Dynamical study of the formation and decay of particle-unbound states

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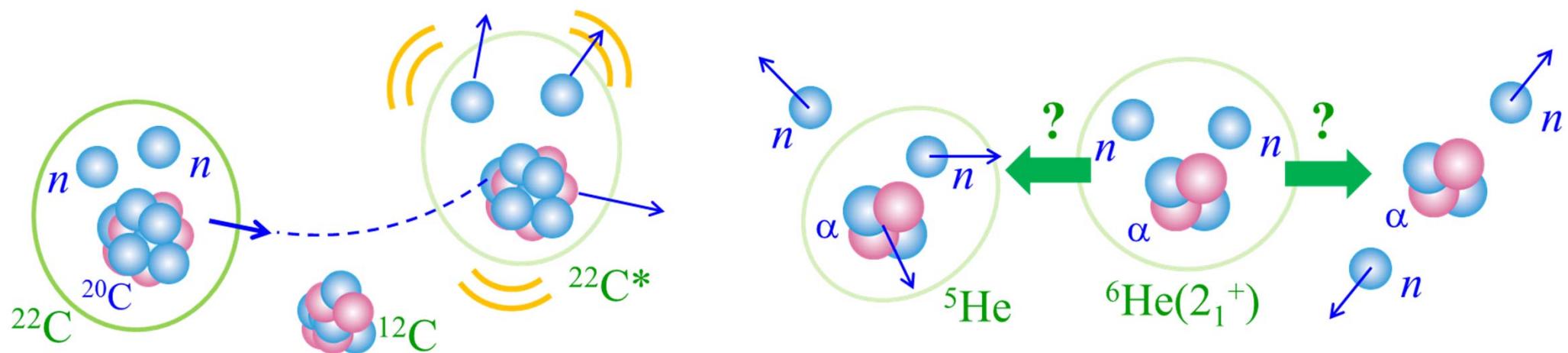
Current interest of physics of unstable nuclei

1. Exploration of *Terra Incognita*
   - Mid. heavy region, outside the drip line
   - Generalization of novel properties (halo, magic #)

2. Ground state to excited states
   - 3-dimensional nuclear chart
   - Understanding of level structure

Description of particle-unbound states is a key subject.

(U)
(Pb) 82
known
Stable nuclei
U Synthesis
(Sn) 50
126
(Ni) 28
82
(Ca) 20
50
(O) 8
28
(He) 2
2 8
20
中性子数

Exploration of unbound (but not free) systems

Our Aim

^{22}C ^{20}C n n

^{12}C $^{22}C^*$

^5He $^6He(2_1^+)$ α n

^8C	^9C	^{10}C	^{11}C	^{12}C	^{13}C	^{14}C	^{15}C	^{16}C	^{17}C	^{18}C	^{19}C	^{20}C	^{21}C	^{22}C	^{24}C

Mizuyama (cPVC)

^7B	^8B	^9B	^{10}B	^{11}B	^{12}B	^{13}B	^{14}B	^{15}B	^{17}B	^{19}B

Ogata-Myo (COSM-CDCC)

^6Be	^7Be	^8Be	^9Be	^{10}Be	^{11}Be	^{12}Be	^{14}Be	^{16}Be

Fukui (transfer)

^6Li	^7Li	^8Li	^9Li	^{11}Li

Today's topic

1. Form of $^{22}C^*$ in a breakup observable
2. Decay mode of the 2_1^+ state of ^6He

^3He	^4He	
	^6He	^7He	^8He

^1H	^2H	^3H
^1n		

Kikuchi-Matsumoto (CDCC-CSLS)

N

Z

KO, Myo, Furumoto, Matsumoto, Yahiro, **PRC88**, 024616 (2013).
Y. Kikuchi, Matsumoto, Minomo, O, **PRC88**, 021602 (2013).

COSM-CDCC for ^{22}C breakup by ^{12}C

Structural part: Cluster Orbital Shell Model (COSM)

✓ Core + valence N system is described well.

✓ Pseudo states covering large space are obtained.

Details of COSM:
   Y. Suzuki and K. Ikeda, PRC **38**, 410 (1988).
   S. Aoyama *et al.*, PTP **116**, 1 (2006) [review].
   T. Myo *et al.*, PL **B691**, 150 (2010) and references therein.
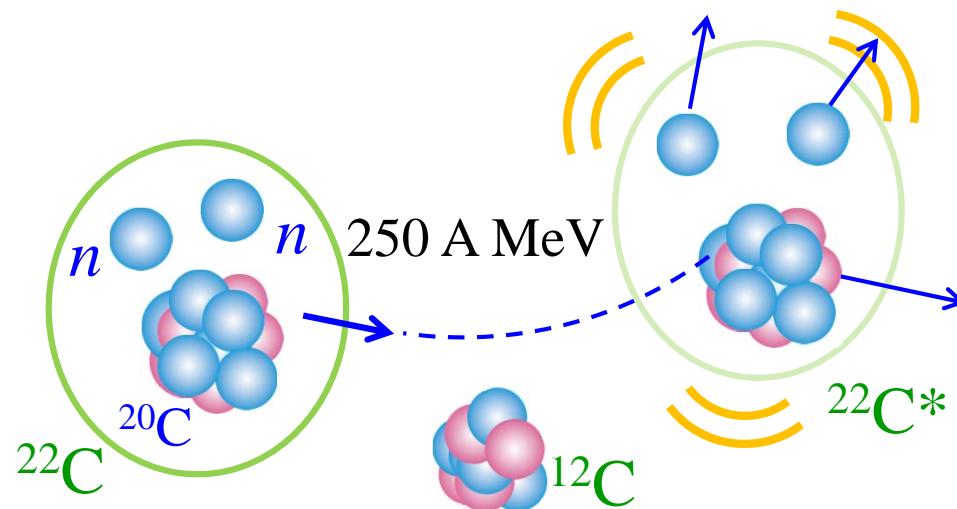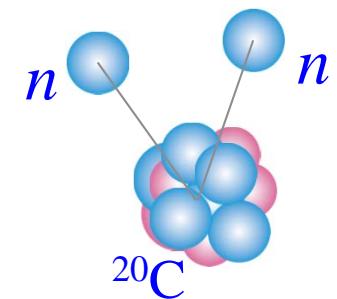
COSM-CDCC for ^{22}C breakup by ^{12}C

