Development of Microscopic Effective Reaction Theory for Nuclear Transmutation Studies

ImPACT International Symposium on
"New Horizons of Partitioning and Transmutation Technologies with Accelerator System"
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**FRIB / Michigan State University*

This work was funded in part by ImPACT Program of Council for Science, Technology and Innovation (Cabinet Office, Government of Japan).

Plan of this talk

I. Brief summary of our activities / achievements

II. Microscopic description of nucleon-nucleus scattering

M. Toyokawa, M. Yahiro, T. Matsumoto, K. Minomo, KO, and M. Kohno, PRC ***92****, 024618 (2015).*

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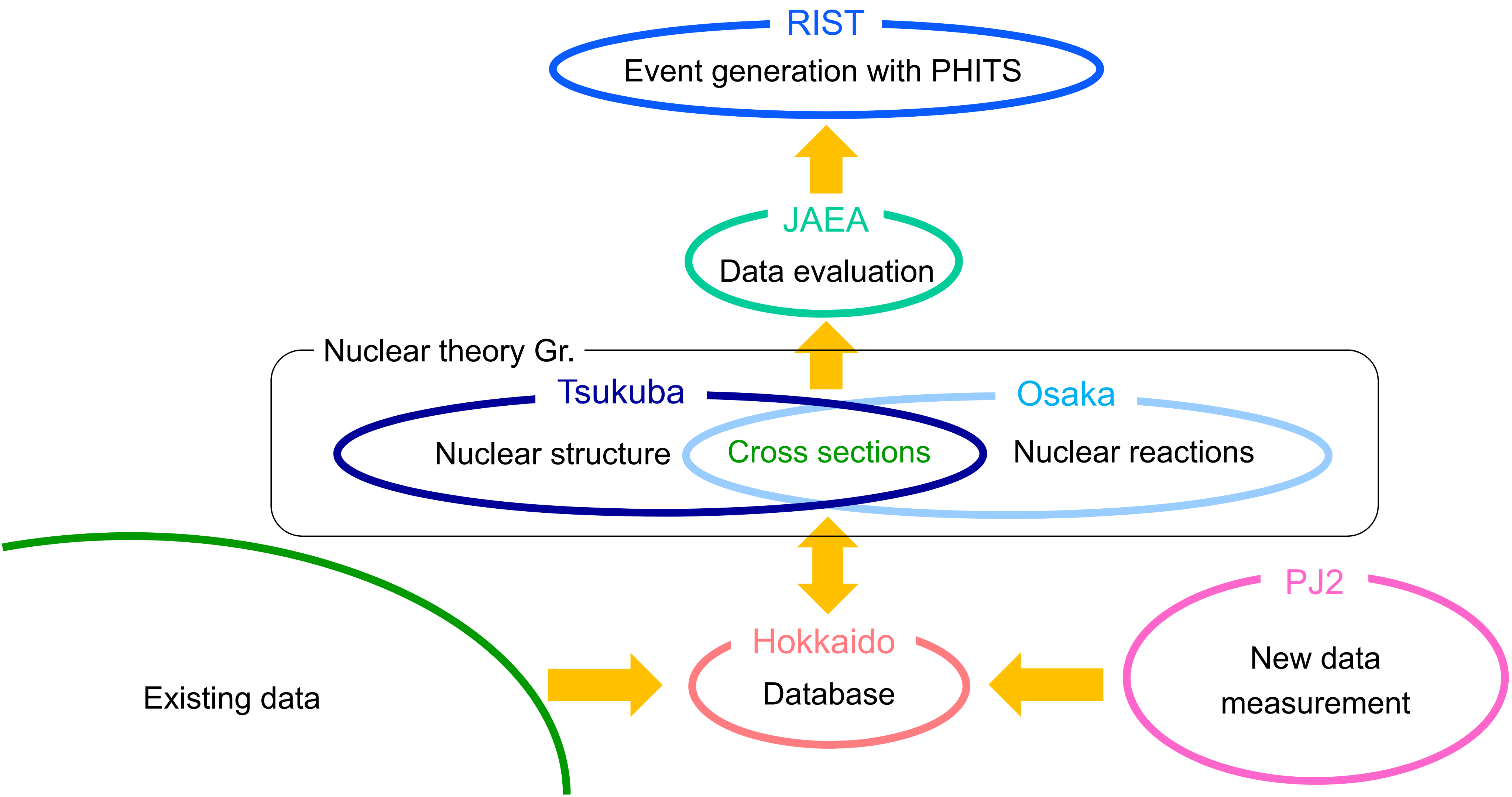
K. Minomo, K. Washiyama, and KO, JNST ***54****, 127 (2017).*

IV. Toward a more realistic description of one-nucleon knockout processes

S. Weili, Y. Watanabe, M. Kohno, KO, and M. Kawai, PRC ***60****, 064605 (1999).*
KO, arXiv:1801.09994.

V. Summary

Role Assignment in PJ3



Publications (peer reviewed journal papers)

1. K. Ogata, K. Yoshida, and K. Minomo, "*Asymmetry of the parallel momentum distribution of (p,pN) reaction residues*", Phys. Rev. C **92** 034616 (2015).
2. K. Minomo, K. Kohno, and K. Ogata, "*Microscopic coupled-channel calculations of nucleus-nucleus scattering including chiral three-nucleon-force effects*", Phys. Rev. C **93**, 014607 (2016).
3. K. Minomo and K. Ogata, "*Consistency between the monopole strength of the Hoyle state determined by structural calculation and that extracted from reaction observables*", Phys. Rev. C **93**, 051601(R) (2016).
4. K. Yoshida, K. Minomo, and K. Ogata, "*Investigating α clustering on the surface of ^{120}Sn via the (p,pα) reaction, and the validity of the factorization approximation*", Phys. Rev. C **94**, 044604 (2016).
5. Y. S. Neoh, K. Yoshida, K. Minomo, and K. Ogata, "*Microscopic effective reaction theory for deuteron-induced reactions*", Phys. Rev. C **94**, 044619 (2016).
6. K. Ogata and K. Yoshida, " *Applicability of the continuum-discretized coupled-channels method to the deuteron breakup at low energies*", Phys. Rev. C **94**, 051603(R) (2016).
7. K. Minomo, K. Washiyama, and K. Ogata, "Deuteron-nucleus total reaction cross sections up to 1 GeV", J. Nucl. Sci. Technol. **54**, 127 (2017).
8. Y. Chazono, K. Yoshida, K. Ogata, "Examination of the adiabatic approximation for (*d, p*) reactions", Phys. Rev. C **95**, 064608 (2018).

+ 3 peer-reviewed conference proceedings and 18 oral presentations (including a lecture at high school)

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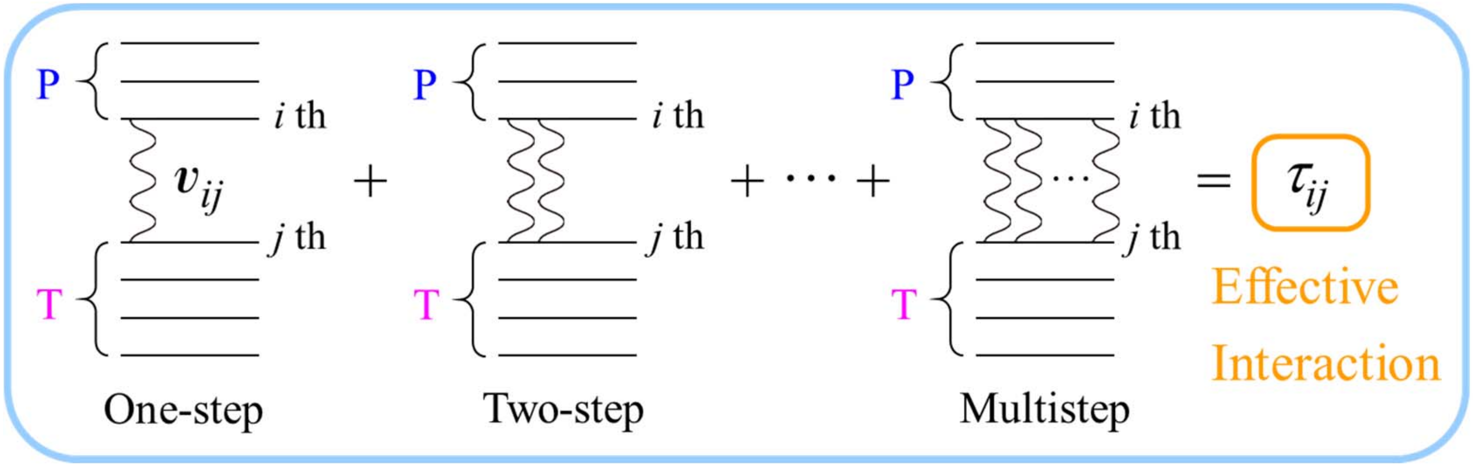
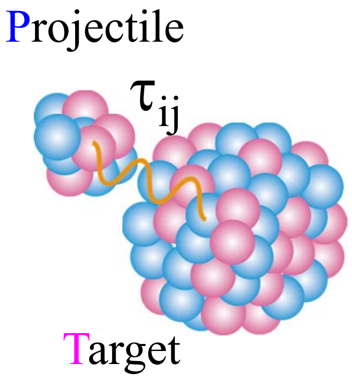
Phenomenology to Microscopic Theory

TABLE I. Optical-Model Parameters Neutrons

NUCLIDE	ENERGY	REAL POTENTIAL			VOL.IMAG. POTENTIAL			SURF.IMAG. POTENTIAL			SPIN-ORBIT POTENTIAL			ST	SR	FIT	NOTE	REF.
	(MEV)	V	R	A	W	RW	AW	WD	RD	AD	VSO	RSO	ASO					
AL	1.	40.	1.25*	0.65*				5.0G*	1.25*	0.98*	10.*	1.25*	0.65*	3520	1340	S3	15	GIL63
AL	1.5	47.4	1.25*	0.46				6.3G	1.25*	0.98*	10.*	1.25*	0.46	3204		S1	10	KOR68
AL	2.47	48.0	1.14	0.65				8.42	1.19	0.48*	8.0*	1.14	0.65	2530	1270	S2	2	HOL71
AL	3.00	47.9	1.13	0.72				7.35	1.08	0.48*	8.0*	1.13	0.72	2520	1250	S2	2	HOL71
AL	3.49	48.7	1.18	0.61				8.46	1.29	0.48*	8.0*	1.18	0.61	2360	1130	S1	2	HOL71
AL	4.00	49.1	1.20	0.62				7.99	1.26	0.48*	8.0*	1.20	0.62	2290	1090	S2	2	HOL71
AL	4.56	50.2	1.18	0.59				8.38	1.26	0.48*	8.0*	1.18	0.59	2060	1020	S1	2	HOL71
AL	6.09	47.8	1.20	0.67				8.23	1.23	0.48*	8.0*	1.20	0.67	1880	1070	S3	2	HOL71
AL	7.	45.5	1.25*	0.65*				9.5G	1.25*	0.98*	8.6	1.25*	0.65*			X3		BJO58
AL	7.05	49.1	1.20	0.68				7.90	1.20	0.48*	8.0*	1.20	0.68	1800	1040	S2	2	HOL71
AL	7.97	49.4	1.20	0.69				12.1	1.30	0.41	9.8	1.20	0.69			S1	2	BRA72

