Investigation on alpha cluster states via knockout reaction

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   - DWIA framework and the comparison with other reaction theories

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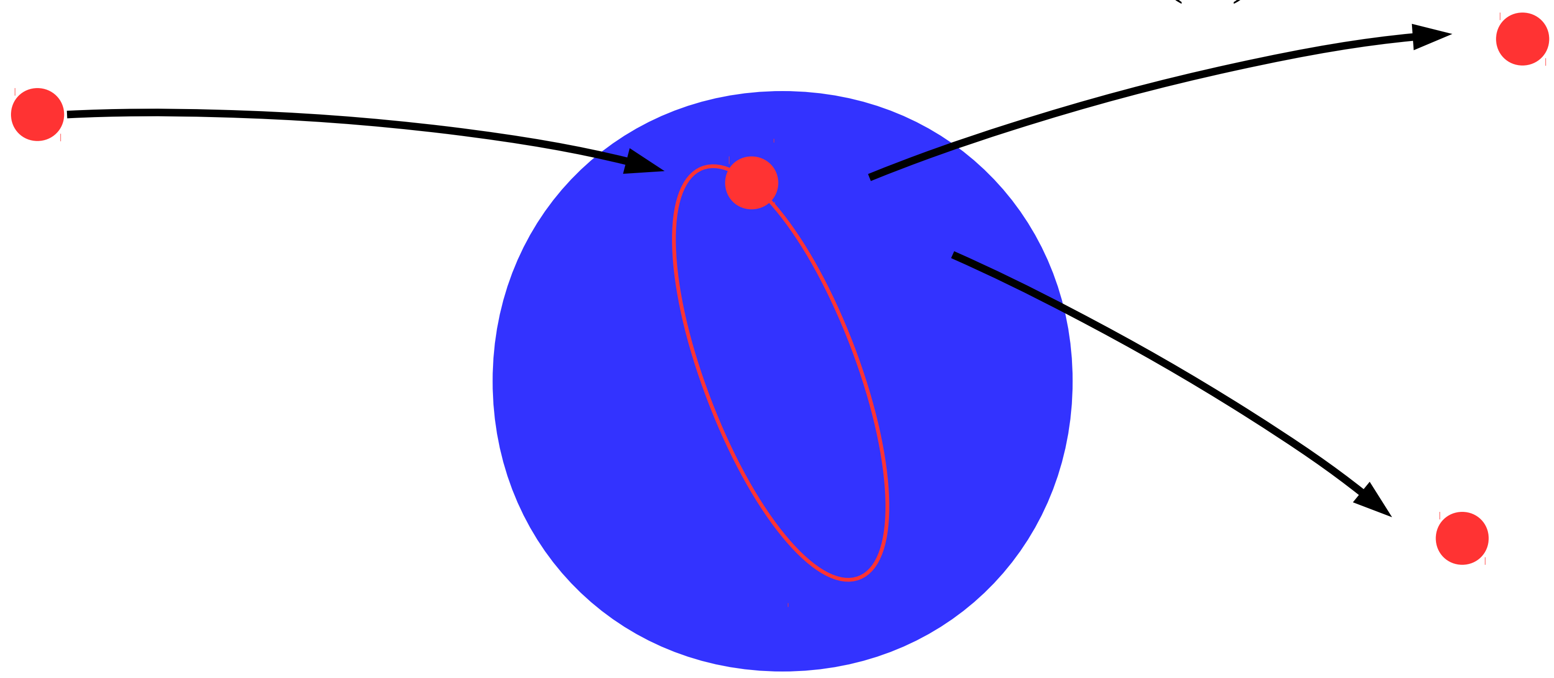
   - ^{10}Be(p,$p\alpha$)^{6}He reaction with a cluster model

3. Summary and perspectives

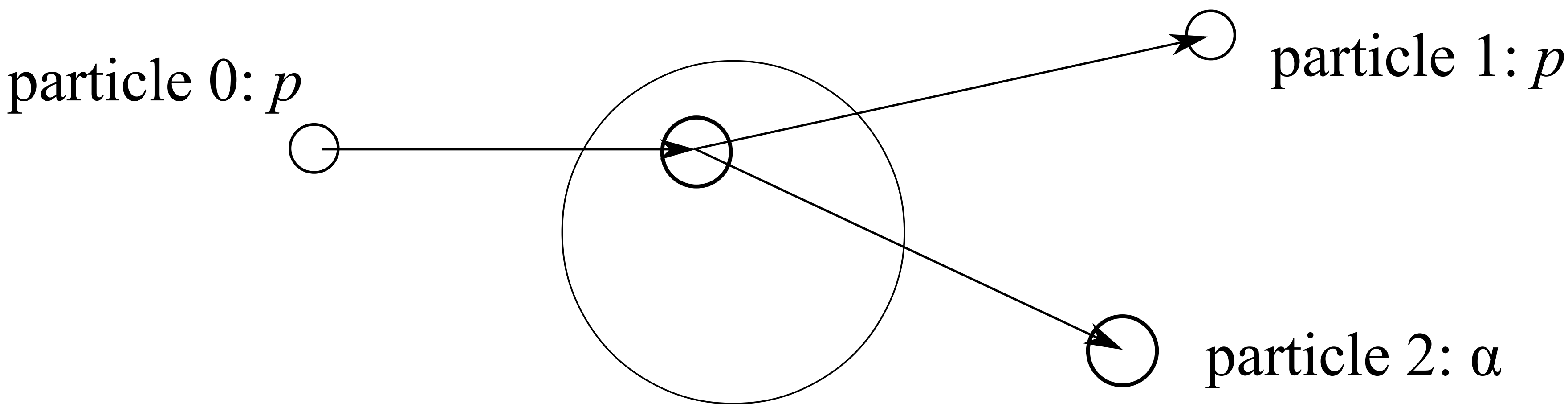
knockout reaction (1)



(p,pN), (p,$p\alpha$)

- Typical incident energy of proton: 100-400 MeV ($\lambda \sim$ 0.5-0.25 fm)
- single-step direct reaction
  - Good probe for single-particle / α-cluster spectroscopy
  - e.g. single-particle orbit, spectroscopic factor, energy levels etc.

knockout reaction (2)



