



$^{65}\text{Cu}(d,p)^{66}\text{Cu}$ excitation function at deuteron energies up to 20 MeV

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Motivation

Motivation

FISPACT code

Cu target

NPI U-120M cyclotron

Irradiation chamber

Irradiated samples

Gamma-spectroscopy

Dead time reduction

$^{65}\text{Cu}(d,2n)^{65}\text{Zn}$

$^{63}\text{Cu}(d,3n)^{62}\text{Zn}$

$^{\text{nat}}\text{Cu}(d,*)^{64}\text{Cu}$

$^{65}\text{Cu}(d,2p)^{65}\text{Ni}$

$^{63}\text{Cu}(d,2n)^{63}\text{Zn}$

$^{65}\text{Cu}(d,p)^{66}\text{Cu}$

Theory

Conclusion

- The proton and deuteron induced activation reactions
- have a great interest for the assessment of induced radioactivities in the accelerator components, targets and beam stoppers as well as isotope production for medicine.
- The IFMIF facility needs such a data for estimation of the potential radiation hazards from the accelerating cavities and beam transport elements (Al, Fe, Cr, Cu, Nb) and metal and gaseous impurities of the Li loop (Be, C, O, N, Na, K, S, Ca, Fe, Cr, Ni).
- The cross sections are needed in the energy range from the threshold (2 - 10 MeV) up to 40 MeV both for deuterons and protons.
- The description of deuteron-nucleus interaction represents an important tests for both the quality of reaction mechanism models and evaluation of nuclear data request especially for fusion reactor technology.



FISPACT-2007

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- **FISPACT** is the inventory code included in the European Activation System (EASY),
- has been developed for neutron-, deuteron-, and proton-induced activation calculations for materials in fusion devices,
- has been adopted by the ITER project as the reference activation code,
- uses external libraries (EAF-libraries) of reaction cross sections and decay data for all relevant nuclides to calculate an inventory of nuclides produced as a result of the irradiation of a starting material with a flux of neutrons (from FISPACT-2007 version also with a charged particles).
- The deuteron cross section data are recorded in VITAMIN-J+ (211) standard group structure (up to 55 MeV).

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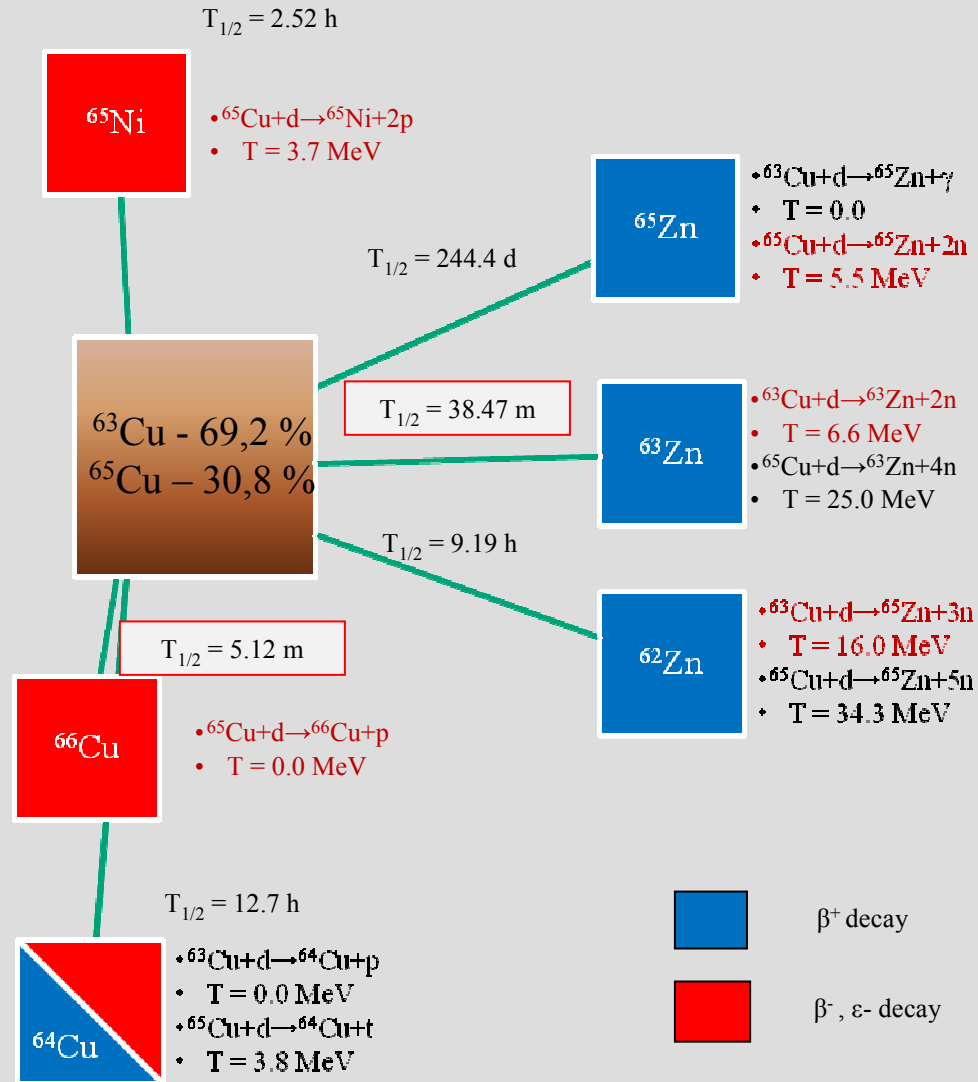
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Cu target