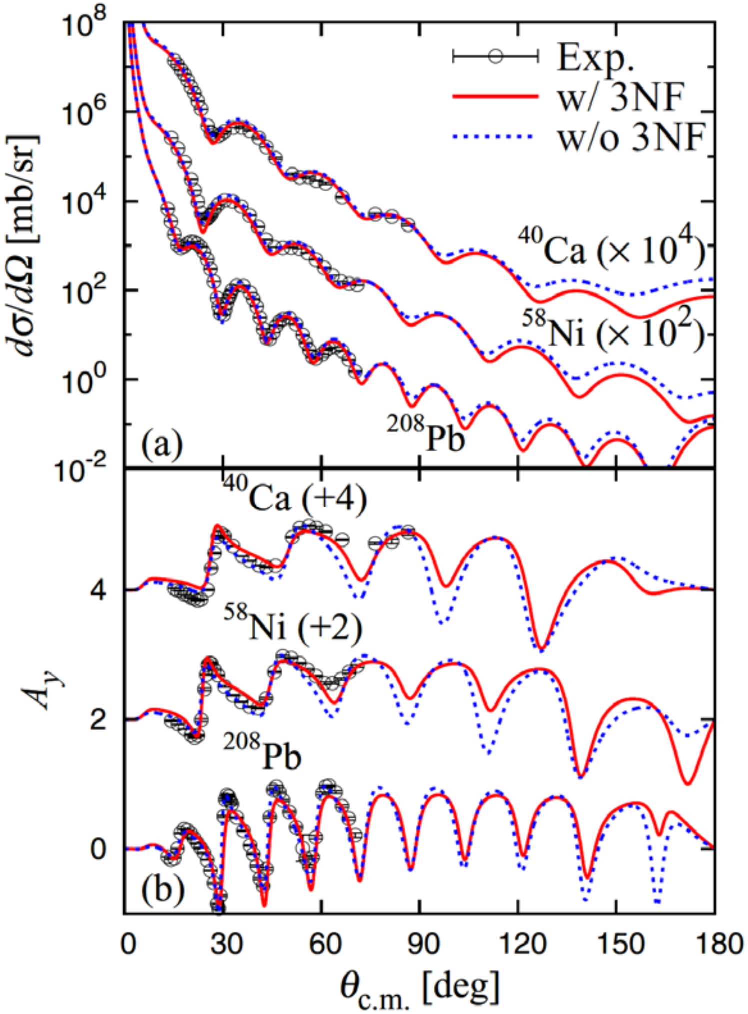




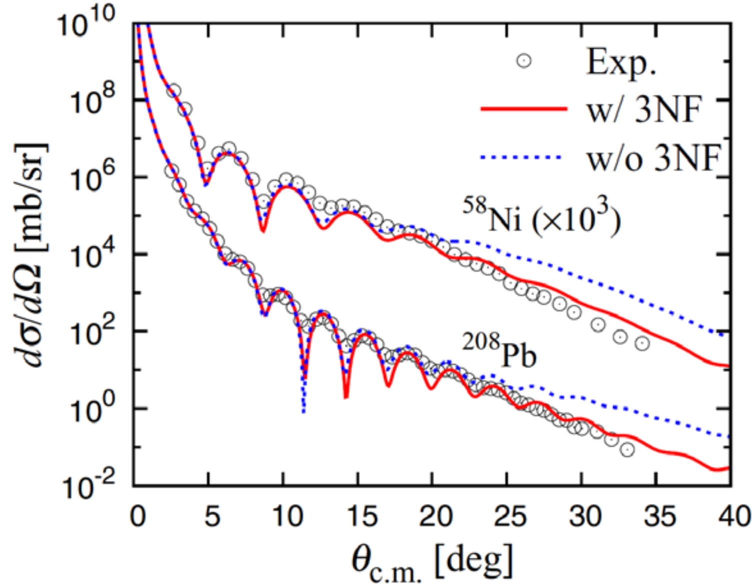
M. Yahiro, K. Minomo, KO, and M. Kawai, PTP **120**, 767 (2008).

Success of microscopic optical potential

p scattering at 65 MeV



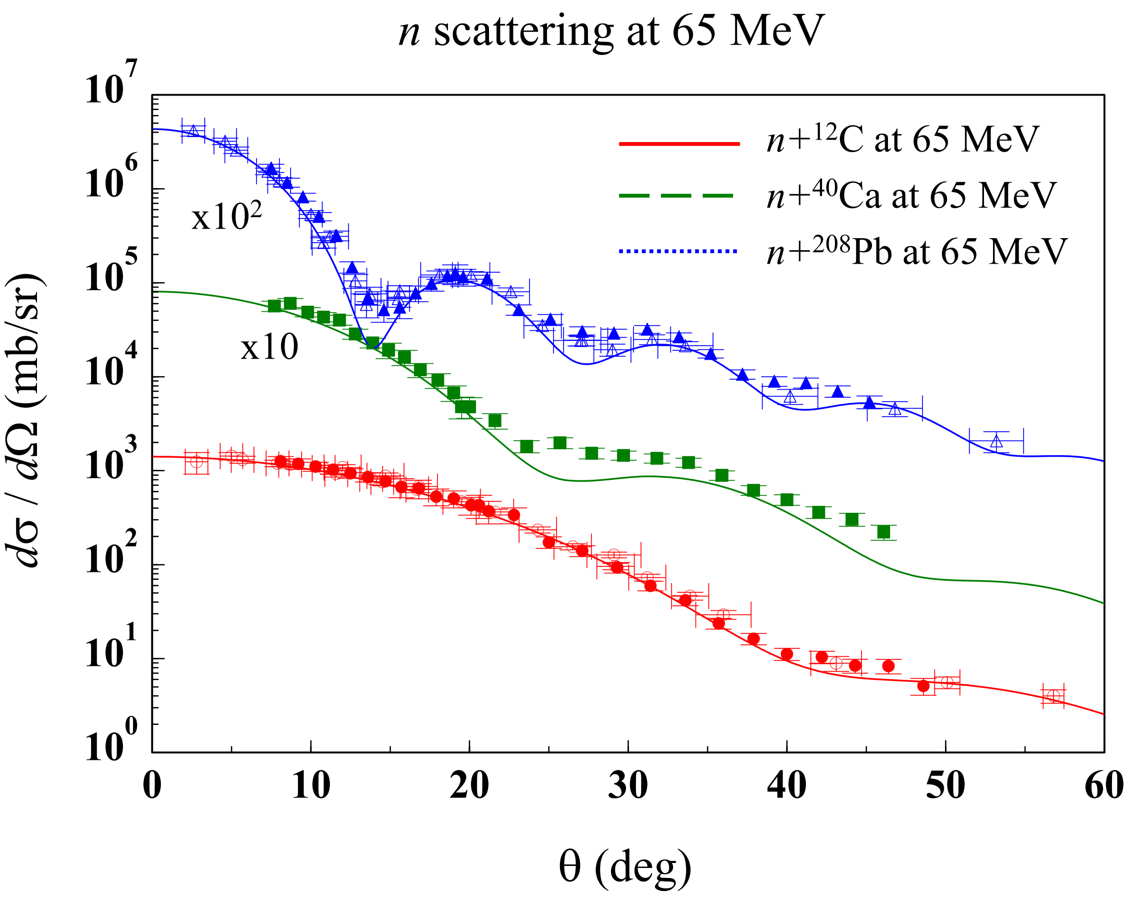
α scattering at 72 A MeV



No free parameter ("prediction")

M. Toyokawa, M. Yahiro, T. Matsumoto, K. Minomo, KO, and M. Kohno, PRC **92**, 024618 (2015).

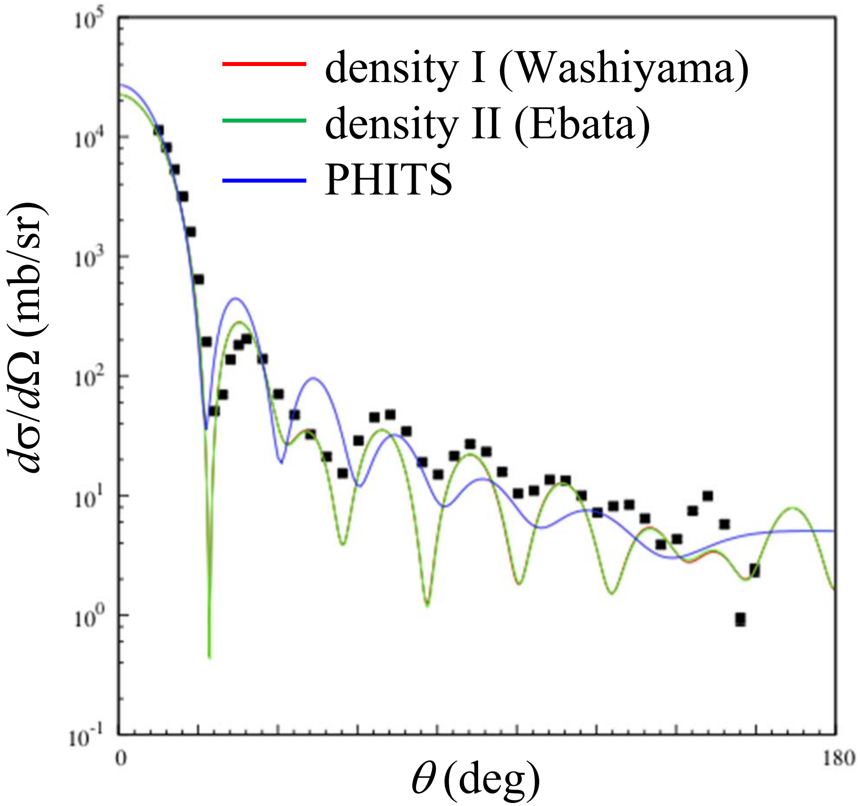
Success of microscopic optical potential (ctnd.)



