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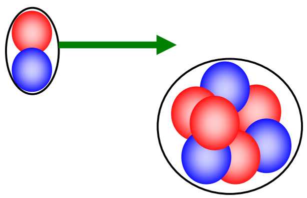
ND2016
Bruges, Sep. 11-16, 2016

Deuteron nuclear data for the design of accelerator-based neutron sources:
measurement, model analysis, evaluation, and application



Yukinobu WATANABE, Tadahiro KIN, Shouhei ARAKI,
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九州大学
KYUSHU UNIVERSITY

Shinsuke NAKAYAMA and Osamu IWAMOTO
Japan Atomic Energy Agency

JAEA

Contents

- Introduction: Background & Motivation
- Outline of the research program
- Measurements
  - (I) TTNYs at KUTL
  - (II) DDXs of (d,xn) at RCNP
- Code development, model analysis
- Nuclear data evaluation
- Application to medical isotopes production
- Summary and outlook

Contents

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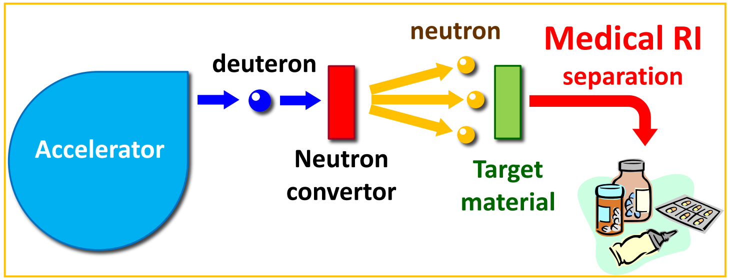
Introduction

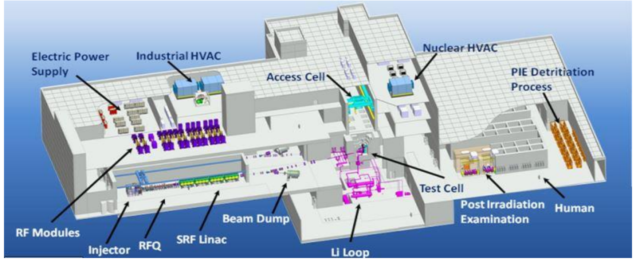
Why are we interested in the study of deuteron nuclear data ?

✓ **Accelerator-based neutron sources with deuteron-induced reactions on ^{7}Li, ^{9}Be, ^{12}C, etc., are proposed for various neutron beam applications as shown below.**

✓ **The R & D of such neutron sources has led to the revival and increasing interest on the study of deuteron-induced reactions.**

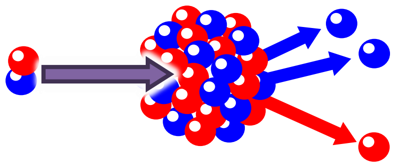


RI production for medical use



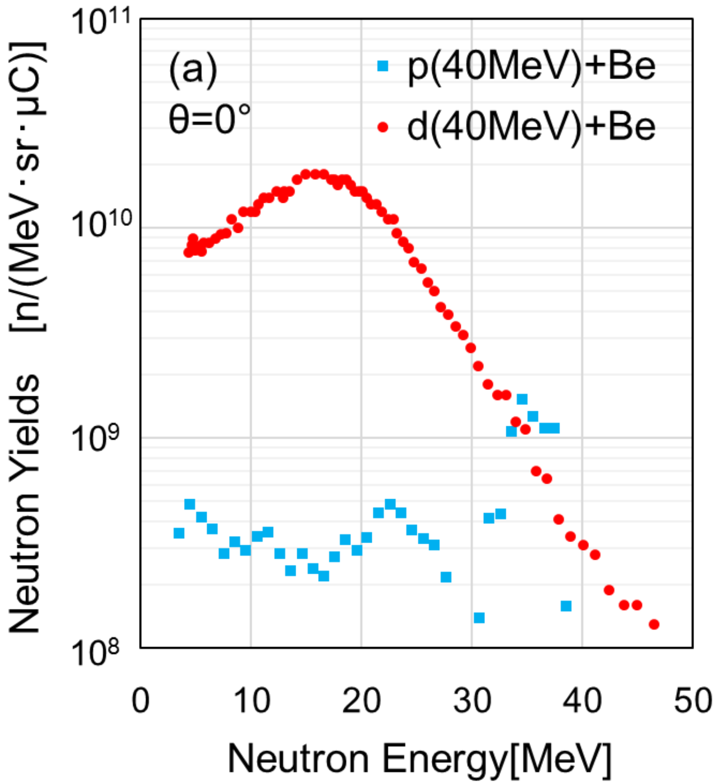
IFMIF@http://www.ifmif.org/

International Fusion Material Irradiation Facility (d + Li)

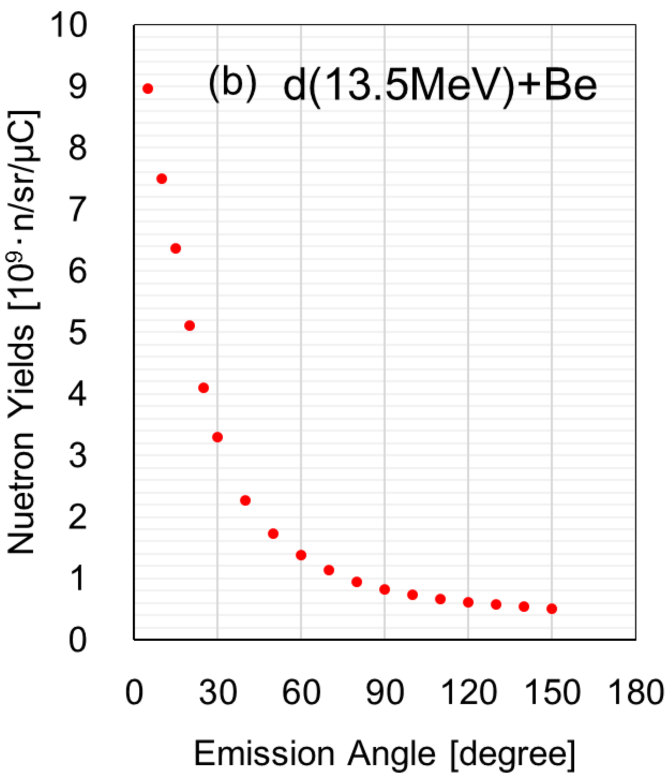


Transmutation of long-lived radioactive nuclear waste

Features of (d,xn) neutron sources



d: M. J. Saltmarsh et al, NIM 145 (1977) 81.
P: Y. Uwamino et al, NIM A 271 (1988) 546.



H.J. Brede, et al., NIM A 274 (1989) 332.

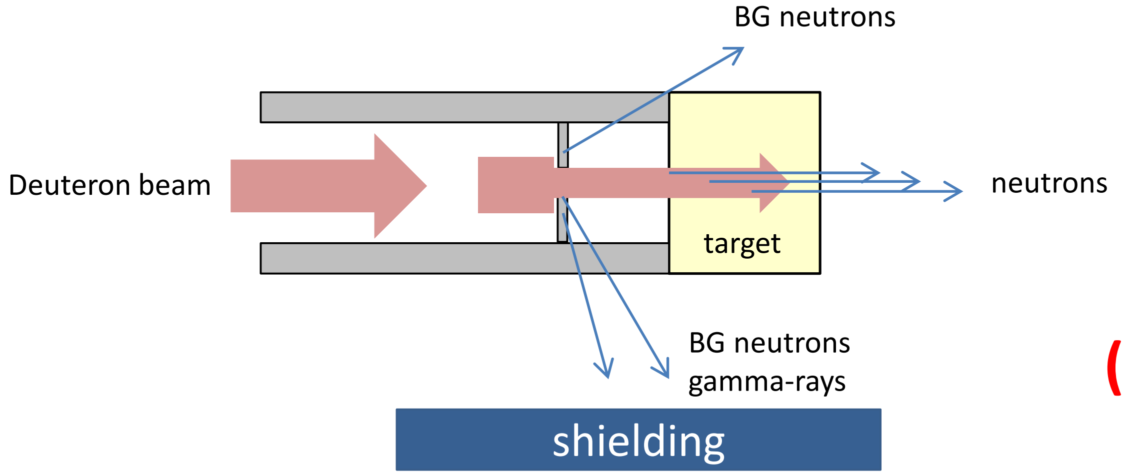
Features

- Intensive neutron yields
- Broad peak structure around half the incident energy
- Strongly forward-peaked angular distributions

Nuclear data necessary for engineering design

The engineering design of the (d,xn) neutron sources requires the following nuclear-physics based knowledge:

- ✓ Interaction of deuterons with target materials
- ✓ Nuclear reactions due to deuteron beam loss in the beam collimators and beam dump in the transport system.



Schematic drawing of a neutron source

(d,xn) data for

- Characterization of the neutron source
- Shielding design of the facility

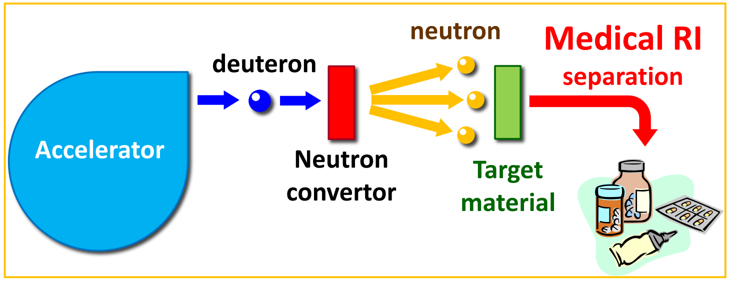
(d,x) activation data for

- Prediction of induced activity

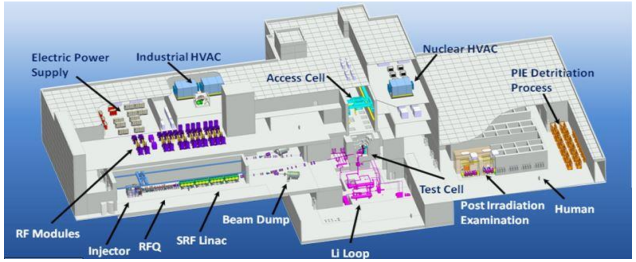
Requirement of Deuteron Nuclear Data

In the engineering design of the (d,xn) neutron sources

Comprehensive nuclear data of deuteron-induced reactions over the wide ranges of incident energy and target mass number are necessary for accurate estimation of neutron yields and induced radioactivity.

