α knockout reaction from light to heavy nuclei

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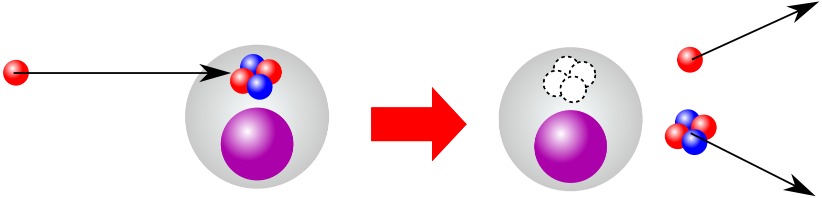
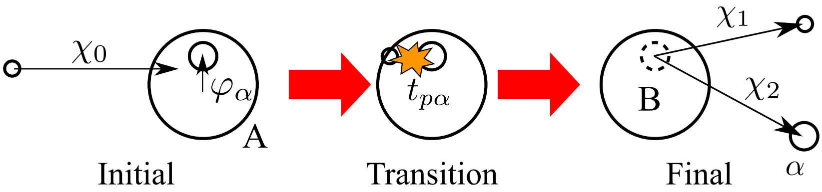
α knockout reaction



- One-step direct reaction with hundreds MeV incident energy
- Alpha is knocked out by a impulse collision
- Reaction probability (cross section) is proportional to the probability of the α cluster
- Cluster component only in the ground state of the target is probed
  - Little contribution from excited (resonance) states

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)

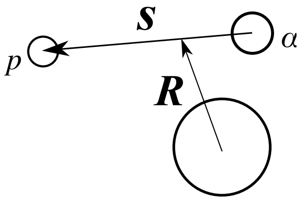
$$\frac{d^3\sigma}{dE_1 d\Omega_1 d\Omega_2} \propto |T|^2$$

$$
\begin{aligned}
T &\approx \langle \chi_1 \chi_2 \,|\, t_{p\alpha} \,|\, \chi_0 \varphi_\alpha \rangle \\
&\xrightarrow[\text{(P.W.)}]{} \left\langle \boldsymbol{\kappa}' \,\middle|\, t_{p\alpha} \,\middle|\, \boldsymbol{\kappa} \right\rangle_{\boldsymbol{s}} \langle \boldsymbol{K}_1 + \boldsymbol{K}_2 - \boldsymbol{K}_0 \,|\, \varphi_\alpha \rangle_{\boldsymbol{R}} \\
&= \left\langle \boldsymbol{\kappa}' \,\middle|\, t_{p\alpha} \,\middle|\, \boldsymbol{\kappa} \right\rangle_{\boldsymbol{s}} \langle -\boldsymbol{K}_\mathrm{B} \,|\, \varphi_\alpha \rangle_{\boldsymbol{R}} \qquad (\boldsymbol{K}_\mathrm{B} = \boldsymbol{K}_0 - \boldsymbol{K}_1 - \boldsymbol{K}_2) \\
&= \left\langle \boldsymbol{\kappa}' \,\middle|\, t_{p\alpha} \,\middle|\, \boldsymbol{\kappa} \right\rangle_{\boldsymbol{s}} \; \tilde{\varphi}_\alpha(\boldsymbol{k}_\alpha) \qquad (-\boldsymbol{K}_\mathrm{B} \approx \boldsymbol{k}_\alpha)
\end{aligned}
$$

p-α collision — Structure

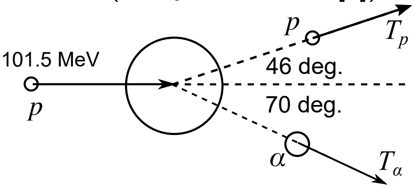
Knockout cross section

$$
|T|^2 \to \frac{d\sigma_{p\alpha}}{d\Omega_{p\alpha}} \, |\tilde{\varphi}_\alpha(\boldsymbol{k}_\alpha)|^2
$$

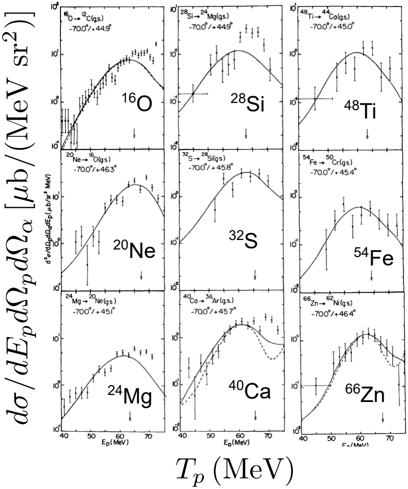


Search for α clustering in the ground state

Systematic experiment of $(p,p\alpha)$ reaction (Carey *et al.* 1984 [1])



