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

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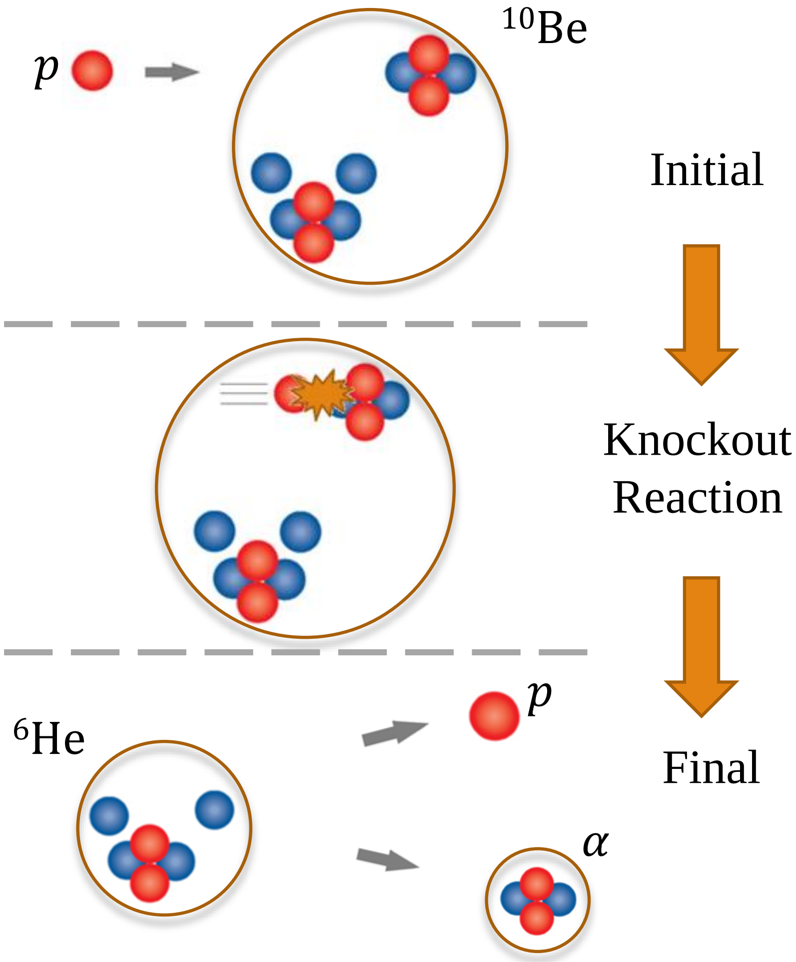
How to probe the α-cluster ?

The α knockout reaction

- *Well established theory*
  employing the DWIA framework

- *Peripherality*
  only the surface region contributes

- *Clean*



DWIA framework for α-knockout reaction

- The *transition amplitude* of α-knockout reaction

$$T_{\boldsymbol{K}_0\boldsymbol{K}_1\boldsymbol{K}_2} = \langle \chi^{(-)}_{1,\boldsymbol{K}_1}(\boldsymbol{R}_1)\chi^{(-)}_{2,\boldsymbol{K}_2}(\boldsymbol{R}_2)\left|t_{p\alpha}(\boldsymbol{s})\right|\chi^{(+)}_{0,\boldsymbol{K}_0}(\boldsymbol{R}_0)\phi_\alpha(\boldsymbol{R}_2)\rangle$$

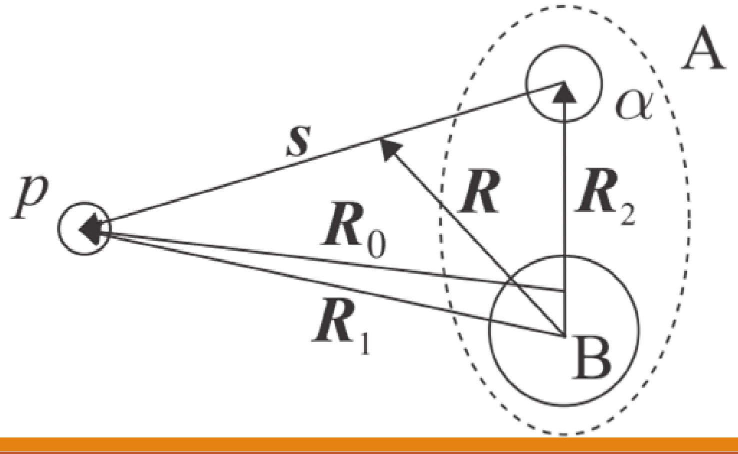
- With the *asymptotic momentum approximation* [1]

$$\bar{T}_{\boldsymbol{K}_0\boldsymbol{K}_1\boldsymbol{K}_2} = \int d\boldsymbol{R} F_{\boldsymbol{K}_0\boldsymbol{K}_1\boldsymbol{K}_2}(\boldsymbol{R})\phi_\alpha(\boldsymbol{R})$$

- where

$$F_{\boldsymbol{K}_0\boldsymbol{K}_1\boldsymbol{K}_2}(\boldsymbol{R}) = \chi^{*(-)}_{1,\boldsymbol{K}_1}(\boldsymbol{R}_1)\chi^{*(-)}_{2,\boldsymbol{K}_2}(\boldsymbol{R}_2)\chi^{(+)}_{0,\boldsymbol{K}_0}(\boldsymbol{R}_0)e^{-i\boldsymbol{K}_0\cdot\boldsymbol{R}\,A_{\boldsymbol{\alpha}}/A}$$

- $\chi^{(-)}_{1,\boldsymbol{K}_1}, \chi^{(-)}_{2,\boldsymbol{K}_2}$ distorted w. f. in initial channel
- $\chi^{(+)}_{0,\boldsymbol{K}_0}$ distorted w. f. in final channel



[1]K. Yoshida, K. Minomo, and K. Ogata, Phys. Rev. C **94**, 044604 (2016).