Triple differential cross section (TDX): the most exclusive cross section

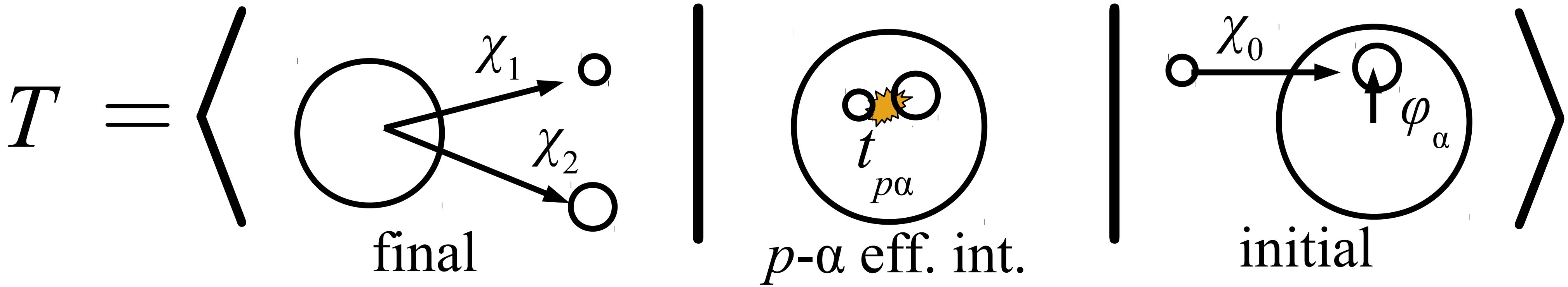
$$\frac{d^3\sigma}{dE_1 d\Omega_1 d\Omega_2} \propto |T|^2$$

Energy and solid angle of particle 1

Solid angle of particle 2

T-matrix
(Transition amplitude)

Distorted Wave Impulse Approximation (1)



$$= \int d\boldsymbol{R}\, \chi^*_{1,\boldsymbol{K}_1}(\boldsymbol{R})\, \chi^*_{2,\boldsymbol{K}_2}(\boldsymbol{R})\, \langle \underline{\boldsymbol{\kappa}'(\boldsymbol{R})} \,|\, t_{p\alpha} \,|\, \underline{\boldsymbol{\kappa}(\boldsymbol{R})} \rangle\, \chi_{0,\boldsymbol{K}_0}(\boldsymbol{R})\, \varphi_\alpha(\boldsymbol{R})$$

p-α local momenta

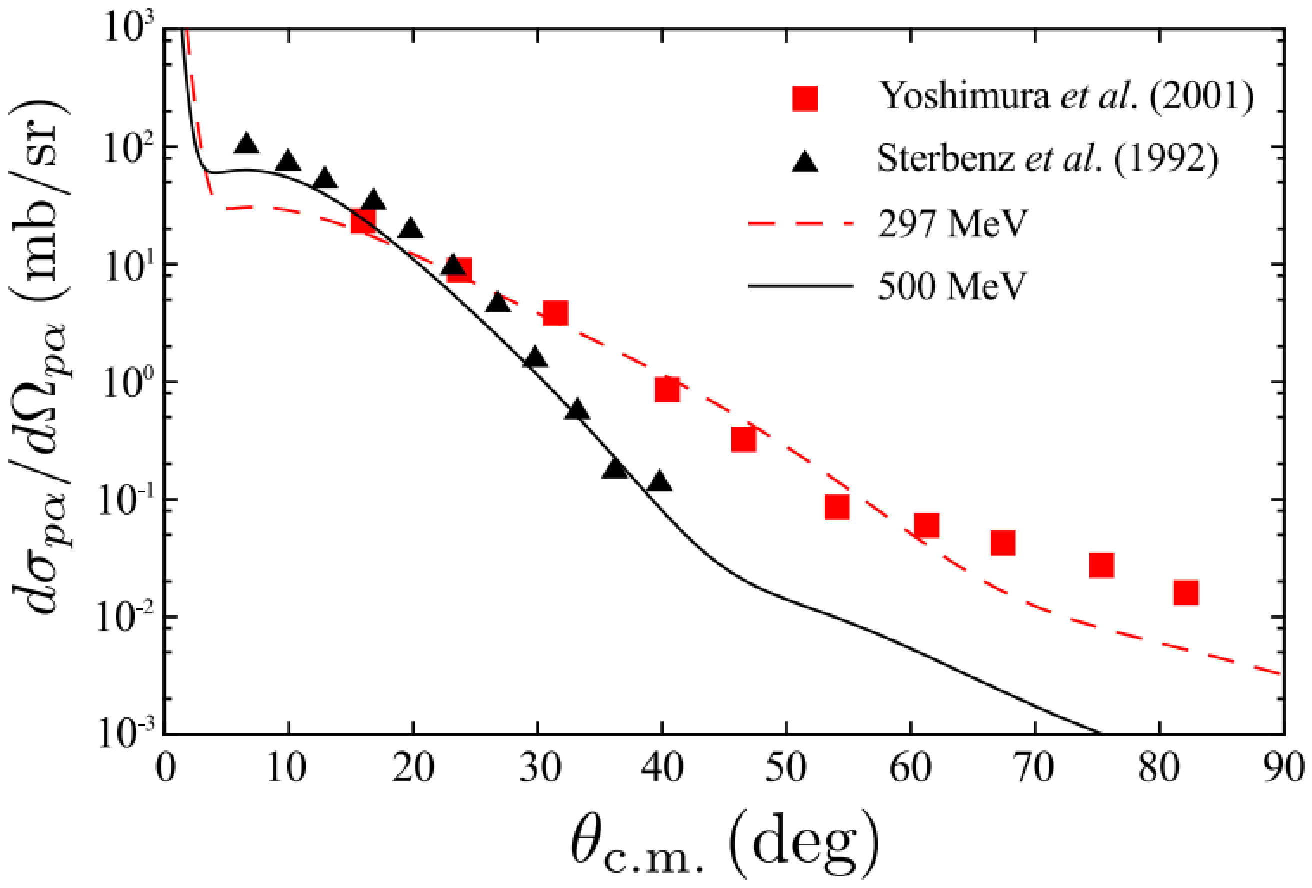
Factorization approx.

$$\longrightarrow \langle \underline{\boldsymbol{\kappa}'} \,|\, t_{p\alpha} \,|\, \underline{\boldsymbol{\kappa}} \rangle \int d\boldsymbol{R}\, \chi^*_{1,\boldsymbol{K}_1}(\boldsymbol{R})\, \chi^*_{2,\boldsymbol{K}_2}(\boldsymbol{R})\, \chi_{0,\boldsymbol{K}_0}(\boldsymbol{R})\, \varphi_\alpha(\boldsymbol{R})$$

