Continuum RPA for microscopic description of direct neutron capture on neutron rich nuclei

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YKIS2022b 26/May/2022

Contents

▶Introduction
direct neutron capture on r process

▶Theoretical method
Continuum RPA for direct neutron capture
beyond potential model

▶Numerical examples
direct neutron capture cross section of ^{139}Sn(g.s.)

pygmy resonance and its impact on r-process

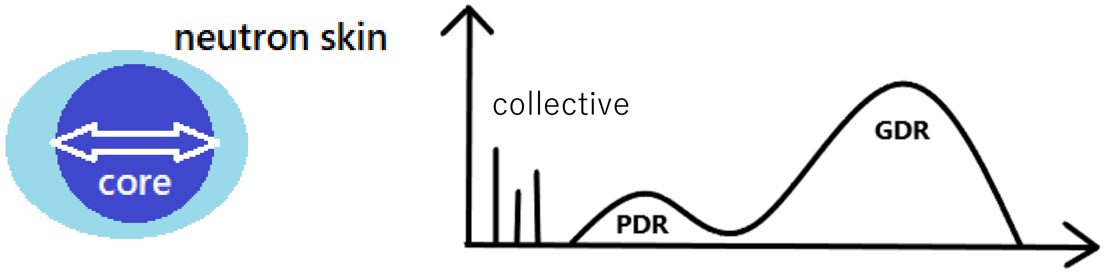
r-process

The origin of half amount of the elements heavier than iron

astrophysical site; NS merger

☞GW170817　B. Abbott et al. PRL 119(2017)

pygmy dipole resonance(PDR)



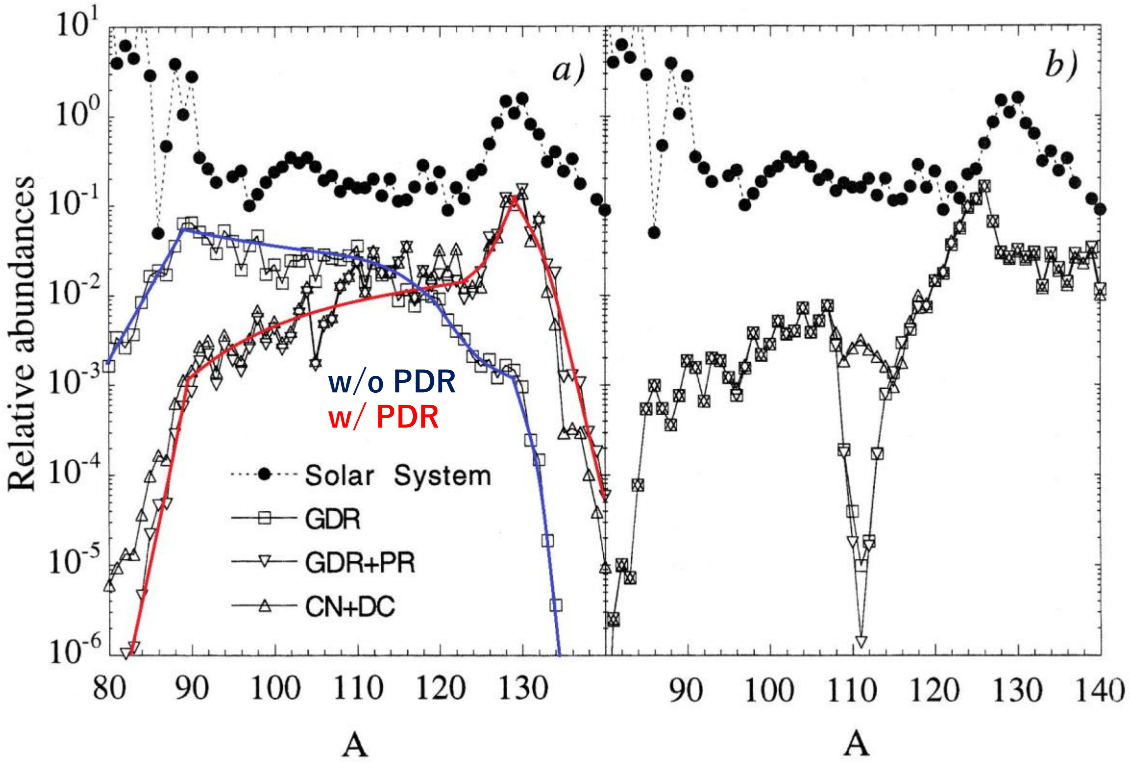
exotic low-energy excited mode in neutron-rich nuclei

PDR may play important role in r-process

S. Goriely(1998)
N. Tsoneva et al. PRC 91(2015)

How about other collective states?

r-abundance



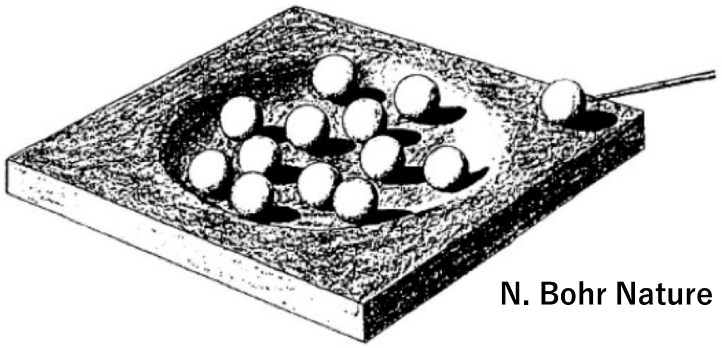
S. Goriely, PRL B 436, 10 (1998)

