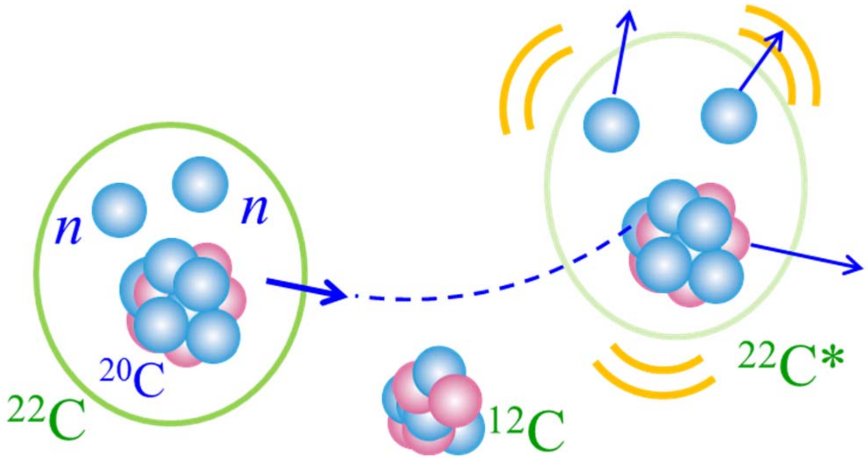
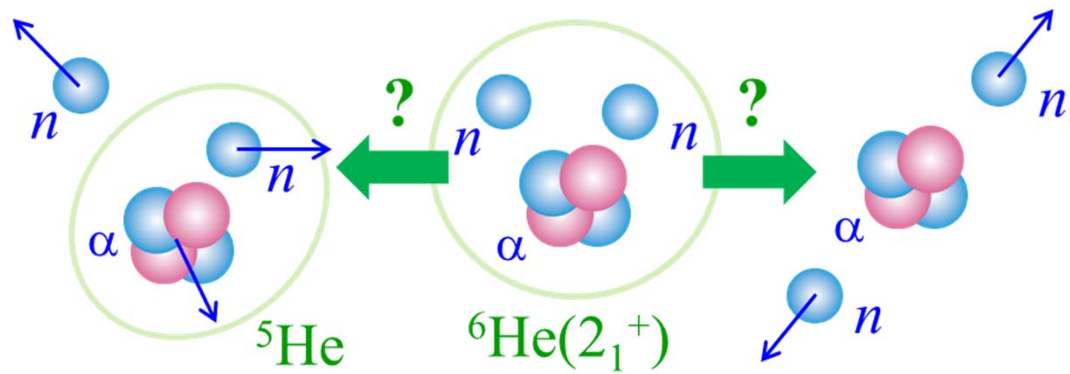
Recent reaction studies on particle-unbound states with CDCC

K. Ogata[1], Y. Kikuchi[2], T. Myo[3], T. Furumoto[4],
K. Minomo[1], T. Matsumoto[5], and M. Yahiro[5]

[1]*RCNP, Osaka University*, [2]*RIKEN Nishina Center*, [3]*Osaka Institute of Technology*,
[4]*Ichinoseki National College of Technology*, [5]*Kyushu University*



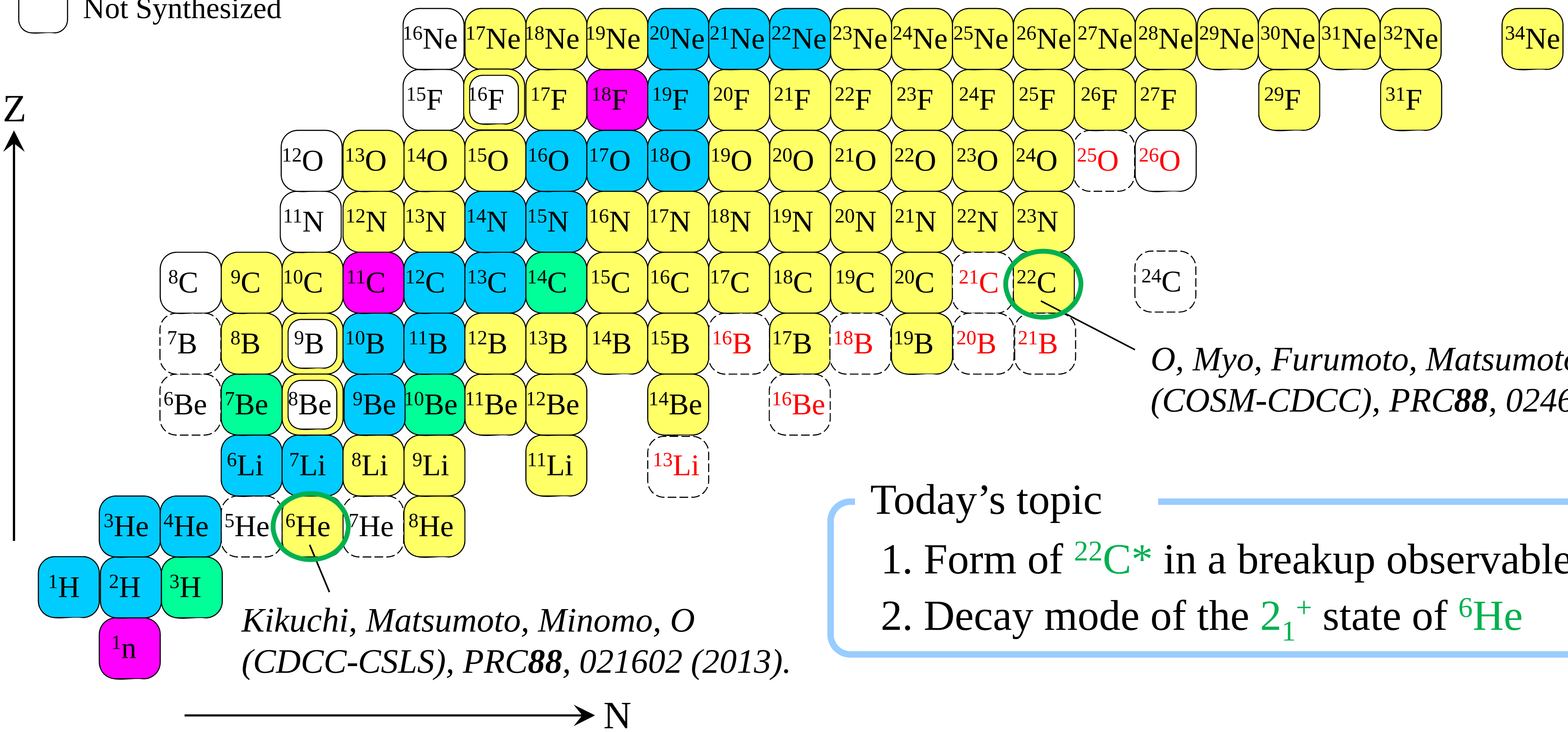


Exploration of unbound (but not free) systems

Our Aim

Dynamical description of Formation and Decay of unbound systems

- 5x10^{8}y < $T_{1/2}$
- 30d < $T_{1/2}$ < 5x10^{8}y
- 10m < $T_{1/2}$ < 30d
- $T_{1/2}$ < 10m
- Not Synthesized



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

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

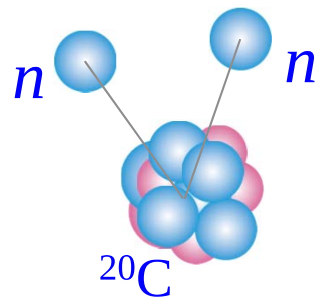
Today's topic

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

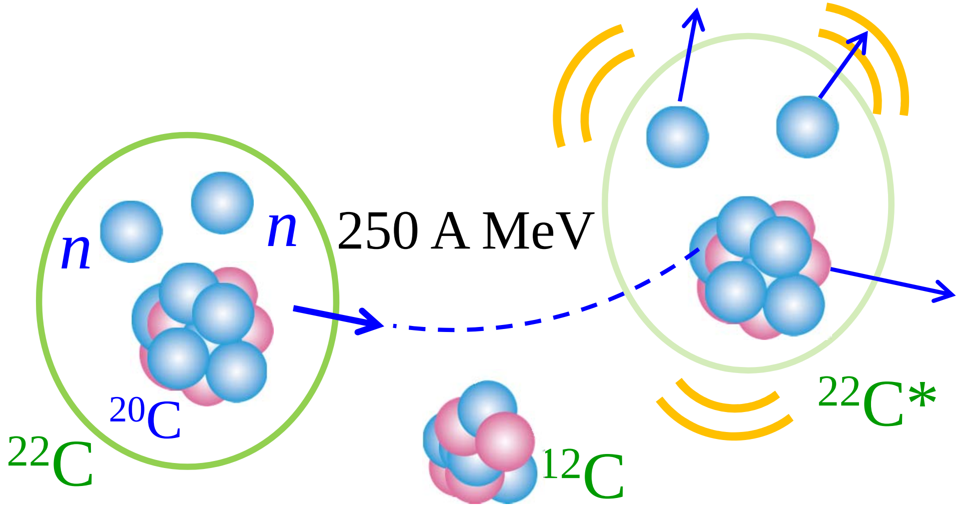
Structural part: Cluster Orbital Shell Model (COSM)

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



Details of COSM:

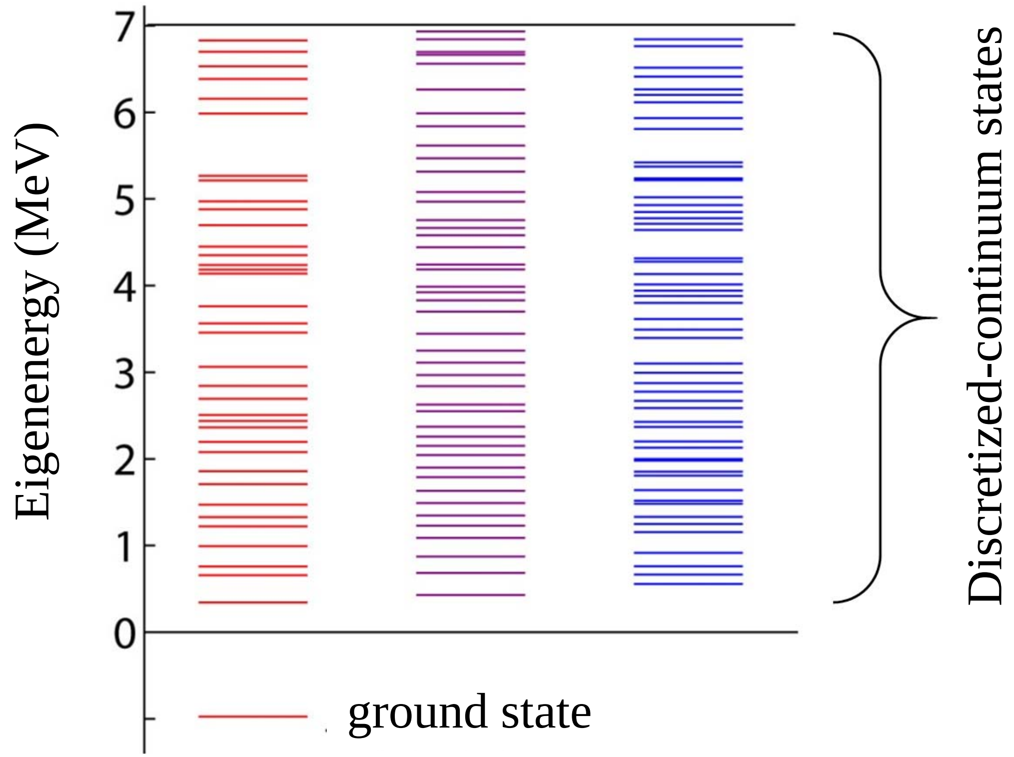
Y. Suzuki and K. Ikeda, PRC **38**, 410 (1988).
S. Aoyama *et al*., PTP **116**, 1 (2006) [review].
T. Myo *et al*., PL **B691**, 150 (2010) and references therein.