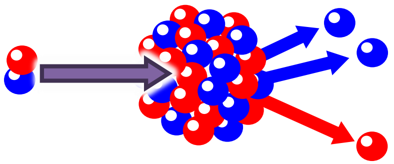


RI production for medical use



IFMIF@http://www.ifmif.org/

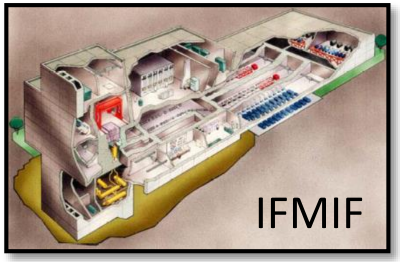
International Fusion Material Irradiation Facility (d + Li)



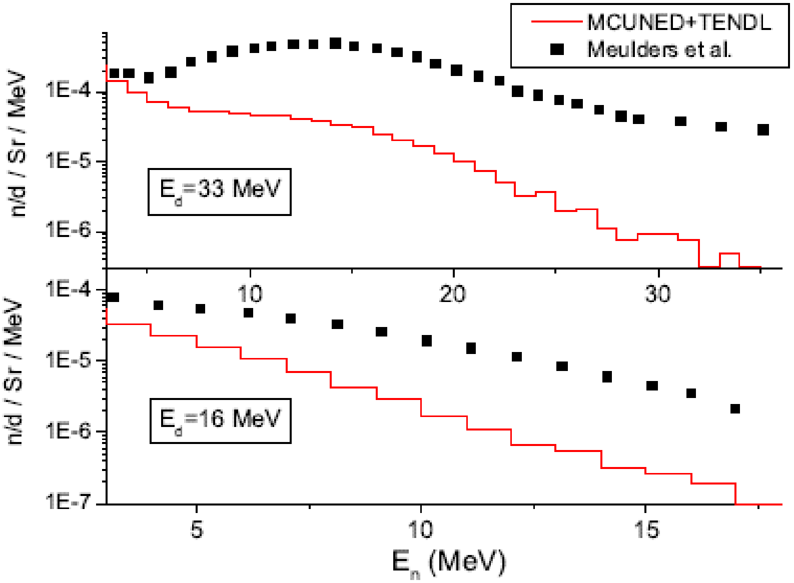
Transmutation of long-lived radioactive nuclear wastes

Evaluated nuclear data library for Deuteron-induced reactions

- ✓ An evaluated nuclear data library called **TENDL** is now available for deuteron-induced reactions up to 200 MeV. http://www.talys.eu/tendl-2015/
- ✓ Recently, a part of the data have been included in **FENDL-3**



- ✓ Recent work with a Monte Carlo code **MCUNED** revealed underestimation of neutron production from thick copper at forward angles.



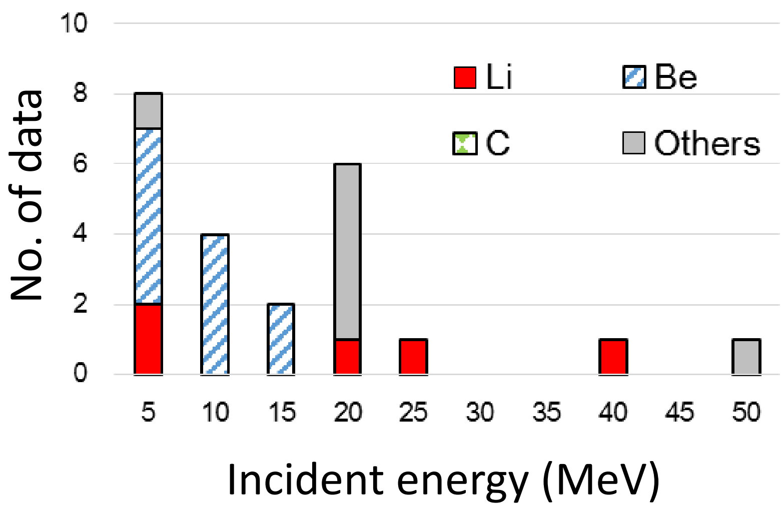
Ref.) P. Sauvan et al., Proc. ND2010 (2011).

Requirement of Experimental Deuteron Nuclear Data

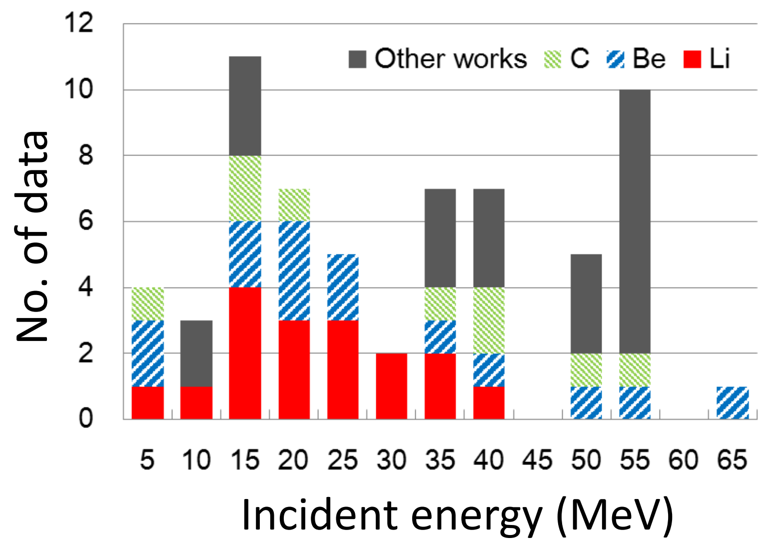
In the engineering design of the (d,xn) neutron sources

Neutron production data over the wide ranges of incident energy and target mass number are indispensable for accurate estimation of neutrons.

Double-differential cross section data (using thin targets)



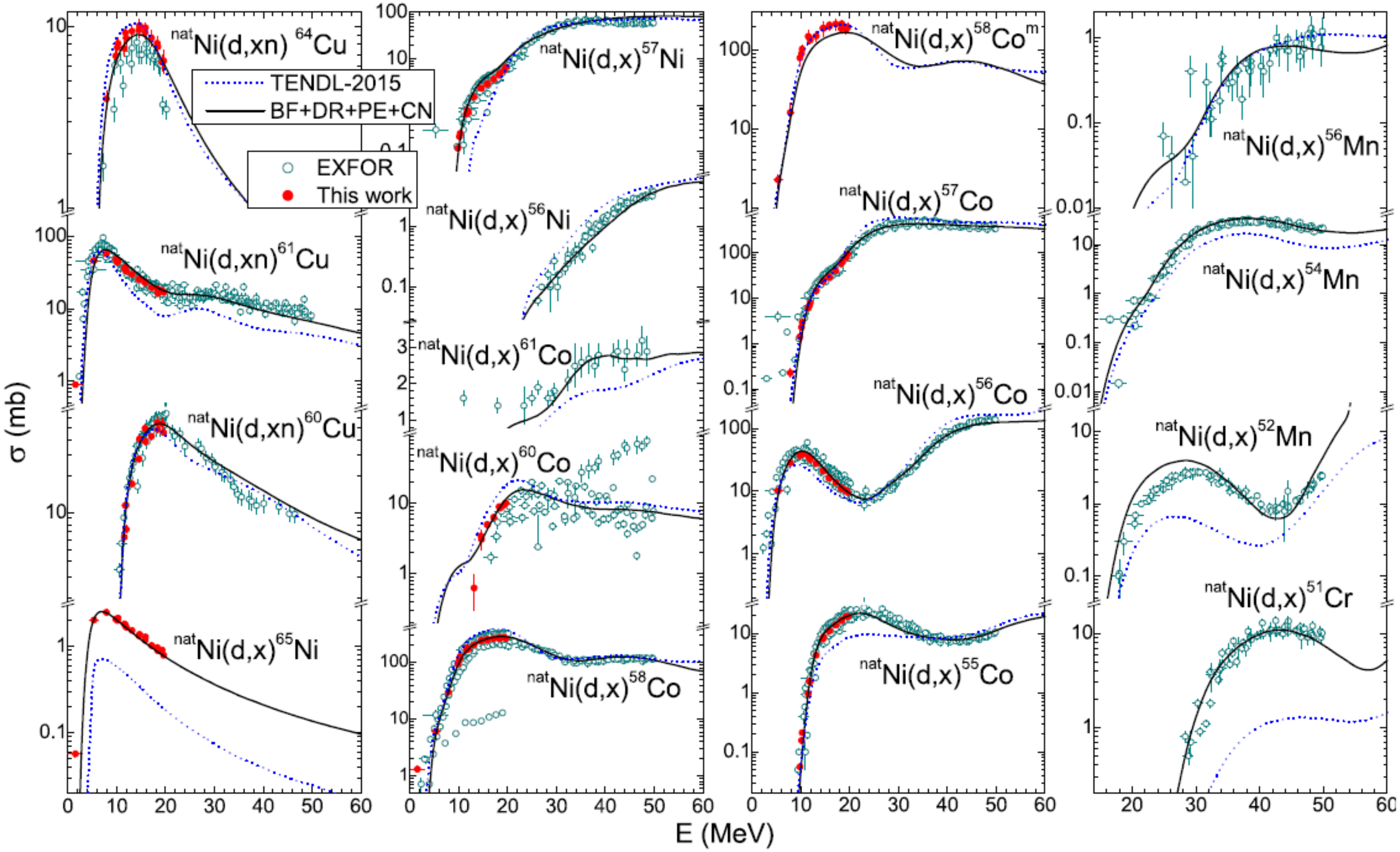
Thick target neutron yields (TTNYs)



Experimental data are lack above 65 MeV

Requirement of Experimental Deuteron Nuclear Data

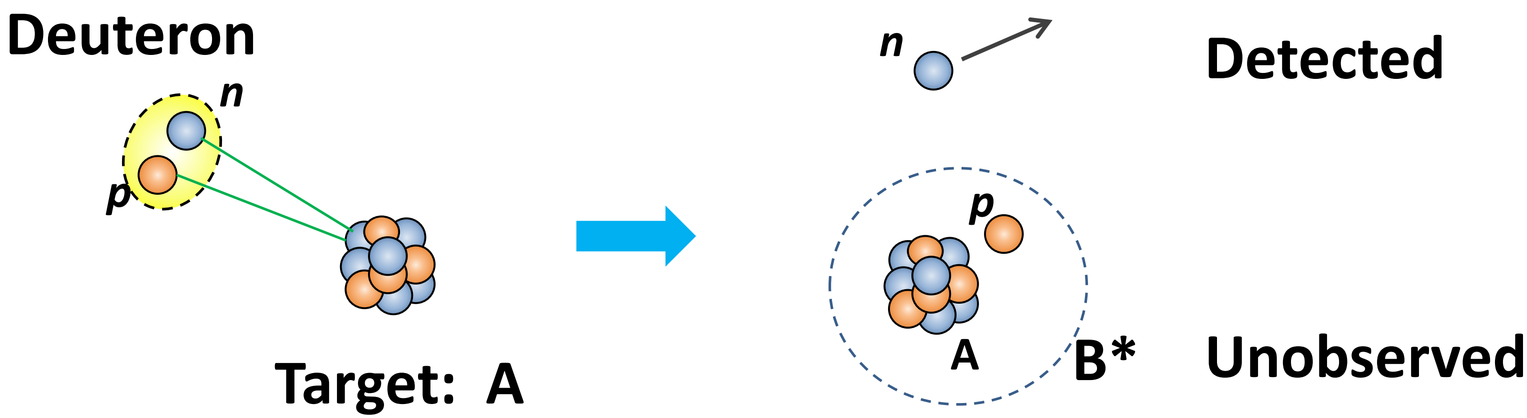
Activation cross sections over the wide ranges of incident energy and target mass number are indispensable for accurate estimation of induced radioactivity in accelerator component materials.



Systematic data are further required.

Ref.) M. Avrigeanu et al., PRC 94, 014606 (2016).

Elastic and Non-elastic breakup



$$d + A \rightarrow n + B^*$$

$\boldsymbol{B^*}$ represents any possible configuration of the $\boldsymbol{p + A}$ system.