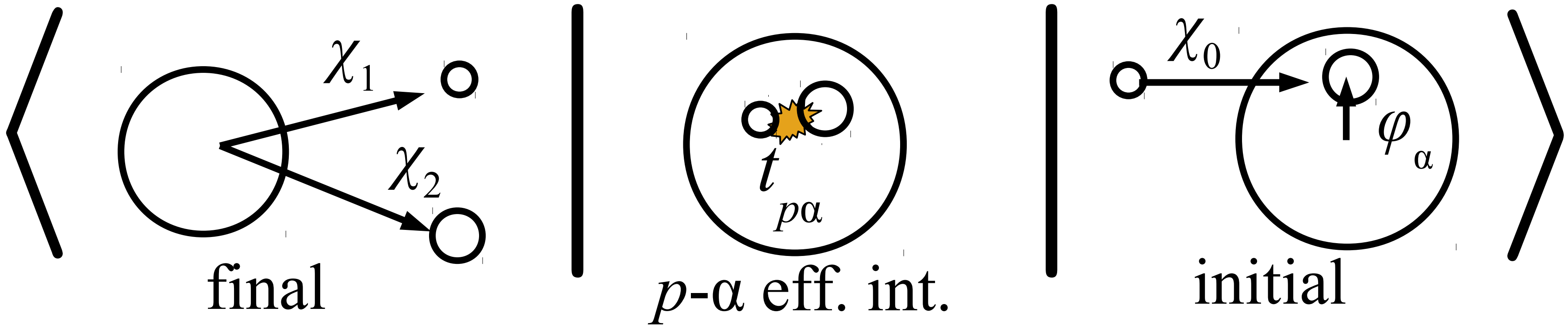
p-α asymptotic momenta

p-α differential cross section

Melbourne g-matrix + folding



Distorted Wave Impulse Approximation (1)

$T =$ 

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p-α local momenta

Factorization approx.

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p-α asymptotic momenta

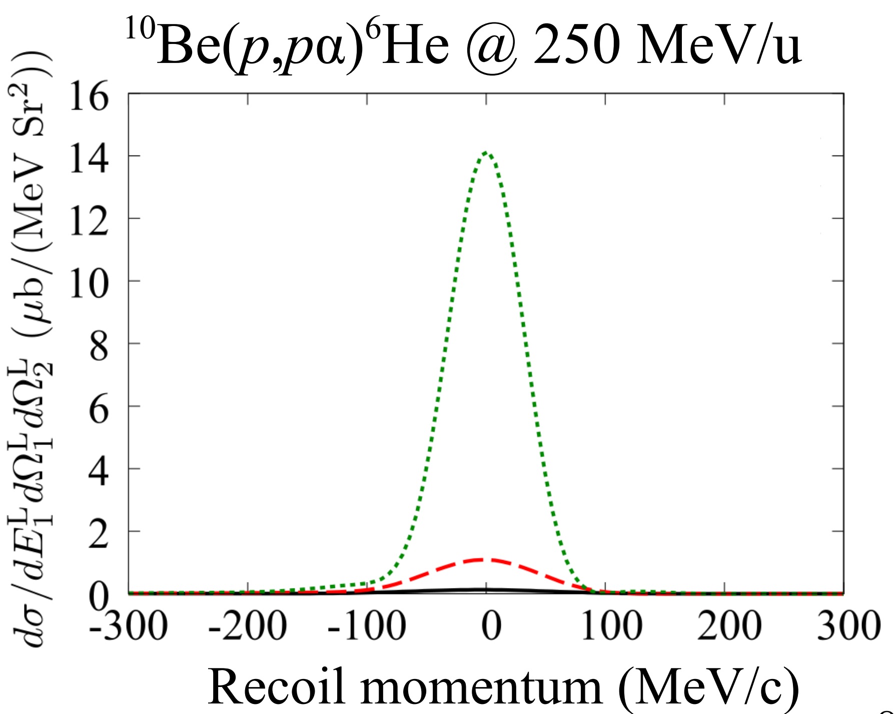
Distorted Wave Impulse Approximation (2)

$$T \approx \langle \boldsymbol{\kappa}' \,|\, t_{p\alpha} \,|\, \boldsymbol{\kappa} \rangle \int d\boldsymbol{R}\, \chi^{*}_{1,\boldsymbol{K}_1}(\boldsymbol{R})\, \chi^{*}_{2,\boldsymbol{K}_2}(\boldsymbol{R})\, \chi_{0,\boldsymbol{K}_0}(\boldsymbol{R})\, \varphi_\alpha(\boldsymbol{R})$$

$$\xrightarrow{\text{plane wave}} \langle \boldsymbol{\kappa}' \,|\, t_{p\alpha} \,|\, \boldsymbol{\kappa} \rangle \int \underline{d\boldsymbol{R}\, e^{i\boldsymbol{q}\cdot\boldsymbol{R}} \varphi_\alpha(\boldsymbol{R})} \qquad (\boldsymbol{q} \equiv \boldsymbol{K}_0 - \boldsymbol{K}_1 - \boldsymbol{K}_2)$$

The Fourier transform of the cluster wave function is essentially observed

- $\boldsymbol{q}$: recoil momentum of the residue B
- Typical *s*-wave shape of the TDX
- $\boldsymbol{q} = 0$: Recoilless condition

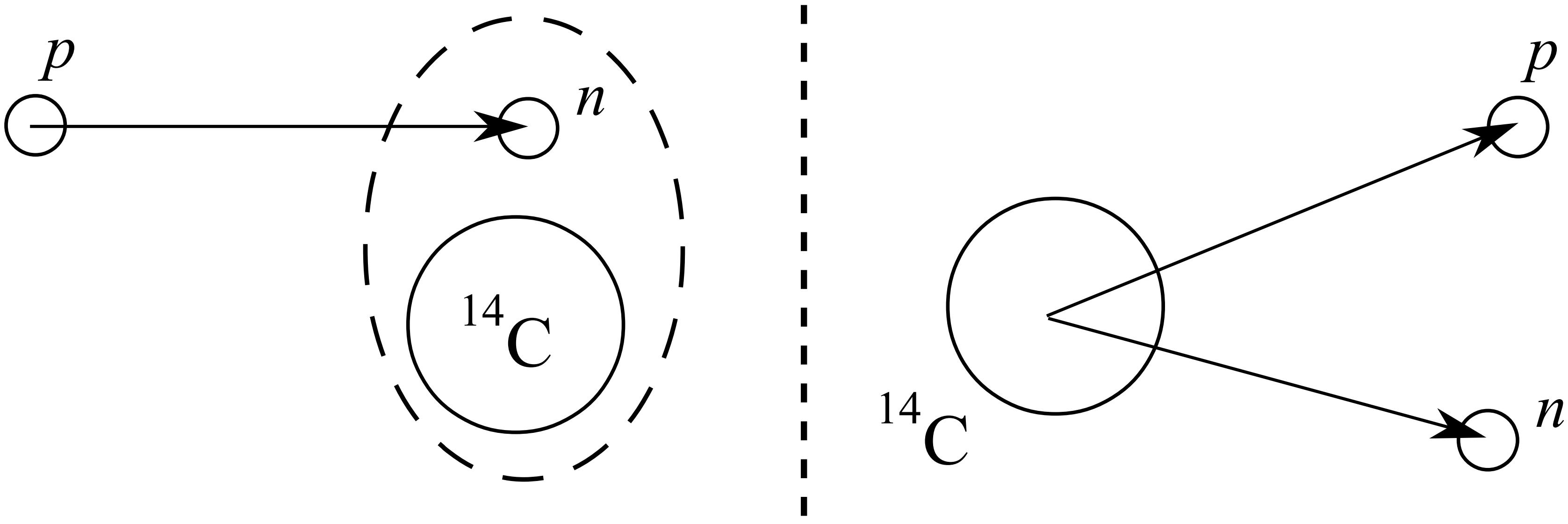


Comparison between reaction theories

K. Yoshida, M. Gómez-Ramos, K. Ogata, and A. M. Moro. Phys. Rev. C **97**, 024608 (2017)

- DWIA: Common reaction model for knockout reaction analyses
- Transfer-to-the-continuum (TC): Derivation of CDCC to knockout reaction

Momentum distribution of $^{15}C(p,pn)^{14}C$ @420MeV
studied with Faddeev/AGS (FAGS) frame work [1]



[1] E. Cravo, R. Crespo, and A. Deltuva, Phys. Rev. C **93** , 054612 (2016).