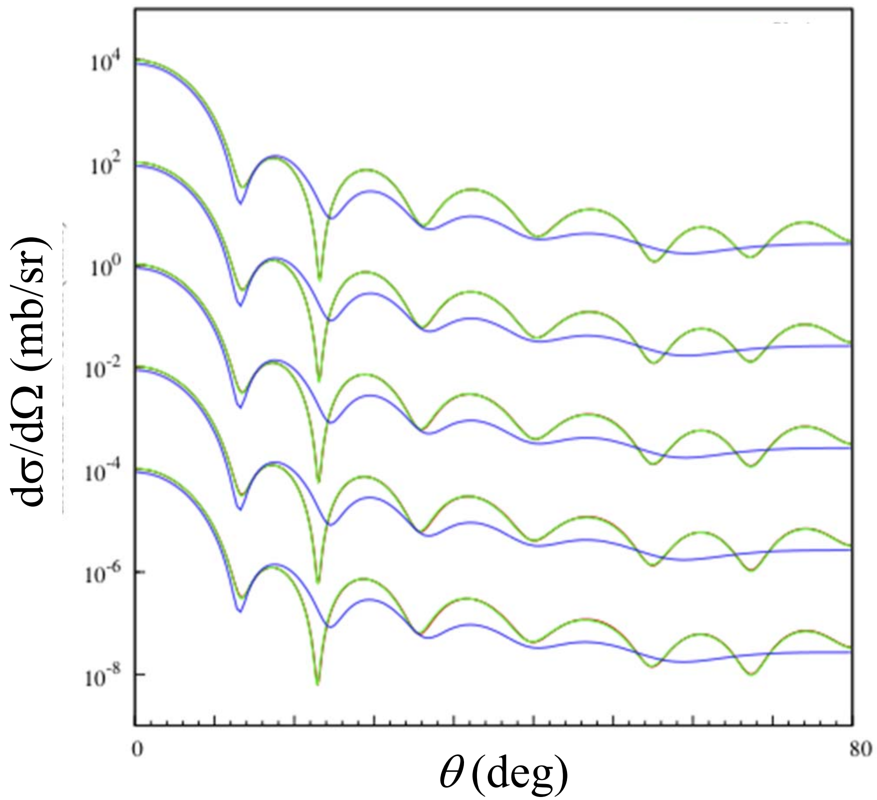
No free parameter ("prediction")

Examination of PHITS

n-^{208}Pb at 24 MeV

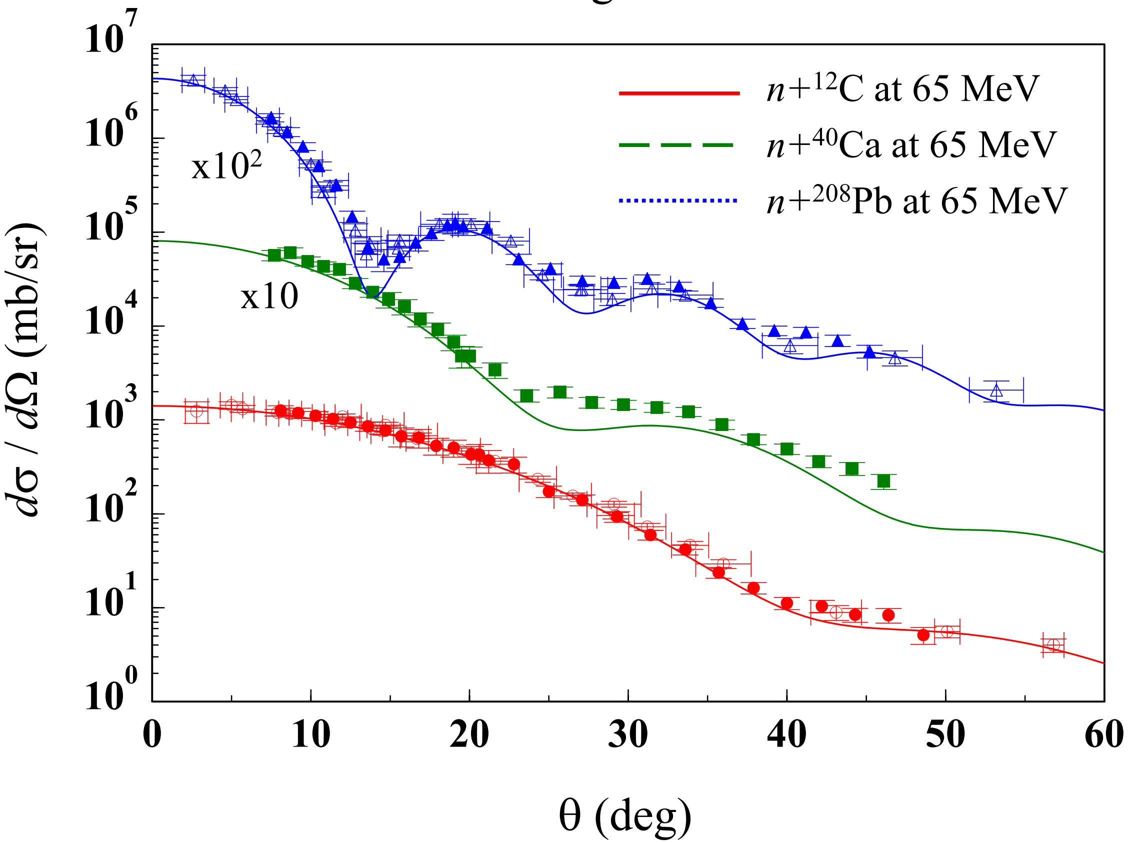


n-$^{104-108}$Pd at 24 MeV



We have validated nucleon-nucleus cross sections implemented in PHITS.

Success of microscopic optical potential (ctnd.)



No free parameter ("prediction")

NOTE

- We can microscopically describe the nucleon elastic scattering and the total reaction cross section (not shown).
- We cannot describe all the reaction processes of the nucleon-nucleus system.
- Thus, our framework is not ab-initio but an <u>effective</u> microscopic theory

"Predictability" and wide applicability

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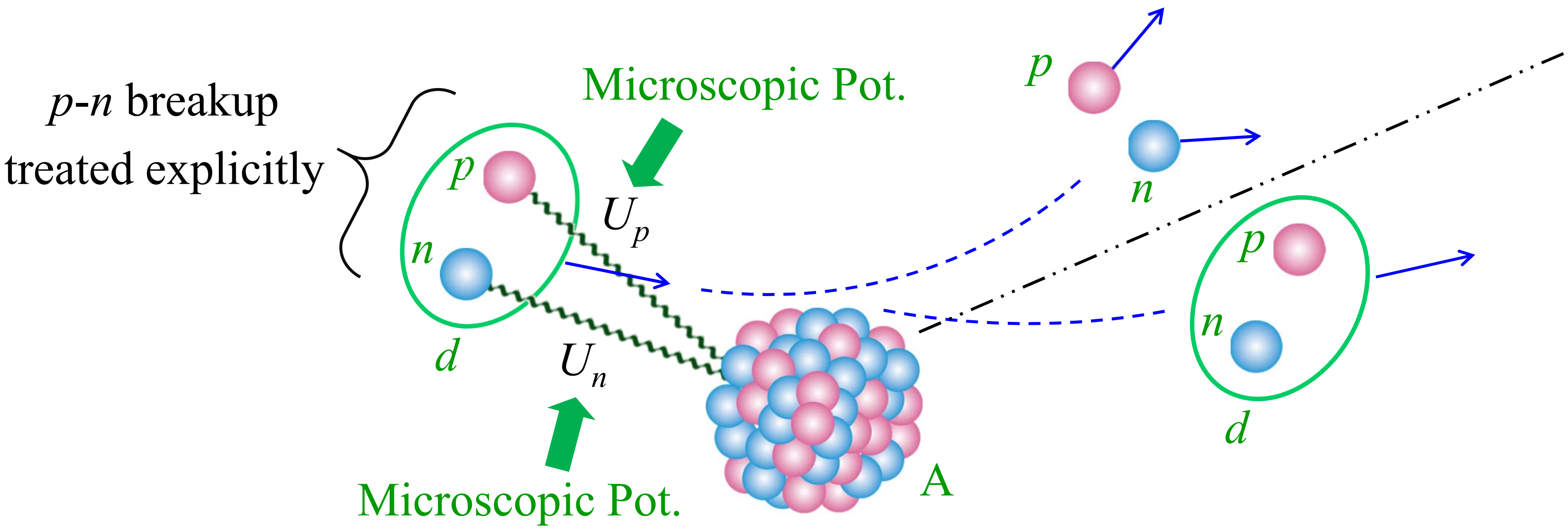
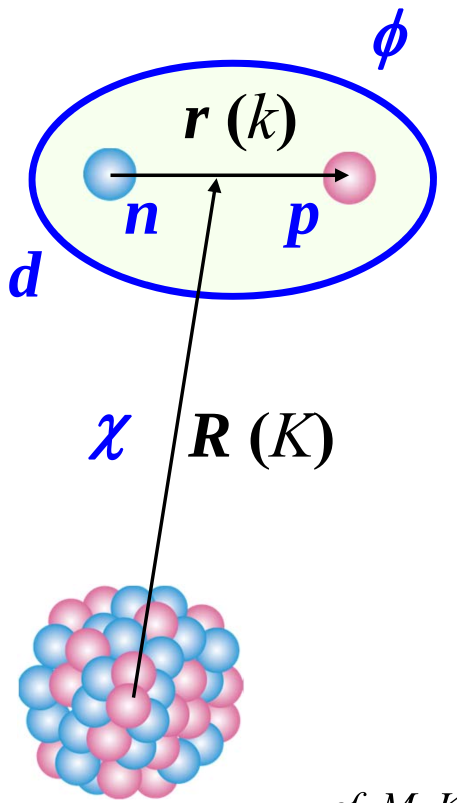
Microscopic description of deuteron scattering

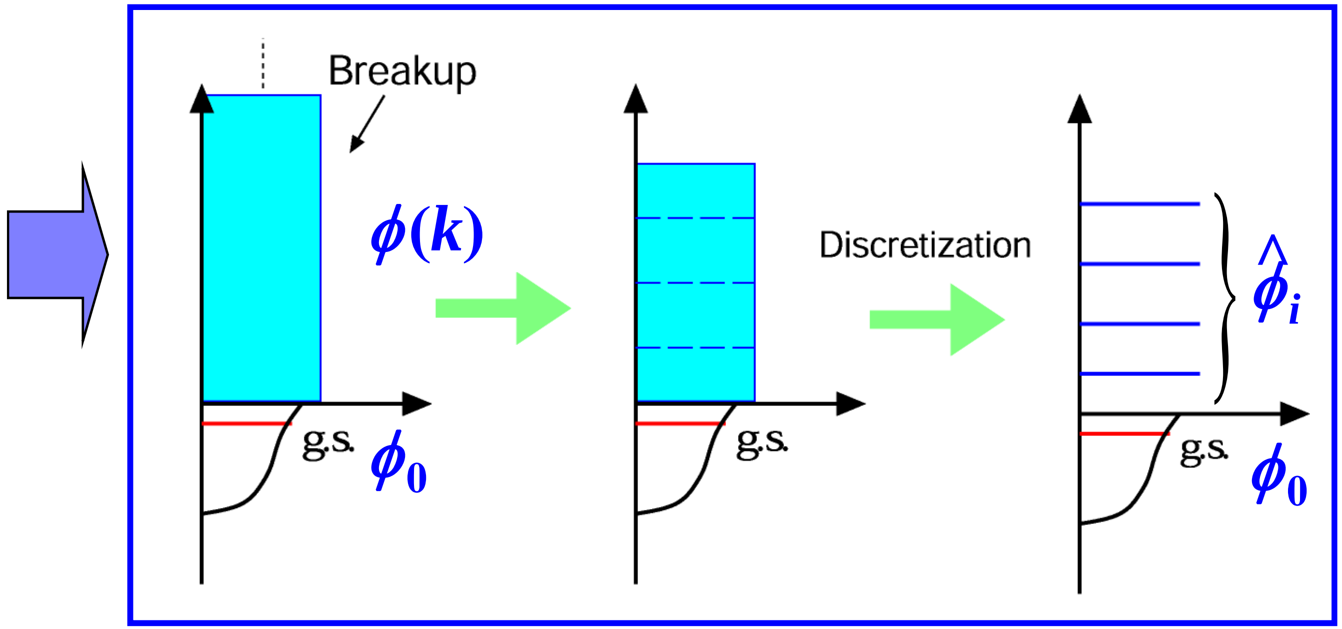


Microscopic <u>Effective</u> Reaction Theory (MERT)

1. Degrees of freedom selected (= setting model space)
2. Distorting ("Mean-field") potential generated microscopically
3. Reaction process due to residual interaction calculated with 1. and 2.

