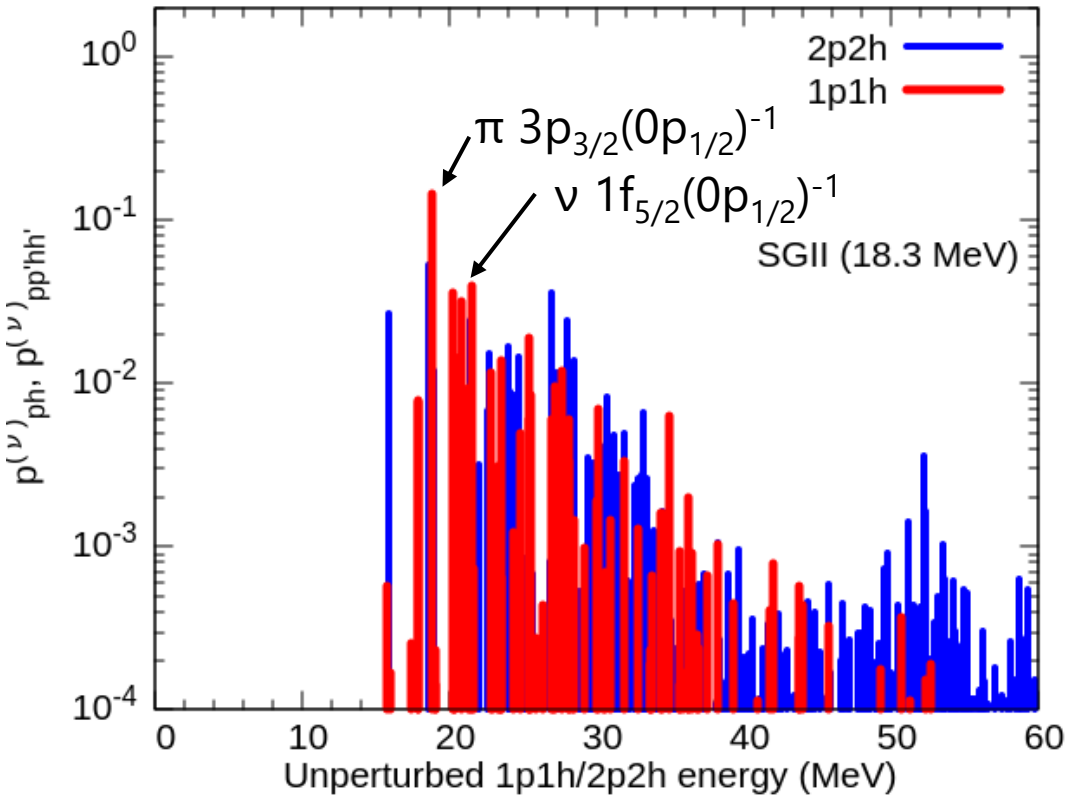
	p h	p′ h′	$\Gamma_{php'h'}$
Main ph combination	π 0d$_{3/2}$(0p$_{3/2}$)$^{-1}$	π 0d$_{3/2}$(0p$_{3/2}$)$^{-1}$	0.7 MeV
	ν 0d$_{3/2}$(0p$_{1/2}$)$^{-1}$	ν 0d$_{3/2}$(0p$_{1/2}$)$^{-1}$	0.3 MeV

	p h	p′ h′	$\Gamma_{php'h'}$
Minor ph	π 1s$_{1/2}$(0p$_{3/2}$)$^{-1}$	ν 0d$_{5/2}$(0p$_{3/2}$)$^{-1}$	−0.5 MeV
	ν 1p$_{3/2}$(0s$_{1/2}$)$^{-1}$	ν 3p$_{3/2}$(0p$_{3/2}$)$^{-1}$	−0.3 MeV

This enhances collectivity!

