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

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Exploration of unbound (but not free) systems

Dynamical description of Formation and Decay of unbound systems

Our Aim

5x10^8y < T1/2
30d < T1/2 < 5x10^8y
10m < T1/2 < 30d
T1/2 < 10m
Not Synthesized

Today’s topic
1. Form of 22C* in a breakup observable
2. Decay mode of the 2_1^+ state of 6He
COSM-CDCC for $^{22}\text{C}$ breakup by $^{12}\text{C}$

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

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

Details of COSM:
**COSM-CDCC for $^{22}\text{C}$ breakup by $^{12}\text{C}$**

**Reaction part: Four-body CDCC**

Eigenstates obtained by diagonalization

Set of the $^{22}\text{C}$ internal wave functions

(basis functions for the 4-body system)

Relative motion between $^{22}\text{C}$ and target

(expansion coefficients)

\[
\Psi_{\text{CDCC}} = \sum_{i=0}^{i_{\text{max}}} \hat{\phi}_i \hat{\chi}_i
\]

Details of four-body CDCC:

T. Matsumoto *et al.*, PRC 70, 061601(R) (2004); ibid. 73, 051602(R) (2006).

CSM Smoothing
(CSM: Complex-Scaling Method)

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

Eigenstates of $H^\theta$
(complex-scaled Hamiltonian)

Index for the pseudostates $\Phi_n$ used in CDCC

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

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

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

**22C wave function**

- Minnesota force for \( n-n \), Woods-Saxon potential for \( n-^{20}\text{C} \).
- \( s_{1/2}, p_{3/2}, p_{1/2}, d_{5/2}, d_{3/2}, f_{7/2}, f_{5/2}, g_{9/2}, g_{7/2}, h_{11/2}, \) and \( h_{9/2} \) for the \( n \) s.p. orbit.
- Each orbit is described by 10 Gaussian basis functions.


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

**22C-^{12}\text{C} breakup reaction**

- 77 (0\(^{+}\)) + 164 (2\(^{+}\)) PS below 10 MeV are included as breakup states of \( ^{22}\text{C} \).
- 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 \( ^{20}\text{C} \) core nucleus.

T. Furumoto et al., PRC 78, 044610 (2008).
$n + n + c$ dynamics explicitly described
The CSM smoothing* is adopted to obtain the BUX.

COSM predicts the following resonances:

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

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

How are these resonances observed?

*T. Matsumoto et al., PRC 82, 054602(R) (2010).
A new smoothing method* is adopted to obtain the BUX. COSM predicts the following resonances:

**22C resonance**
- $0^+_{22}$: $1.02 - i 0.52/2$
- $1^+_{21}$: $0.86 - i 0.10/2$
- $2^+_{22}$: $1.80 - i 0.26/2$

**21C resonance**
- $d_{3/2}$: $1.1 - i 0.10/2$

How are these resonances observed?

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The CSM smoothing* is adopted to obtain the BUX.

COSM predicts the following resonances:

\[ ^{22}\text{C resonance} \]
- \[ 0^+_2: 1.02 - i 0.52/2 \]
- \[ 2^+_1: 0.86 - i 0.10/2 \]
- \[ 2^+_2: 1.80 - i 0.26/2 \]

\[ ^{21}\text{C resonance} \]
- \[ d_{3/2}: 1.1 - i 0.10/2 \]

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**CSM Smoothing**

*(CSM: Complex-Scaling Method)*

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Eigenstates of $H^\theta$

(complex-scaled Hamiltonian)

\[ \tilde{T}_i^\theta = \sum_{n} \langle \tilde{\phi}_i^\theta \mid C(\theta) \mid \Phi_n \rangle T_n^{\text{CDCC}} \]

index for the pseudostates $\Phi_n$ used in CDCC

\[ \frac{d\sigma}{d\epsilon} = \frac{1}{\pi} \text{Im} \sum_i \frac{T_i^\theta \tilde{T}_i^\theta}{\epsilon - \epsilon_i} \]

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  - $2_2^+ : 1.80 - i 0.26/2$

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

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How are these resonances observed?
DDBUX of $^{22}$C by $^{12}$C

- The CSM smoothing* is adopted to obtain the BUX.
- COSM predicts the following resonances:
  
  $^{22}$C resonance
  
  $0^+_2: 1.02 - i 0.52/2$
  
  $2^+_1: 0.86 - i 0.10/2$
  
  $2^+_2: 1.80 - i 0.26/2$ negligible

  $^{21}$C resonance
  
  $d^{3/2}_3: 1.1 - i 0.10/2$ negligible

How are these resonances observed?

*T. Matsumoto et al., PRC 82, 054602(R) (2010).
The narrow peak around 0.8 MeV is due to the $2_1^+$ resonance of $^{22}\text{C}$.

The shape of the $0_2^+$ resonance is due to background phase effect.
In nuclear physics, we always have $\delta_{\text{bg}}$.

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.
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
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 $^{22}\text{C}^*$ in a breakup observable?

KO, Myo, Furumoto, Matsumoto, Yahiro, PRC88, 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 $^{22}\text{C}$ in the observables.
What is the decay mode of the $2_1^{+}$ state of $^6$He?


Sequential decay

$^6$He($2_1^{+}$) → $^5$He + $n$

Di-neutron decay

$^6$He($2_1^{+}$) → $^4$He + $2n$

Democratic decay

$^6$He($2_1^{+}$) → $^3$He + $3n$
CDCC-CSLS

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


\[ T(p, k) = \sum_n \left< \Phi^{(-)}(p, k) \left| \Phi_n \right> \right> T_n^{\text{CDCC}} \]

\[ \equiv \sum_n f_n(p, k) T_n^{\text{CDCC}} \]

\[ f_n(p, k) = \left< \varphi_{\text{free}}(p, k) \left| \Phi_n \right> \right> + \sum_i \left< \varphi_{\text{free}}(p, k) \left| V_{\alpha nn} C^{-1}(\theta) \phi_i \right> \right> \]

\[ \times \frac{1}{\varepsilon - \varepsilon_i} \left< \phi_i \left| C(\theta) \right| \Phi_n \right> \]
Sequential decay quenched

When $\varepsilon \sim 1\text{ MeV}$ and $\varepsilon_{\alpha-n} \sim 0.7\text{ MeV}$, the other neutron ($\sim 0.3\text{ MeV}$) 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

$^6\text{He}(2_1^+) \rightarrow 2n$

$\varepsilon \sim 1 \text{ MeV}$

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

$\rightarrow$ Decay of a di-neutron in the $2_1^+$ state not due to the FSI.
What is the decay mode of the $2_{1}^{+}$ state of $^{6}$He?


Sequential decay  di-neutron decay  democratic decay
Summary of the 2nd topic

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

**Exploration of unbound (but not free) systems**

### Our Aim

**Dynamical description of Formation and Decay of unbound systems**

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

**Today’s topic**

1. Form of $^{22}$C* in a breakup observable
2. Decay mode of the $^{21}_{1}^{+}$ state of $^{6}$He

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Mizuyama and O (cPVC), PRC89, 034620 (2014).
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1. Form of $^{22}\mathrm{C}^*$ in a breakup observable
2. Decay mode of the $2_{1}^+$ state of $^{6}\mathrm{He}$

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