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)

$$\Psi^{\mathrm{CDCC}} = \sum_n \Phi_n \chi_n$$

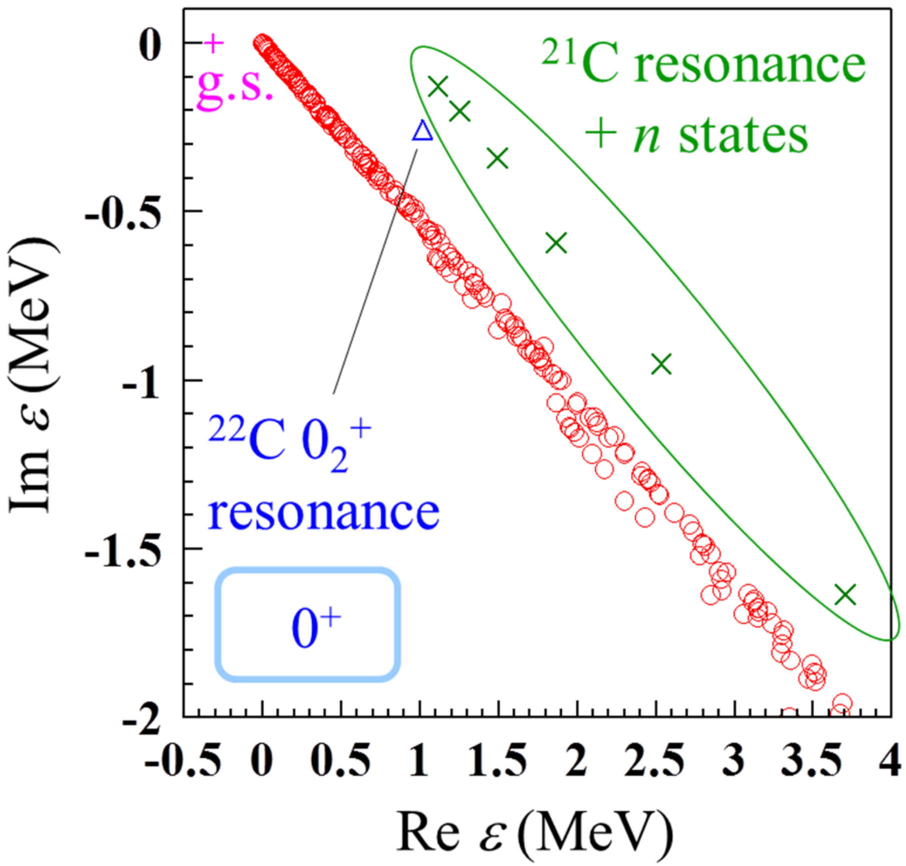
Relative motion between ^{22}C and target
(*expansion coefficients*)

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^θ
(complex-scaled Hamiltonian)



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

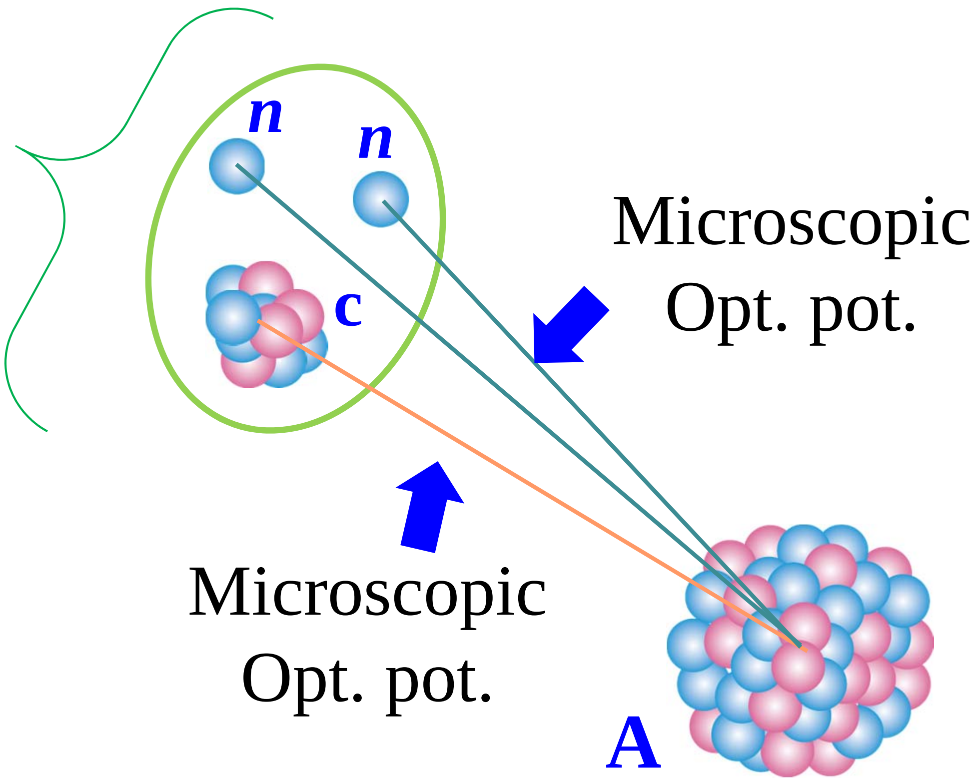
index for the pseudostates Φ_n used in CDCC

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

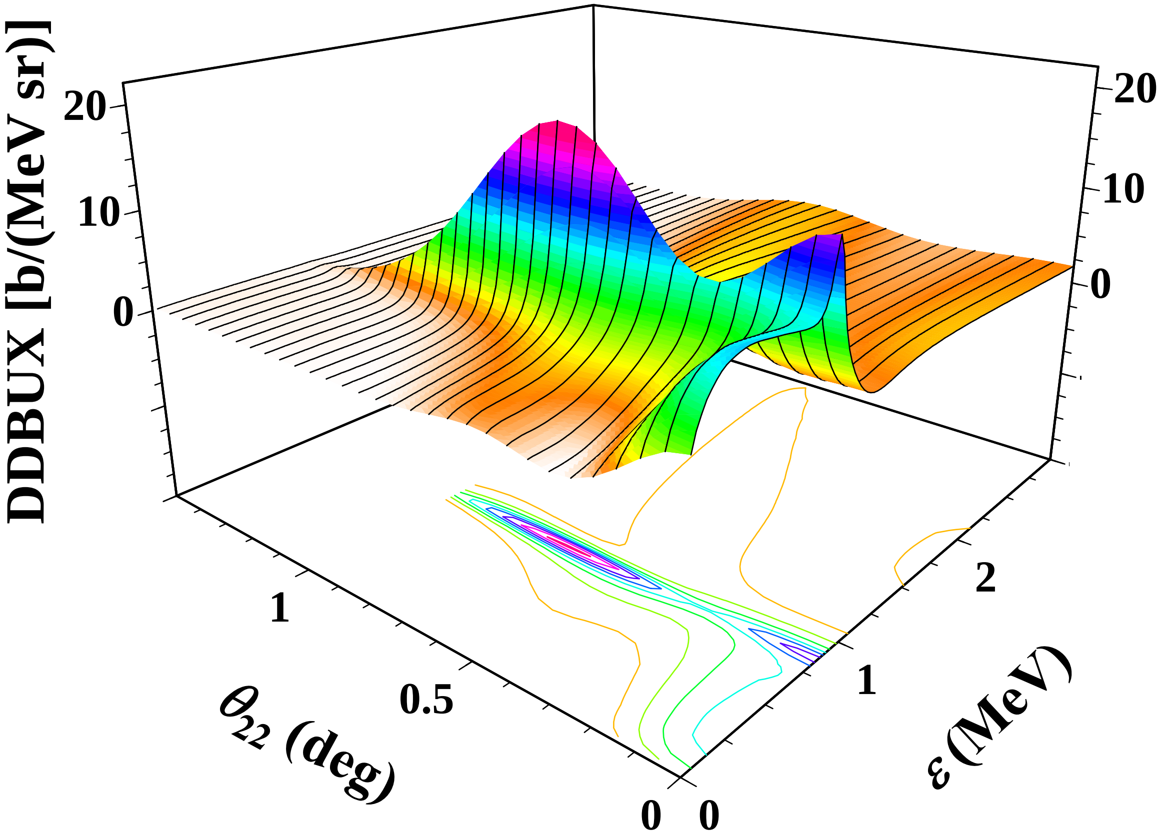
index for the eigenstates ϕ_i^θ of H^θ

Microscopic CDCC

n + *n* + c dynamics
explicitly described



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?

*T. Matsumoto *et al.*, PRC **82**, 054602(R) (2010).

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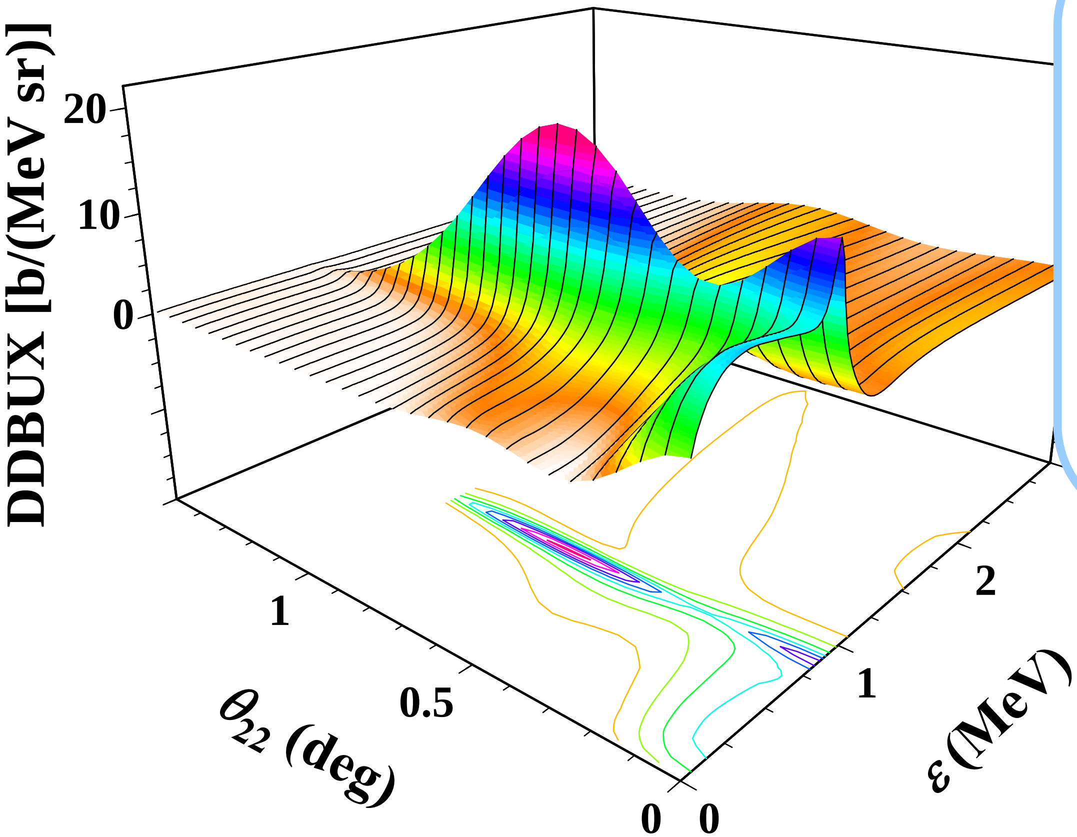

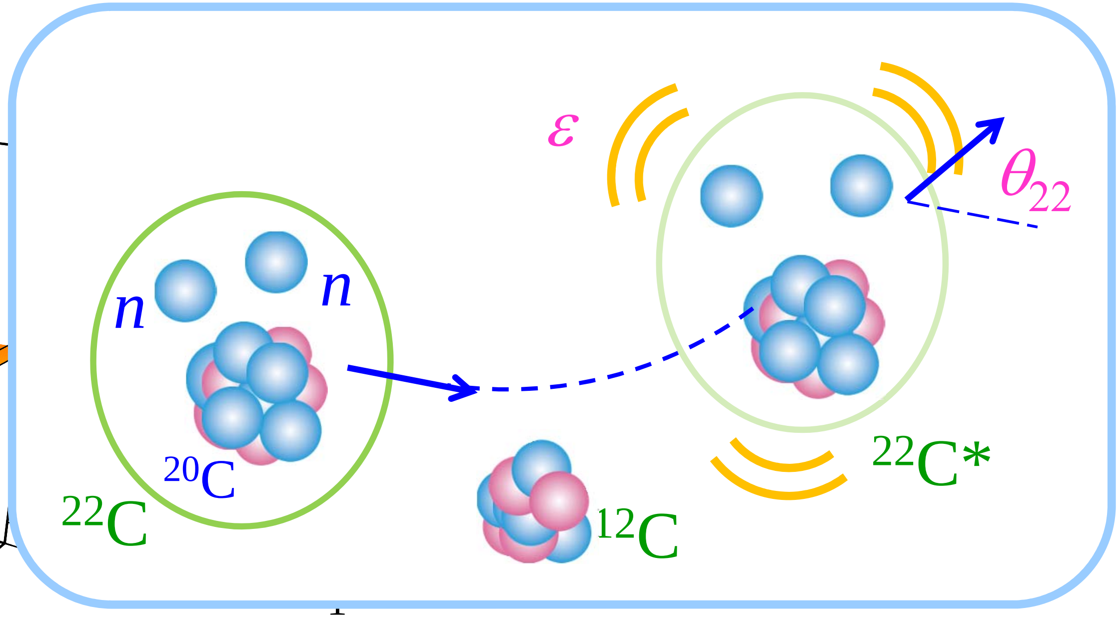

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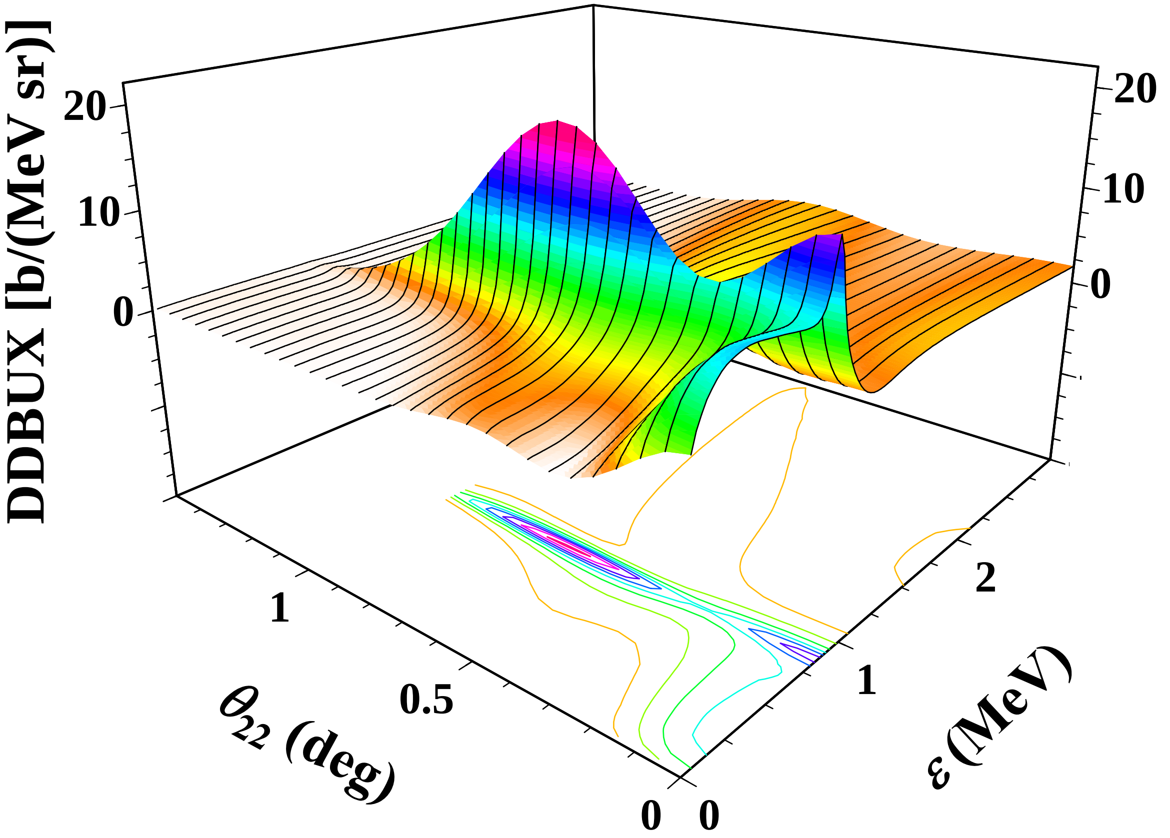