ND2007 Nice

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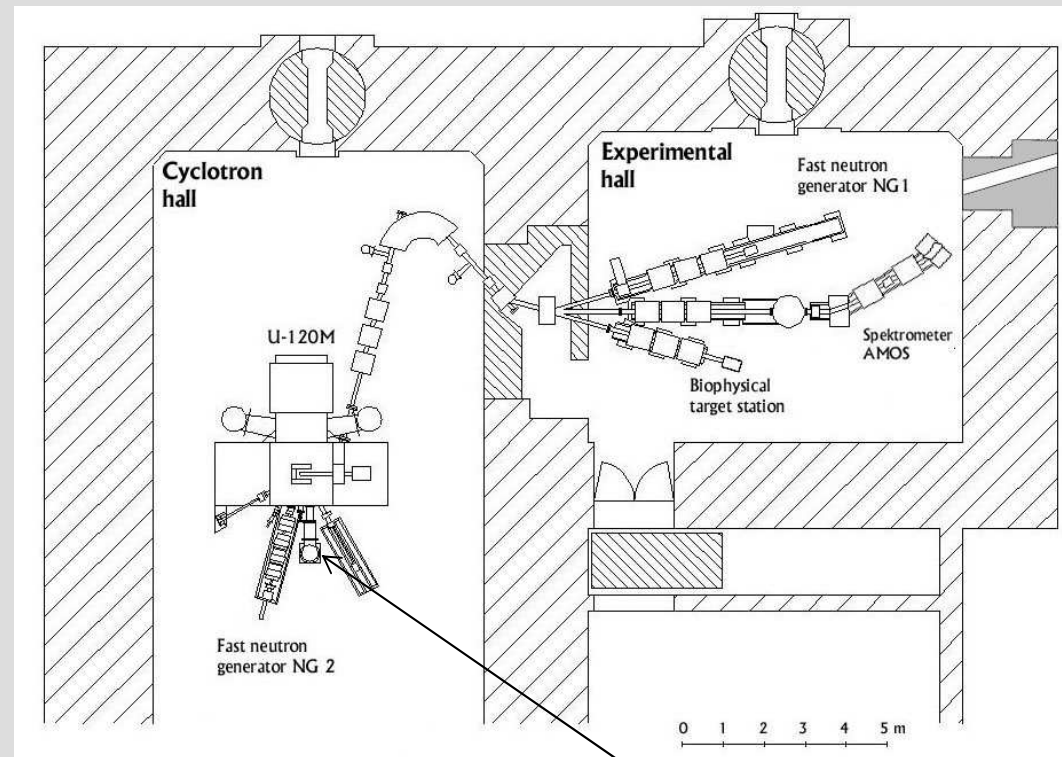
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U-120M cyclotron of NPI

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Theory
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Variable energy cyclotron U-120M of NPI Řež



$$E_d = 20.4 (0.2) \text{ MeV}$$

Target station

NG2 target station - negative ion mode.

The cross-sections for deuteron provoked reactions on Al and Cu were measured by the stacked-foil technique

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Irradiation chamber

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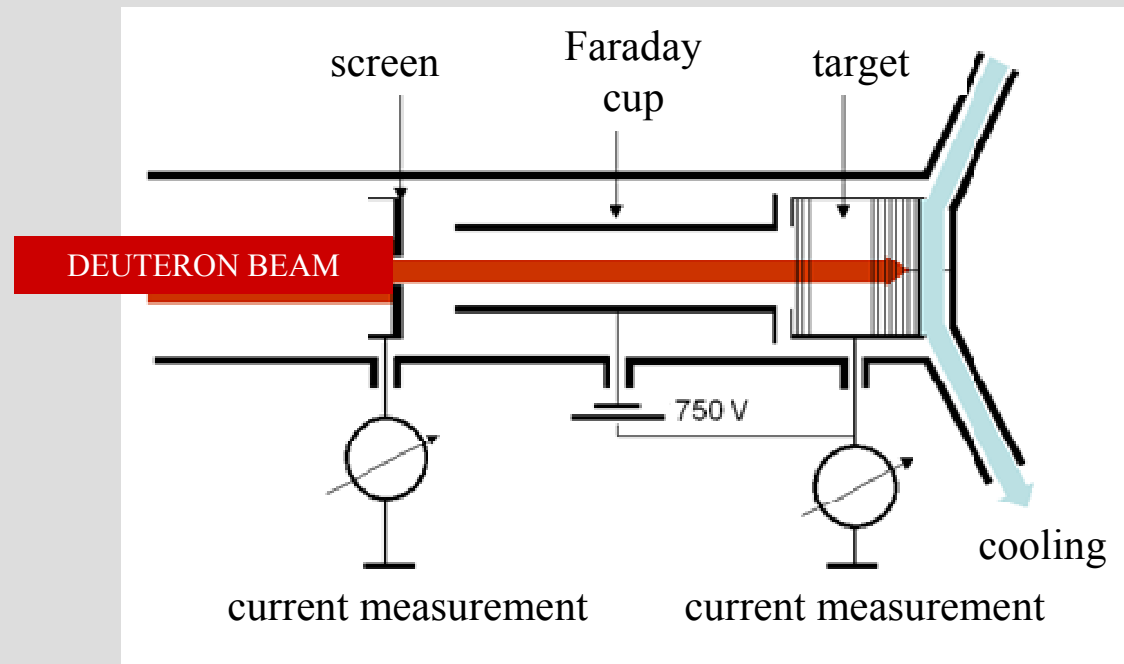
$^{65}\text{Cu}(d,p)^{66}\text{Cu}$