Triple differential cross section for α-knockout reaction

- The triple *differential cross section* (*TDX*)

$$\frac{d^3\sigma}{dE_1 d\Omega_1 d\Omega_2} = F_{kin} C_0 \frac{d\sigma_{p\alpha}}{d\Omega_{p\alpha}}(\theta_{p\alpha}, E_{p\alpha}) \left|\bar{T}_{\boldsymbol{K}_0 \boldsymbol{K}_1 \boldsymbol{K}_2}\right|^2$$

- F_{kin}: kinematical factor

$$F_{kin} = J_L \frac{K_1 K_2 E_1 E_2}{\hbar^4 c^4}\left[1 + \frac{E_2}{E_B} + \frac{E_2}{E_B}\frac{(\boldsymbol{K}_1 \cdot \boldsymbol{K}_2)}{K_2^2}\right]$$

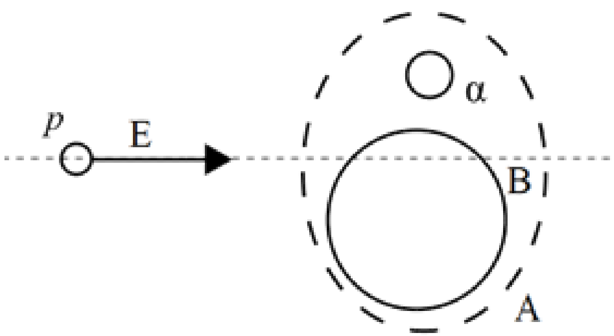
- $C_0 = \frac{E_0}{(\hbar c)^2 K_0} \frac{\hbar^4}{(2\pi)^3 \mu_{p\alpha}^2}$

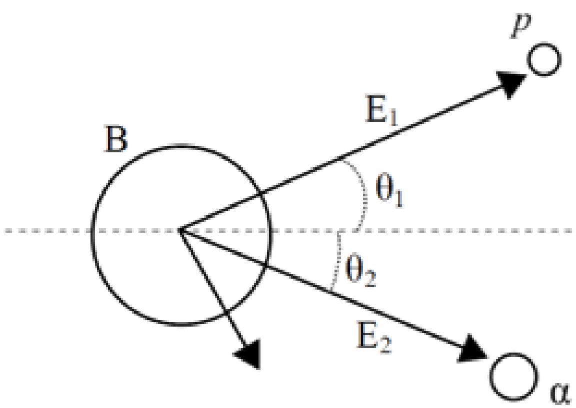
- J_L: Jacobian

- Scattering energy

$$E_{p\alpha} = \frac{\hbar^2 \boldsymbol{\kappa}'^2}{2\mu_{p\alpha}}$$

- $\boldsymbol{\kappa}'$: asympototic $p\alpha$ relative momentum





[1]K. Yoshida, K. Minomo, and K. Ogata, Phys. Rev. C **94**, 044604 (2016).

THSR description of Be and He

- *THSR wave function* for nuclei composed of α-clusters and valence neutrons [1,2]

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

- *α-clusters*

$$C_\alpha^\dagger = \int d^3\boldsymbol{R} \exp\left(-\frac{R_x^2 + R_y^2}{\beta_{\alpha,xy}^2} - \frac{R_z^2}{\beta_{\alpha,z}^2}\right) \int d^3\boldsymbol{r}_1 \cdots d^3\boldsymbol{r}_4$$

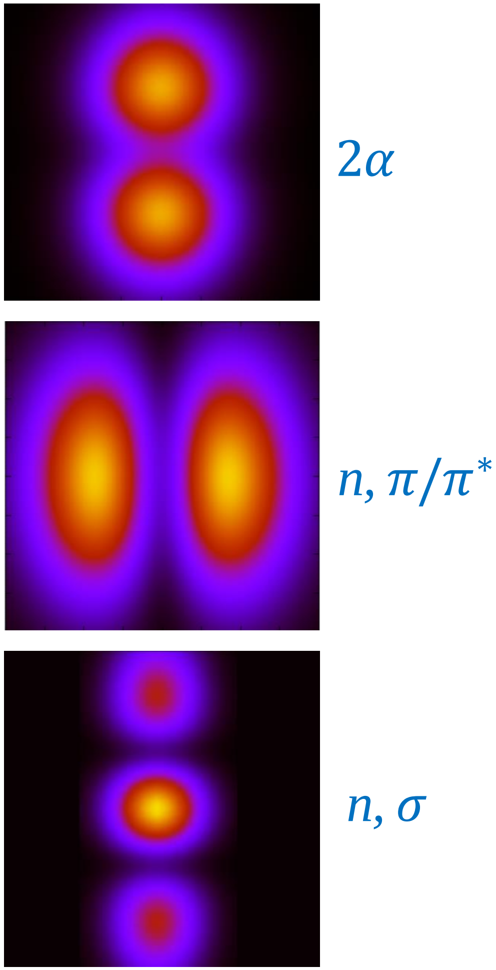
$$\times \psi(\boldsymbol{r}_1 - \boldsymbol{R}) a_{\sigma 1,\tau 1}^\dagger(\boldsymbol{r}_1) \cdots \psi(\boldsymbol{r}_4 - \boldsymbol{R}) a_{\sigma 4,\tau 4}^\dagger(\boldsymbol{r}_4)$$

