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Theoretical nuclear reaction database based on the microscopic calculations

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Introduction

At present, nuclear reaction data measured in all over the world, are accumulated and distributed to public under the international collaborations (NRDC). A nuclear database is one of the most important infrastructure for developments in several fields.

Important items for the database

- ✓ Certainty
- ✓ Accuracy
- ✓ Completeness …

← *difficulties*

Compilation miss,
Difficultness of measurements,
Evaluation based on empirical ways …

We construct the nuclear database with ***only*** theoretical methods.

- ✓ Density distribution (about 3,500 nuclide),
- ✓ Reaction cross section,
- ✓ Differential cross section,
  for the reaction with 3,500 nuclide + p, n and α at 20 -1000 A MeV

Collaborators: Y. Hirabayashi, S. Hatakeyama, W. Horiuchi (Hokkaido Univ.)

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Methods

For ground state: 3D Skyrme Hartree-Fock+BCS (HF+BCS)

For low-energy reaction: Folding model w/ DDM3Y Int.

For high-energy reaction: Glauber model

Method (3D Skyrme HF+BCS)

S.E. done

$$\begin{cases} [h, \rho] = 0, \\ 2\tilde{\varepsilon}_k u_k v_k + \Delta_k (v_k^2 - u_k^2) = 0, \quad k > 0, \end{cases}$$

HF+BCS Equation

Density matrix

$$\rho_{ij} = \langle \Psi | \hat{c}_j^\dagger \hat{c}_i | \Psi \rangle \qquad |\Psi_{\rm HF}\rangle = \prod_{i=1}^{A} \hat{a}_i^\dagger |0\rangle \qquad |\Psi_{\rm BCS}\rangle = \prod_{k>0} (u_k + v_k \hat{a}_k^\dagger \hat{a}_{\bar{k}}) |0\rangle,$$

Single particle Hamiltonian

$$u_k^2 + v_k^2 = 1$$

$$h = t + \sum_{\beta,\nu} V_{\alpha\beta\mu\nu}$$

$$\tilde{\varepsilon}_k = \frac{1}{2}\{t_{kk} + t_{\bar{k}\bar{k}} + \sum_l (V_{klkl} + V_{\bar{k}l\bar{k}l}) v_l^2\} - \lambda$$

Coordinate space represented s.p. state

$$\phi_l(\boldsymbol{r};\sigma) = \langle \boldsymbol{r} | \hat{a}_l^\dagger(\sigma) | 0 \rangle$$

In 3D coordinate space representation, Skyrme effective interaction $V_{\rm sky}$ ⇒ Pauli principal, Nuclear pairing, Nuclear deformation

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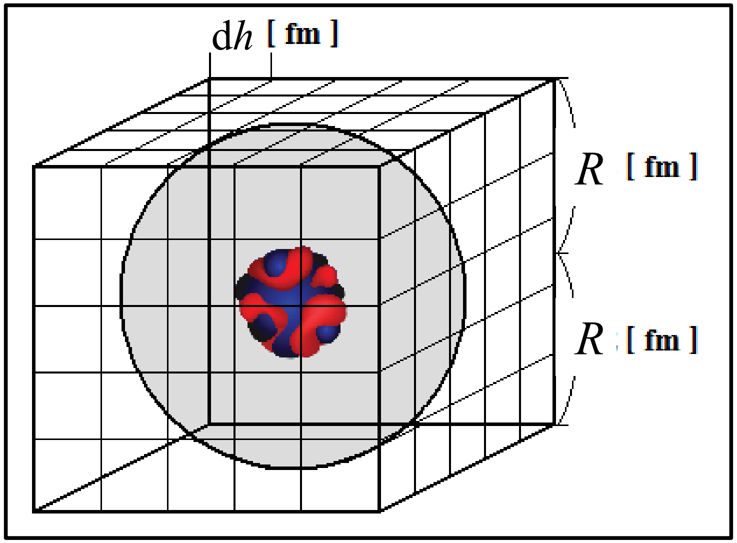
Method (3D Skyrme HF+BCS)

S.E. done



HF

$$|\Phi_{\rm HF}\rangle \equiv \prod_{l=1}^{A} a_l^\dagger |-\rangle$$

HF+BCS

$$|\Phi_{\rm BCS}\rangle \equiv \prod_{k>0} (u_k + v_k a_k^\dagger a_{\bar{k}}^\dagger)|-\rangle$$

$$\phi_l(\boldsymbol{r};\sigma) = \langle \boldsymbol{r}|\hat{a}_l^\dagger(\sigma)|0\rangle$$

$$u_k^2 + v_k^2 = 1$$

$$\phi_l(\boldsymbol{r};\sigma) \rightarrow \phi_l(x,y,z;\sigma)$$

For light nuclei	$6 \leq Z \leq 20$	$R = 12$ fm, $\mathrm{d}h = 0.8$ fm
For middle & heavy nuclei	$20 \leq Z \leq 82$	$R = 15$ fm, $\mathrm{d}h = 1.0$ fm
For heavy nuclei	$82 \leq Z \leq 92$	$R = 20$ fm, $\mathrm{d}h = 1.0$ fm

