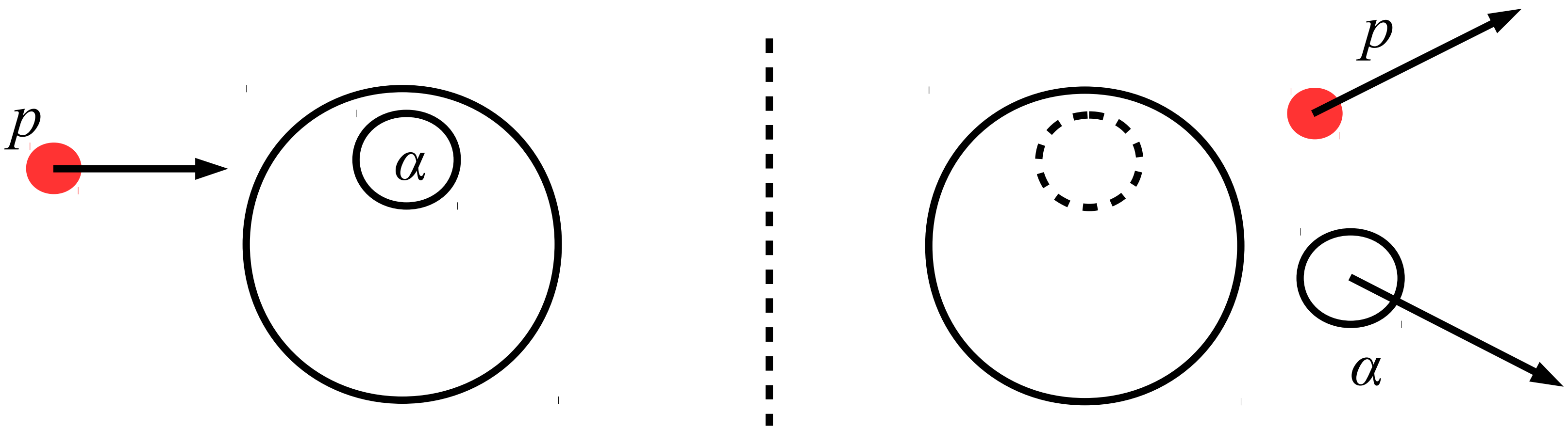
Alpha particle formation probed with the knockout reaction



Kazuki Yoshida

Japan Atomic Energy Agency

Outline

1. Introduction
   1.1. Universality of the α formation: from light to heavy nuclei
   1.2. α knockout reaction as a probe of α clustering

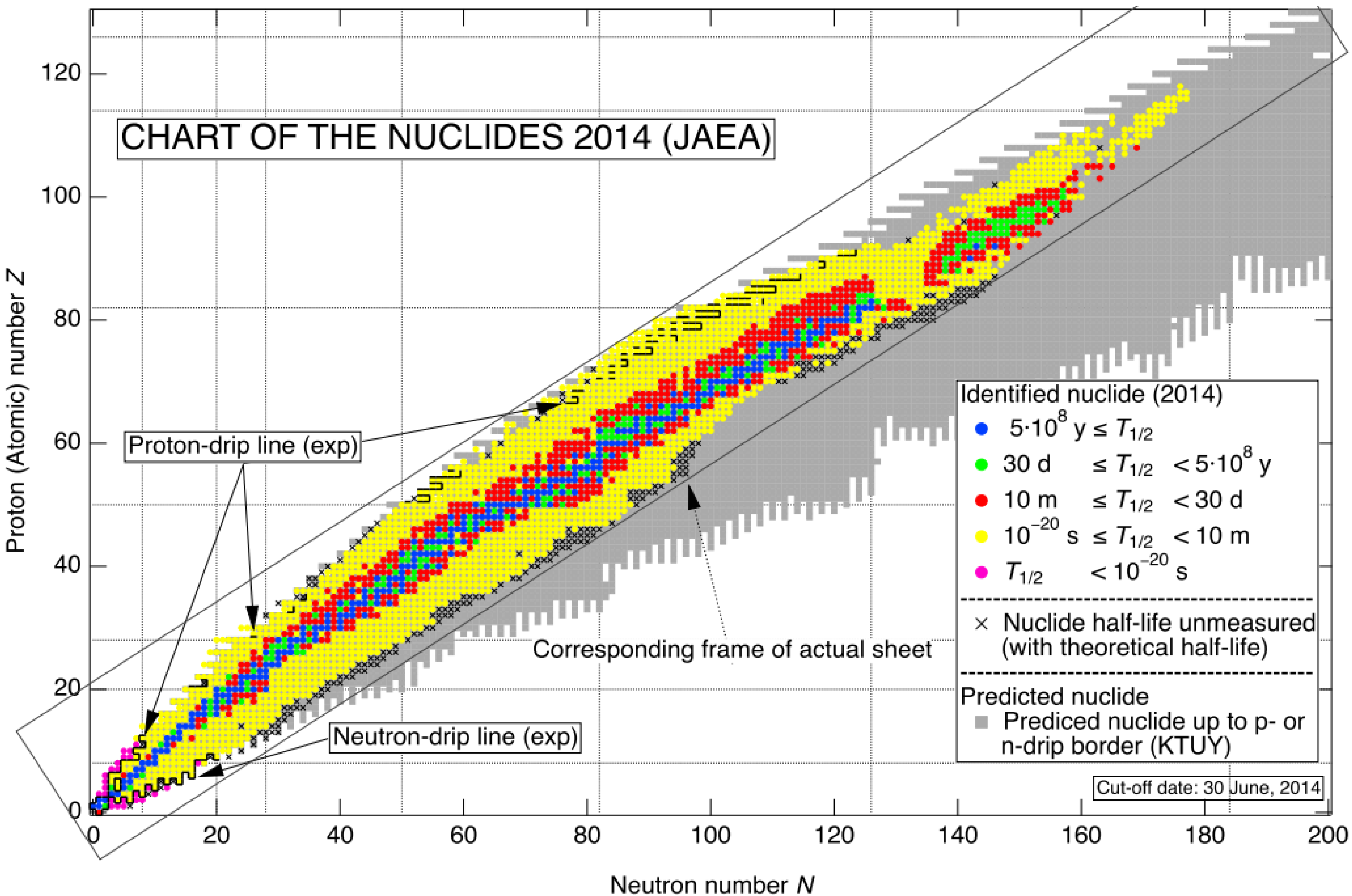
2. Description and picture of Distorted Wave Impulse Approximation

3. Recent results
   3.1. Knockout reaction from ^{20}Ne (and ^{48}Ti) with AMD wave function
   in collaboration with Y. Chiba, Y. Taniguchi, M. Kimura, Y. Kanada-En'yo, and K. Ogata.

