Reaction dynamics of slow collisions in light neutron excess systems

一 Unified studies from bounds to continuum in Be isotopes

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I. Introduction
II. Framework
III. Varieties of structures in $^{12}$Be and Be isotopes
IV. Enhancements induced by large amplitude motions
V. Summary and feature plan
Cluster structures in 4N nuclei

Ikeda’s Threshold rules
Molecular structures will appear close to the respective cluster threshold.

Be isotopes
Molecular Orbital: Itagaki et al., Abe et al.,…

$^\alpha$-Particle $\Rightarrow$ Stable

$^3\text{H} + p \sim 20 \text{ MeV}$

Systematic Appearance of $\alpha$ cluster structures

PRC61,62 (2000)
Studies on Exotic Nuclear Systems in $(E_x, N, Z, J)$ Space

Slow RI beam → Unbound Nuclear Systems → Decays in Continuum

Systematics of $^{16}_{8-16}\text{Be}$

Low-lying Molecular Orbital:
$\pi^-, \sigma^+\cdots$

Is Threshold Rule valid??

Structural Change

$(N, Z)$: Two Dimensions
Interests from the viewpoints of large amplitude collective motions

Reactions are extreme limits of large amplitude collective motions!

Combined states \[\xrightarrow{\text{Breakup}}\] Binary states

How to characterize...
Reaction path in adiabatic energy surfaces (AESs)

Subjects

1. Pursuit of structural changes over a wide region in AESs
2. Investigation of reaction path in AESs and enhancements in connection to AESs structures

Today’s report

1. Global features of structures in $^{12}\text{Be}$ and Be isotopes
2. Non-adiabatic phenomena in large amplitude reactions
Extension of microscopic cluster model (Test calculation for $^{10}$Be)

$^{10}$Be=$\alpha+\alpha+N+N$

Unified model between M.O. and He clusters: PLB588 (04)

\[
\Psi = C_1 + C_2 + C_3 + \ldots
\]

$0\Pi$ ($i=x,y,z$) Coupled channels with Atomic orbitals

$S, C_i$: Variational PRM.

Absorbing B.C. | Scattering B.C. | Tr. densities
---|---|---
Decay width PTP113 (05) | $\alpha+^{6}$He Cross sections PLB636 (06) | $^{10}$Be $\rightarrow$ $\alpha+^{6}$He Breakup
Femto Molecules: $^{12}\text{Be}=\alpha+\alpha+4N$

Various structures are generated by excitation of $\alpha-\alpha$ and neutron degree of freedom.
Be isotopes from bounds to continuums: $J^\pi = 0^+$

- $^8\text{Be}$
- $^{10}\text{Be}$
- $^{12}\text{Be}$
- $^{14}\text{Be}$
- $^{16}\text{Be}$

Deformed states (Clusters)

Compact states (Shell model)

Excitation of $\alpha-\alpha$ rel. motion

$^\kappa\text{He}$ $^\nu\text{He}$
Global behaviors of Level Crossings in Be isotopes

- Compact (Normal)
- Clusters (Intruder)
- Internal States

Energy

Core-Core distance

Small ↔ Large

Asymptotic States

Levels Crossing

A + B

E + F

E + F*

C + D
Level Crossings in $^{12,14}\text{Be}=\alpha+\alpha+XN \ (X=2,6)$

Graphs showing the excitation energy versus distance for $^{10}\text{Be}$ and $^{14}\text{Be}$, highlighting level crossings for specific nuclear states.
Adiabatic surfaces ($J^\pi = 0^+$)

Energy spectra ($J^\pi = 0^+$)

$^4\text{He} + ^6\text{He}_{g.s.}$

Cluster

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

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

$^10\text{Be}$ ($0^+$) case: M.I., PLB636, 236 (2006)
Nuclea breakup: $^{10}\text{Be} + ^{12}\text{C} \Rightarrow ^{10}\text{Be}(0^+ \text{ conti.}) + ^{12}\text{C} (\text{CDCC cal.})$

**Smat. (Conti.←G.S.)**

S-matrices to continuums

- $S_{\text{mat.}}(\text{Conti.}\leftarrow\text{G.S.})$

**Smat. (Poles ← G.S.)**

S-matrices to Poles

- $S_{\text{mat.}}(\text{Poles}\leftarrow\text{G.S.})$

Decay energy (MeV)

