

Development of a code system DEURACS for theoretical analysis and prediction of deuteron-induced reactions

Shinsuke Nakayama^{1,*}, *Hiroshi Kouno*², *Yukinobu Watanabe*²,
*Osamu Iwamoto*¹, *Tao Ye*^{2,3}, and *Kazuyuki Ogata*⁴

¹ Nuclear Data Center, JAEA, Japan

² Department of Advanced Energy Engineering Science, Kyushu University, Japan

³ Institute of Applied Physics and Computational Mathematics, China

⁴ Research Center for Nuclear Physics, Osaka University, Japan

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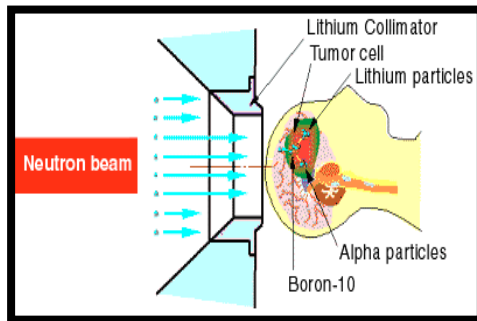
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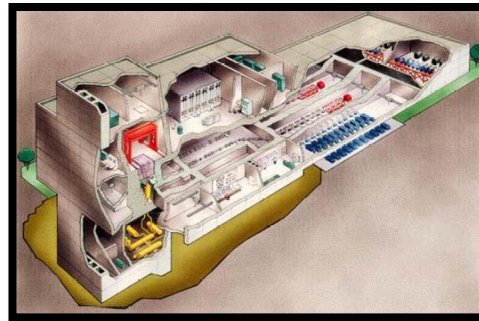
Deuteron accelerator neutron sources

- ✓ Intensive neutron sources using **deuteron accelerator** have been proposed for various applications.

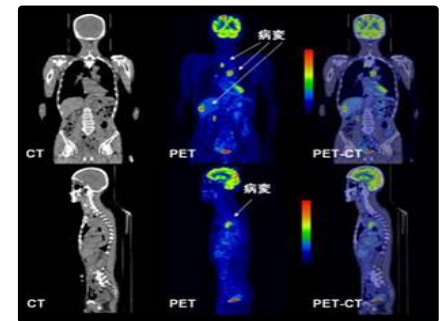
Boron Neutron Capture Therapy (BNCT)



Irradiation testing of fusion reactor material (IFMIF)



Production of medical RI



- ✓ **(d, xn) reactions on light nuclei** (${}^7\text{Li}$, ${}^9\text{Be}$, ${}^{12}\text{C}$) are regarded as a promising reaction to generate intensive neutron.

Code system for deuteron-induced reactions

- ✓ Toward evaluation of deuteron nuclear data, we have so far developed **DEURACS**. [1,2]
(**DEU**teron-induced **R**eaction **A**nalysis **C**ode **S**ystem)
- ✓ DDXs of (d, xn) reactions are critically important in the engineering design of neutron sources.



We have so far examined the applicability of DEURACS to **nucleon emission** from deuteron-induced reactions.

[1] S. Nakayama and Y. Watanabe, JNST **53**, 89 (2016).

[2] S. Nakayama et al., PRC **94**, 014618 (2016).