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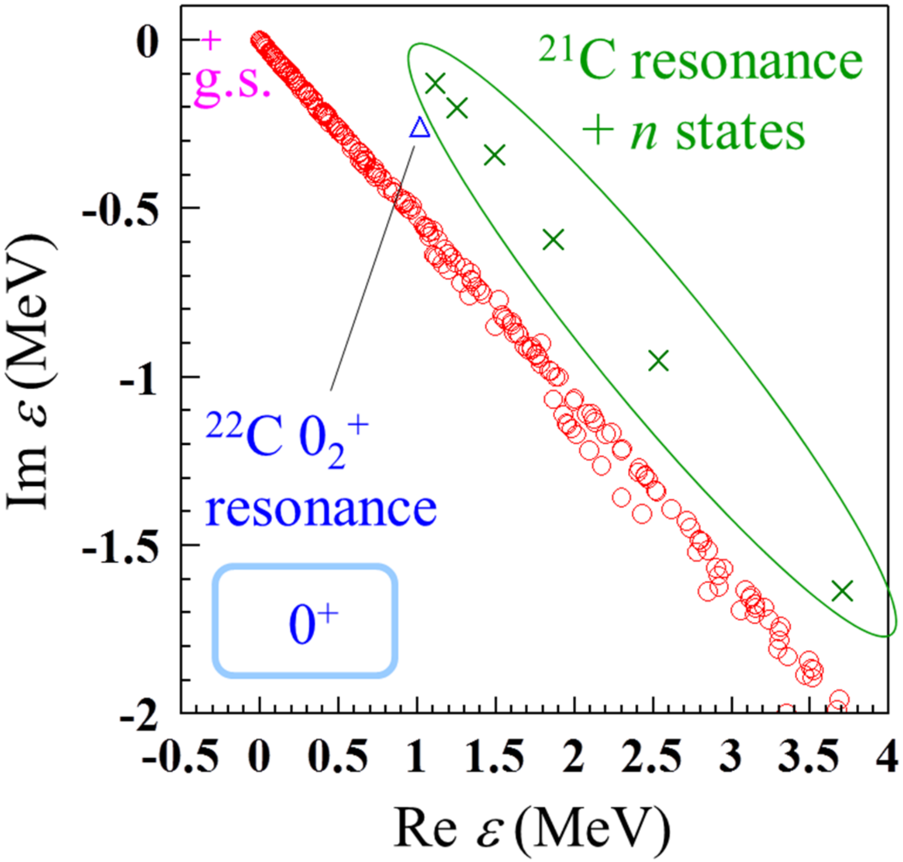

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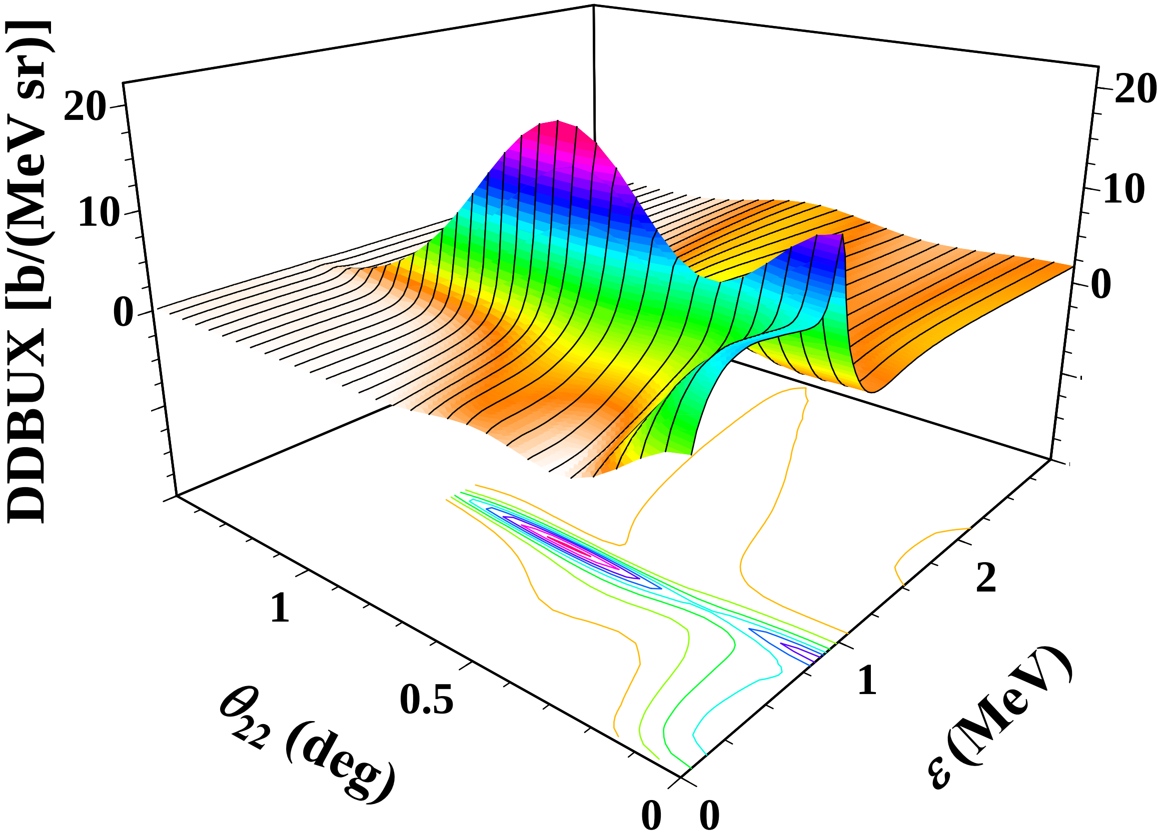

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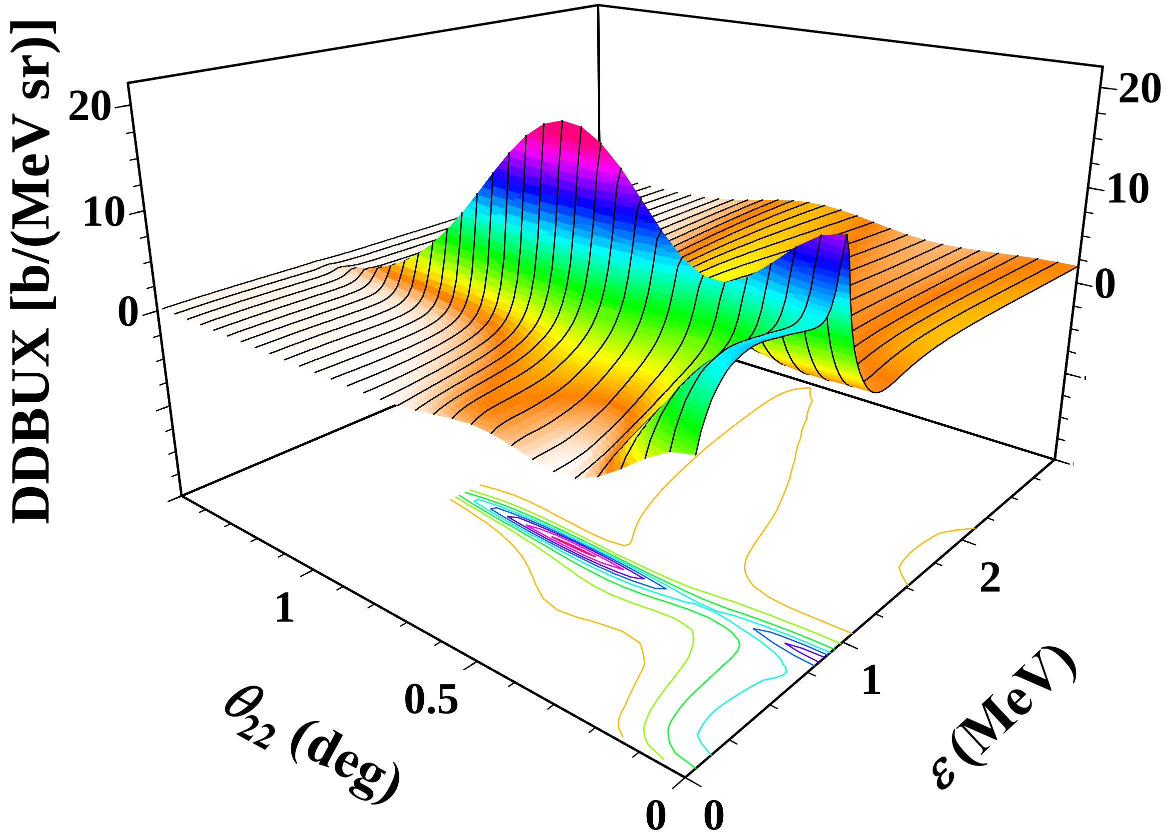

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^{21}C resonance

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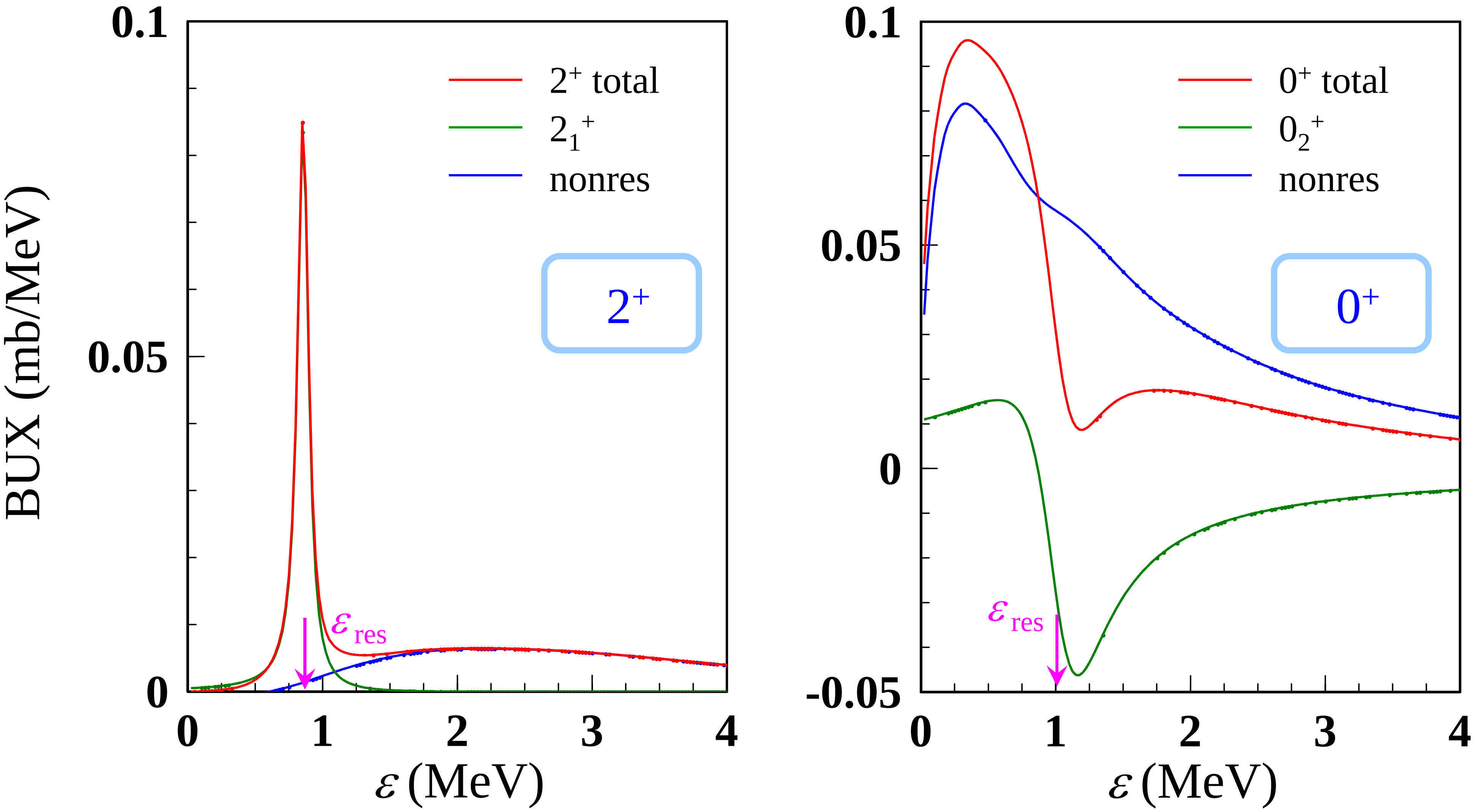
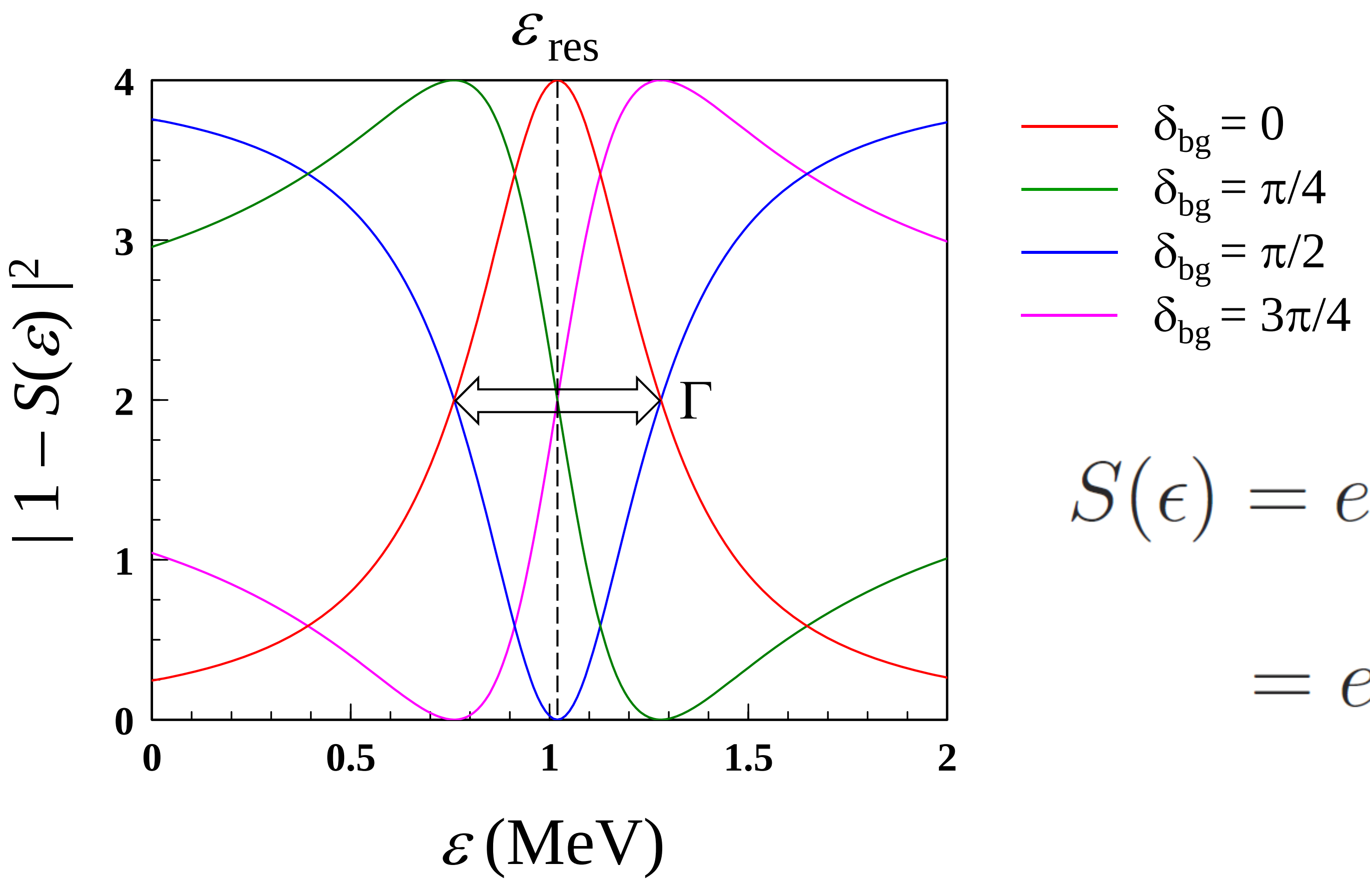
Integrated BUX (0 – 0.1 deg)