^{16}O Isoscalar Quadrupole Transition (IS 2^+)

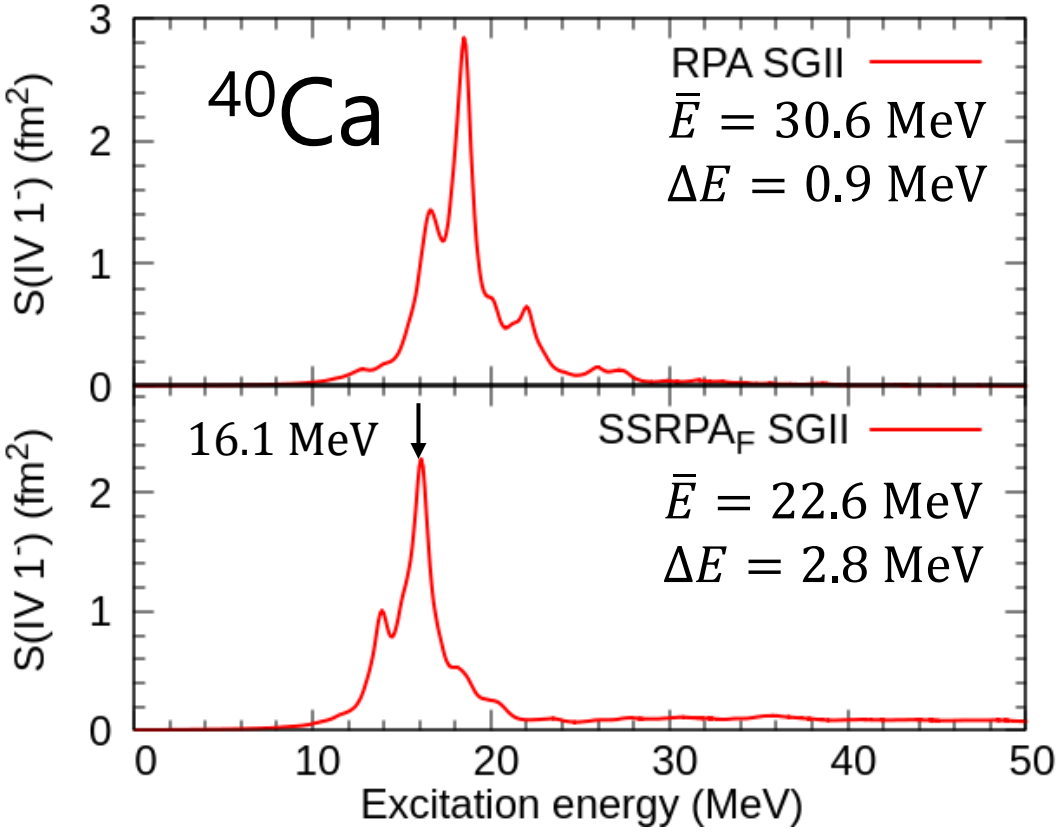


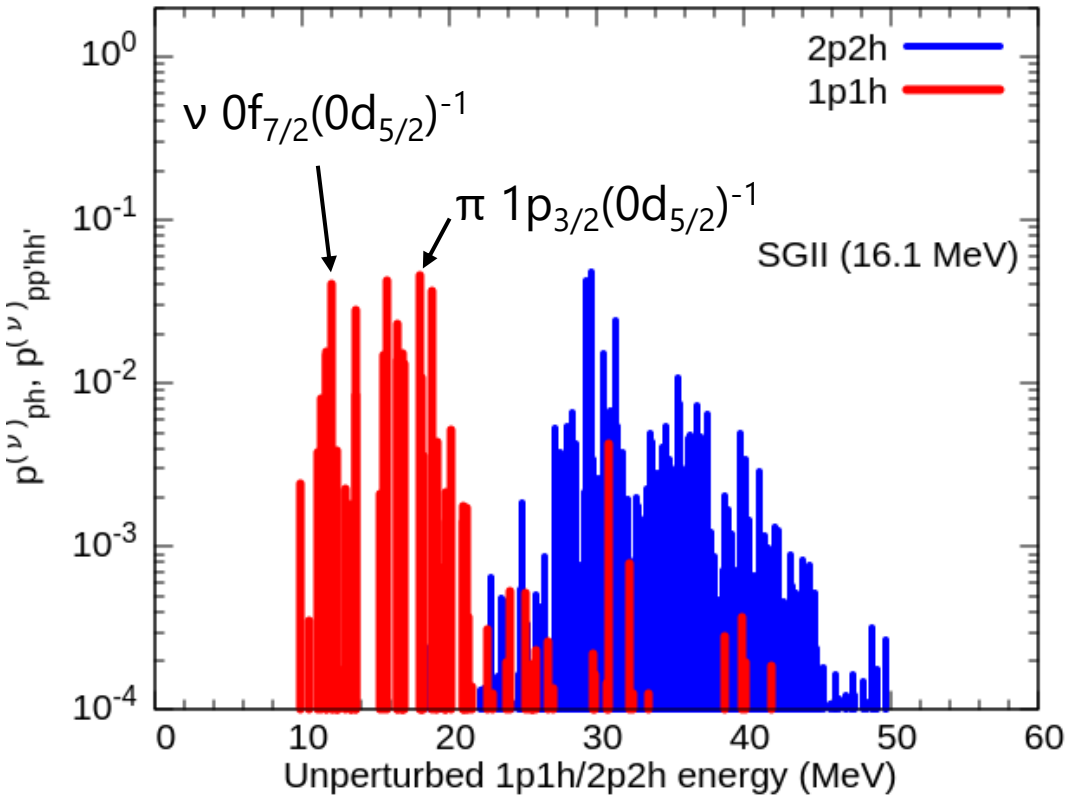


	p	h	p′	h′	$\Gamma_{php'h'}$
Main component of GQR	π $3p_{3/2}(0p_{1/2})^{-1}$		π $3p_{3/2}(0p_{1/2})^{-1}$		0.5 MeV
	ν $1f_{5/2}(0p_{1/2})^{-1}$		ν $1f_{5/2}(0p_{1/2})^{-1}$		0.5 MeV

	p	h	p′	h′	$\Gamma_{php'h'}$
Minor ph	ν $0d_{5/2}(0s_{1/2})^{-1}$		ν $0d_{3/2}(0s_{1/2})^{-1}$		−3.8 MeV
	π $0d_{5/2}(0s_{1/2})^{-1}$		π $0d_{3/2}(0s_{1/2})^{-1}$		−0.8 MeV

^{40}Ca Isovector dipole Transition (IV 1-)





	p	h	p′	h′	$\Gamma_{php'h'}$
Main ph combination	ν 0f$_{7/2}$(0d$_{5/2}$)$^{-1}$		ν 0f$_{7/2}$(0d$_{5/2}$)$^{-1}$		4.7 MeV
	π 1p$_{3/2}$(0d$_{5/2}$)$^{-1}$		π 1p$_{3/2}$(0d$_{5/2}$)$^{-1}$		0.7 MeV
Minor ph ones	ν 6d$_{5/2}$(0p$_{1/2}$)$^{-1}$		ν 0f$_{5/2}$(0d$_{3/2}$)$^{-1}$		−0.2 MeV
	ν 1p$_{3/2}$(0d$_{5/2}$)$^{-1}$		ν 0f$_{5/2}$(0d$_{3/2}$)$^{-1}$		−0.2 MeV