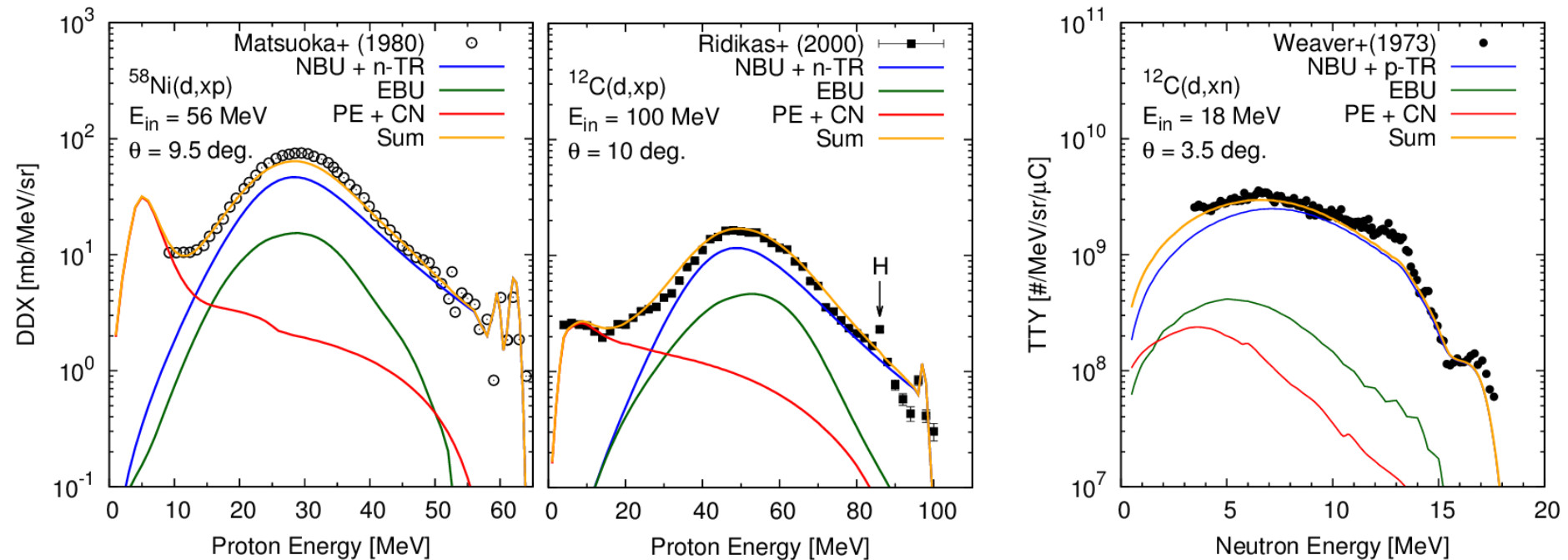
Results of our previous analysis

Double differential cross-section

Double differential yield

$^{58}\text{Ni}(d, xp)@56\text{MeV}$ [1] $^{12}\text{C}(d, xp)@100\text{MeV}$ [1]

$^{12}\text{C}(d, xn)@18\text{MeV}$ [2]



DEURACS was successfully applied to the (d, xp) and (d, xn) reactions.

[1] S. Nakayama and Y. Watanabe, JNST **53**, 89 (2016).

[2] S. Nakayama et al., PRC **94**, 014618 (2016).

Purposes in the present work

- ✓ A **new measurement** of DDXs for (d, xn) reactions has been performed at 102 MeV [3].



Purposes

1. To perform further investigation for applicability of DEURACS to (d, xn) reactions.
2. To apply DEURACS to analysis of (d, xd) reactions.

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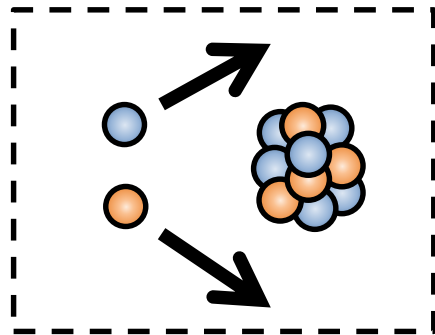
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Calculation method (1)

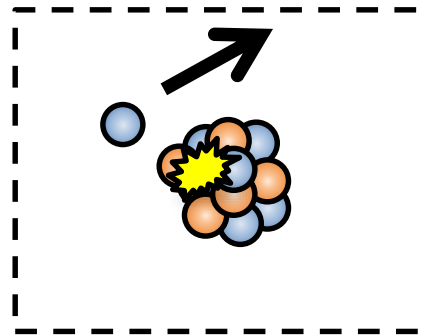
- ✓ DDXs of (d, xn) reactions are expressed as follows.

