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Cross-section Measurements of Relativistic Deuteron Reactions on Copper by Activation Method

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for collaboration "Energy and Transmutation of Radioactive Waste"

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Relativistic Nuclear Physics and Quantum Chromodynamics
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Outline

- Experiments of E&T RAW collaboration
- QUINTA setup and goals of the experimental program
- Beam integral and profile monitoring
- Cross-section measurements of d+Cu reactions
- Comparison of results with EXFOR and TALYS & MCNPX
- Summary

Energy + Transmutation Project

- Different set-ups irradiated by JINR Nuclotron accelerator beams
- Studies of spallation reactions, production and transport of neutrons in thick targets with fissile blanket and with/without moderator irradiated by relativistic protons and deuterons
- Measurement of reaction rates on threshold neutron activation detectors, samples of fissile material and samples of fission products and higher actinides intended for transmutation
- Comparison of experimental data with Monte Carlo simulations, testing the accuracy of nuclear models and cross-section libraries

Experimental Setups of the E+T RAW Project

JINR Dubna, Russia

Gamma - 2

Gamma - 3

Energy + Transmutation

QUINTA

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Introduction

Exp. set-ups
- *Main goals*
- *QUINTA set-up*

Beam monitors

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Conclusion

Main Objectives of the Quinta Setup

- Systematics of experiments with deuteron beams with energies above 1 GeV and low moderation neutron spectra
- Set-up for benchmark studies of neutron production and transport and testing of Monte Carlo simulation codes
- Measurement of neutrons and delayed neutrons during low intensity beam irradiation by scintillation and gas detectors
- Measurement of neutron field during high intensity beam irradiation by threshold activation and solid state track detectors
- Measurement of fission yields in thorium and uranium samples in fast neutron spectra
- Measurement of reaction rates in samples of isotopes designated for transmutation in fast neutron field

Quinta Setup

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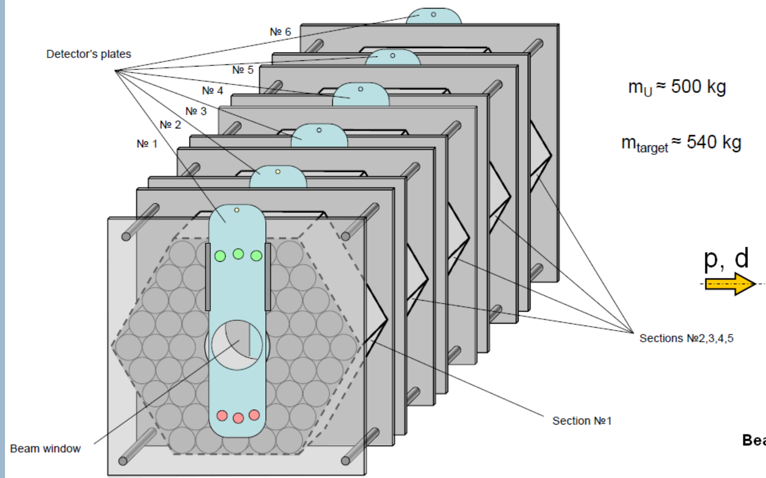