Kinematical setup



Targets

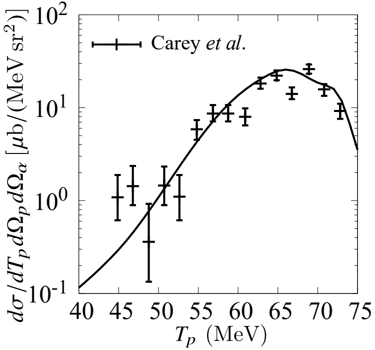
- ^{16}O, ^{20}Ne, ^{24}Mg, ^{28}Si, ^{32}S, ^{40}Ca, ^{48}Ti, ^{54}Fe, ^{66}Zn

[1] T. A. Carey *et al.*, PRC **29**, 1273 (1984).

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

- α cluster wave function by a Woods-Saxon potential
- $S_\alpha = 0.54$ (exp. + reaction)
- $S_\alpha = 0.18$
- 0.23 (Structure theory [2–4])

Inconsistent by a factor of two

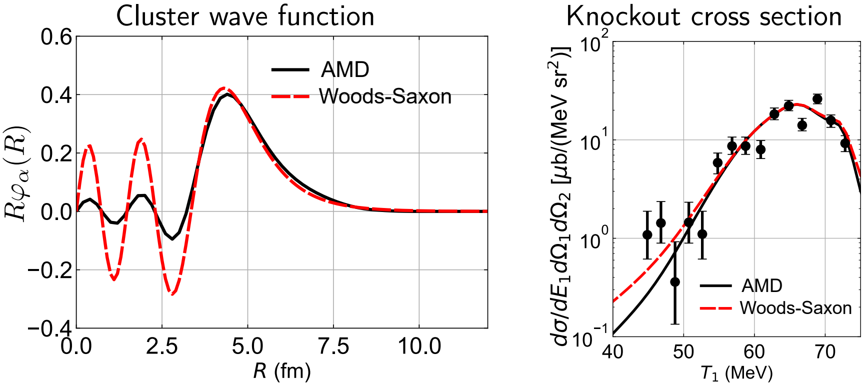


K. Yoshida *et al.* (2019) [5].

- DWIA + AMD wave function [6]
- $S_\alpha = 0.26$ (Consistent)

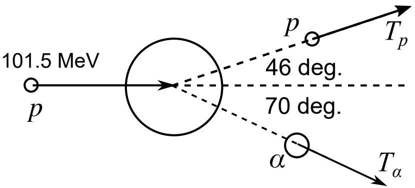
[1] T. A. Carey *et al.*, PRC **29**, 1273 (1984). [2] W. Chung *et al.*, PLB **79**, 381 (1978). [3] J. Draayer, NPA **237**, 157 (1975). [4] K. Hecht and D. Braunschweig, NPA **244**, 365 (1975). [5] K. Yoshida *et al.*, PRC **100**, 044601 (2019). [6] Y. Chiba and M. Kimura, PTEP **2017**, 053D01 (2017).

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).

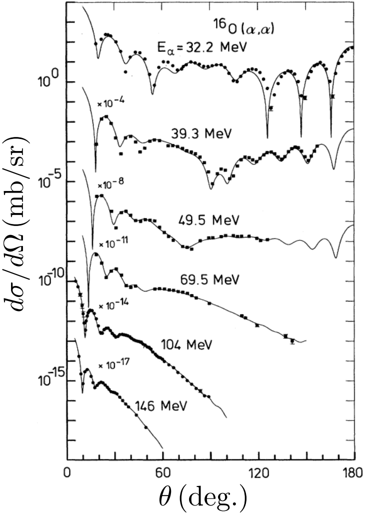
Validity of optical potential



Nice fit of the optical potential by Michel *et al.* [7]

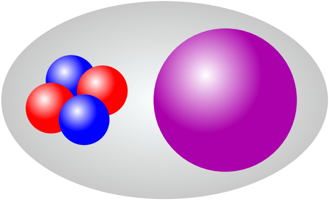
- $T_\alpha = 30 – 150$ MeV
- Backward angles are perfectly reproduced

α-^{16}O differential cross section

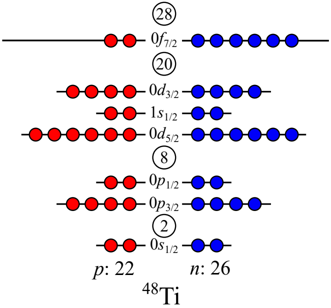


[7] F. Michel *et al.*, PRC **28**, 1904 (1983).

