Alpha knockout reaction as a probe for alpha formation in light to heavy nuclei

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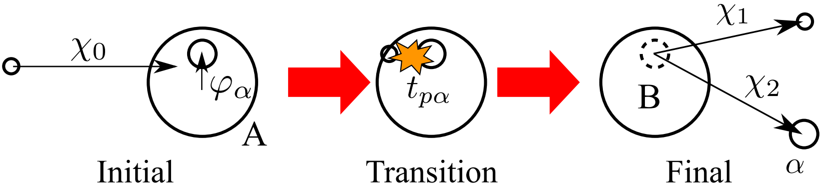
Japan Atomic Energy Agency

Reaction model: Distorted Wave Impulse Approximation



Transition matrix

$$T = \langle \chi_1 \chi_2 \Phi_\alpha \Phi_\mathrm{B} \,|\, t_{p\alpha} \,|\, \chi_0 \Phi_\mathrm{A} \rangle = \langle \chi_1 \chi_2 \,|\, t_{p\alpha} \,|\, \chi_0 \varphi_\alpha \rangle$$

χ_i: Distorted waves under optical potentials

$t_{p\alpha}$: p-α effective interaction in free space

φ_α: Cluster wave function $\langle [\Phi_\alpha \otimes \Phi_\mathrm{B}] \,|\, \Phi_\mathrm{A} \rangle$

Knockout cross section (Triple differential cross section)

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

α+^{16}O cluster state in ^{20}Ne$_{g.s.}$

PHYSICAL REVIEW C **100**, 044601 (2019)

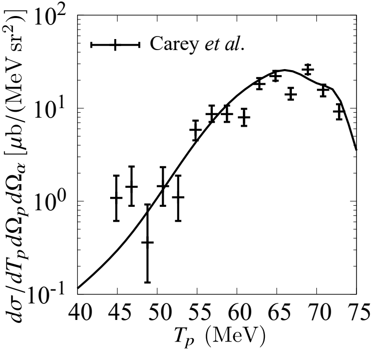
Quantitative description of the ^{20}Ne(p, $p\alpha$)^{16}O reaction as a means of probing the surface α amplitude

Kazuki Yoshida,[1,2,*] Yohei Chiba,[3,4,2] Masaaki Kimura,[5,6,2] Yasutaka Taniguchi,[7,2]
Yoshiko Kanada-En'yo,[8,2] and Kazuyuki Ogata[2,3,4]

$\alpha+^{16}$O cluster state in ^{20}Ne$_{g.s.}$

K. Yoshida +, PRC **100**, 044601 (2019)

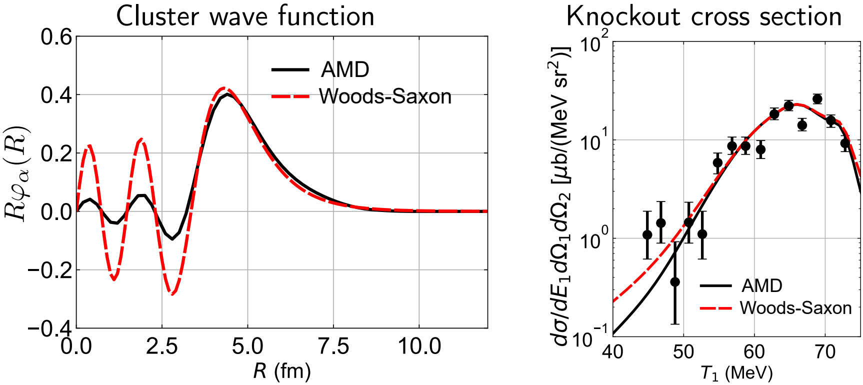
- DWIA + AMD wave function [2]
- $S_\alpha = 0.26$ (AMD)
- Precise α-^{16}O optical potential by Michel *et al.* [3]
- EDAD1 optical potential for p-^{20}Ne and p-^{16}O [4, 5]



Data: Carey *et al.* [6].

[6] T. A. Carey +, PRC **29**, 1273 (1984). [2] Y. Chiba and M. Kimura, PTEP **2017**, 053D01 (2017). [3] F. Michel +, PRC **28**, 1904 (1983). [4, 5] S. Hama +, PRC **41**, 2737 (1990), E. D. Cooper +, PRC **47**, 297 (1993).

Peripherality of reaction and surface α amplitude



- Pauli principle is taken into account within the Antisymmetrized Molecular Dynamics (AMD) framework
- Both wave functions agree on the surface
- Knockout cross section is determined by the surface α amplitude, not the whole region (S-factor).