✓ 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

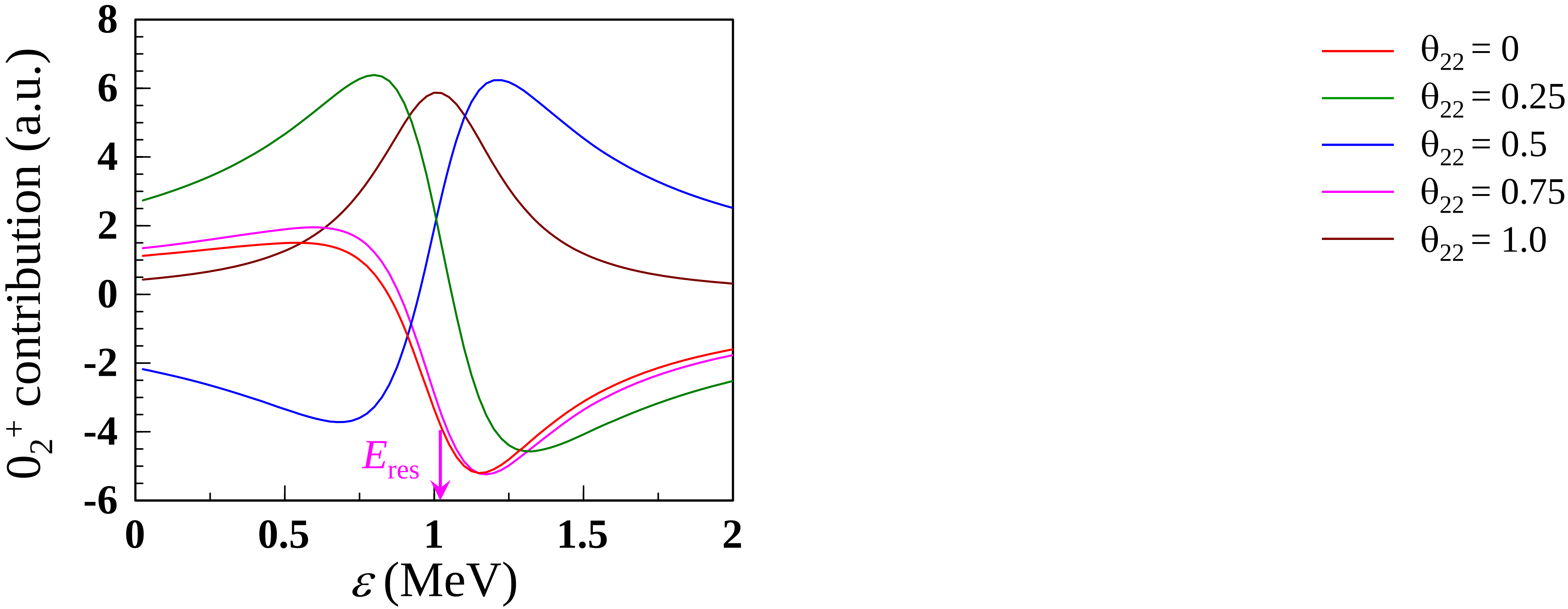


$$S(\epsilon) = e^{2i\delta_{\rm bg}(\epsilon)+2i\delta_{\rm res}(\epsilon)}$$

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

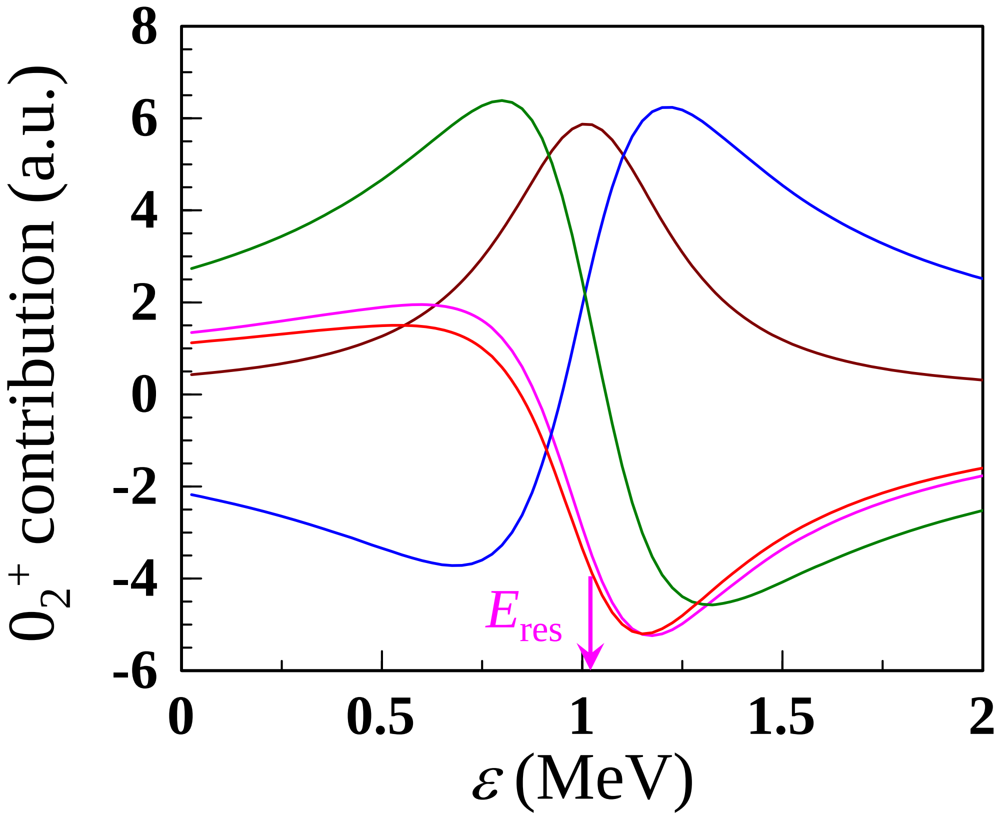
- ✓ In nuclear physics, we always have δ_{bg}.
- ✓ There are many examples of this effect in many research fields.
- ✓ In most cases, this effect is observed as small changes in the resonance energy and width.

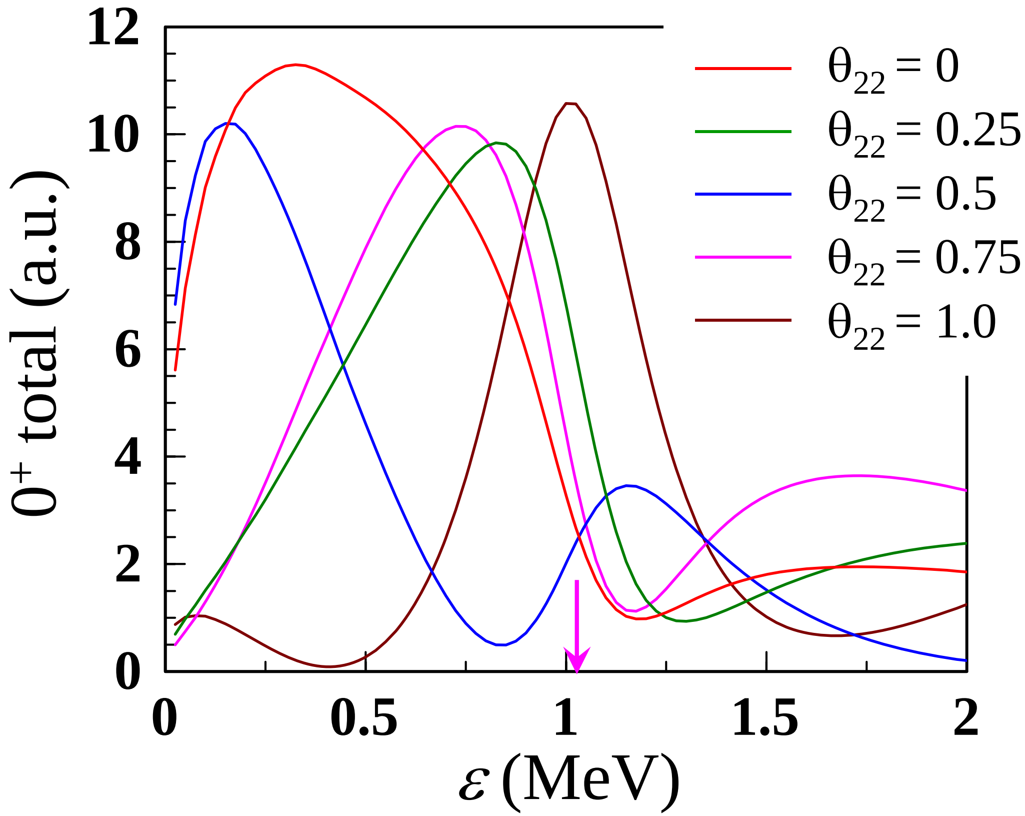
BGP effect on the DDBUX



- ✓ 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

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?