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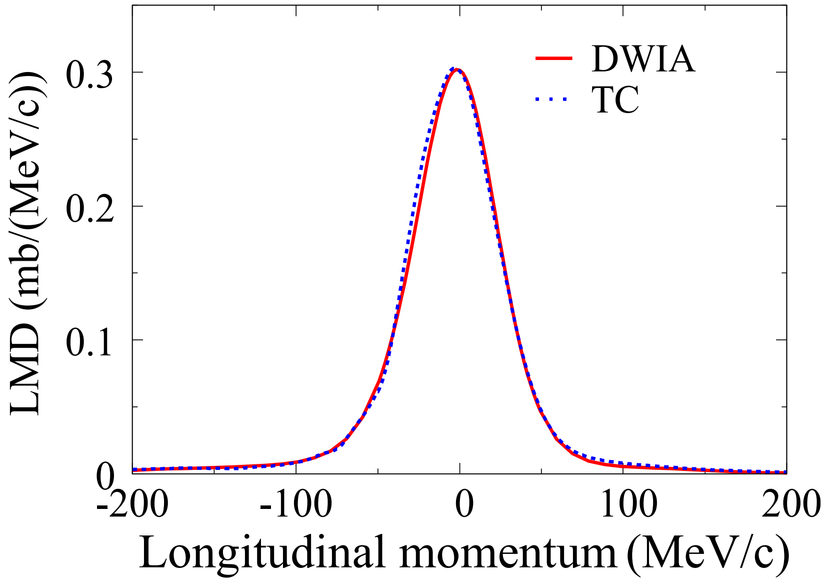
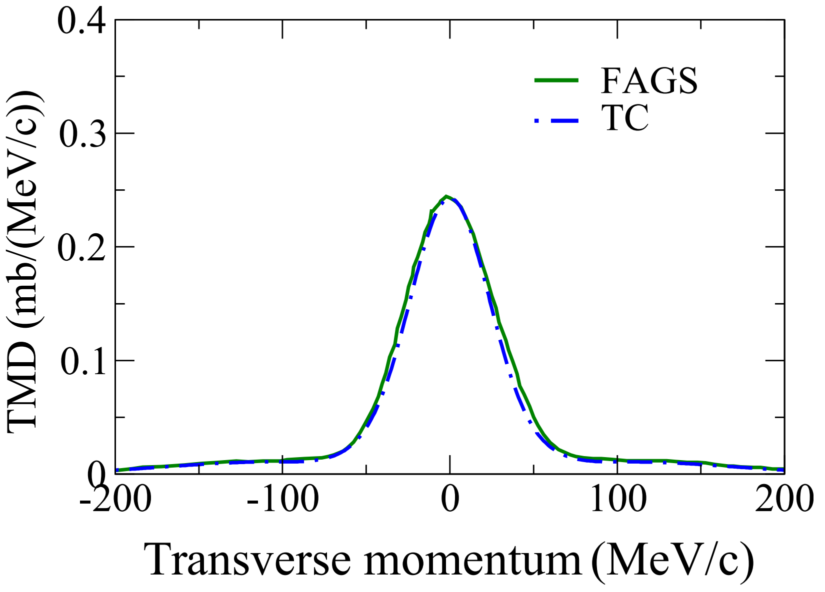
DWIA v.s. TC



TC v.s. FAGS



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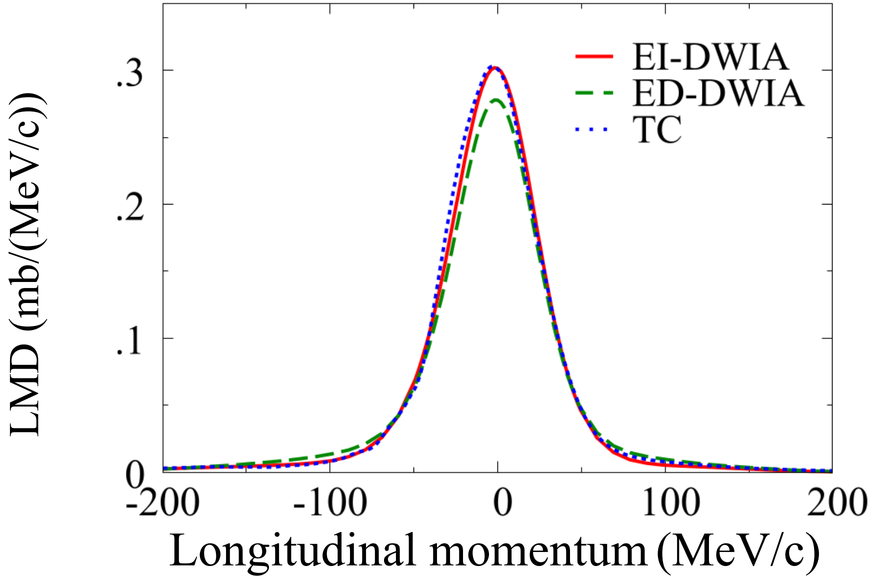
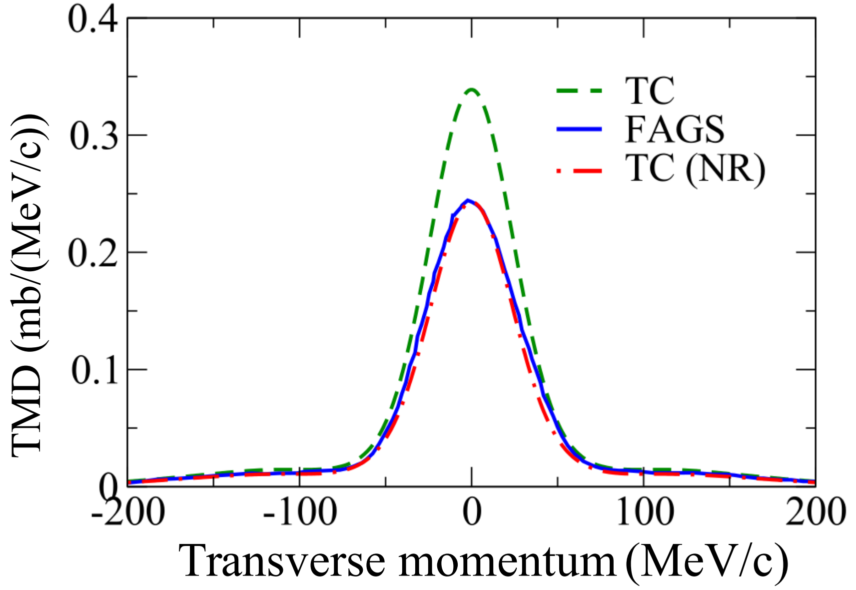
Energy dep. of opt. potential



Relativistic treatment of NN collision



[1] E. Cravo, R. Crespo, and A. Deltuva, Phys. Rev. C **93** , 054612 (2016).