Reaction part: Four-body CDCC

Eigenstates obtained by diagonalization

Eigenenergy (MeV)
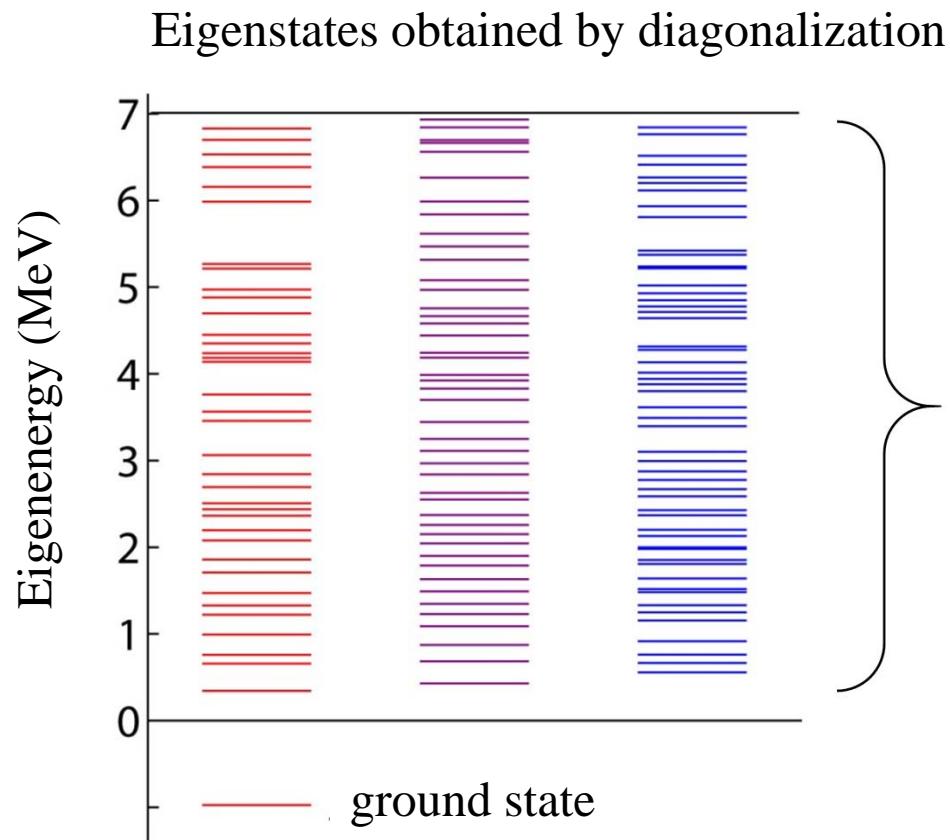
Discretized-continuum states

ground state
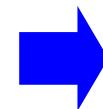
Set of the ^{22}C internal wave functions
(*basis functions* for the 4-body system)

$$\Psi^{\mathrm{CDCC}} = \sum_{i=0}^{i_{\mathrm{max}}} \hat{\phi}_i \hat{\chi}_i$$

Relative motion between ^{22}C and target
(*expansion coefficients*)

A new CDCC review article:
Yahiro, O, Matsumoto, Minomo, Prog. Theor. Exp. Phys. **2012**, 01A209 (2012).

Numerical inputs

^{22}C wave function

✓ Minnesota force[10] for n-n, Woods-Saxon potential[3] for n-^{20}C.
✓ $s_{1/2}$, $p_{3/2}$, $p_{1/2}$, $d_{5/2}$, $d_{3/2}$, $f_{7/2}$, $f_{5/2}$, $g_{9/2}$, $g_{7/2}$, $h_{11/2}$, and $h_{9/2}$ for the n s.p. orbit.
✓ Each orbit is described by 10 Gaussian basis functions.
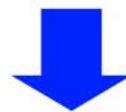
[10]D. R. Thompson *et al.*, NP **A286**, 53 (1977).

0^+ ground state with $S_{2n} = 289$ keV, 604 0^+ and 1,385 2^+ PS

c.f. Talks by Matsumoto, Kohno, Toyokawa, Yoshida, Fukui, <u>Minomo</u>

^{22}C-^{12}C breakup reaction

✓ 77 (0^+) + 164 (2^+) PS below 10 MeV are included as breakup states of ^{22}C.
✓ Distorting potentials are calculated by a microscopic folding model with CEG07[11] nucleon-nucleon g matrix.
✓ We adopt the so-called no-recoil approximation for the ^{20}C core nucleus.

[11]T. Furumoto *et al.*, PRC **78**, 044610 (2008).

Microscopic CDCC

$n + n + c$ dynamics
explicitly described

n   **n**

c

Microscopic
Opt. pot.

Microscopic
Opt. pot.