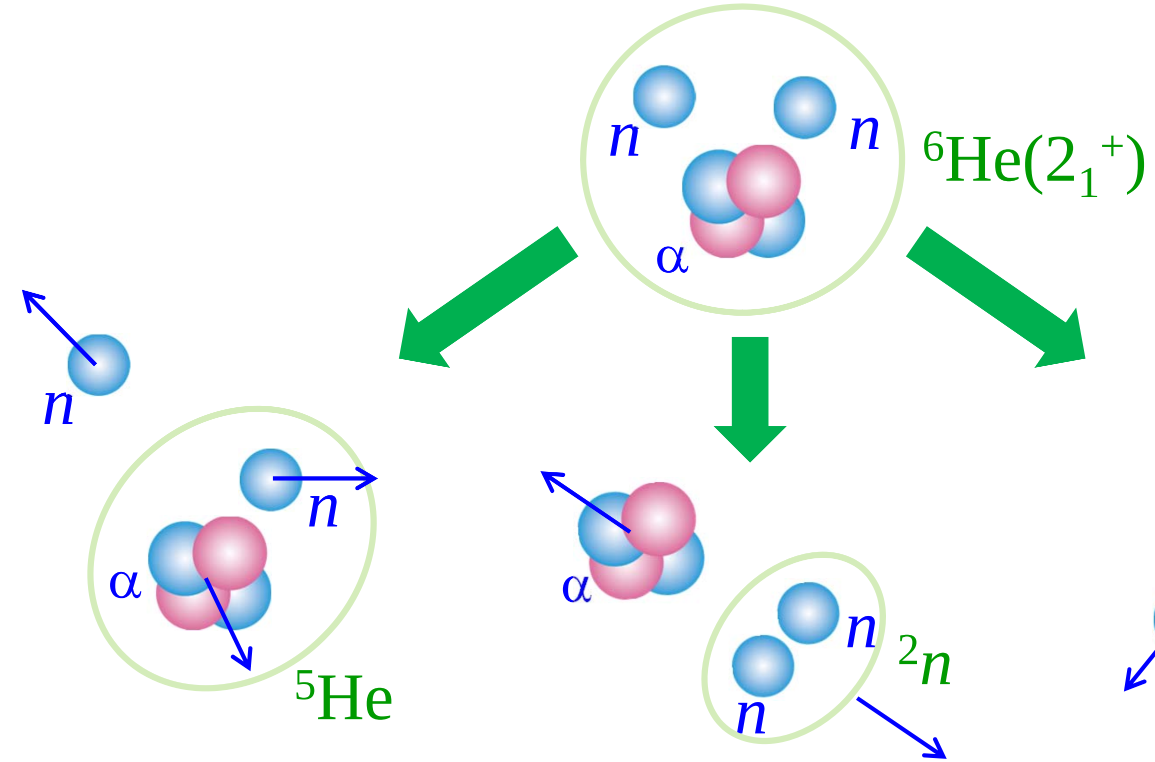
KO, Myo, Furumoto, Matsumoto, Yahiro, PRC**88**, 024616 (2013).

- ✓ 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).

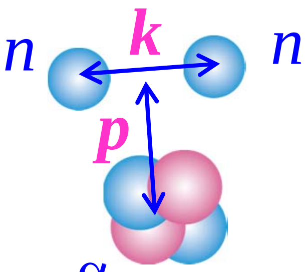


Sequential decay   di-neutron decay   democratic decay

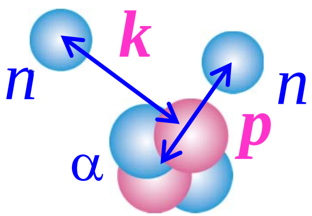
CDCC-CSLS

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

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



or



$$T(\boldsymbol{p},\boldsymbol{k}) = \left\langle \Phi^{(-)}(\boldsymbol{p},\boldsymbol{k})\, e^{i\boldsymbol{K}\cdot\boldsymbol{R}} \left|U\right| \Psi^{\mathrm{CDCC}} \right\rangle$$

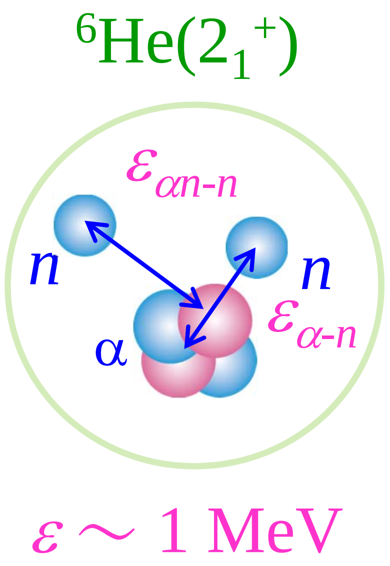
$$\sum_n |\Phi_n\rangle\langle\Phi_n| \approx 1$$

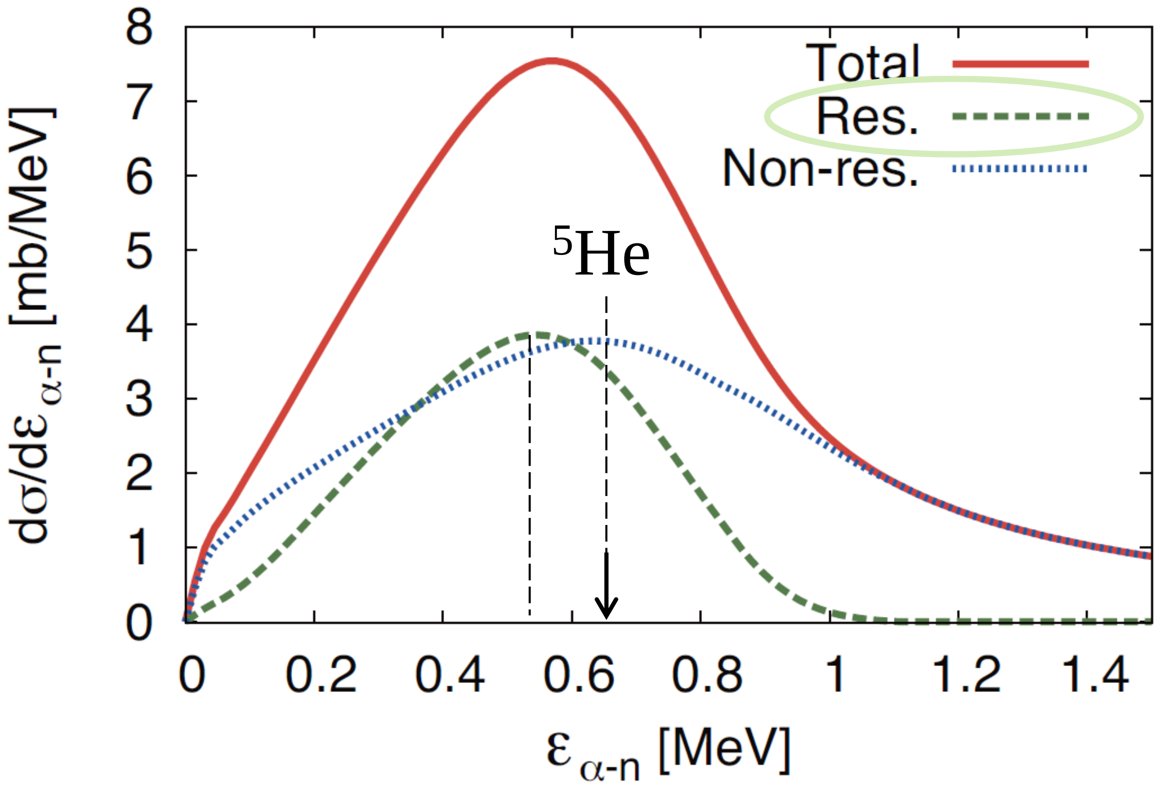
$$\approx \sum_n \left\langle \Phi^{(-)}(\boldsymbol{p},\boldsymbol{k}) \middle| \Phi_n \right\rangle T_n^{\mathrm{CDCC}}$$

$$\equiv f_n(\boldsymbol{p},\boldsymbol{k})$$

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

Sequential decay quenched



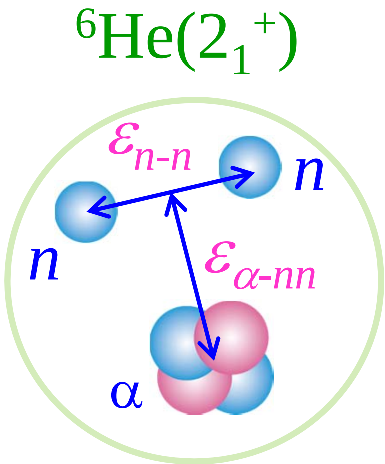


✓ When $\varepsilon \sim 1$ MeV and $\varepsilon_{\alpha\text{-}n} \sim 0.7$ MeV, the other neutron (~ 0.3 MeV) hardly penetrates the centrifugal barrier (*p*-wave).

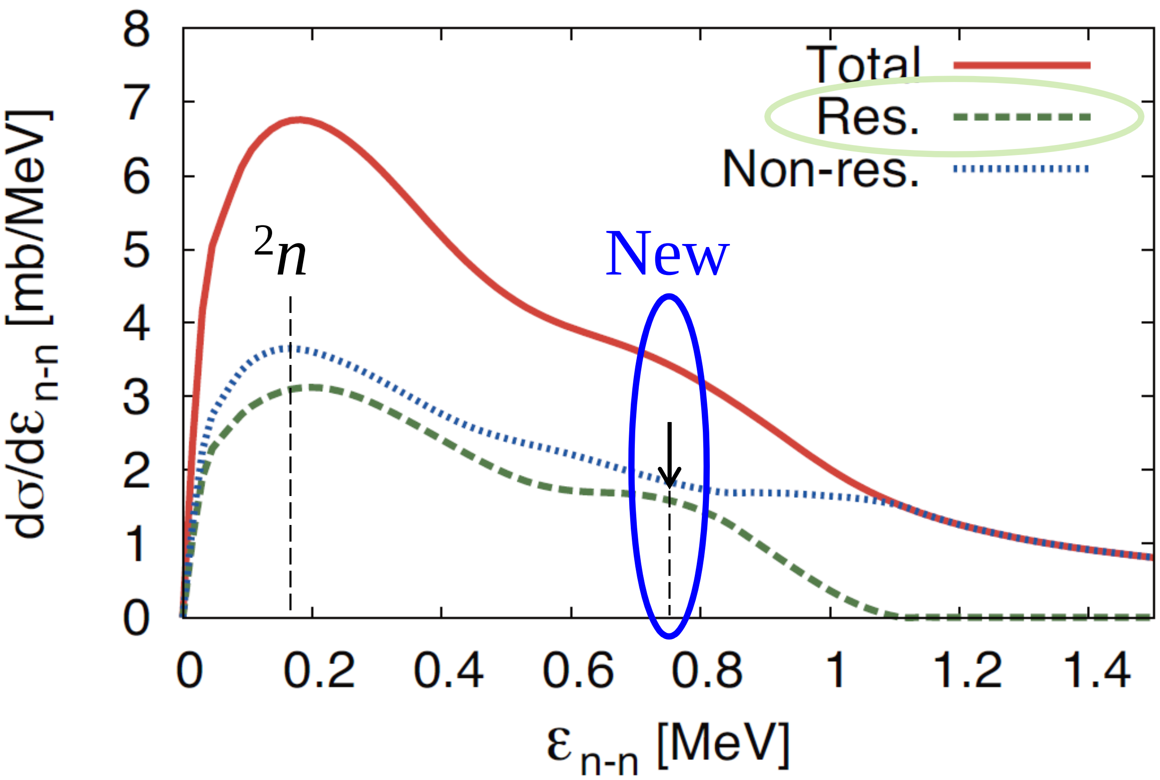
✓ The peak of the green line suggests the di-neutron decay or the democratic decay.

Coexistence of two decay modes

^{6}He(2_1^+)



$\varepsilon \sim 1$ MeV



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

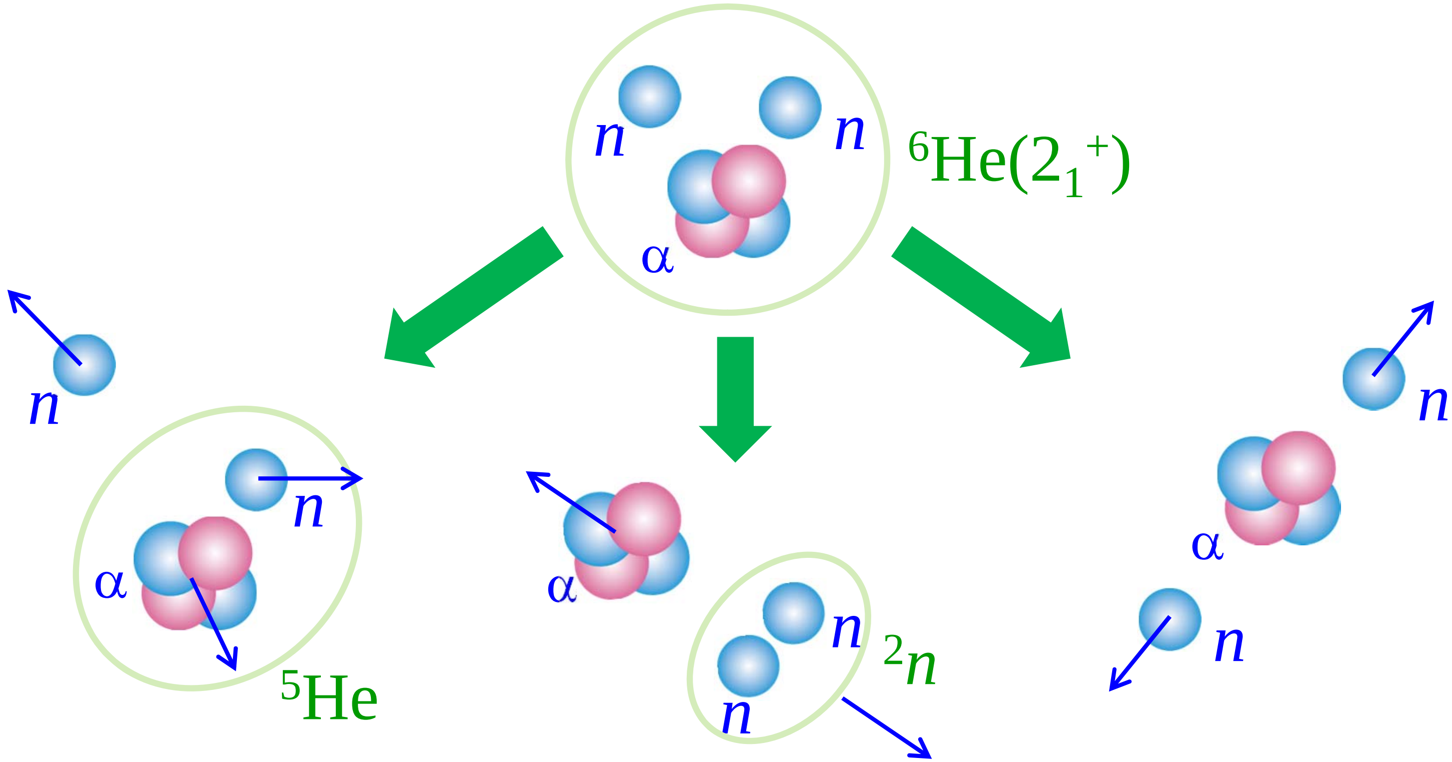
✓ The higher peak indicates the democratic decay.