- *valance neutrons*

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

$$\times \psi(\boldsymbol{r}_n - \boldsymbol{R}) a_{\sigma n,\tau=\downarrow}^\dagger(\boldsymbol{r}_n)$$

- $f(\boldsymbol{R}_n)$: factors to adjust neutron w. f. $\phi_n = c_n^\dagger|0\rangle$ into *p-orbits* or molecular *π-orbit* and *σ-orbits* [1,2]



[1] M. Lyu *et al*., *Phys. Rev. C* **91**, 14313 (2015) & *Phys. Rev. C* **93**, 54308 (2016)..
[2] M. Lyu *et al*,, arXiv:1706.06538 [nucl-th] (2017).

Approximation for reduced width amplitude

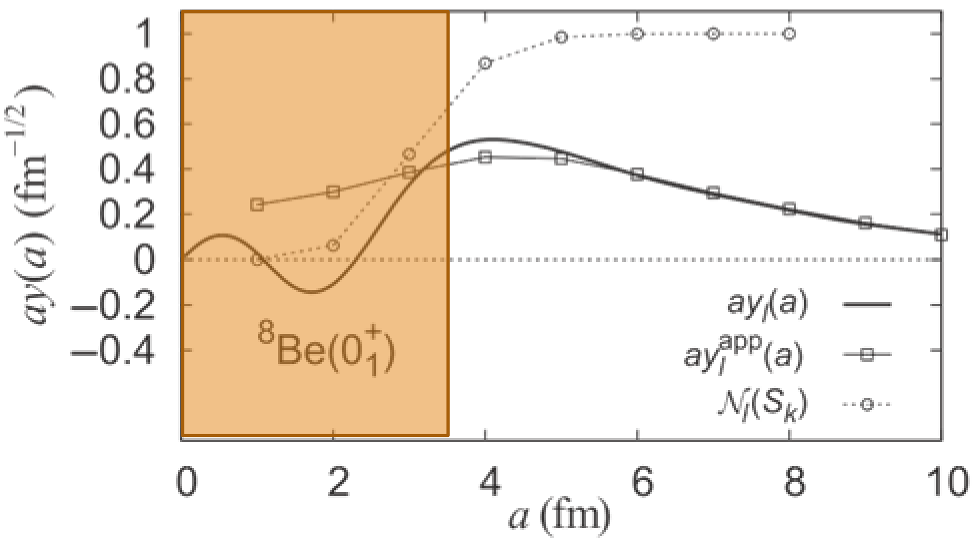
- The *reduced width amplitude* (*RWA*) of α-cluster

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

- is approximated by [1]

$$|ay(a)| \approx ay^{\mathrm{app}}(a) = \frac{1}{\sqrt{2}}\left(\frac{n_B n_\alpha}{n_A \pi b^2}\right)^{\frac{1}{4}} \left\langle \Phi_A \middle| \Phi_{\mathrm{BB}}^{(0+)}\left(\Phi_B^{(0+)}, \alpha; S=a\right) \right\rangle$$