Theory

Conclusion

Faraday cup

Full beam stop



During an irradiation, the beam current was recorded with the uncertainty of 5 % in a PC keeping time synchronization with the γ -ray spectrometry device.

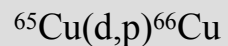
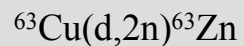
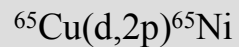
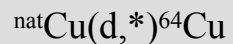
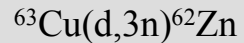
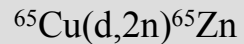


Irradiated samples

Motivation
FISPACT code
Cu target
NPI U-120M cyclotron
Irradiation chamber

Irradiated samples

Gamma-spectroscopy
Dead time reduction

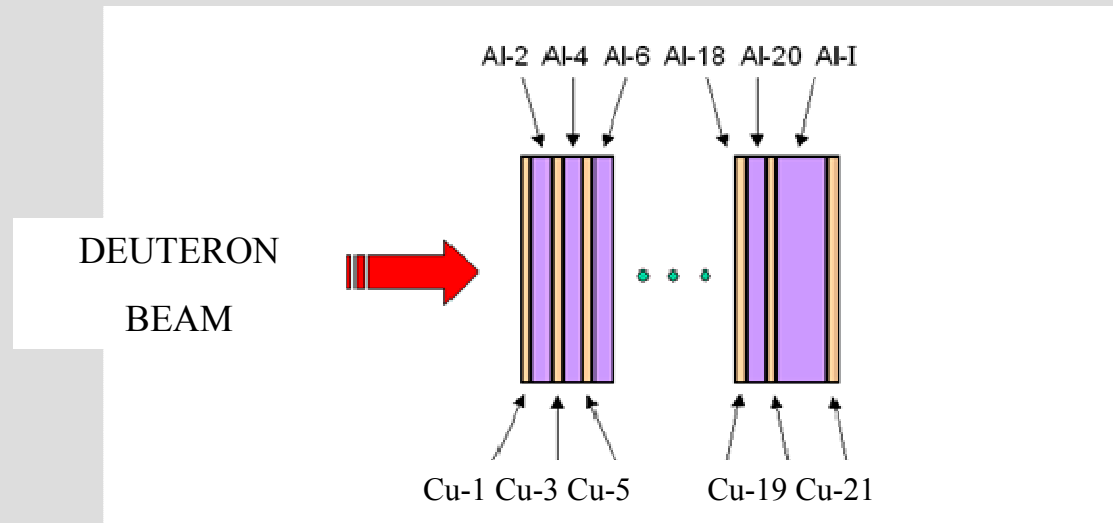


Theory

Conclusion

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The cross-sections for deuteron provoked reactions on Cu were measured by the stacked-foil technique and its absolute values were calculated from the measured induced activities.



stacks of Cu and Al foils placed by turns
Cu, Al – purity 99.9 % (Goodfellow product)
thickness Cu - 25 μm ; Al - 50 μm

The foils were weighed to avoid relatively large uncertainties in the foil thickness declared by producer \rightarrow (2 %).

Al foils served for additional monitoring of beam current and for appropriate reduction of deuteron energy, as well.

Energy attenuation, target density - **SRIM 2003**

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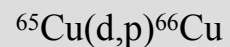
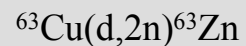
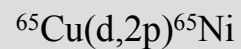
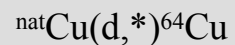
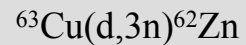
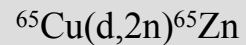


Gamma-spectroscopy

Motivation
 FISPACT code
 Cu target
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 Irradiation chamber
 Irradiated samples

Gamma-spectroscopy

Dead time reduction



Theory

Conclusion

The gamma-rays from the irradiated foils were measured repeatedly by two calibrated HPGe detectors of 23 and 50 % efficiency and of FWHM 1.8 keV at 1.3 MeV.

Experimental reaction rates were calculated from the specific activities at the end of irradiation corrected to decay during irradiation using total charge and foil characteristics as well.