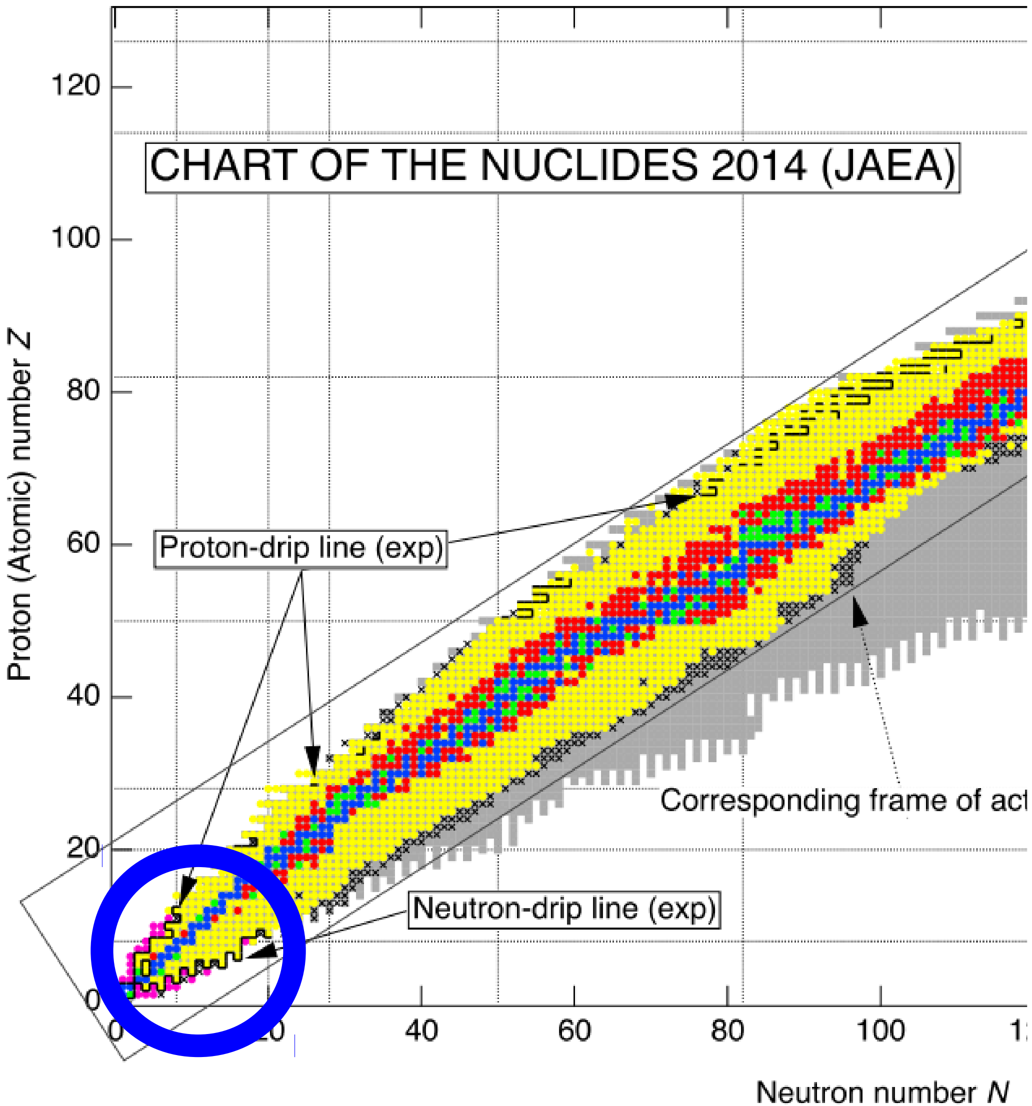
   3.2. α knockout from α-decaying nuclei ^{210,212}Po
   in collaboration with C. Qi.