The Continuum-Discretized Coupled-Channels method: CDCC

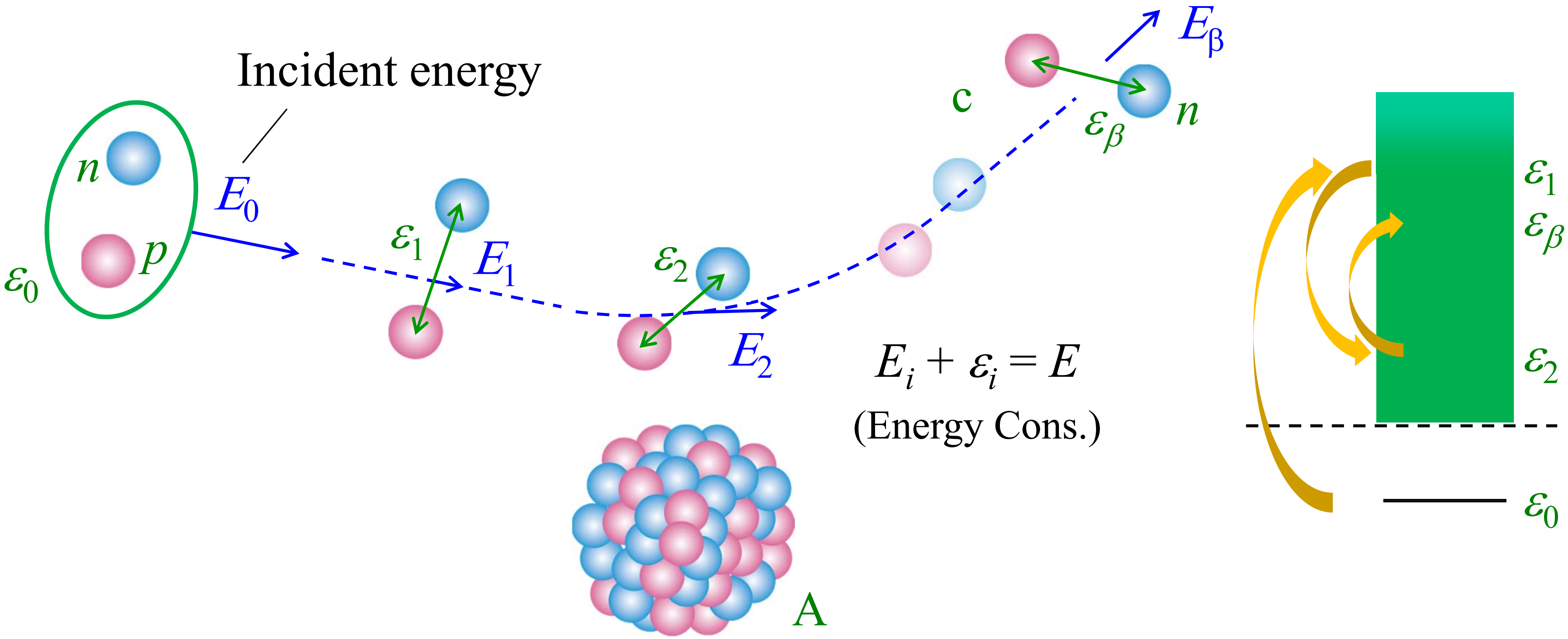




$$\psi = \phi_0 \chi_0 + \int_0^\infty \phi_k \chi_k dk \Rightarrow \psi^{\mathrm{CDCC}} = \sum_i^{i_{\max}} \hat{\phi}_i \hat{\chi}_i$$

cf. *M. Kamimura, Yahiro, Iseri, Sakuragi, Kameyama, and Kawai, PTP Suppl.* **89**, *1 (1986);*
N. Austern, Iseri, Kamimura, Kawai, Rawitscher, and Yahiro, Phys. Rep. **154** *(1987) 126;*
M. Yahiro, Ogata, Matsumoto, and Minomo, PTEP **2012**, *01A206 (2012).*

Description of deuteron breakup process by CDCC



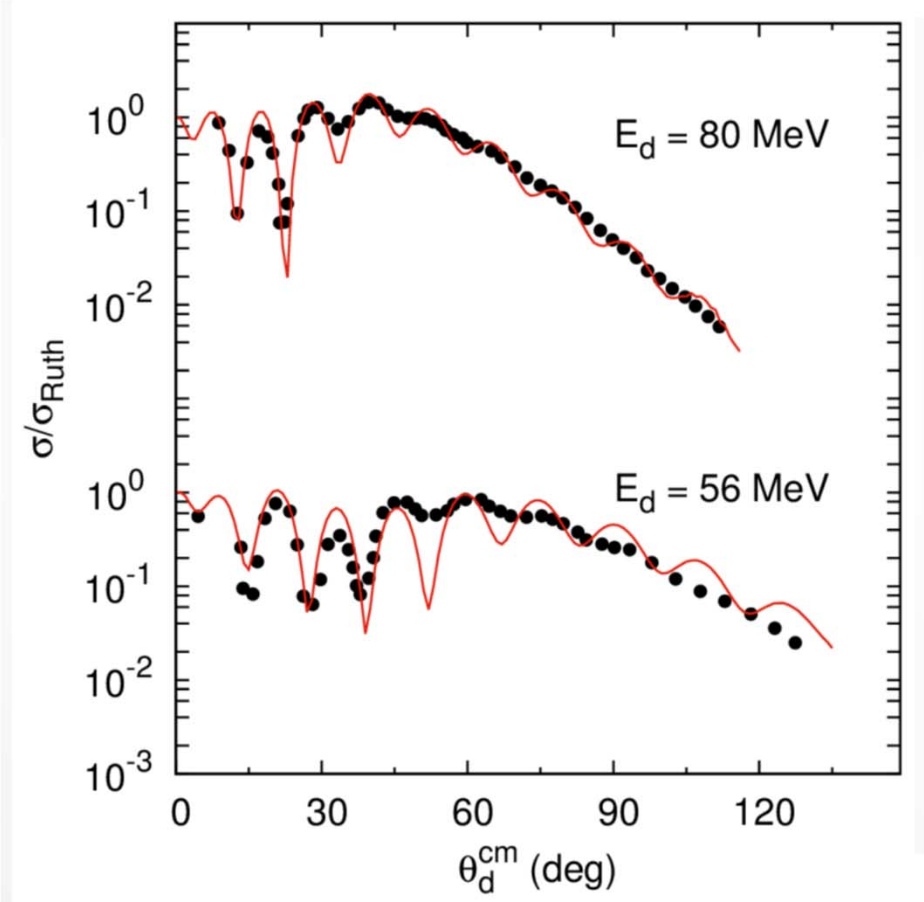
$$E_i + \varepsilon_i = E$$

(Energy Cons.)

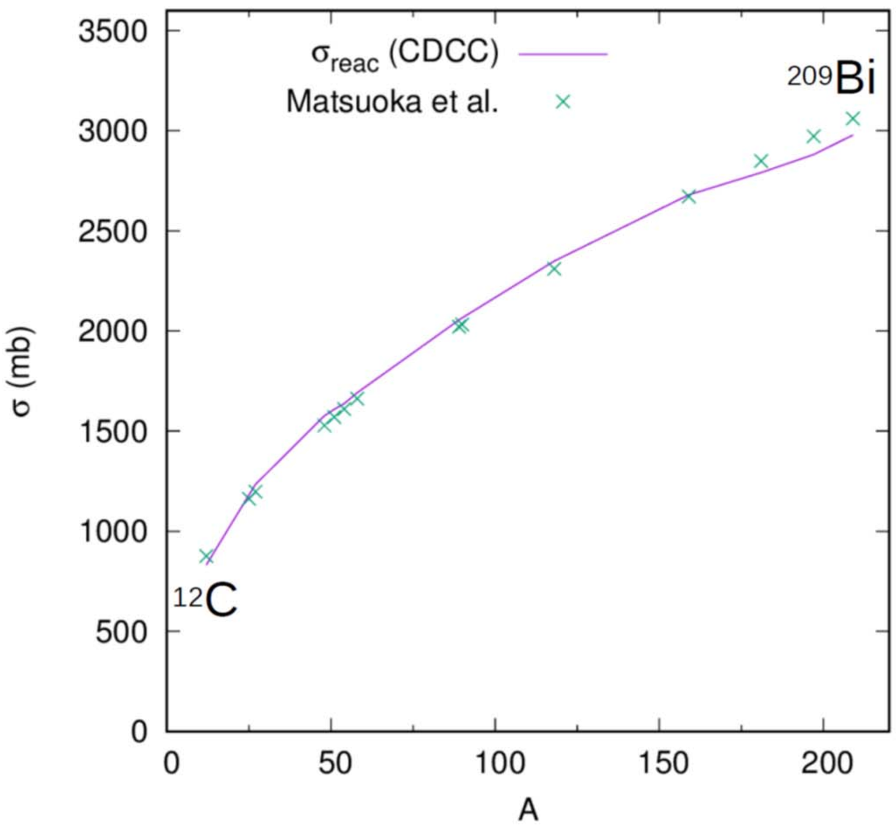
MERT (M-CDCC) for deuteron-induced reactions