α-^{44}Ca cluster of ^{48}Ti and ^{48}Ti(p,$p\alpha$)^{44}Ca reaction [8]



α+^{44}Ca cluster of ^{48}Ti



- $Z \neq N$ stable nucleus
- magic number 20 core ^{40}Ca + (2p + 6n)
- Structure theories based on the nucleon degrees of freedom are available

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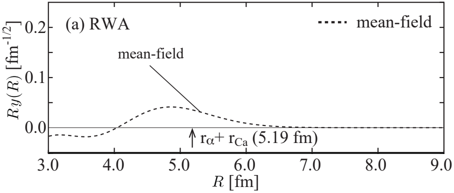
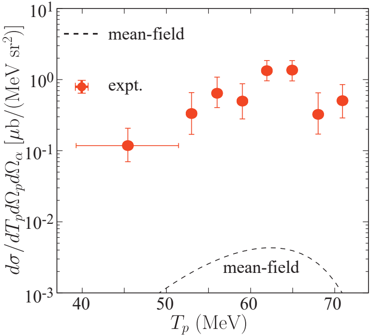
[8] Y. Taniguchi *et al.*, PRC **103**, L031305 (2021).

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

Cluster amplitude



Knockout cross section

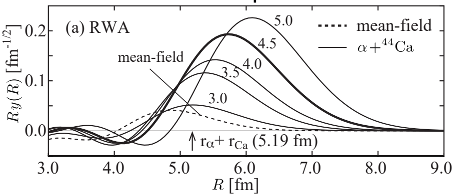


- Mean-field like structure fails to reproduce the reaction data

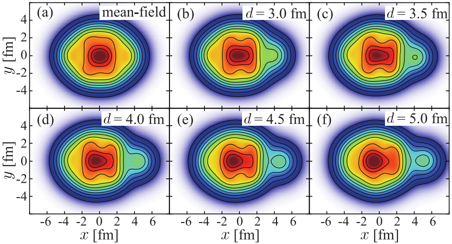
[8] Y. Taniguchi *et al.*, PRC **103**, L031305 (2021).

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

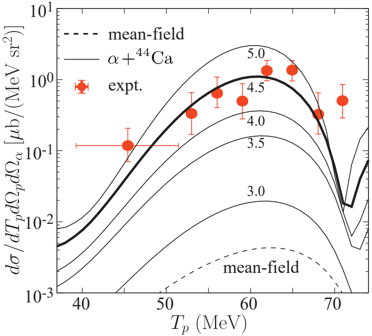
Cluster amplitude

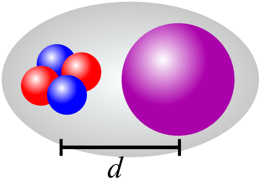


Density



Knockout cross section

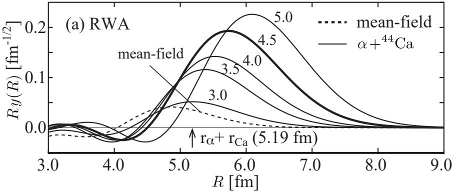




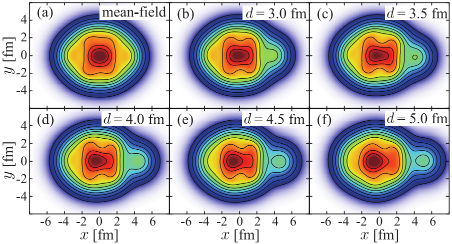
[8] Y. Taniguchi *et al.*, PRC **103**, L031305 (2021).