Compound neutron capture

Hauser-Feshbach statistical model

- compound nucleus γ decay strength function
- level density
- Brink-Axel hypothesis

P. Axel PR 126(1962)



N. Bohr Nature 137(1936)

Direct neutron capture

- explicit treatment of excited states related with only few degrees(ex. doorway states)
  =1p1h
- nuclear reaction model suited for a choice of excited states set

potential model(single particle motion)

- pure 1p1h states, non-collectivity
- one-step transition

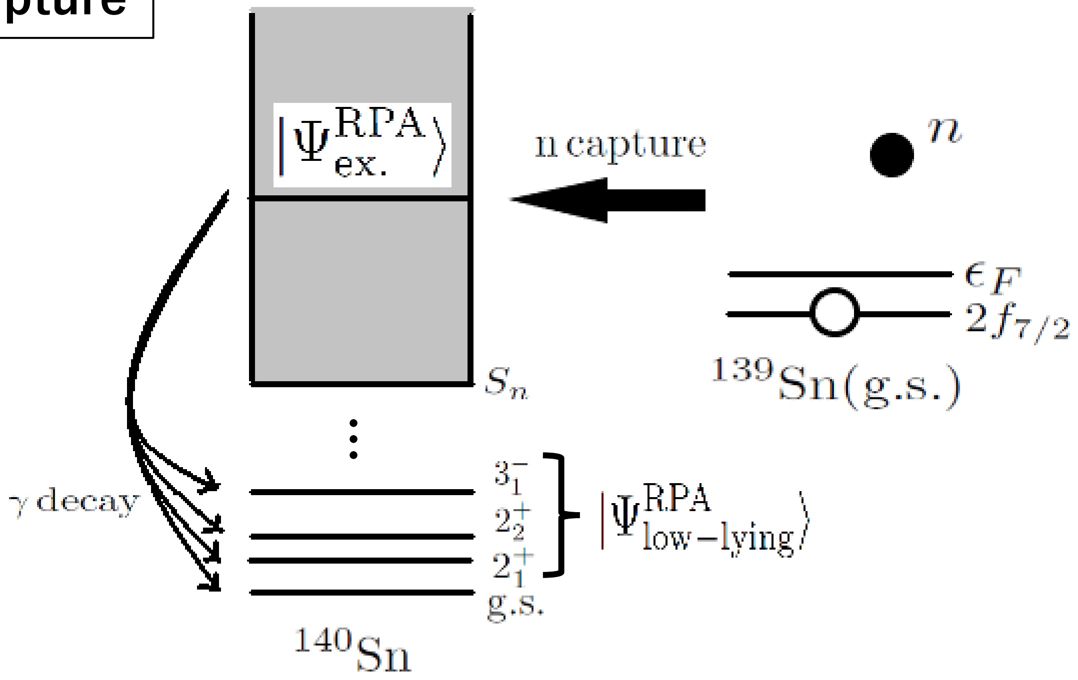
Y. Xu and S. Goriely, PRC 86(2012) Y. Xu et al. PRC 90(2014)

continuum RPA(cRPA) model

- RPA excited states, collectivity
- self interaction multi-step transition(ring diagram)
  ＝ RPA one-step transition

The Image of cRPA direct neutron capture

^{139}Sn direct neutron capture



Excited states of ^{140}Sn are evaluated by linear response theory(DFT+cRPA).

After neutron capture, a nucleus form a collective(RPA) excited state.

A nucleus γ decay to a collective(RPA) excited state.

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▶Introduction
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Original Zangwill-Soven method for（γ ,n）process

photo-absorption strength function

$$S(E) = \sum_k |\langle k|\hat{V}_\gamma|0\rangle|^2 \delta(E - E_k)$$

evaluated by linear response theory（DFT+cRPA）

self consistent representation（DFT）

$$S(E) = \sum_{ph} |\langle ph|\hat{V}_{\rm scf}(\omega)|0\rangle|^2 \delta(E - (\epsilon_p - \epsilon_h))$$

$$V_{\rm scf}(\omega) = \frac{\delta E[\rho]}{\delta\rho}\delta\rho(\omega) + V_\gamma$$

decomposing S(E)

（γ ,n）cross section

$$\sigma_{(\gamma,n)}(E_\gamma) = \frac{(2\pi)^4}{\hbar c}\sum_p |\langle ph|\hat{V}_{\rm scf}(\omega_\gamma)|0\rangle|^2 \delta(E_\gamma - (\epsilon_p - \epsilon_h))$$

Zangwill-Soven method

(n, γ) cross section

$$\sigma_{(n,\gamma)}(e_{\rm kin}) = \frac{E_\gamma^2}{2mc^2 e_{\rm kin}}\sigma_{(\gamma,n)}(E_\gamma)$$

detailed balance

A. Zangwill and P. Soven, PRA 21（1980）

M. Matsuo, PRC 91（2015）

Original Zangwill-Soven method for（γ ,n）process

general（γ ,n）T-matrix

$$T_{(\gamma,n)} = \langle \Psi^{(-)}_{n(A-1)} | \hat{V}_\gamma | \Psi_A \rangle$$