- Elastic scattering of *p* by A → **Elastic Breakup (EBU)**

  3-body final state: n + p + A

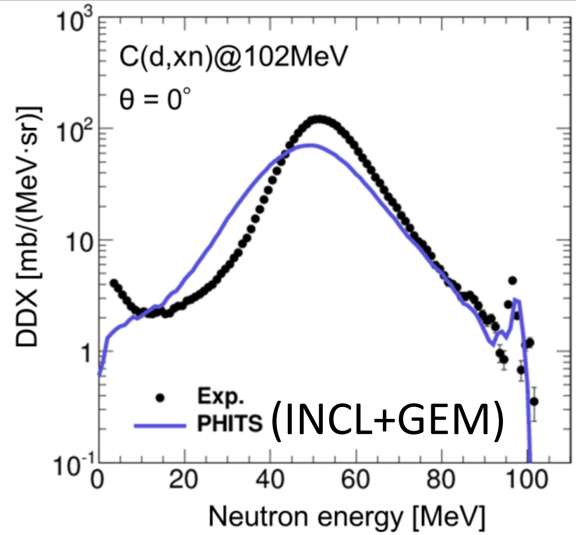
- Target excitation, the absorption of *p* by A, etc.

  → **Nonelastic breakup (NBU)**

Inclusive breakup = EBU + NBU

Evolution of Inclusive breakup model

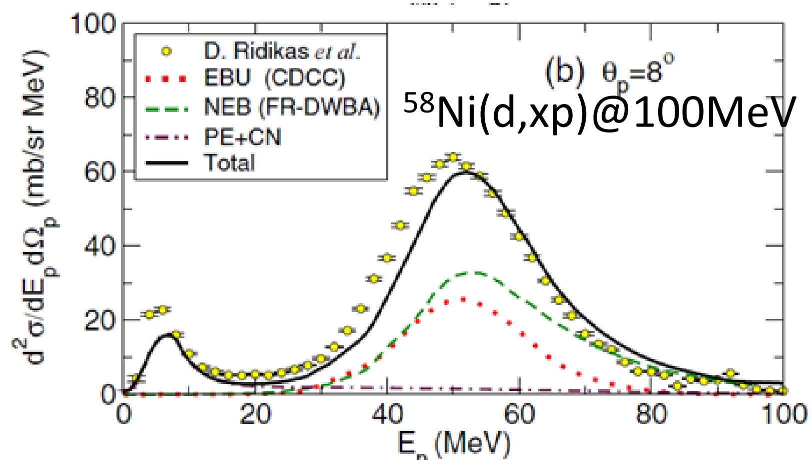
- **Semi-classical approach:**
  - ✓ Serber model
  - ✓ Glauber model (adiabatic & eikonal approx.)



S. Araki et al., R361 in ND2016

- **Intra-nuclear cascade model:**
  - ✓ INCL 4.6 (A. Boudard +. PRC87, 014606 (2013))

- **Latest works on DWBA:**
  - ✓ G. Potel et al., PRC92, 034611 (2015)
  - ✓ J. Lei & A.M. Moro, PRC92,044616 (2015)
  - ✓ B.V. Carlson et al., Few-Body syst. 57, 307 (2016)



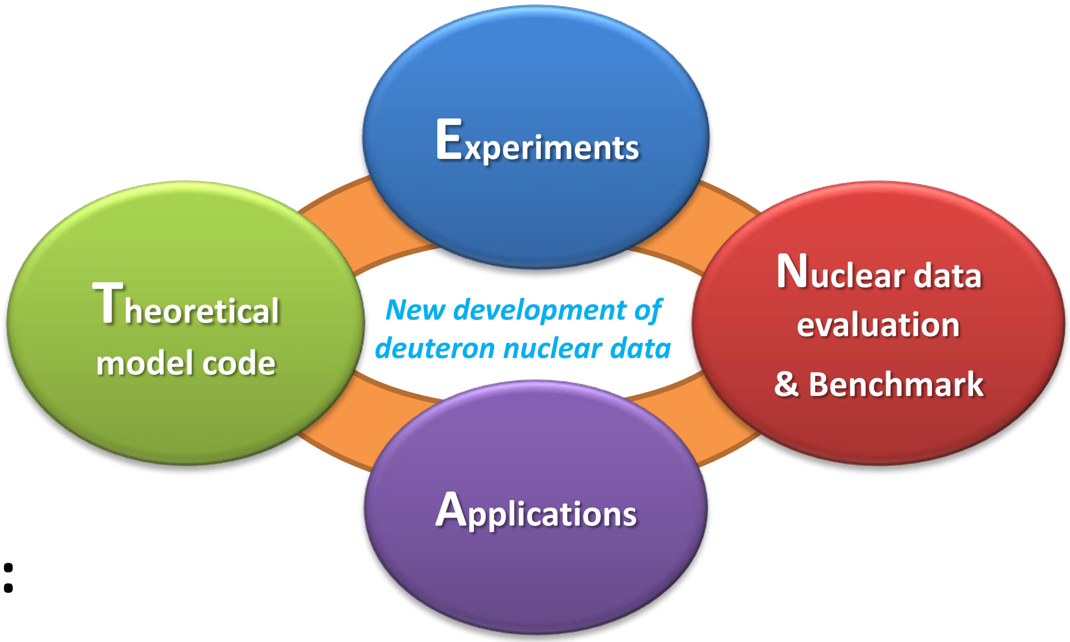
J. Lei, A.M. Moro, PRC92,044616 (2015)

- **Integrated code for cross section evaluation:**
  - ✓ **DEURACS**: S. Nakayama et al., PRC 94, 014618 (2016).

Outline of
- A new research program on deuteron nuclear data -

Our goal is to develop a state-of-the-art nuclear data library up to 200 MeV necessary for the design of (d,xn) neutron sources.

What we should do toward the goal:



Action items:

- **Measurements** of neutron and gamma-ray production DDXs and TTYs
- Modelling of deuteron-induced reactions and **Code development**
- **Nuclear data evaluation** and **Benchmark test**
- Its application to **Medical radioisotopes production**

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Measurement (I): TTNY and TTGY @ Kyushu U.

Double-differential thick target neutron and gamma-rays yields

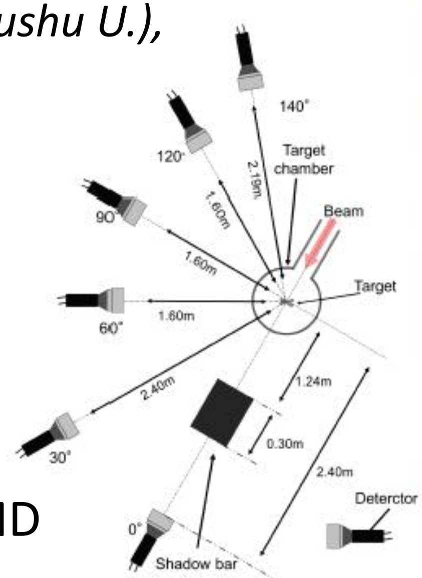
Measurement

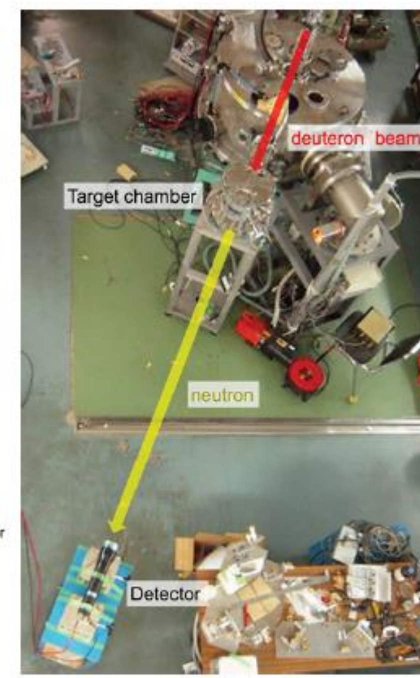
Facility:	Kyushu University Tandem Accelerator
Incident beam:	5 and 9 MeV deuterons
Detector:	NE213(Φ50.8mm × 50.8mm thick)
Target:	C, Al, Ti, Cu, Nb, Ta
Angle:	0, 15, 30, 45, 60, 75, 90, 120, 140 degrees (nine angles)

In collaboration with N. Shigyo and K. Sagara (Kyushu U.), S. Maebara, H. Takahashi, and H. Sakaki (JAEA)

Data analysis

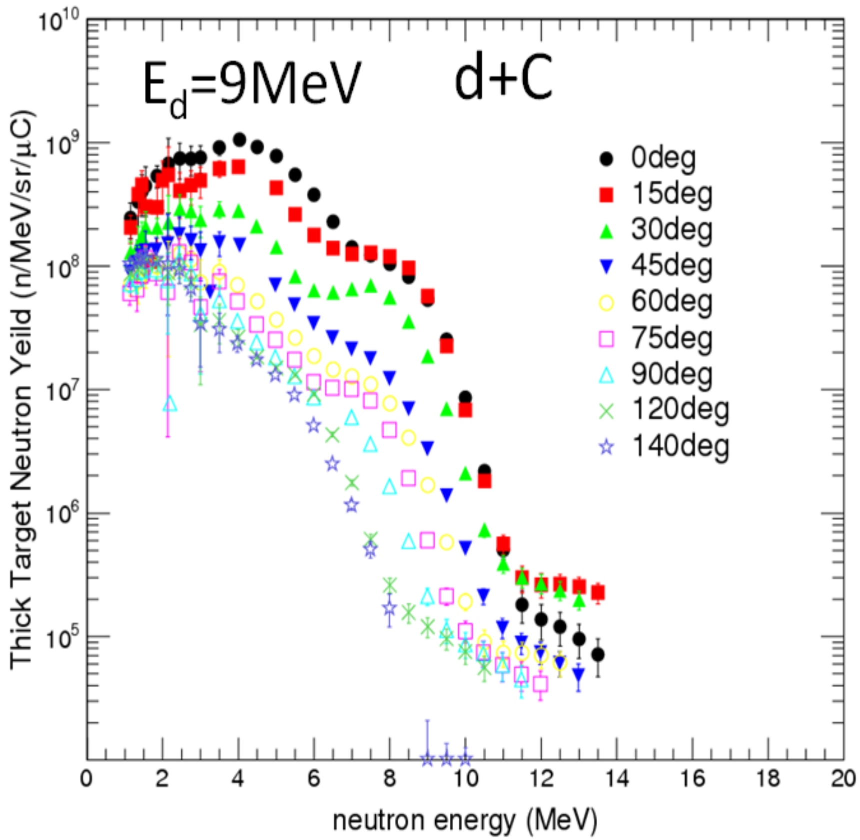
- Pulse shape discrimination of n and γ
  - ➢ Two gate integration method
- Unfolding
  - ➢ Unfolding code: FORIST
  - ➢ Response function n: SCINFUL-QMD
    γ : PHITS-EGS





Measurement of TTNY @ Kyushu U.