Summary

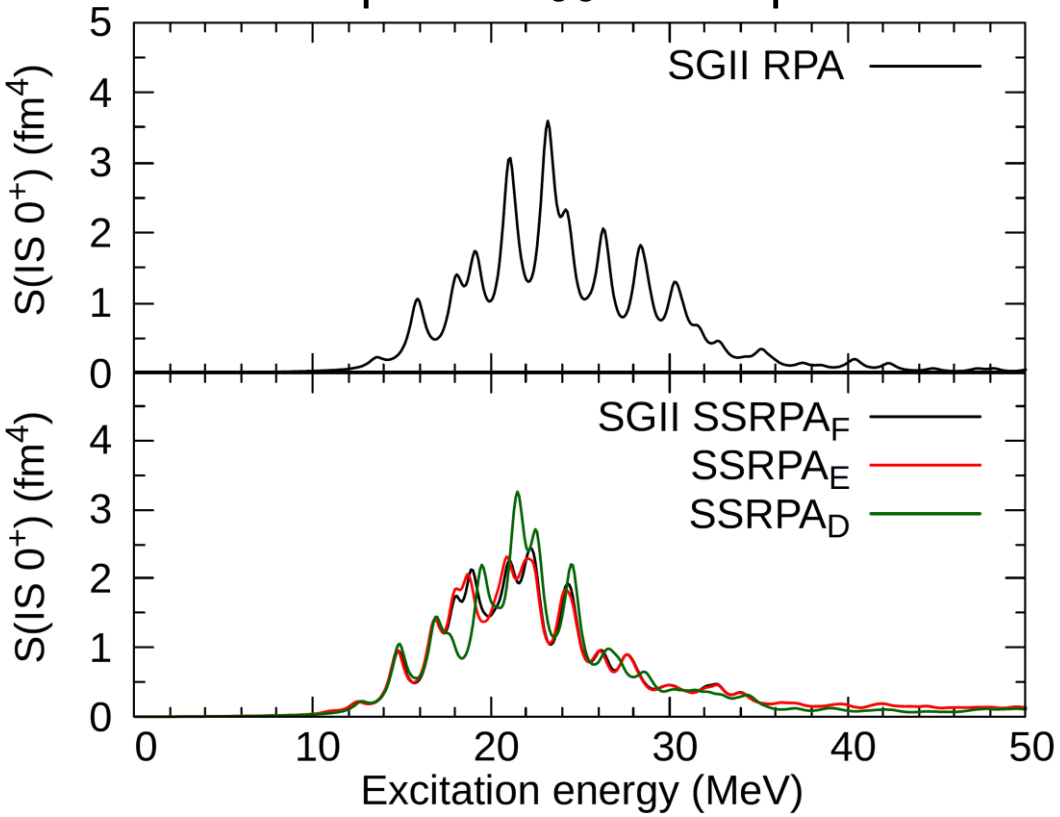
Studied Nuclear monopole, dipole, and quadrupole excitations within SSRPA method and discuss the Spreading Widths

- Resonance distribute more widely, when 2particle-2hole configurations are considered
- Main 1particle-1hole configurations of resonances dissipate to 2particle-2hole states
- Minor 1particle-1hole configurations of those are enhanced by 2p-2h coupling, enhancing the collectivity of resonance

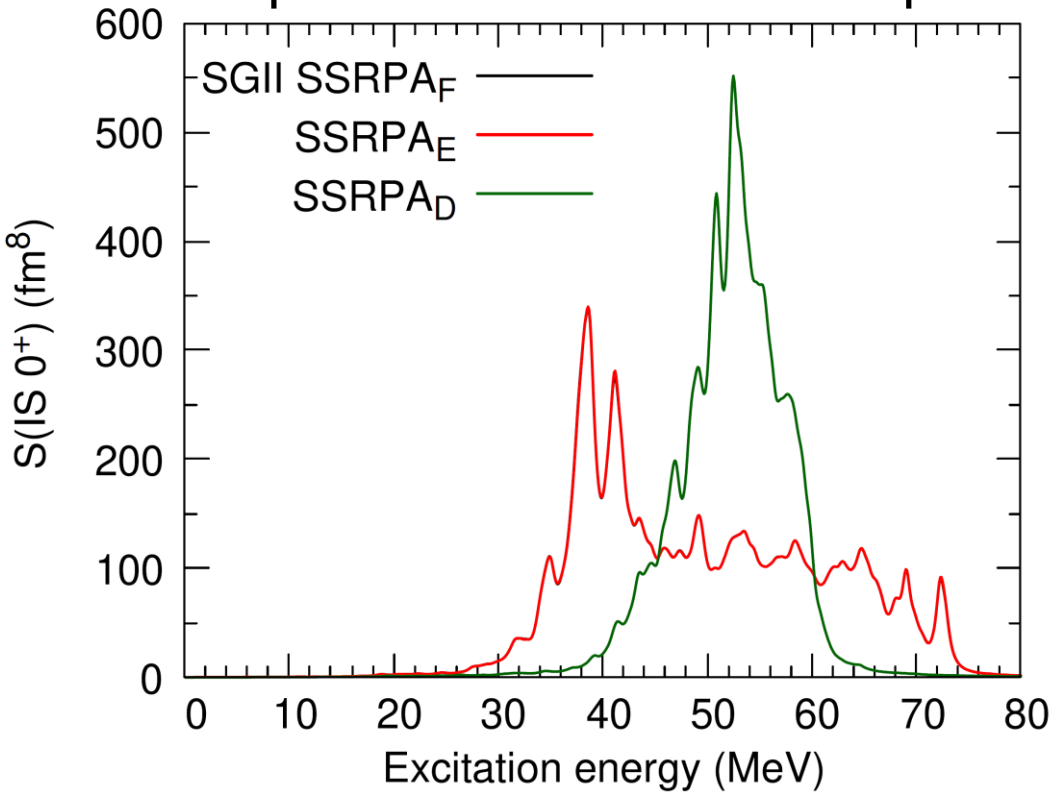
This work was supported by JSPS KAKENHI Grant Numbers JP23K03426 and JP24K00647, JP25H00641, and by JST ERATO Grant No. JPMJER2304, Japan.