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



α-cluster RWA of ^{10}Be

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

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

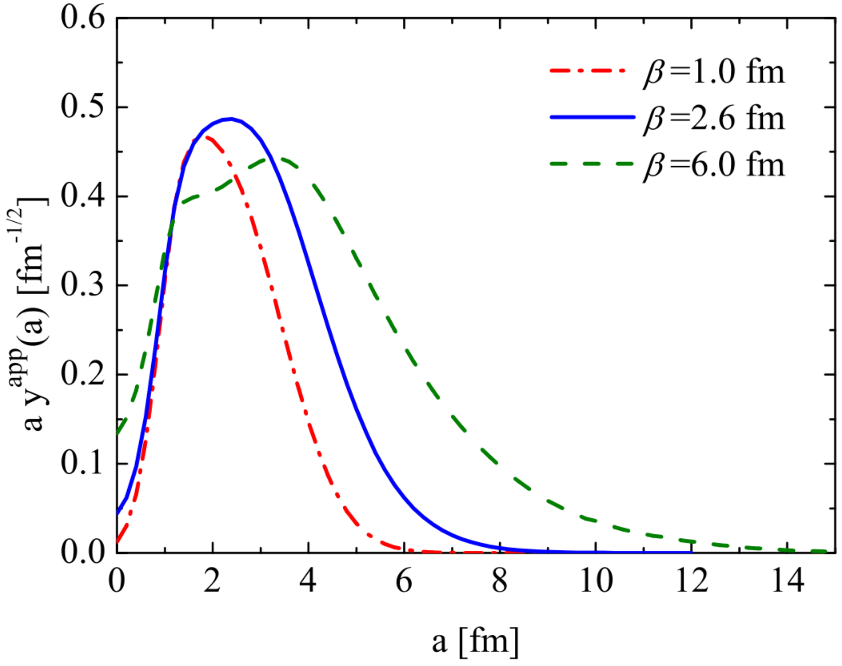
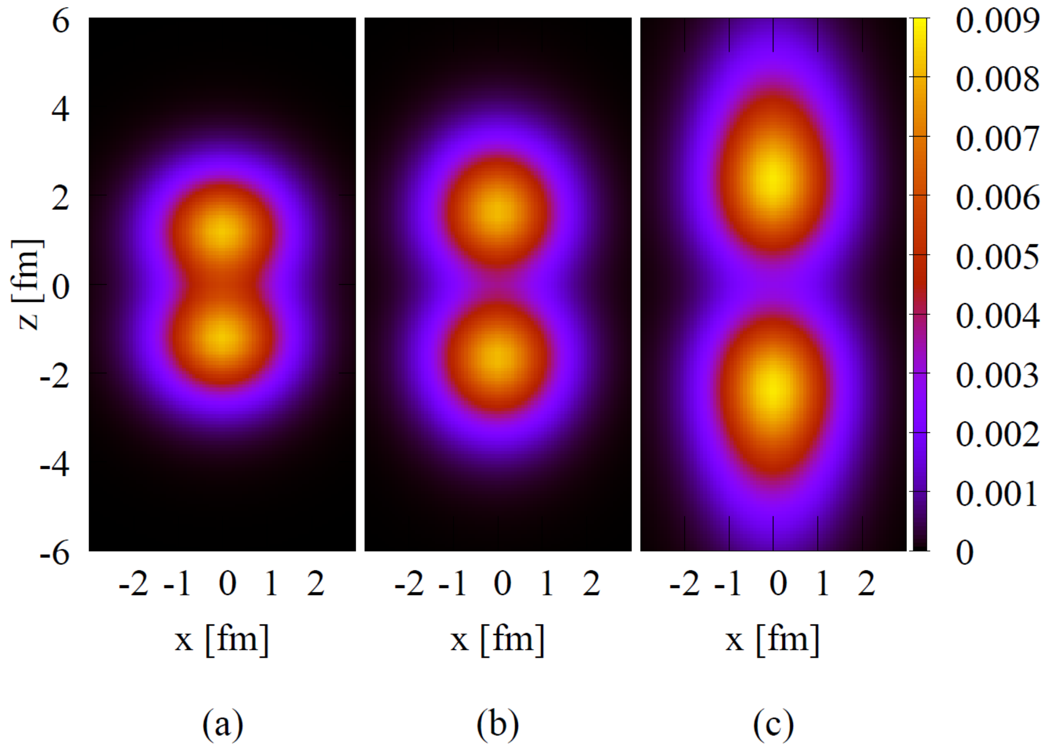


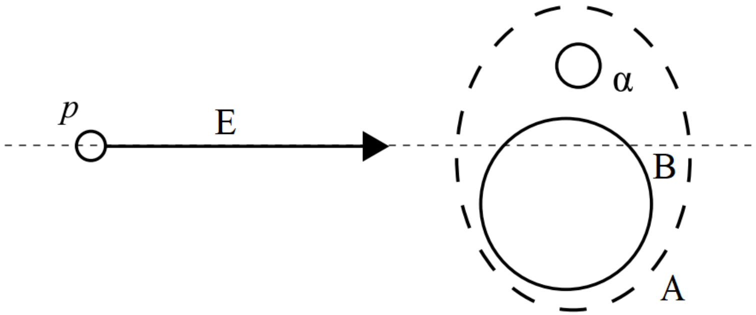
Figure: Reduced width amplitude of ^{10}Be

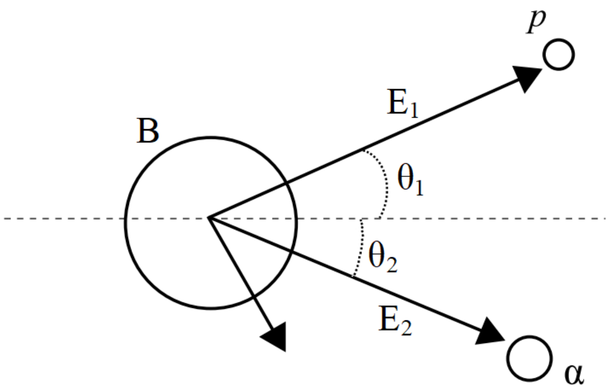
Density distribution of ^{10}Be



- (a): β_α =1.0 fm (*shell-model limit*)
- (b): β_α =2.6 fm (*physical, molecular-like*)
- (c): β_α =6.0 fm (*gas like*)