$$\frac{d^2 \sigma^{(d, xn)}}{dE d\Omega} = \frac{\text{Elastic breakup}}{d^2 \sigma_{EBU}} \frac{d^2 \sigma}{dE d\Omega} + \frac{\text{Nonelastic breakup + Proton transfer}}{d^2 \sigma_{NBU+p-TR}} \frac{d^2 \sigma}{dE d\Omega} + \frac{\text{Pre-equilibrium + Compound nucleus}}{d^2 \sigma_{PE+CN}} \frac{d^2 \sigma}{dE d\Omega}$$

CDCC method ^[4]



Glauber model ^[5] +
DWBA (DWUCK4 ^[6])



Next Slide...

[4] M. Yahiro et al., PTEP **2012**, 1A206 (2012) [5] T. Ye et al., PRC **84**, 054606 (2011).

[6] P. D. Kunz, <http://spot.colorado.edu/~kunz/DWBA.html>.

Input parameters

- ✓ CDCC method / Glauber model
 - OMP for n, p → **Koning and Delaroche** OMP^[8]
- ✓ DWBA calculation
 - OMP for d → **Adiabatic** potential^[9] from **K-D**
 - OMP for n → **K-D** OMP^[8]
 - Spectroscopic factor
 - same as those extracted in our previous work^[2].
(${}^9\text{Be}(d,n){}^{10}\text{B}$: 8 levels, ${}^{12}\text{C}(d,n){}^{13}\text{N}$: 4 levels)
- ✓ CCONE code
 - OMP → **K-D**^[8] (for n, p) , **An-Cai**^[10] (for d)
 - Level-density → Systematics by **Mengoni-Nakajima**^[11].

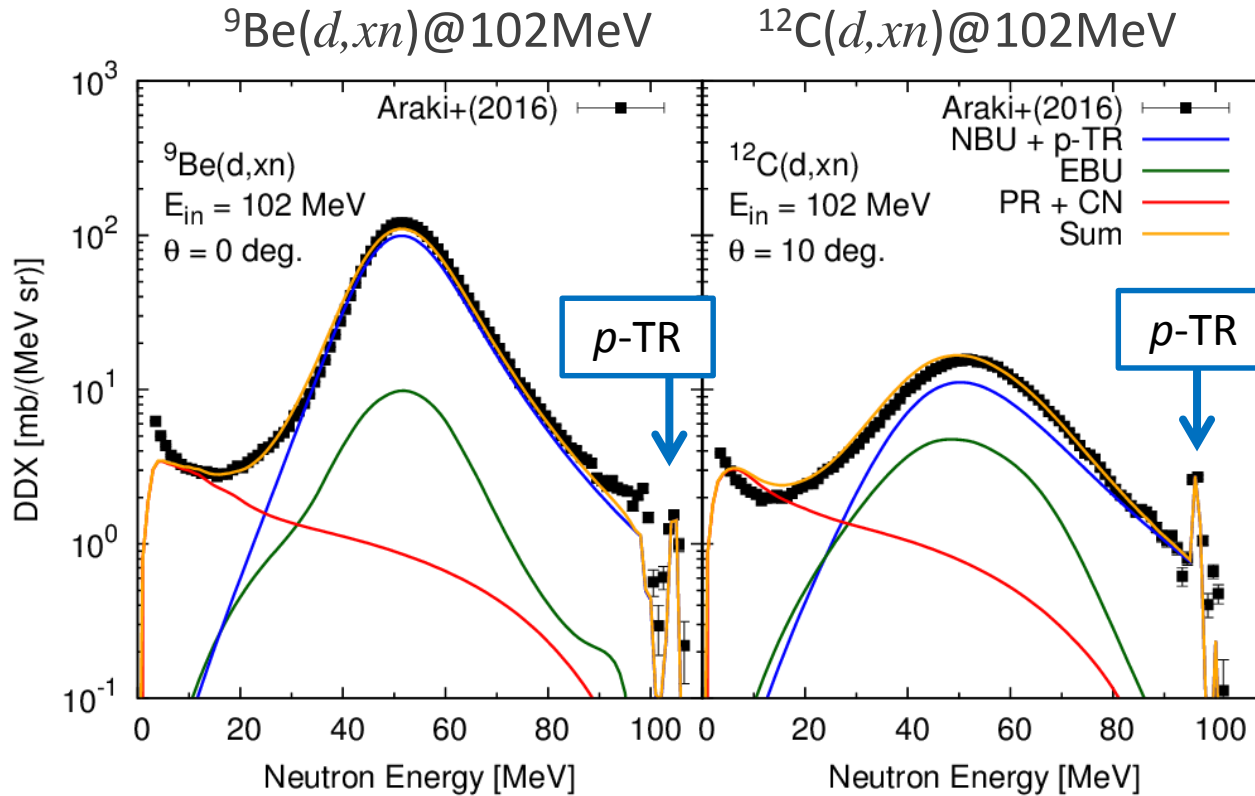
[8] A. J. Koning and J. P. Delaroche, NPA **713**, 231 (2003). [10] H. An and C. Cai, PRC **73**, 054605 (2006).