A
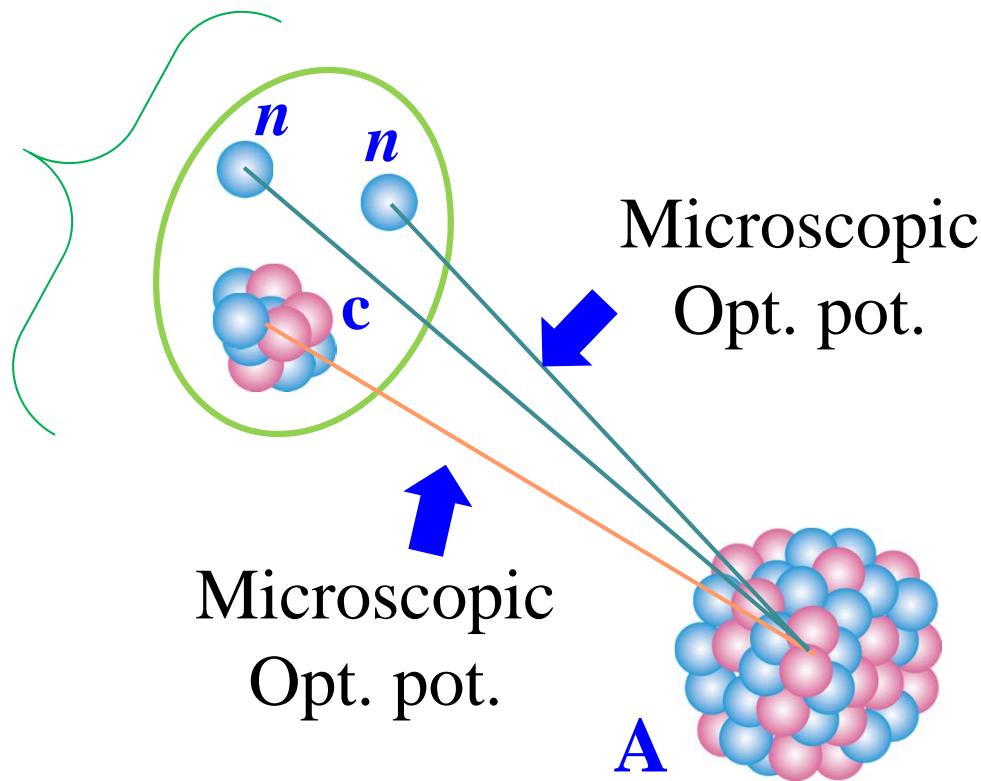
c.f. Talk by Iseri

DDBUX of ^{22}C by ^{12}C

DDBUX [b/(MeV sr)] — θ_{22} (deg) — ε (MeV)
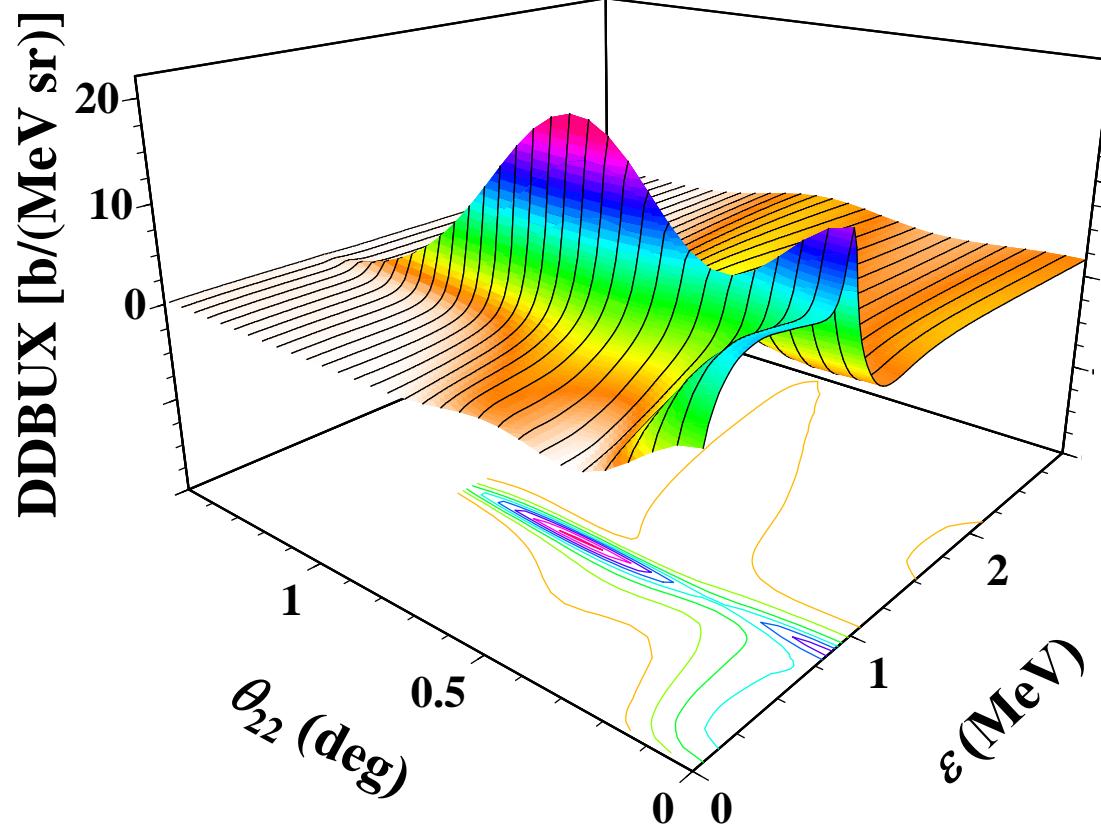
✓ A new smoothing method* is adopted to obtain the BUX.

✓ COSM predicts the following resonances:

^{22}C resonance
0_2^+: $1.02 - i\,0.52/2$
2_1^+: $0.86 - i\,0.10/2$
2_2^+: $1.80 - i\,0.26/2$ negligible

^{21}C resonance
$d_{3/2}$: $1.1 - i\,0.10/2$ negligible

How are these resonances observed?

*T. Matsumoto *et al.*, PRC **82**, 054602(R) (2010) [new smoothing method].

