Microscopic optical potential and NN interaction in knockout reaction

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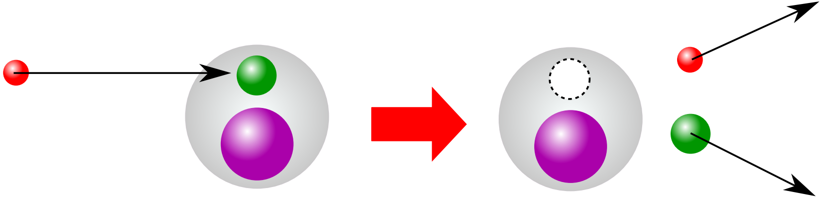
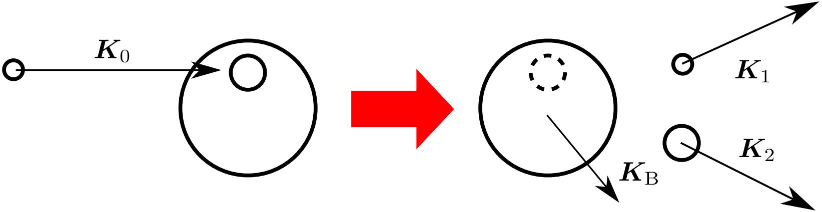
NN int., optical potential and knockout reaction

- I will discuss the relevance of the NN interaction and the optical potential to the nucleon and α knockout reactions.
- Theoretical framework for the knockout reactions: Distorted Waves Impulse Approximation (DWIA)
  - Microscopic and phenomenological inputs for DWIA
    - Optical potential
    - NN interaction
    - Single-particle / α cluster wave function

Particle knockout reaction



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



$$d\sigma = \frac{(2\pi)^4}{\hbar v} d\boldsymbol{K}_1 d\boldsymbol{K}_2 d\boldsymbol{K}_\mathrm{B}\, \delta(\boldsymbol{K}_i - \boldsymbol{K}_f)\delta(E_i - E_f) \quad \times |T|^2$$

conservation law — Transition amp.

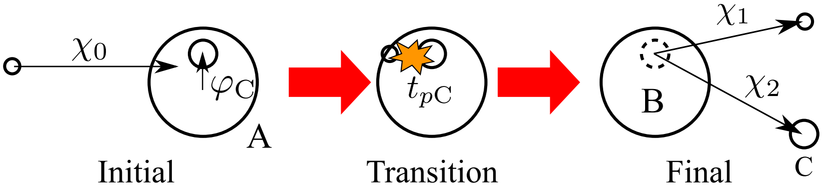
Knockout cross section (Triple differential cross section)

$$\frac{d\sigma}{dE_1 d\Omega_1 d\Omega_2} = \frac{(2\pi)^4}{\hbar v} F_\mathrm{kin} |T|^2$$

F_kin: Kinematical factor

$$F_\mathrm{kin} = \frac{E_1 K_1 E_2 K_2}{(\hbar c)^4}\left[1 + \frac{E_2}{E_\mathrm{B}} + \frac{E_2}{E_\mathrm{B}} \frac{(\boldsymbol{K}_1 - \boldsymbol{K}_0 - \boldsymbol{K}_\mathrm{A})\cdot \boldsymbol{K}_2}{\boldsymbol{K}_2^2}\right]^{-1}$$

Reaction model: Distorted Wave Impulse Approximation



Transition matrix

$$T = \langle \chi_1 \chi_2 \Phi_C \Phi_B \,|\, t_{pC} \,|\, \chi_0 \Phi_A \rangle = \langle \chi_1 \chi_2 \,|\, t_{pC} \,|\, \chi_0 \varphi_C \rangle$$

χ_i: Distorted waves under optical potentials

t_{pC}: p-C effective interaction in free space

φ_C: Cluster wave function $\langle [\Phi_C \otimes \Phi_B] \,|\, \Phi_A \rangle$

Knockout cross section (Triple differential cross section)

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

Our knockout reaction code: PIKOE

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Computer Programs in Physics

PIKOE: A computer program for distorted-wave impulse approximation calculation for proton induced nucleon knockout reactions ☆

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Optical potential and NN interaction

- Phenomenological optical potential (for stable nuclei)
  - Koning-Delaroche optical potential [1]
  - Dirac phenomenology [2]
- Folding model calculation: effective NN int. + nuclear density
  - Franey-Love effective int. (free space) [3]
  - Melbourne g-matrix int. (in-medium) [4]
  - Chiral effective int. [5]
  - Density profile from structure theories
- Dispersive Optical Model (DOM): Optical potential and s.p.w.f. on the same footing [6][7]