$^{10}\mathrm{Be}(p, p\alpha)^{6}\mathrm{He}_{g.s.}$

PHYSICAL REVIEW LETTERS **131,** 212501 (2023)

Featured in Physics

Validation of the ^{10}Be Ground-State Molecular Structure Using $^{10}\mathrm{Be}(p, p\alpha)^{6}\mathrm{He}$ Triple Differential Reaction Cross-Section Measurements

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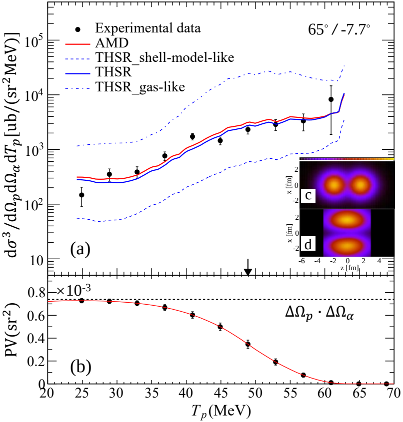
$^{10}\text{Be}(p, p\alpha)^{6}\text{He}_{g.s.}$

[7] P. J. Li +, PRL **131**, 212501 (2023).



- First $(p, p\alpha)$ TDX measurement in the inverse kinematics
- Both AMD and THSR α amplitude gave remarkable agreement with the data.
- Analysis for $^{12}\text{Be}(p, p\alpha)^{8}\text{He}$ is now ongoing.

PHYSICAL REVIEW C **103**, L031305 (2021)

Letter

Unexpectedly enhanced α-particle preformation in ^{48}Ti probed by the $(p, p\alpha)$ reaction

Yasutaka Taniguchi,[1,2,*] Kazuki Yoshida,[3,2] Yohei Chiba,[4,5,2] Yoshiko Kanada-En'yo,[6,2] Masaaki Kimura,[7,8,2] and Kazuyuki Ogata[2,4,5]

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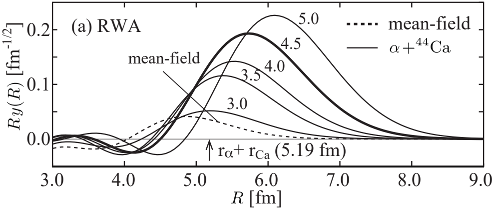
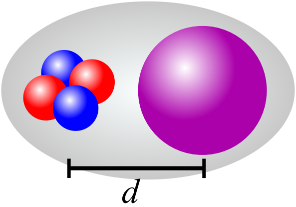
α+^{44}Ca cluster and ^{48}Ti(p,$p\alpha$)^{44}Ca reaction

Cluster amplitude



Inter-cluster distance d

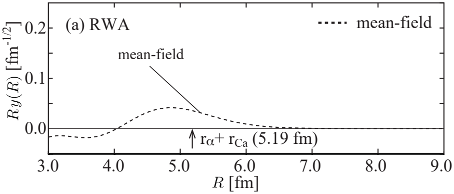


- Stricture theory based on the nucleon degrees of freedom (Antisymmetrized molecular dynamics:AMD)
- Constraint on the inter-cluster distance d

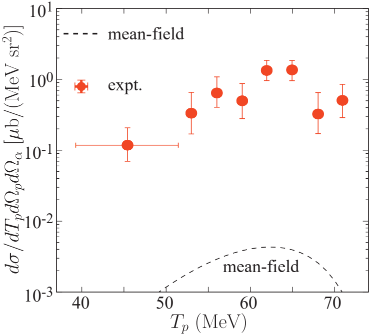
[8] Y. Taniguchi +, PRC **103**, L031305 (2021).
α-^{44}Ca potential:[9] T. Delbar +, PRC **18**, 1237 (1978).

α+^{44}Ca cluster and ^{48}Ti(p,$p\alpha$)^{44}Ca reaction

Cluster amplitude



Knockout cross section

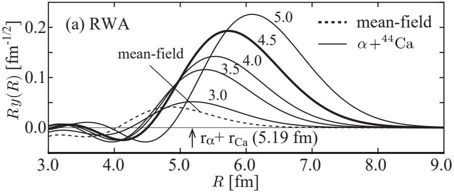


- Mean-field like structure fails to reproduce the reaction data

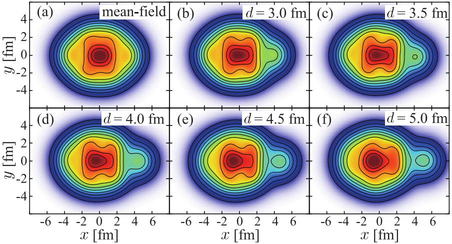
[8] Y. Taniguchi +, PRC **103**, L031305 (2021).