➡ 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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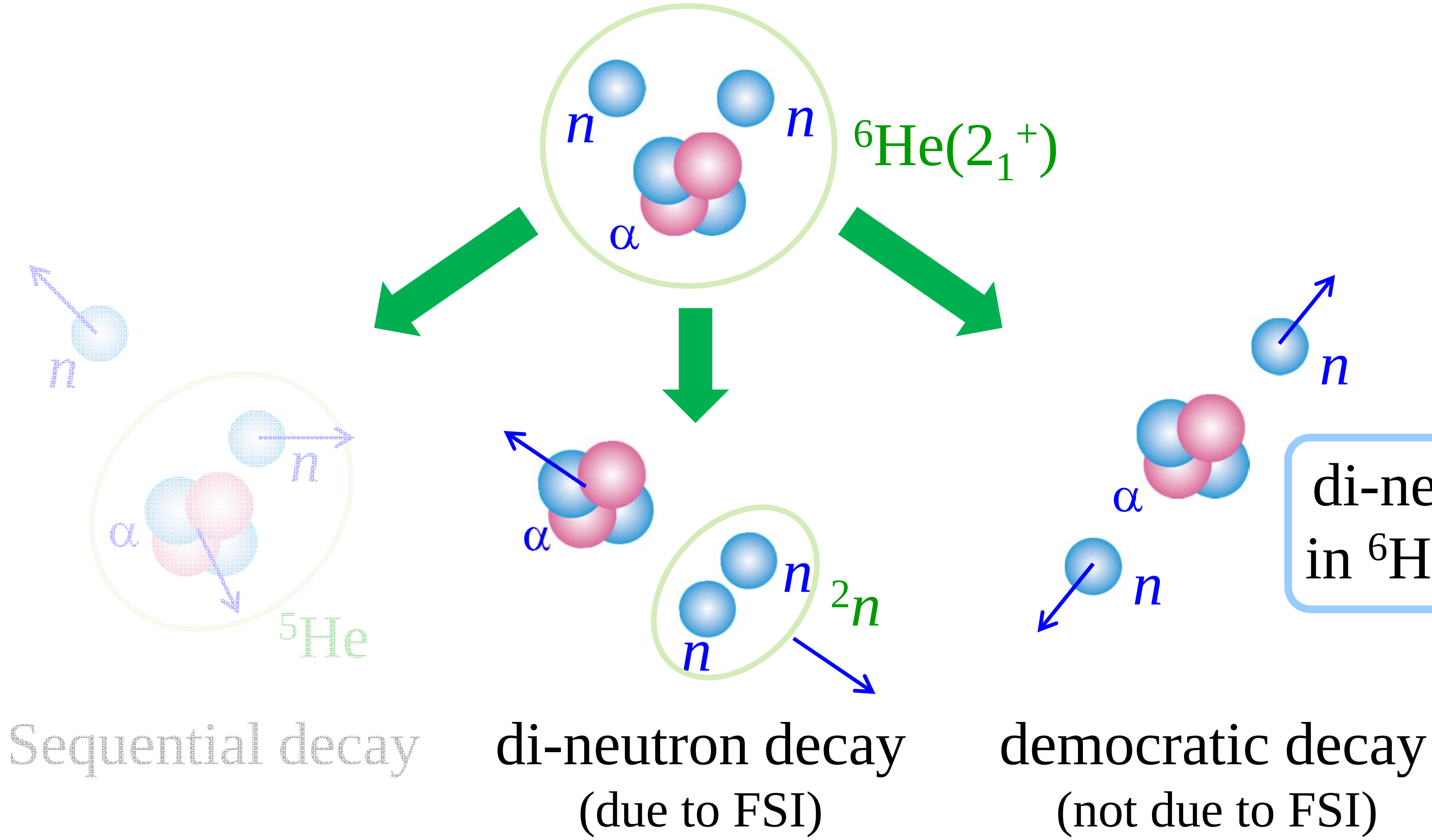

di-neutron in ^{6}He(2_1^+)

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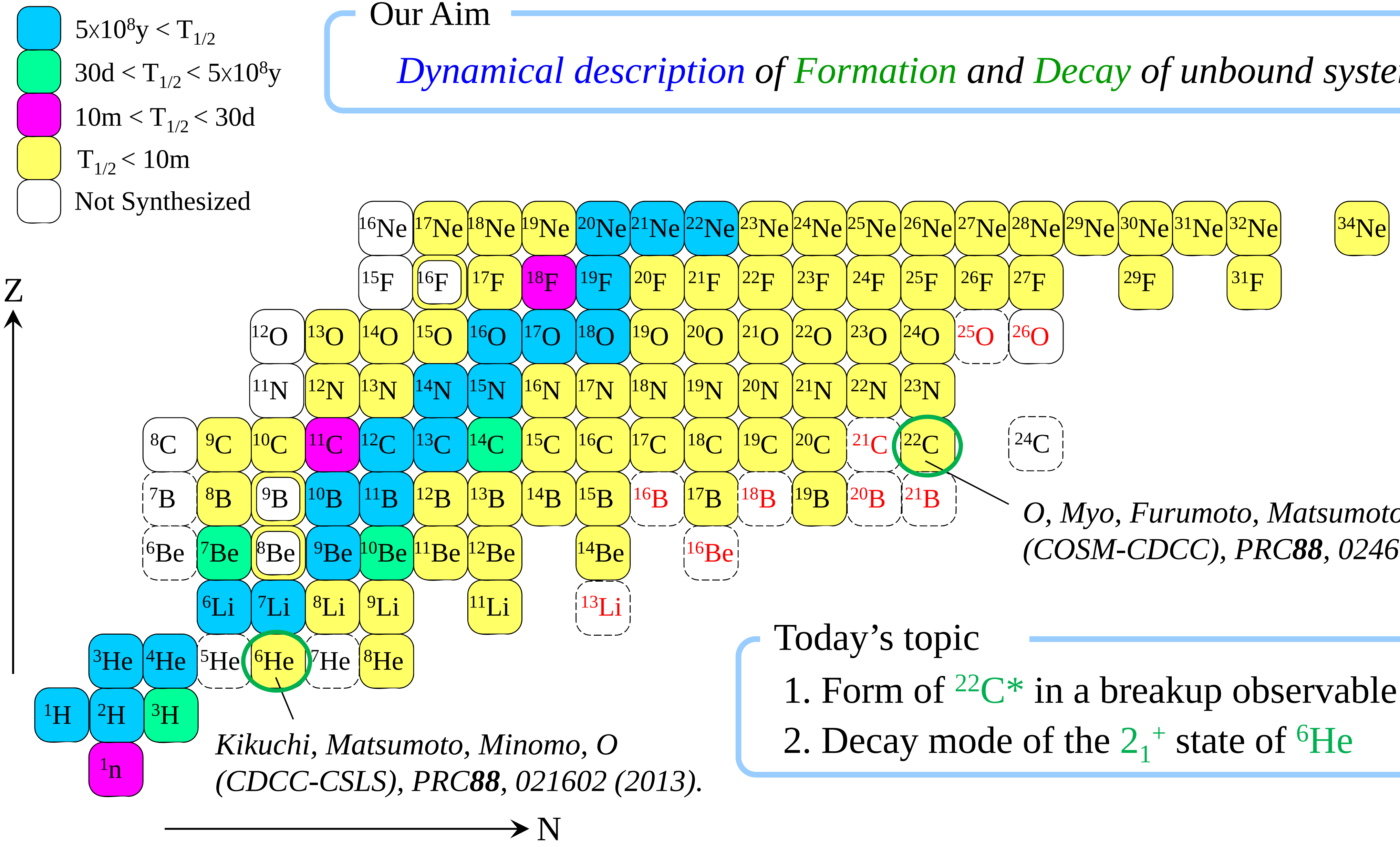

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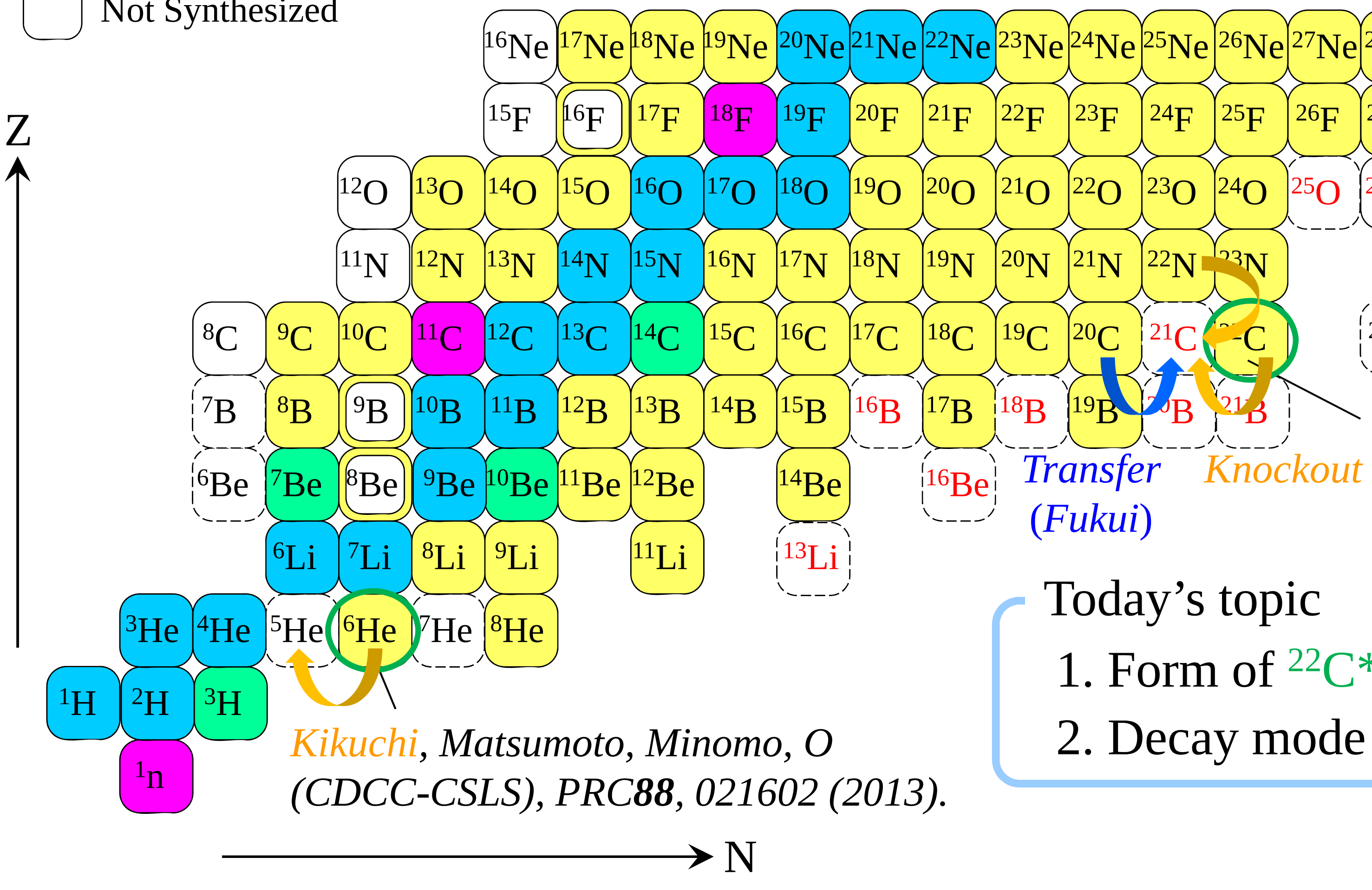