4. Summary and perspectives

Universality of the α formation

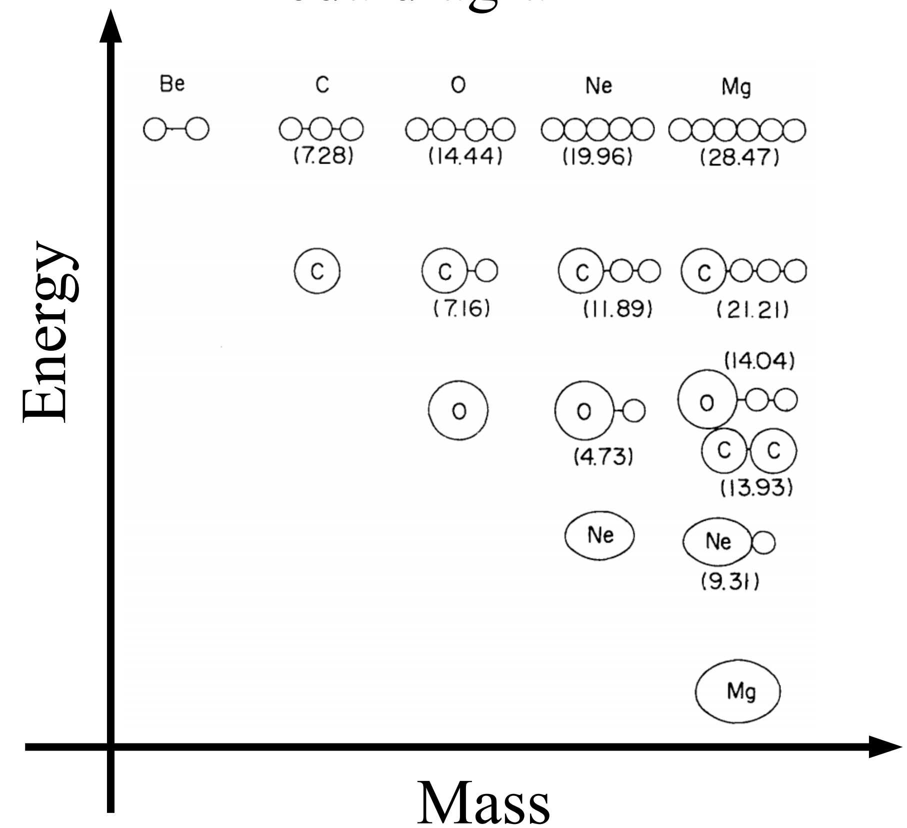


Universality of the α formation



α cluster states of light nuclei

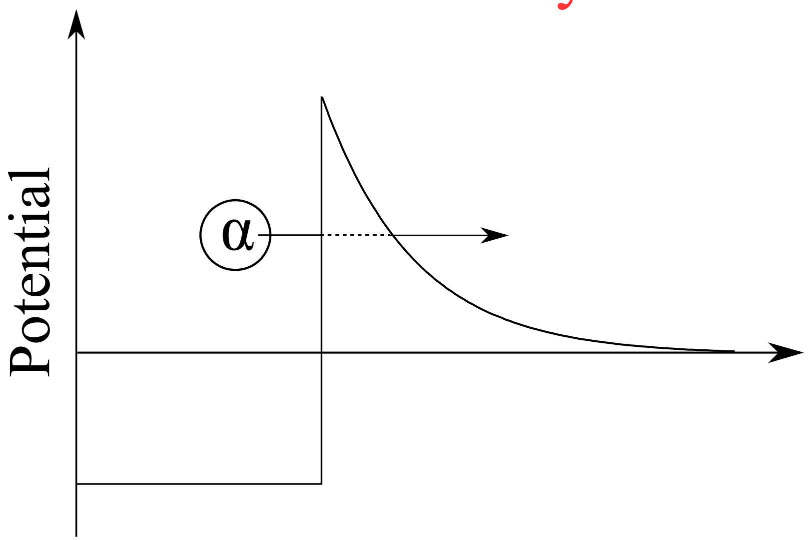
Ikeda diagram



K. Ikeda, N. Takigawa and H. Horiuchi, Supp. of Prog. Theor. Phys. (1968).

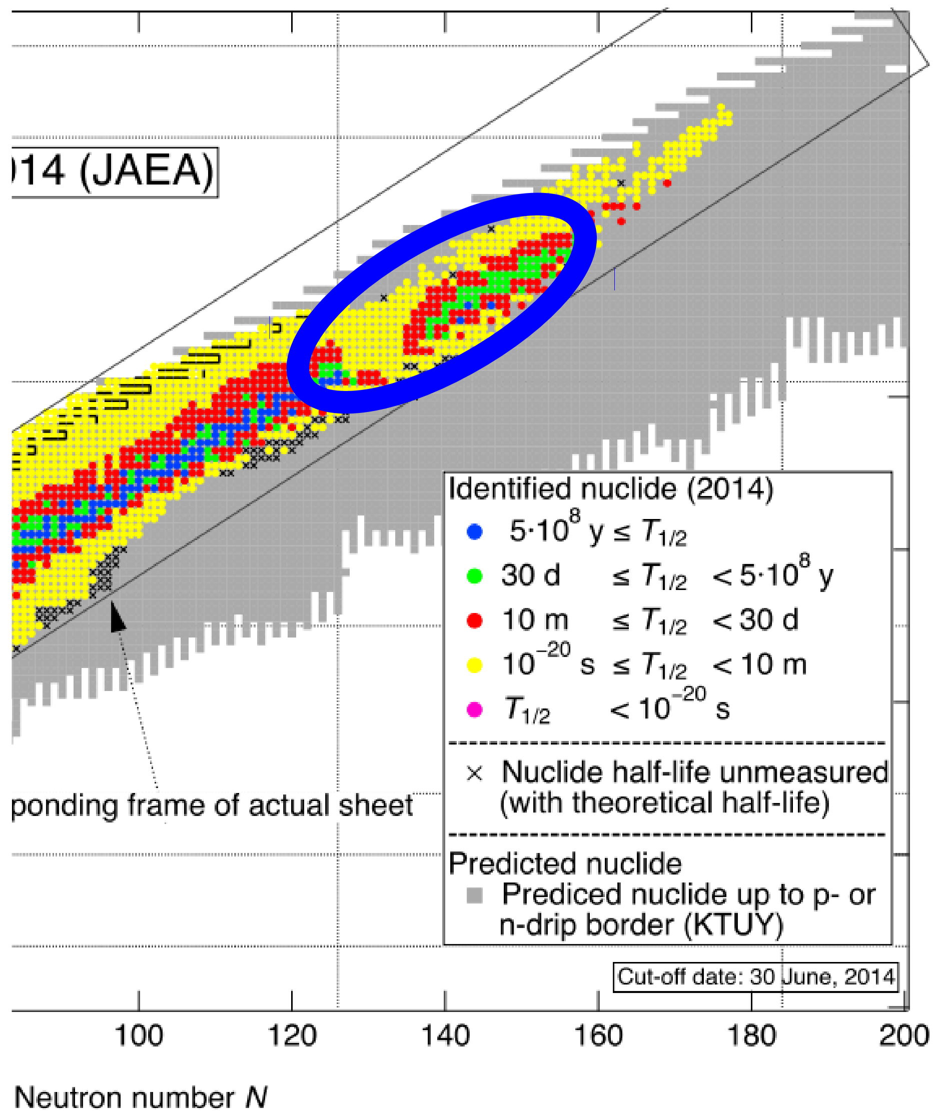
Universality of the α formation

α formation in heavy nuclei

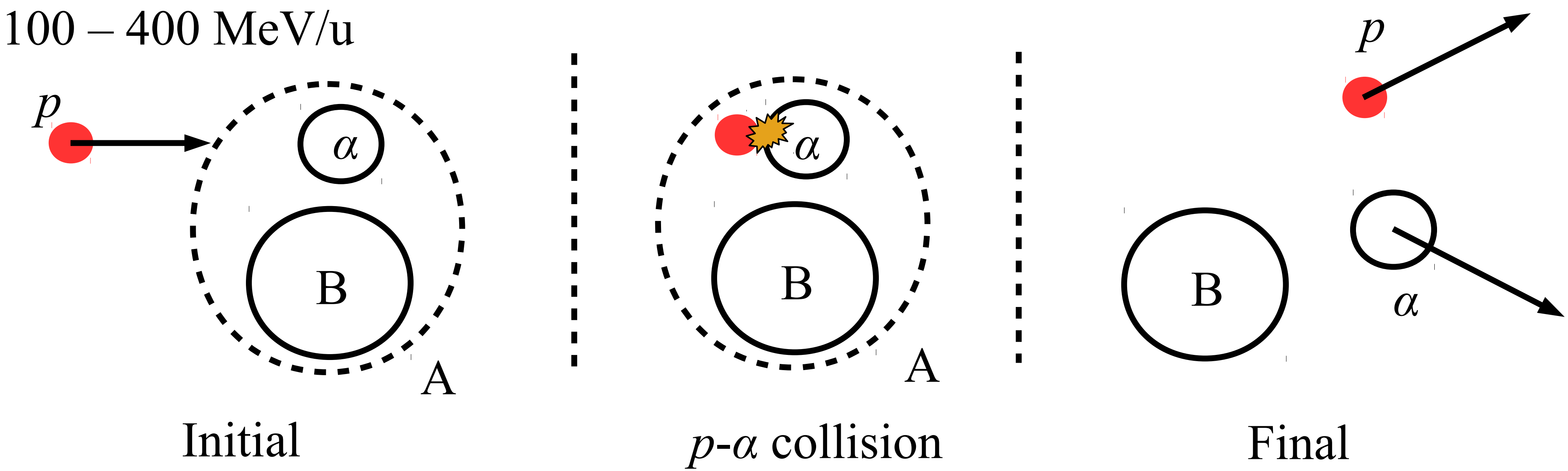


The α-decay process is described by

- formation of α
- penetration through the barrier



α knockout reaction



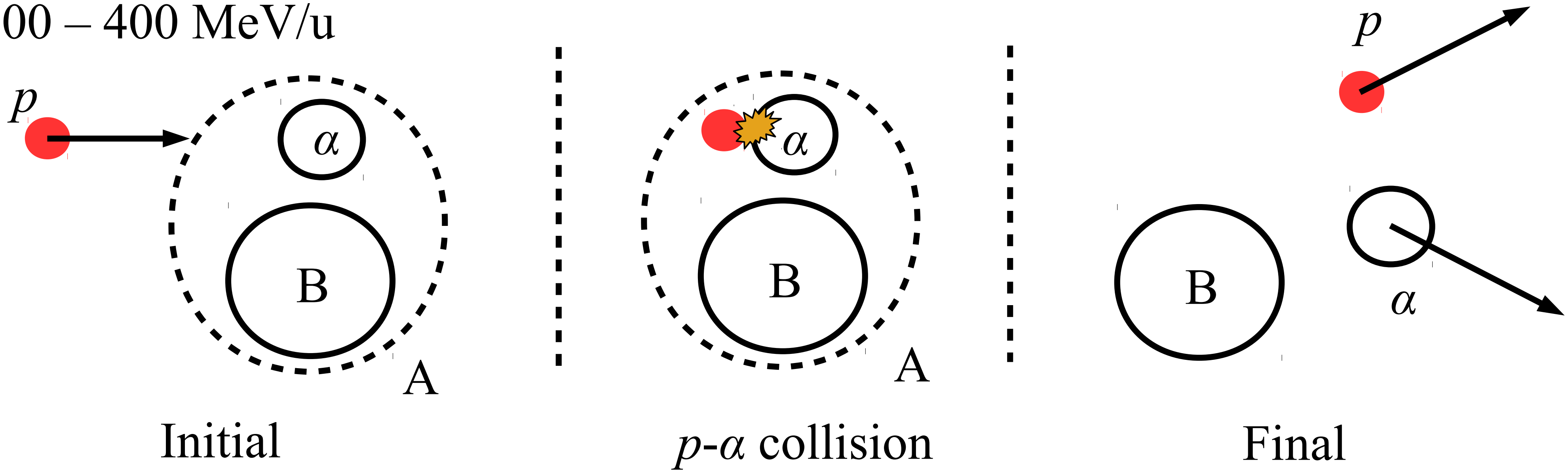
1. Single step: Quasi-free *p*-*α* collision

2. Direct reaction: Participant + Spectator picture
→ Can be applied only to the α-clustering in the ground state
c.f. transfer reaction.

3. Short time scale: ~ 10^{-22} sec. << α-decay life

Distorted Wave Impulse Approximation

100 – 400 MeV/u



Transition matrix