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

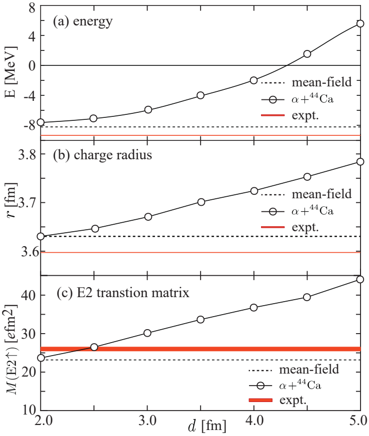
Cluster amplitude



Density



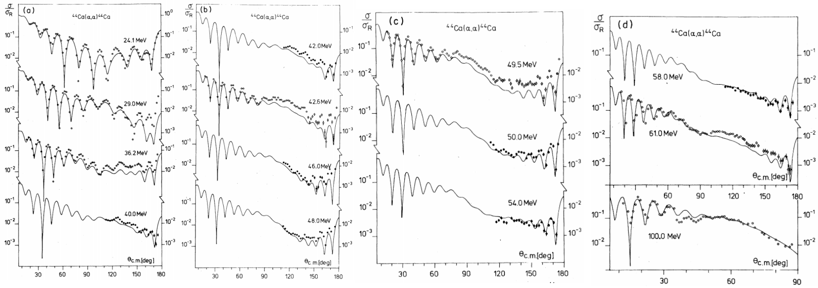
Energy, radius, M(E2)



Inter cluster distance

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

Validity of optical potential



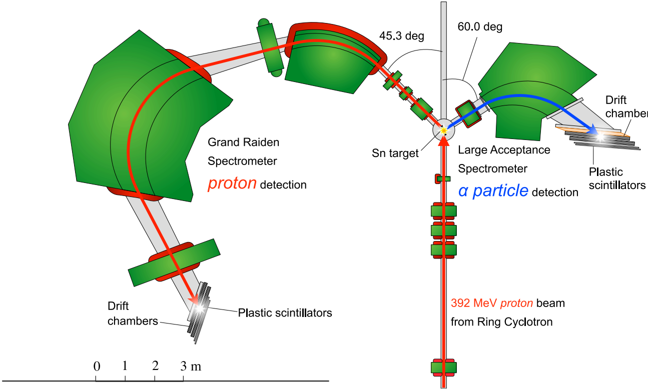
α-^{44}Ca optical potential fit by Delbar *et al.* [9]

- $T_\alpha = 24.1$ – 100 MeV
- Up to 180 deg.

[9] T. Delbar *et al.*, PRC **18**, 1237 (1978).

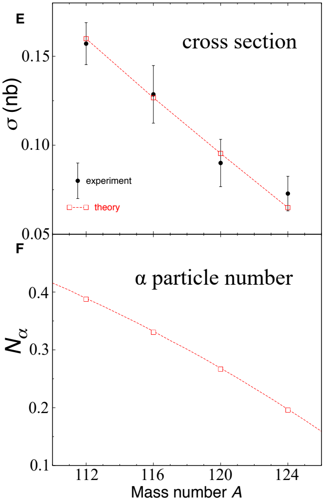
Formation of α clusters in dilute neutron-rich matter

Junki Tanaka[1,2,3]*, Zaihong Yang[3,4]*, Stefan Typel[1,2], Satoshi Adachi[4], Shiwei Bai[5], Patrik van Beek[1], Didier Beaumel[6], Yuki Fujikawa[7], Jiaxing Han[5], Sebastian Heil[1], Siwei Huang[5], Azusa Inoue[4], Ying Jiang[5], Marco Knösel[1], Nobuyuki Kobayashi[4], Yuki Kubota[3], Wei Liu[5], Jianling Lou[5], Yukie Maeda[8], Yohei Matsuda[9], Kenjiro Miki[10], Shoken Nakamura[4], Kazuyuki Ogata[4,11], Valerii Panin[3], Heiko Scheit[1], Fabia Schindler[1], Philipp Schrock[12], Dmytro Symochko[1], Atsushi Tamii[4], Tomohiro Uesaka[3], Vadim Wagner[1], Kazuki Yoshida[13], Juzo Zenihiro[3,7], Thomas Aumann[1,2,14]



[10] J. Tanaka *et al.*, Science **371**, 260 (2021).

α-knockout experiment from Sn isotopes



- The experiment was performed at RCNP, Osaka Univ.
- Theoretical α-knockout cross sections are obtained by introducing a scaling factor of 0.148 for the imaginary potential depth (for all isotopes).
- An isotopic trend of the cross sections is well reproduced by the theoretical calculation using predicted α-particle density distribution.

[10] J. Tanaka *et al.*, Science **371**, 260 (2021).