Run	Time	Current
A	15 min	0.09 μA
B	5 min	0.33 μA

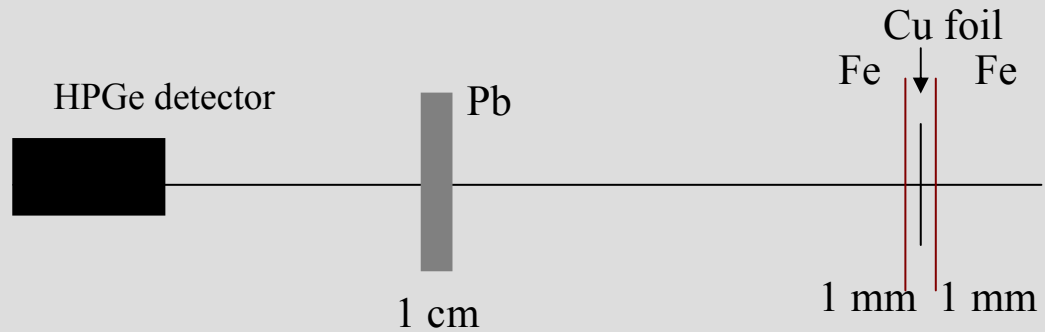


Isotop	$T_{1/2}$	E_{γ} [keV]	I_{γ} [%]
^{65}Zn	244.36 d	1115.55	50.6
^{64}Cu	12.7 h	1345.84	0.475
^{62}Zn	9.186 h	596.56	26
		548.35	15.3
^{65}Ni	2.517 h	1481.84	24
		1115.55	15.43



Dead time reduction

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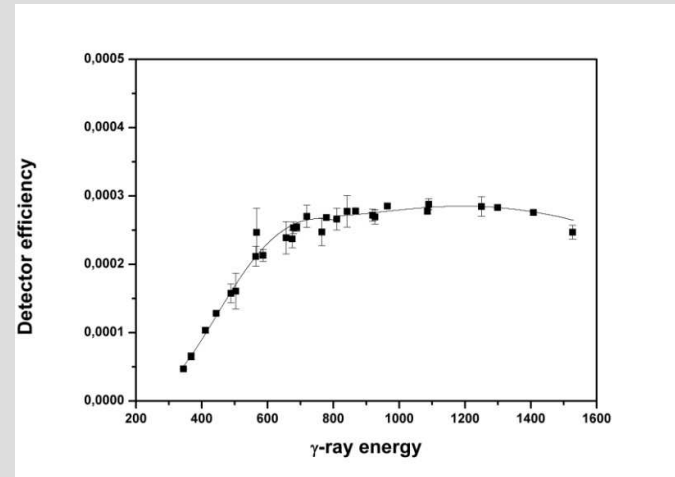


^{152}Eu

Attenuation:

511 5.2 x

1022 2.1 x



Calibration uncertainty - 3 %

Isotop	$T_{1/2}$	E_{γ} [keV]	I_{γ} [%]
^{66}Cu	5.12 m	1039.2	9
^{63}Zn	38.47 m	669.62	8
		962.1	6.5
		1412.1	.75

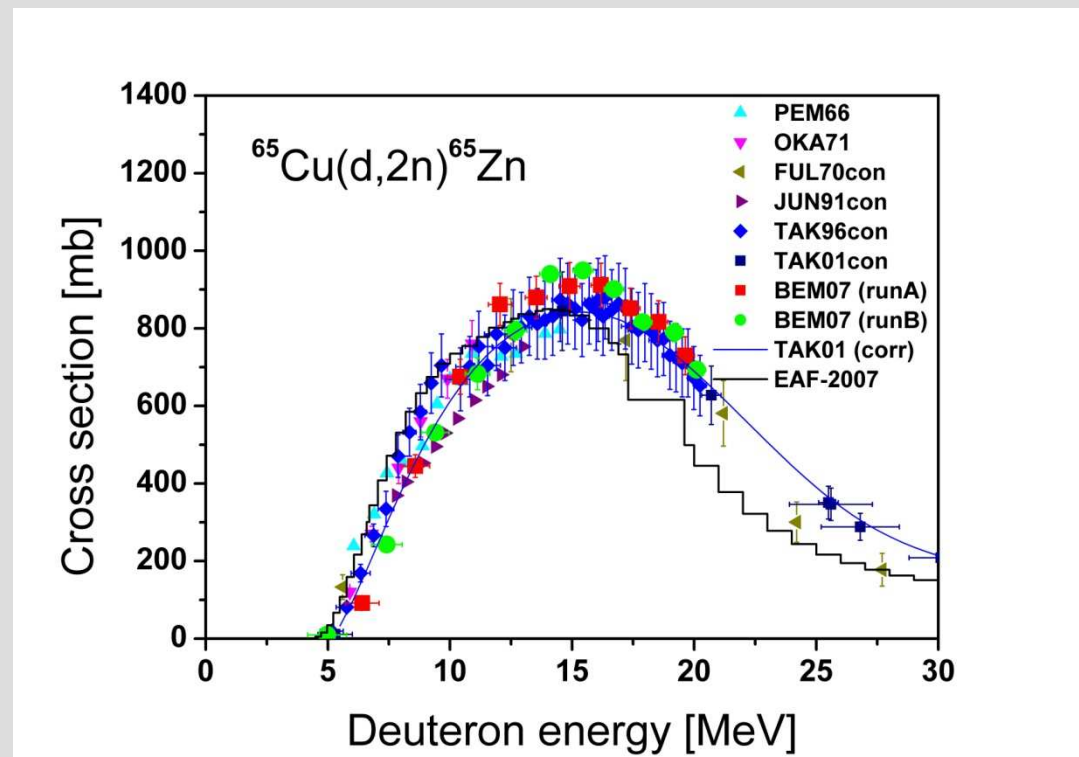
Run	Time	Current
C	335 s	0.24 μA
D	300 s	0.36 μA



