# Dynamical Studies of the Formation and Decay of Particle-Unbound States

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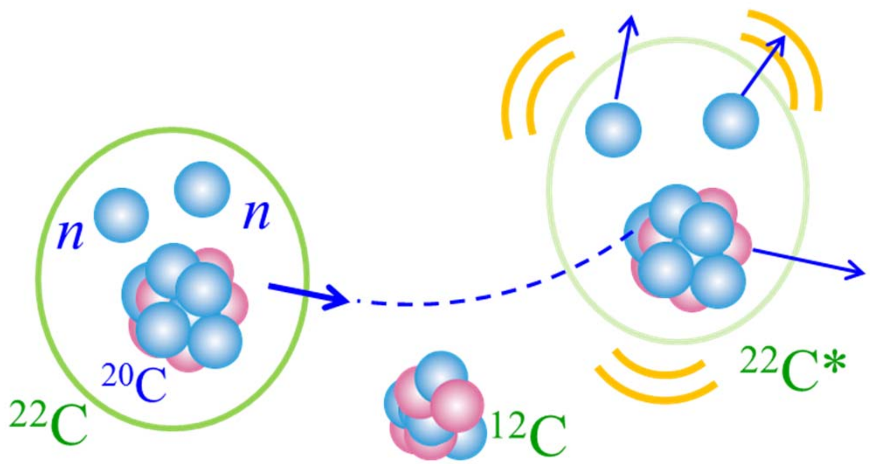
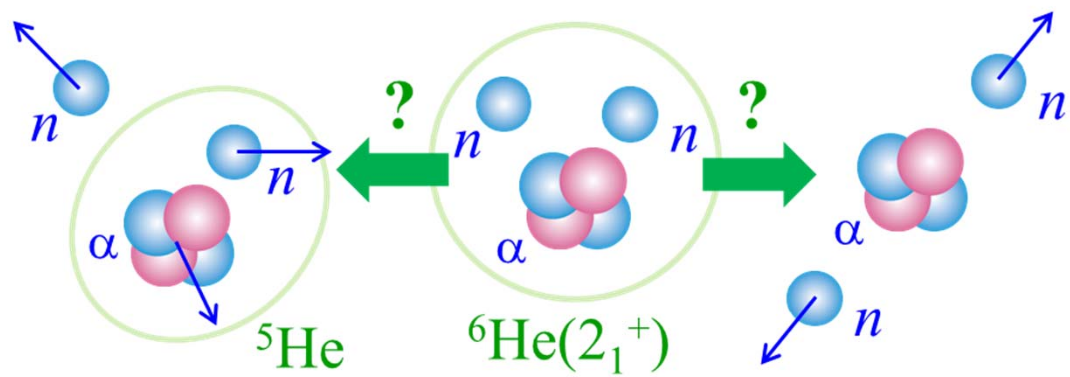
[4]*Ichinoseki National College of Technology*, [5]*Kyushu University*



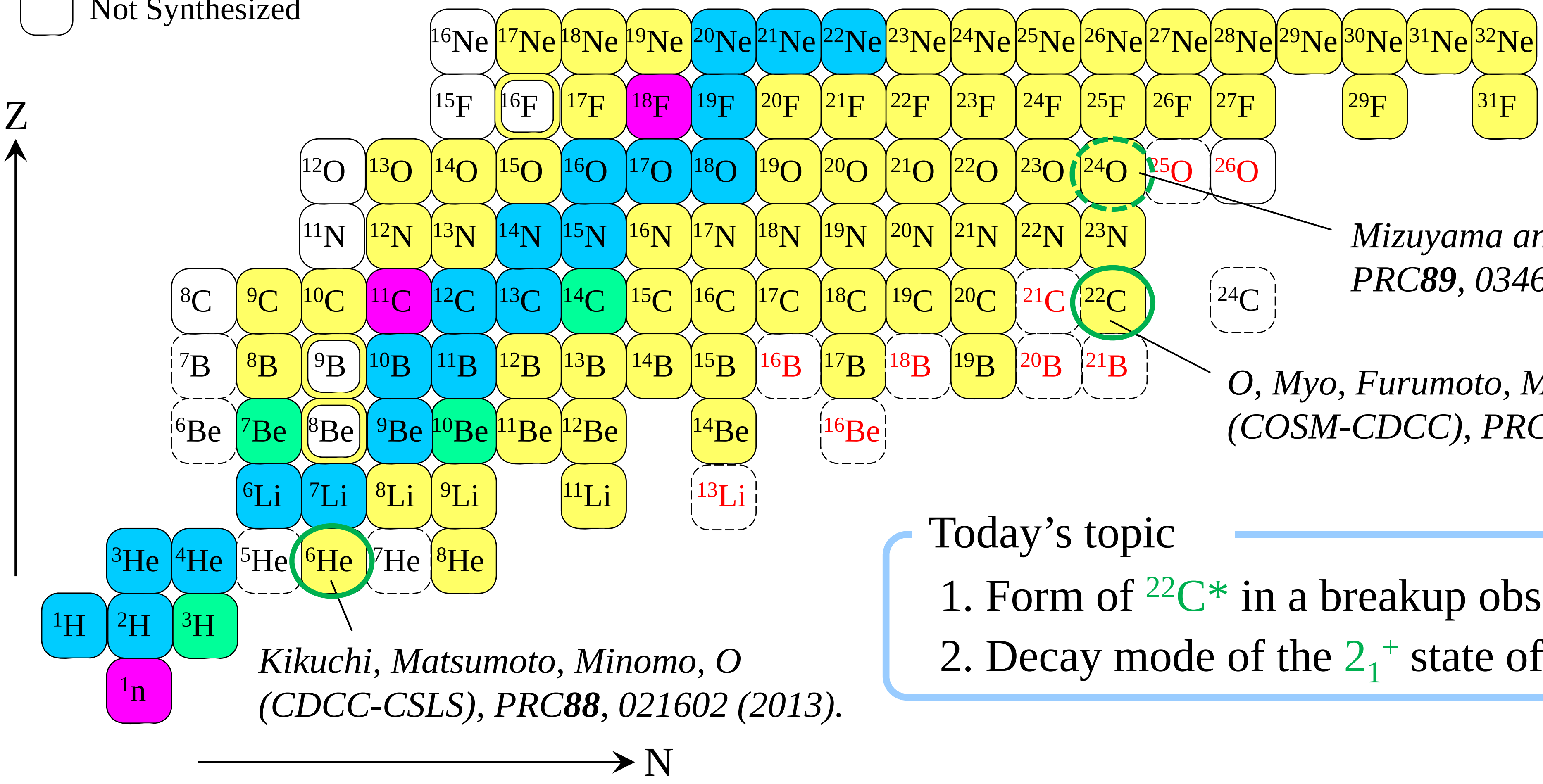
# Exploration of unbound (but not free) systems

**Our Aim**

*Dynamical description of Formation and Decay of unbound systems*

- $5\times10^{8}$y < $T_{1/2}$
- 30d < $T_{1/2}$ < $5\times10^{8}$y
- 10m < $T_{1/2}$ < 30d
- $T_{1/2}$ < 10m
- Not Synthesized

A: discussed in this conference (cf. talks by Gade, Hagino, Marques, Kondo, Obertelli…)




*Mizuyama and O (cPVC), PRC**89**, 034620 (2014).*

*O, Myo, Furumoto, Matsumoto, Yahiro, (COSM-CDCC), PRC**88**, 024616 (2013).*

*Kikuchi, Matsumoto, Minomo, O (CDCC-CSLS), PRC**88**, 021602 (2013).*

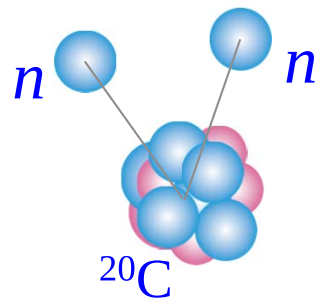
**Today's topic**

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

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

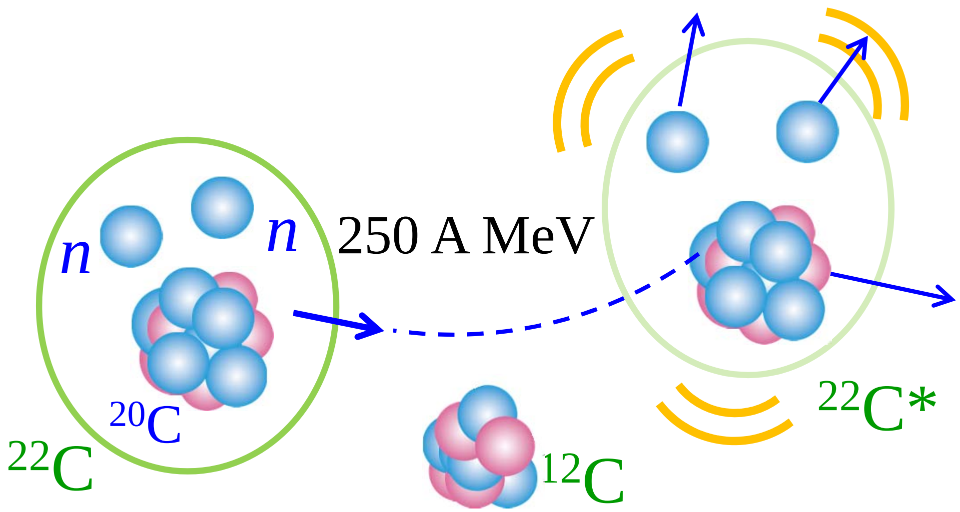
**Structural part**: Cluster Orbital Shell Model (COSM)

- ✓ Core + valence *N* system is described well.
- ✓ Pseudo states covering large space are obtained.