$$T = \langle \Phi_{\mathrm{B}} \Phi_\alpha \chi_{p'} \chi_\alpha \,|\, t_{p\alpha} \,|\, \chi_p \Phi_{\mathrm{A}} \rangle$$

$$= \langle \underline{\chi_{p'} \chi_\alpha} \,|\, \underline{t_{p\alpha}} \,|\, \underline{\chi_p} \underline{\varphi_\alpha} \rangle$$

distorted wave

cluster wave function

$$\langle \Phi_{\mathrm{B}} \Phi_\alpha \,|\, \Phi_{\mathrm{A}} \rangle$$

p-*α* effective interaction (in free space)

Simple understanding in the plane-wave limit

Transition matrix $T = \langle \chi_{p'} \chi_\alpha \,|\, t_{p\alpha} \,|\, \chi_p \varphi_\alpha \rangle$

Plane-wave limit $\rightarrow \langle \boldsymbol{K}_{p'} \boldsymbol{K}_\alpha \,|\, t_{p\alpha} \,|\, \boldsymbol{K}_p \varphi_\alpha \rangle$

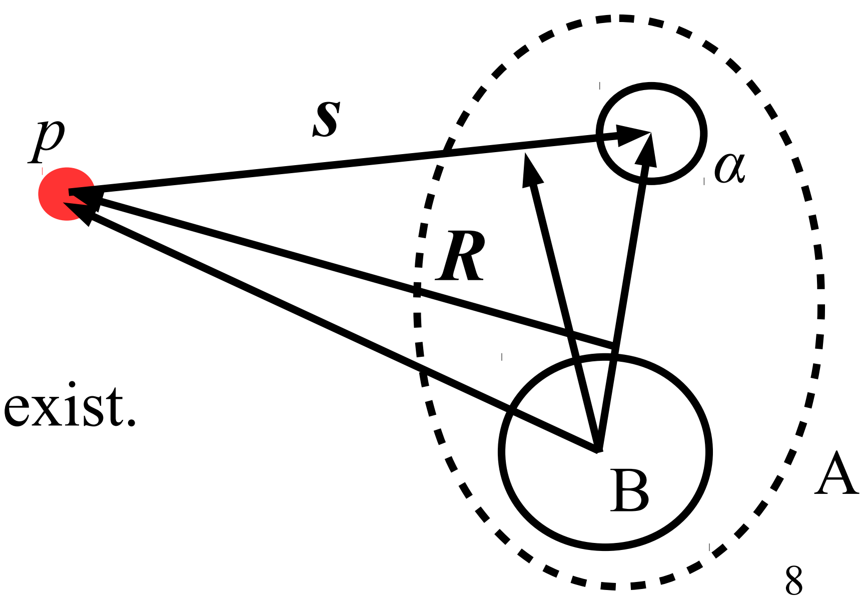
Factorization approx. $\rightarrow \langle \boldsymbol{\kappa}' \,|\, t_{p\alpha} \,|\, \boldsymbol{\kappa} \rangle_{\boldsymbol{s}} \langle \boldsymbol{q} \,|\, \varphi_\alpha \rangle_{\boldsymbol{R}}$