Double-differential thick target neutron yields

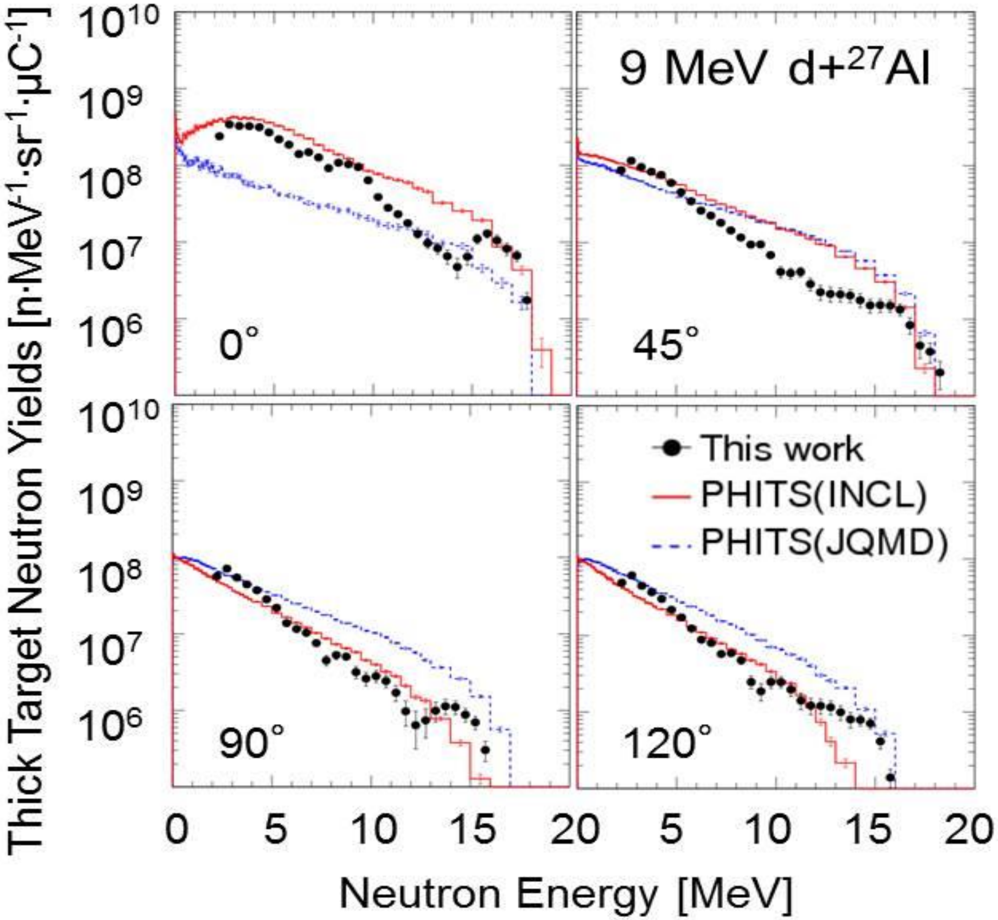


References

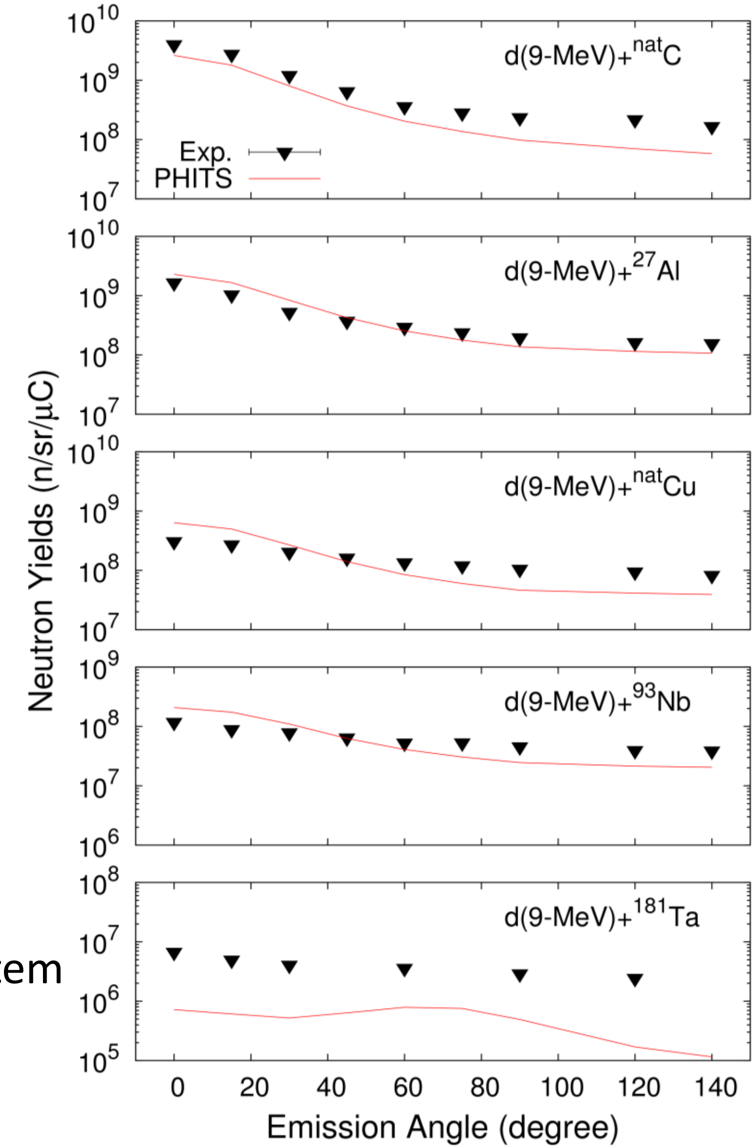
1) N. Shigyo et al., "Measurement of Deuteron Induced Thick Target Neutron Yields at 9 MeV", J. Korean Phys. Soc. **59**, 1725-1728 (2011).
2) K. Hirabayashi et al., "Measurement of Neutron Yields from Thick Al and SUS304 Targets Bombarded by 5-MeV and 9-MeV Deuterons", Prog. in Nucl. Sci. and Technol. **1**, 60-64 (2012).
3) Y. Tajiri et al., "Measurement of double differential neutron yields from thick carbon target irradiated by 5 MeV and 9 MeV deuterons", Prog. in Nucl. Sci. and Technol. **4**, 582-586 (2014).
4) S. Araki et al., "Measurement of double differential neutron yields from thick aluminum target irradiated by 9 MeV deuteron", Energy Procedia, **71**, 197-204 (2015).

Measurement of TTNY @ Kyushu U.

Double-differential TTNY



Angular distribution of TTNY



PHITS* : Particle and Heavy Ion Transport code System

PHITS(INCL) = INCL 4.6 + GEM

PHITS(QMD) = JQMD + GEM

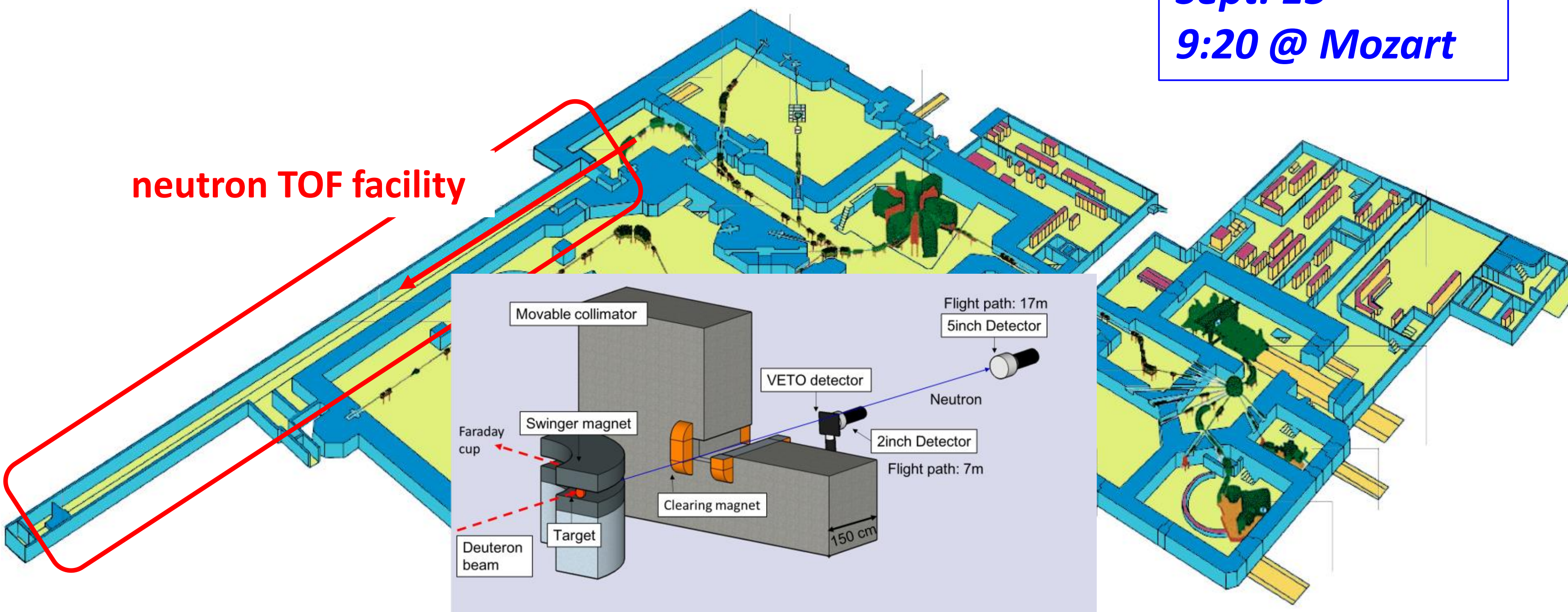
*) T. Sato et al., JNST **50**, 913 (2013).

Measurement (II) Neutron DDXs @ RCNP

Systematic measurement of double-differential (d,xn) cross sections at 102 MeV using conventional TOF method

- **Experimental Facility: Neutron TOF facility at RCNP**
- **Targets: Li, Be, C, Al, Cu, and Nb**
- **Emission angles : 0, 5, 10, 25, 20, 25 degrees**

S. Araki, R361
Sept. 15
9:20 @ Mozart

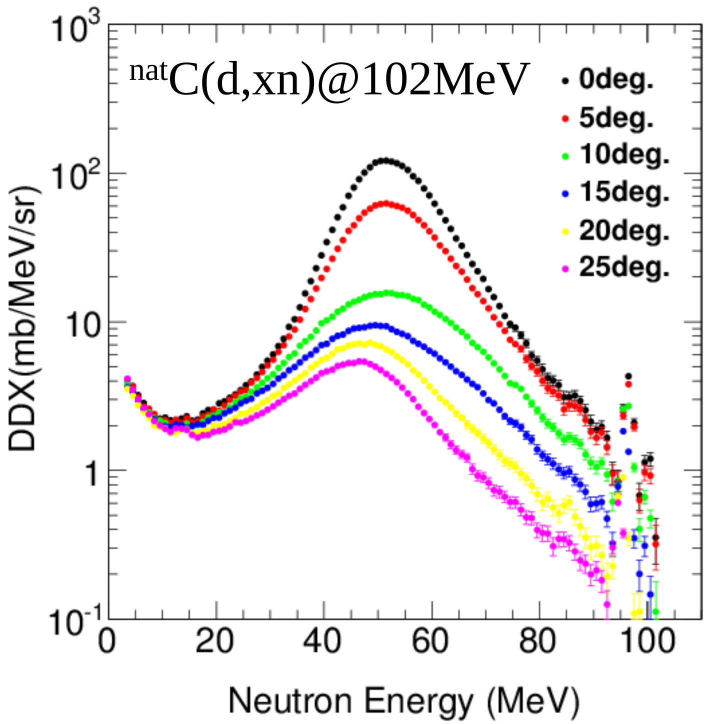


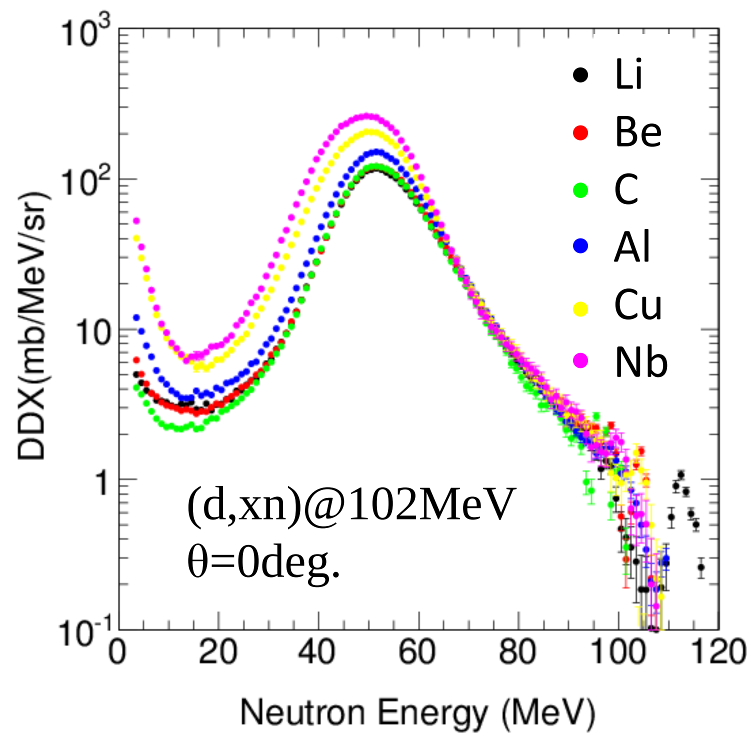
Experimental setup in the neutron TOF facility @ RCNP, Osaka U