Details of COSM:

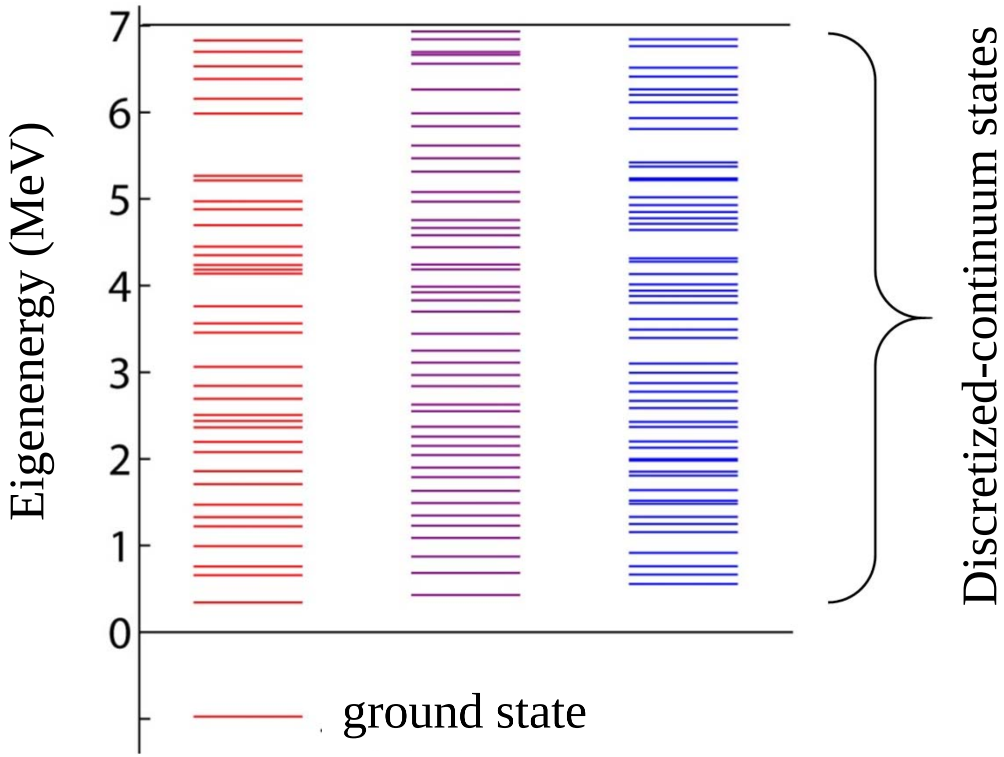
Y. Suzuki and K. Ikeda, PRC **38**, 410 (1988).
S. Aoyama *et al*., PTP **116**, 1 (2006) [review].
T. Myo *et al*., PL **B691**, 150 (2010) and references therein.



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

## **Reaction part**: Four-body CDCC

Eigenstates obtained by diagonalization




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

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

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

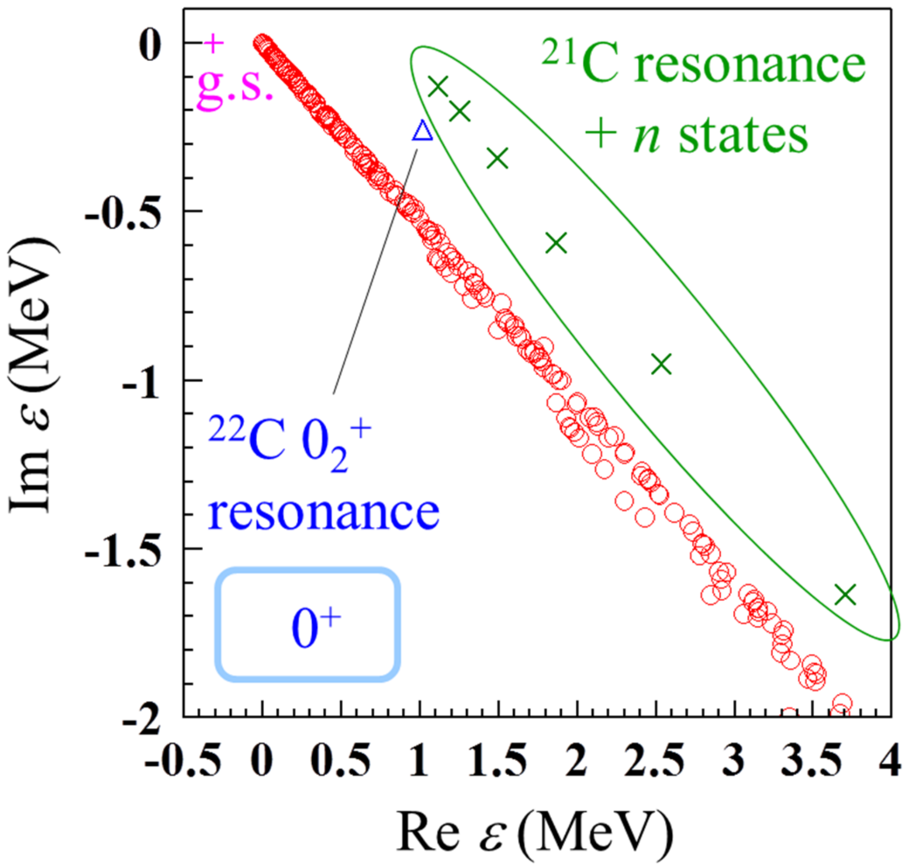
Details of four-body CDCC:
T. Matsumoto *et al.*, PRC **70**, 061601(R) (2004); ibid. 73, 051602(R) (2006).
M. Rodriguez-Gallardo *et al.*, PRC **80**, 051601 (2009).

# CSM Smoothing
## (CSM: Complex-Scaling Method)

T. Matsumoto, Kato, and Yahiro, PRC **82**, 054602(R) (2010).

Eigenstates of $H^\theta$

(complex-scaled Hamiltonian)




$$\tilde{\mathcal{T}}_i^\theta = \sum_n \langle \tilde{\phi}_i^\theta | C(\theta) | \Phi_n \rangle T_n^{\mathrm{CDCC}}$$

index for the pseudostates $\Phi_n$ used in CDCC

$$\frac{d\sigma}{d\epsilon} = \frac{1}{\pi} \mathrm{Im} \sum_i \frac{\mathcal{T}_i^\theta \tilde{\mathcal{T}}_i^\theta}{\epsilon - \epsilon_i}$$

index for the eigenstates $\phi_i^\theta$ of $H^\theta$

# Numerical inputs

## $^{22}$C wave function

- ✓ Minnesota force for $n$-$n$, Woods-Saxon potential 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.

D. R. Thompson *et al.*, NP **A286**, 53 (1977).

↓

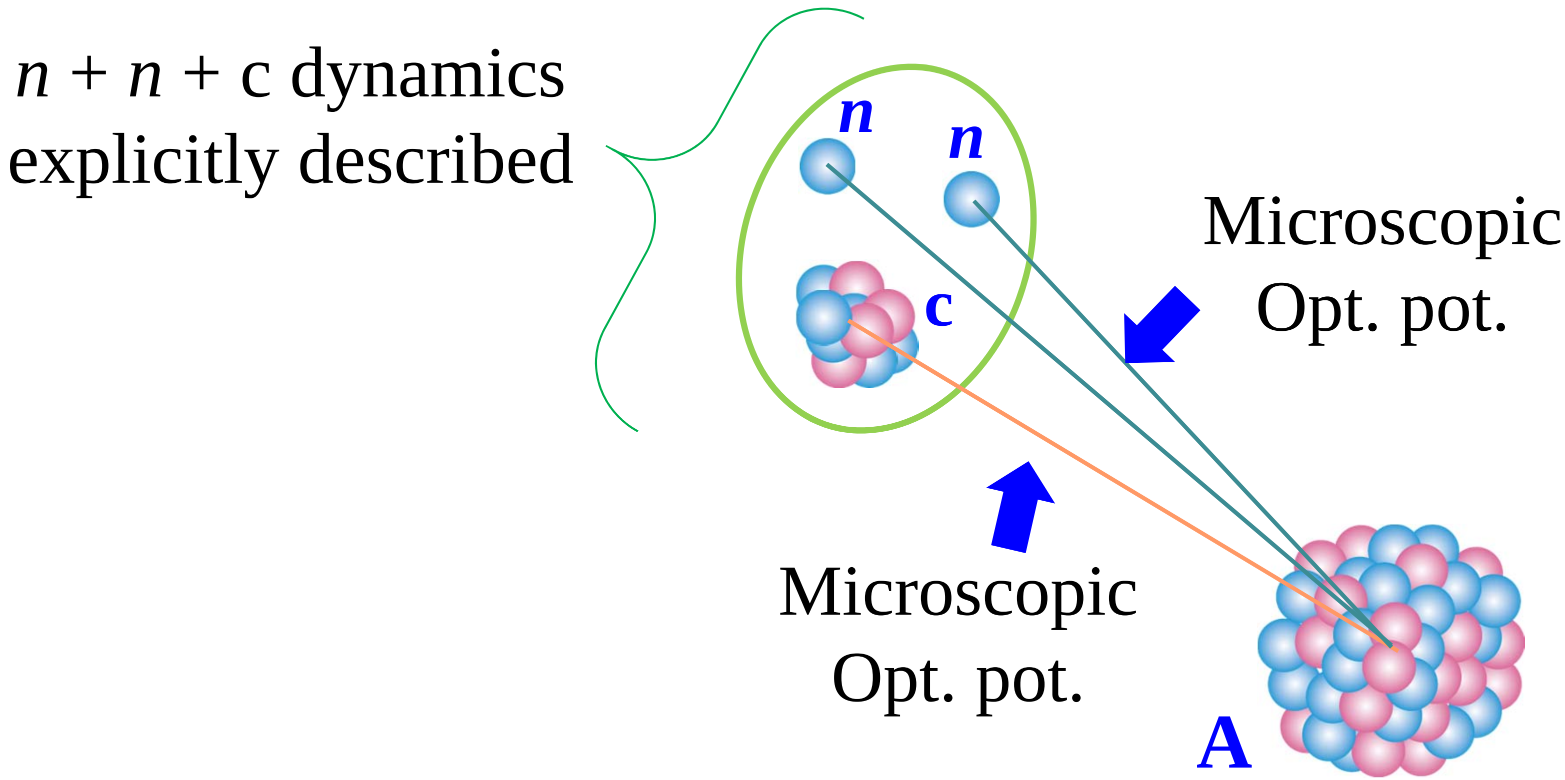
$0^+$ ground state with $S_{2n}$ = 289 keV, 604 $0^+$ and 1,385 $2^+$ PS