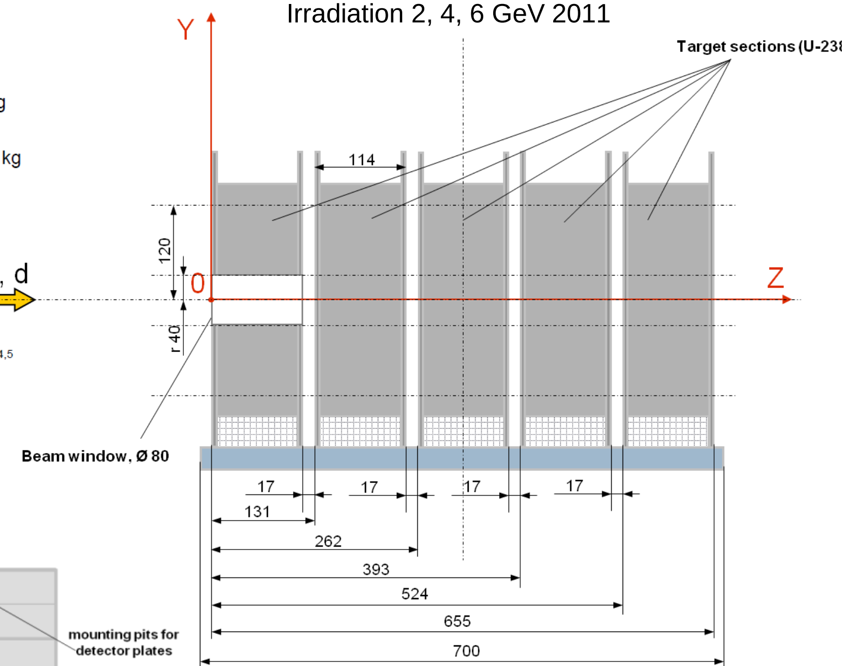

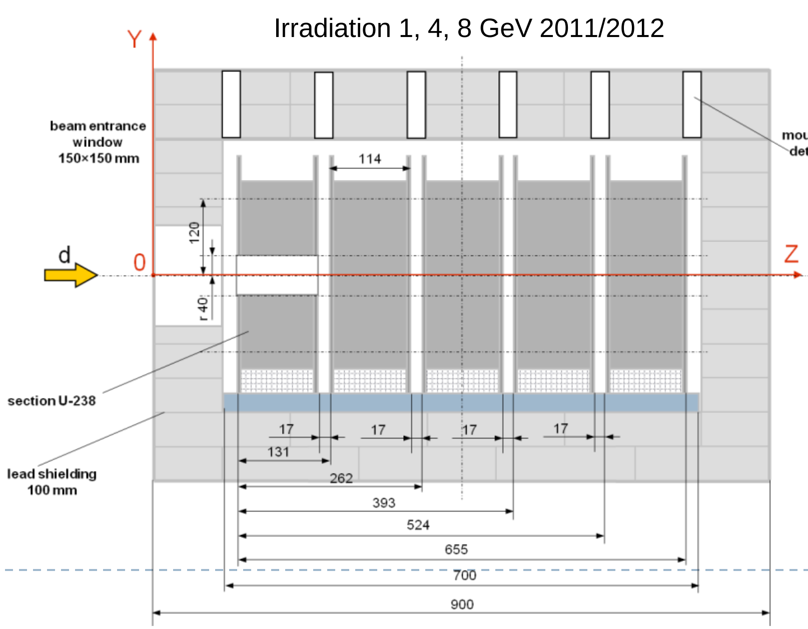

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Quinta Setup Irradiations

QUINTA set-up				
Beam energy [GeV]	Beam particles	Month Year	Irradiation time [h:m]	Integral beam flux [x10^{13}]
2.0	deuterons	March 2011	18:50	1.44(14)
4.0			17:58	1.42(18)
6.0			17:13	1.94(20)
1.0	deuterons	December 2011	14:26	1.50(4)
4.0			12:24	1.94(5)
8.0			04:11	0.0063
1.0	deuterons	March 2012	04:56	1.86(5)
4.0			08:52	2.72(7)
8.0			09:01	0.539(17)
2.0	deuterons	December 2012	6:15	3.052(9)
4.0			9.21	3.569(15)
8.0			16:10	1.390(8)
1.3	deuterons	March 2013	7:51	0.906(5)
2.0			13:31	4.01(4)
4.0			12:27	1.861(19)