$\hat{V}$: interaction of（A-1)+n system

LS solution

$$|\Psi^{(-)}_{n(A-1)}\rangle = |\phi_n \Psi_{A-1}\rangle + (\hat{G}_0^{(-)} + \hat{G}_0^{(-)} \hat{V} \hat{G}_0^{(-)} + \cdots) \hat{V} |\phi_n \Psi_{A-1}\rangle$$

$$\hat{V} \leftrightarrow \hat{V}_{ph}$$

$$\hat{G}_0 \leftrightarrow \hat{R}_0 = \hat{P}^{-1} \hat{G}_0 \hat{P} \quad \hat{P} = \sum_{ph} |ph\rangle \langle ph|$$

RPA

$$\hat{V} \leftrightarrow \hat{V} = 0$$

single particle motion model
（potential model）

RPA（γ ,n）T-matrix

$$T^{\mathrm{RPA}}_{(\gamma,n)} = \langle \Psi^{(-)\mathrm{RPA}}_{n(A-1)} | \hat{V}_\gamma | \Psi_A \rangle = \sum_p \langle ph | \hat{V}_{\mathrm{scf}}(\omega) | 0 \rangle$$

$$|\Psi^{(-)\mathrm{RPA}}_{n(A-1)}\rangle = |\phi_n \Psi_{A-1}\rangle + (\hat{R}_0^{(-)} + \hat{R}_0^{(-)} \hat{V}_{ph} \hat{R}_0^{(-)} + \cdots) \hat{V}_{ph} |\phi_n \Psi_{A-1}\rangle$$

Extension for (n, γ) decay to low-lying states

RPA $A_{\mathrm{g.s.}}$ (γ,n) (A-1) T-matrix

$$T^{\mathrm{RPA}}_{A_{\mathrm{g.s.}}(\gamma,n)(A-1)} = \langle \Psi^{(-)\mathrm{RPA}}_{n(A-1)} | \hat{V}_\gamma | \Psi_{A_{\mathrm{g.s.}}} \rangle = \sum_p \langle ph | \hat{V}_{\mathrm{scf}}(\hat{V}_\gamma ; \omega) | 0 \rangle$$

$$\hat{V}_\gamma \to \hat{F} \equiv [\hat{V}_\gamma , \hat{O}^\dagger_{\mathrm{ex.}}] \qquad |A_{\mathrm{ex.}}\rangle = \hat{O}^\dagger_{\mathrm{ex.}} |A_{\mathrm{g.s.}}\rangle$$

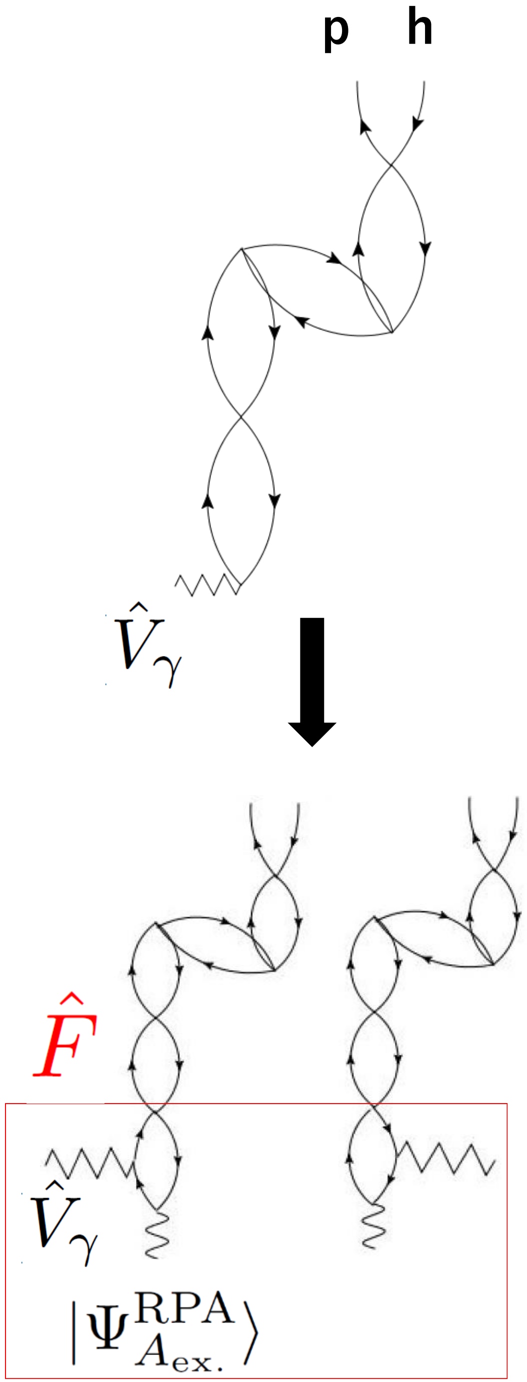
F is a non-local one-body op.

T. Saito and M. Matsuo, PRC 104(2021)

RPA $A_{\mathrm{ex.}}$ (γ,n) (A-1) T-matrix

$$T^{\mathrm{RPA}}_{A_{\mathrm{ex.}}(\gamma,n)(A-1)} = \langle \Psi^{(-)\mathrm{RPA}}_{n(A-1)} | \hat{V}_\gamma | \Psi^{\mathrm{RPA}}_{A_{\mathrm{ex.}}} \rangle = \sum_p \langle ph | \hat{V}_{\mathrm{scf}}(\hat{F} ; \omega) | 0 \rangle$$

$$= \sum_p \langle ph | \hat{V}_{\mathrm{scf}}(\hat{V}_\gamma ; \omega) | \Psi^{\mathrm{RPA}}_{A_{\mathrm{ex.}}} \rangle$$