$^{65}\text{Cu}(d,2n)^{65}\text{Zn}$

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The radioactive capture reaction cross-sections are known to be very small (of the order of a few hundred μb or less). Hence, $^{63}\text{Cu}(d,\gamma)$ reaction, for which the Q-value is as large as 13.5 MeV, would not be expected to contribute appreciably to the measured yield of ^{65}Zn .



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$^{63}\text{Cu}(d,3n)^{62}\text{Zn}$

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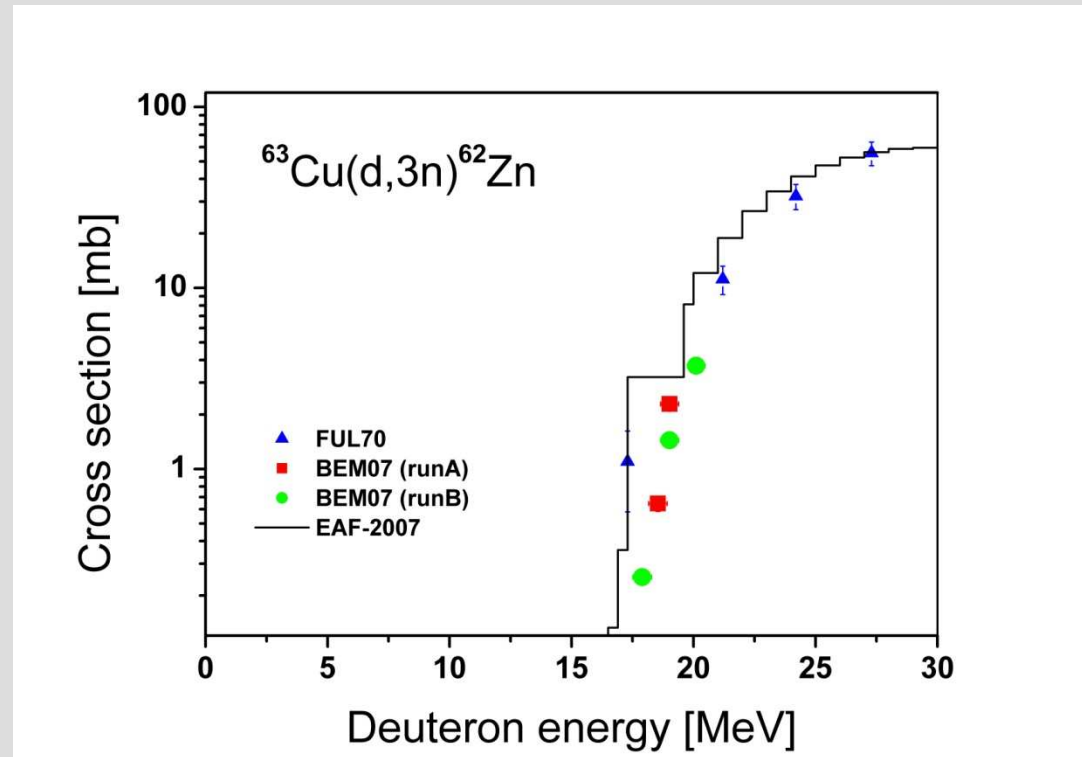
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$^{63}\text{Cu}(d,2n)^{63}\text{Zn}$

$^{65}\text{Cu}(d,p)^{66}\text{Cu}$

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Threshold = 15.983 MeV

Q = - 15.487 MeV

SPIRAL2 - 1 day experiment

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$^{nat}\text{Cu}(d,*)^{64}\text{Cu}$