Quinta Setup and Experimental Equipment

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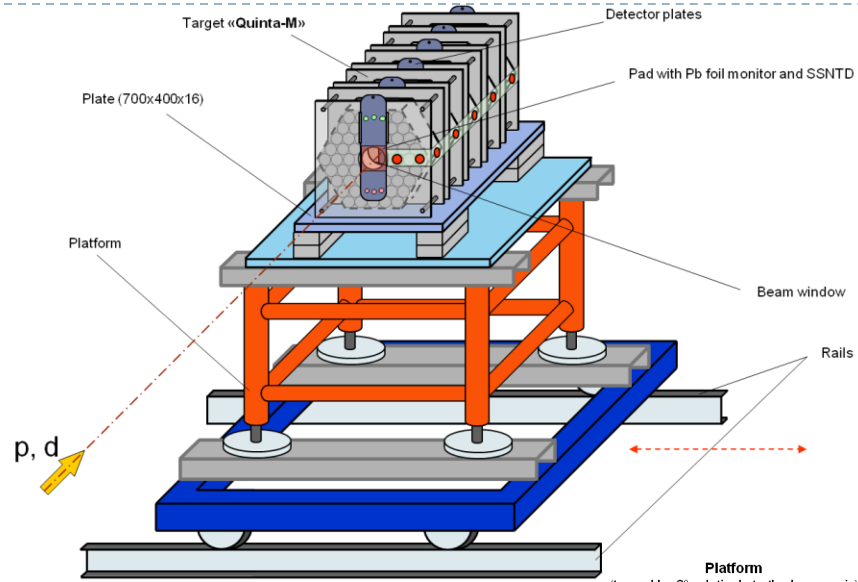
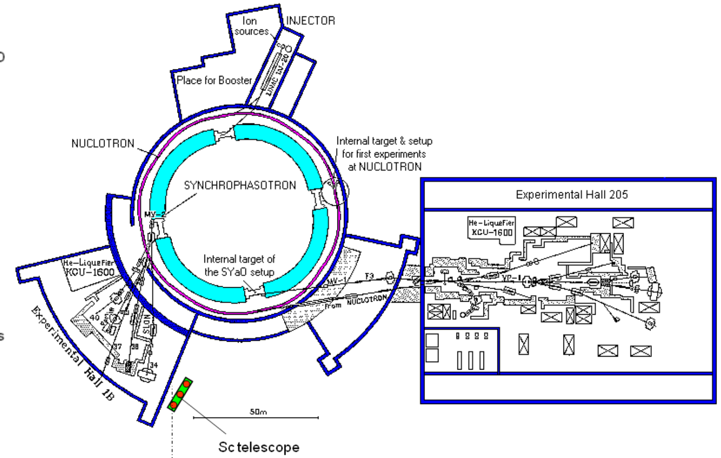
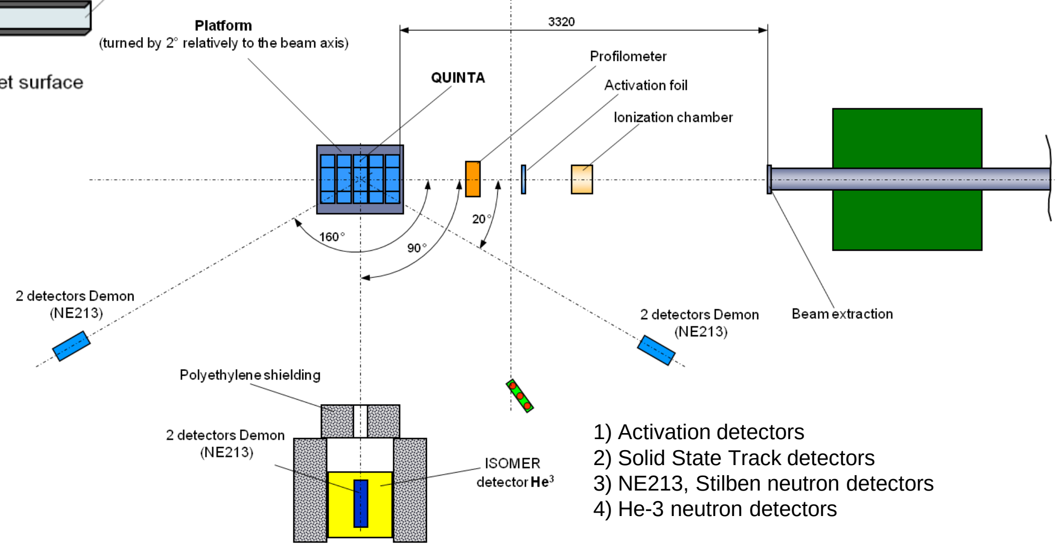


SSNTD and AD positions on the QUINTA-M target surface





1) Activation detectors
2) Solid State Track detectors
3) NE213, Stilben neutron detectors
4) He-3 neutron detectors

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- *γ-spectra analysis*
- *Beam integral*
- *Beam profile*

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Gamma Spectra Analysis

Beam integral determination by Al foil

$$N_{yield} = \frac{S_p \cdot C_{abs}(E) \cdot B_a}{I_\gamma \cdot \varepsilon_P(E) \cdot C_g \cdot C_{area} \cdot Coi} \cdot \frac{t_{real}}{t_{live}} \cdot \frac{e^{(\lambda \cdot t_0)}}{1 - e^{(-\lambda \cdot t_{real})}} \cdot \frac{\lambda \cdot t_{irr}}{1 - e^{(-\lambda \cdot t_{irr})}}$$