Experimental Result

Double-differential (d,xn) cross sections

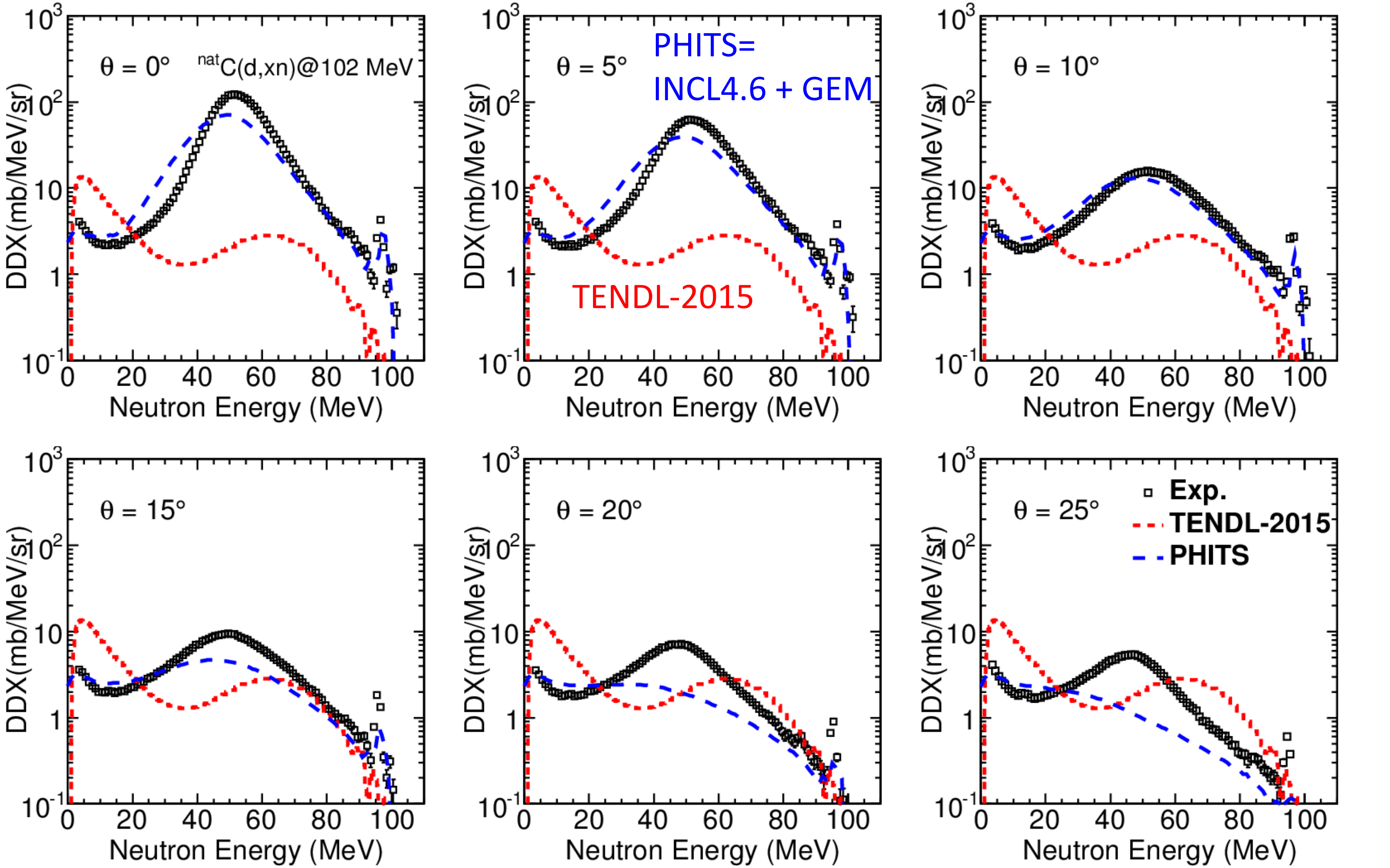
- **Incident energy : 102 MeV**
- **Targets: Li, Be, C, Al, Cu, and Nb**
- **Emission angles : 0, 5, 10, 25, 20, 25 degrees** (0, 10 degrees for Li, Cu, Nb)
- **Experimental Facility: Neutron TOF facility at RCNP**





S. Araki , YW, et al., presented at Symp. on Nuclear Data, Tokai, Japan, Nov., 19-20 (2015).

C(d,xn) at 102 MeV: TENDL-2015 vs PHITS



Contents

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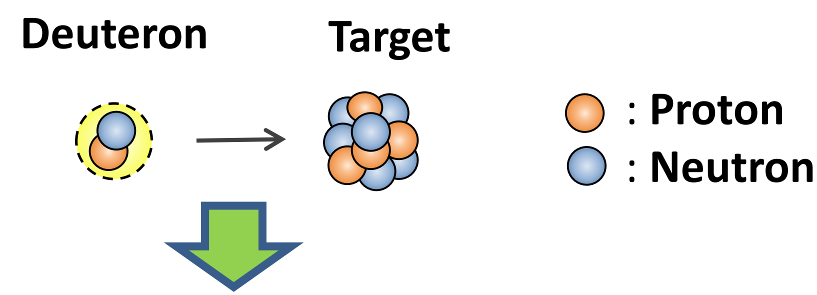
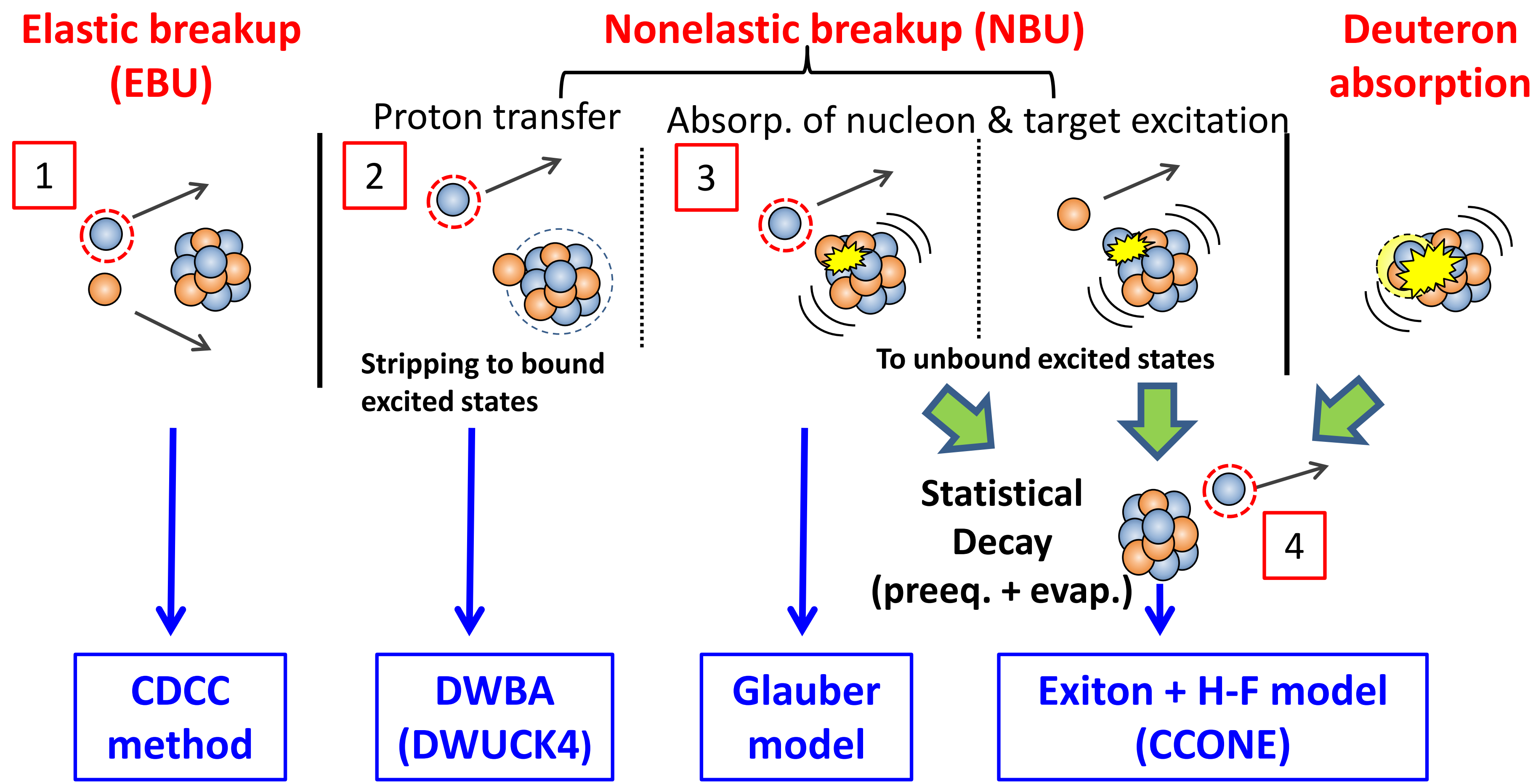
Code system development: DEURACS