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[1] A. Koning and J. Delaroche, NPA **713**, 231 (2003).
[2] S. Hama *et al.* PRC **41**, 2737 (1990).
[3] M. A. Franey and W. G. Love, PRC **31**, 488 (1985).
[4] K. Amos *et al.* Adv. Nucl. Phys. **25**, 276 (2000).
[5] E. Epelbaum *et al.* NPA **747**, 362 (2005).
[6] W. H. Dickhoff *et al.* J. of Phys. G: Nucl. and Part. Phys. **44**, 033001 (2017).
[7] M. C. Atkinson *et al.* PRC **98**, 044627 (2018).

Structure (s.p.w.f./Cluster w.f./Density profile)

- Phenomenology (Woods-Saxon pot.)
- Shell model
- Few-body method
  - No core shell model [8]
  - Gaussian expansion: $\alpha + p + n$ for ^{6}Li$(p, pn)^{5}$He reaction [9]
- Anti-symmetrized molecular dynamics (AMD) [10]
- Tohsaki-Horiuchi-Schuck-Röpke (THSR) w.f. [11]
- Mean-field type theories [12, 13]

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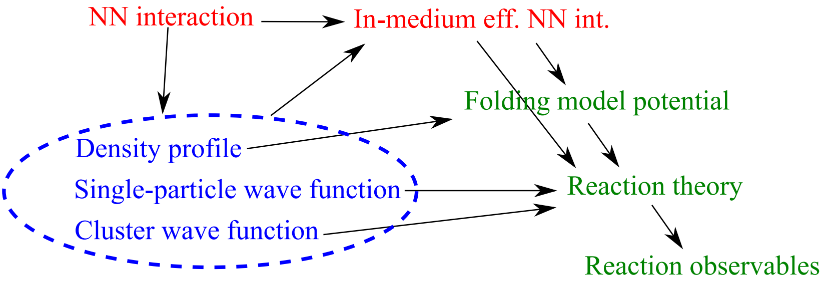
[8] T. Otsuka *et al.* Nature Communications **13**, 2234 (2022).
[9] S. Ogawa *et al.* arXiv:2404.17814 (2024).
[11] A. Tohsaki *et al.* PRL **87**, 192501 (2001).
[12, 13] S. Typel, PRC **89**, 064321 (2014), T. Nakatsukasa and N. Hinohara, PRC **108**, 014318 (2023).

Consistency between NN int., structure, and reaction

- In-medium effective NN interaction is the key interface for the (knockout) reaction theory
- Can we describe both the structure and the scattering (reaction) based on the same NN interaction?



. . . ultimate goal?

Distorted Wave Impulse Approximation (DWIA)

- Quasi-free scattering and distortion effect

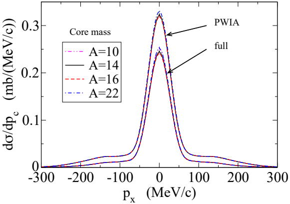
Quantum Transfer-to-the-Continuum model (QTC)

- Coupled channels problem with discretized continuum states

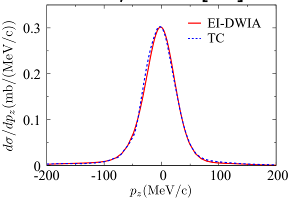
Faddeev theory

- Exact solution of the three-body scattering problem

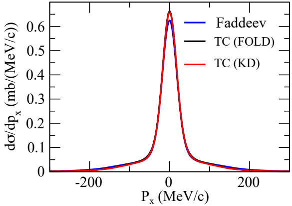
DWIA/Faddeev [14]



DWIA/QTC [15]



QTC/Faddeev [16]



[14] E. Cravo *et al.* PRC **93**, 054612 (2016). [15] K. Yoshida *et al.* PRC **97**, 024608 (2018). [16] M. Gómez-Ramos *et al.* PRC **102**, 064613 (2020).