Contents

▶Introduction

direct neutron capture on r-process

▶Theoretical method

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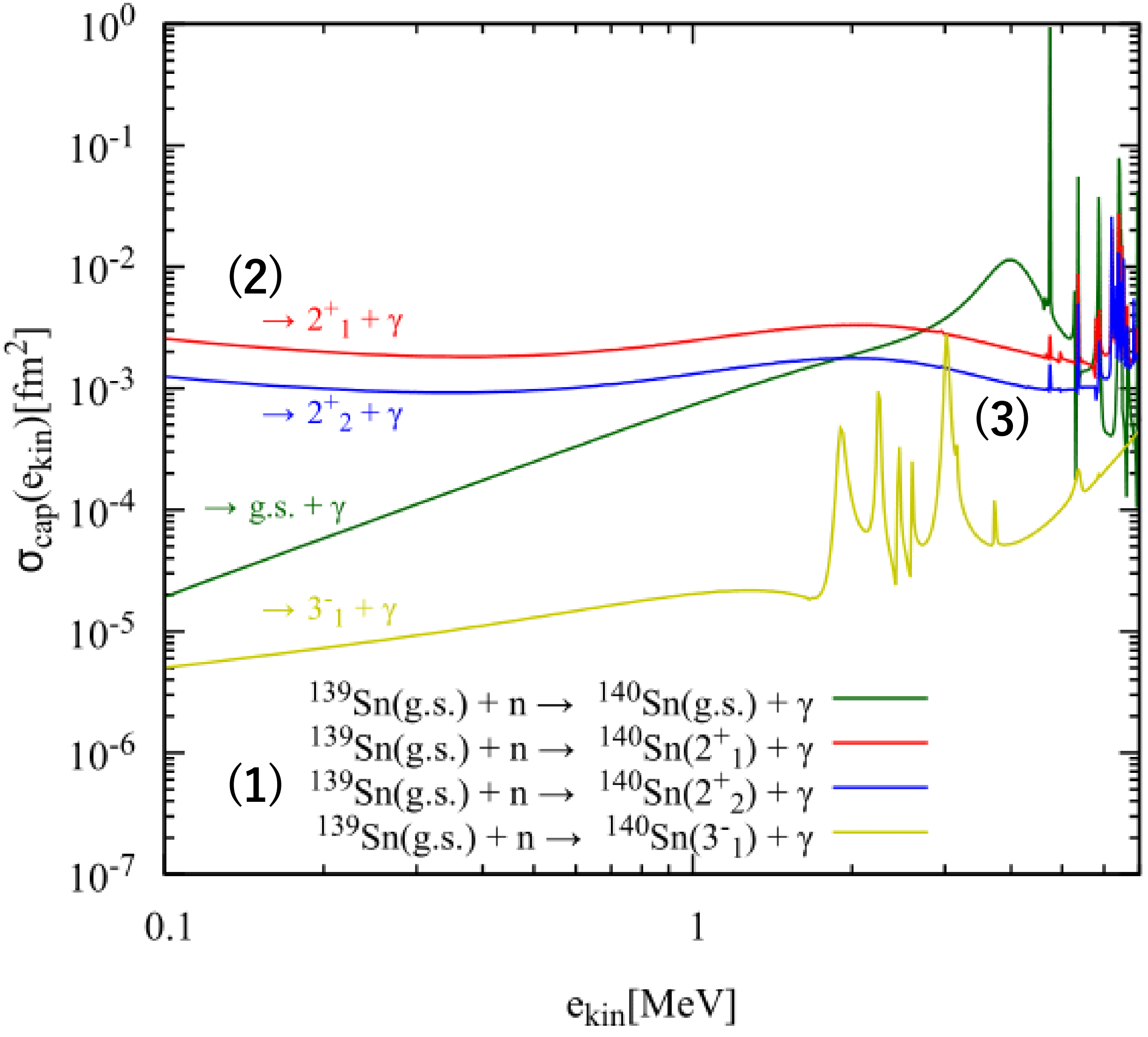
▶**Numerical examples**

direct neutron capture cross section on 139Sn(g.s.)

E1 direct neutron capture of ^{139}Sn(g.s.)