# of lattice point
15,000 ~ 34,000
(half of cubic)

$R_{\rm A=300} \sim 8$ fm

$\bar{R} \sim 1.2 A^{1/3}$

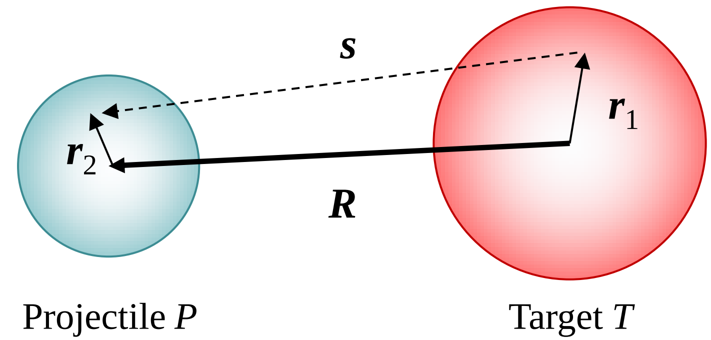
Method (Folding Model w/ DDM3Y for low-energy reaction)

w/ Y.Hirabayashi

Potential scattering theory: How to prepare the potential?

Schrodinger Eq.

$$\left\{-\frac{\hbar^2}{2m}\boldsymbol{\nabla}^2 + U(\boldsymbol{R})\right\}\Psi(\boldsymbol{R}) = E\Psi(\boldsymbol{R})$$



w/ the boundary condition:

$$\Psi(\boldsymbol{R}) \to e^{ikz} + f(\theta)\frac{e^{ikR}}{R} \qquad (R \to \infty)$$

$$\Rightarrow \quad \frac{d\sigma}{d\Omega} = |f(\theta)|^2$$

nucleon-nucleon Int. (DDM3Y)

Single Folding: $$U_{SF}(\boldsymbol{R}) = \int d\boldsymbol{r}_1\ \rho_T(\boldsymbol{r}_1)v_{NN}(E, \boldsymbol{R} - \boldsymbol{r}_1)$$

When projectile is nucleon.

Double Folding: $$U_{DF}(\boldsymbol{R}) = \int\!\!\int d\boldsymbol{r}_1 d\boldsymbol{r}_2\ \rho_T(\boldsymbol{r}_1)\rho_P(\boldsymbol{r}_2)v_{NN}(E, \boldsymbol{s})$$

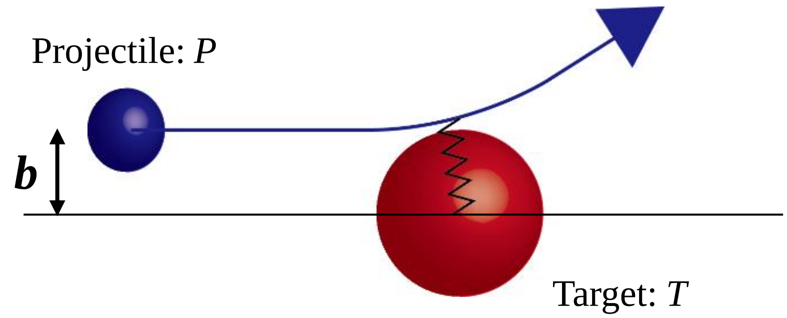
Method (Glauber Model for high-energy reaction)

w/ S.Hatakeyama, W.Horiuchi

In the eikonal and adiabatic approximation, …

$$\sigma_{\mathrm{R}}(E) = \int d\boldsymbol{b}\ \left(1 - |e^{i\chi(\boldsymbol{b},E)}|^2\right)$$

