Manifestation of α-clustering in Be isotopes via α-knockout reaction

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How to probe the $\alpha$-cluster?

The $\alpha$ knockout reaction

- *Well established theory* employing the DWIA framework

- *Peripherality* only the surface region contributes

- *Clean*
DWIA framework for $\alpha$-knockout reaction

- The *transition amplitude* of $\alpha$-knockout reaction
  
  \[ T_{K_0K_1K_2} = \langle \chi^{(-)}_{1,K_1}(R_1)\chi^{(-)}_{2,K_2}(R_2) | t_\alpha(s) | \chi^{(+)}_{0,K_0}(R_0) \phi_\alpha(R_2) \rangle \]

- With the *asymptotic momentum approximation* [1]
  
  \[ \bar{T}_{K_0K_1K_2} = \int dR F_{K_0K_1K_2}(R) \phi_\alpha(R) \]

- where
  
  \[ F_{K_0K_1K_2}(R) = \chi^{*(-)}_{1,K_1}(R_1)\chi^{*(-)}_{2,K_2}(R_2)\chi^{(+)}_{0,K_0}(R_0)e^{-iK_0\cdot R A_\alpha/A} \]

- $\chi^{(-)}_{1,K_1}, \chi^{(-)}_{2,K_2}$ distorted w. f. in initial channel

- $\chi^{(+)}_{0,K_0}$ distorted w. f. in final channel

Triple differential cross section for $\alpha$-knockout reaction

- The triple differential cross section (TDX)
  \[ \frac{d^3 \sigma}{dE_1 d\Omega_1 d\Omega_2} = F_{\text{kin}} C_0 \frac{d\sigma_{p\alpha}}{d\Omega_{p\alpha}}(\theta_{p\alpha}, E_{p\alpha}) \left| \bar{T}_{K_0K_1K_2} \right|^2 \]

- $F_{\text{kin}}$: kinematical factor
  \[ F_{\text{kin}} = J_L \frac{K_1K_2E_1E_2}{\hbar^4 c^4} \left[ 1 + \frac{E_2}{E_B} + \frac{E_2 (K_1 \cdot K_2)}{K_2^2} \right] \]

- $C_0 = \frac{E_0}{(\hbar c)^2 K_0} \frac{\hbar^4}{(2\pi)^3 \mu_{p\alpha}^2}$

- $J_L$: Jacobian

- Scattering energy
  \[ E_{p\alpha} = \frac{\hbar^2 \kappa'^2}{2\mu_{p\alpha}} \]

- $\kappa'$: asymptototic $p\alpha$ relative momentum

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THSR description of Be and He

• **THSR wave function** for nuclei composed of $\alpha$-clusters and valence neutrons [1,2]

$$|\Psi\rangle = (C_\alpha^\dagger)^m (c_n^\dagger)^n |\text{vac}\rangle$$

• $\alpha$-clusters

$$C_\alpha^\dagger = \int d^3 R \exp \left( -\frac{R_x^2 + R_y^2}{\beta_{\alpha,xy}^2} - \frac{R_z^2}{\beta_{\alpha,z}^2} \right) \int d^3 r_1 \cdots d^3 r_4$$

$$\times \psi(r_1 - R)a_{\sigma_1,\tau_1}^\dagger(r_1) \cdots \psi(r_4 - R)a_{\sigma_4,\tau_4}^\dagger(r_4)$$

• valance neutrons

$$c_n^\dagger = \int d^3 R_n \exp \left( -\frac{R_{n,x}^2 + R_{n,y}^2}{\beta_{n,xy}^2} - \frac{R_{n,z}^2}{\beta_{n,z}^2} \right) f(R_n) \int d^3 r_n$$

$$\times \psi(r_n - R)a_{\sigma_n,\tau=\downarrow}^\dagger(r_n)$$

• $f(R_n)$: factors to adjust neutron w. f. $\phi_n = c_n^\dagger |0\rangle$ into $p$-orbits or molecular $\pi$-orbit and $\sigma$-orbits [1,2]

Approximation for reduced width amplitude

- The *reduced width amplitude* (RWA) of $\alpha$-cluster

$$y_l(a) \equiv \frac{1}{M} \left\langle \frac{\delta(r-a)}{r^2} Y_{00}(\hat{r}) \phi_A \phi_A \phi_{c.m.} | \Phi \right\rangle$$

- is approximated by [1]

$$|ay(a)| \approx ay^{\text{app}}(a) = \frac{1}{\sqrt{2}} \left( \frac{n_B n_\alpha}{n_A \pi b^2} \right)^{1/4} \left\langle \Phi_A | \Phi^{(0+)}_{BB} \left( \Phi^{(0+)}_B, \alpha; S = a \right) \right\rangle$$