Y. S. Neoh, K. Yoshida, K. Minomo, and KO, PRC **94**, 044619 (2016).

Elastic scattering on ^{58}Ni

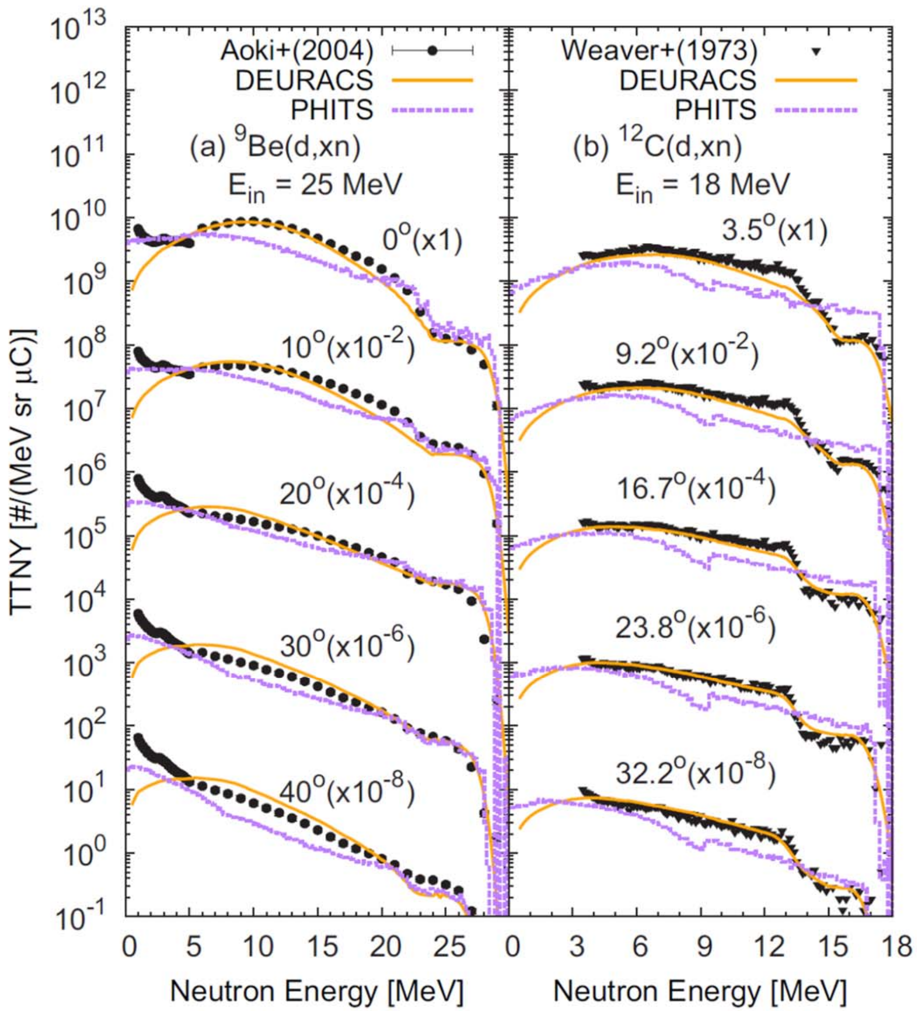


Total reaction cross section at 56 MeV



Deuteron-induced reaction analysis code system (DEURACS)

S. Nakayama, H. Kouno, Y. Watanabe, O. Iwamoto, and KO, PRC **94**, 014618 (2016).



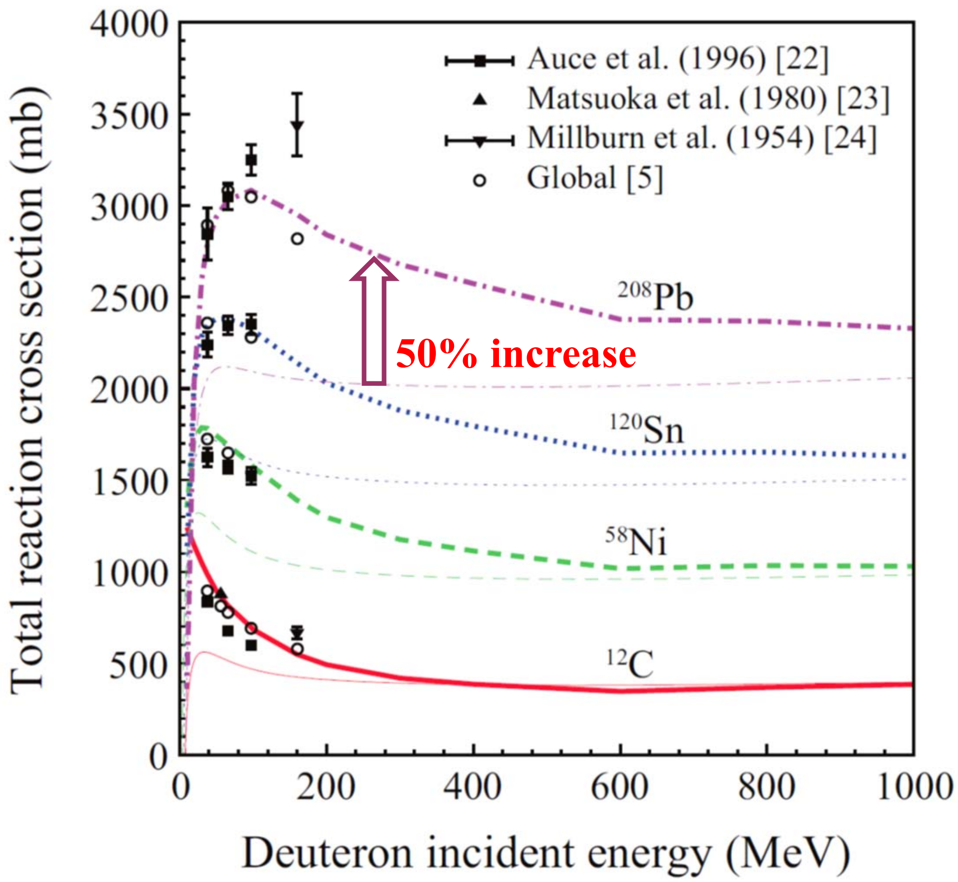
✓ CDCC is implemented in DEURACS to evaluate elastic breakup cross sections of deuteron.

FIG. 7. Calculated and experimental TTNYs at several angles for (a) the ^{9}Be(d,xn) reactions and (b) the ^{12}C(d,xn) reactions. The solid curves represent the TTNYs derived from the DEURACS calculation. The dashed lines are results of the Monte Carlo simulation codes PHITS.

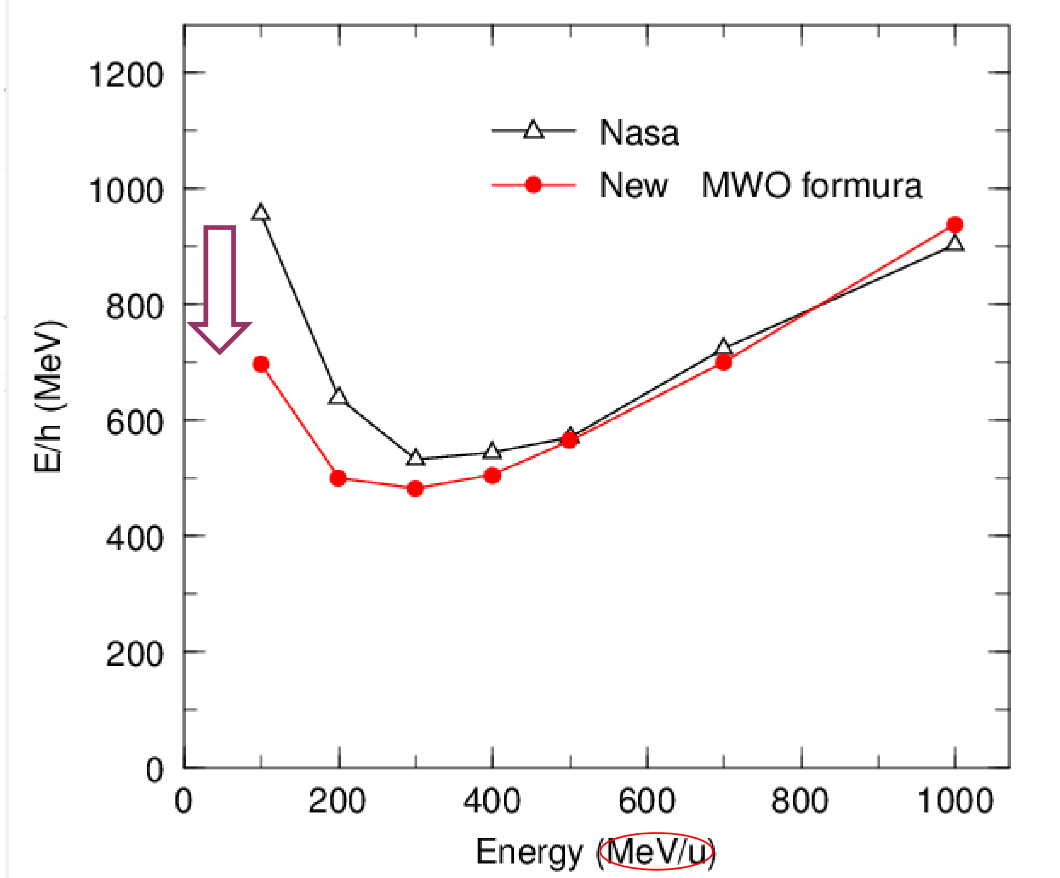
MERT evaluation for deuteron reaction cross sections