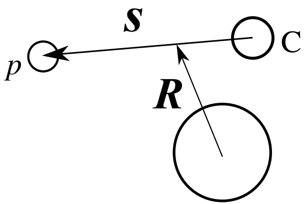
Plane-wave limit (PWIA)

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

p-C collision — Structure

Knockout cross section

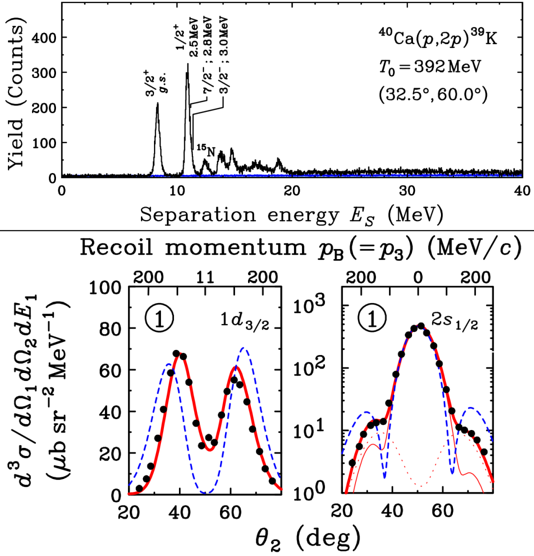
$$
|T|^2 \to \frac{d\sigma_{pC}}{d\Omega_{pC}} \, |\tilde{\varphi}_C(\boldsymbol{k}_C)|^2
$$



Hight $\leftrightarrow$ Spectroscopic factor

Width $\leftrightarrow$ momentum distribution

Single-particle orbital and shape of cross section



Figs.: T. Wakasa *et al.* PPNP **96**, 32 (2017)

First application of Dispersive Optical Model to $(p,2p)$

PHYSICAL REVIEW C **105**, 014622 (2022)

First application of the dispersive optical model to $(p, 2p)$ reaction analysis within the distorted-wave impulse approximation framework

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First application of Dispersive Optical Model to $(p,2p)$

K. Yoshida, M. C. Atkinson, K. Ogata, and W. H. Dickhoff, PRC **105**, 014622 (2022).

^{40}Ca$(p,2p)^{39}$K$_{g.s.}$ @ 197 MeV

- Knockout from $0d_{3/2}$
- T_1^{L} distribution of TDX
- Inconsistent with $(e,e'p)$ result by $\sim 20\%$: $\mathcal{Z}_{0d_{3/2}} = 0.71$
- Need for in-medium, off-shell p-p interaction?

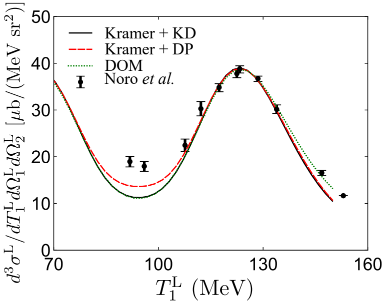

TABLE I. Setup and resulting spectroscopic factors.

SPWF	Optical pot.	p-p int.	$\mathcal{Z}_{0d_{3/2}}$
Kramer	KD	FL	0.623 ± 0.006
Kramer	Dirac	FL	0.672 ± 0.006
DOM	DOM	FL	0.560 ± 0.005
DOM	DOM	Mel	0.489 ± 0.005
DOM	DOM	Mel (free)	0.515 ± 0.005

3NF effect on $(p, 2p)$ cross section

PHYSICAL REVIEW C **96**, 024609 (2017)

Probing three-nucleon-force effects via $(p,2p)$ reactions

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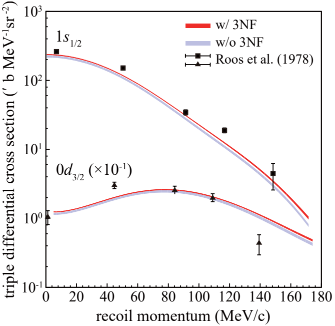
(Received 28 April 2017; published 10 August 2017)

3NF effect on $(p, 2p)$ cross section

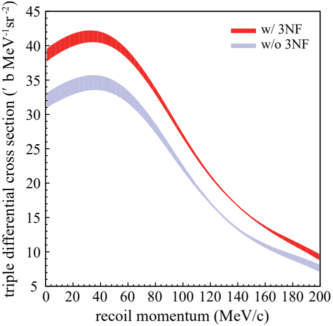
K. Minomo *et al.* PRC **96**, 024609 (2017)

^{40}Ca$(p, 2p)^{39}$K reaction analysis using the chiral interactions [5]

Knockout from $1s_{1/2}$ and $0d_{3/2}$



Knockout from $0p_{3/2}$



- Clear 3NF effect in the knockout cross section from $0p_{3/2}$ orbit.
- Mean densities: $\bar{\rho}(1s_{1/2}) = 0.022$, $\bar{\rho}(0p_{3/2}) = 0.076$ fm^{-3}.