Kinematics for α-knockout reaction of ^{10,12}Be





- *Incident proton*
  - $E = 250$ MeV
- *Outgoing proton*
  - $E_1 = 180$ MeV
  - $(\theta_1, \phi_1) = (60.9°, 0°)$
- *Outgoing α*
  - θ_2: variated around 51°
  - ϕ_2: 180°

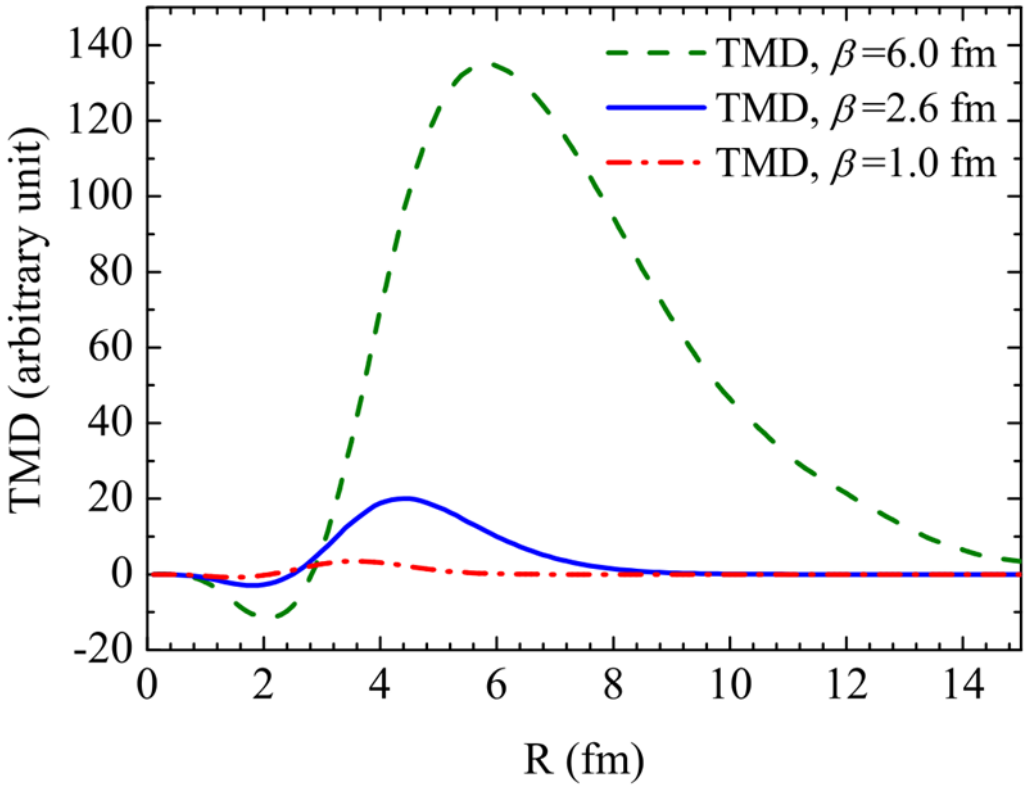
Transition matrix density (TMD)