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

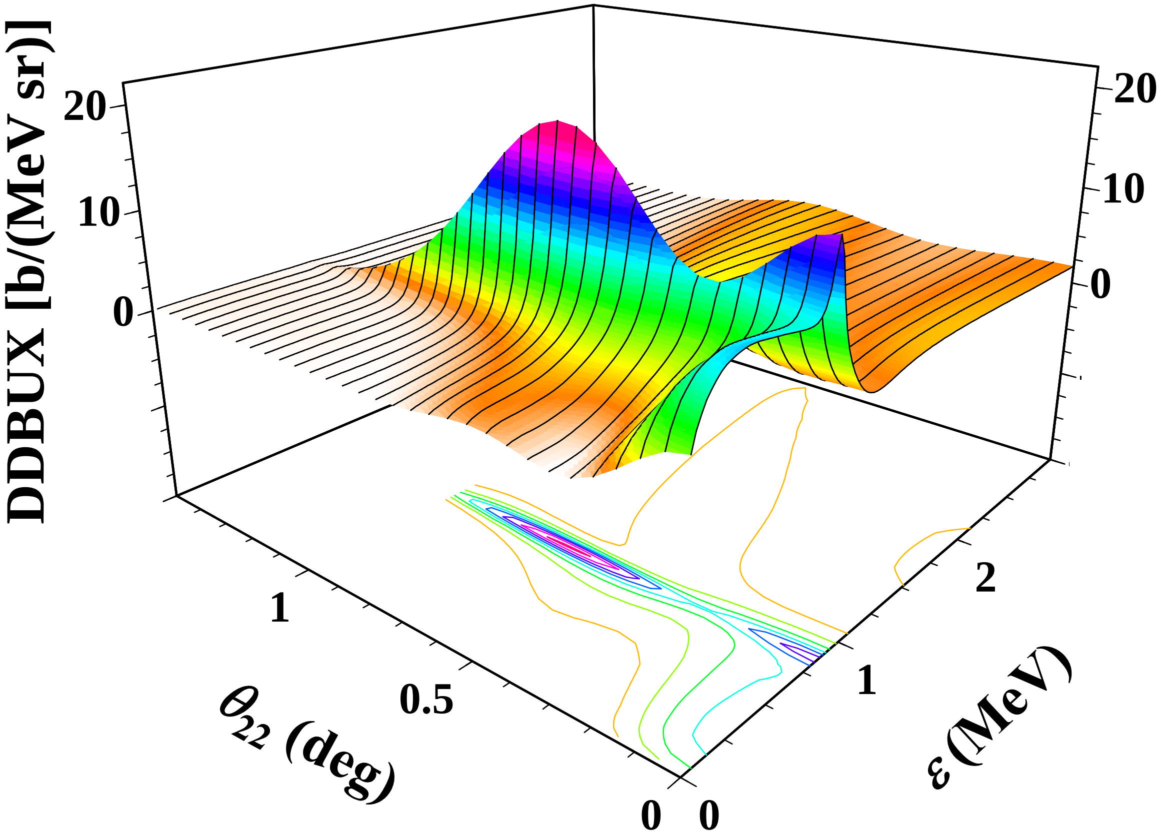
- ✓ 77 ($0^+$) + 164 ($2^+$) PS below 10 MeV are included as breakup states of $^{22}$C.
- ✓ Distorting potentials are calculated by a microscopic folding model with CEG07 nucleon-nucleon g matrix.
- ✓ We adopt the so-called no-recoil approximation for the $^{20}$C core nucleus.

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

# Microscopic CDCC



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




- ✓ The CSM smoothing* 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

$^{21}$C resonance

$d_{3/2}$: 1.1 – $i$ 0.10/2

*How are these resonances observed?*

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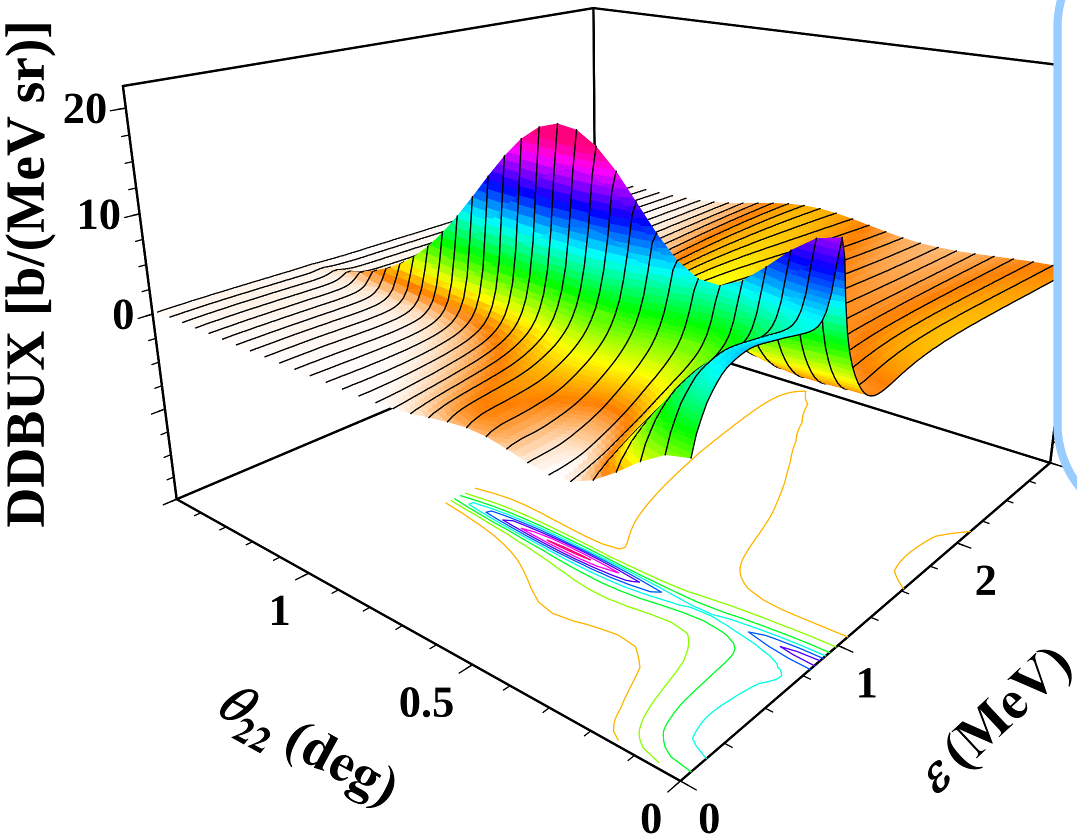


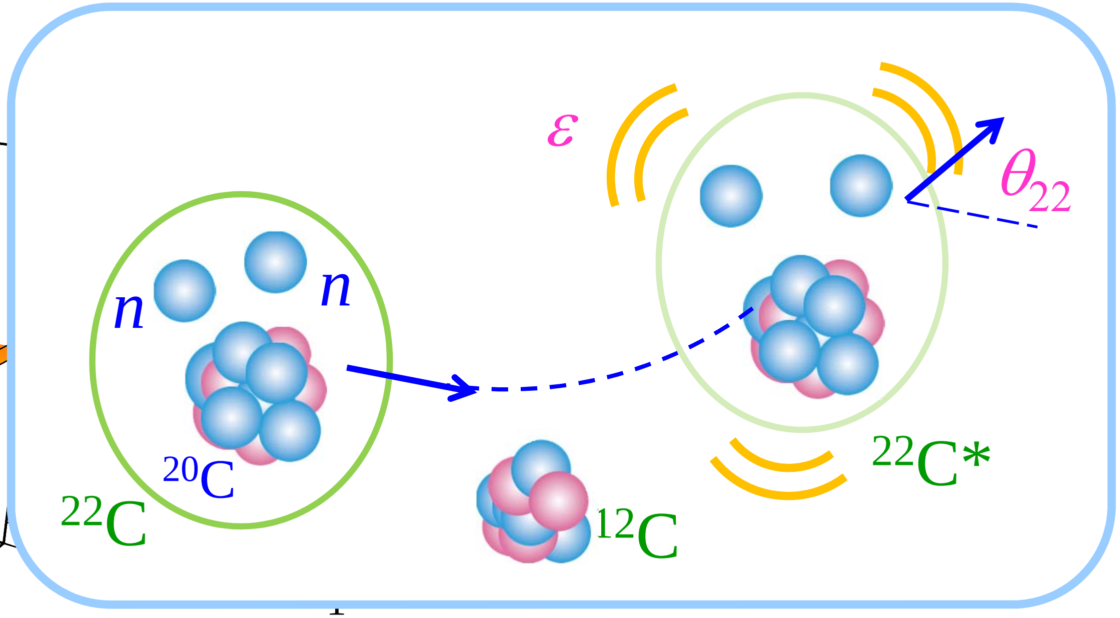


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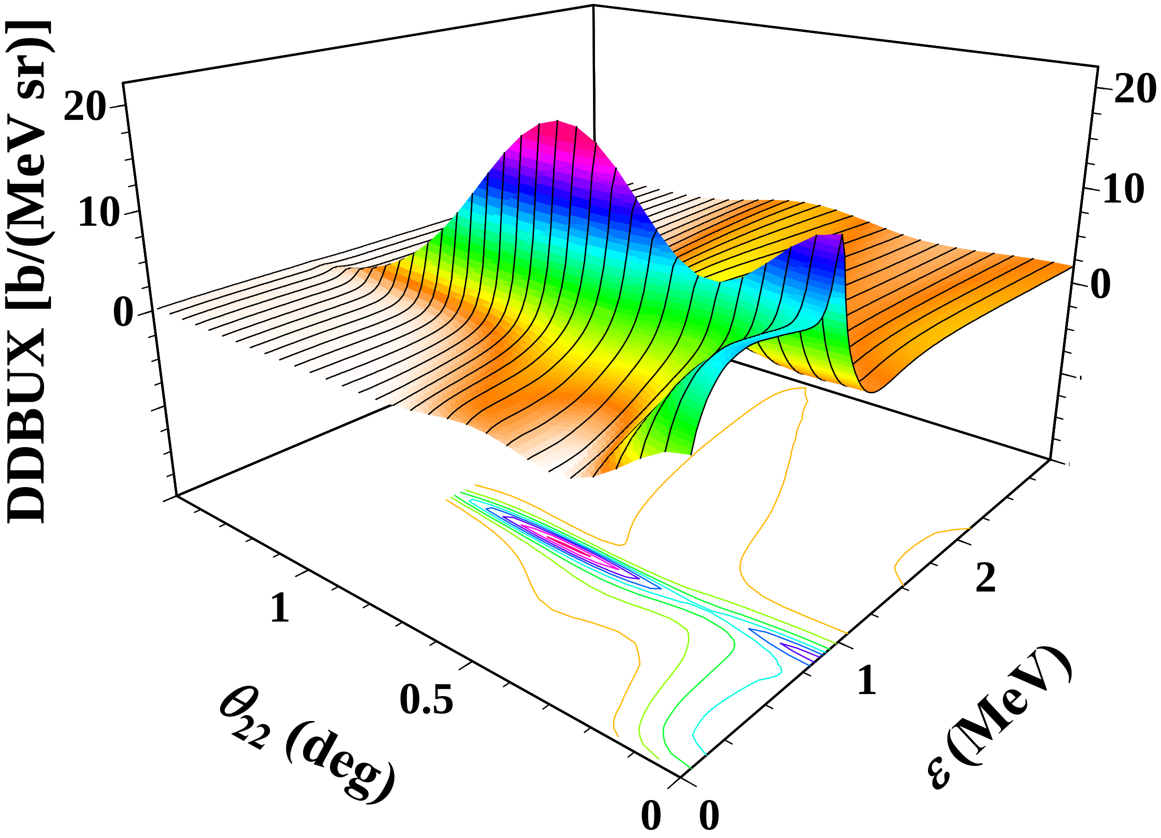