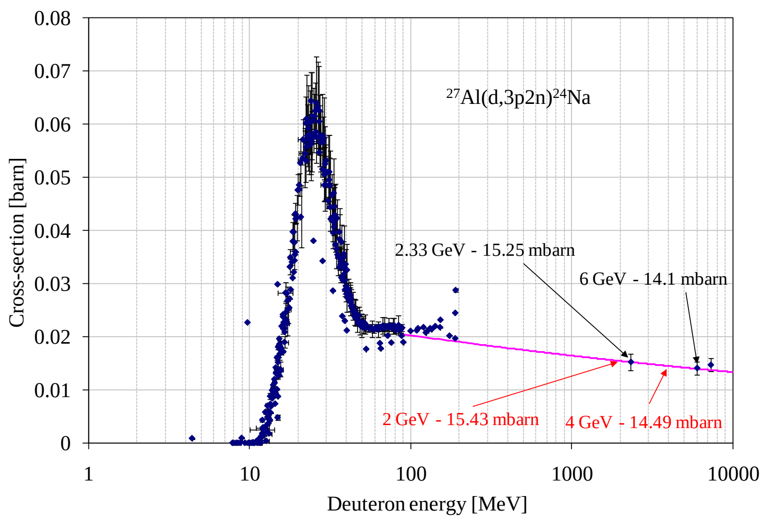
- S_p – Peak area
- $C_{abs}(E)$ – Self-absorption correction
- B_a – Beam instability correction
- C_{area} – Square-emitter correction
- $e^{(\lambda \cdot t_0)} / (1 - e^{(-\lambda \cdot t_{real})})$ – Decay during cooling and measurement
- I_γ – γ line –intensity per decay
- $\varepsilon_P(E)$ – Detector efficiency
- C_g – Correction for geometry change
- Coi – Correction for Coincidences
- t_{real}/t_{live} – Dead time correction
- $\lambda \cdot t_{irr} / (1 - e^{(-\lambda \cdot t_{irr})})$ – Decay during irradiation

λ – decay constant,
t_{irr} – irradiation time,
t_{real} – real measurement time,
t_{live} – live time of the detector,
t_0 – cooling time.

- Spectroscopy software DEIMOS32 – Gaussian fit of gamma peaks
- All necessary spectroscopic corrections applied
- Yield = amount of nuclei of a certain isotope produced per gram of activation material and per beam particle

Beam Monitors

- Beam intensity monitoring by ionization chambers and aluminium activation foils
- Beam position and profile monitoring by copper activation foils and SSNTD
- Cross-sections measurement of relativistic deuterons reactions on copper activation detectors placed together with aluminium foils



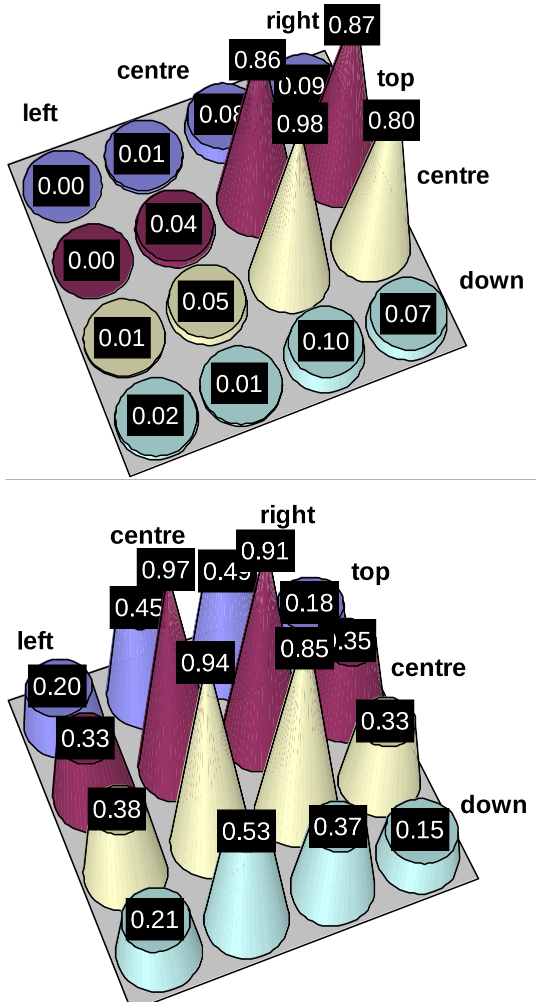
Production of ^{24}Na on Al foil by deuteron beam