$$\sigma_R = \sigma_T - \sigma_{\mathrm{el.}}$$



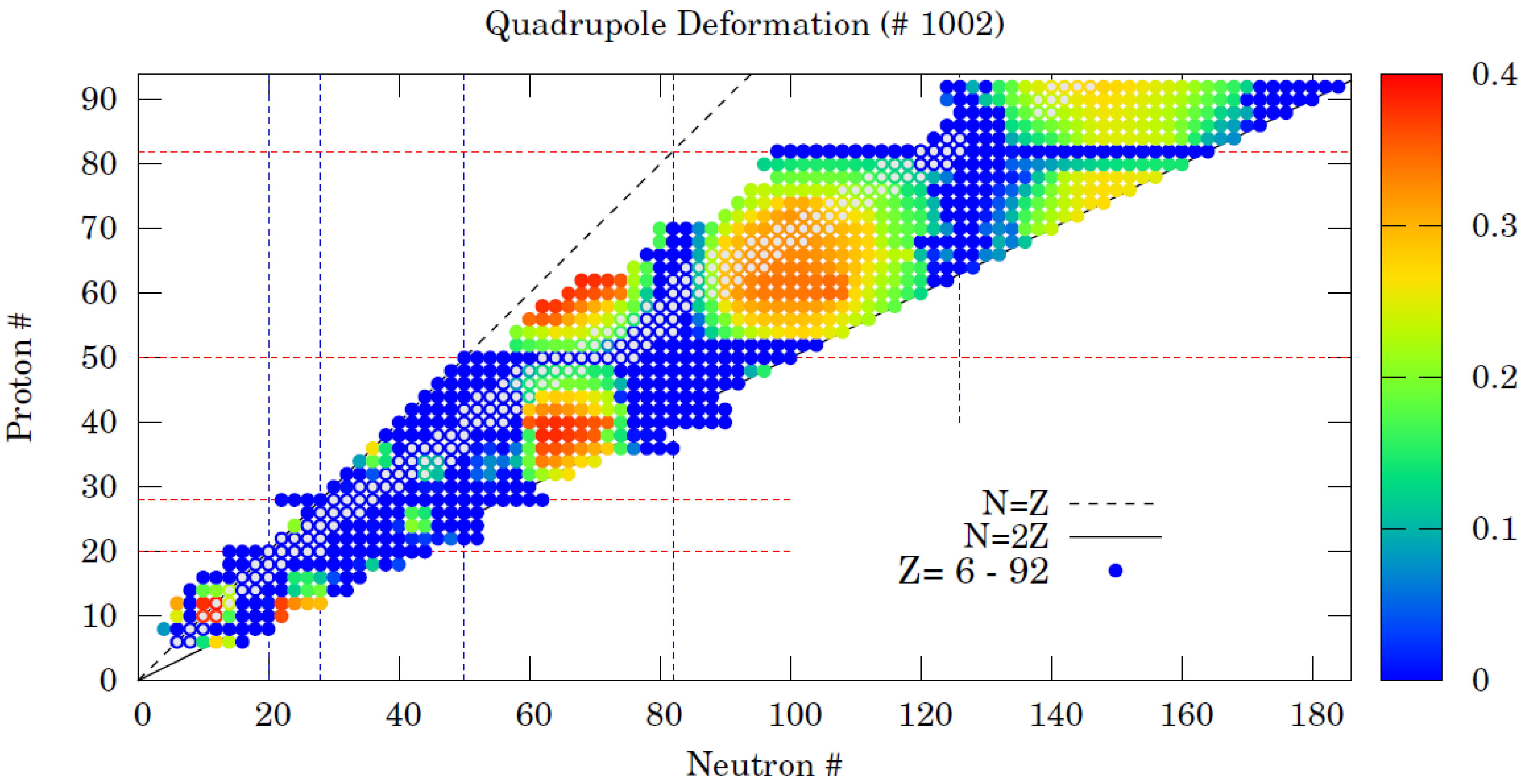
Glauber model + OLA + NTG
(Optical Limit Approximation, Nucleon-Target formalism in the Glauber)

Phase shift function: $i\chi(\boldsymbol{b}, E) \simeq -\iint d\boldsymbol{r}_P d\boldsymbol{r}_T\ \rho_P(\boldsymbol{s}_P)\rho_T(\boldsymbol{s}_T)\Gamma(\boldsymbol{s}_P - \boldsymbol{s}_T + \boldsymbol{b}, E)$