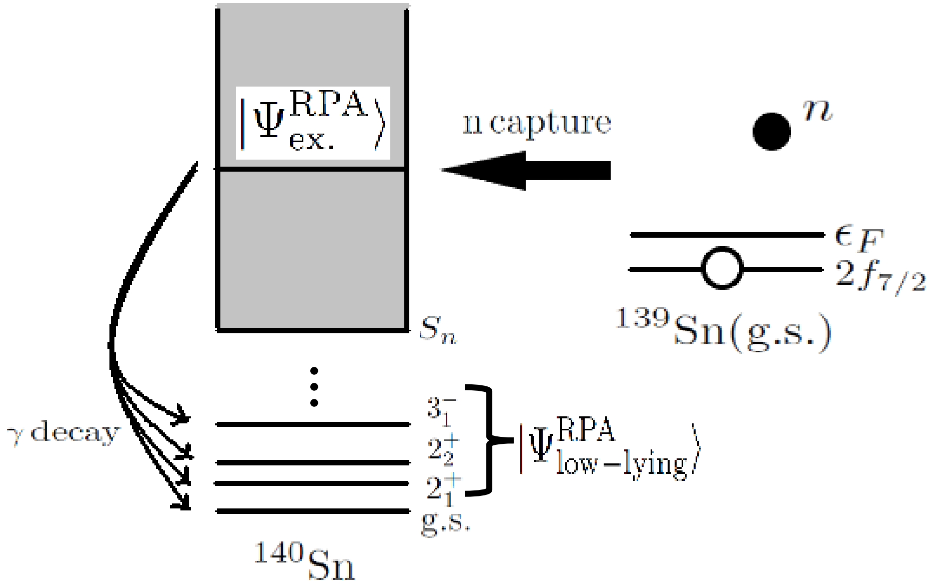
all E1 channels

$$
\begin{aligned}
{}^{139}\mathrm{Sn(g.s.)} + n \rightarrow {}^{140}\,\mathrm{Sn}(1^-) &\rightarrow {}^{140}\,\mathrm{Sn(g.s.)} + \gamma \\
\rightarrow {}^{140}\,\mathrm{Sn}(1^-, 2^-, 3^-) &\rightarrow {}^{140}\,\mathrm{Sn}(2^+_{1,2}) + \gamma \\
\rightarrow {}^{140}\,\mathrm{Sn}(2^+, 3^+, 4^+) &\rightarrow {}^{140}\,\mathrm{Sn}(3^-_1) + \gamma
\end{aligned}
$$

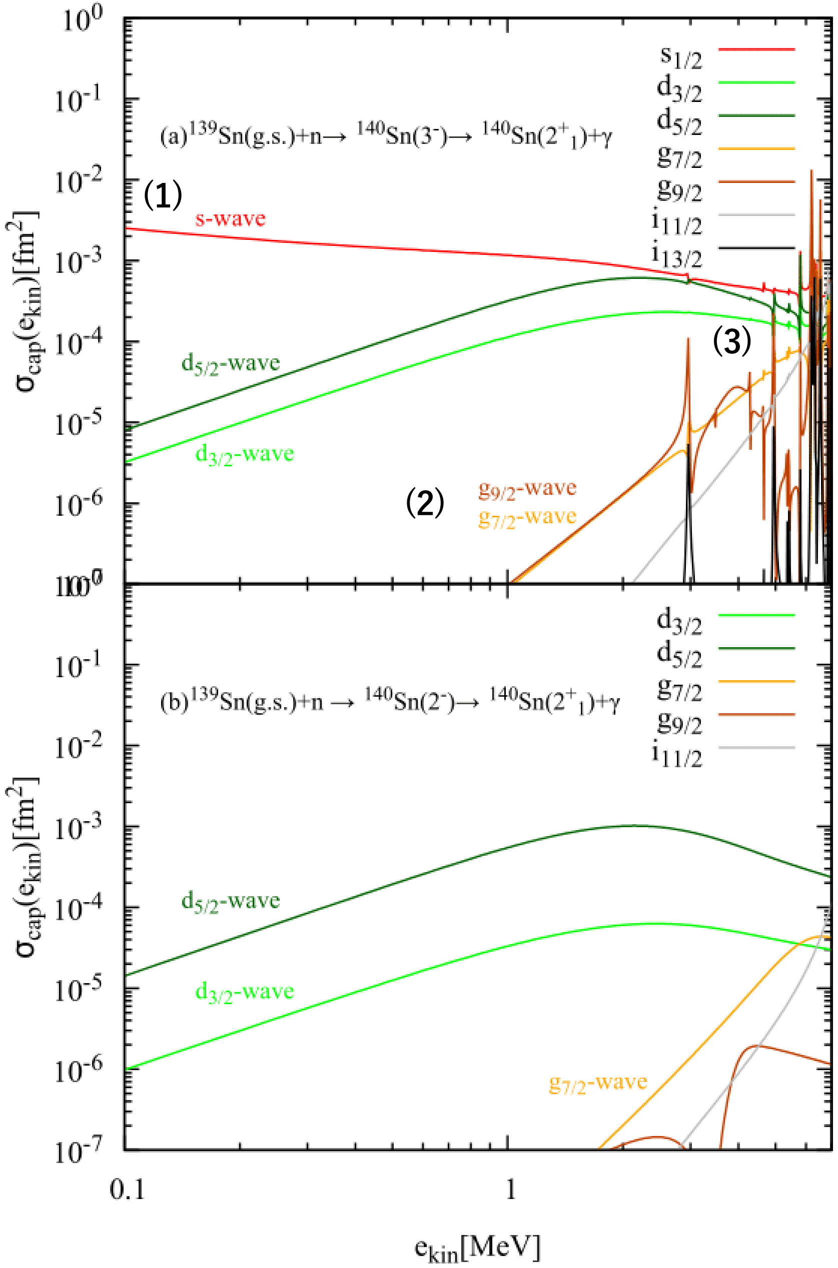
(1)decay to low-lying collective $2^+_{1,2}$ and 3^-_1 are evaluated

(2)decay to $2^+_{1,2}$ dominate at low energy

(3)correlation in excited state produces resonances



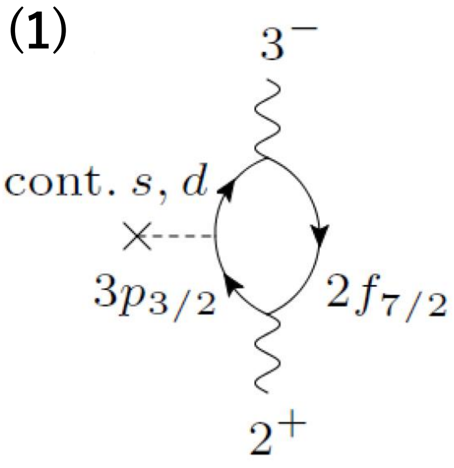
Decay channel to 2^+_1 $\quad {}^{139}\mathrm{Sn(g.s.)}+n \to {}^{140}\mathrm{Sn}(2^-,3^-) \to {}^{140}\mathrm{Sn}(2^+_1)+\gamma$