Uncertainties

1. DWIA, TC and Fadeev/AGS calculations of the momentum distribution of $^{15}C(p,pn)^{14}C$ reaction @420MeV agree almost perfectly once the same input are adopted

2. The uncertainty coming from the energy dependence of the optical potential have been investigated within the DWIA framework
   - A miner effect (~8% difference)

3. Relativistic treatment on the NN collision is essential (~30% difference)

4. Knockout from deeply bound orbit with finite angular momentum?

5. Lower incident energy?

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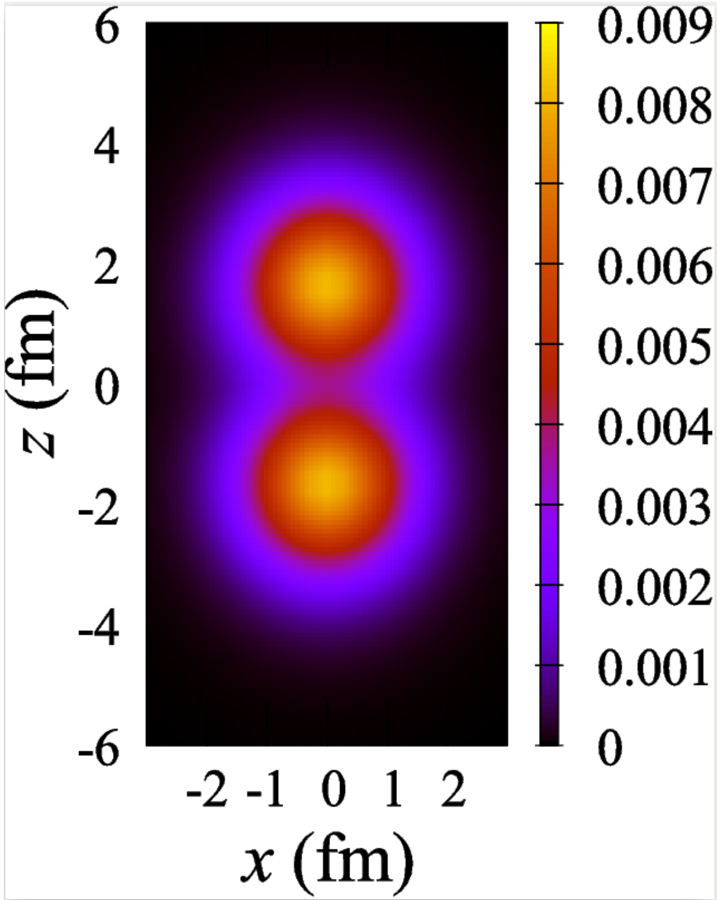
α-cluster states

Charge distribution of ^{10}Be



- α cluster as a subunit of the many nucleon system

  Nucleon degrees of freedom (shell picture)

  ↕

  cluster degrees of freedom (molecular-like picture)

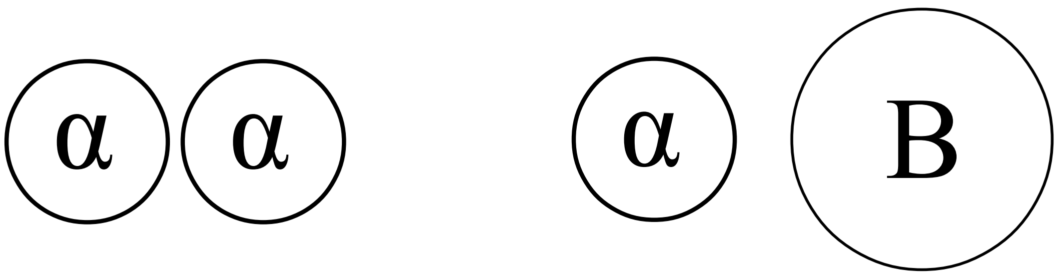
- α-cluster states are established in...
  - Near α + α (α + B) threshold
  - Light nuclei
- α-clustering in
  - heavy nuclei?
  - unstable nuclei?
- Below the α threshold?

(p,$p\alpha$) as a probe for α-cluster states

How (what kind of) α-cluster states can be probed with (p,$p\alpha$) ?

- (p,$p\alpha$) reaction is peripheral
- α-particle on the nuclear surface is selectively probed
- The peripherality of the reaction is described by the "masking function"

- "Typical" α cluster states are selectively reflected to the observables
  - α particle around the nuclear surface
  - Free from the Pauli principle, anti-symmetrization and the melting effect of α



Masking function

K. Yoshida, K. Ogata, and Y. Kanada-En'yo. Submitted to Phys. Rev. C (arXiv:1712.09079).

Masking function defines the probed region through knockout reactions

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Masking function defines the probed region through knockout reactions

$$T = \langle \boldsymbol{\kappa}' \,|\, t_{p\alpha} \,|\, \boldsymbol{\kappa} \rangle \int d\boldsymbol{R}\, \chi^{*}_{1,\boldsymbol{K}_1}(\boldsymbol{R}) \chi^{*}_{2,\boldsymbol{K}_2}(\boldsymbol{R}) \chi_{0,\boldsymbol{K}_0}(\boldsymbol{R}) \varphi_{\alpha}(\boldsymbol{R})$$

$$\propto \sqrt{4\pi} \int dR\, R^2\, \underline{\phi_{\alpha}(R)} \times \frac{1}{\sqrt{4\pi}} \int d\Omega\, \underline{\chi^{*}_{1,\boldsymbol{K}_1}(\boldsymbol{R}) \chi^{*}_{2,\boldsymbol{K}_2}(\boldsymbol{R}) \chi_{0,\boldsymbol{K}_0}(\boldsymbol{R})}\, \underline{Y_{00}(\Omega)}$$

Cluster W.F. (structure)

Distorted waves (reaction)