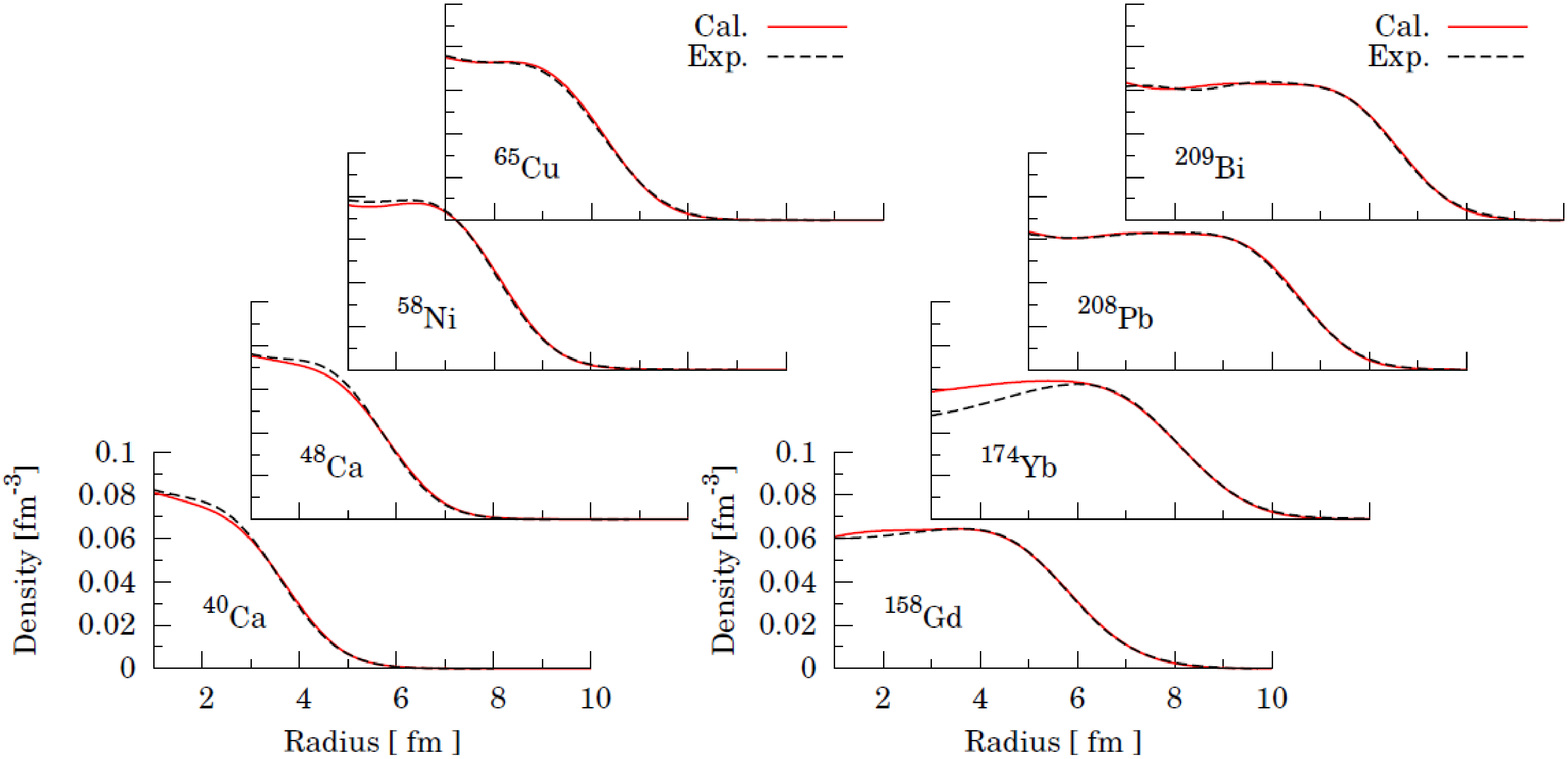
Profile function: $\Gamma(\boldsymbol{b}, E) = \dfrac{1 - i\alpha_{NN}(E)}{4\pi\beta_{NN}(E)}\sigma_{NN}^{\mathrm{tot}}(E)\exp\left[-\dfrac{1}{2\beta_{NN}(E)}\beta^2\right]$

to reproduce the nucleon-nucleon collision

Results (ground state)

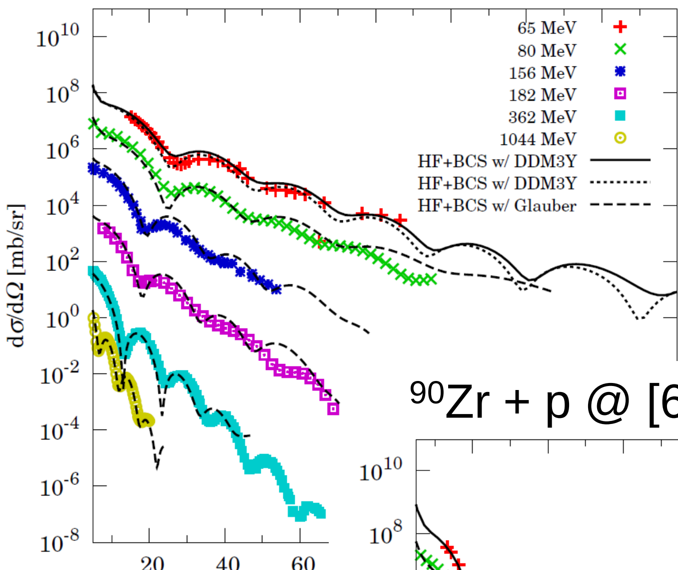


Results (charge density)

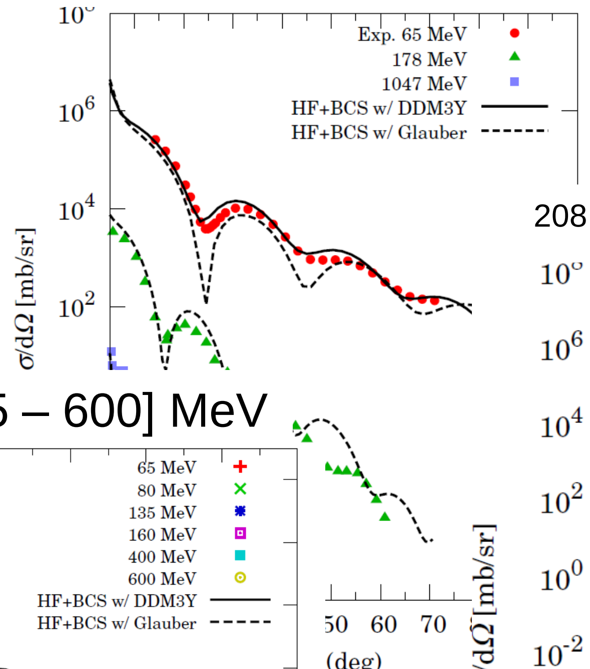


Results (Differential cross section σ_{el})