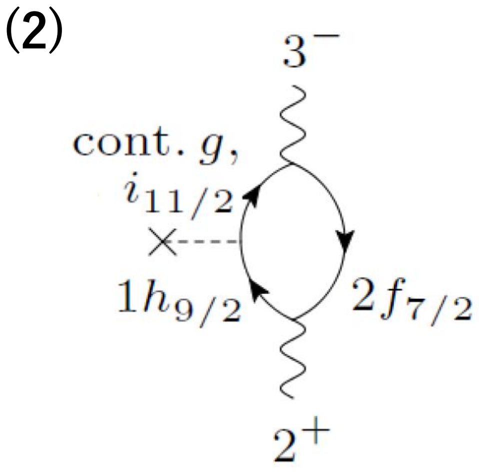


(1)s-wave capture for 2^+_1 exists in ^{139}Sn(g.s.)+n

(2)g-waves capture appear due to config. mixing of 2^+_1

(3)3^- correlation produces resonances

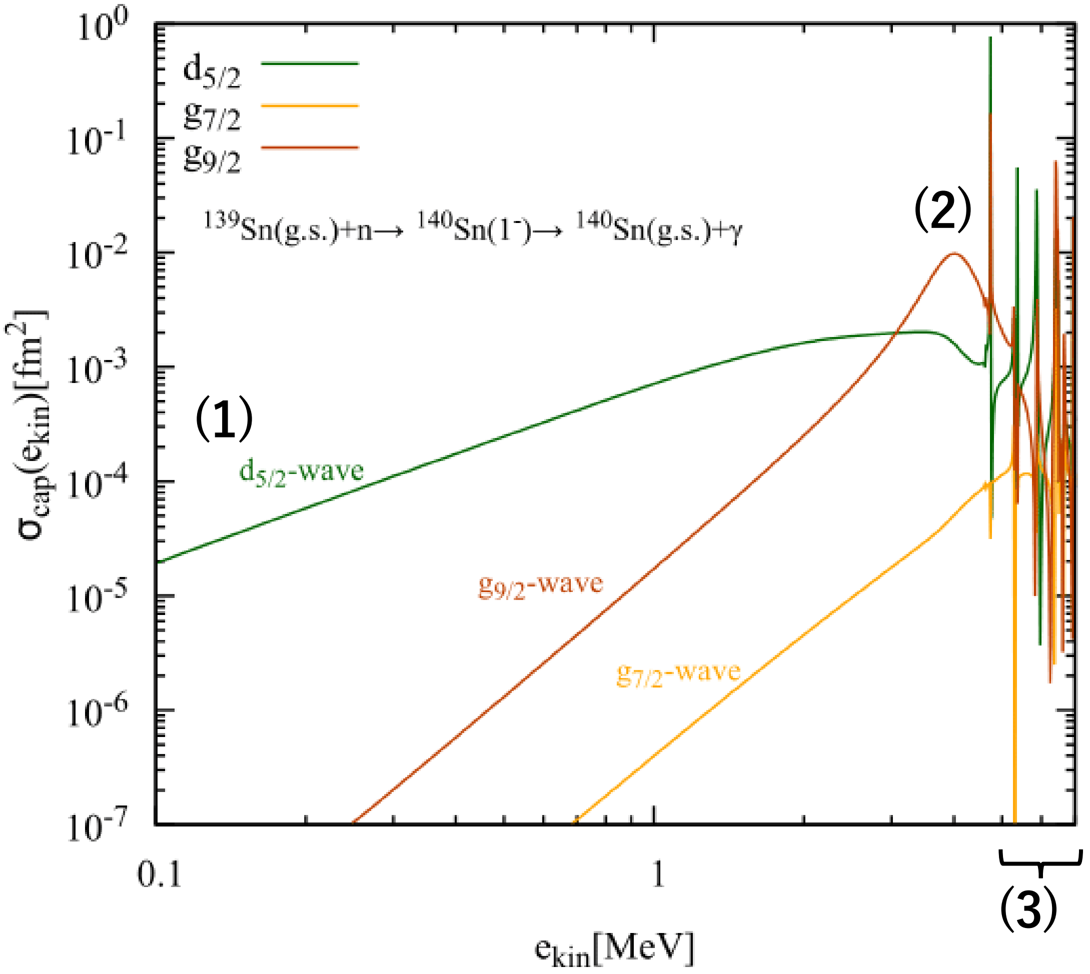




w/o correlation in 2- states

(spin dependence of residual interaction is neglected in this calculation)