[9] R. C. Johnson and P. J. R. Soper. PRC **1**, 976 (1970).

[11] A. Mengoni and Y. Nakajima, JNST **31**, 151 (1994).

Calculation results

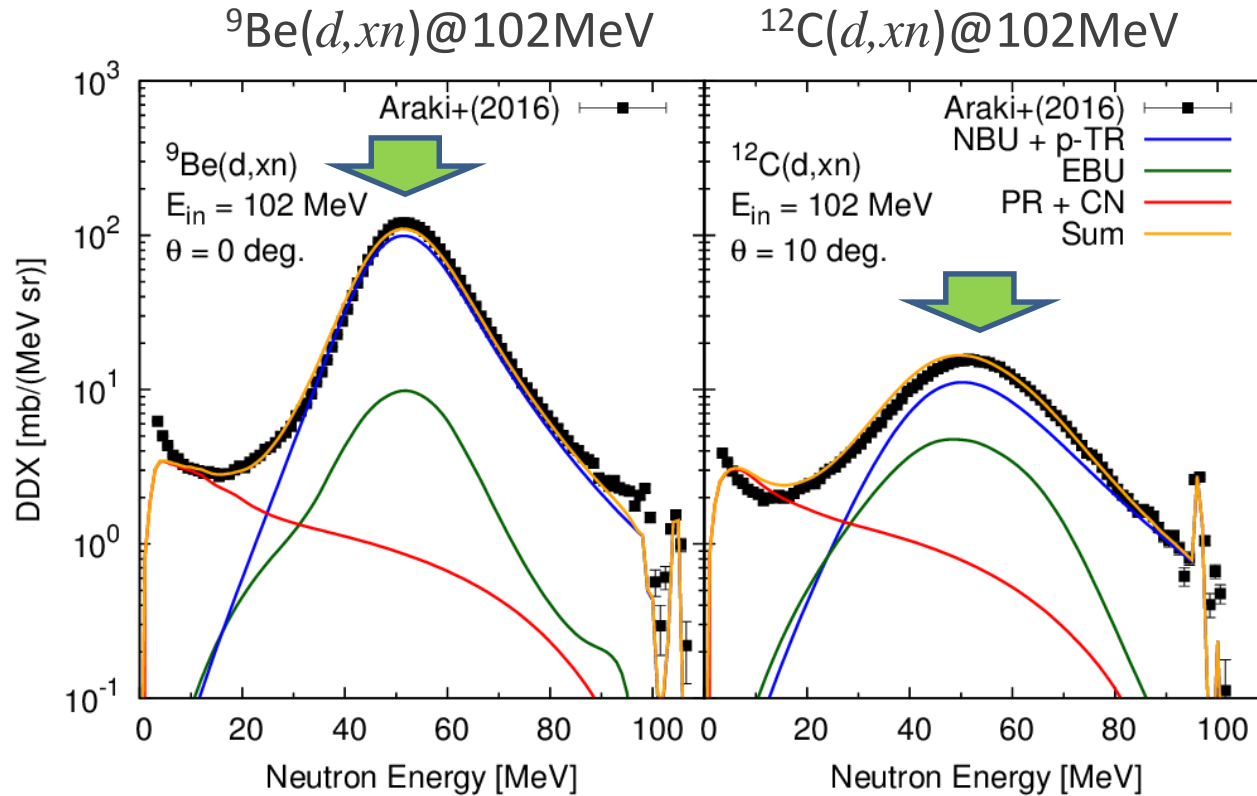
- ✓ DEURACS reproduces well the experimental data.