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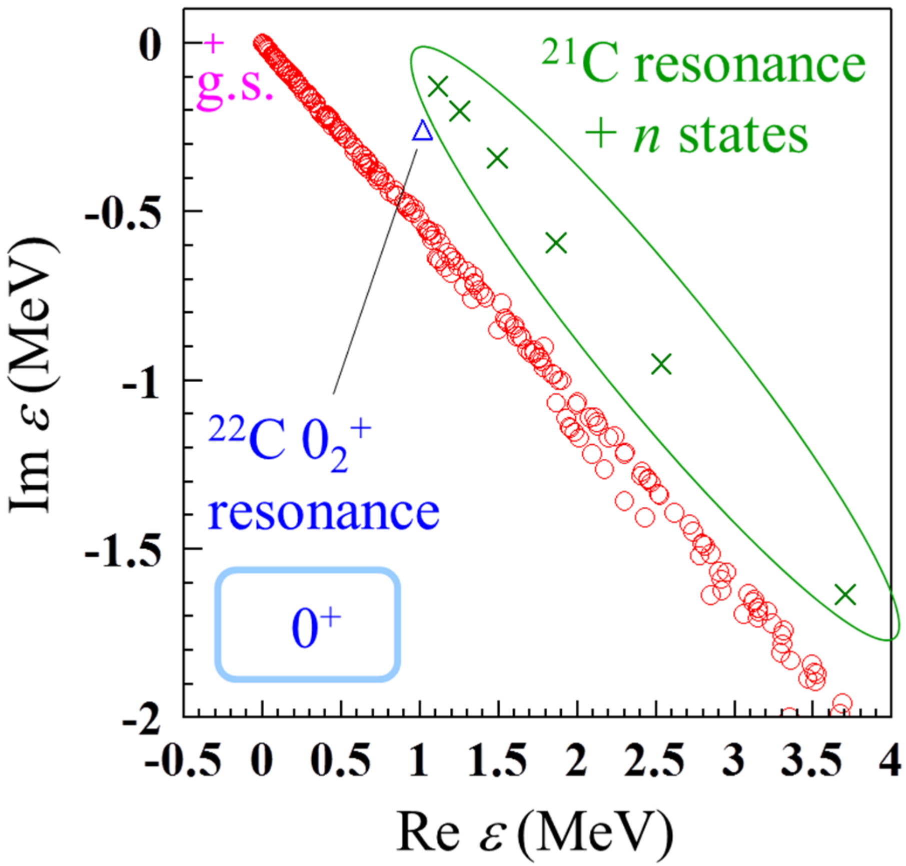


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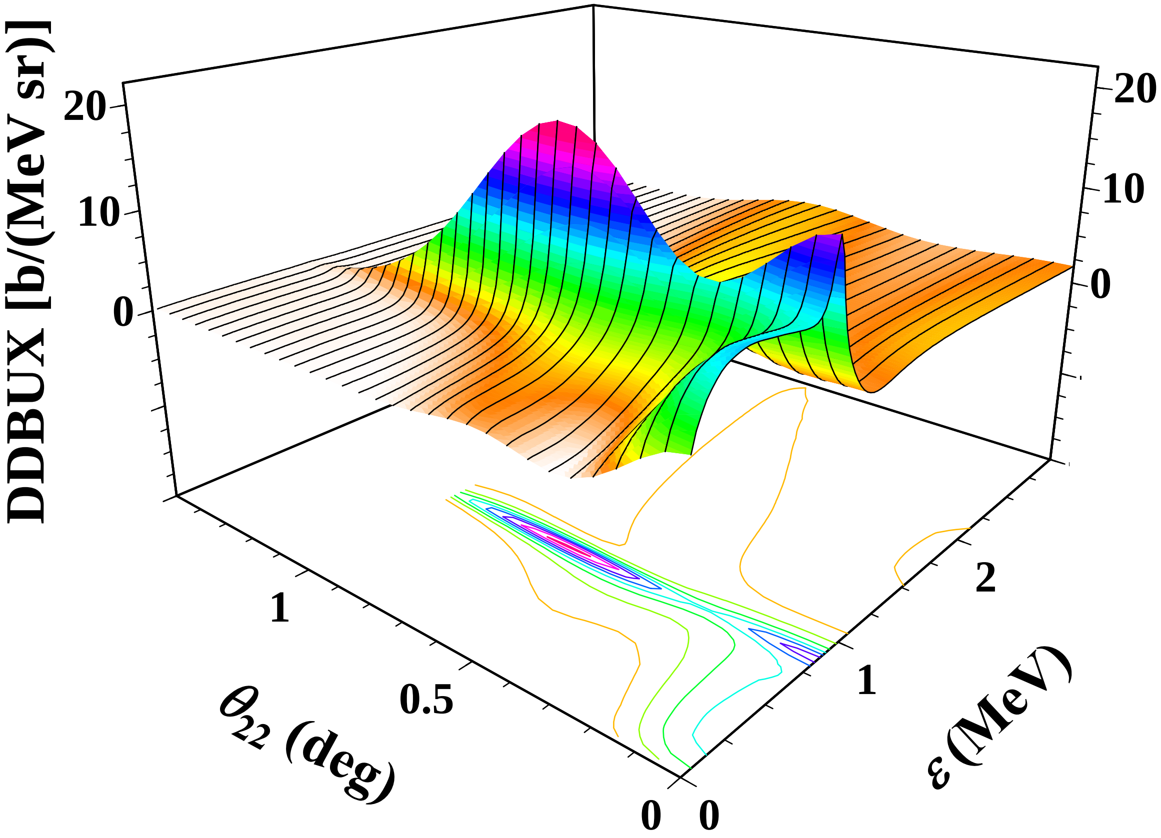
# DDBUX of $^{22}C$ by $^{12}C$

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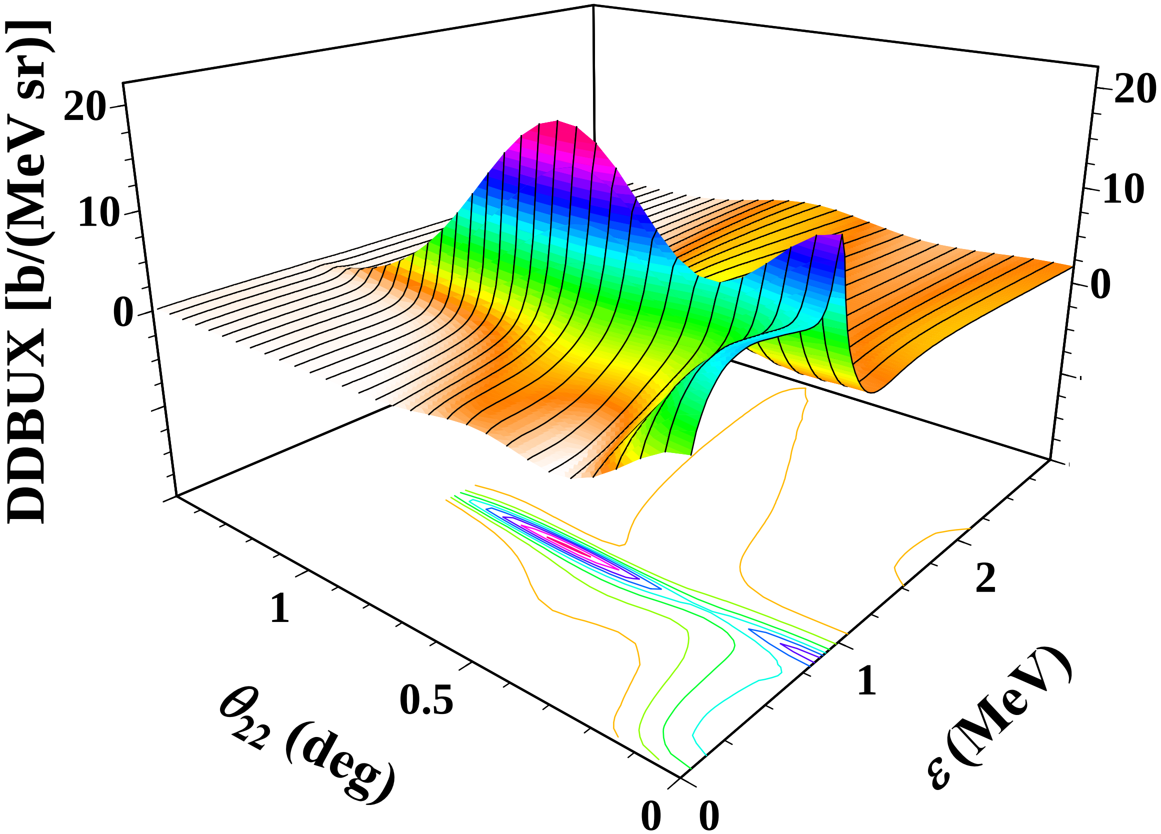