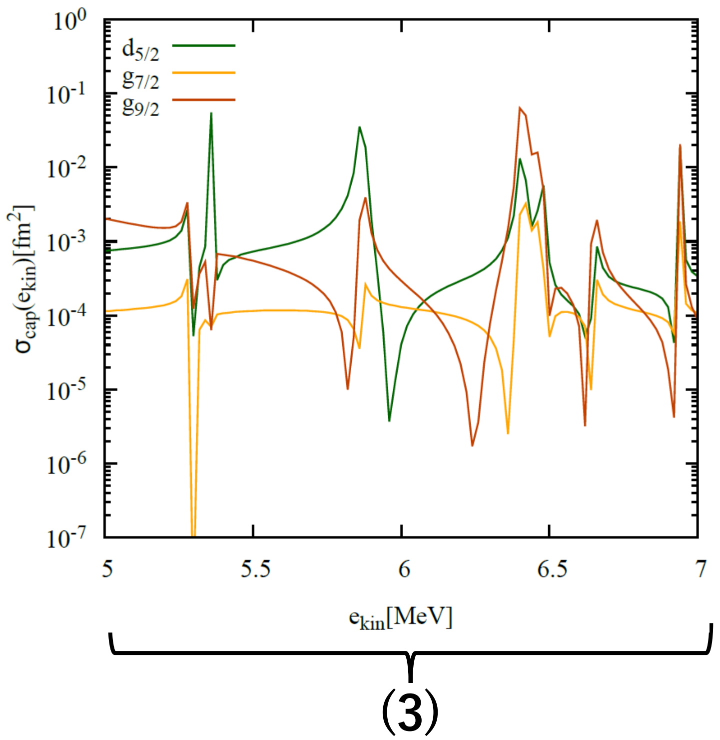
Decay channel to g.s. $^{139}\mathrm{Sn(g.s.)} + n \rightarrow ^{140}\mathrm{Sn}(1^-) \rightarrow ^{140}\mathrm{Sn(g.s.)} + \gamma$



(1)There is no s-wave capture due to angular momentum coupling

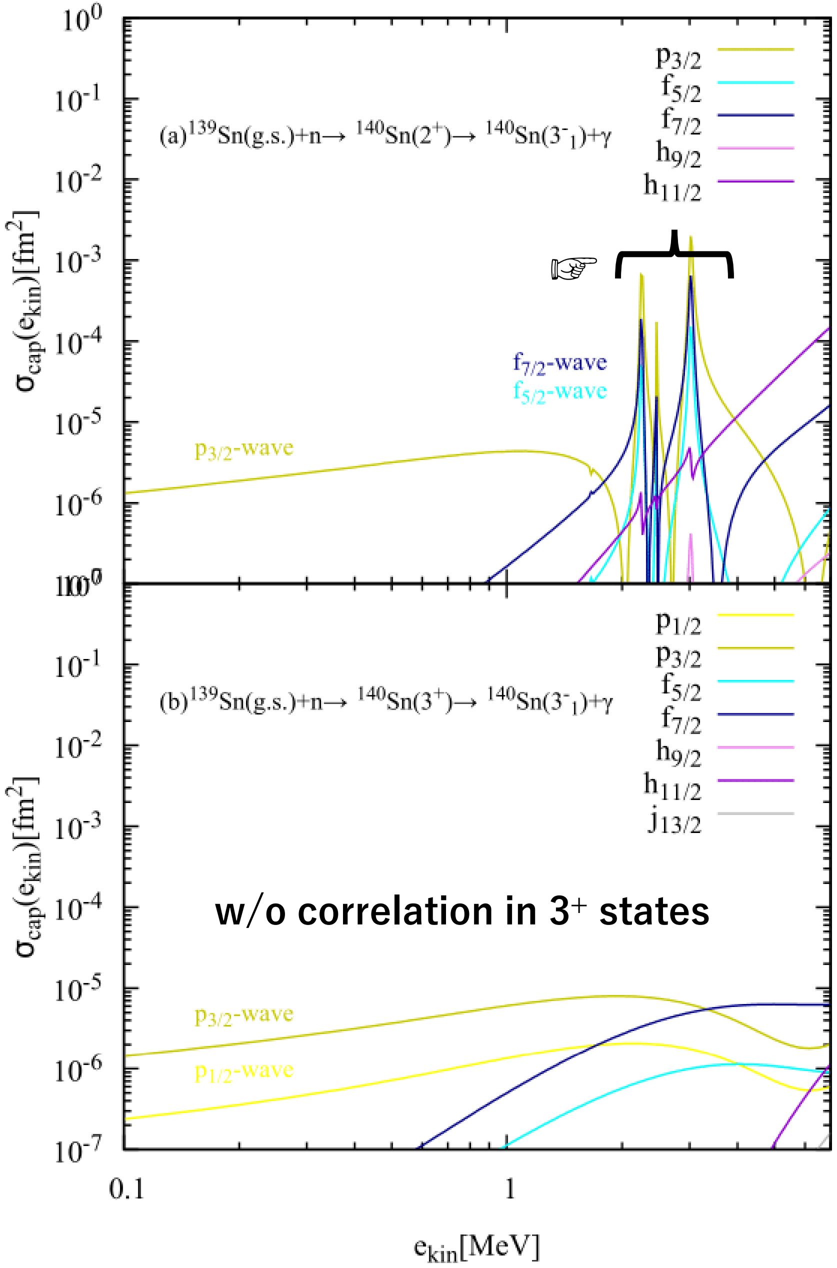
(2)Wide peak caused by ingle particle g resonance

(3)interference between continuum and resonance



Decay channel to 3^-_1

$$^{139}\mathrm{Sn(g.s.)} + n \rightarrow {}^{140}\mathrm{Sn}(2^+, 3^+) \rightarrow {}^{140}\mathrm{Sn}(3^-_1) + \gamma$$



w/o correlation in 3^+ states

initial state(A-1) + n

$$|(2f_{7/2})^{-1} + p_{3/2}\rangle + |(2f_{7/2})^{-1} + f_{5/2}\rangle + |(2f_{7/2})^{-1} + f_{7/2}\rangle + \cdots$$

n cap.