The applicability of DEURACS to the (d,xn) reactions are demonstrated.

Calculation results

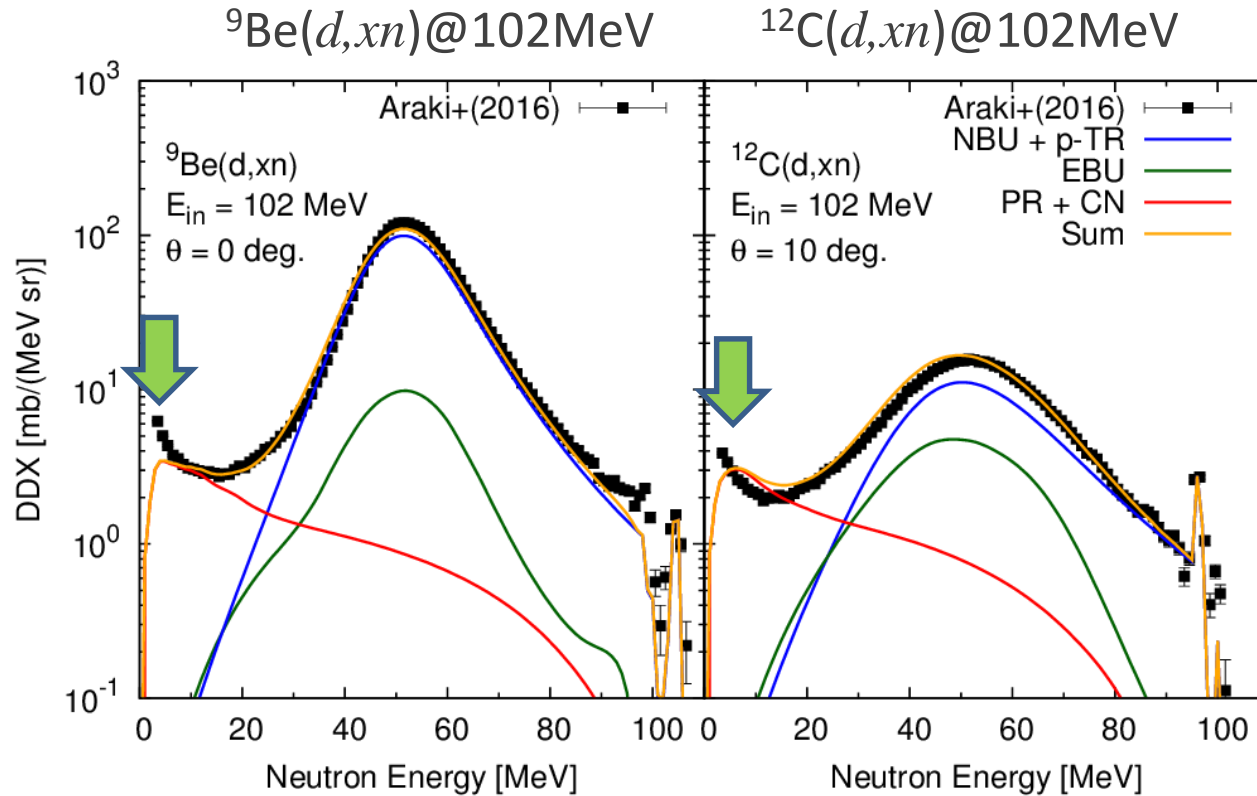
- ✓ Broad peak is formed mainly by **nonelastic breakup**.