K. Minomo, K. Washiyama, and K. Ogata, Journal of Nuclear Science and Technology, **54**, 127 (2017).

MERT vs Exp. / PHITS



Transmutation energy for ^{135}Cs



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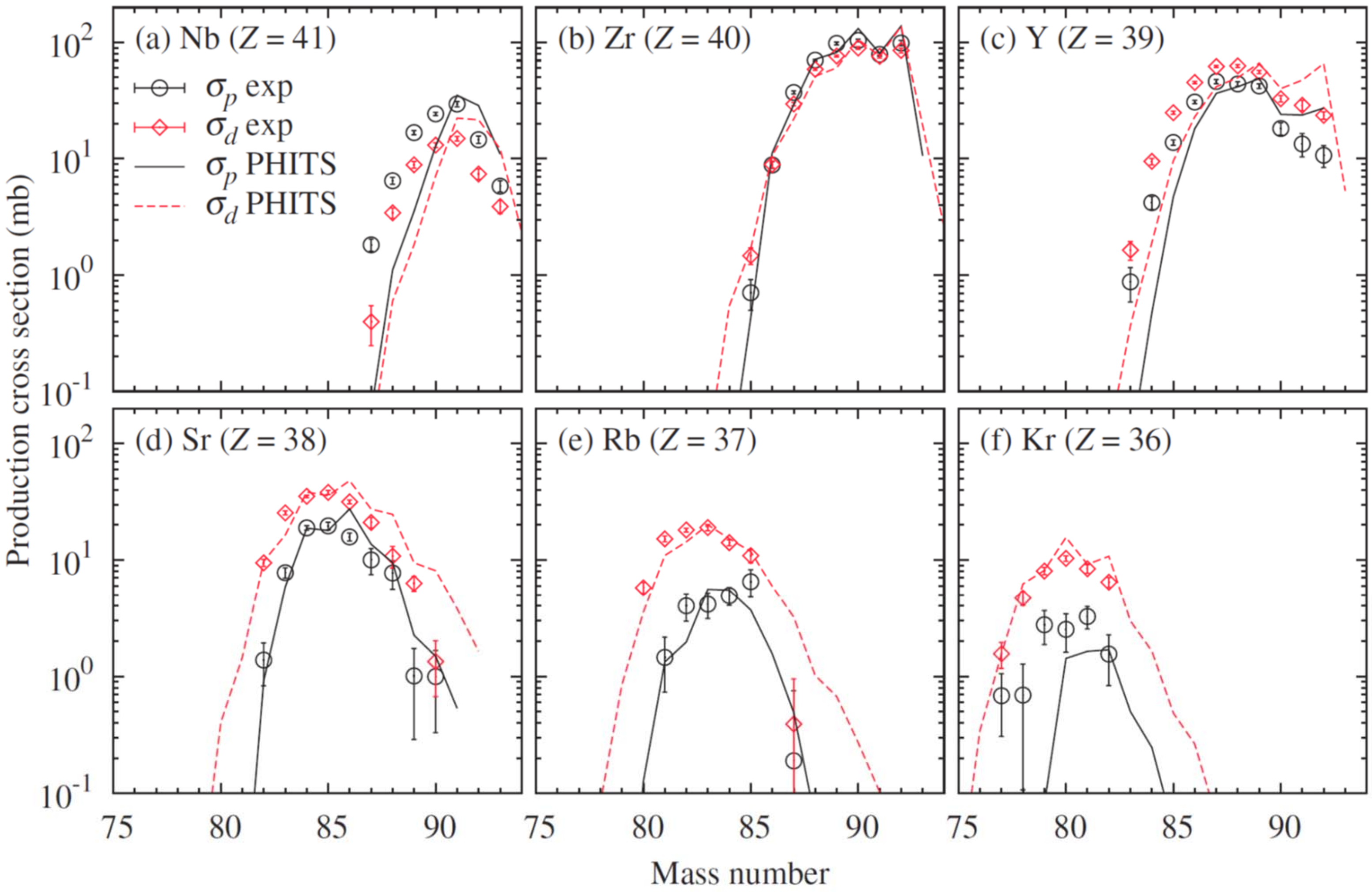
Spallation cross section taken at RIBF

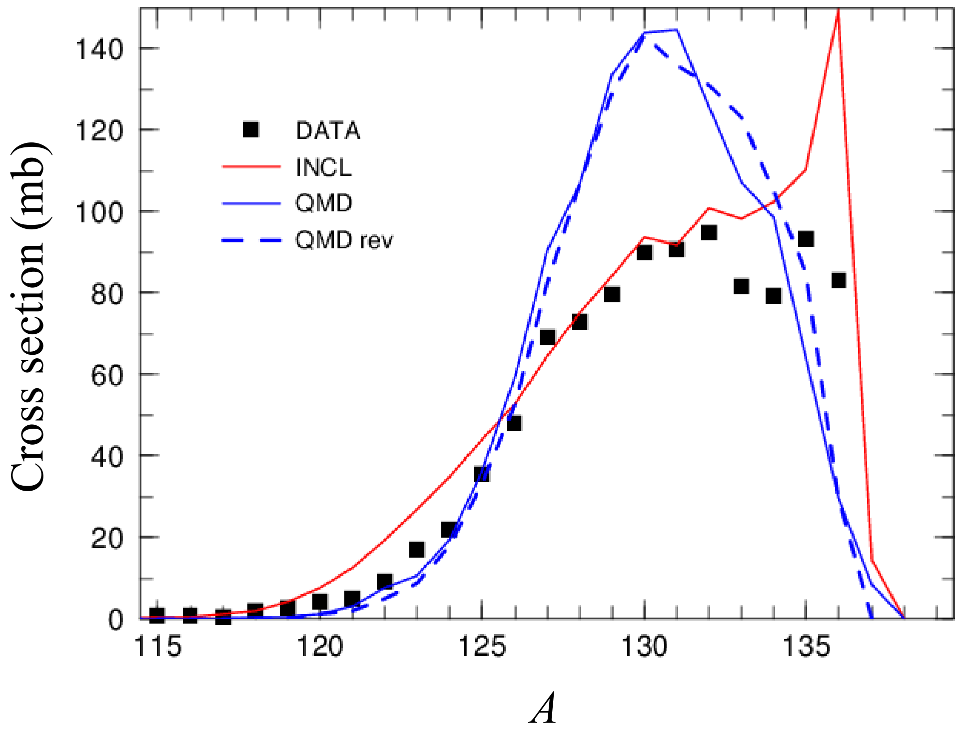
^{93}Zr at 100 MeV/nucleon

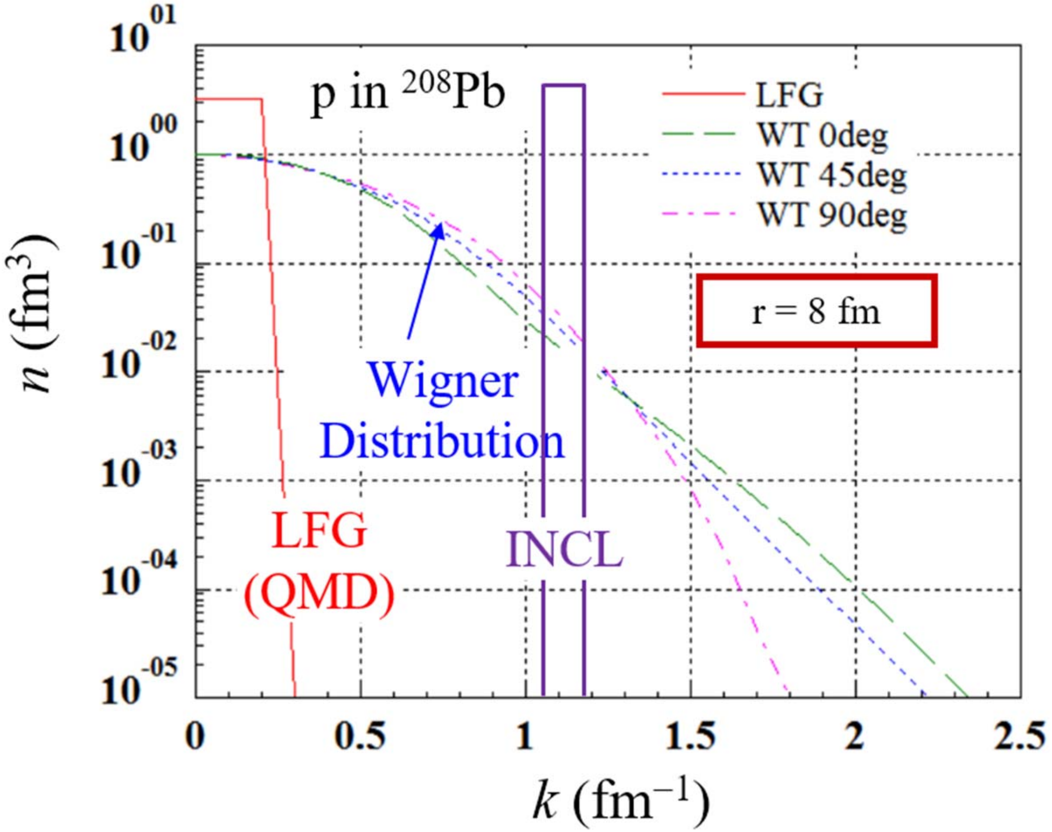
*S. Kawase et al., PTEP**2017**, 093D03 (2017).*



Problem on –1N process

^{137}Cs 185MeV on proton





cf. D. Mancusi et al., PRC ***91****, 034602 (2015).*

$$E_{\text{ex}} = E_{\text{F}} - E_{\text{kin}}$$

kinetic energy of a nucleon inside a nucleus

Outline of the model

✓ SemiClassical Distorted Wave model (SCDW) [QM-INC] is adopted.

S. Weili, Y. Watanabe, M. Kohno, KO, and M. Kawai, PRC ***60****, 064605 (1999).*

DDX for (*p*,*p*'*x*)

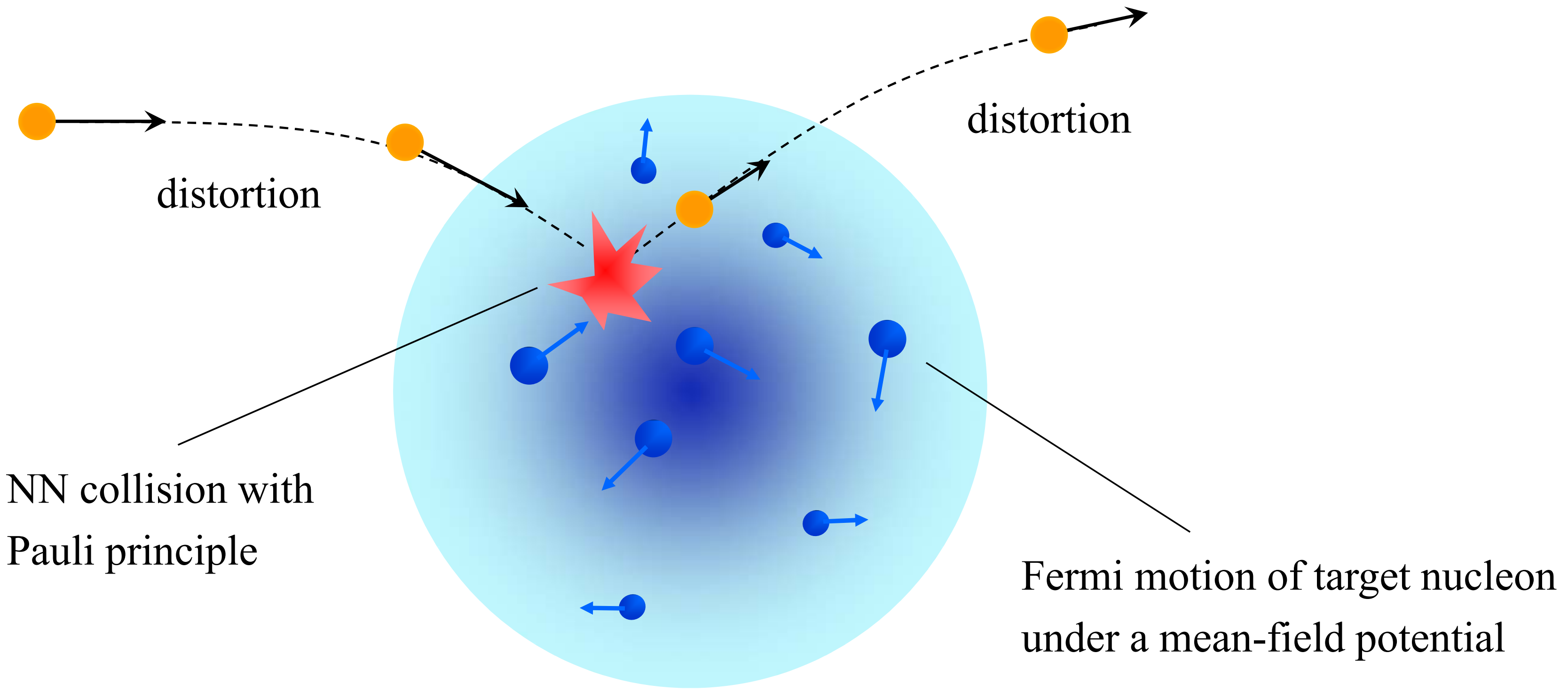
$$\frac{d^2\sigma}{dE_f d\Omega_f} = C\int d\boldsymbol{k}_\beta d\boldsymbol{k}_\alpha \,\delta\left(\boldsymbol{K}_f + \boldsymbol{k}_\beta - \boldsymbol{K}_i - \boldsymbol{k}_\alpha\right)\delta\left(E_f + \varepsilon_\beta - E_i - \varepsilon_\alpha\right)$$