Double Multipole Excitations

$\left|\langle\nu|r^2Y_{00}(\hat{r})|0\rangle\right|^2$

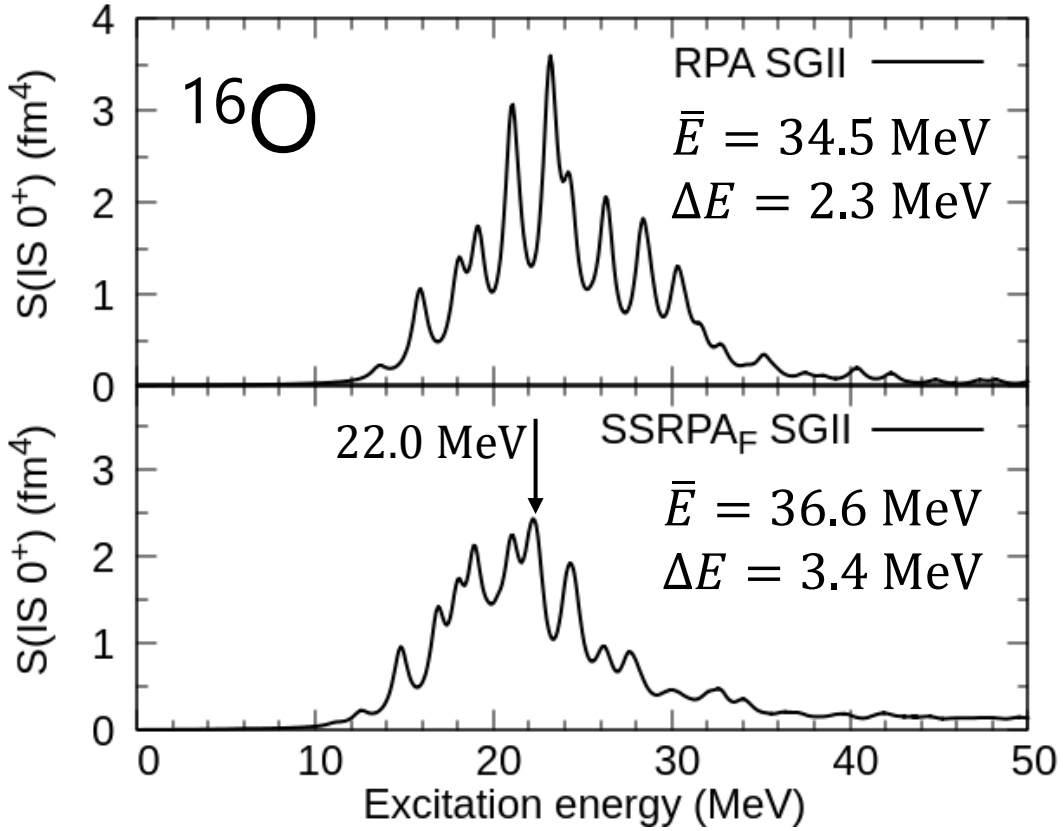


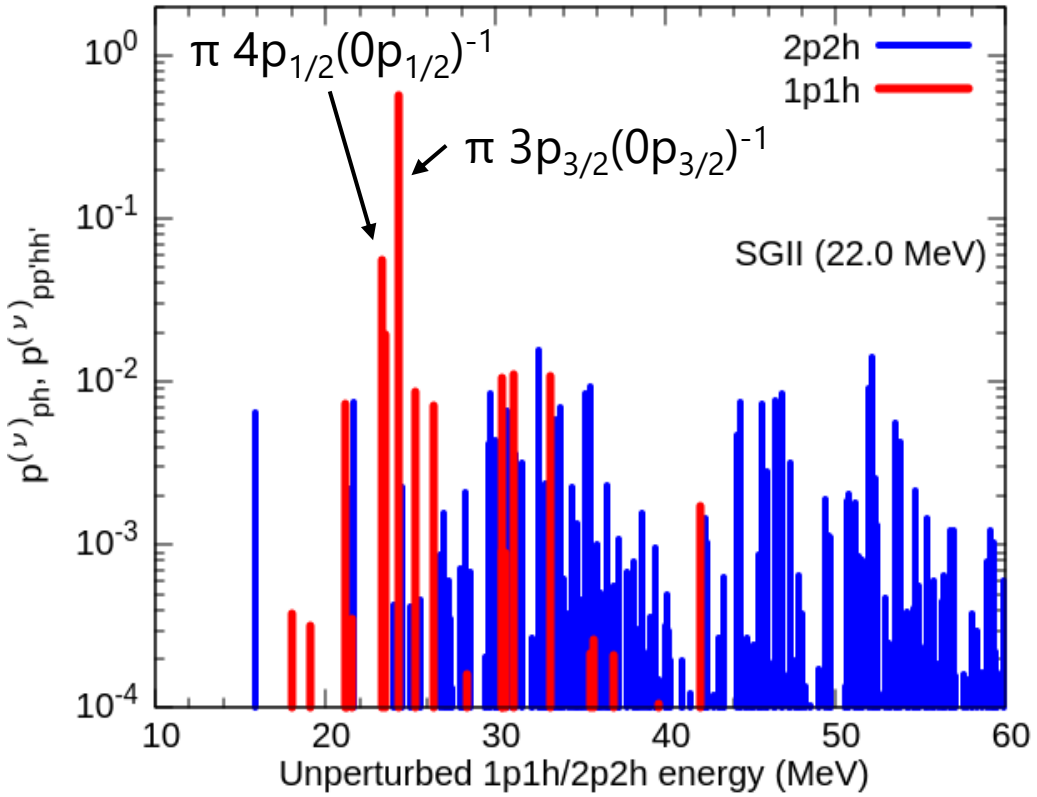
$\left|\langle\nu|\left[[r^2Y_2][r^2Y_2]\right]^{00}|0\rangle\right|^2$



SSRPA$_F$: Fully consider transition from a 2p2h to another in SRPA and Subtracted method
SSRPA$_E$: Neglect transition from a 2p2h to another in Subtracted method
SSRPA$_D$: Neglect transition from a 2p2h to another

^{16}O Isoscalar Monopole Transition (IS 0^+)





	p	h	p′	h′	$\Gamma_{php'h'}$
Main ph combination	π 3p$_{3/2}$(0p$_{3/2}$)$^{-1}$		π 3p$_{3/2}$(0p$_{3/2}$)$^{-1}$		0.8 MeV
	π 4p$_{1/2}$(0p$_{1/2}$)$^{-1}$		π 4p$_{1/2}$(0p$_{1/2}$)$^{-1}$		0.6 MeV

	p	h	p′	h′	$\Gamma_{php'h'}$
Minor ph	ν 1s$_{1/2}$(0s$_{1/2}$)$^{-1}$		ν 1p$_{3/2}$(0p$_{3/2}$)$^{-1}$		−0.5 MeV
	ν 1s$_{1/2}$(0s$_{1/2}$)$^{-1}$		ν 1p$_{1/2}$(0p$_{1/2}$)$^{-1}$		−0.3 MeV