Modeling of the nonelastic breakup reaction is essential for prediction of neutron yields.

Calculation results

- ✓ DEURACS underestimates the data in **low energy region**.



This underestimation is likely to arise from the absence of **sequential neutron emission** from the discrete levels.

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Calculation method

- ✓ In the case of (d,xd) reactions, there is no contribution from deuteron breakup reactions.

$$\frac{d^2\sigma^{(d,xd)}}{dEd\Omega} = \frac{d^2\sigma_{S-ELA}}{dEd\Omega} + \frac{d^2\sigma_{DIR}}{dEd\Omega} + \frac{d^2\sigma_{PE+CN}}{dEd\Omega}$$

Shape elastic scattering
Direct inelastic scattering
Pre-equilibrium + Compound nucleus

↓

Optical model

Giant resonance state

Discrete level

↓

DWBA with parameters by Kalbach^[12]

(not considered ...)

↓

Same as (d,xn)

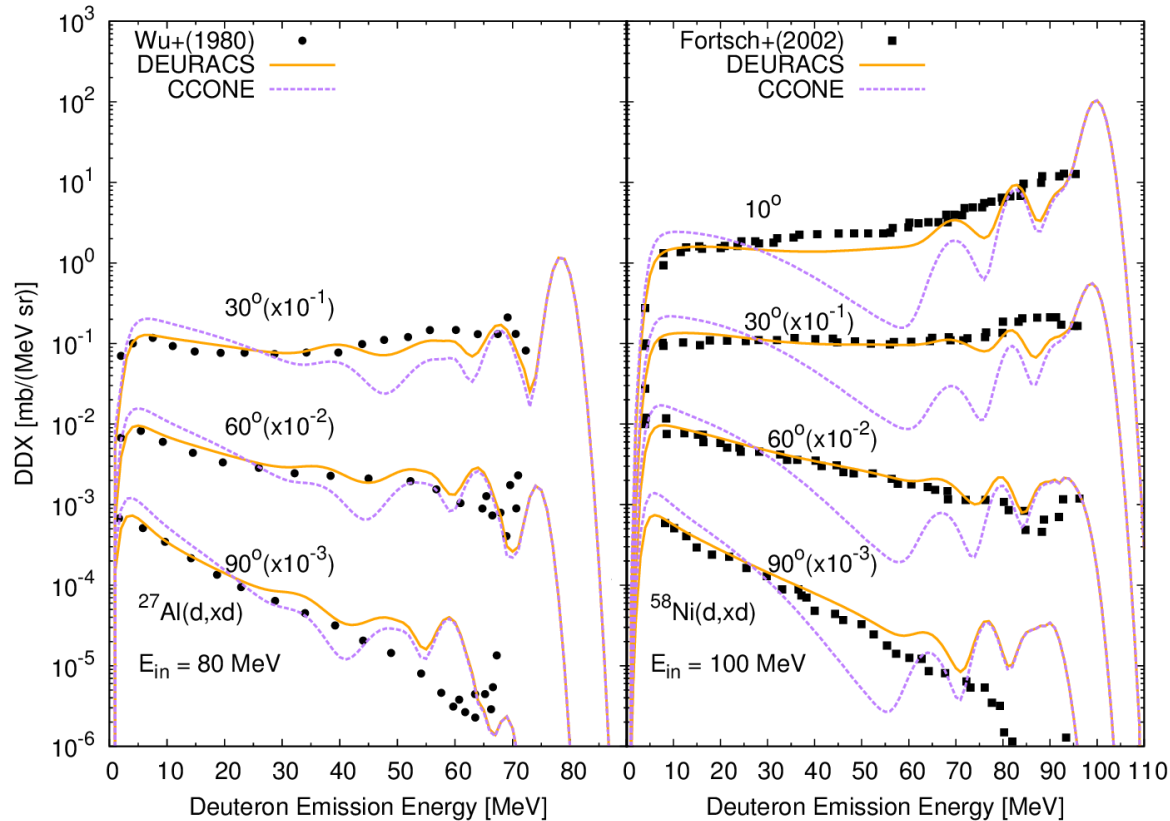
Kalbach's inelastic model

- ✓ We extend the semi-empirical inelastic scattering model proposed by Kalbach^[13].
- It was developed for the inelastic scattering by **alpha particles**.
- ✓ The model expresses the effect of excitation of a nucleon in the target nucleus by the incident **composite particle**.
- This effect is not included in the exciton model.