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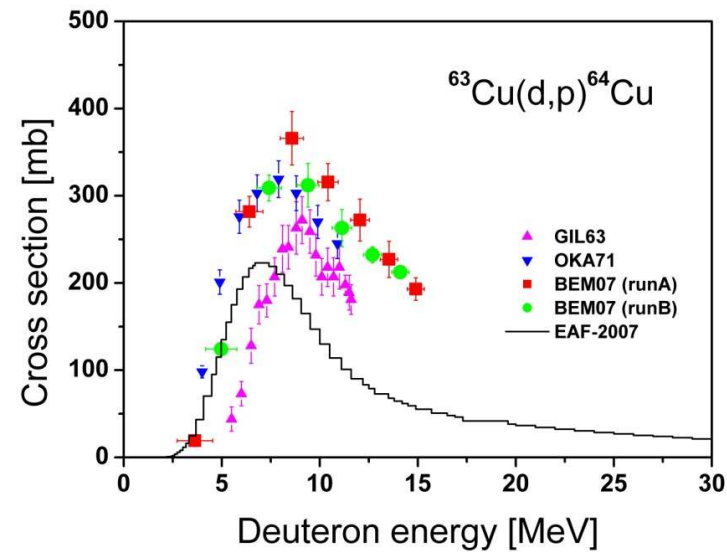
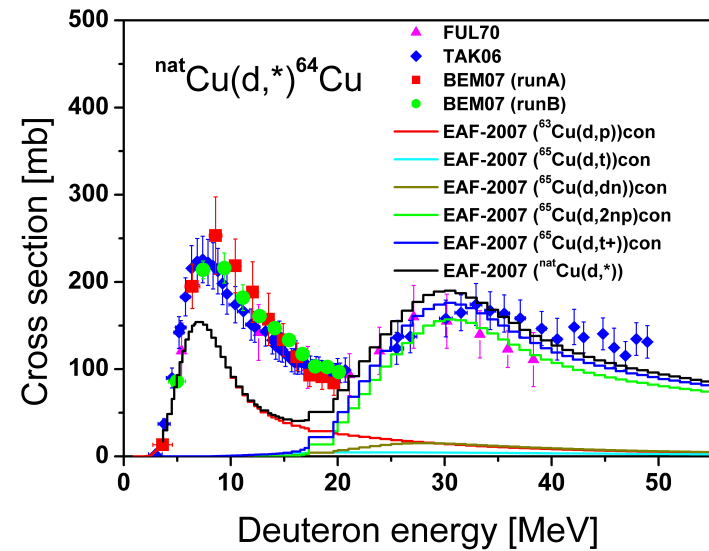
$^{65}\text{Cu}(d,p)^{66}\text{Cu}$

Theory

Conclusion

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Two contribution reactions



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$^{65}\text{Cu}(d,2p)^{65}\text{Ni}$

$T_{1/2} = 2.5172 \text{ h}$

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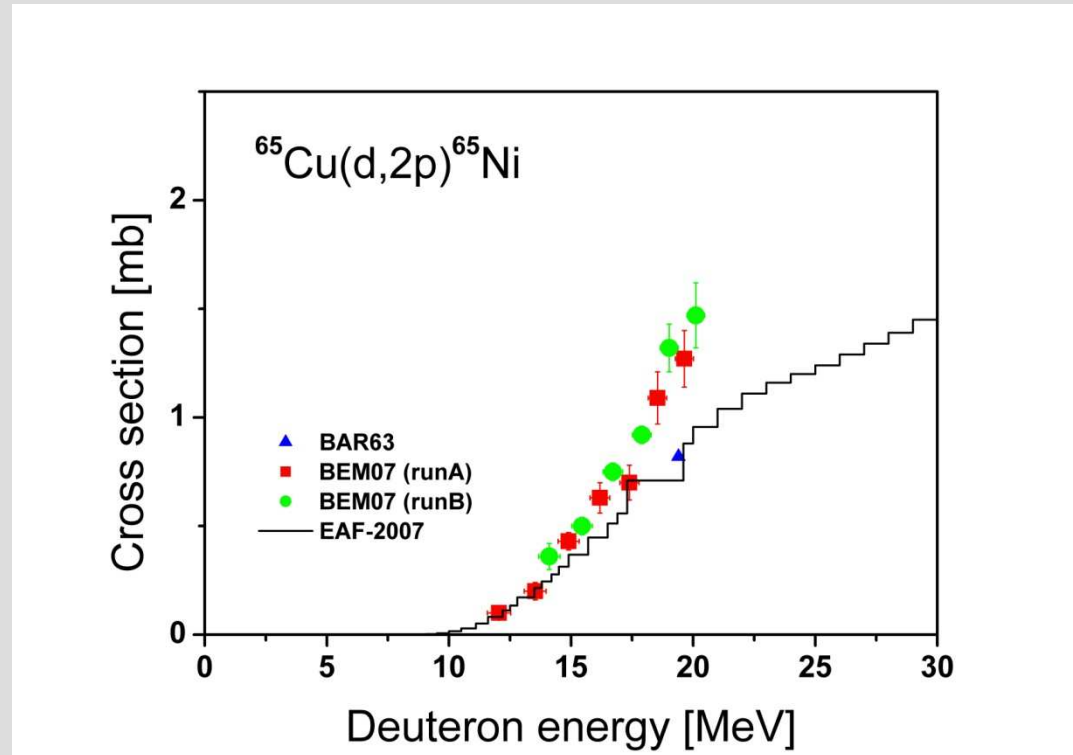
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Theory