$\boldsymbol{\kappa}, \boldsymbol{\kappa}'$: p-α relative momenta in the initial and final states

$\boldsymbol{q} \equiv \boldsymbol{K}_{p'} + \boldsymbol{K}_\alpha - \boldsymbol{K}_p$ corresponds to the Fermi momentum of α

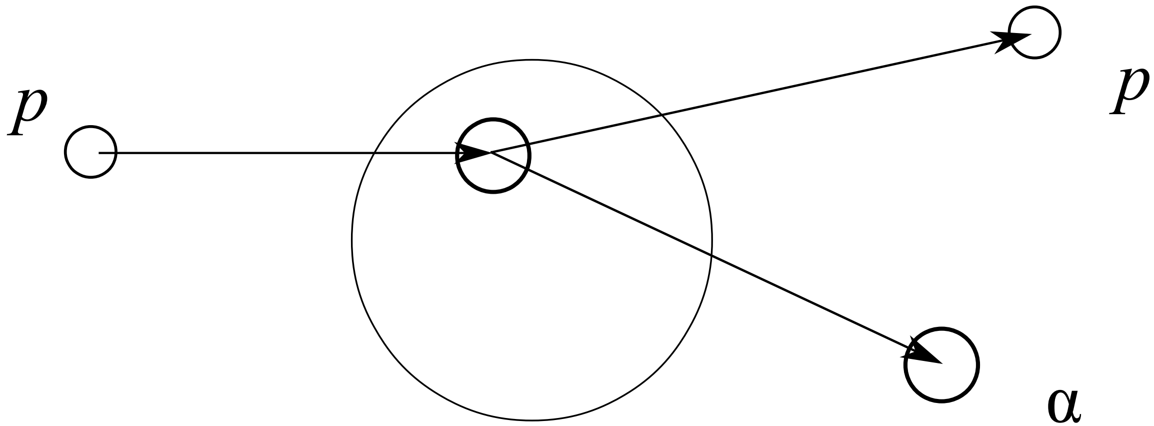
α-knockout cross section:

$$|T|^2 \propto \frac{d\sigma_{p\alpha}}{d\Omega_{p\alpha}} |\varphi_\alpha(\boldsymbol{q})|^2$$



In reality distortion and absorption effect exist.

Triple differential cross section of (p,$p\alpha$) reaction



Triple differential cross section (TDX): The most kinematically exclusive cross section

$$\frac{d^3\sigma}{dT_p d\Omega_p d\Omega_\alpha} \propto |T|^2$$

T-matrix

Emitted energy and direction of p

Emitted direction of α

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4. Summary and perspectives

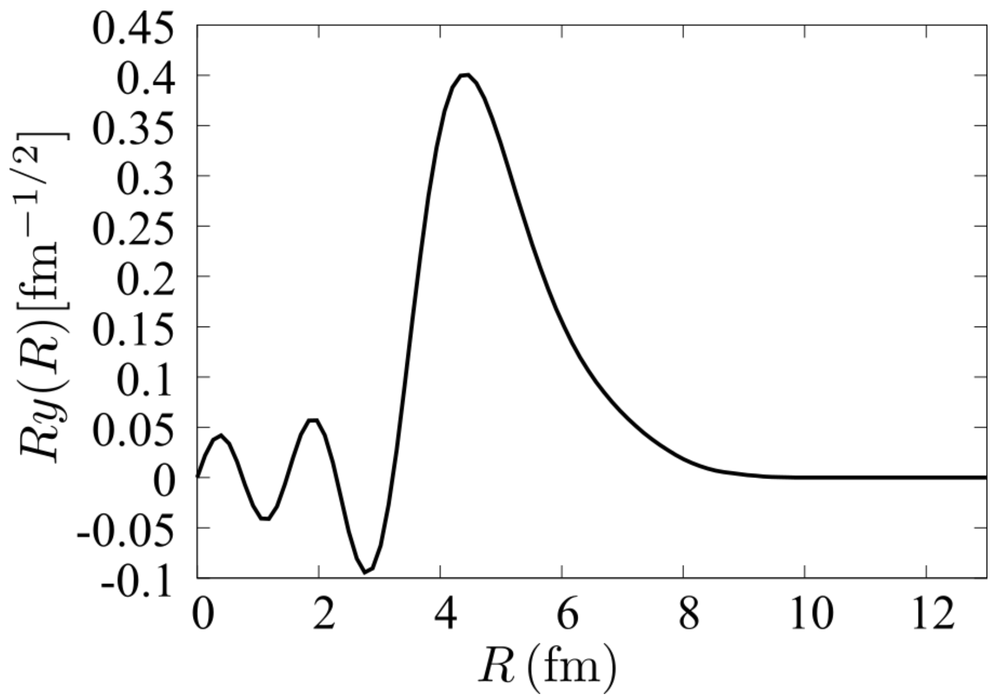
α + ^{16}O state of ^{20}Ne

- α + ^{16}O state in the ^{20}Ne ground state and the reduced-width amplitude (cluster wave function) is described with the Antisymmetrized Molecular Dynamics (AMD) [1].

$$\hat{H} = \sum_{i=1}^{A} \hat{t}_i - \hat{t}_{\rm cm} + \sum_{i<j}^{A} \underline{\hat{v}_{\rm NN}} + \sum_{i<j}^{A} \hat{v}_{\rm Coul}$$

Gogny D1S effective NN interaction [2].