Integrated BUX (0 − 0.1 deg)
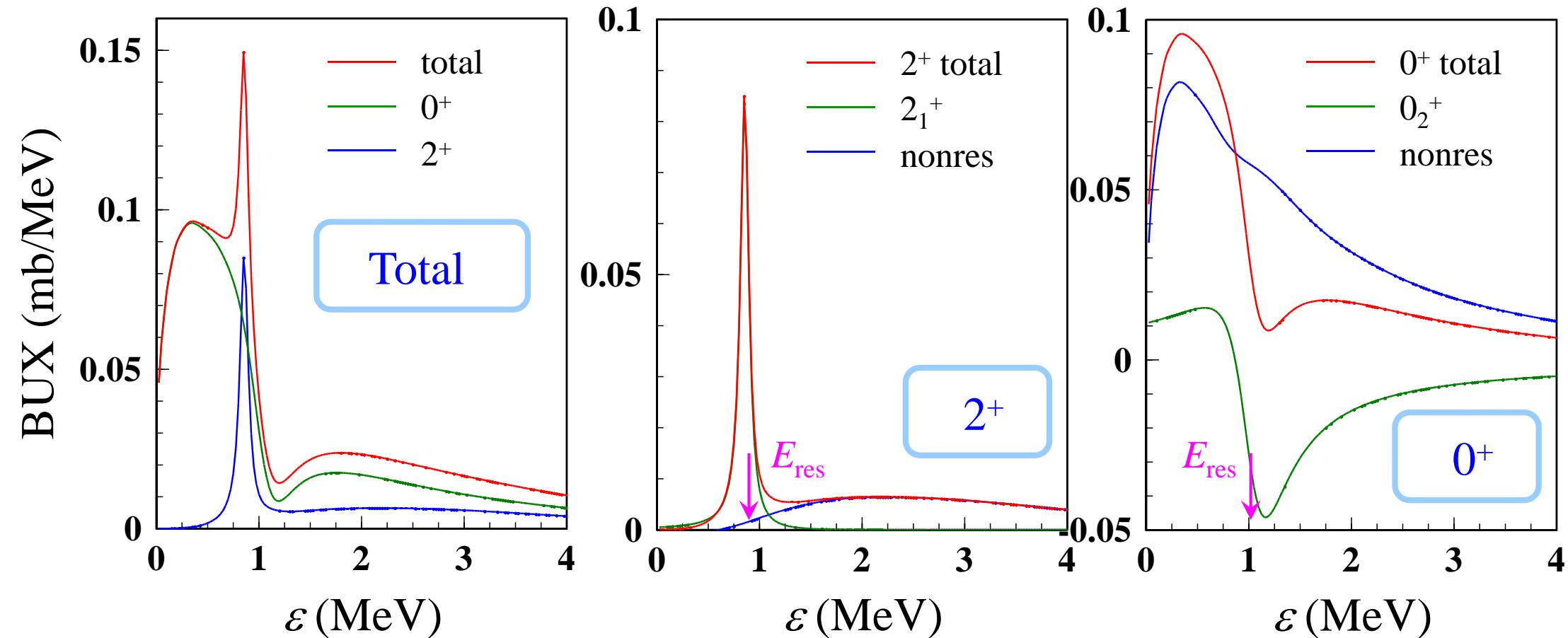
✓ The narrow peak around 0.8 MeV is due to the 2_1^+ resonance of ^{22}C.
✓ The shape of the 0_2^+ resonance is due to background phase effect.

# BackGround Phase (BGP) effect

ε_{res}

—	$\delta_{bg} = 0$
—	$\delta_{bg} = \pi/4$
—	$\delta_{bg} = \pi/2$
—	$\delta_{bg} = 3\pi/4$

Vertical axis: $|1 - S(\varepsilon)|^2$

Horizontal axis: ε (MeV)

Γ
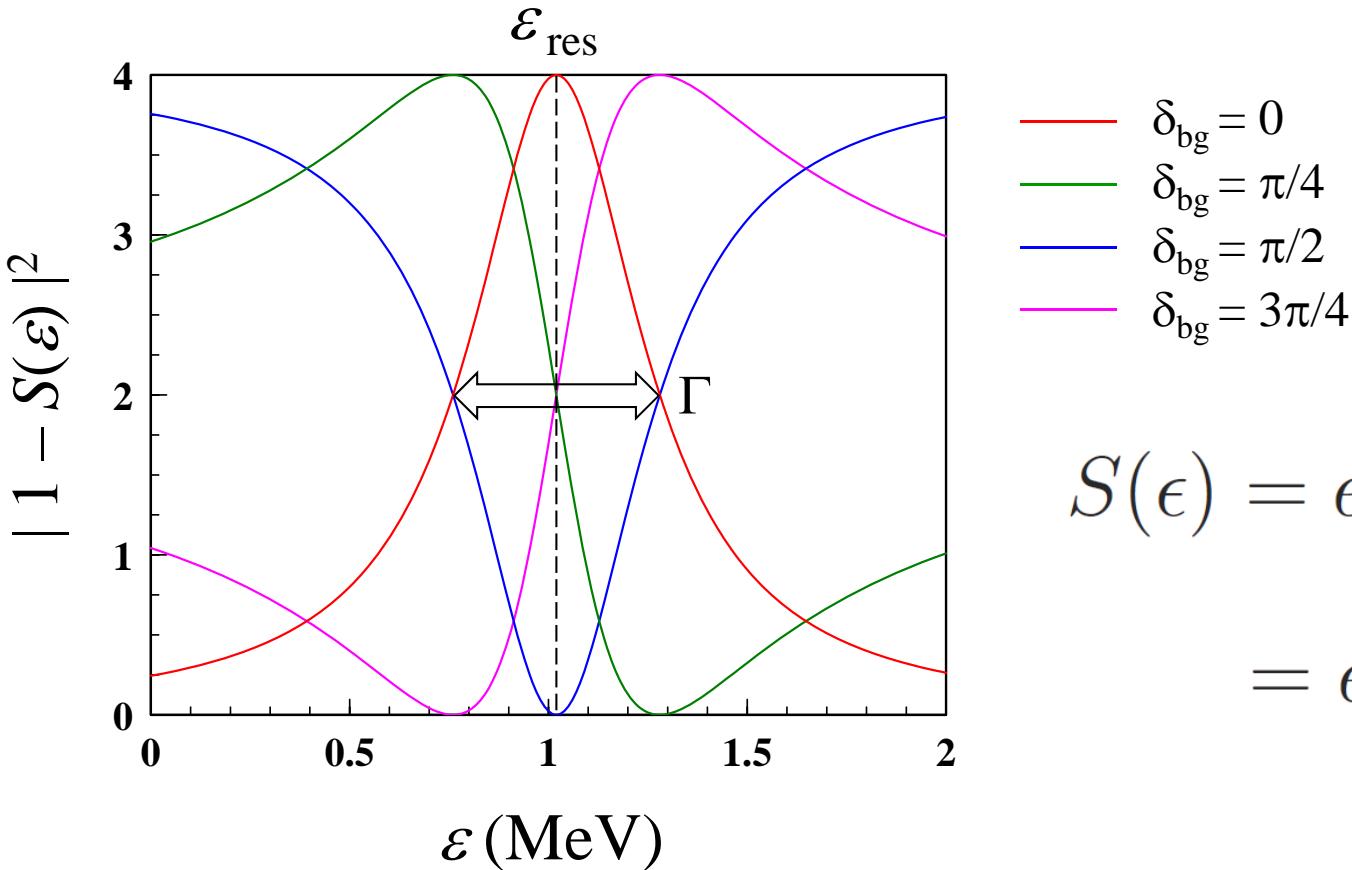
$$S(\epsilon) = e^{2i\delta_{bg}(\epsilon) + 2i\delta_{res}(\epsilon)}$$

$$= e^{2i\delta_{bg}(\epsilon)} \frac{\epsilon - \epsilon_{res} - i\Gamma/2}{\epsilon - \epsilon_{res} + i\Gamma/2}$$

✓ In nuclear physics, we always have δ_{bg}.