Cross-section data are available on reaction ^{27}Al(d,3p2n)^{24}Na (only 3 values from EXFOR) → uncertainty of the fit ~10%

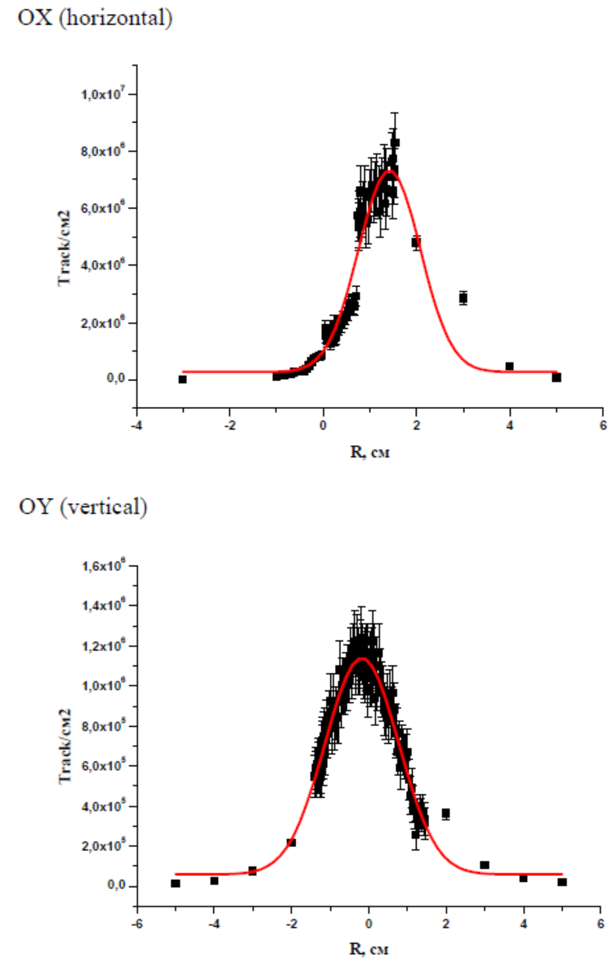
$$N_d = \frac{N_{yield} \cdot S \cdot A}{\sigma \cdot m \cdot N_A}$$

N_{yield} – total amount of produced ^{24}Na nuclei,
A – molar weight,
σ – microscopic cross-section,
m – weight of the foil,
S – area of the foil,
N_A – Avogadro's number.

Beam Monitors



Results from activation foils (NPI Řež group)



Results from SSNTD (Minsk group)

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Beam monitors

- *γ-spectra analysis*
- *Beam integral*
- ***Beam profile***

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Cross-sections Measurements

- Datasets on ^{27}Al(p,x) and ^{nat}Cu(p,x) reactions for relativistic energies can be found in EXFOR database
- Very scarce data on high energy ^{27}Al(d,x) reaction cross-sections, almost no data on high energy ^{nat}Cu(d,x) reaction cross-sections
- Series of cross-sections measurements of relativistic deuteron reactions on Cu were carried out during QUINTA set-up irradiations by JINR Nuclotron
- Energy range of deuteron beam from 1 GeV up to 8 GeV was covered during 5 series of irradiations; some deuteron energies were measured more times
- Aluminum foils were used as beam integral monitor for copper foils
- Al and Cu foils had square shape (10×10 cm) with thickness 0.0196 cm and 0.0128 cm respectively
- Cu foils with natural isotope composition (69.15% of ^{63}Cu and 30.85% of ^{65}Cu) were used, purity of Cu metal was better than 99%

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Cross-sections Measurements

- Activation method and gamma spectroscopy measurement on HPGe detectors were used for evaluation of irradiated samples
- Samples were measured many times in different detectors and geometries to suppress influence of systematic uncertainties
- Cumulative and/or independent production cross-sections were determined using activation method
- Overall 38 different radioisotopes were identified by their respective gamma lines (^{7}Be, ^{22}Na, ^{24}Na, ^{28}Mg, ^{28}Al, ^{38}S, ^{38}Cl, ^{39}Cl, ^{42}K, ^{43}K, ^{47}Ca, ^{43}Sc, ^{44}Sc, ^{44m}Sc, ^{46}Sc, ^{47}Sc, ^{48}Sc, ^{48}V, ^{48}Cr, ^{49}Cr, ^{51}Cr, ^{52}Mn, ^{54}Mn, ^{56}Mn, ^{52}Fe, ^{59}Fe, ^{55}Co, ^{56}Co, ^{57}Co, ^{58}Co, ^{60}Co, ^{56}Ni, ^{57}Ni, ^{65}Ni, ^{61}Cu, ^{64}Cu, ^{62}Zn, ^{65}Zn)
- Half-life span of the identified radionuclides varies from less than one hour to hundreds of days
- Some couples of radionuclides decay to the same daughter nucleus, in this case decay curves were analyzed to distinguish separate radionuclides