- *TMD*: Transition strength as a function of R

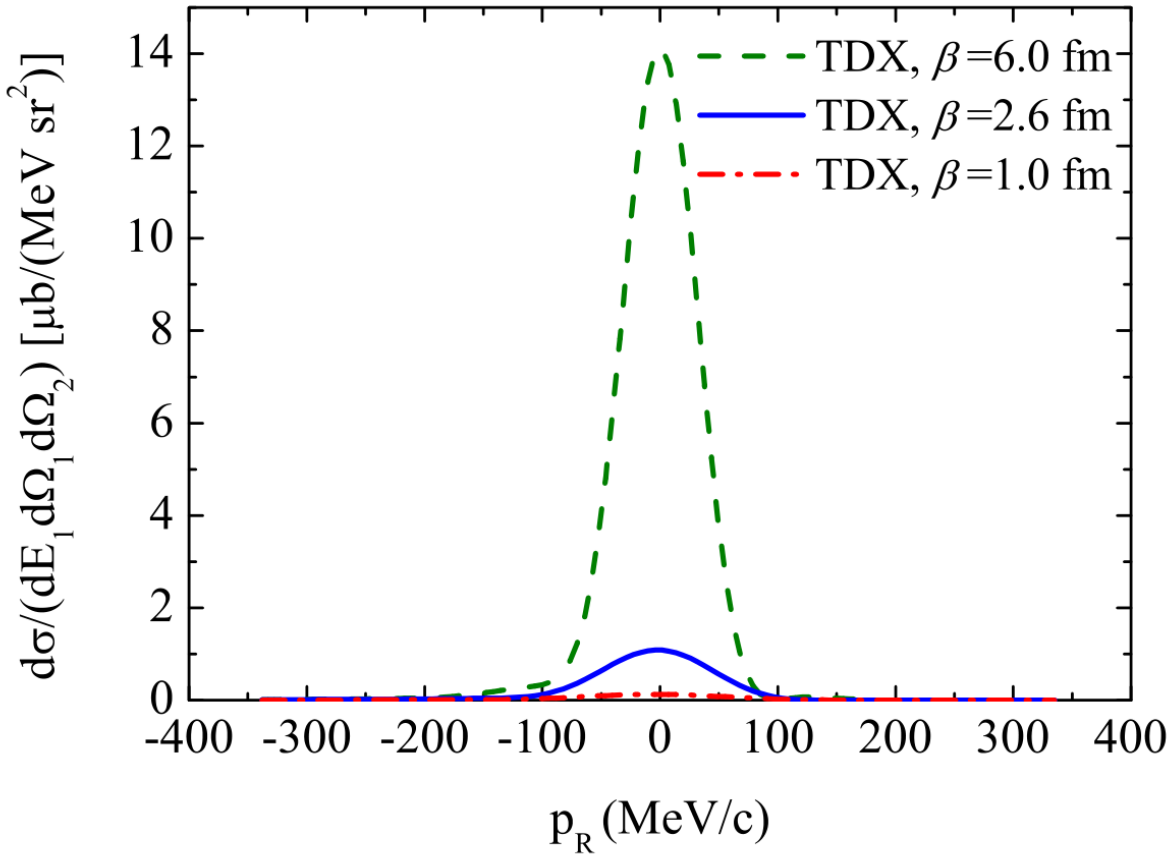
- TMD is defined as $\delta(R)$ where

$$\int dR\delta(R) \propto \frac{d^3\sigma}{dE_1 d\Omega_1 d\Omega_2}$$

- mostly contributed by the surface region



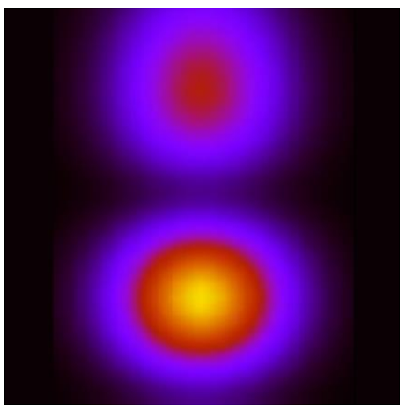
TDX for the $^{10}Be(p,p\alpha)^{6}He$ reaction



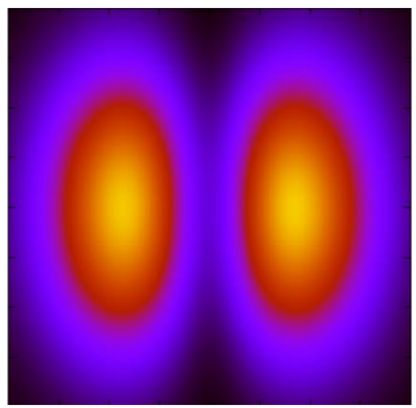
$$\frac{d^3\sigma}{dE_1 d\Omega_1 d\Omega_2} = F_{kin} C_0 \frac{d\sigma_{p\alpha}}{d\Omega_{p\alpha}}(\theta_{p\alpha}, E_{p\alpha}) \left| \bar{T}_{\boldsymbol{K}_0 \boldsymbol{K}_1 \boldsymbol{K}_2} \right|^2$$

Coupling of clustering configurations in ^{12}Be

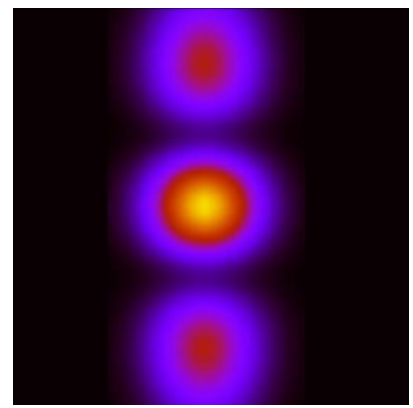
- Coupling of $^{4}He+^{8}He$, $^{10}Be+2n(\pi^{*})$ and $^{10}Be+2n(\sigma)$ configurations
- Breaking of neutron magic number $N=8$
- *Probing* of α-cluster and clustering configurations in ^{12}Be



^{4}He+^{8}He
($1p_{3/2}$)
(schematic)