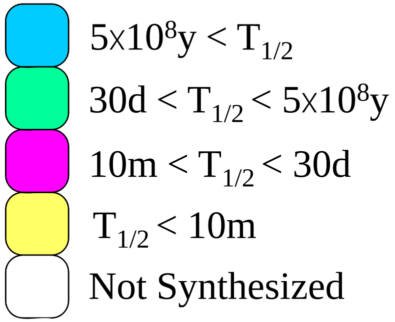

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Numerical inputs

^{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

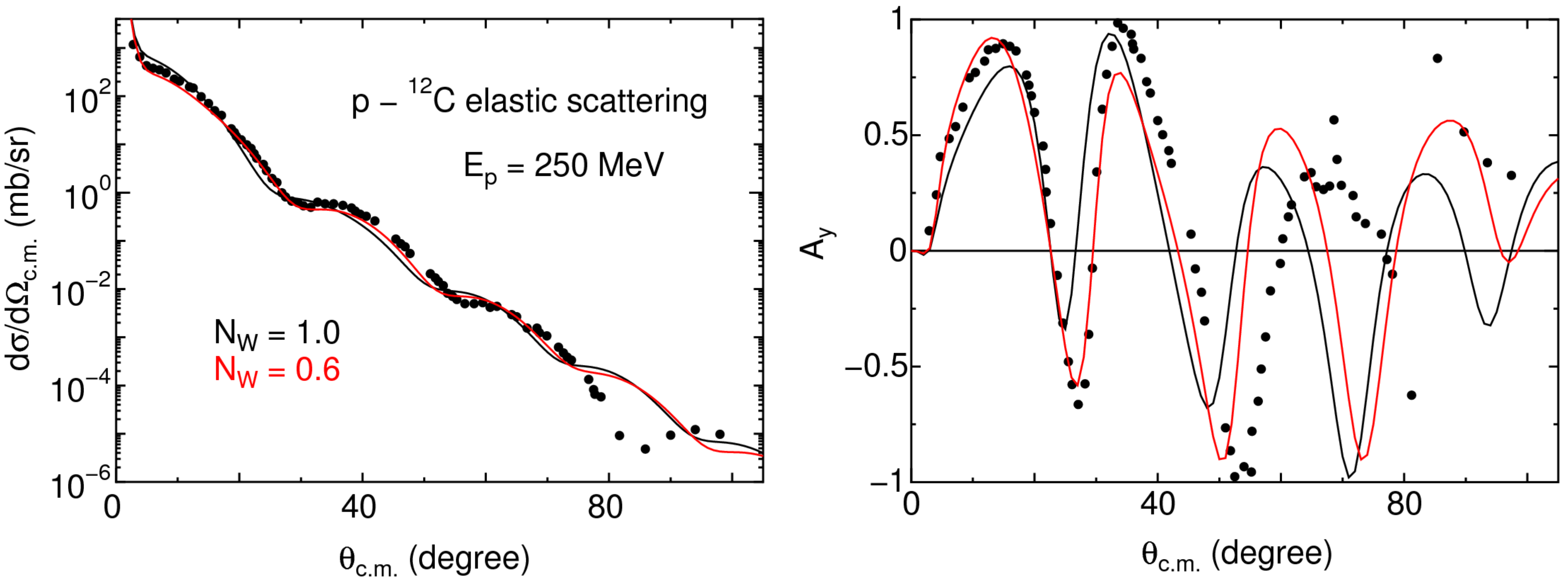
^{22}C-^{12}C breakup reaction

- ✓ 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).

p-12C scattering at 250 MeV

Nuclear density: L. C. Chamon *et al*., PRC 66, 014610 (2002) [Sao Paulo group]



Complex Scaling Method (CSM)

Courtesy of Matsumoto

S. Aoyama, T. Myo, K. Kato, and K. Ikeda,
Prog. Theor. Phys. 116, 1 (2006)

Complex-scaling operator: U^θ

$$U^\theta f(r) = e^{i3/2\theta} f(re^{i\theta})$$

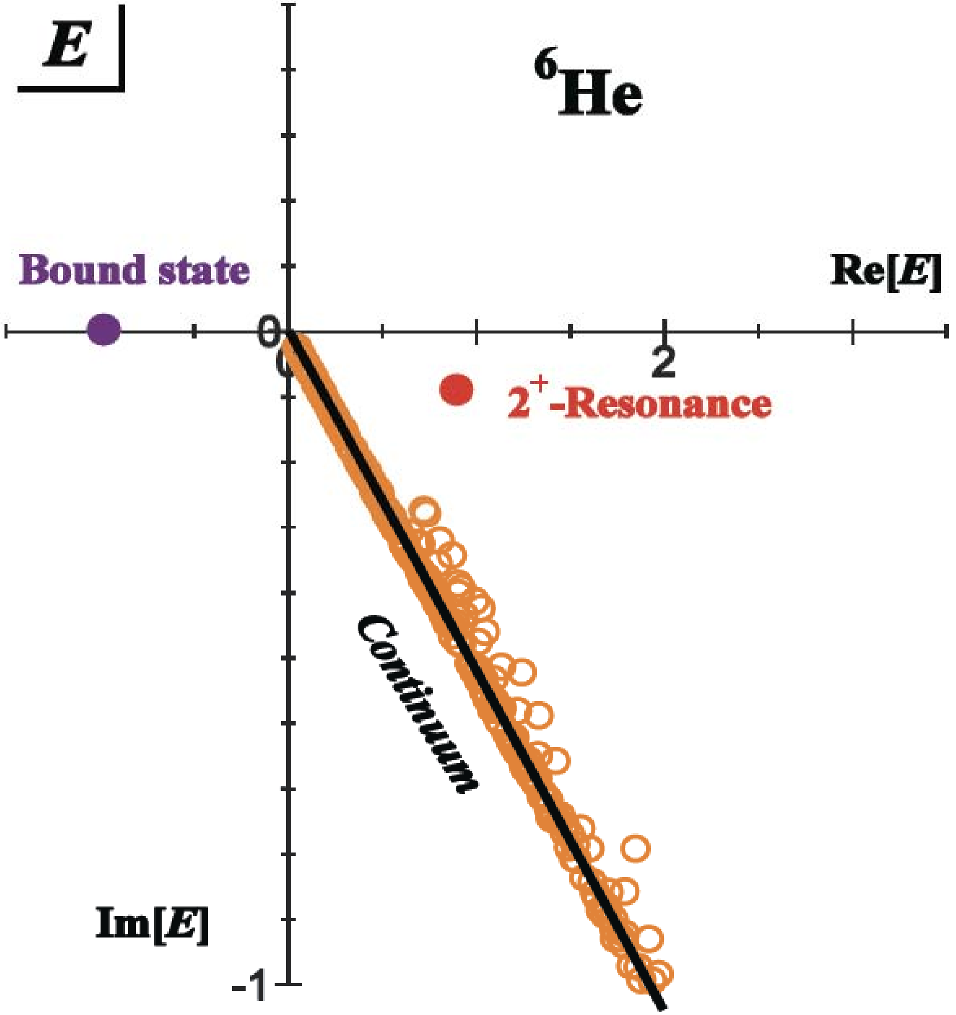
Coordinate: $r \to re^{i\theta}$

Momentum: $k \to ke^{-i\theta}$

Asymptotic form

$$e^{ikr} \longrightarrow e^{ikr\cos\theta} e^{-kr\sin\theta}$$

Useful for searching many-body resonances



Green's function with Complex-Scaling Method (CDCS Green's function)

$$\mathcal{G}^{(-)}(E,\xi,\xi') = \frac{1}{E-H-i\epsilon} \approx \sum_\nu U^{-\theta} \frac{|\Phi_\nu^\theta\rangle\langle\tilde{\Phi}_\nu^\theta|}{E-E_\nu^\theta} U^\theta$$

New Smoothing Procedure with *CSM*

T.M., K. Kato, and M. Yahiro, PRC82, 051602 (2010).

$$\frac{d\sigma}{dE} = \int T^{\dagger}(E')T(E')\delta(E-E')dE' = \frac{1}{\pi}\mathrm{Im}\mathcal{R}(E)$$

$$T(E) = \langle\psi^{(-)}(E,\xi)\chi_C^{(-)}(\mathbf{R})|V|\Psi^{(+)}(\xi,\mathbf{R})\rangle$$

Final state of the projectile

Response function

$$\mathcal{R}(E) = \int d\xi d\xi' \langle\Psi^{(+)}(\xi,\mathbf{R})|V^*|\chi_C^{(-)}(\mathbf{R})\rangle_{\mathbf{R}}\mathcal{G}^{(-)}(E,\xi,\xi')\langle\chi_C^{(-)}(\mathbf{R})|V|\Psi^{(+)}(\xi,\mathbf{R})\rangle_{\mathbf{R}}$$

Green's function with Complex-Scaling Method (CDCS Green's function)

$$\mathcal{G}^{(-)}(E,\xi,\xi') = U^{-\theta}\frac{1}{E-H^{\theta}-i\epsilon}U^{\theta} \approx \sum_{\nu} U^{-\theta}\frac{|\Phi_\nu^\theta\rangle\langle\tilde{\Phi}_\nu^\theta|}{E-E_\nu^\theta}U^{\theta}$$

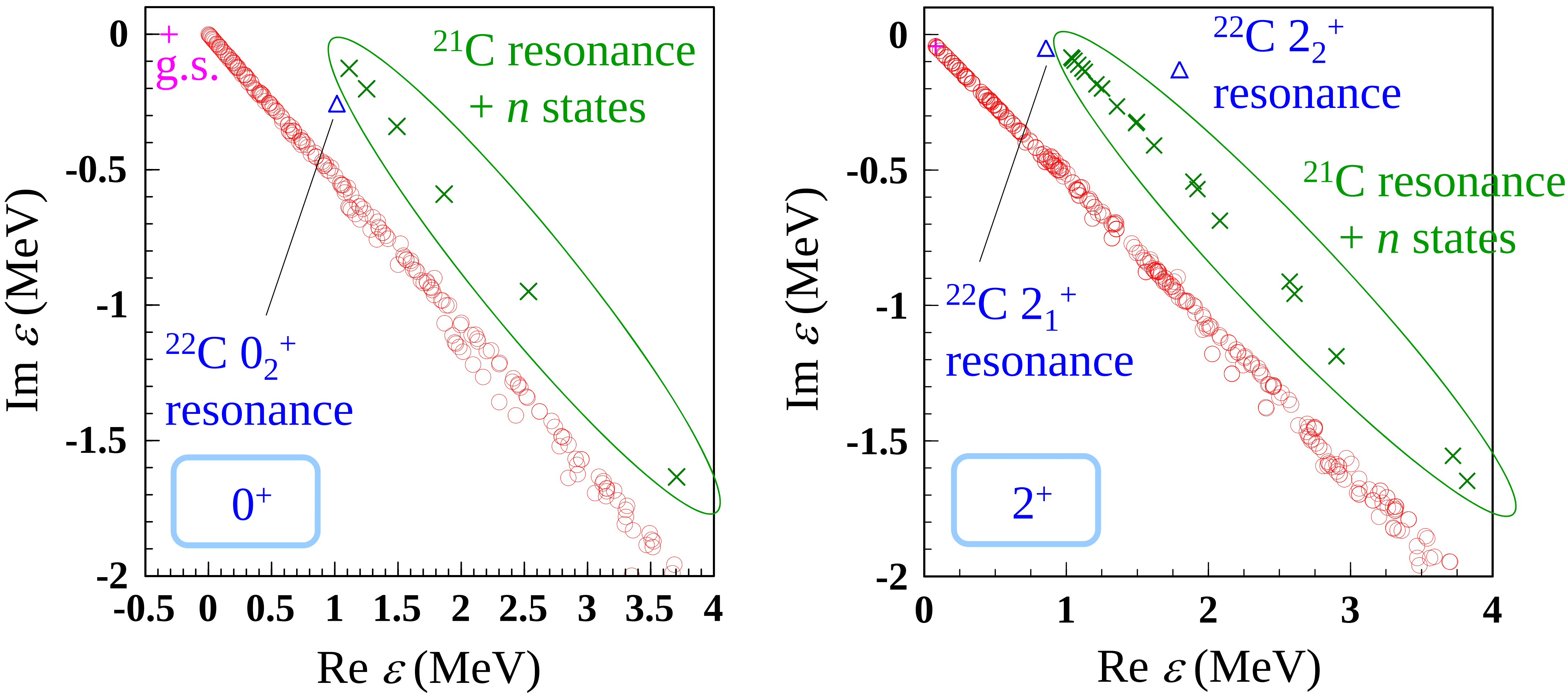
$$\mathcal{G}^{(-)}(E,\xi,\xi') \approx \sum_{\nu}\sum_{i,j}|\Phi_i\rangle\frac{\langle\Phi_i|U^{-\theta}|\Phi_\nu^\theta\rangle\langle\tilde{\Phi}_\nu^\theta|U^{\theta}|\Phi_j\rangle}{E-E_\nu^\theta}\langle\Phi_j|$$

$$\mathcal{R}(E) = \sum_{\nu}\sum_{i,j}\langle\Psi^{(+)}|V^*|\chi_C^{(-)}\Phi_i\rangle\frac{\langle\Phi_i|U^{-\theta}|\Phi_\nu^\theta\rangle\langle\tilde{\Phi}_\nu^\theta|U^{\theta}|\Phi_j\rangle}{E-E_\nu^\theta}\langle\Phi_j\chi_C^{(-)}|V|\Psi^{(+)}\rangle$$

T-matrix calculated by CDCC

Courtesy of Matsumoto

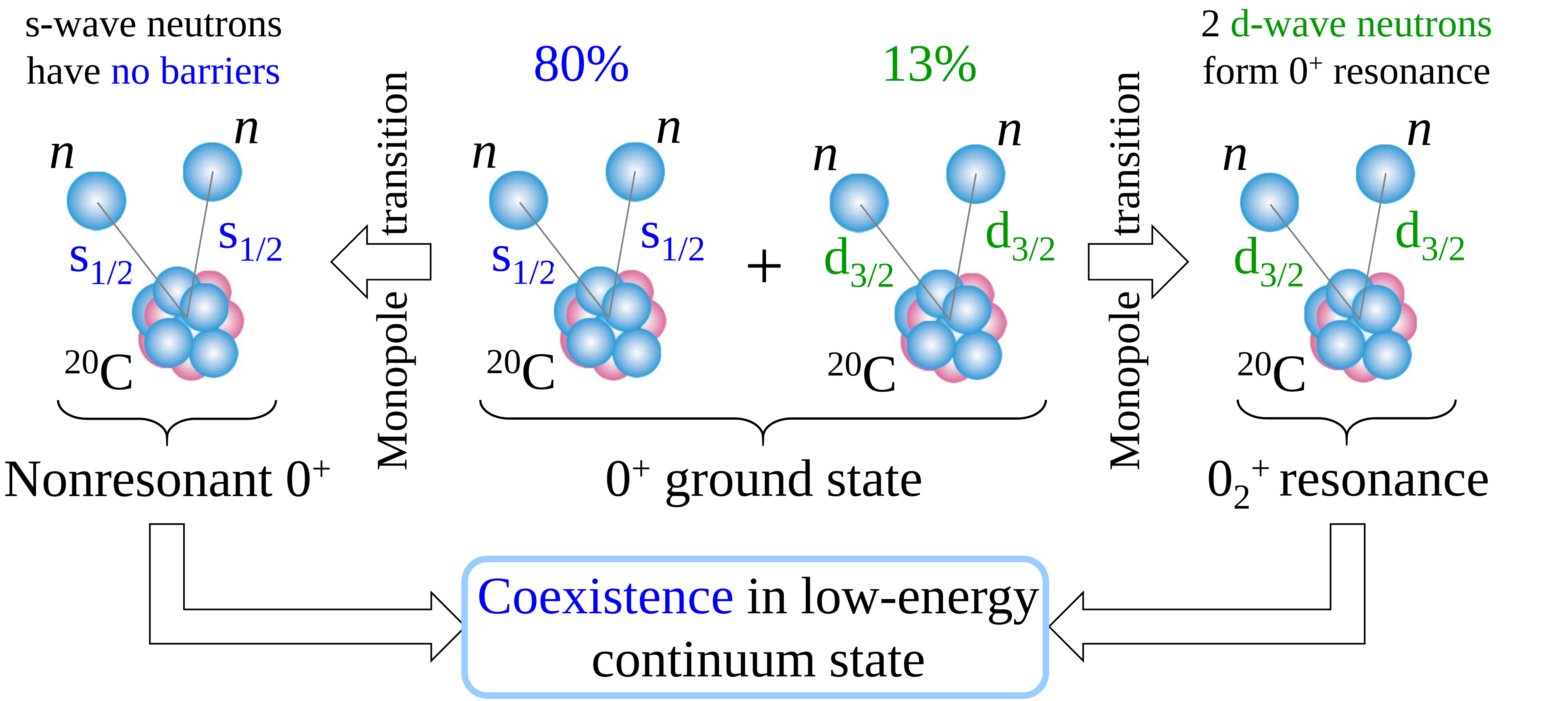
PS in the complex energy plane



✓ The complex-scaling method classifies the continuum states of ^{22}C.