2^+ resonances at 2~4 MeV

$$\nu[(2f_{7/2})^{-1} \otimes p_{3/2}]_{2+} \qquad \nu[(1h_{11/2})^{-1} \otimes 1h_{9/2}]_{2+}$$

$$\nu[(2f_{7/2})^{-1} \otimes f_{5/2}]_{2+} \quad + \quad \pi[(1g_{9/2})^{-1} \otimes 1g_{7/2}]_{2+}$$

$$\nu[(2f_{7/2})^{-1} \otimes f_{7/2}]_{2+} \qquad \pi[(1g_{9/2})^{-1} \otimes 2d_{5/2}]_{2+}$$

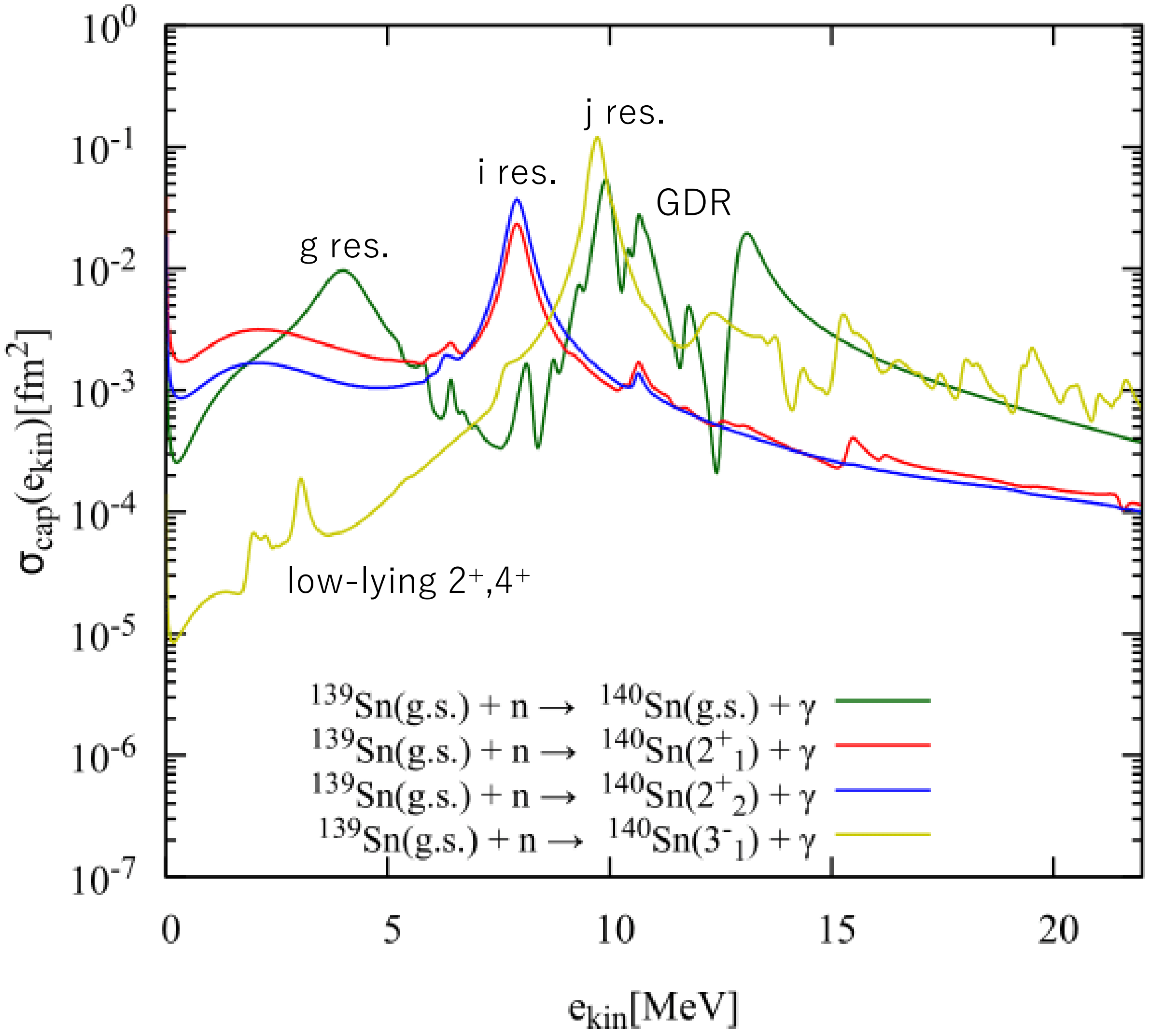
continuum 1p1h　　　bound 1p1h

E1(isovector dipole)

final state $3^-_1 + \gamma$

Collective 3^-_1 state
also includes **proton 1p1h**

E1 direct neutron capture on ^{139}Sn(g.s.) including GDR region



single particle motion

single particle g, i ,j resonance

resonance, collective state

low-lying resonances
GDR

cf. direct semi-direct(DSD) model
=potential model + GDR phonon

S. Chiba et al. PRC 77(2008)

Conclusions

continuum RPA direct neutron capture is possible!

☑only nucleon degrees of freedom
☑channels γ decay to low-lying states
☑collectivity in both initial and final states of γ decay
☑continuum and resonances
☑suitable for neutron-rich nuclei

Theoretical extensions are needed!

synthesized…
☐open shell nuclei ➡ extension to cQRPA (work in progress)
☐odd nuclei
☐odd odd nuclei