α-knockout reaction as a probe for α on nuclear surface

PHYSICAL REVIEW C **94**, 044604 (2016)

Investigating α clustering on the surface of ^{120}Sn via the $(p, p\alpha)$ reaction, and the validity of the factorization approximation

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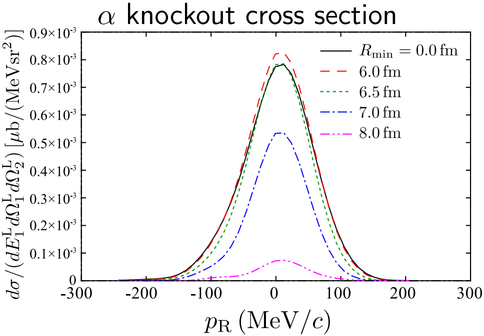
(Received 2 March 2016; revised manuscript received 15 July 2016; published 10 October 2016)

α-knockout reaction as a probe for α on nuclear surface



- Theoretical studied on the proton induced α knockout reaction from ^{120}Sn
- The reaction is sensitive surface region and only $r > 6$ fm region contributes to the reaction cross section

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

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

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(Received 14 November 2021; accepted 15 July 2022; published 25 July 2022)

Heavy and unstable: α formation on decaying nuclei

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

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

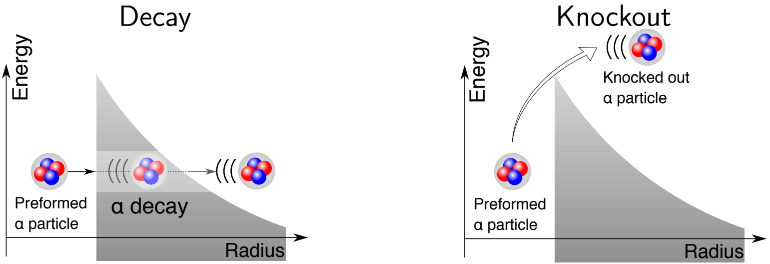
$$\Gamma = 2 \underbrace{\frac{kR}{F^2(kR) + G^2(kR)}}_{\text{Penetrability}} \underbrace{\frac{\hbar^2}{2\mu R} |RF(R)|^2}_{\text{reduced } \alpha \text{ width}}$$

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

^{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)

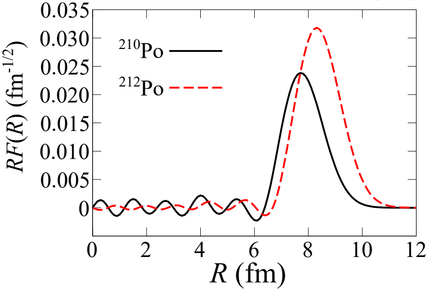


Knockout an α before it penetrates the barrier

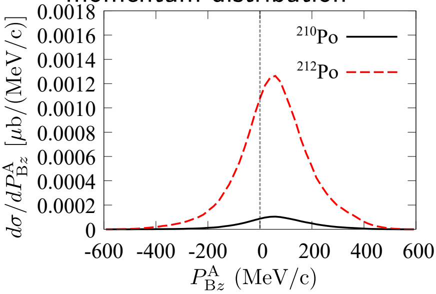
- $T_{\mathrm{decay}} \sim 0.3\ \mu s$ (^{212}Po), $T_{\mathrm{knockout}} \sim 10^{-22}\ s \sim 30\ \mathrm{fm}/c$
- Free from the penetration process, direct access to α amplitude
- Clean probe for the α component in the g.s.

α knockout from ^{210,212}Po case

α amplitude from decay study [12]



momentum distribution



Recoil momentum of the residue

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

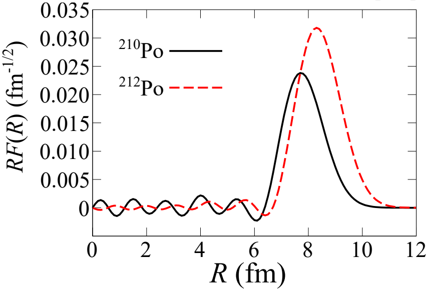
Difference is magnified by the peripherality of the reaction

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

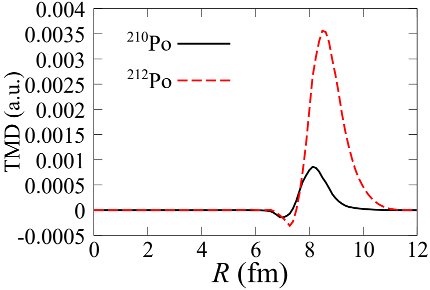
[12] C. Qi *et al.*, PRC **81**, 064319 (2010).