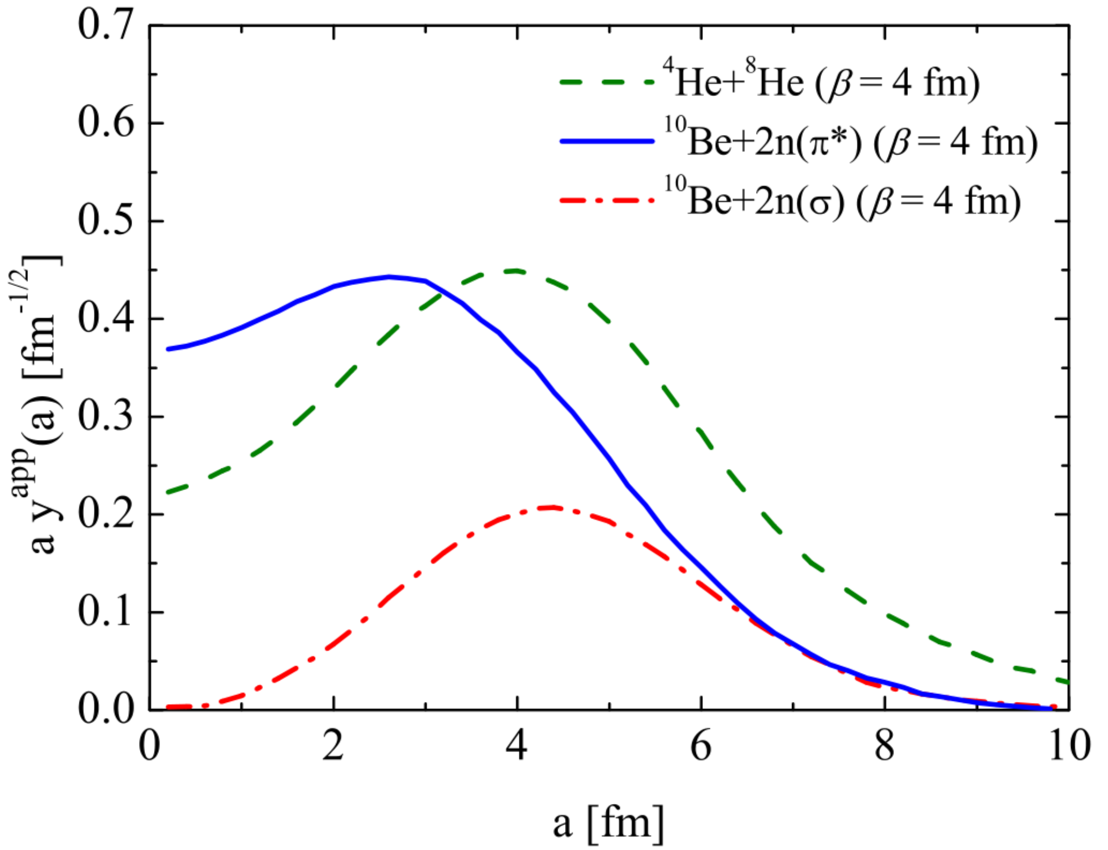
^{10}Be+2n
(π^{*})



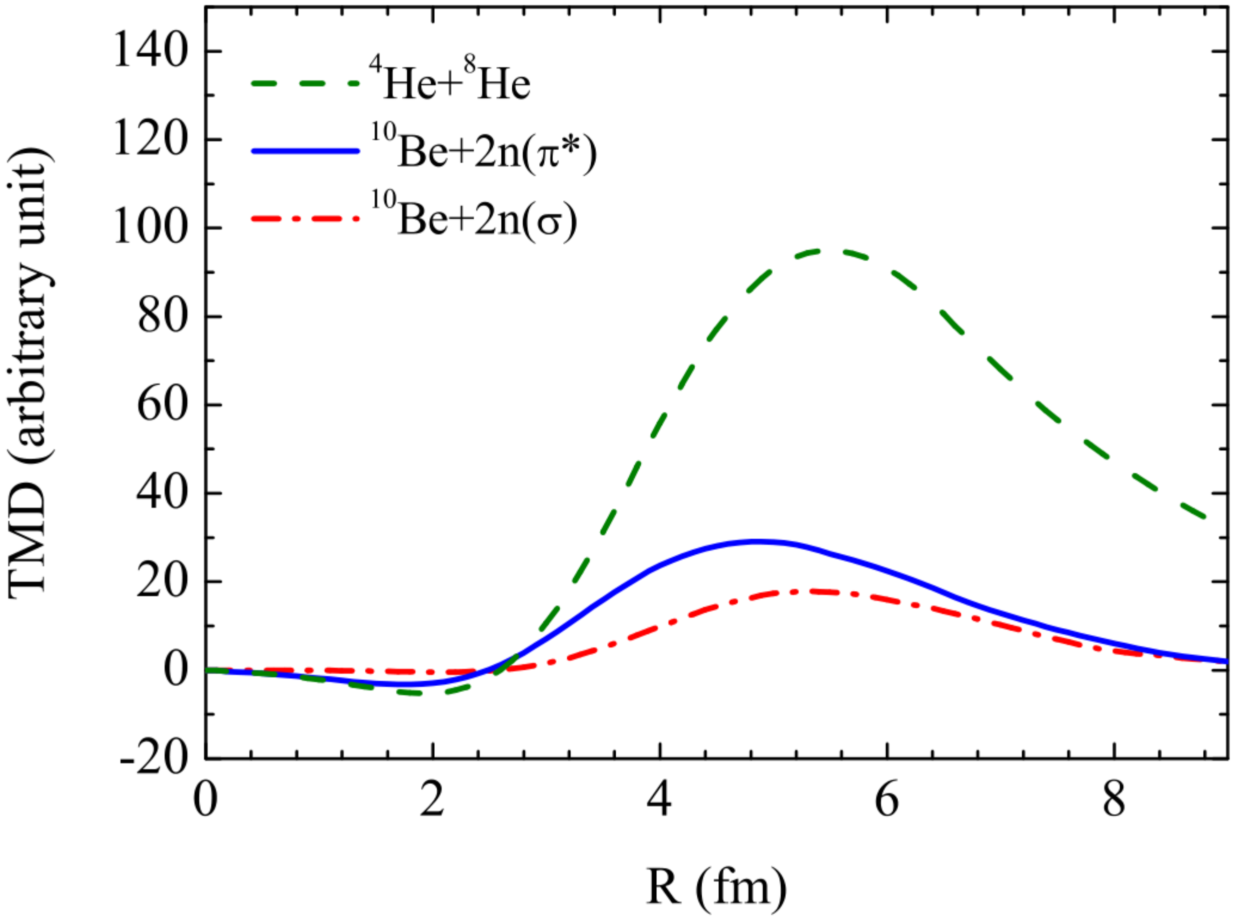
^{10}Be+2n
(σ)