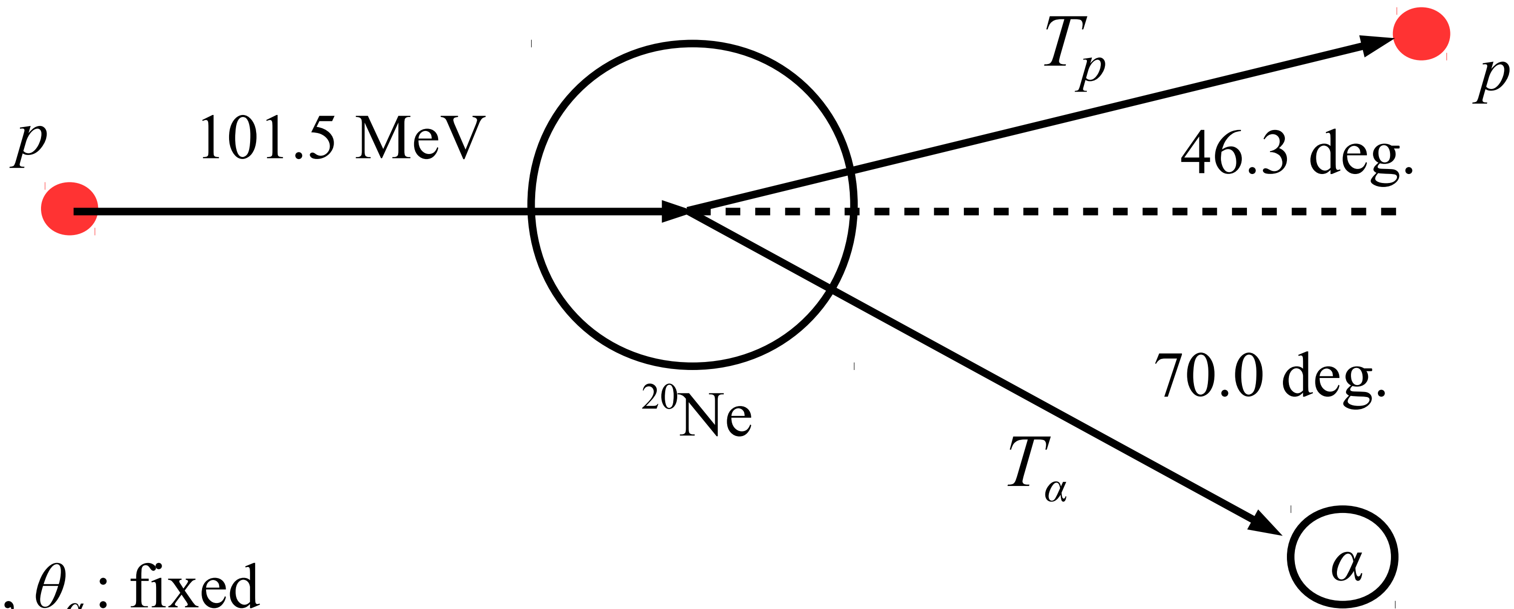
α-cluster wave function



[1] Y. Chiba and M. Kimura, Prog. Theor. Exp. Phys. **2017**, 053D01 (2017).
[2] J. F. Berger, M. Girod, and D. Gogny, Comput. Phys. Commun. 63, 365 (1991).

$^{20}Ne(p,p\alpha)^{16}O$ @101.5 MeV

T. A. Carey *et al*., Phys. Rev. C **29**, 4 (1984).



- θ_p, θ_α : fixed
- T_p, T_α: Varies satisfying the energy conservation
  - ^{16}O has no recoil momentum at $T_p = 63$ MeV, $T_\alpha = 29$ MeV

T_p distribution of the TDX is discussed (energy sharing distribution).

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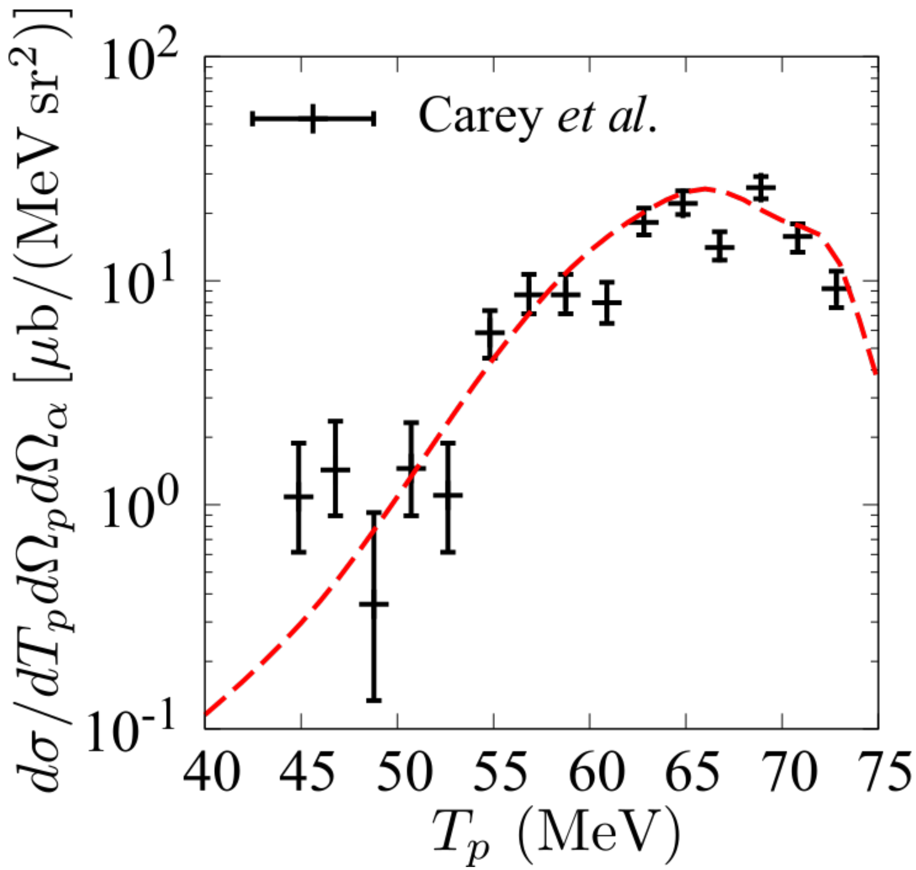

Reaction input

- p-^{20}Ne and p-^{16}O optical potential
  EDAD1 parameterization of the Dirac phenomenology [1].
- α-^{16}O optical potential
  Global fit by Michel *et al*. [2].
- p-α effective interaction
  Melbourne *g*-matrix [3]
  + single-folding model [4]
  (tuned to reproduce p-α differential cross section @ 85 MeV)

[1] S. Hama, B. C. Clark, E. D. Cooper, H. S. Sherif, and R. L. Mercer, Phys Rev. C **41** 2737 (1990);
E. D. Cooper, S. Hama, B. C. Clark, and R. L. Mercer, *ibid*. **47** 297 (1993).
[2] F. Michel *et al*., Phys Rev C 28 5 (1983).
[3] K. Amos *et al*., Advances in Nuclear Physics **25**, 275 (2000).
[4] M. Toyokawa, K. Minomo, and M. Yahiro, Phys. Rev. C **88**, 054602 (2013).