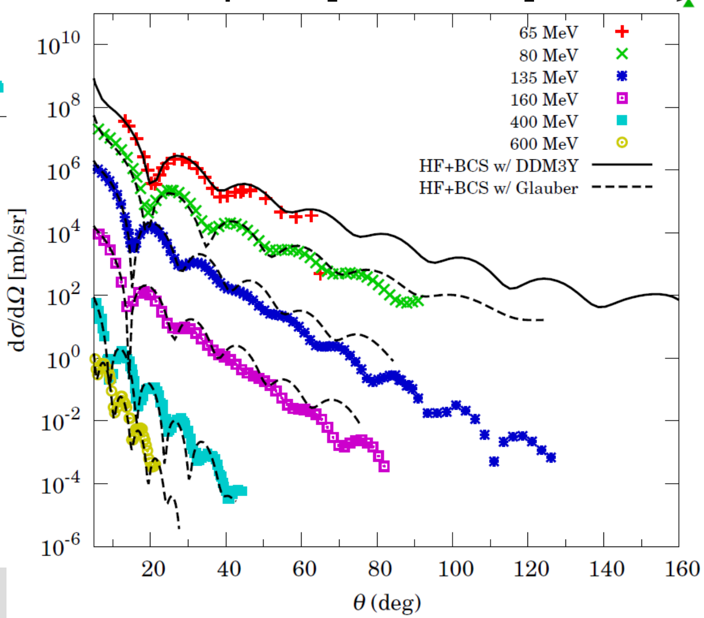
^{40}Ca + p @ [65 – 1044] MeV



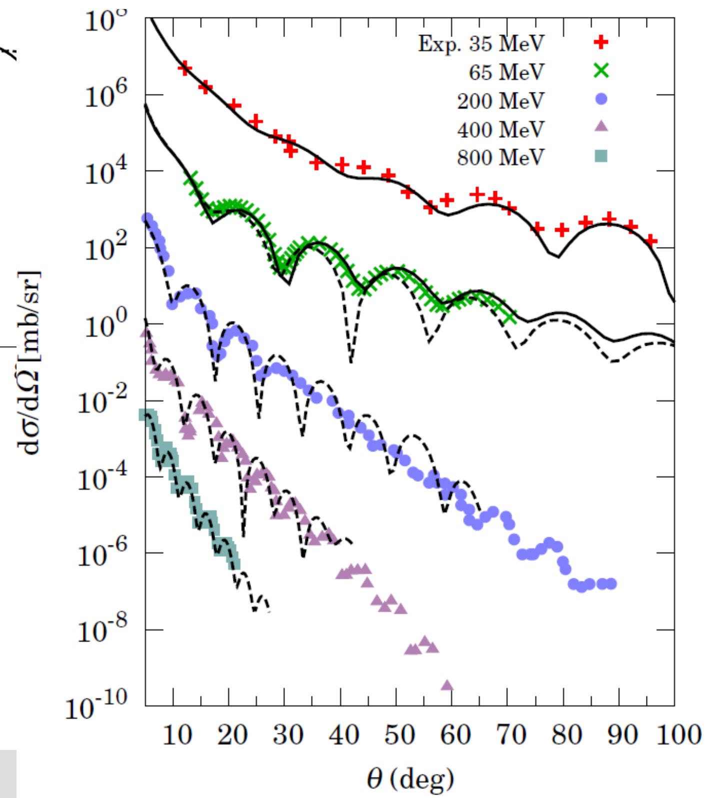
^{58}Ni + p @ [65 – 1047] MeV



^{90}Zr + p @ [65 – 600] MeV