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$0_2^+$: 1.02 – *i* 0.52/2

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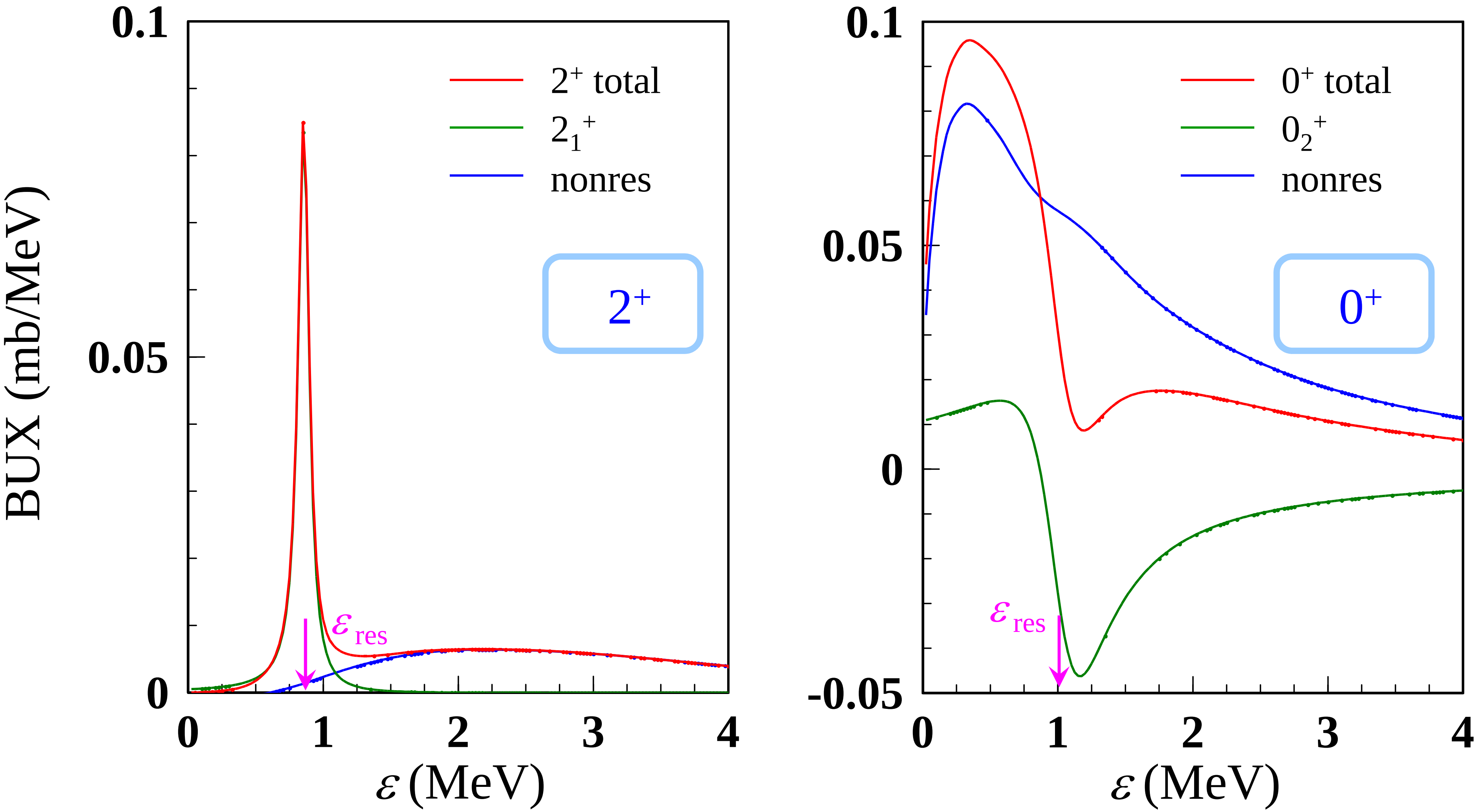
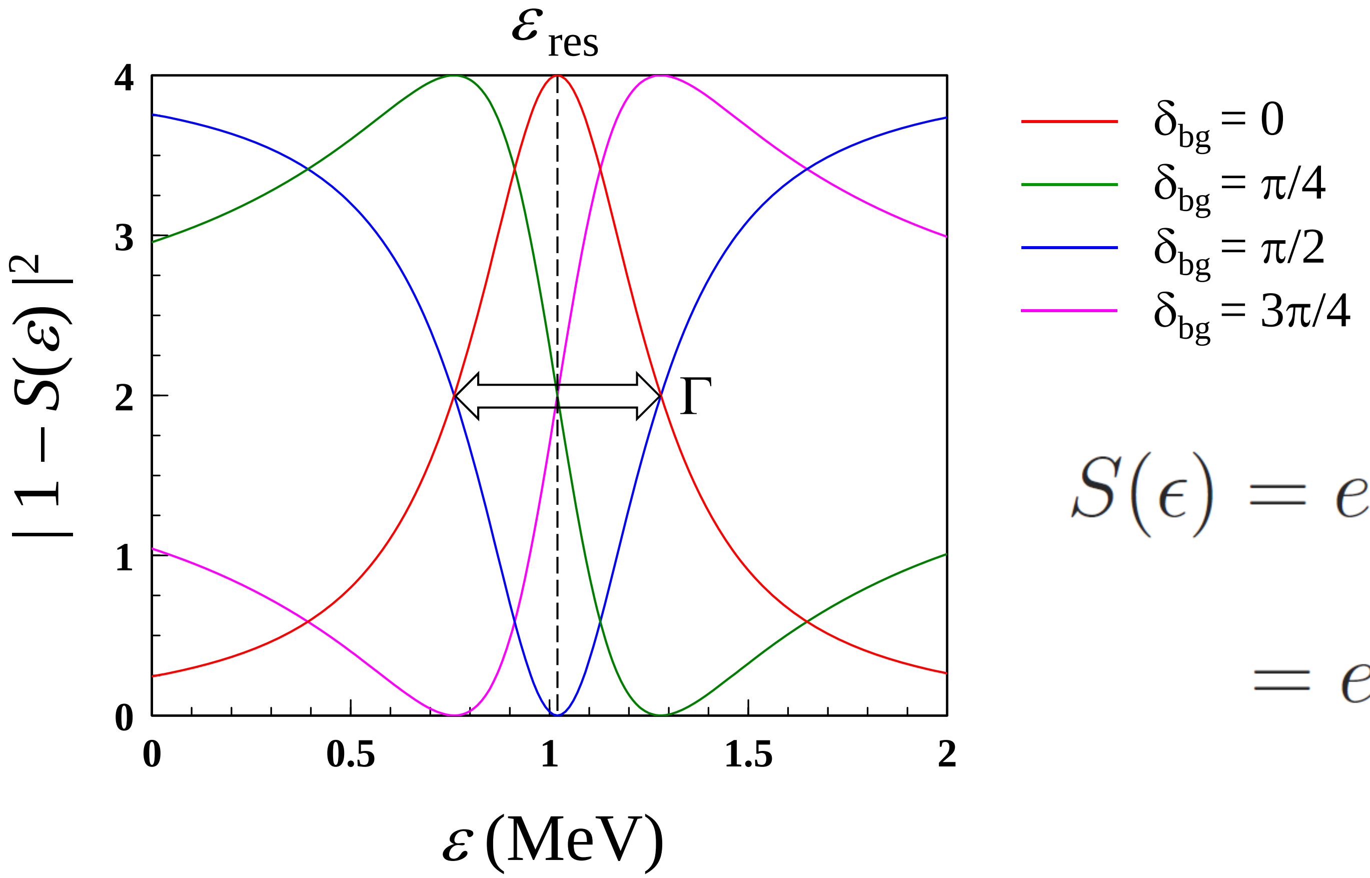
# Integrated BUX (0 – 0.1 deg)