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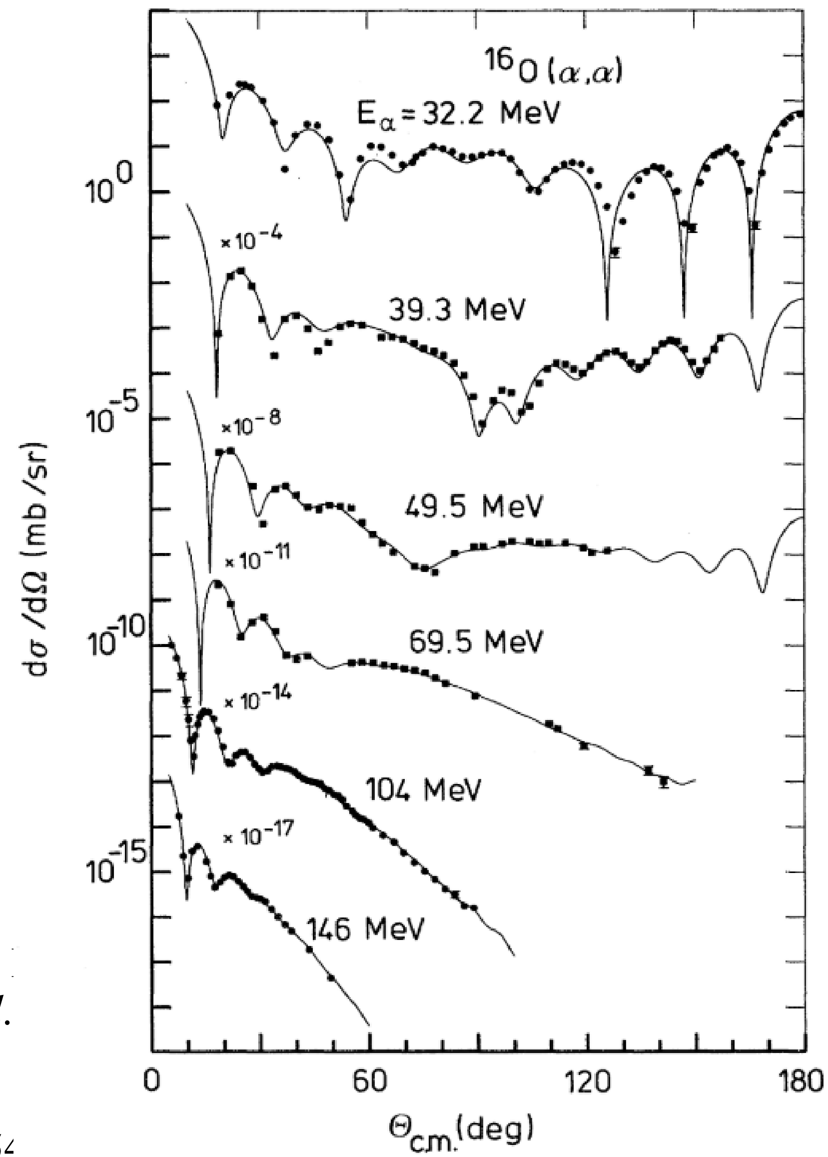

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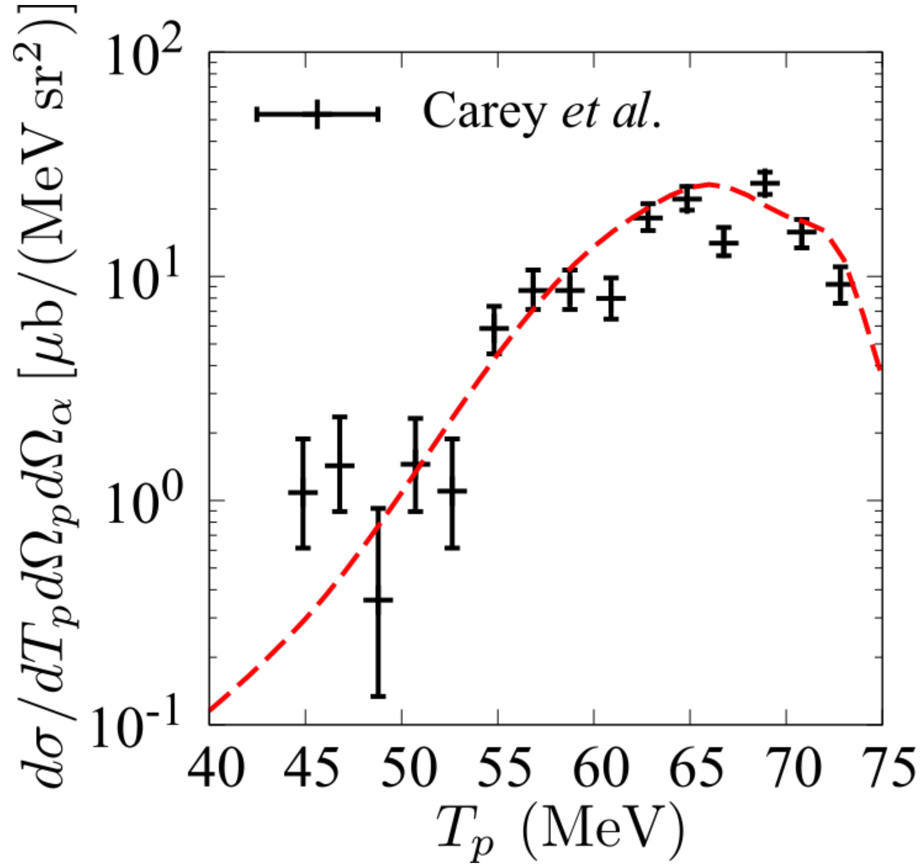

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α formation in Po

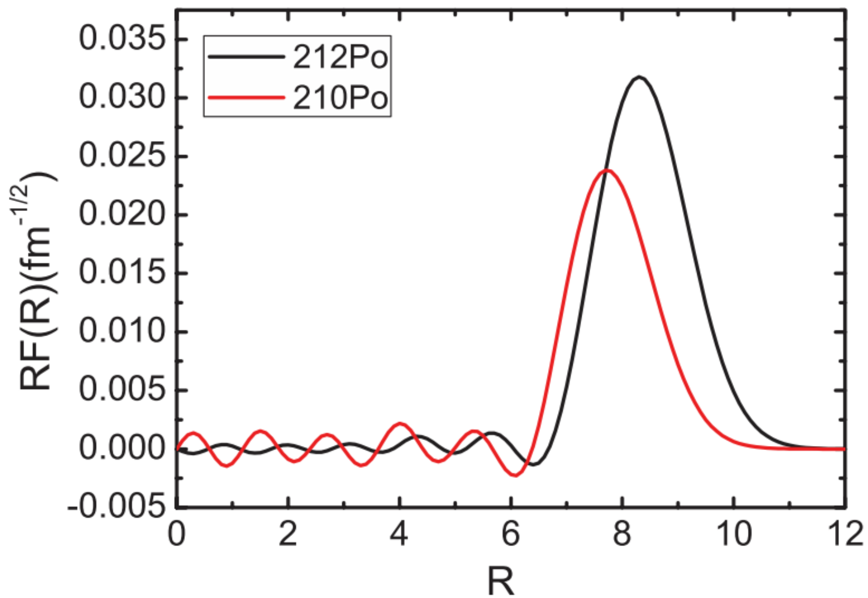
Four-particle state $^{212}\text{Po}(\alpha_4)$ is described by a mixture of *nn* state $^{210}\text{Pb}(\alpha_2)$ and *pp* state $^{210}\text{Po}(\beta_2)$

$$|^{212}\text{Po}(\alpha_4)\rangle = \sum_{\alpha_2\beta_2} X(\alpha_2\beta_2;\alpha_4)|^{210}\text{Pb}(\alpha_2) \otimes {}^{210}\text{Po}(\beta_2)\rangle$$