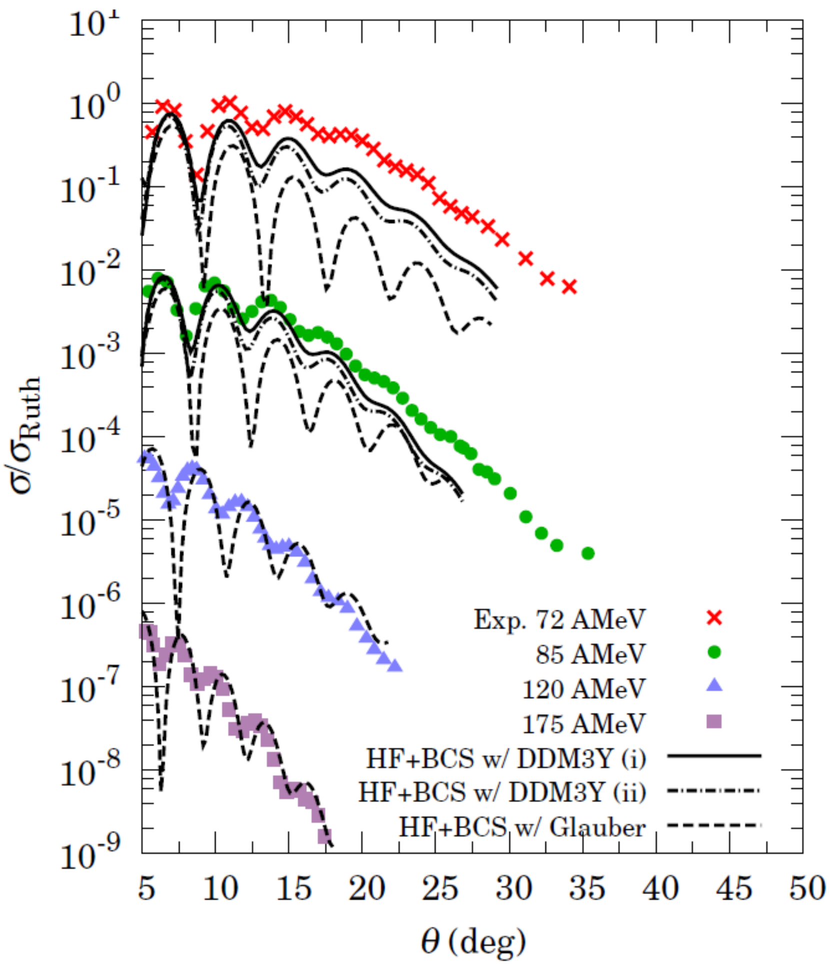


^{208}Pb + p @ [35 – 800] MeV

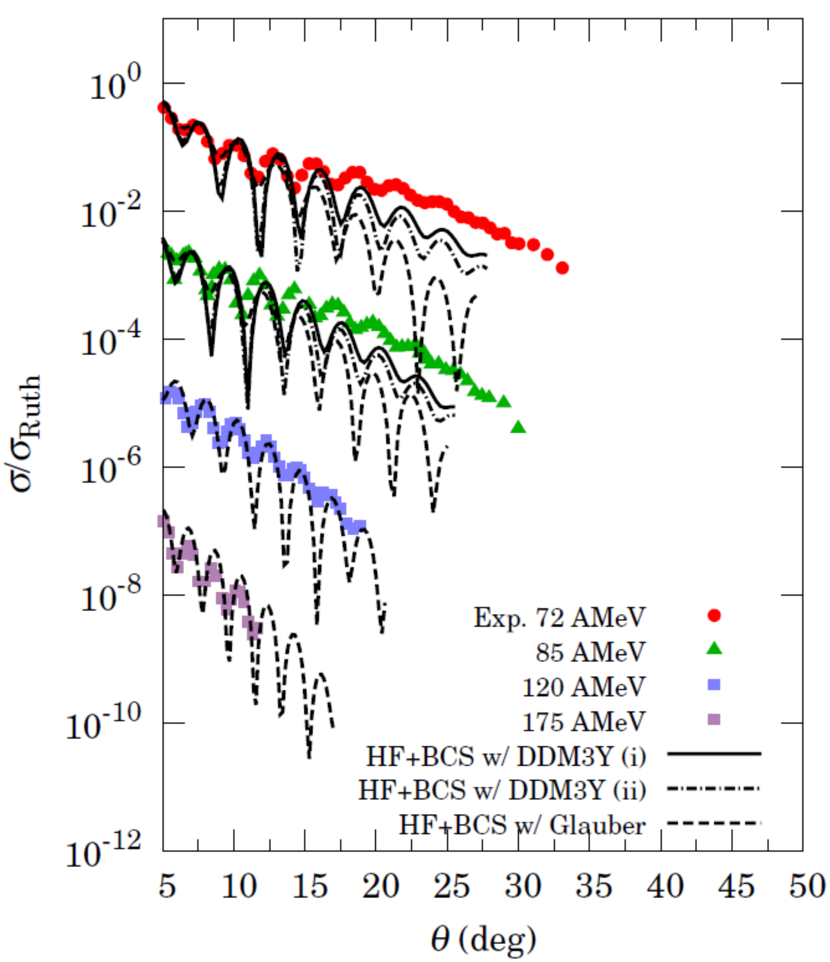


Results (Differential cross section σ_{el})