✓ 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

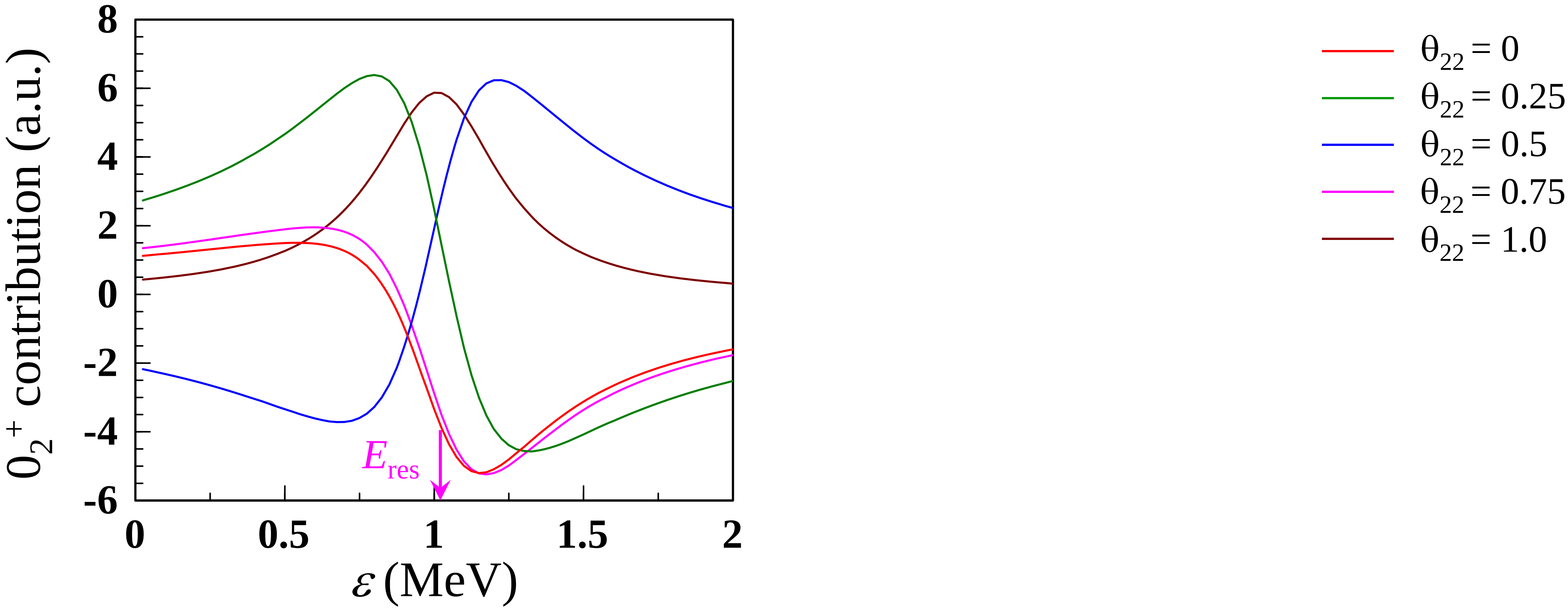



$$S(\epsilon) = e^{2i\delta_{\rm bg}(\epsilon)+2i\delta_{\rm res}(\epsilon)}$$

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

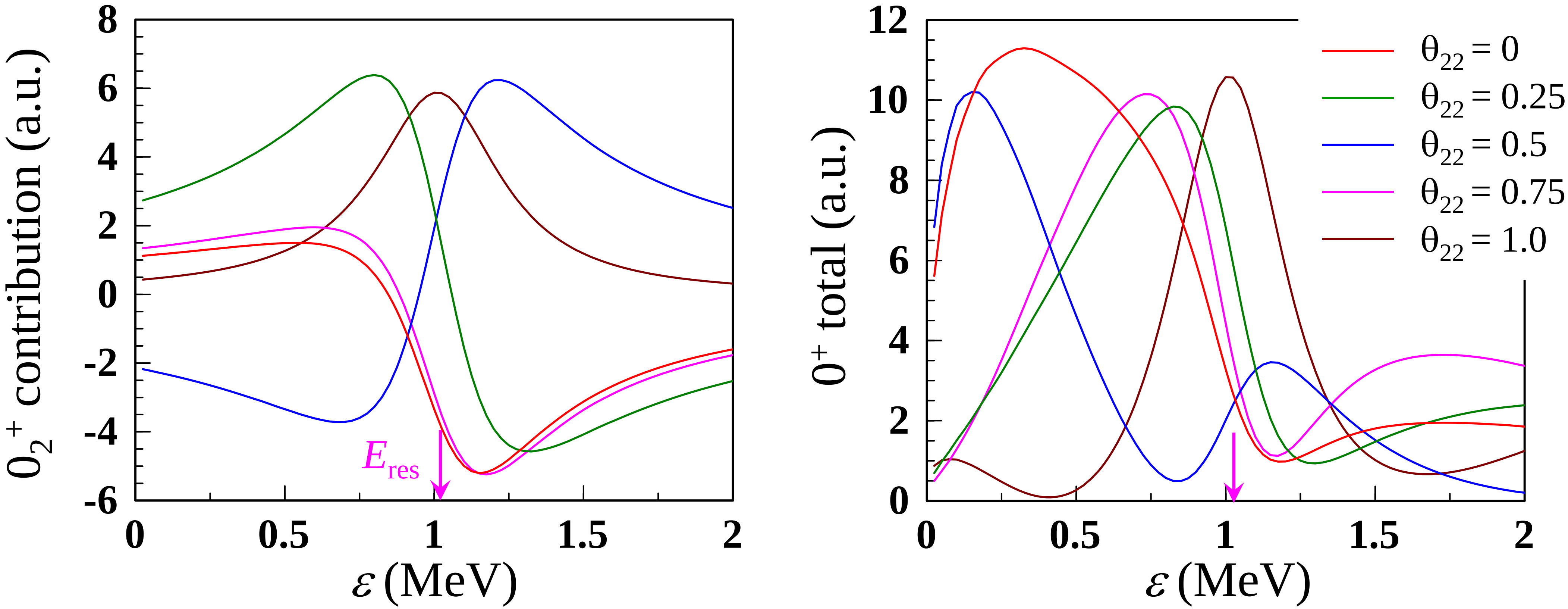
- ✓ In nuclear physics, we always have $\delta_{bg}$.
- ✓ There are many examples of this effect in many research fields.
- ✓ In most cases, this effect is observed as small changes in the resonance energy and width.

# 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

# BGP effect on the DDBUX

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# Summary of the 1st topic

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

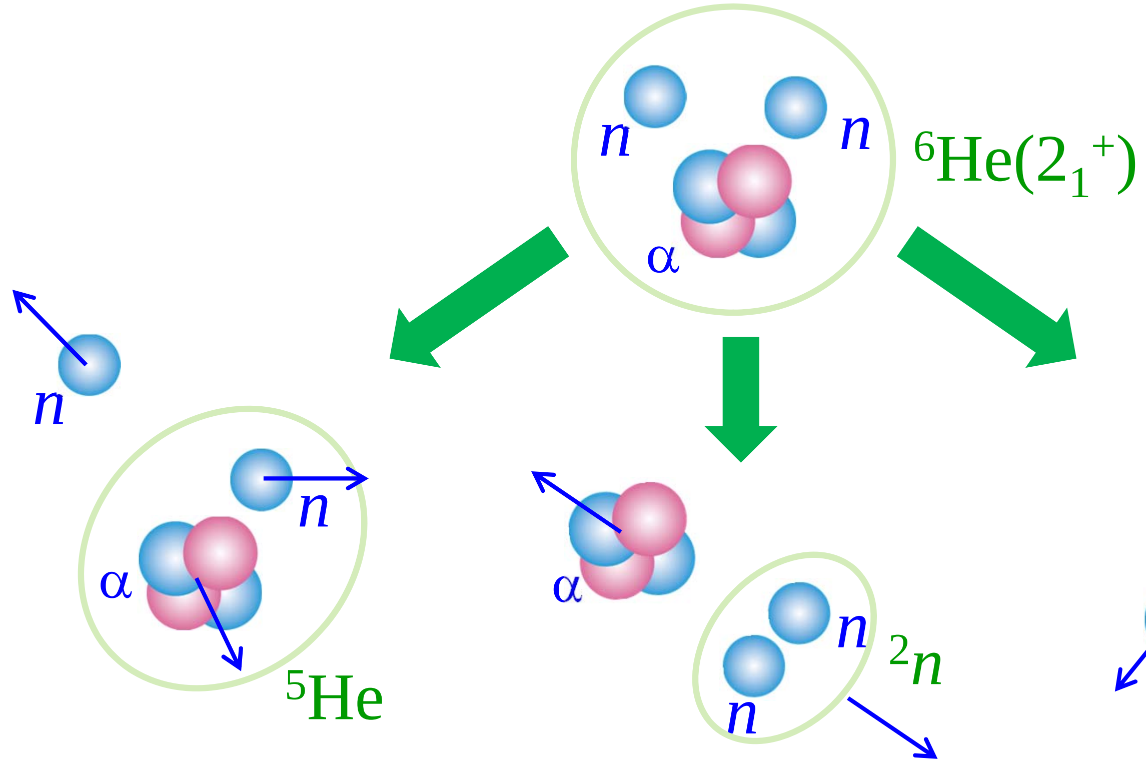
KO, Myo, Furumoto, Matsumoto, Yahiro, PRC**88**, 024616 (2013).

- ✓ 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.
- ✓ We should be careful to identify the $0_2^+$ state of $^{22}C$ in the obserbavles.

# $2^{nd}$ topic

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

Y. Kikuchi, Matsumoto, Minomo, O, PRC**88**, 021602 (2013).

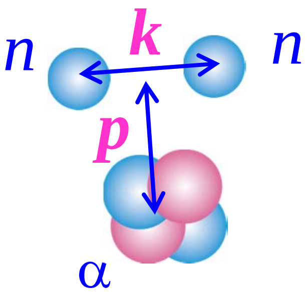



Sequential decay    di-neutron decay    democratic decay

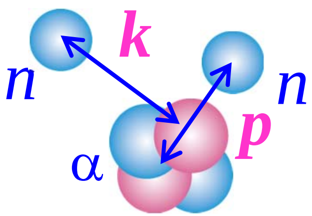
# CDCC-CSLS

✓ The method of Complex-Scaled solutions of the Lippmann-Schwinger Eq.

Y. Kikuchi, Myo, Takashina, Kato, Ikeda, PTP**122**, 499 (2009).




or

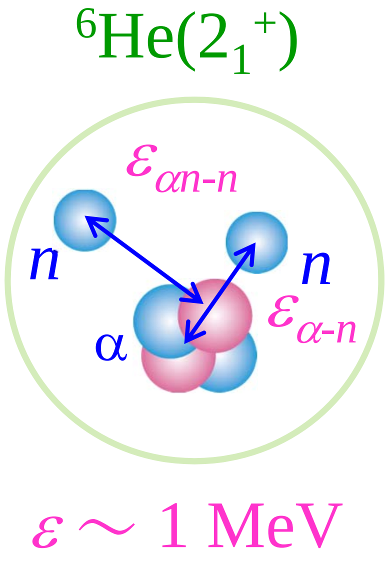


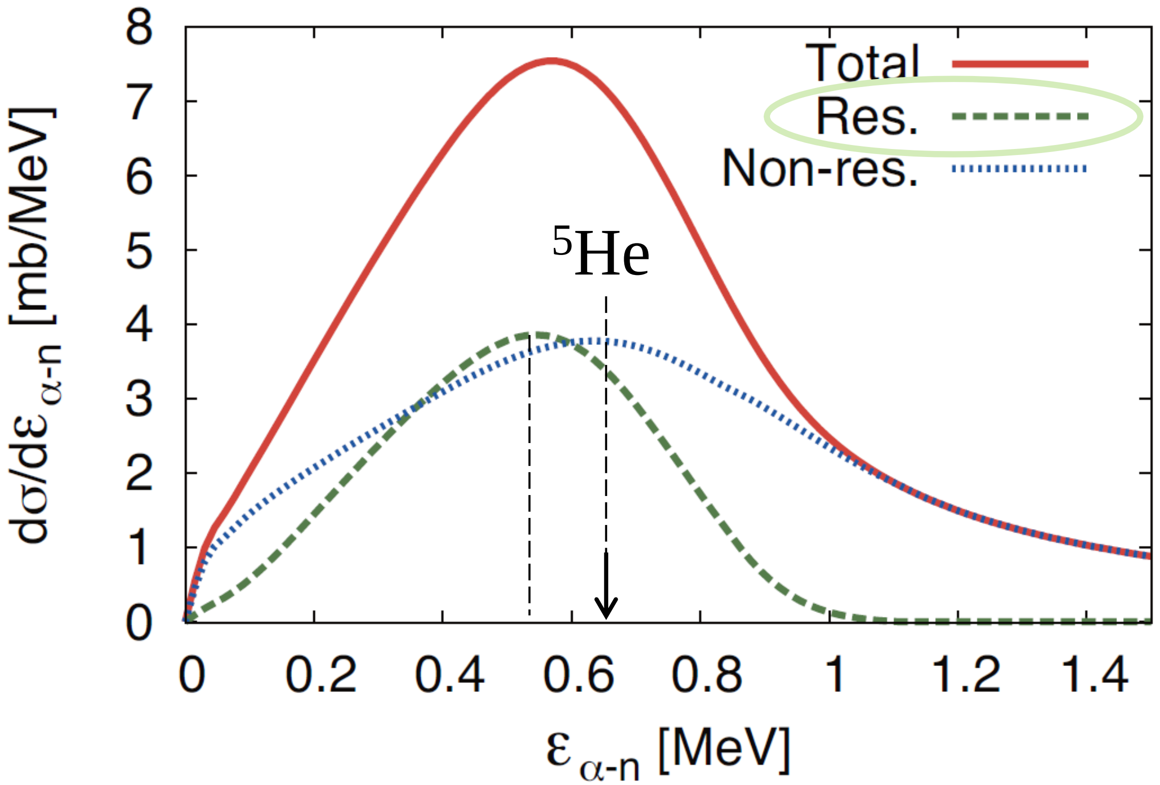

$$T(\boldsymbol{p},\boldsymbol{k}) = \sum_n \left\langle \Phi^{(-)}(\boldsymbol{p},\boldsymbol{k}) \middle| \Phi_n \right\rangle T_n^{\mathrm{CDCC}}$$