α-formation amplitude is given by

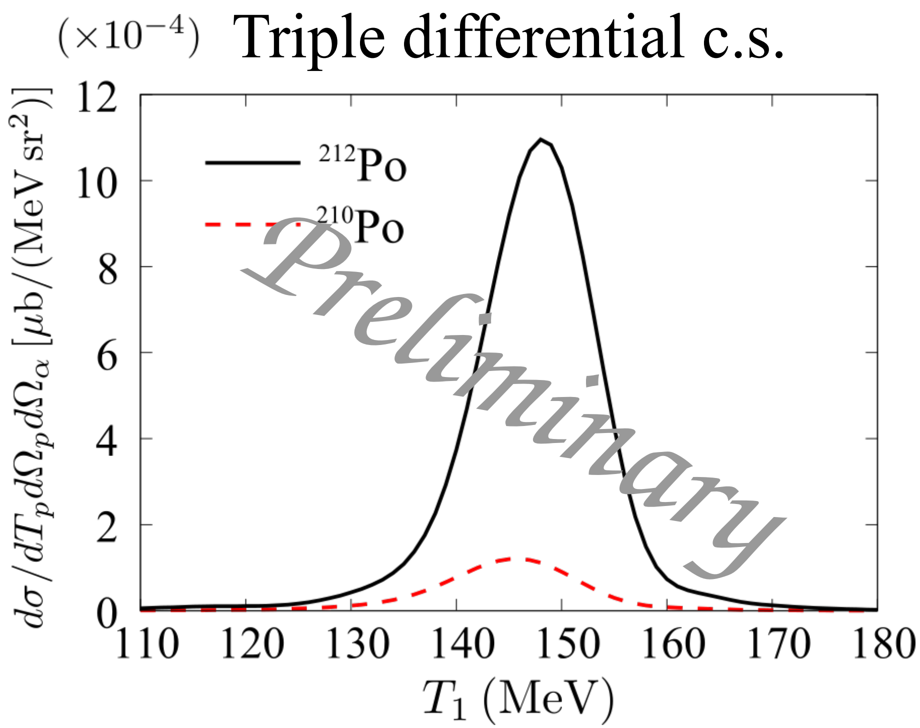
$$\mathcal{F}_\alpha[R;{}^{212}\text{Po(gs)}] = \int d\mathbf{R}d\xi_\alpha\phi_\alpha(\xi_\alpha)\Psi[\mathbf{r_1},\mathbf{r_2};{}^{210}\text{Pb(gs)}] \times \Psi[\mathbf{r_3},\mathbf{r_4};{}^{210}\text{Po(gs)}]$$

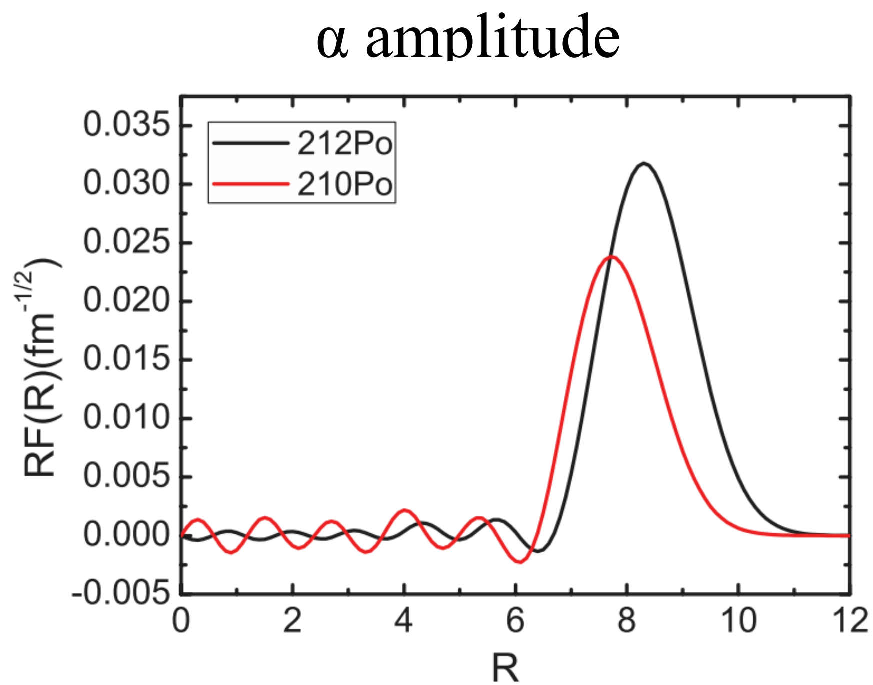
α amplitude



[1] C. Qi *et al.*, Phys. Rev. C **81**, 064319 (2010).

^{210,212}Po(p,$p\alpha$)^{206,208}Pb @ 200 MeV





[1] C. Qi *et al*., Phys. Rev. C **81**, 064319 (2010).

- optical potential
  - p-A: global parameterization by Koning and Delaroche [2]
  - α-A: parameter set by Nolte *et al*. [3]

[2] Koning and Delaroche, Nucl. Phys. A **713**, 231-310 (2003).
[3] M. Nolte, H. Machner, and J. Bojowald, Phys. Rev. C **36**, 4 (1987).

Summary and Perspective

- α-kockout reaction is a powerful reaction probe for α clustering in the ground state
  - Clear one-to-one correspondence between the α amplitude and $(p,p\alpha)$ cross section
  - We have succeeded in reproducing ^{20}Ne$(p,p\alpha)^{16}$O cross section quantitatively with the AMD cluster wave function and the DWIA description of the knockout reaction
- Application of $(p,p\alpha)$ reaction to α-decaying nuclei
  - Change in the α-amplitude in ^{210,212}Po may be seen as a One-order difference in Po$(p,p\alpha)$Pb cross section
- α-knockout reaction on unstable nuclei can be performed in inverse kinematics