- $\Phi_A$: THSR w. f. of target A
- $\Phi^{(0+)}_{BB} (\Phi_B, \alpha; S = a)$: Brink-Bloch-type w. f. of residual B and $\alpha$-cluster
- $\Phi^{(0+)}_B$: THSR w. f. of residual B

α-cluster RWA of $^{10}$Be

- **physical $^{10}$Be nucleus**
  - $\beta_\alpha = 2.6$ fm (optimized) (molecular like)
  - $E = -61.4$ MeV
  - $R_c = 2.31$ fm (Exp: 2.35 fm)

- **artificial $^{10}$Be nucleus**
  - $\beta_\alpha = 1.0$ fm (shell-model limit)
  - $\beta_\alpha = 6.0$ fm (gas like)

**Figure:** Reduced width amplitude of $^{10}$Be
Density distribution of $^{10}$Be

- (a): $\beta_\alpha = 1.0$ fm (shell-model limit)
- (b): $\beta_\alpha = 2.6$ fm (physical, molecular-like)
- (c): $\beta_\alpha = 6.0$ fm (gas like)
Kinematics for $\alpha$-knockout reaction of $^{10,12}\text{Be}$

- **Incident proton**
  - $E = 250\text{ MeV}$

- **Outgoing proton**
  - $E_1 = 180\text{ MeV}$
  - $(\theta_1, \phi_1) = (60.9^\circ, 0^\circ)$

- **Outgoing $\alpha$**
  - $\theta_2$: varied around $51^\circ$
  - $\phi_2: 180^\circ$
Transition matrix density (TMD)

- **TMD**: Transition strength as a function of $R$
- TMD is defined as $\delta(R)$ where
  \[ \int dR \delta(R) \propto \frac{d^3 \sigma}{dE_1 d\Omega_1 d\Omega_2} \]
- mostly contributed by the surface region
TDX for the $^{10}$Be(p,pα)$^6$He reaction

\[
\frac{d^3\sigma}{dE_1d\Omega_1d\Omega_2} = F_{kin} C_0 \frac{d\sigma_{p\alpha}}{d\Omega_{p\alpha}}(\theta_{p\alpha}, E_{p\alpha}) |\bar{T}_{K_0 K_1 K_2}|^2
\]
Coupling of clustering configurations in $^{12}\text{Be}$

- Coupling of $^4\text{He}+^8\text{He}$, $^{10}\text{Be}+2n(\pi^*)$ and $^{10}\text{Be}+2n(\sigma)$ configurations
- Breaking of neutron magic number $N=8$
- *Probing* of $\alpha$-cluster and clustering configurations in $^{12}\text{Be}$

$^4\text{He}+^8\text{He}$

$^{10}\text{Be}+2n(\pi^*)$

$^{10}\text{Be}+2n(\sigma)$

(schematic)
α-cluster RWA of $^{12}\text{Be}$ in three configurations

- $^4\text{He}+^8\text{He}$ configuration
  - $\beta_\alpha = 4.0$ fm (optimized)

- $^{10}\text{Be}+2n(\pi^*)$ configuration
  - $\beta_\alpha = 4.0$ fm (optimized)

- $^{10}\text{Be}+2n(\sigma)$ configuration
  - $\beta_\alpha = 4.0$ fm (adjusted, preliminary)
Transition matrix density (TMD)

\[ \int dR \delta(R) \propto \frac{d^3 \sigma}{dE_1 d\Omega_1 d\Omega_2} \]
TDX for the $^{12}\text{Be}(p, p\alpha)^8\text{He}$ reaction

\[
\frac{d^3\sigma}{dE_1 d\Omega_1 d\Omega_2} = F_{\text{kin}} C_0 \frac{d\sigma_{p\alpha}}{d\Omega_{p\alpha}}(\theta_{p\alpha}, E_{p\alpha}) |\tilde{T}_{K_0K_1K_2}|^2
\]
Summary

- Proposed fully microscopic framework for $\alpha$-knockout reaction by integrating microscopic clustering model into DWIA framework.
- Approximation of RWA extracted from the THSR description for $^{10}$Be and three configurations of $^{12}$Be.
- Observables (TDX) predicted for future experiment.
- For $^{10}$Be, results compared for the shell-model limit, molecular-like and gas-like states.
- For $^{12}$Be, results compared for $^4\text{He}+^8\text{He}, ^{10}\text{Be}+2n(\pi^*)$ and $^{10}\text{Be}+2n(\sigma)$ configurations.
- TDX found to be highly sensitive to the extent of clustering, and also to the cluster/molecular configurations.
Many thanks for all collaborators

and

thank you very much for your attention!