Masking function

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$$\propto \sqrt{4\pi} \int dR\, R^2\, \phi_\alpha(R) \times \boxed{\frac{1}{\sqrt{4\pi}} \int d\Omega\, \chi^*_{1,\boldsymbol{K}_1}(\boldsymbol{R}) \chi^*_{2,\boldsymbol{K}_2}(\boldsymbol{R}) \chi_{0,\boldsymbol{K}_0}(\boldsymbol{R}) Y_{00}(\Omega)}$$

$$\equiv \sqrt{4\pi} \int dR\, R^2\, \phi_\alpha(R) \times \boxed{D(R)}$$

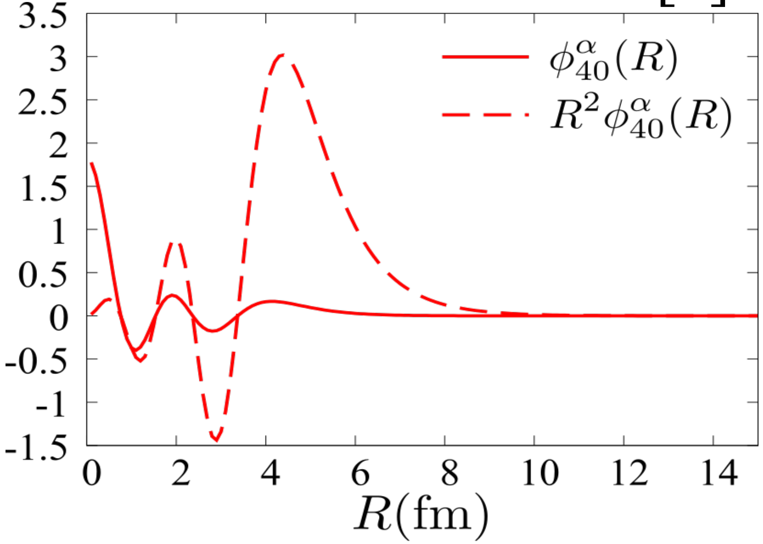
Maksing function:
Relation between the structure and the reaction observable

- Normalization of the Masking function

$$D(R) \xrightarrow[\text{P.W. limit}]{} \frac{1}{4\pi} \int d\Omega\, e^{i\boldsymbol{q}\cdot\boldsymbol{R}} \xrightarrow[\boldsymbol{q}=0]{} 1$$

^{20}Ne(p,$p\alpha$)^{16}O @392 MeV

Cluster wave function [1]



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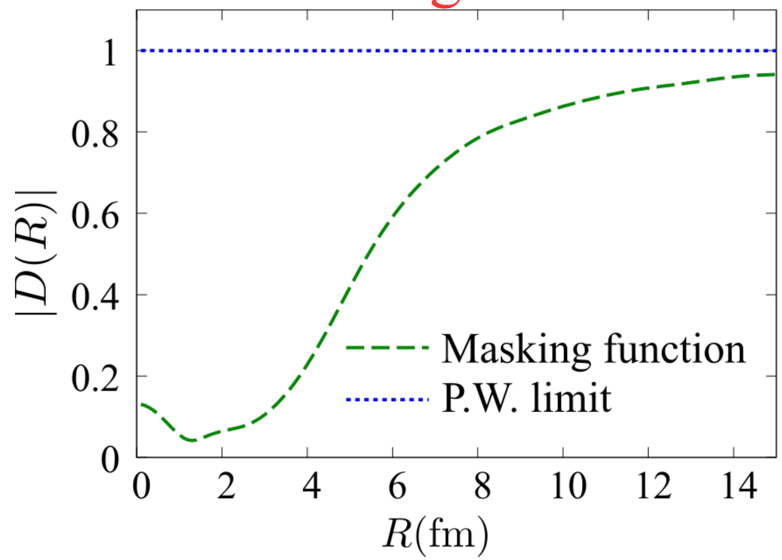
Masking function



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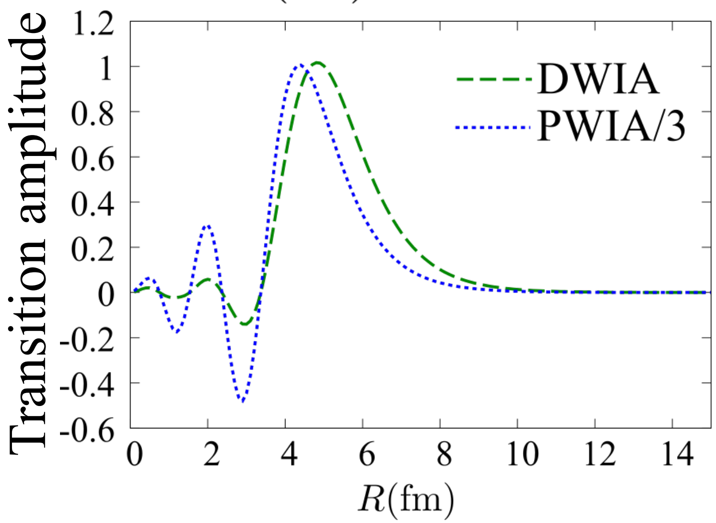


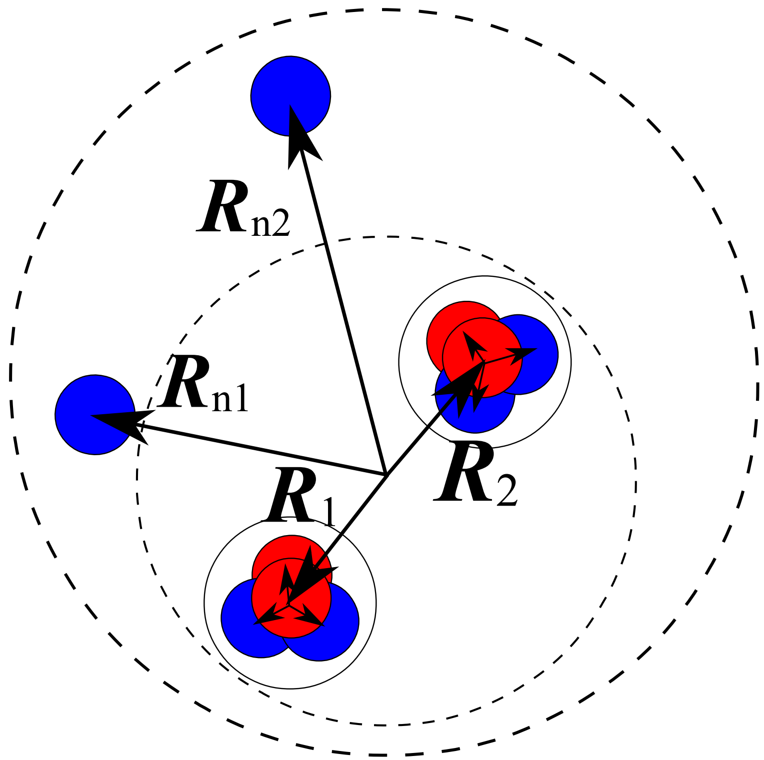
- Selectivity on the surface region →α-cluster around the surface is probed through (p,$p\alpha$) reaction

[1] T. Fukui, Y. Taniguchi, T. Suhara, Y. Kanada-En'yo, and K. Ogata, Phys. Rev. C **93**, 034606 (2016).