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Threshold = 3.690 MeV

Q = - 3.579 MeV

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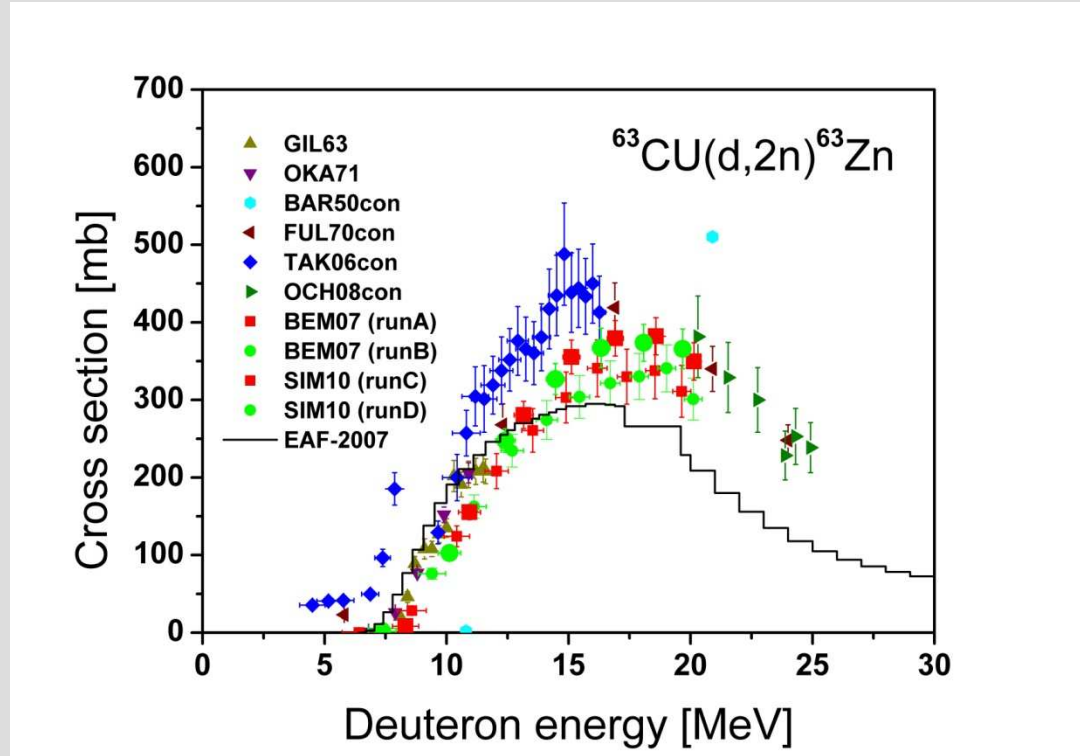
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$^{63}\text{Cu}(d,2n)^{63}\text{Zn}$

$T_{1/2} = 38.47 \text{ m}$

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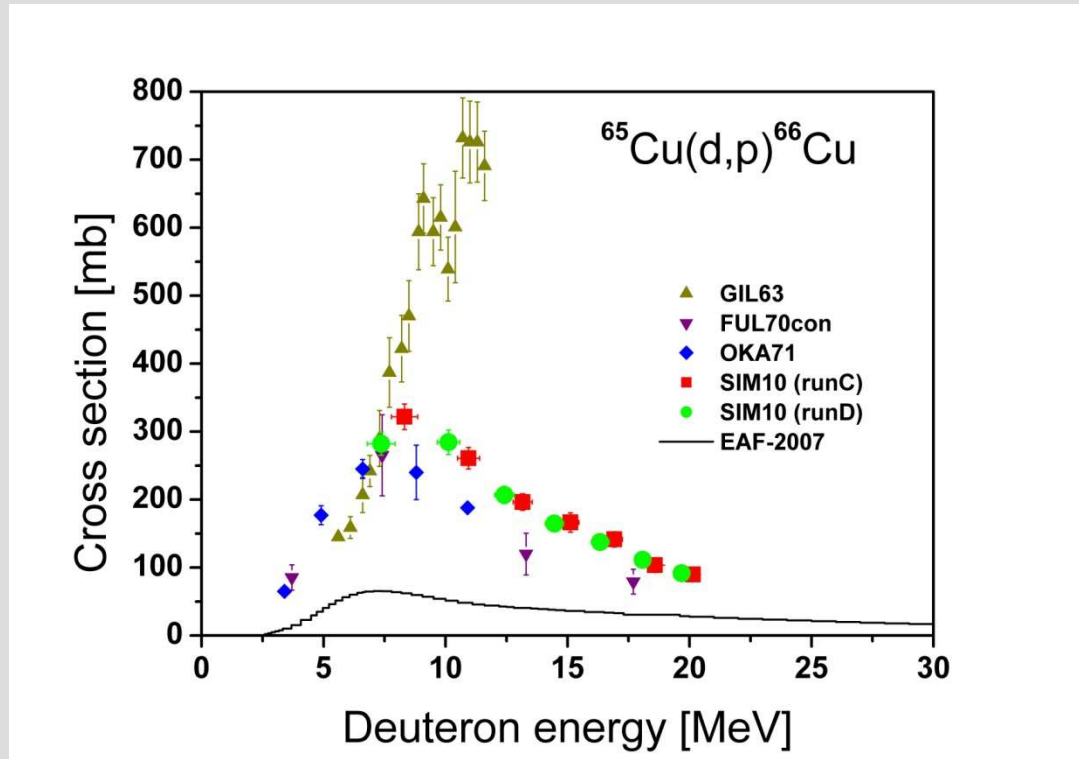
Threshold = 6.578 MeV
Q = - 6.3734 MeV