$\alpha+^{44}$Ca cluster and ^{48}Ti$(p,p\alpha)^{44}$Ca reaction

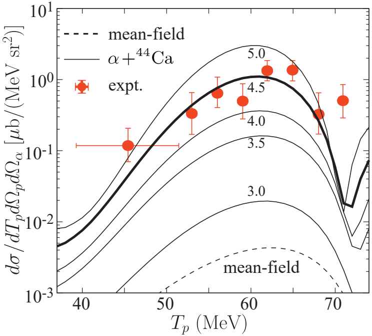
Cluster amplitude

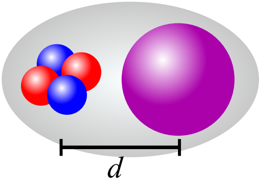


Density



Knockout cross section

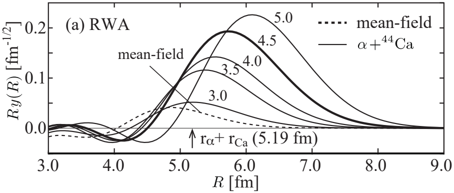




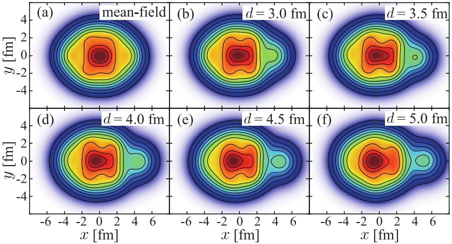
[8] Y. Taniguchi +, PRC **103**, L031305 (2021).

$\alpha+^{44}$Ca cluster and ^{48}Ti$(p,p\alpha)^{44}$Ca reaction

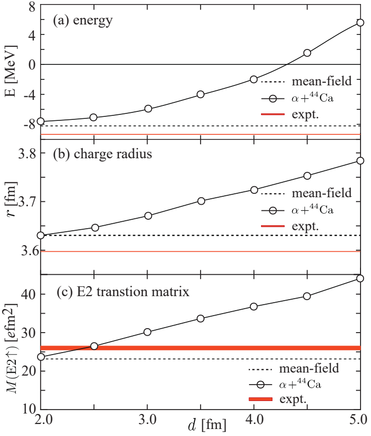
Cluster amplitude



Density



Energy, radius, M(E2)



Inter cluster distance

[8] Y. Taniguchi +, PRC **103**, L031305 (2021).

α knockout reaction from α-decay nuclei

PHYSICAL REVIEW C **106**, 014621 (2022)

α knockout reaction as a new probe for α formation in α-decay nuclei

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Heavy and unstable: α formation on decaying nuclei

α-decay lifetime and its width (independent of channel radius R)

$$T_{1/2} = \frac{\hbar \ln 2}{\Gamma_l},$$

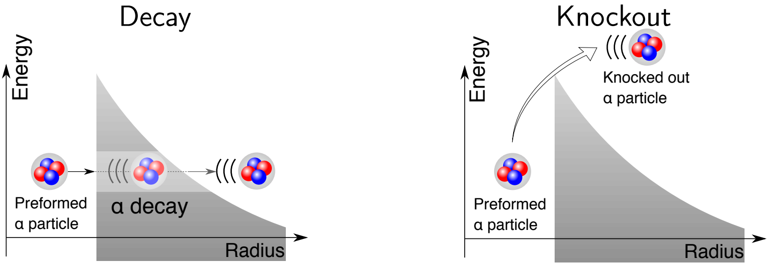
$$\Gamma = 2 \underbrace{\frac{kR}{F^2(kR) + G^2(kR)}}_{\text{Penetrability}} \underbrace{\frac{\hbar^2}{2\mu R} |RF(R)|^2}_{\text{reduced } \alpha \text{ width}}$$

$$= 2\, P(R)\, \gamma^2(R)$$

^{212}Po case, $T_{1/2} \sim 0.3\,\mu s$, which means $\Gamma \sim 1.5 \times 10^{-15}\,\mathrm{MeV}$ (cf. $Q_\alpha \sim 9.0\,\mathrm{MeV}$)