$$\equiv \sum_n f_n(\boldsymbol{p},\boldsymbol{k})\, T_n^{\mathrm{CDCC}}$$

$$f_n(\boldsymbol{p},\boldsymbol{k}) = \langle \varphi_{\mathrm{free}}(\boldsymbol{p},\boldsymbol{k}) | \Phi_n \rangle + \sum\!\!\!\!\!\!\int_i \langle \varphi_{\mathrm{free}}(\boldsymbol{p},\boldsymbol{k}) | V_{\alpha nn} C^{-1}(\theta) | \phi_i^\theta \rangle \times \frac{1}{\varepsilon - \varepsilon_i^\theta} \langle \tilde{\phi}_i^\theta | C(\theta) | \Phi_n \rangle$$

# Sequential decay quenched

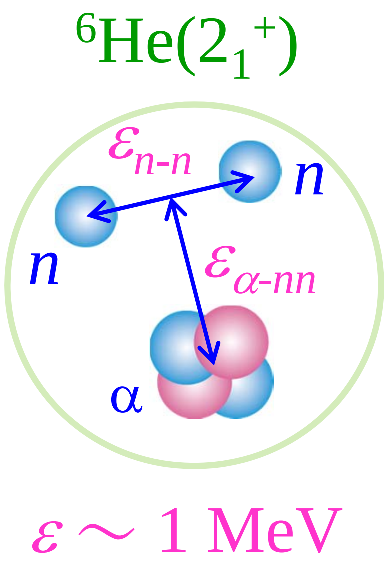


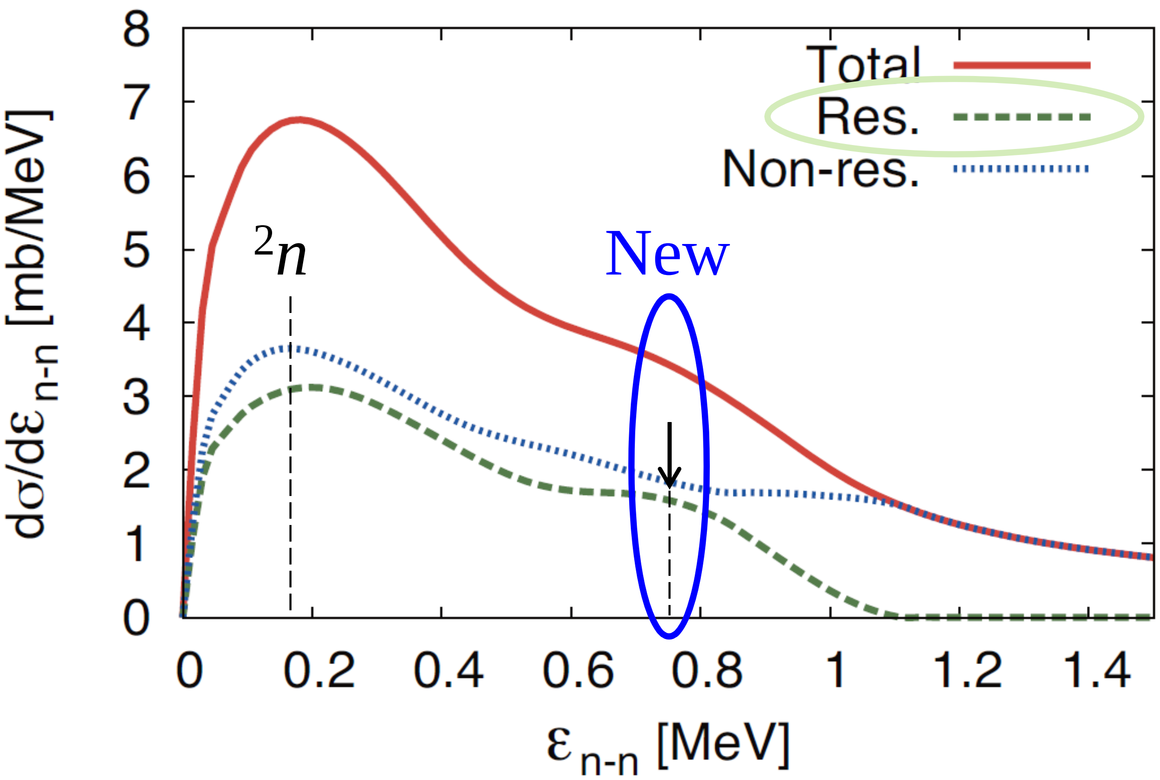




✓ When $\varepsilon \sim 1$ MeV and $\varepsilon_{\alpha\text{-}n} \sim 0.7$ MeV, the other neutron ($\sim 0.3$ MeV) hardly penetrates the centrifugal barrier ($p$-wave).

✓ 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).

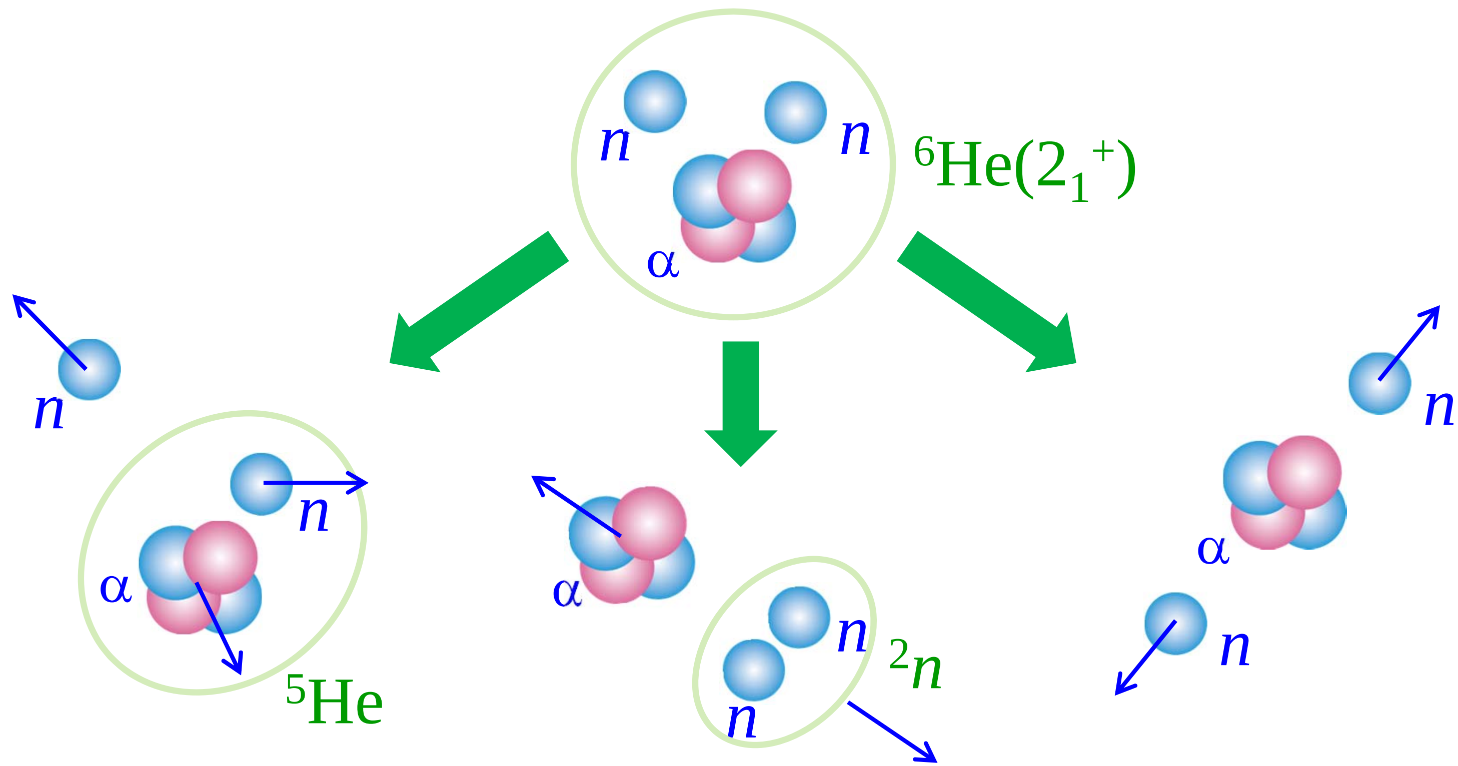
✓ The higher peak indicates the democratic decay.

➡ 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?