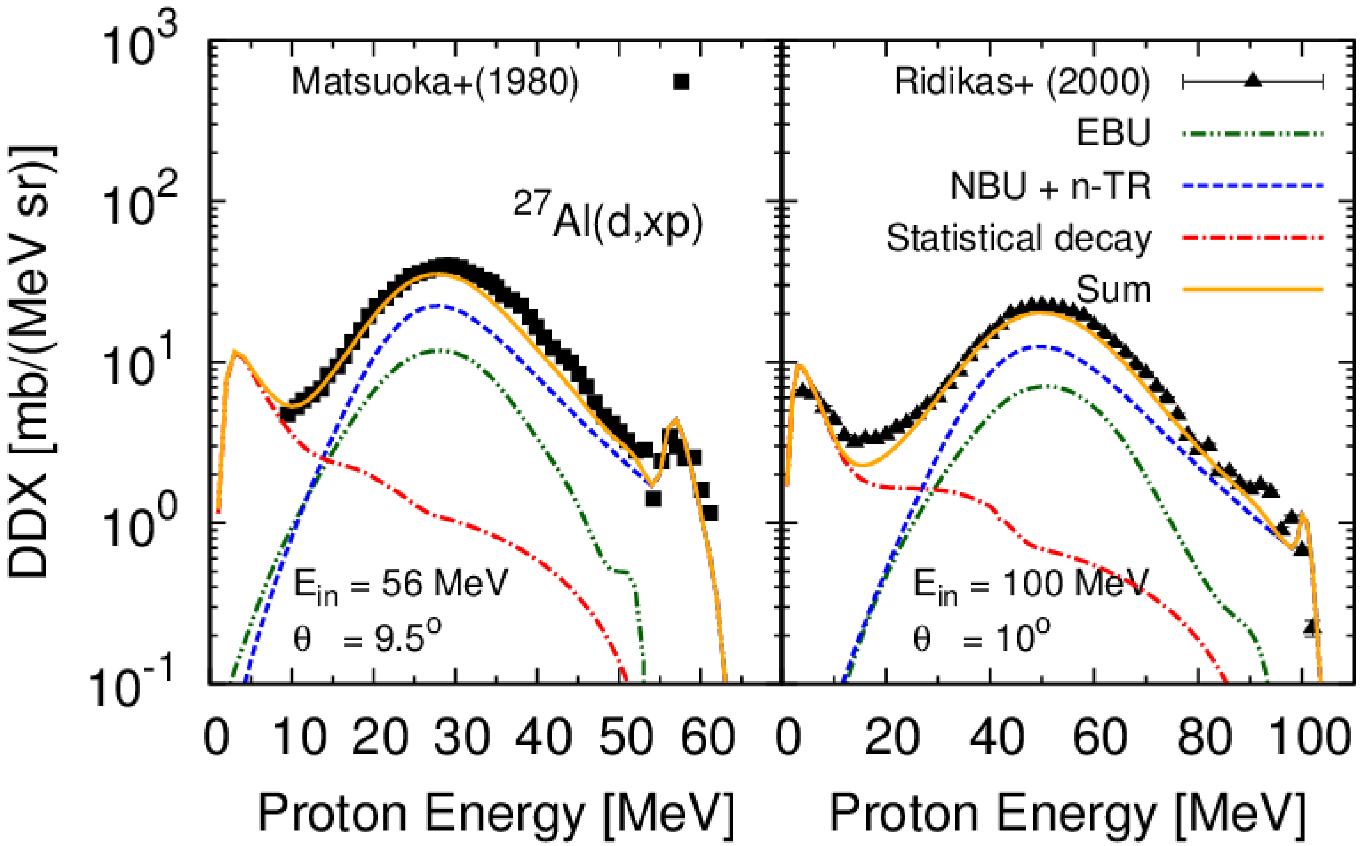
DEUtron-induced Reaction Analysis Code System

By S. Nakayama, R406
Sept. 15, 11:50 @ Vives





(d,xp) reactions on ^{27}Al at 56 and 100 MeV

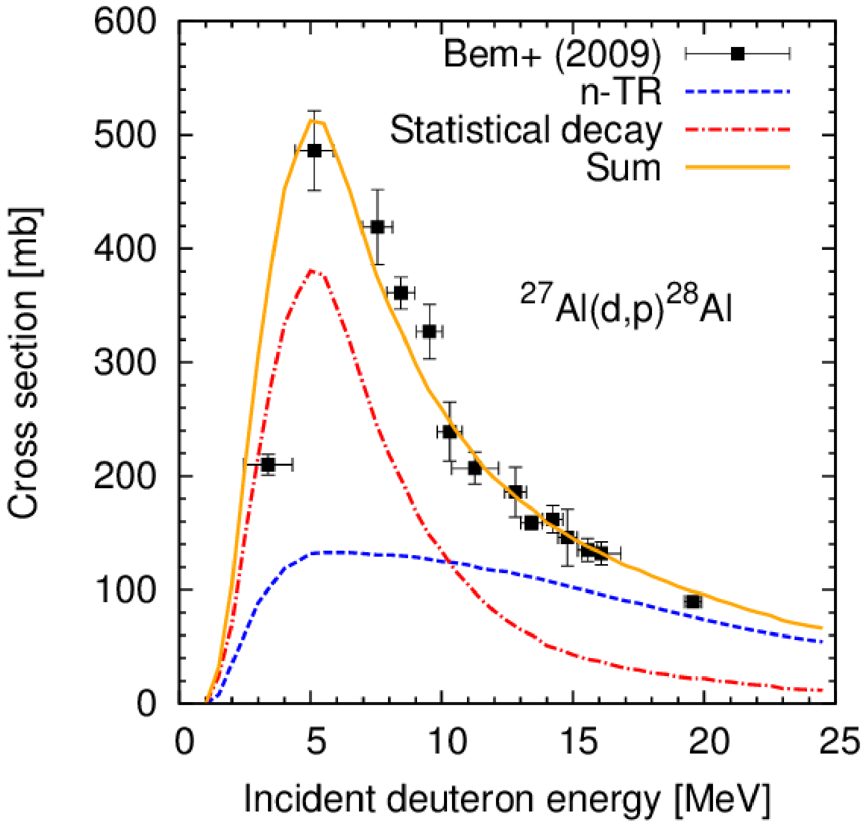


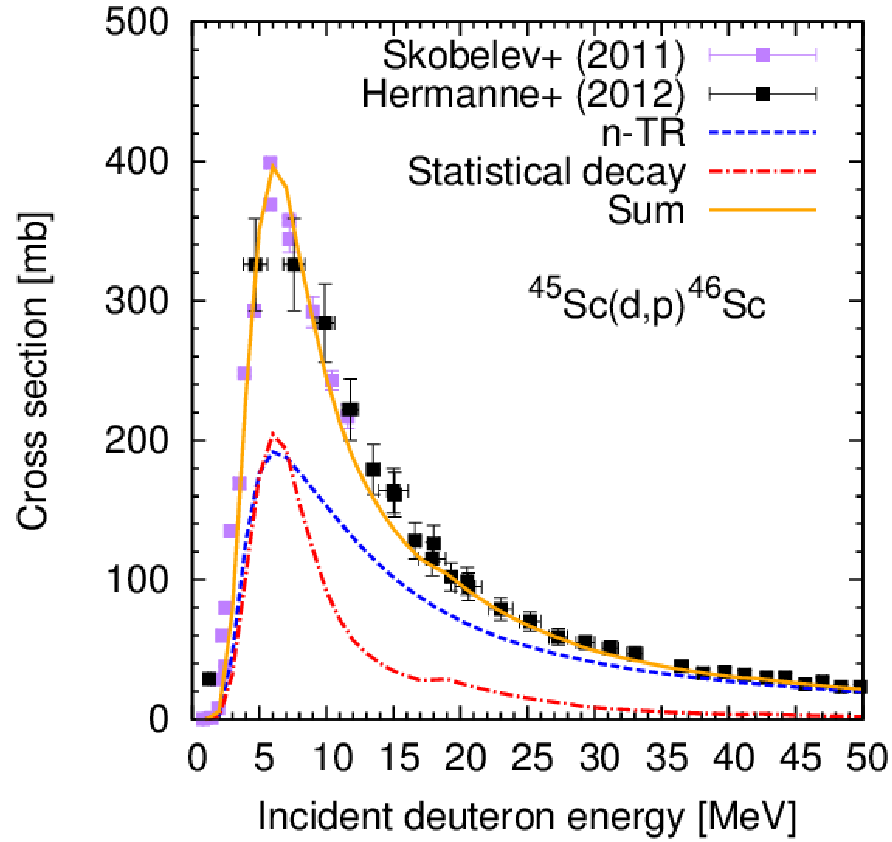
Input parameters

- CDCC and Glauber cal. → Nucleon Optical Potential (OP) : Koning-Delaroche (K-D)
- DWBA cal. → d-OP : Adiabatic OP and Spectroscopic factors deduced from exp. (d,p) data
- CCONE → N-OP: K-D, d-OP: An-Cai, Level density para. : Mengoni-Nakajima systematics

Ref.) S. Nakayama and Y. Watanabe, JNST 53, 89-101 (2016).

Activation cross sections: (d,p) reactions





Refs.)
S. Nakayama and Y. Watanabe, J. Nucl. Sci. Technol. 53, 89 (2016).
S. Nakayama and Y. Watanabe, JAEA-Conf 2015-003, 105 (2015).

TTNYs for the ^{9}Be(d,xn) reactions at 0°

Double-Differential Thick Target Neutron Yields

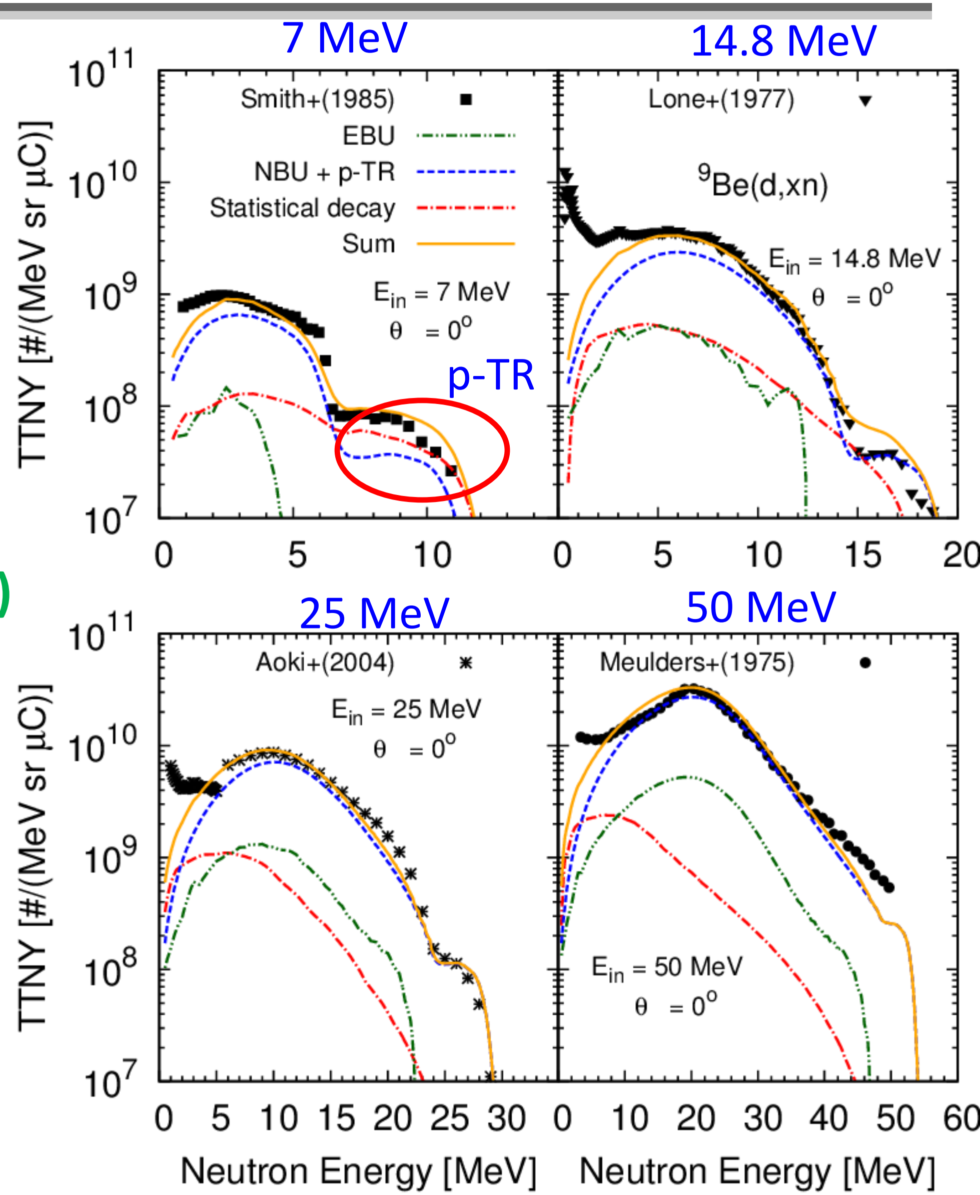
$$\frac{d^2Y}{dEd\Omega}(E_{in}) = \int_0^{E_{in}} dE_d N \boxed{\frac{d^2\sigma_{(d,xn)}}{dEd\Omega}(E_d)} \boxed{\left[\frac{dE}{dx}(E_d)\right]^{-1}} D(E_d)$$