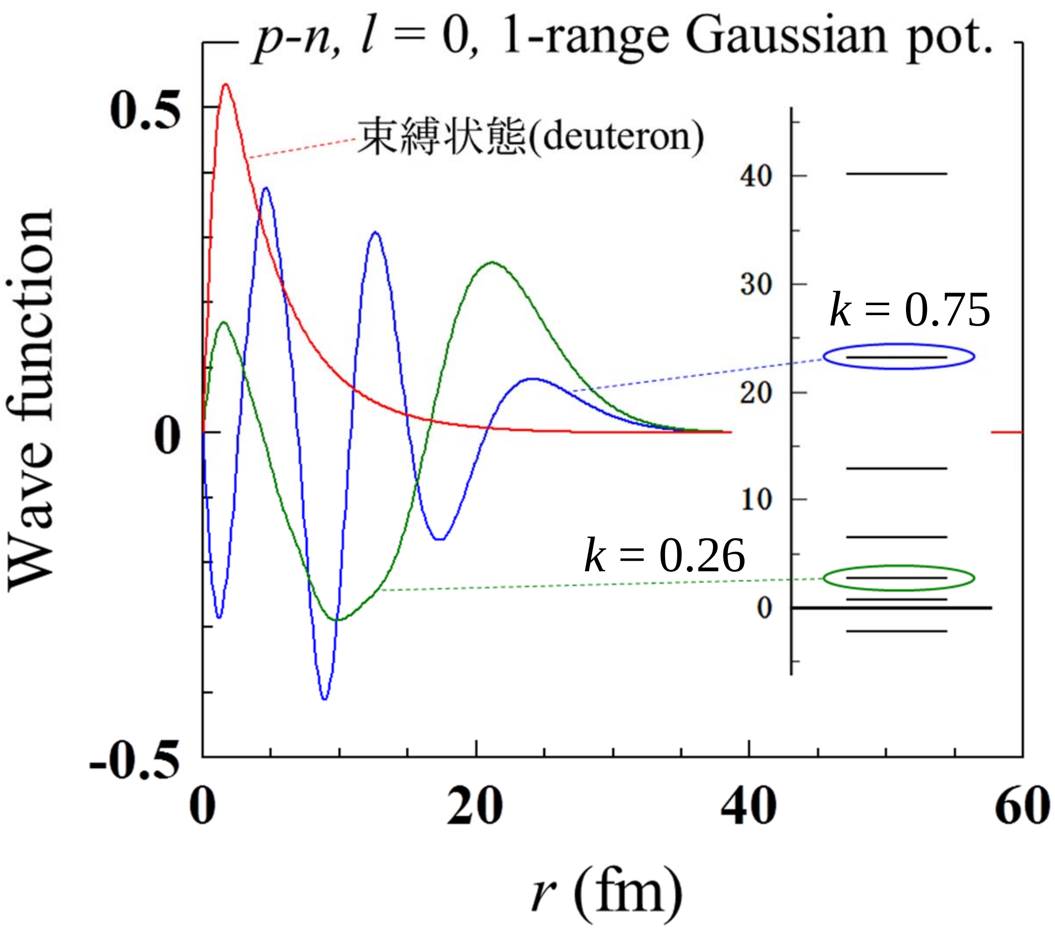
J. Aguilar and J. M. Combes, Comm. Math. Phys. **22**, 269 (1971);
E. Balslev amd J. M. Combes, ibid. **22**, 280 (1971).

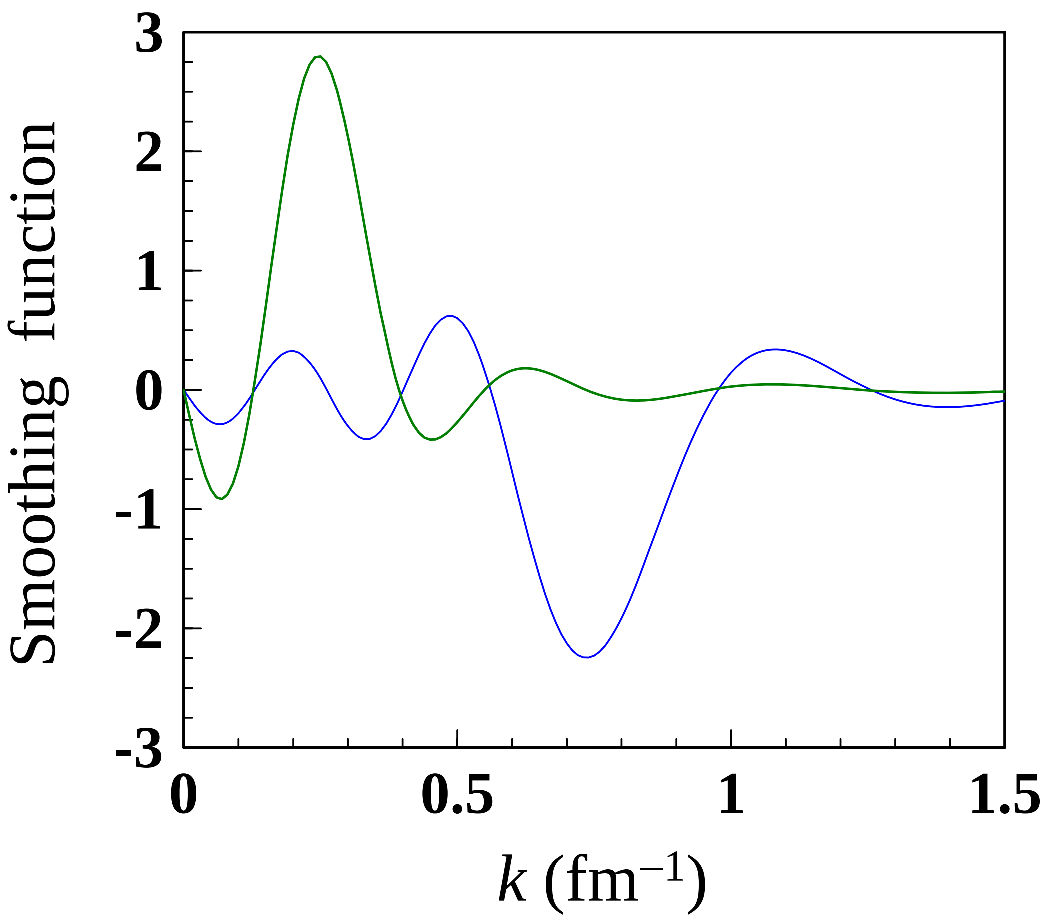
Why so large BGP effect?



- ✓ In a core + *n* system, this will hardly be realized.
- ✓ This resonant-nonresonant 0^+ coexistence is expected for (s-wave) two-neutron halo nuclei generally.

平滑化関数(PS法)



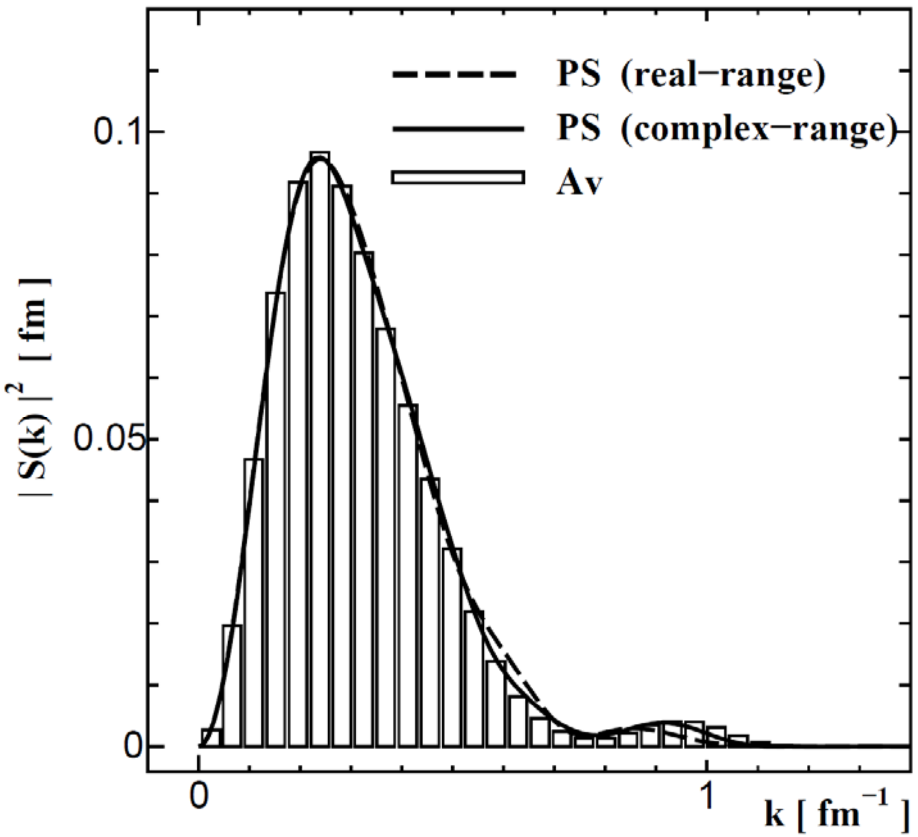


固有値に対応する k にピークを持つが、かなりの拡がりを持つ。

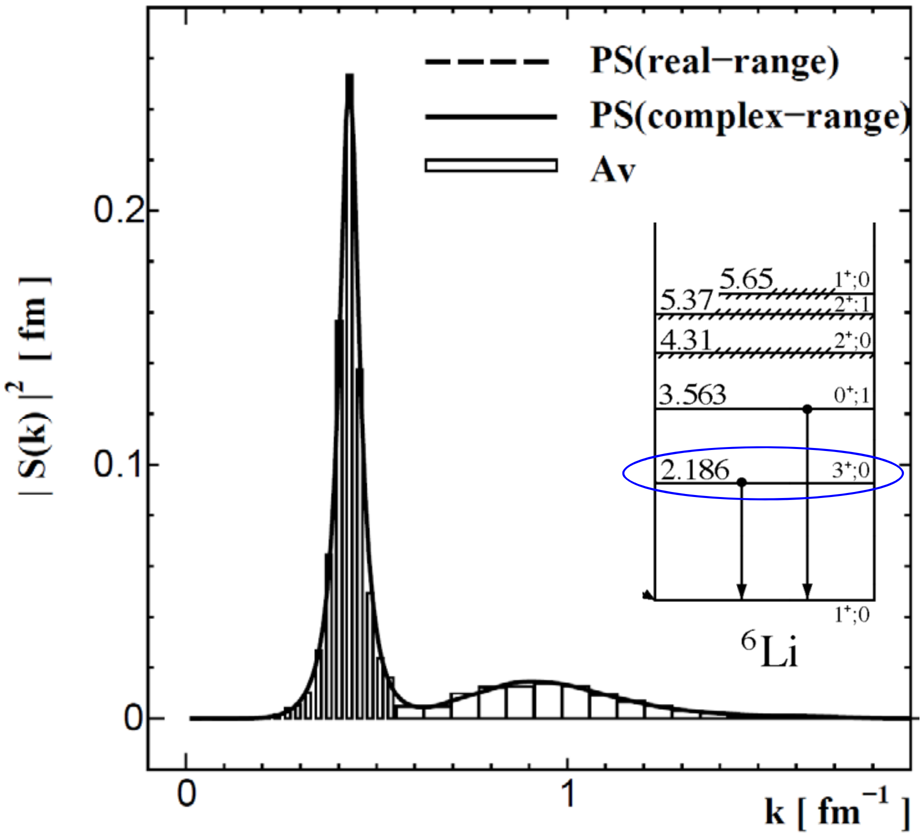
平滑化の実例(Av法 vs PS法)

T. Matsumoto, Kamizato, O, Iseri, Hiyama, Kamimura, Yahiro, Phys. Rev. C ***68****, 064607 (2003).*

$d+^{58}$Ni at 80 MeV



^{6}Li+^{40}Ca at 156 MeV



平滑化した遷移強度は両者で極めて良く一致。