α knockout from ^{210,212}Po case

α amplitude from decay study [12]



Radial dist. of the cross section



Radius

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

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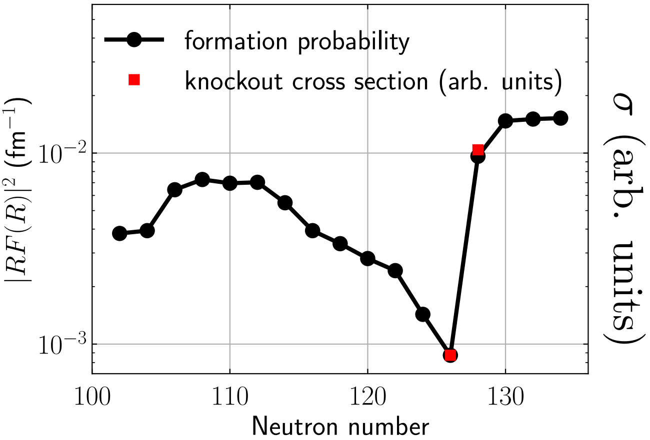


Data: A. N. Andreyev *et al.*, PRL **110**, 242502 (2013)

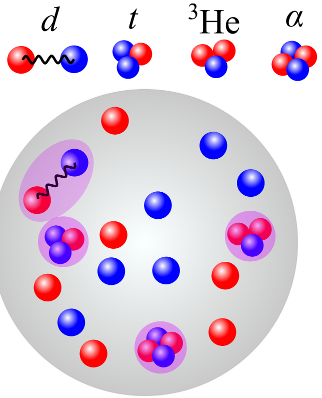
Difference is magnified by the peripherality of the reaction
$\rightarrow$ sensitive probe for preformed α particle on the surface

Beyond the α correlation: Onokoro project

Led by Uesaka-san(RIKEN),

FY2021–2025

- Cluster knockout experiments to investigate
  - Non-uniform distribution in nuclear mean-field and nuclear matter (clustering)
  - d, t, ^{3}He cluster formation and (local) spin symmetry breaking
  - Clustering in the sparse nuclear matter and the nuclear surface



Summary

- The knockout reaction is a good probe for the α clustering
  - One-to-one correspondence between the α amplitude (on nuclear surface) and $(p, p\alpha)$ cross section
  - Clean probe for the α clusters in the ground state
  - Less access to the α clustering in excited and resonance states
- Good reproduction of the $^{20}\mathrm{Ne}(p, p\alpha)^{16}\mathrm{O}$
  - Both the peak height and the distribution of the $(p, p\alpha)$ cross section is reproduced
    - Peak height $\leftrightarrow$ α Formation probability (at the surface)
    - Cross section distribution $\leftrightarrow$ Momentum distribution of α
- Heavier mass region
  - Something is missing in $^{48}\mathrm{Ti}(p, p\alpha)^{44}\mathrm{Ca}$ case
  - $(p, p\alpha)$ reaction on α decay nuclei will be a good probe for the α formation probability, reduced α width, etc.

Reference i

[1] T. A. Carey *et al.*, PRC **29**, 1273 (1984) (cit. on pp. 5, 6).

[2] W. Chung *et al.*, PLB **79**, 381 (1978) (cit. on p. 6).

[3] J. Draayer, NPA **237**, 157 (1975) (cit. on p. 6).

[4] K. Hecht and D. Braunschweig, NPA **244**, 365 (1975) (cit. on p. 6).

[5] K. Yoshida *et al.*, PRC **100**, 044601 (2019) (cit. on p. 6).

[6] Y. Chiba and M. Kimura, PTEP **2017**, 053D01 (2017) (cit. on p. 6).

[7] F. Michel *et al.*, PRC **28**, 1904 (1983) (cit. on p. 8).

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

[9] T. Delbar *et al.*, PRC **18**, 1237 (1978) (cit. on p. 13).

[10] J. Tanaka *et al.*, Science **371**, 260 (2021) (cit. on pp. 14, 15).

[11] K. Yoshida and J. Tanaka, PRC **106**, 014621 (2022) (cit. on p. 20).

[12] C. Qi *et al.*, PRC **81**, 064319 (2010) (cit. on pp. 21, 22).

[13] A. N. Andreyev *et al.*, PRL **110**, 242502 (2013) (cit. on p. 23).