2α state of ^{10}Be

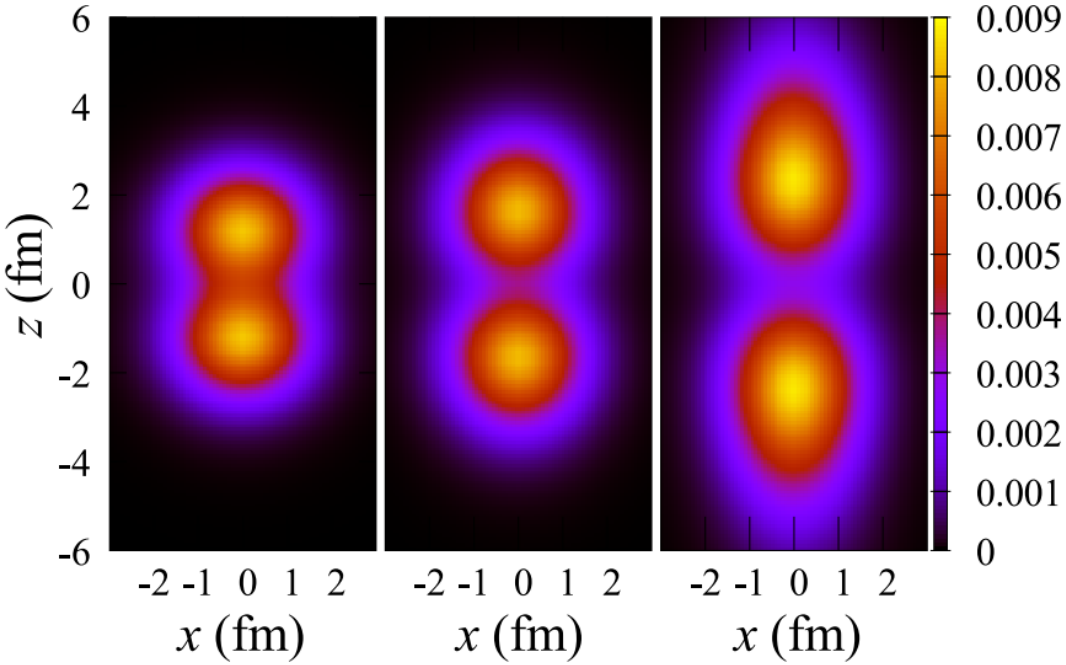
M. Lyu, **K. Yoshida**, Y. Kanada-En'yo, and K. Ogata. Submitted to Phys. Rev. C [arXiv:1712.09753].

Tohsaki-Horiuchi-Schuck-Röpke (THSR) wave function
Volkov No.2 (central) + G3RS (spin-orbit)



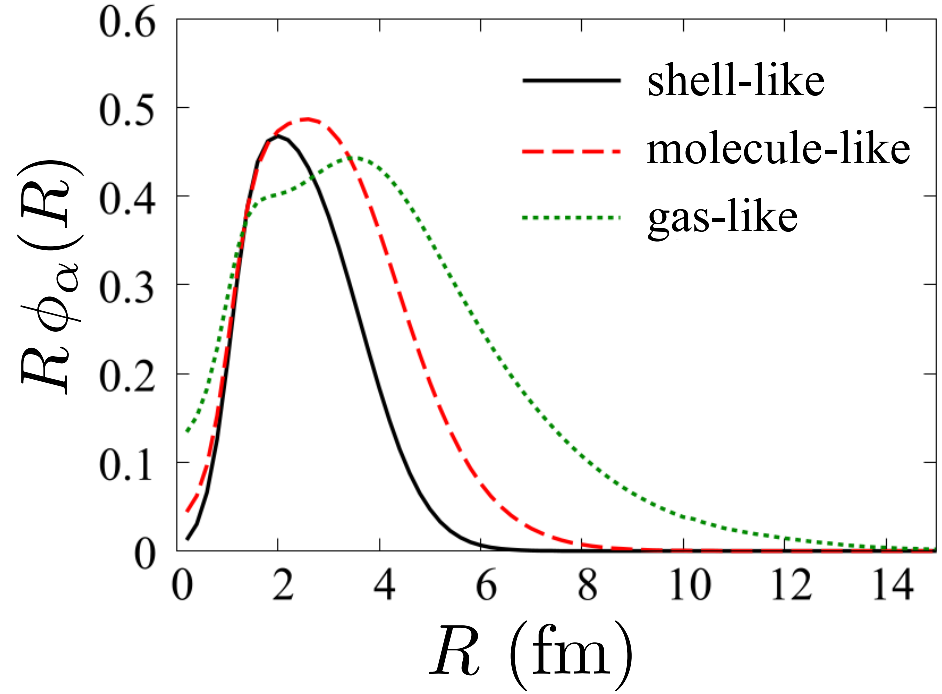
2α state of ^{10}Be

Charge distribution of ^{10}Be



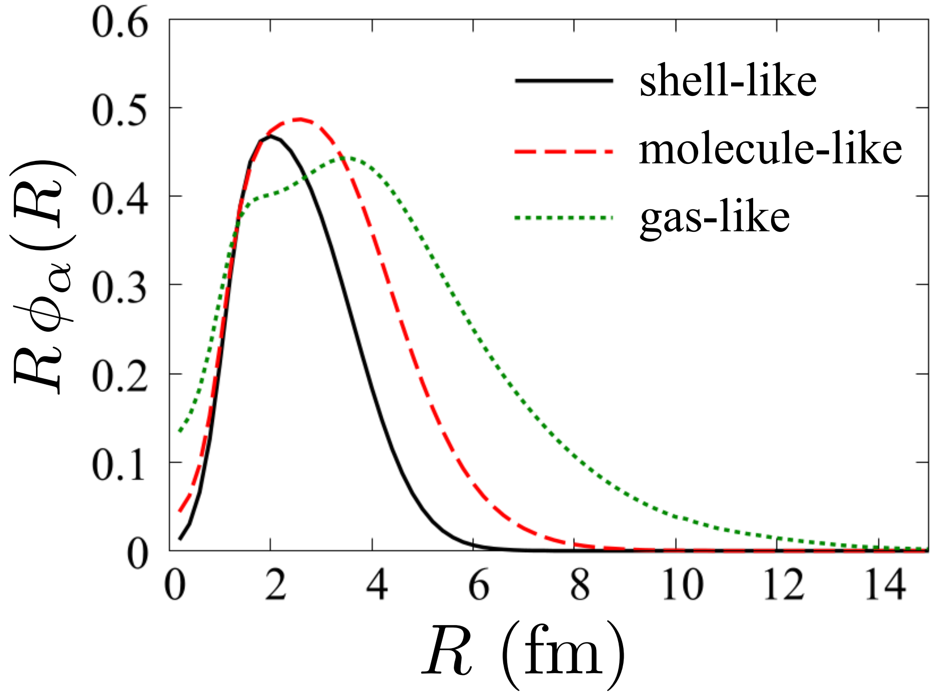
shell-like | molecule-like (variation) | gas-like