✓ There are many examples of this effect in many research fields.

✓ In most cases, this effect is observed as small changes in the resonance energy and width.

BGP effect on the DDBUX
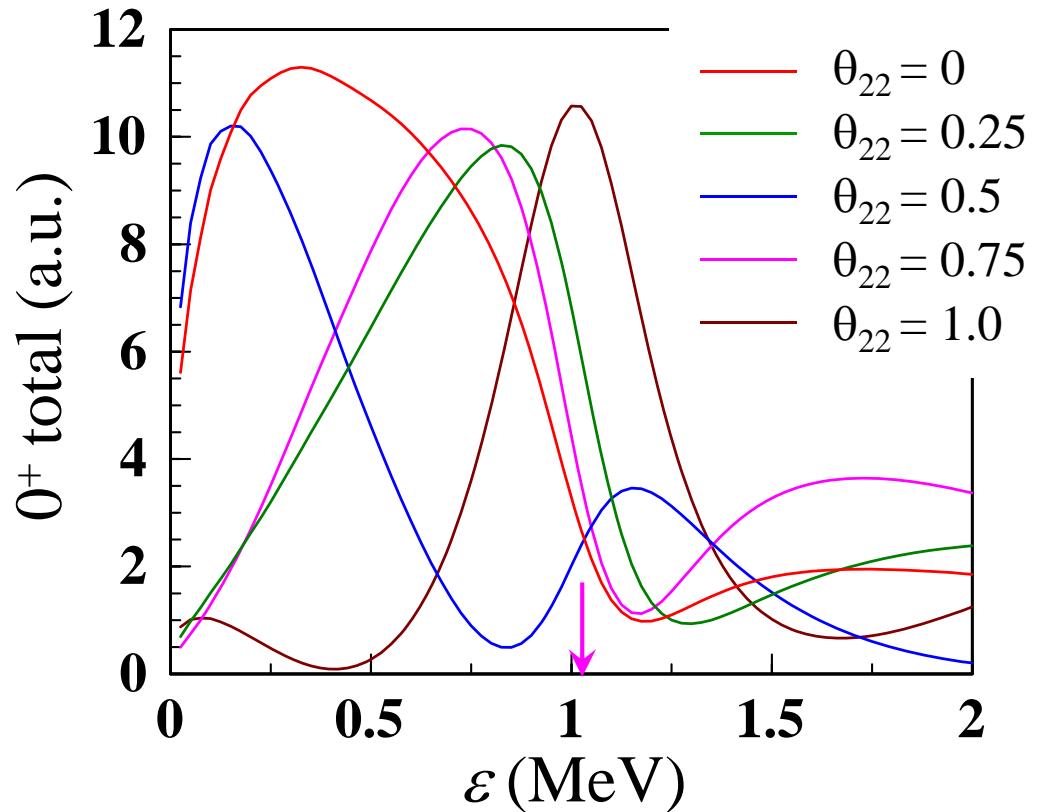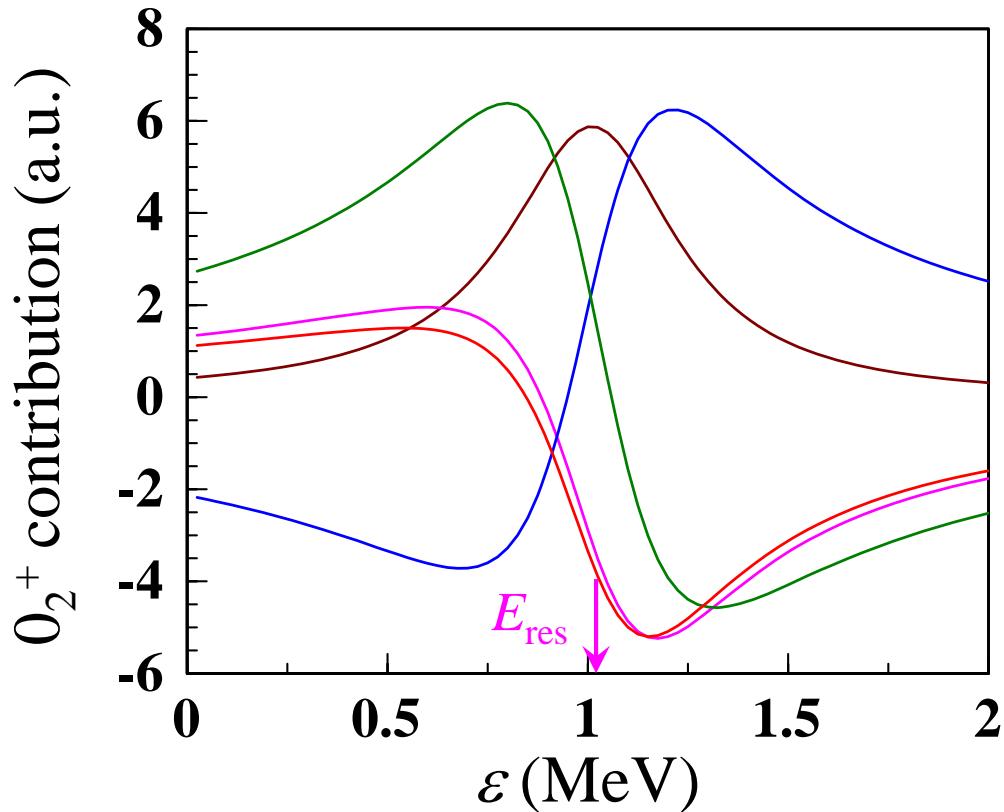
✓ The BGP effect is indeed sizable.

✓ We have a variety of patterns of the resonant (and 0^+) cross section.

✓ Appear in only the 0^+ state

Summary of the 1ˢᵗ topic

What is the form of $^{22}\mathrm{C}^*$ in a breakup observable?