α knockout reaction from decaying nuclei

K. Yoshida and J. Tanaka, PRC **106**, 014621 (2022)

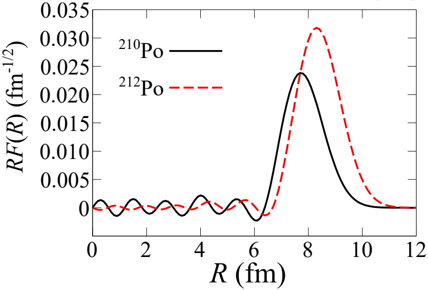


Knockout an α before it penetrates the barrier

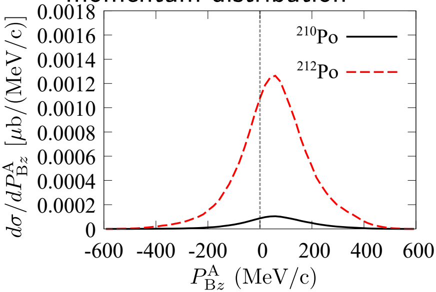
- $T_{\mathrm{decay}} \sim 0.3\ \mu s$ (^{212}Po), $T_{\mathrm{knockout}} \sim 10^{-22}\ s \sim 30\ \mathrm{fm}/c$
- Free from the penetration process, direct access to α amplitude
- Clean probe for the α component in the g.s.

α knockout from ^{210,212}Po case

α amplitude from decay study [11]



momentum distribution



Recoil momentum of the residue

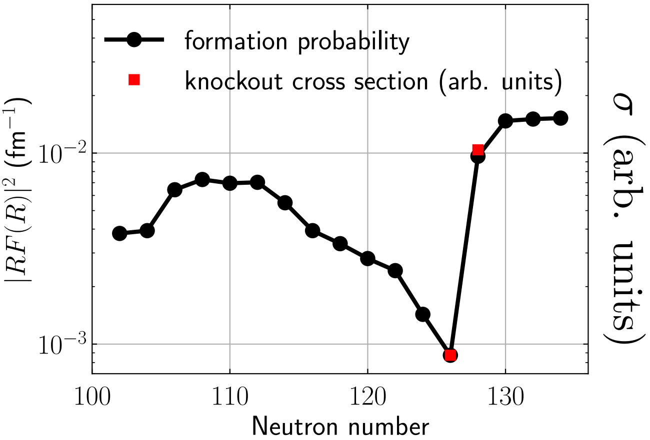
	S-factor	peak height	Cross section	$\|RF(R)\|^2$
^{212}Po / ^{210}Po	1.92	12.1	11.9	10.2

Difference is magnified by the peripherality of the reaction

$\rightarrow$ sensitive probe for preformed α particle on the surface

[11] C. Qi +, PRC **81**, 064319 (2010).

α knockout from ^{210,212}Po case



Data: A. N. Andreyev +, PRL **110**, 242502 (2013)

Difference is magnified by the peripherality of the reaction
$\rightarrow$ sensitive probe for preformed α particle on the surface

Summary

- The discovery of the α formation on Sn isotopes, and what comes next?
- Problems in the α amplitude and the $(p, p\alpha)$ cross section in medium and heavy mass region
  - Insufficient α amplitude on the surface?
    - Basic property of a nucleus must remain unchanged.
  - Validity of the optical potential and (in-medium) p-α effective iteration?
  - Reaction mechanism beyond the quasi-free $(p, p\alpha)$ knockout?
- $(p, p\alpha)$ reaction as a new probe for the α reduced width of α-decay nuclei

Reference i

[1] K. Yoshida +, PRC **100**, 044601 (2019) (cit. on p. 4).

[2] Y. Chiba and M. Kimura, PTEP **2017**, 053D01 (2017) (cit. on p. 4).

[3] F. Michel +, PRC **28**, 1904 (1983) (cit. on p. 4).

[4] S. Hama +, PRC **41**, 2737 (1990) (cit. on p. 4).

[5] E. D. Cooper +, PRC **47**, 297 (1993) (cit. on p. 4).

[6] T. A. Carey +, PRC **29**, 1273 (1984) (cit. on p. 4).

[7] P. J. Li +, PRL **131**, 212501 (2023) (cit. on p. 7).

[8] Y. Taniguchi +, PRC **103**, L031305 (2021) (cit. on pp. 9–12).

[9] T. Delbar +, PRC **18**, 1237 (1978) (cit. on p. 9).

[10] K. Yoshida and J. Tanaka, PRC **106**, 014621 (2022) (cit. on p. 15).

[11] C. Qi +, PRC **81**, 064319 (2010) (cit. on p. 16).

[12] A. N. Andreyev +, PRL **110**, 242502 (2013) (cit. on p. 17).