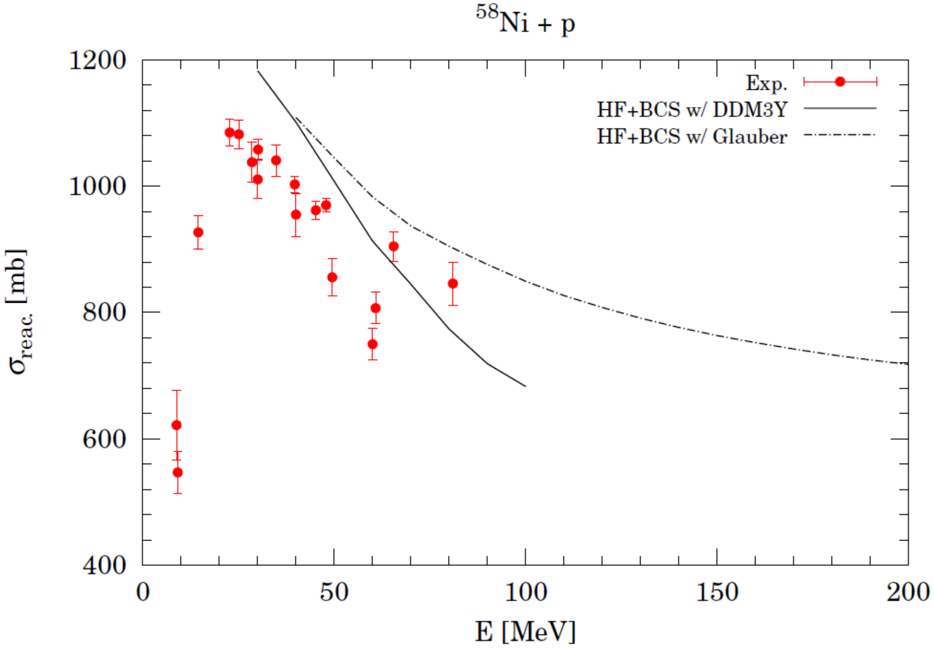
^{58}Ni + a @ [72 – 175] AMeV

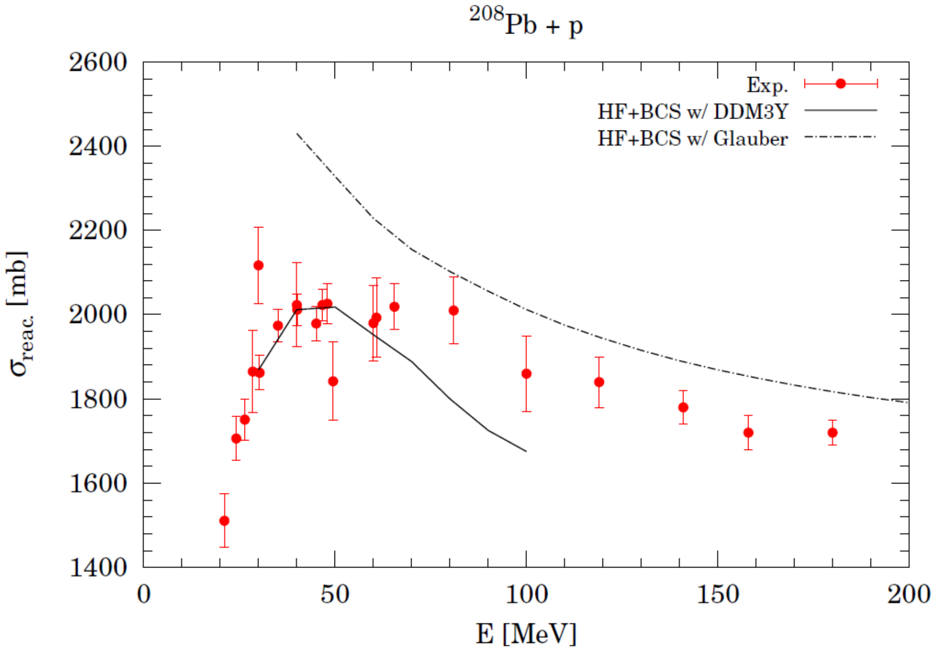


^{208}Pb + a @ [72 – 175] AMeV

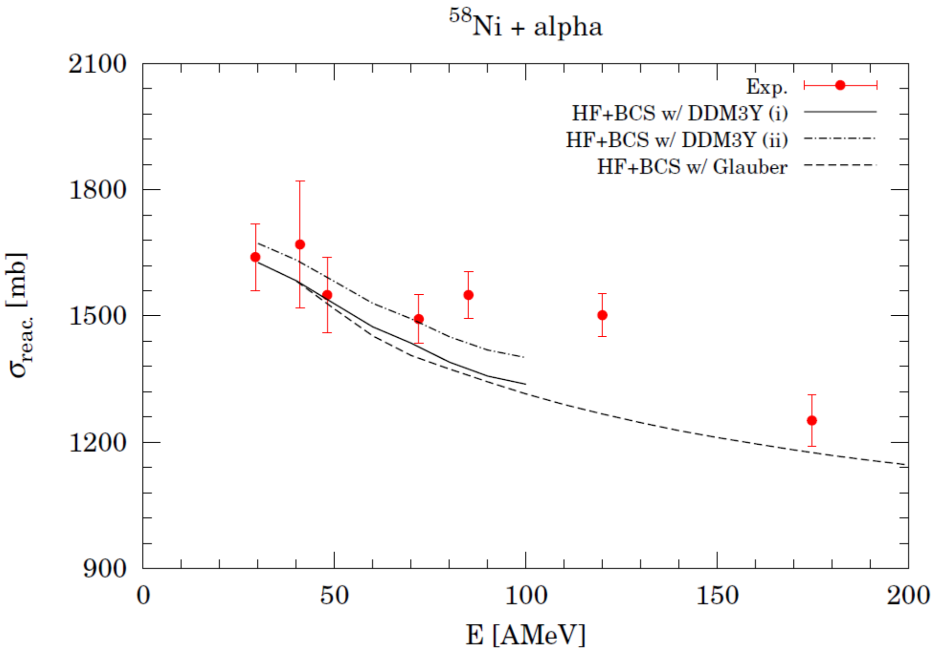


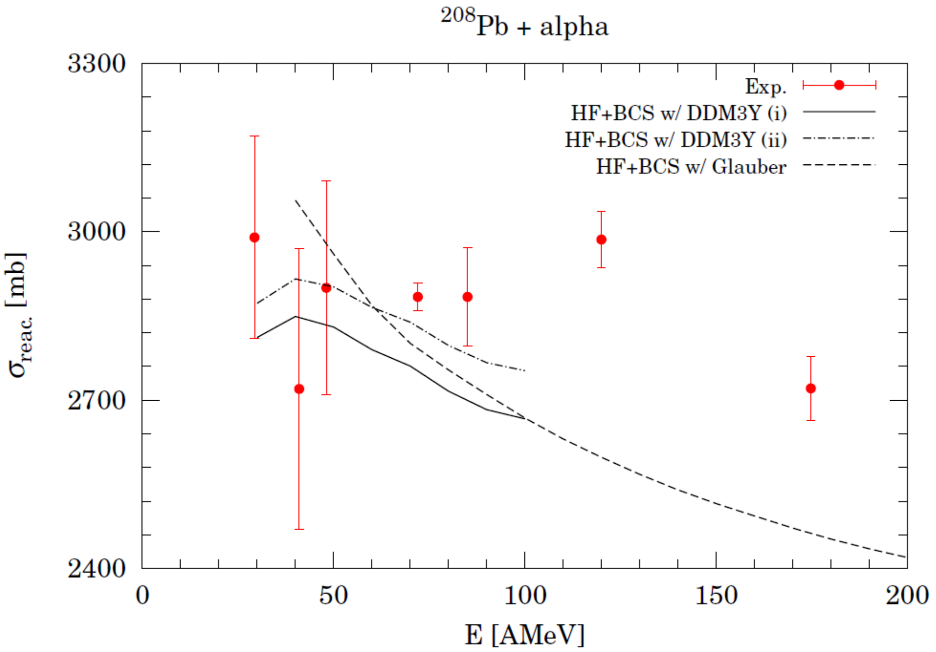
Results (Reaction cross section)





Results (Reaction cross section)





Interface to use the Database

MFG Theoretical Nuclear Reaction Database

MFG: **M**ean-field model, **F**olding model and **G**lauber model

HOME

What is the MFG Theoretical Nuclear Reaction Reaction Database?

This database is constructed by using the results of theoretical calculation only, which can provide the reaction data without depending on empirical way.
The ground states of nuclei are calculated by self-consistent Skyrme Hartree-Fock+BCS method, and for the reaction calculation Folding and Glauber model are employed. The details of theoretical methods are explained in the paper. When you use the data listed in the MFG database, please refer to it.
Subject nuclide: about 3,500 isotopes with Z=6-92 including odd-nuclide, as following periodic table.

Subject nuclide for MFG database