- ✓ The 2_1^+ state: Breit-Wigner form
- ✓ The 0_2^+ state: peculiar form due to the BGP effect (coexistence of the 0^+ resonant and nonresonant waves)
- ✓ The BGP has a strong scattering-angle dependence.

2nd topic

What is the decay mode of the 2_1^+ state of ^{6}He?

^{6}He(2_1^+)

n n

α

n

n

^{5}He

α

Sequential decay

α

n $2n$

n

di-neutron decay

n

α

n

democratic decay
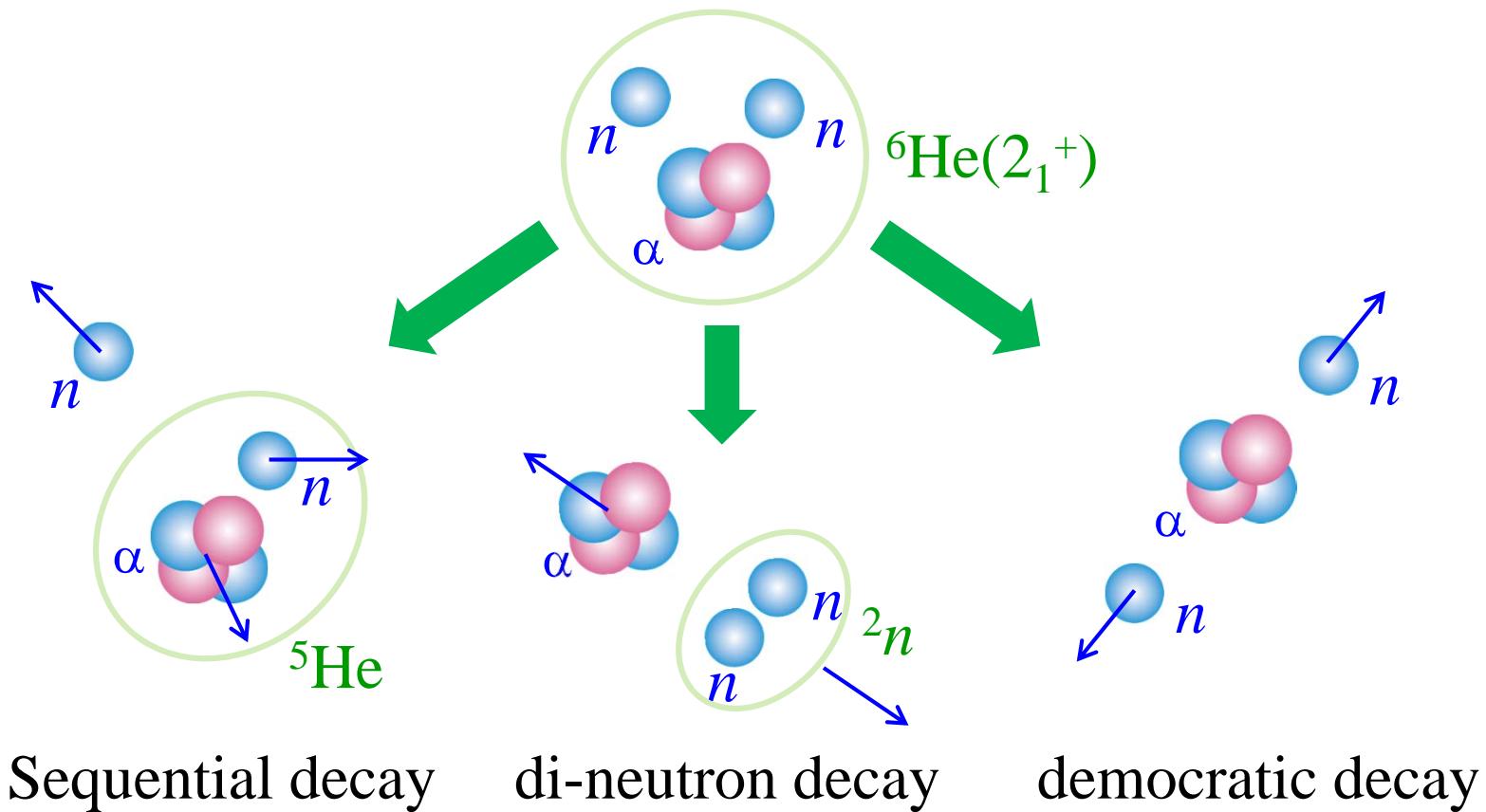
CDCC-CSLS

✓ The method of Complex-Scaled solutions of the Lippmann-Schwinger Eq.
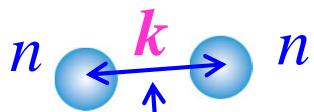
$$T_\varepsilon(\boldsymbol{p}, \boldsymbol{k}, \boldsymbol{P}) \approx \sum_i \langle \Phi_\varepsilon^{(-)}(\boldsymbol{p}, \boldsymbol{k}) | \Phi_i \rangle T_i^{\mathrm{CDCC}}$$
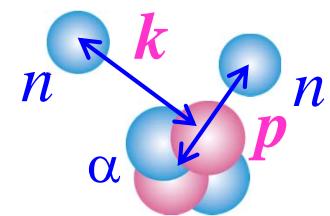
$$= \sum_i f_i(\boldsymbol{p}, \boldsymbol{k}) T_i^{\mathrm{CDCC}}$$

$$f_i(\boldsymbol{p}, \boldsymbol{k}) = \langle \varphi_0(\boldsymbol{p}, \boldsymbol{k}) | \Phi_i \rangle + \sum_n \!\!\!\!\!\int \langle \varphi_0(\boldsymbol{p}, \boldsymbol{k}) | \hat{V} U^{-1}(\theta) | \Phi_n^\theta \rangle$$

$$\times \frac{1}{\varepsilon - \varepsilon_n^\theta} \langle \tilde{\Phi}_n^\theta | U(\theta) | \Phi_i \rangle$$