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[5] E. Epelbaum *et al.* NPA **747**, 362 (2005).

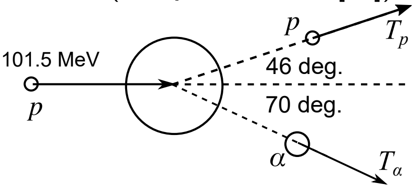
$\alpha+^{16}$O cluster state in ^{20}Ne$_{g.s.}$

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]

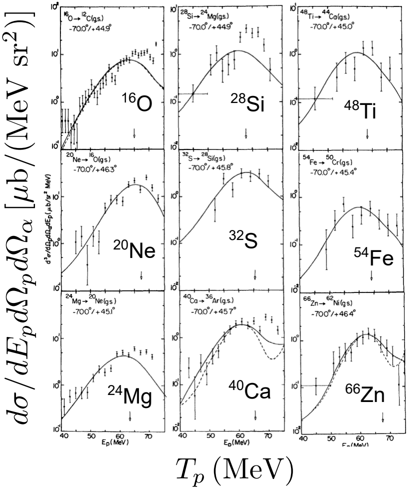
Systematic experiment of $(p,p\alpha)$ reaction (Carey *et al.* 1984 [19])



Kinematical setup

Targets

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



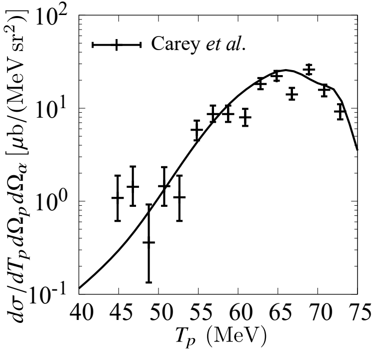
[19] T. A. Carey *et al.* PRC **29**, 1273 (1984).

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

Carey *et al.* (1984) [19].

- α cluster wave function by a Woods-Saxon potential
- $S_\alpha = 0.54$ (exp. + reaction)
- $S_\alpha = 0.18$
- 0.23 (Structure theory [20–22])

Inconsistent by a factor of two

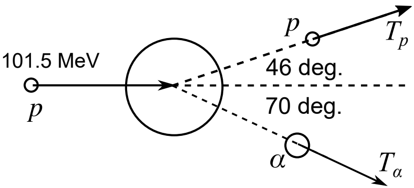


K. Yoshida *et al.* (2019) [23].

- DWIA + AMD wave function [10]
- $S_\alpha = 0.26$ (Consistent)

[19] T. A. Carey *et al.* PRC **29**, 1273 (1984). [20] W. Chung *et al.* PLB **79**, 381 (1978). [21] J. Draayer, NPA **237**, 157 (1975). [22] K. Hecht and D. Braunschweig, NPA **244**, 365 (1975). [23] K. Yoshida *et al.* PRC **100**, 044601 (2019).
[10] Y. Chiba and M. Kimura, PTEP **2017**, 053D01 (2017).

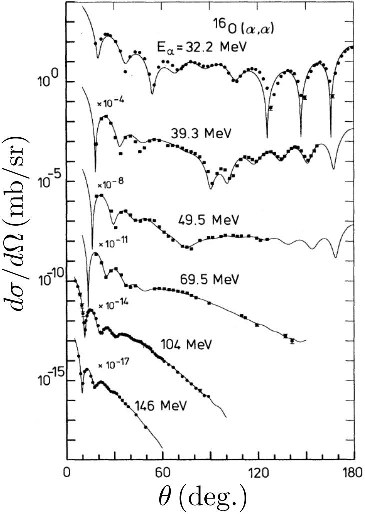
Validity of optical potential



Nice fit of the optical potential by Michel *et al.* [24]

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

α-^{16}O differential cross section

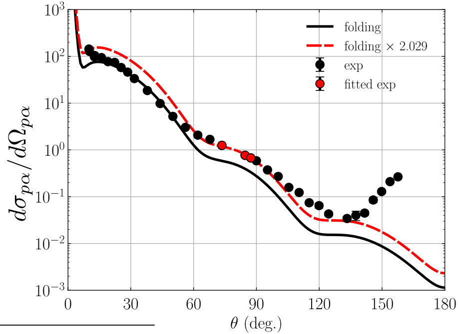


[24] F. Michel *et al.* PRC **28**, 1904 (1983).