- 0.001
- 0.002
- 0.25
- 0.5

$|S_{k\leftarrow i}|^2$

- $^{4}\text{He} + ^{6}\text{He}(2_1^+)$ Cluster
- $(\pi_{1/2}^-)^2$

$0_3^+$

$0_4^+$
Reaction path in $^{10}\text{Be} \rightarrow x\text{He} + y\text{He}$ Breakup reaction (Positive Parity)

$^{10}\text{Be}(0^+) \rightarrow [\alpha + ^6\text{He}(2_1^+)] 0^+$

$0_1^+ \rightarrow 0_3^+$ is the dominant transition.

Non-adiabatic path is main process.
\[ \alpha + ^6\text{He}_{\text{g.s.}} \Rightarrow \alpha + ^6\text{He}(2_1^+) \text{ scattering (Negative Parity)} \]

**Diagrams:**

- **Left Diagram:**
  - Plot of Excitation Energy vs. Distance (\( \alpha - \alpha \) Distance (\( \text{fm} \)))
  - Adiabatic energy surfaces (\( \text{JP} = 1^- \))
  - \( \pi_{3/2}^- \sigma_{1/2}^+ \)
  - Avoided crossing at the surface

- **Right Diagram:**
  - Plot of Excitation Energy vs. Distance (\( \alpha - \alpha \) Distance (\( \text{fm} \)))
  - \( \alpha + ^6\text{He}(0_1^+) \rightarrow \alpha + ^6\text{He}(2_1^+) \)
  - Landau-Zener type enhancement

**Equation:**

\[ ^4\text{He} + ^6\text{He}_{\text{g.s.}} \Rightarrow ^4\text{He} + ^6\text{He}(2_1^+) \]
Level Crossing in $^{12}\text{Be}$ (1)

Un correlated AESs

Correlated AESs

Two AESs are almost degenerated due to correlations ⇒ Crossing occurs at inner region!
Level Crossing in $^{12}$Be (2)

Correlated AESs

AESs with full coupling

Coupling with all configurations

Lowest minimum smoothly connected to $\alpha + ^8\text{He}_{\text{g.s.}} \Rightarrow$ Formation of adiabatic conjunction
Monopole transition of $^{12}$Be

$$M(E0, IS) = \langle 0_f^+ \mid \sum_{i=1}^{A} r_i^2 \mid 0_1^+ \rangle$$

Adiabatic conjunction enhances the monopole transition!
Contents of present report

1. Unified studies form bounds to continuums in Be isotopes
2. Reactions with large amplitudes in connection to adiabatic energy surfaces

Results

1. There appears a wide variety of structures in excited states (Cluster + excess N) Enhancements occur depending on the structures of AESs.
   
   $^{10}$Be : Non-adiabatic path is dominant in monopole breakup and slow scattering.
   
   $^{12}$Be : Adiabatic path is dominant in monopole b.u. (Formation of conjunction)

Feature studies

Recently, we have just succeeded in extending the model to general two centers.

Extension to SD shell $\Rightarrow$ $O=\alpha+^{12}C+XN, Ne=\alpha+^{16}O+XN$

Generalities and Specialities : hybrid structures of clusters + excess neutrons in O and Ne
**Systematics based on the Cluster Picture**

\[ \begin{align*}
\text{10Be} & : L:(OP_{3/2})^{-4} & \text{14Be} & : L:(OP_{3/2})^4 \\
\text{8Be} & : L:(OP_{3/2})^{-4} & \text{16Be} & : L:(OP_{3/2})^4
\end{align*} \]

**Special feature in 12Be**

\[ ^{12}\text{Be}=^6\text{He}+^6\text{He}, \ \alpha+^8\text{He} \text{ is a self conjugate when atomic p-h are exchanged.} \]

⇒ This is a special nucleus in even Be isotopes.

We are now analyzing wave functions.
Adiabatic surfaces ($J^\pi = 0^+$)

Energy spectra ($J^\pi = 0^+$)

GTCM + Absorbing Boundary Condition: PLB (2006)