Sequential decay quenched
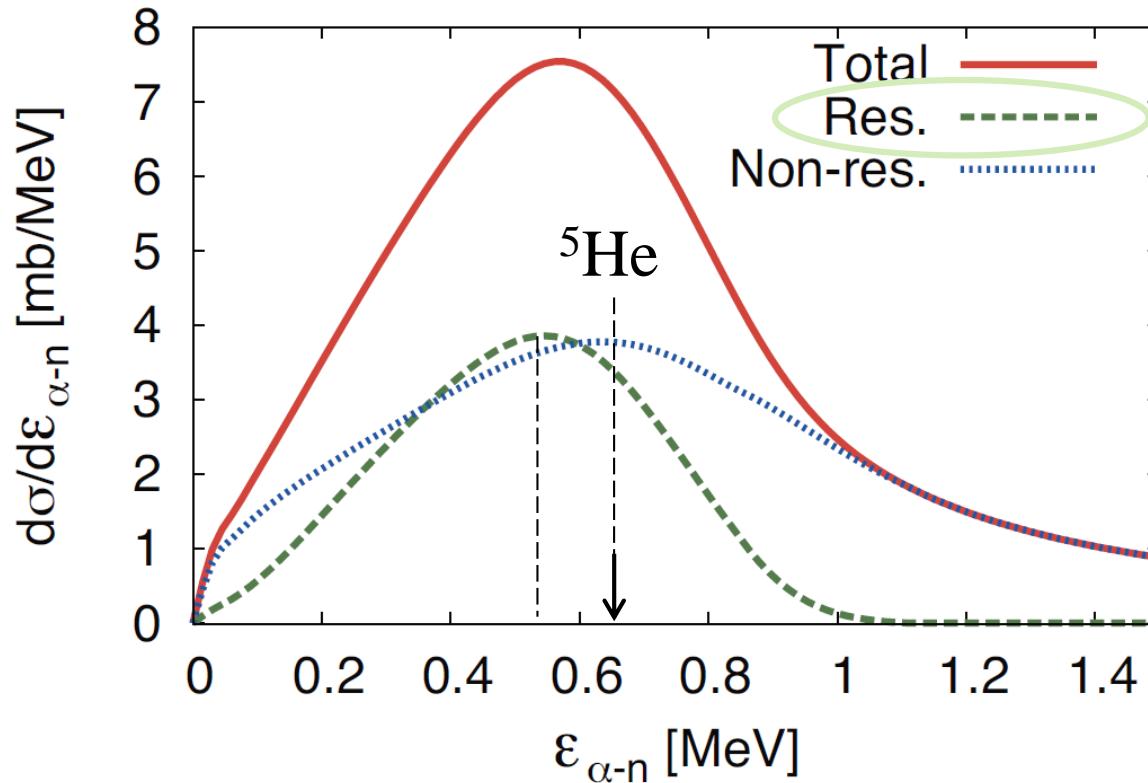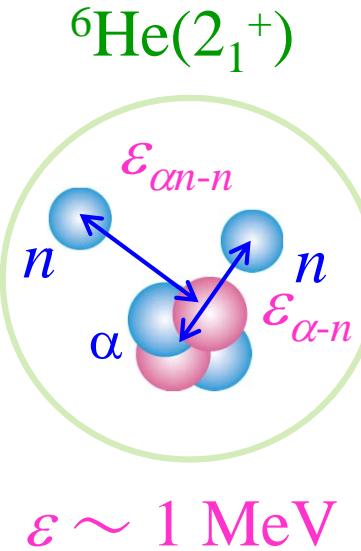
✓ When $\varepsilon \sim 1$ MeV and $\varepsilon_{\alpha\text{-}n} \sim 0.7$ MeV, the other neutron (~ 0.3 MeV) hardly penetrates the centrifugal barrier (*p*-wave).

✓ The peak of the green line suggests the di-neutron decay or the democratic decay.

Coexistence of two decay modes
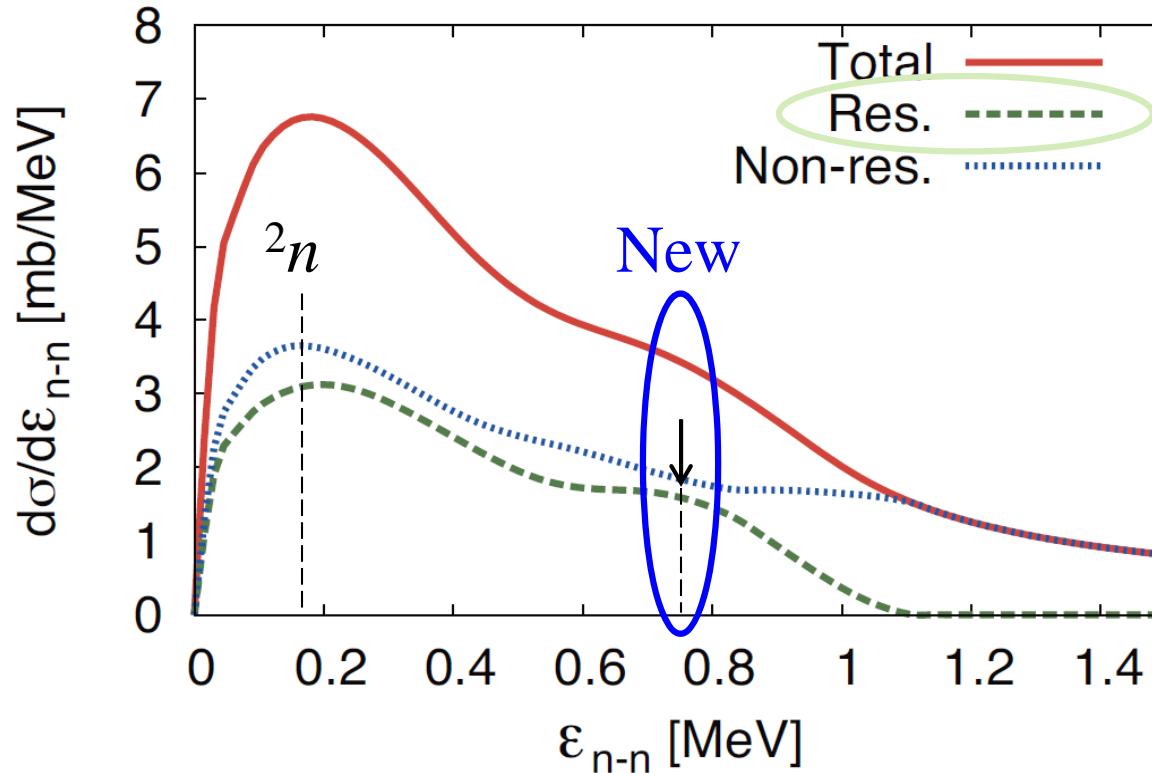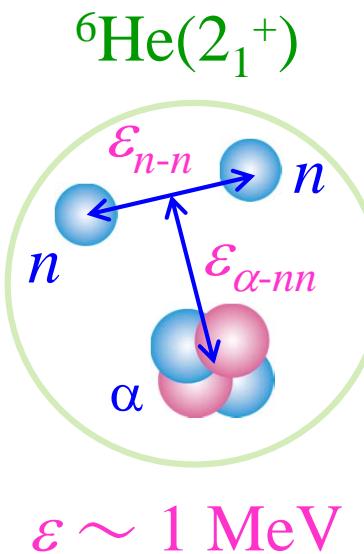