DDX

Stopping power (SRIM)

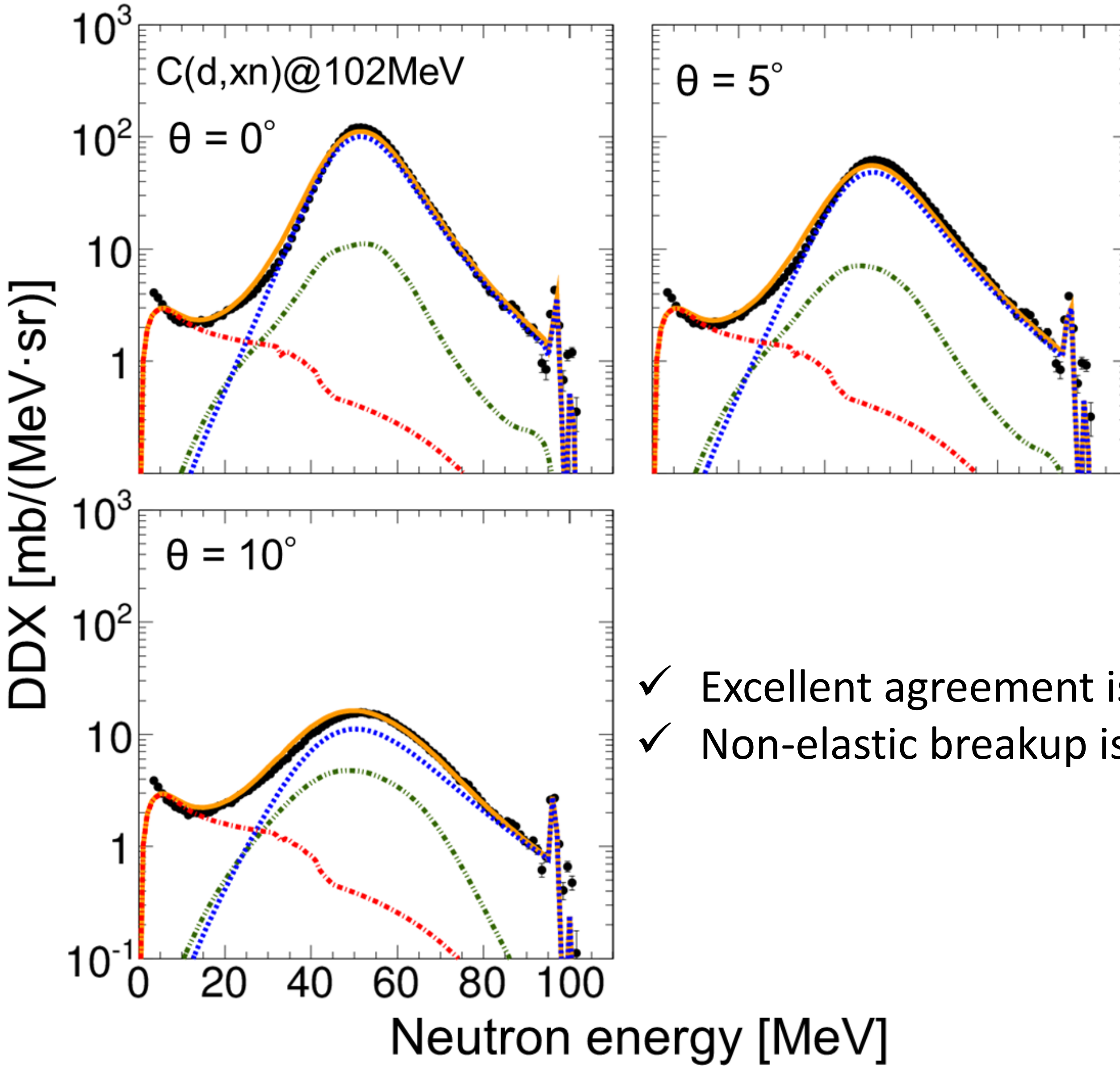
$$D(E_d) = \exp\left[-\int_{E_d}^{E_{in}} dE' N \boxed{\sigma_r(E')} \left[\frac{dE}{dx}(E')\right]^{-1}\right],$$

Total reaction cross section



Ref.) S. Nakayama et al., PRC 94, 014618 (2016).

(d,xn) reactions on C at 102 MeV



- ✓ Excellent agreement is obtained.
- ✓ Non-elastic breakup is dominant.

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- Summary and outlook

Nuclear Data Evaluation

Experimental data

EXFOR + New measurements

Theoretical model cal.

DEURACS

"Evaluated " Nuclear data

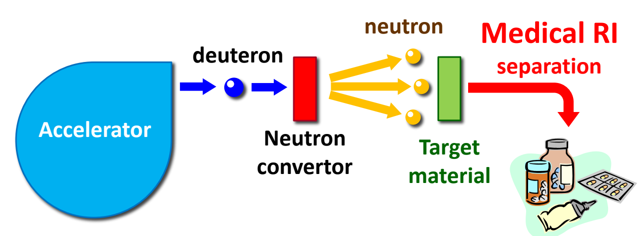
Up to 200MeV

Production of **a prototype nuclear data library for a few specific nuclei (*e.g.*, Li, Be, and C)** contained in neutron converters.

Benchmark test using TTNY data

MC code e.g., PHITS, MCUNED

Applications



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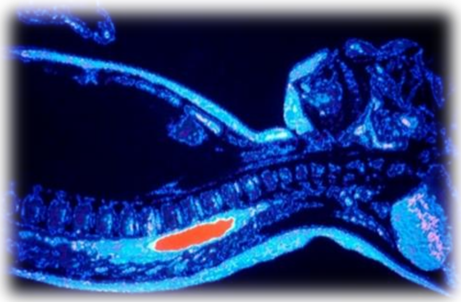
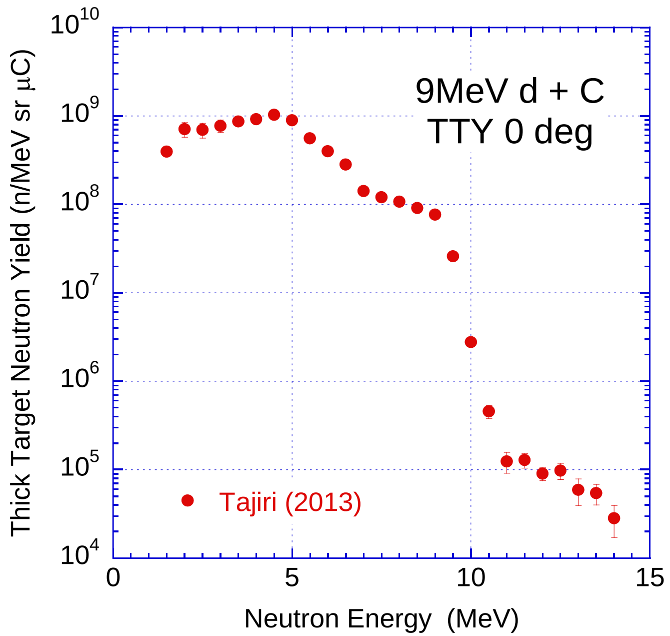
Application: Medical RI production

^{64}Cu ($T_{1/2}$ = 12.7 h)

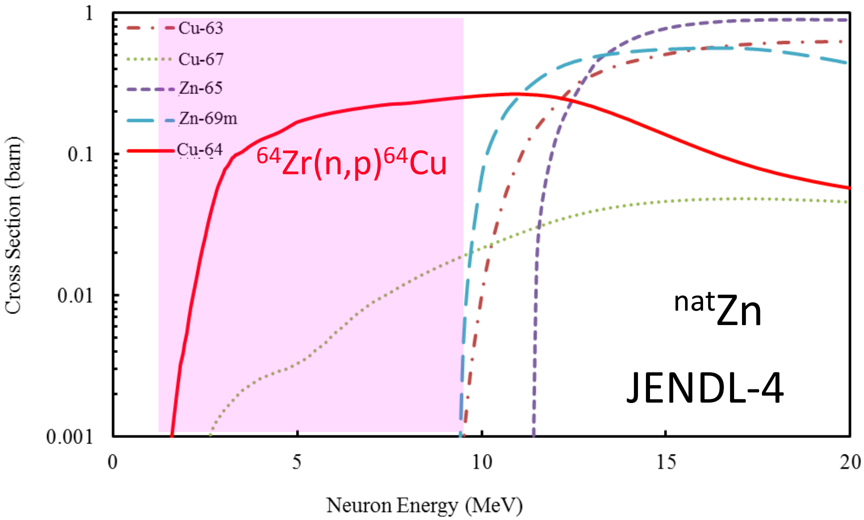
- Needs for a longer half-lived PET radionuclide to diagnose the dynamics of a medicine in living body (cf. ^{18}F: $T_{1/2}$ = 1.8 h)
- A promising radionuclide suitable for labeling many radiopharmaceuticals for PET imaging, since it decays by positron emission with a maximum energy of 0.653MeV.