$$\times \int d\boldsymbol{R} \left|\bar{\chi}^{(-)}_{f,\boldsymbol{K}_f}\left(\boldsymbol{R}\right)\right|^2 \left[2 - f_h^{(\beta)}\left(\boldsymbol{k}_\beta, \boldsymbol{R}\right)\right] f_h^{(\alpha)}\left(\boldsymbol{k}_\alpha, \boldsymbol{R}\right) \left|\tilde{t}_{NN}\left(\boldsymbol{\kappa}', \boldsymbol{\kappa}\right)\right|^2 \left|\bar{\chi}^{(+)}_{i,\boldsymbol{K}_i}\left(\boldsymbol{R}\right)\right|^2$$

Incoherent sum of contributions from collision points

Wigner Transform of nucleon in a nucleus (“Pauli principle”)

Schematic illustration of SCDW



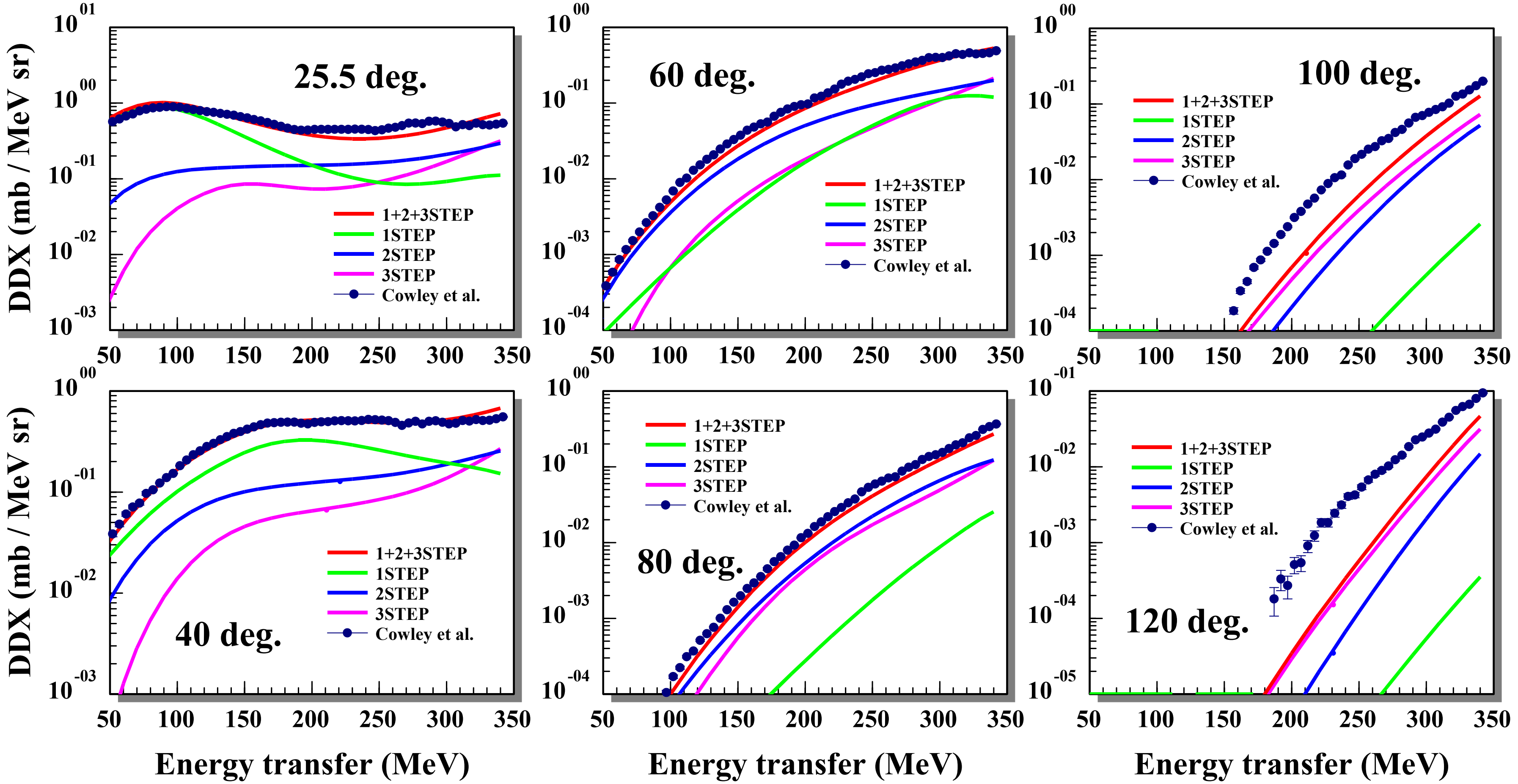
Y. L. Luo and M. Kawai, PRC ***43****, 2367 (1991); M. Kawai and H. A. Weidenmüller, PRC* ***45****, 1856 (1992);*

Y. Watanabe et al., PRC ***59****, 2136 (1999); S. Weili et al., PRC* ***60****, 064605 (1999); K. Ogata et al., NPA* ***703****, 152 (2002);*

KO et al., Proc. Kyudai-RCNP Int. Mini Symp. on Nuclear Many-body and Medium Effects in Nuclear Interaction and Reactions (MEDIUM02), p.231 (2003).

DDX for $^{40}Ca(p,p'x)$ at 392 MeV

—— KO, Y. Watanabe, W. Sun, M. Kohno, and M. Kawai, Proc. of MEDIUM02, p.231 (2003).16



Exp. data: A.A. Cowley *et al.*, PRC**62**, 044604 (2000).

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$$\times \int d\boldsymbol{R} \left|\bar{\chi}^{(-)}_{f,\boldsymbol{K}_f}(\boldsymbol{R})\right|^2 \left[2 - f_h^{(\beta)}(\boldsymbol{k}_\beta, \boldsymbol{R})\right] f_h^{(\alpha)}(\boldsymbol{k}_\alpha, \boldsymbol{R}) \left|\tilde{t}_{NN}(\boldsymbol{\kappa}', \boldsymbol{\kappa})\right|^2 \left|\bar{\chi}^{(+)}_{i,\boldsymbol{K}_i}(\boldsymbol{R})\right|^2$$

Incoherent sum of contributions from collision points

Wigner Transform of nucleon in a nucleus ("Pauli principle")

adjustable parameter

ω: energy transfer

$$\frac{d^4\sigma}{dE_f d\Omega_f dk_\alpha dR} \Rightarrow \frac{d^3\sigma}{d\omega dk_\alpha dR} \Rightarrow \frac{d^2\sigma}{d\varepsilon_\beta d\varepsilon_{\rm ex}^{(A-1)}}$$

$$\Rightarrow \frac{d\sigma}{d\varepsilon_{\rm ex}^{(A-1)}}$$

$\varepsilon_\beta >$ Coulomb barrier and $\varepsilon_{\rm ex}^{(A-1)} > \varepsilon_0$:

[Pre-Fragment = A–1]

$$\Rightarrow \frac{d\sigma}{d\omega} \equiv \frac{d\sigma}{d\varepsilon_{\rm ex}^{(A)}}$$