Tuning the p-α cross section

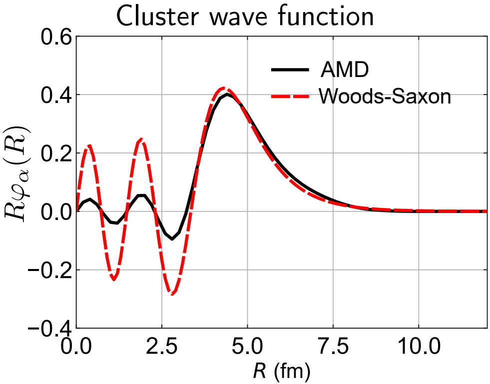
- The folding model [25] using the Melbourne g-matrix [4] for calculating $d\sigma_{p\alpha}/d\Omega_{p\alpha}$
- p-α cross section is scaled to fit the required $E_{p\alpha}$ and $\theta_{p\alpha}$ relevant to the $(p,p\alpha)$ kinematics

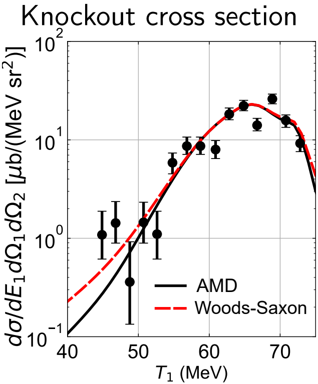
p-α differential cross section



[25] M. Toyokawa *et al.* PRC **88**, 054602 (2013).
[4] K. Amos *et al.* Adv. Nucl. Phys. **25**, 276 (2000).

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).

PTEP

Prog. Theor. Exp. Phys. **2024** 013D01(16 pages)
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Global density-dependent α–nucleon interaction for α–nucleus elastic scattering

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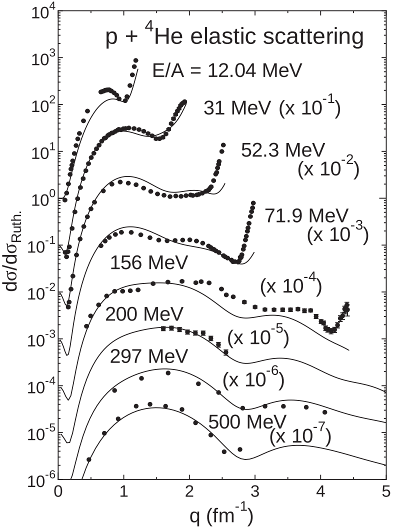
Folding potential for α scattering

T. Furumoto *et al.* PTEP **2024**, 013D01 (2023)

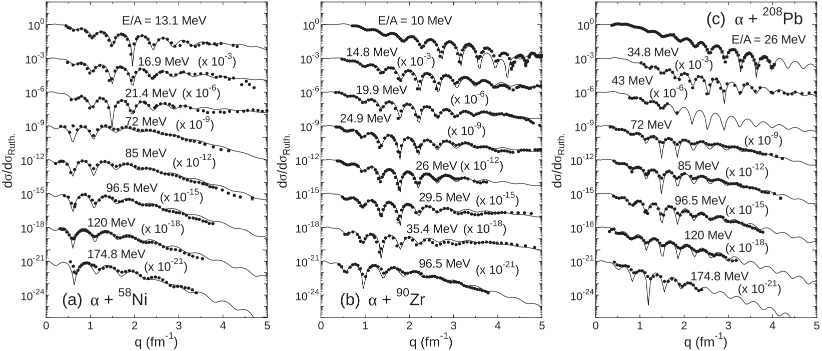
- α-A potential based on the density-dependent α-nucleon interaction and the folding model.
- Strategy: Phenomenological density-dependent double Woods-Saxon shaped α-N interaction

$\downarrow$

Folding calculation by the density profile of the mean-field theory.



α-A differential cross sections for wide mass and energy ranges



T. Furumoto *et al.* PTEP **2024**, 013D01 (2023)

- The folding model for the consistency between the optical potential and the NN interaction
- DOM for the optical potential and the single-particle wave function (and NN interaction? Talk by M. Atkinson on Thur.)
- In the α knockout case, ^{20}Ne$(p, p\alpha)^{16}$O data can be quantitatively reproduced, but heavy and unstable nuclei are challenging