Production of ^{64}Cu by using neutrons from the C(d,xn) reaction

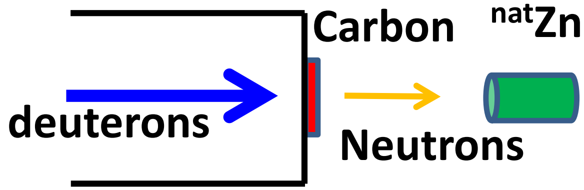
$^{64}Zn(n,p)^{64}Cu$

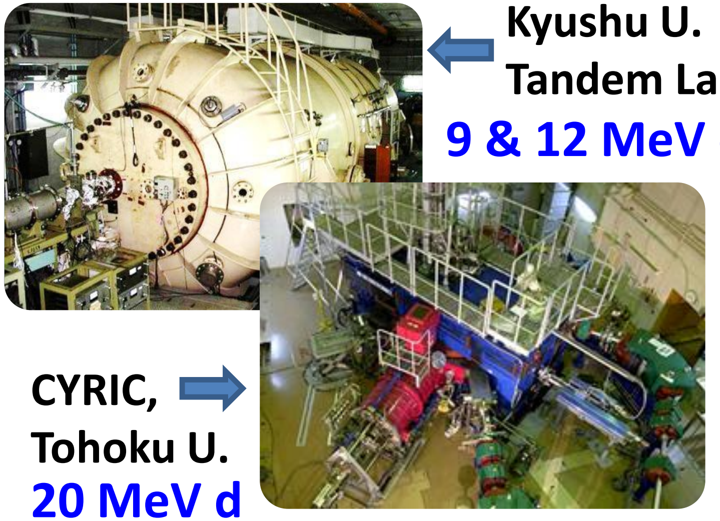


Ref.) T. Kin et al., J. Phys. Soc. Jpn. 82 (2013) 034201; Y. Nagai et al., J. Phys. Soc. Jpn. 82 (2013) 064201

Application: Medical RI production

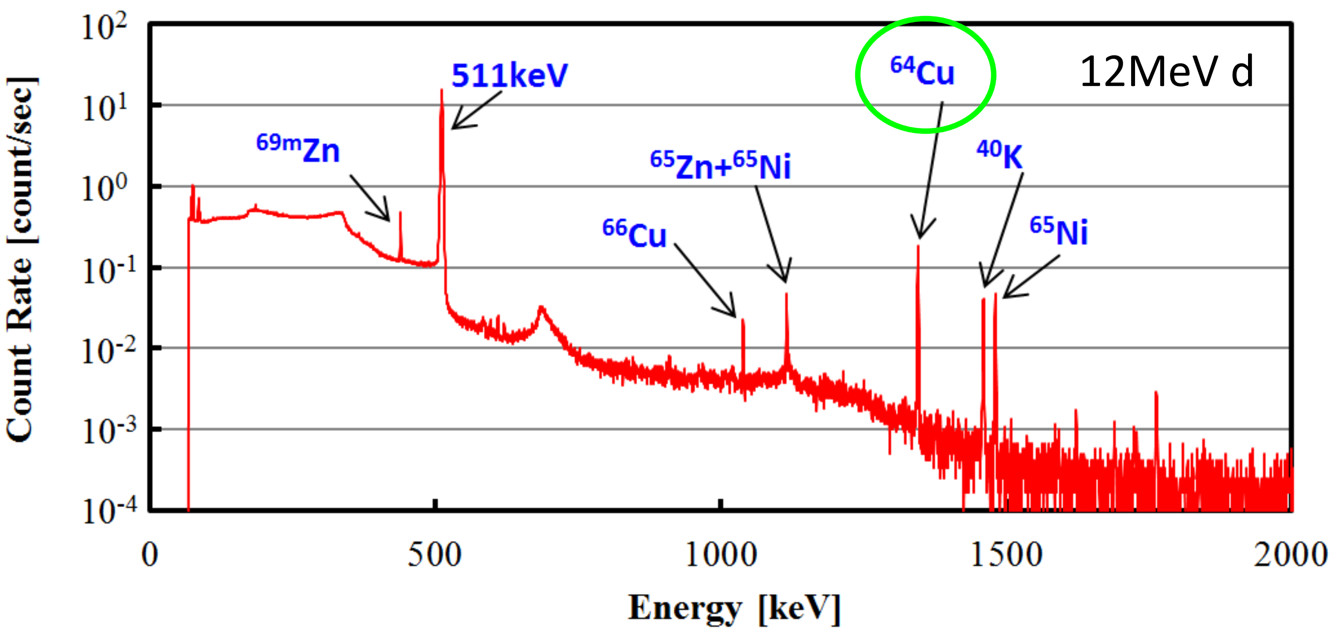
Feasibility study of production of ^{64}Cu in ^{nat}Zn irradiated by neutrons from C(d,n) by using experiment and simulation

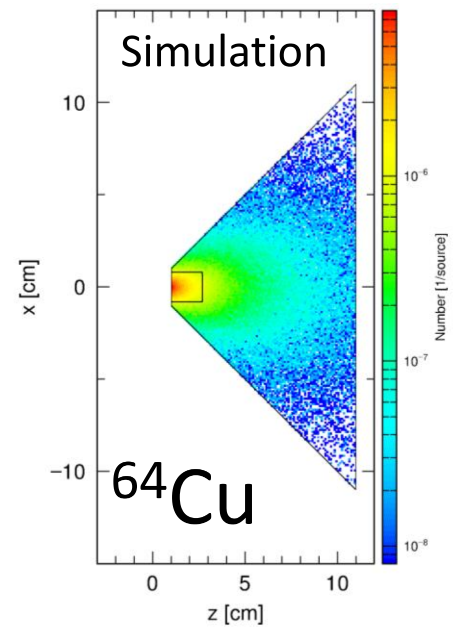




Kyushu U. Tandem Lab.
9 & 12 MeV d

CYRIC, Tohoku U.
20 MeV d





Ref.) T. Kawagoe et al., JAEA-Conf 2015-003, 297 (2015).

Contents

- Introduction: : Background & Motivation
- Outline of the research program
- Measurements
  - (I) TTNYs at KUTL
  - (II) DDXs of (d,xn) at RCNP
- Code development, model analysis
- Nuclear data evaluation
- Application to medical isotopes production
- **Summary and outlook**

Summary

A comprehensive research program toward development of a new nuclear data library up to 200 MeV necessary for the design of (d,xn) neutron sources.

- **Measurements** of neutron and gamma-ray production DDXs and TTYs : ***S. Araki (R361) 9:20 on Sept. 15 @ Mozart***
- Modelling of deuteron-induced reactions and **Code development (DEURACS)** : ***S. Nakayama (R406) 11:50 on Sept. 15 @ Vives***
- **Nuclear data evaluation** and **Benchmark test**
- Its application to **Medical radioisotopes production (e.g, ^{64}Cu, ^{92}Y)** ***T. Kin (R243) 11:40 on Sept. 14 @ Vives***

Outlook

- Continued measurements of neutron and gamma-ray production from deuteron-induced reactions at incident energies **up to 200 MeV**. → 200MeV (d,xn) DDXs measurement in FY2016 or 2017
- Validation of **DEURACS** using a variety of differential data and its improvement.
- Cross section **evaluation and production of a prototype nuclear data library for a few specific nuclei (*e.g*., Li, Be, and C)** contained in neutron converters.
- **Benchmark testing** by Monte Carlo transport codes (e.g., PHITS) with newly-evaluated nuclear data library using experimental thick target neutron yields (TTNYs).
- Application of deuteron transport simulation to **the design of neutron sources for medical radioisotopes production, etc.**

Special thanks to all collaborators

Measurements

- *KUTL experiment*

Nobuhiro SHIGYO, Keiichi HIRABAYASHI, Yuta TAJIRI, Kenshi SAGARA (Kyushu U)
Sunao MAEBARA, Hiroki TAKAHASHI, Hironao SAKAKI (JAEA)

- *RCNP experiment*

Mizuki KITAJIMA, Keita NAKANO, Hiroki SADAMATSU (Kyushu U),
Yusuke IWAMOTO, Daiki SATOH (JAEA), Masayuki HAGIWARA(KEK),
Hiroshi YASHIMA(Kyoto U), Tatsushi SHIMA (RCNP, Osaka U)

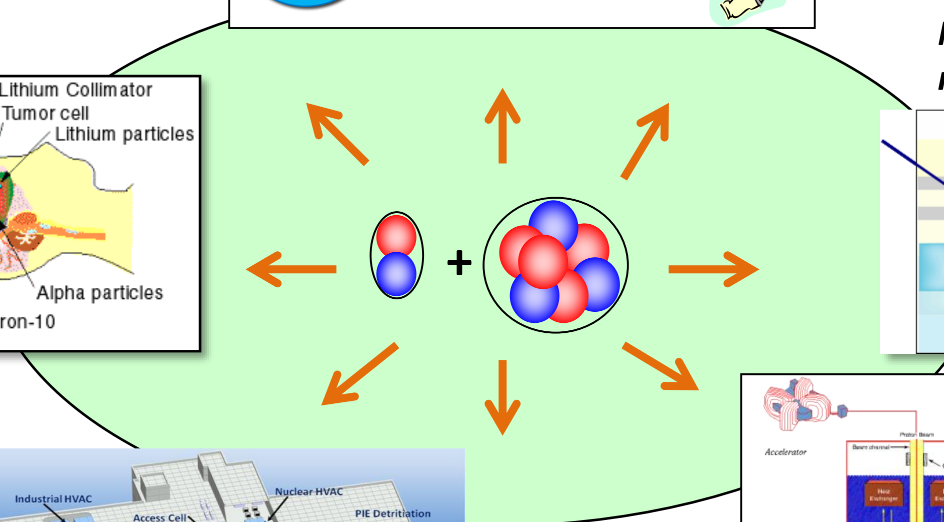
Theoretical model and code development

Kazuyuki OGATA (RCNP, Osaka U), Tao YE (IAPCM)

Medical isotopes production

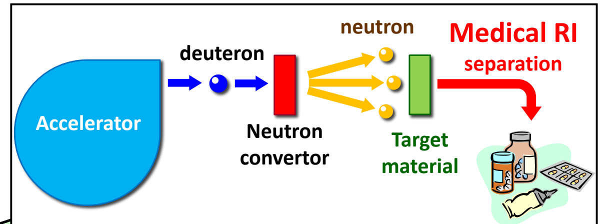
Yukimasa SANZEN, Masaki KAMIDA (Kyushu U), Masatoshi ITO (Tohoku U)

Thank you for your attention.



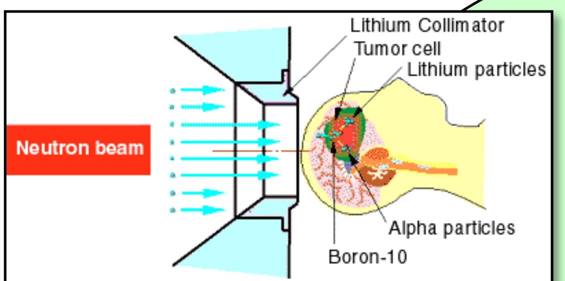
Medicine

RI production for medical use



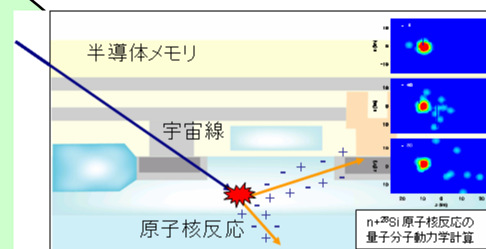
Cancer therapy

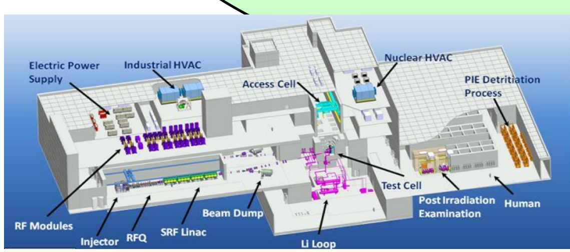
Boron Neutron Capture Therapy (BNCT)



Microelectronics

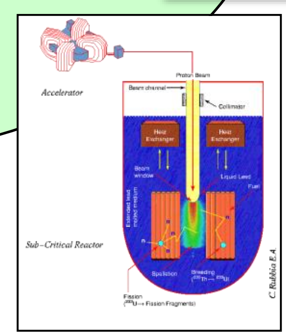
Neutron induced Soft errors in microelectronics





Fusion Technology

International Fusion Material Irradiation Facility (IFMIF)



Nuclear Technology

Transmutation of long-lived radioactive nuclear wastes