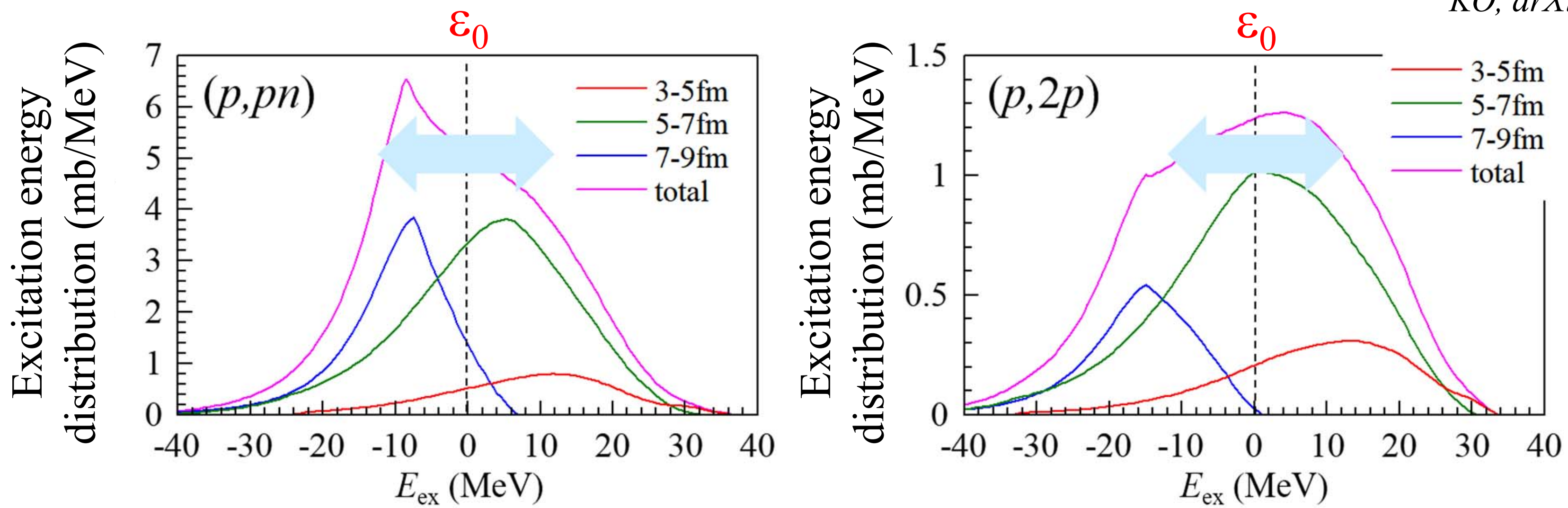
Otherwise

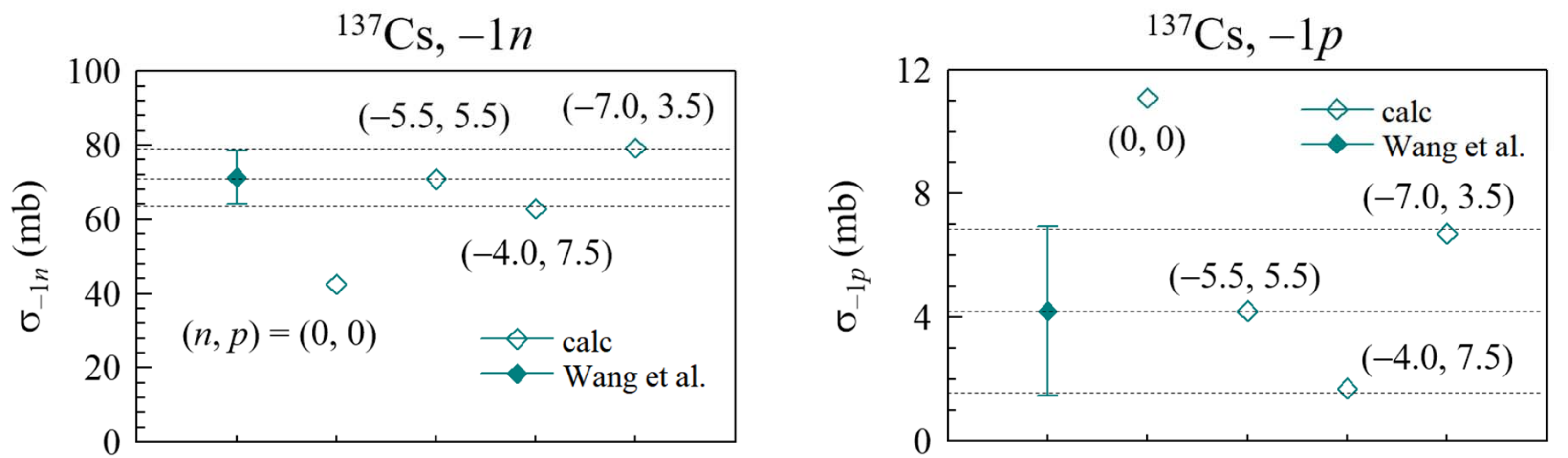
[Pre-Fragment = A]

Note: R and k_α determine nucleon s.p. energy, hence the excitation energy of the residual nucleus

Excitation energy distribution

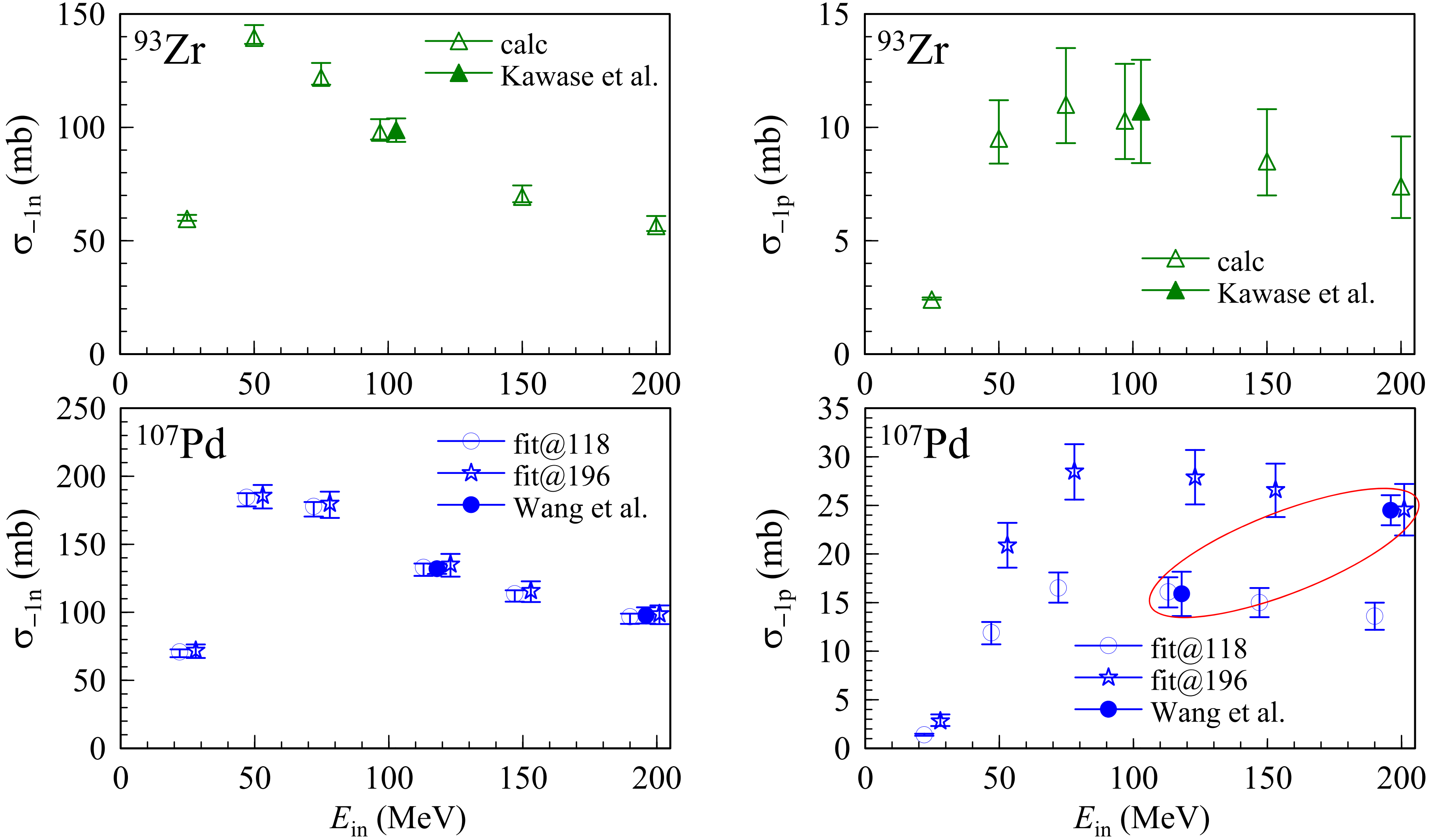
KO, arXiv:1801.09994.





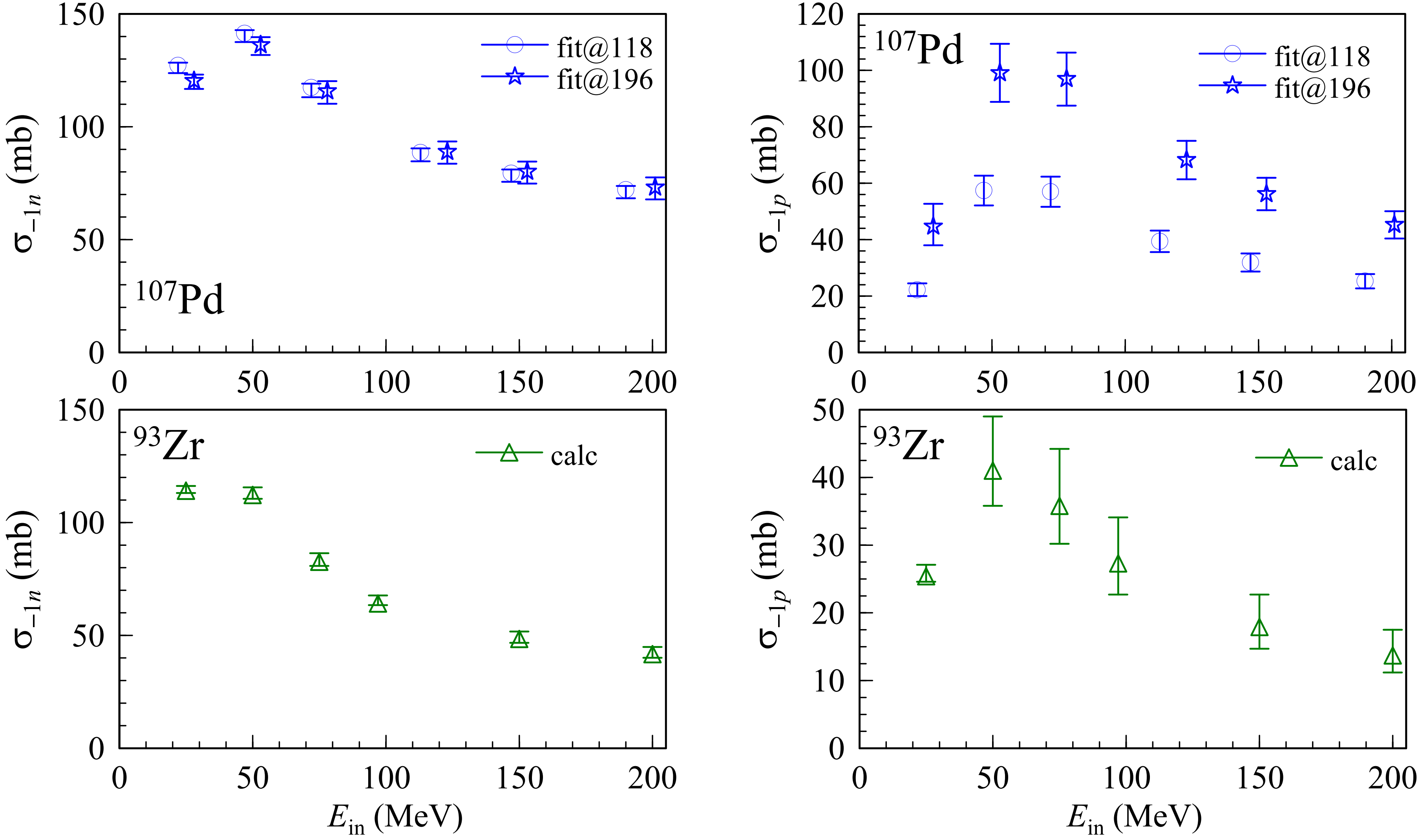
Incident energy dependence

KO, arXiv:1801.09994.



–1N cross sections by neutron

KO, arXiv:1801.09994.



Summary

- The microscopic description of nucleon-nucleus elastic scattering and total reaction cross sections at energies higher than about 30 MeV is now feasible.
- We have proposed a framework of the microscopic effective reaction theory (MERT) for describing various direct reaction processes.
  - ✓ Essential degrees of freedom for the process of interest are taken into account explicitly.
  - ✓ Microscopic optical potentials between the constituents of the reaction system are used.
  - ✓ It is not ab-initio but has a wide applicability.
- As an example of MERT, we use a microscopic CDCC for describing deuteron scattering.
  - ✓ We have improved significantly the deuteron reaction cross sections used by PHITS.
  - ✓ This reduces the energy cost for transmutation with deuteron.
- We proposed a new model for describing one-nucleon knockout reactions.
  - ✓ It seems that this model needs further validation/improvement by looking carefully all the data taken in this program (PJ2).