Reduced width amplitude × R

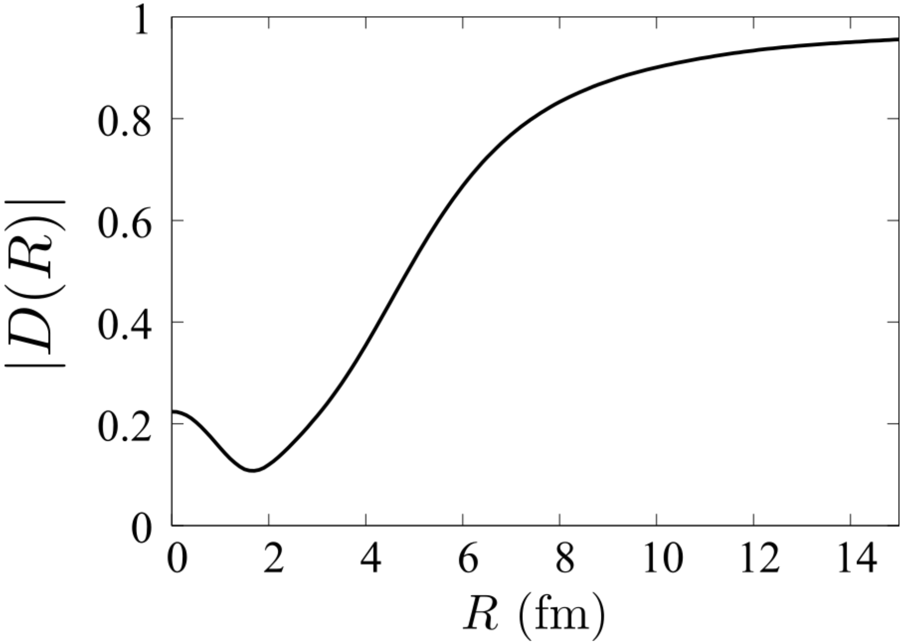


Masking function of $^{10}Be(p,p\alpha)^6He$ @250 MeV

Reduced width amplitude × *R*

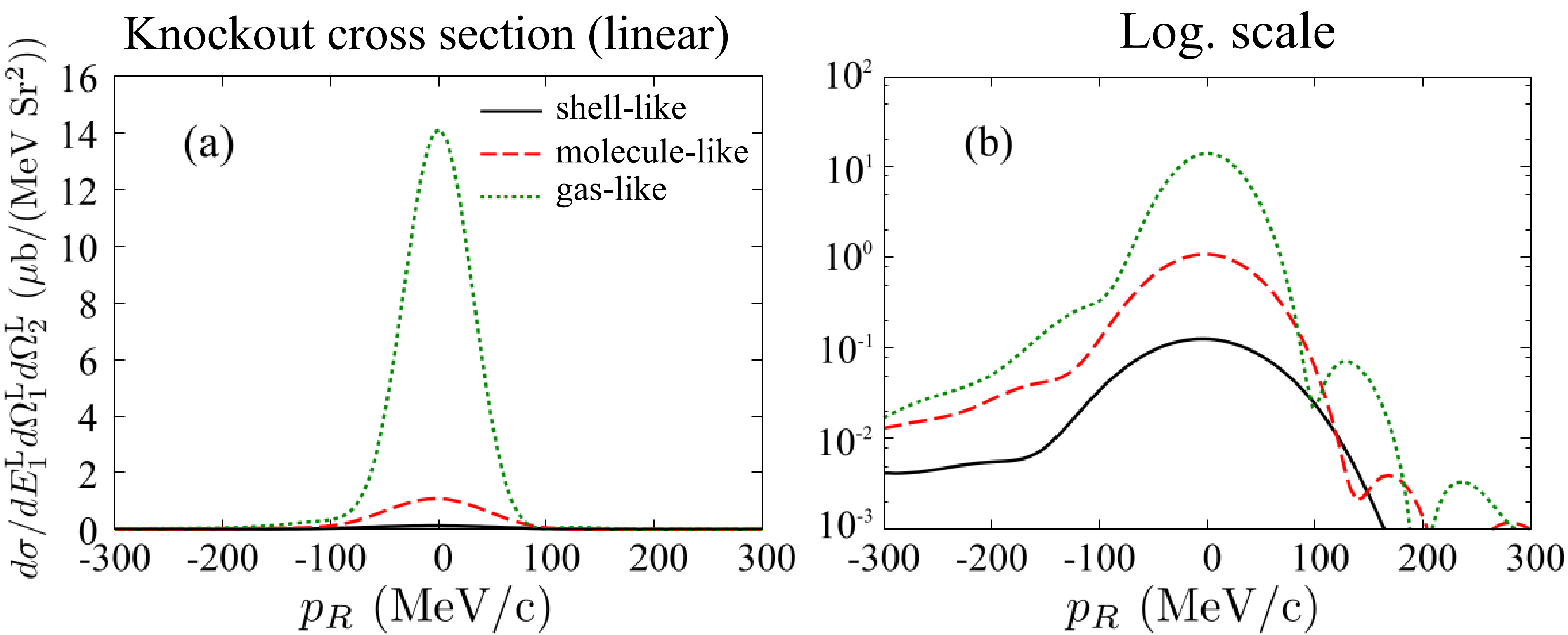


Masking function



- Optical potentials: Melbourne *g*-matrix + folding (~20% uncertainty)

^{10}Be(p,$p\alpha$)^{6}He @250 MeV



- Optical potentials: Melbourne g-matrix + folding (~20% uncertainty)
- ~10 times difference in TDXs

Summary

- Knockout reaction as a probe for the single-particle/α-cluster states
  - Relatively high energy reaction: 100-400 MeV (λ ~ 0.5-0.25 fm)
  - ➢ single-step direct reaction → reaction is clear and clean

- Studies on the (*p*,*p*α) reaction from ^{20}Ne, ^{10}Be
  - The reaction is peripheral due to the absorption (short mean free path) of the α particle
  - Masking function
    - ➢ Weighting function of radius *R* which defines the probed region
    - ➢ The relation between the cluster state and the knockout reaction observables
  - THSR description of the cluster state of ^{10}Be and the prediction of the ^{10}Be(*p*,*p*α)^{6}He cross section

"Typical" (spatially developed) α-cluster state is probed through knockout reactions