α-cluster RWA of ^{12}Be in three configurations

- *$^{4}He+^{8}He$ configuration*
  - β_{α}=4.0 fm (optimized)
- *$^{10}Be+2n(\pi^*)$ configuration*
  - β_{α}=4.0 fm (optimized)
- *$^{10}Be+2n(\sigma)$ configuration*
  - β_{α}=4.0 fm (adjusted, preliminary)

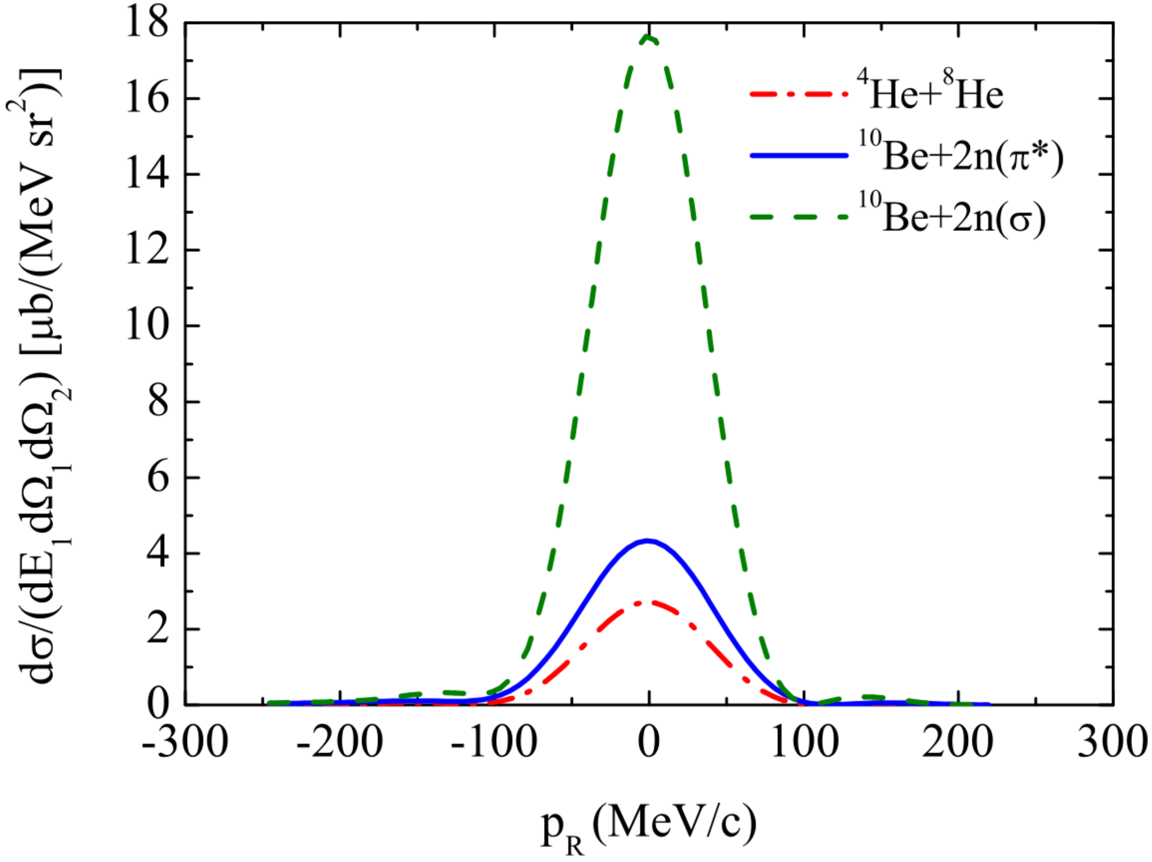


Transition matrix density (TMD)



$$\int dR\delta(R) \propto \frac{d^3\sigma}{dE_1 d\Omega_1 d\Omega_2}$$

TDX for the $^{12}Be(p,p\alpha)^{8}He$ reaction



$$\frac{d^3\sigma}{dE_1 d\Omega_1 d\Omega_2} = F_{kin} C_0 \frac{d\sigma_{p\alpha}}{d\Omega_{p\alpha}} (\theta_{p\alpha}, E_{p\alpha}) \left|\bar{T}_{\boldsymbol{K}_0 \boldsymbol{K}_1 \boldsymbol{K}_2}\right|^2$$

Summary

- Proposed fully microscopic framework for α-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}He+^{8}He, ^{10}Be+2n(π^*) and ^{10}Be+2n(σ) 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!