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57-71 Lanthnide	72 Hf	73 Ta	74 W	75 Re	72 Os	72 Ir	72 Pt	72 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89-103 Actinide	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og

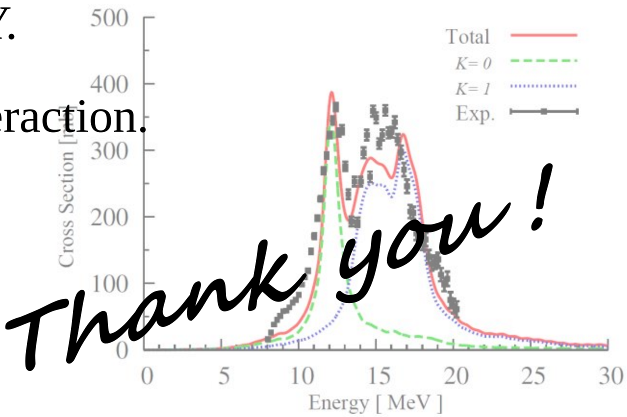
57-71 Lanthnide	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
89-103 Actinide	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Summary & Future works

- ✓ We construct the theoretical reaction database included the ground state nucleon densities, reaction and differential elastic reaction cross sections for the whole nuclear mass region (A=12-276, with Z=6-92) and in the whole energy region (E_{in}=20 - 1000 AMeV).
  - ✓ For the ground state: 3D Skyrme HF+BCS model.
    For the low- and high-energy reaction: Folding and Glauber models

  Collaborators: Y. Hirabayashi, S. Hatakeyama, W. Horiuchi (Hokkaido Univ.)

- ✓ We will complete the database construction, in this FY.
  - ✓ We will extent the database to those with other interaction.
  - ✓ New projectile will be added (deuteron, photon)
  - ✓ Comparison with TALYS results



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