Y. Kikuchi, Matsumoto, Minomo, O, PRC**88**, 021602 (2013).




Sequential decay    di-neutron decay    democratic decay

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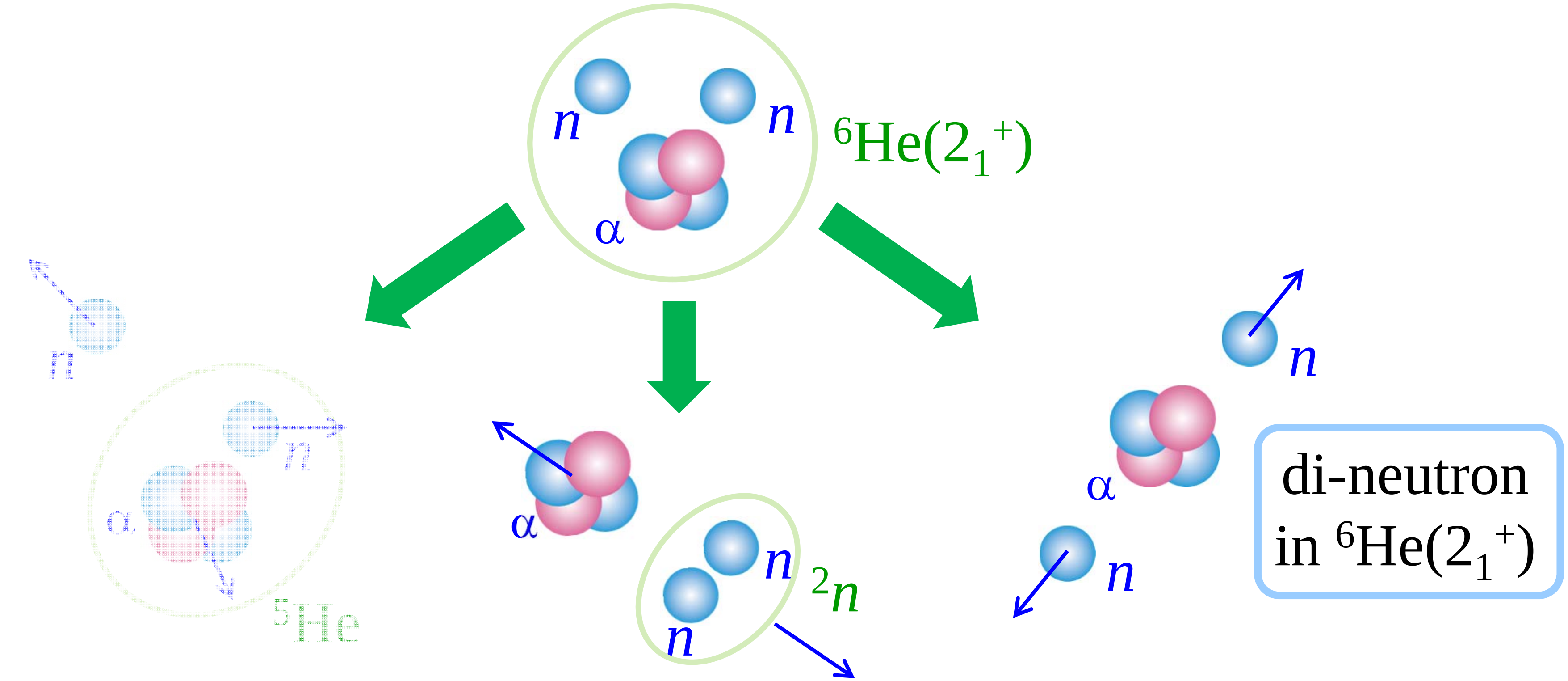


Sequential decay

di-neutron decay
(due to FSI)

democratic decay
(not due to FSI)

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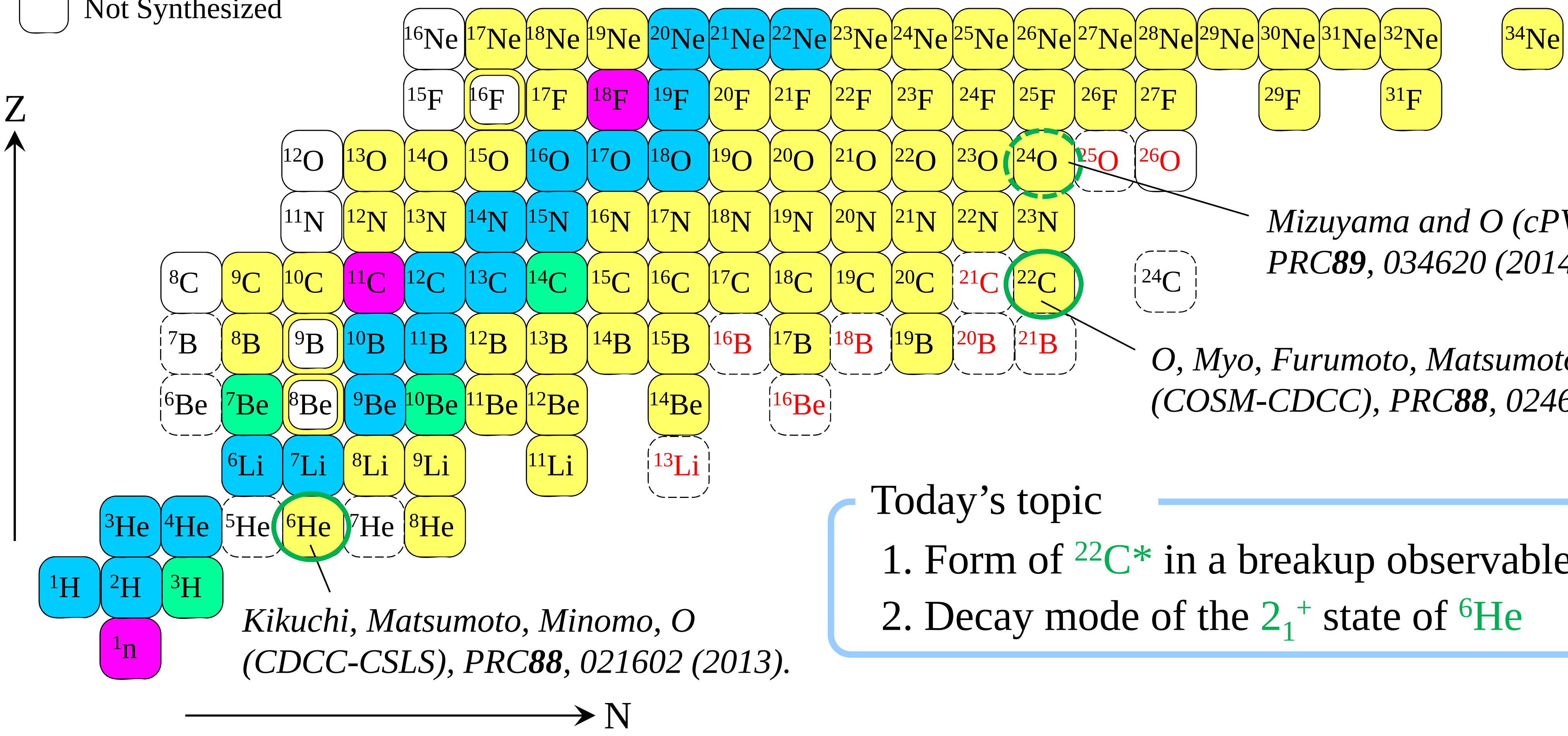


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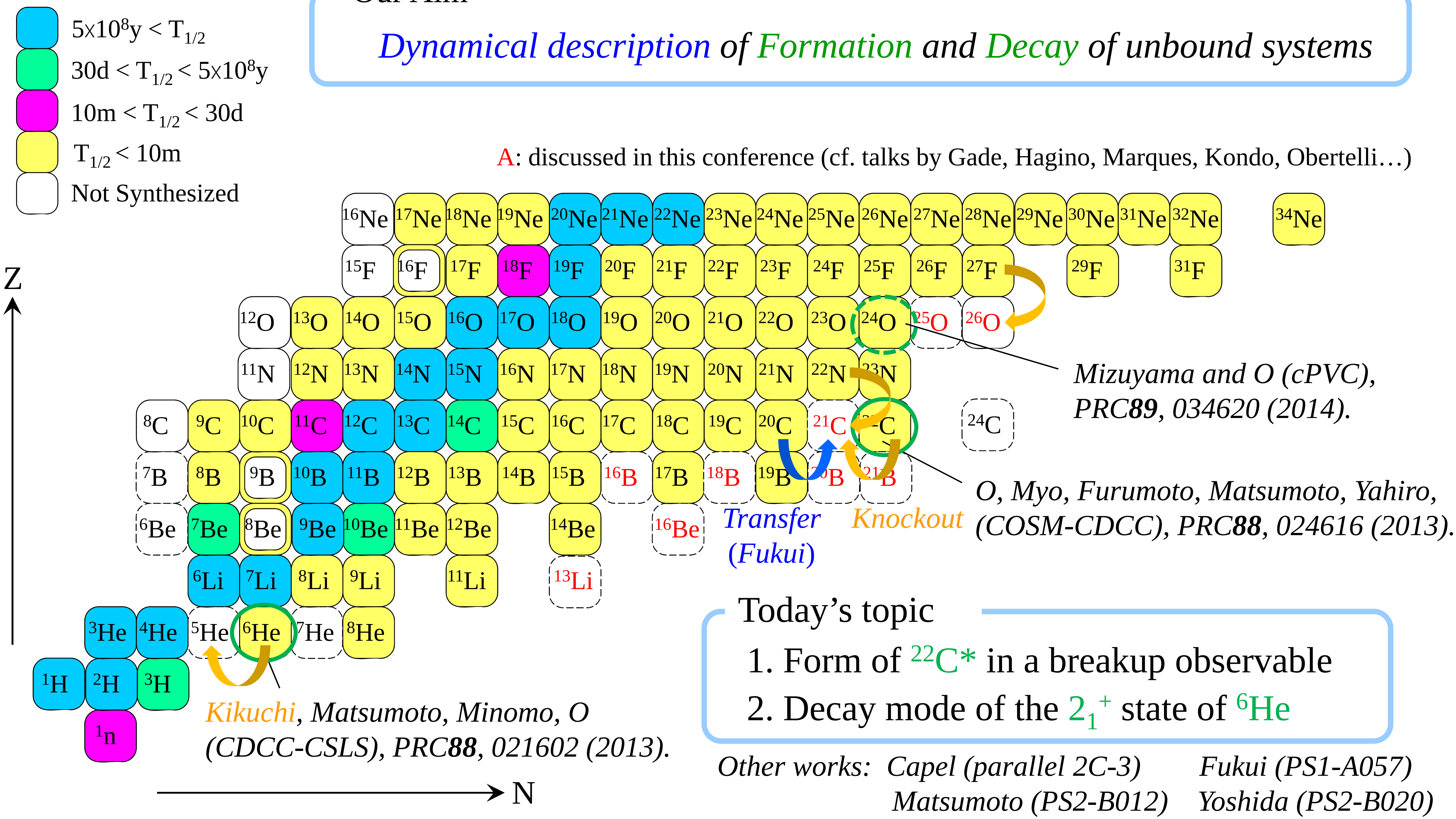


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*Other works: Capel (parallel 2C-3) Fukui (PS1-A057) Matsumoto (PS2-B012) Yoshida (PS2-B020)*