✓ The lower peak suggests the di-neutron decay due to the Fin. State Int. (FSI).
✓ The higher peak indicates the democratic decay.

➡ Decay of a di-neutron in the 2_1^+ state not due to the FSI.

Summary of the 2nd topic

What is the decay mode of the 2_1^+ state of ^{6}He?

^{6}He(2_1^+)

Sequential decay

di-neutron decay
(due to FSI)

democratic decay
(not due to FSI)

di-neutron
in ^{6}He(2_1^+)

Exploration of unbound (but not free) systems

Our Aim

Dynamical description of *Formation* and *Decay* of unbound systems
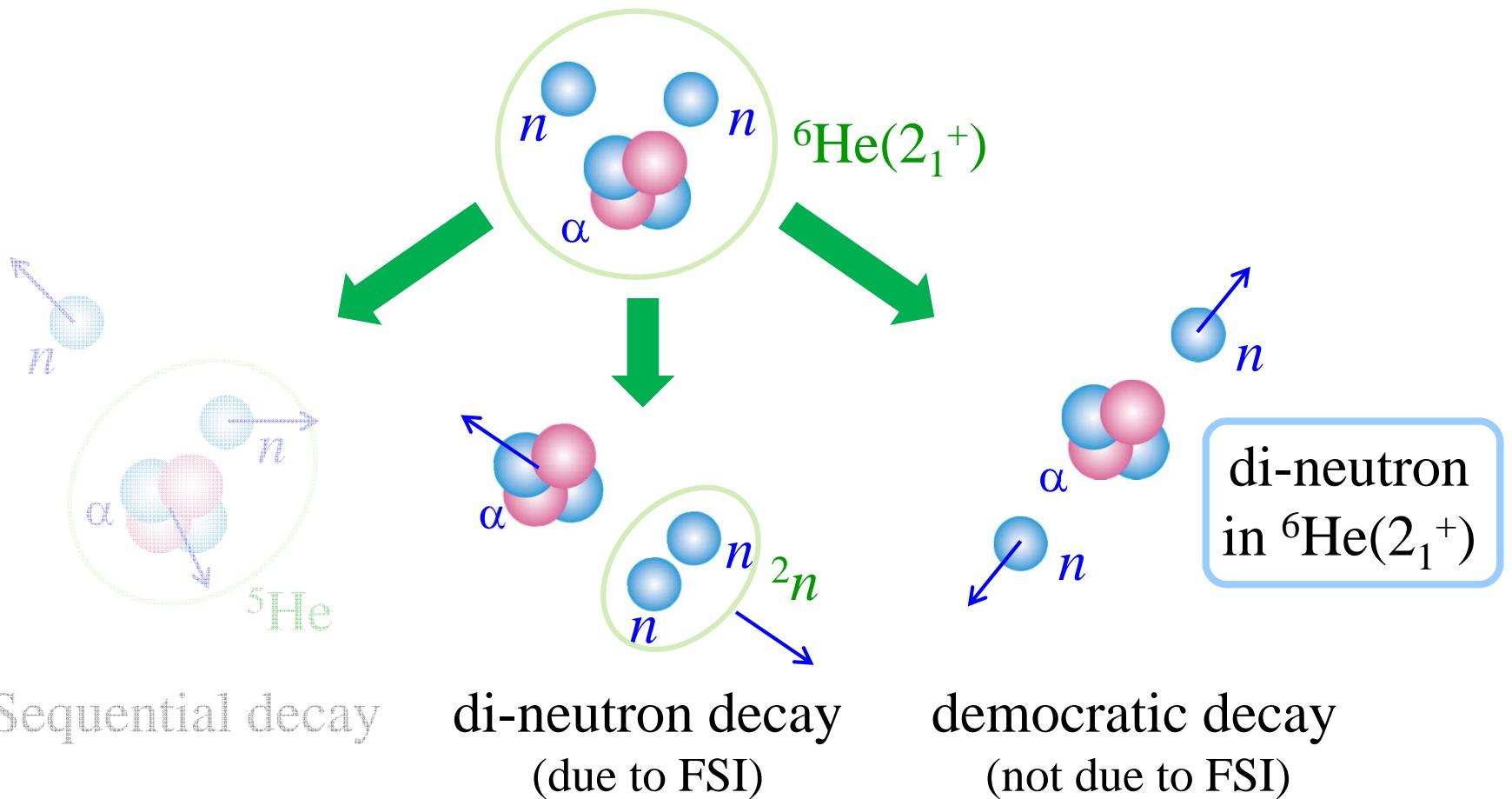
Legend:
- $5\times10^8\text{y} < T_{1/2}$
- $30\text{d} < T_{1/2} < 5\times10^8\text{y}$
- $10\text{m} < T_{1/2} < 30\text{d}$
- $T_{1/2} < 10\text{m}$
- Not Synthesized

Unbound <u>ex. state</u> studied
K. Tshoo *et al.*, PRL**109**, 022501 (2012).

Unbound g.<u>s.</u> observed
E. Lunderberg *et al.*, PRL**108**, 142503 (2012).

More Collaboration!!

Mizuyama (cPVC)

Ogata-Myo (COSM-CDCC)

Fukui (transfer)

Kikuchi-Matsumoto (CDCC-CSLS)

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