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$^{65}\text{Cu}(d,p)^{66}\text{Cu}$

$$T_{1/2} = 5.12 \text{ m}$$

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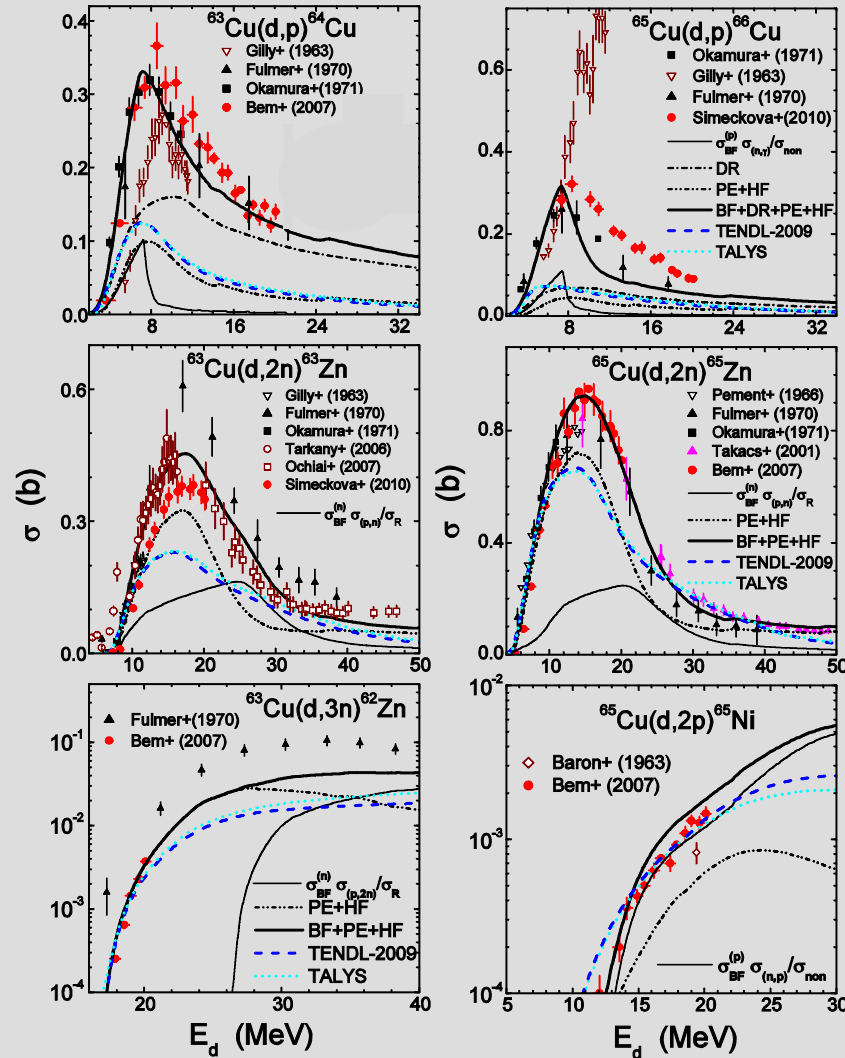


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Theory

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Elastic scattering data \rightarrow optical potential

Breakup mechanism – elastic, breakup fusion contribution to activation cross section

Direct reaction contribution (one nucleon stripping)

Pre-equilibrium and compound-nucleus cross-section calculation

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Conclusion

- The cross-sections of (d,x) reactions induced by 20 MeV deuterons on stack of Al and Cu foils were measured for following nuclei:
 ${}^{\text{nat}}\text{Cu}(d,p){}^{64}\text{Cu}$,
 ${}^{63}\text{Cu}(d,3n){}^{62}\text{Zn}$,
 ${}^{65}\text{Cu}(d,2n){}^{65}\text{Zn}$, (d,2p) ${}^{65}\text{Ni}$, ND2007, Nice
 ${}^{63}\text{Cu}(d,2n){}^{63}\text{Zn}$ and ${}^{65}\text{Cu}(d,p){}^{66}\text{Cu}$ new
- An extended analysis of the nuclear reaction mechanism involved in the deuterons interaction with ${}^{63,65}\text{Cu}$ was done
- The overall agreement between the measured and calculated deuteron activation cross-section was achieved



Next program

- The accuracy of a beam-current monitoring and the calculation of energy degrading by the STRIM code will be tested utilizing variable-energy proton/deuteron beams
- The cross sections of (d,x) reactions will be investigated for IFMIF relevant materials (Co, Fe and Nb) in the energy range up to 20 MeV
- The deuteron induced cross section measurement on Cu in the energy region 20 – 40 MeV would be performed as the first day experiment at SPIRAL 2