Calculation results

$^{27}\text{Al}(d,xd)$ @80MeV

$^{58}\text{Ni}(d,xd)$ @100MeV

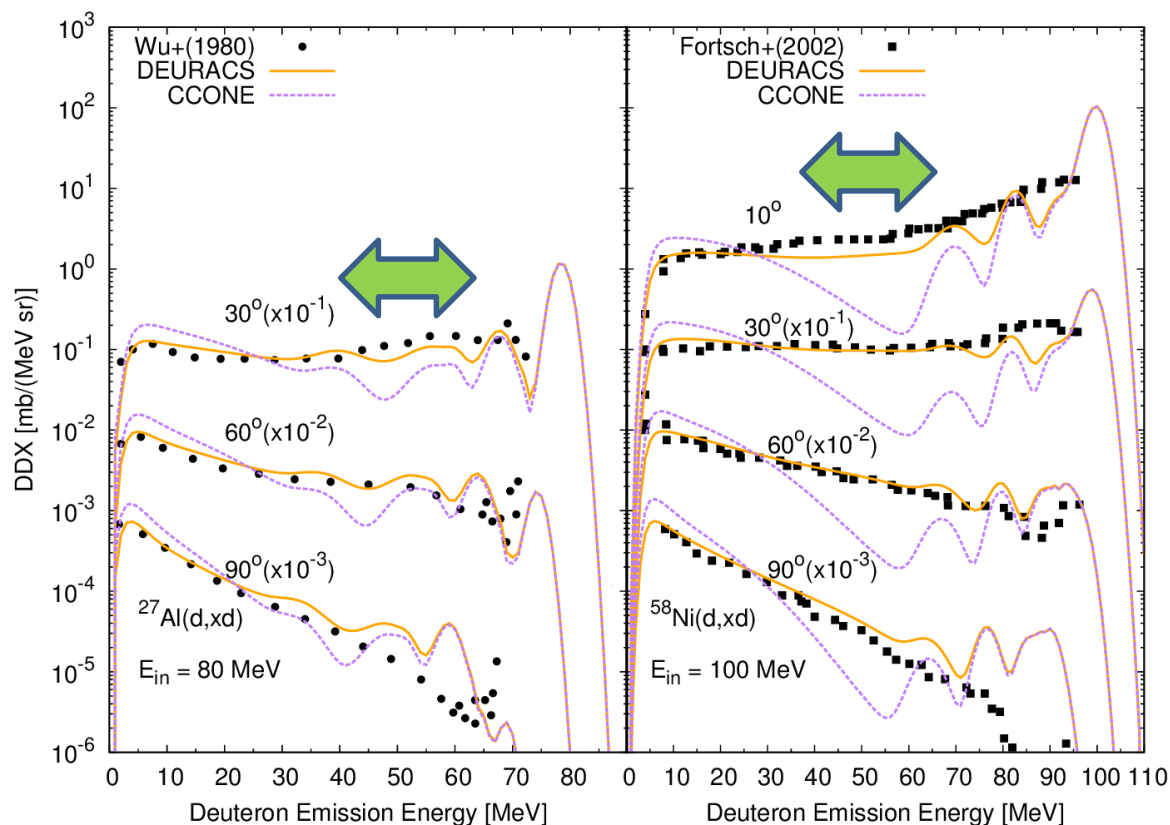


DEURACS reproduces the experimental data better than the original CCONE code.

Calculation results

$^{27}\text{Al}(d,xd)$ @80MeV

$^{58}\text{Ni}(d,xd)$ @100MeV

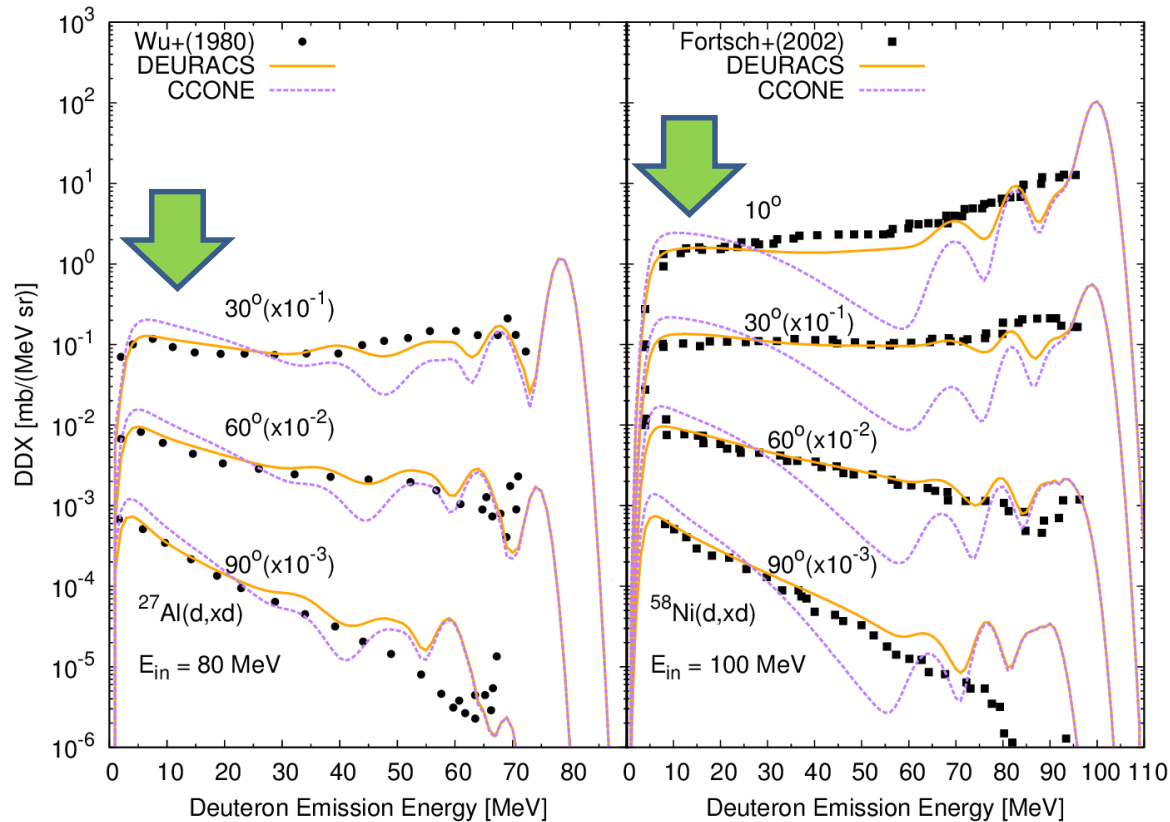


- ✓ By introducing the Kalbach's inelastic scattering model, cross sections in **the high energy region** are enhanced.

Calculation results

$^{27}\text{Al}(d,xd)$ @80MeV

$^{58}\text{Ni}(d,xd)$ @100MeV



✓ Cross sections in **the low energy region** are reduced.
(by leakage of incident deuteron flux to breakup channel)

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Summary and outlook

- ✓ We have analyzed (d, xn) and (d, xd) reactions using **DEURACS**.
- ✓ DEURACS calculations reproduce well the experimental (d, xn) and (d, xd) data at incident energies of 80 and around 100 MeV.
- ✓ In the future, we plan to perform **deuteron nuclear evaluation** using DEURACS.
→ First priority : light nuclei (Li, Be, C)