Analysis of Results

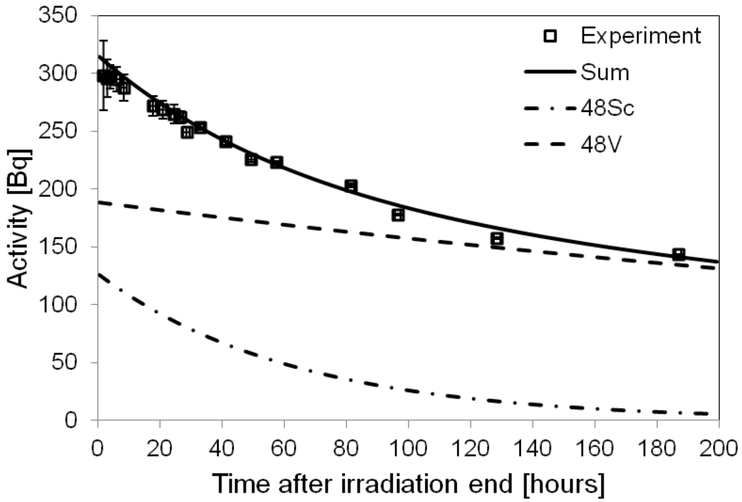
$^{48}Sc \rightarrow {}^{48}Ti \leftarrow {}^{48}V$

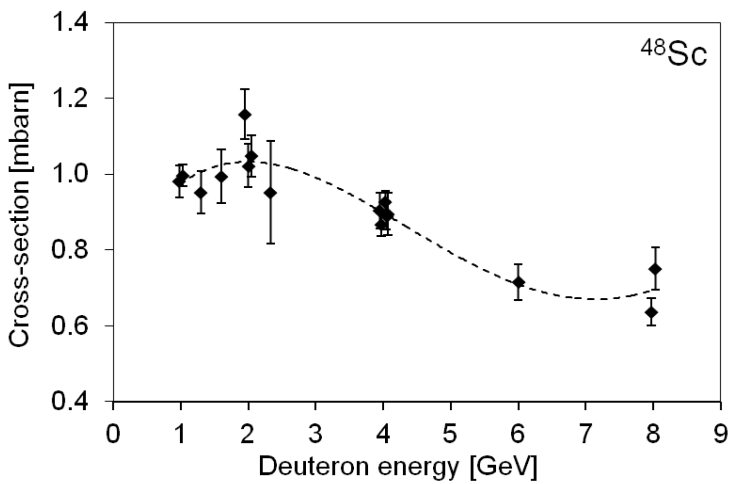
$T_{1/2}$	43.7 h	383.3 h

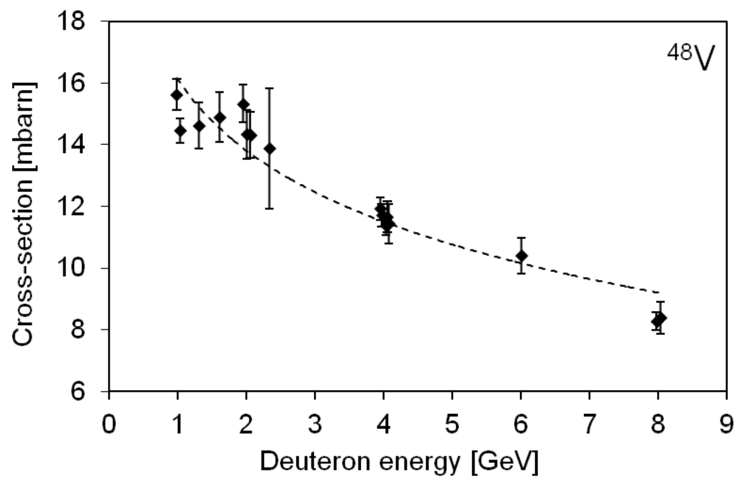
Gamma lines:

^{48}Sc only: 1037.6 keV (subtracted ^{56}Co)

^{48}Sc + ^{48}V: 983.5 keV and 1312.1 keV







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Cross-sections

- ***Analysis of decay***
- *d-p exp. data*
- *exp. data vs. sim.*

Conclusion

Analysis of Results

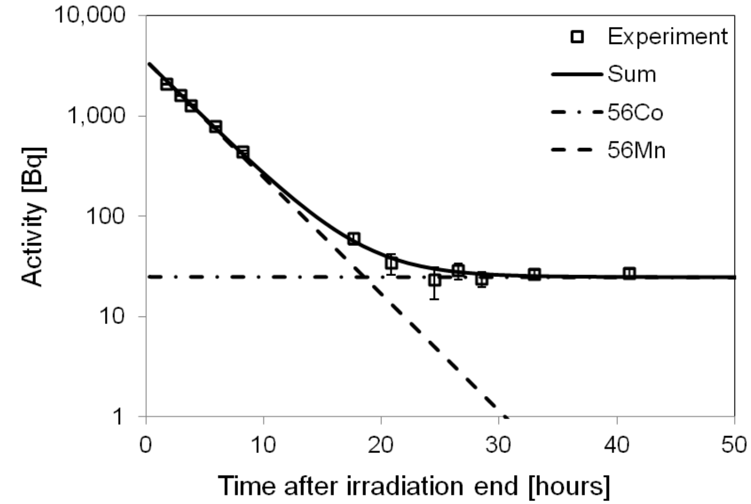
$^{56}Mn \rightarrow {}^{56}Fe \leftarrow {}^{56}Co$

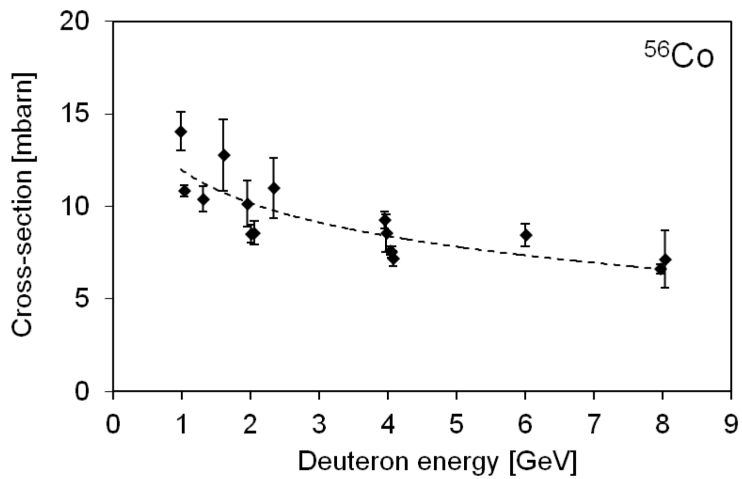
$T_{1/2}$ 2.6 h 1854.5 h

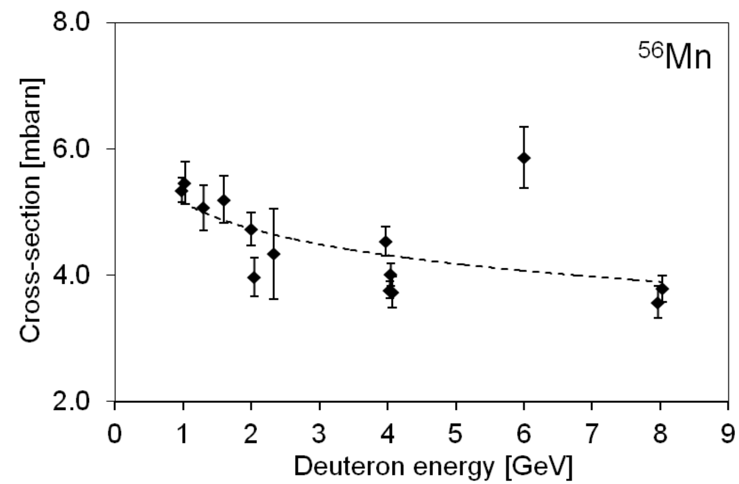
Gamma lines:

^{56}Co only: 1238.3 keV

^{56}Co + ^{56}Mn: 846.8 keV







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Analysis of Results

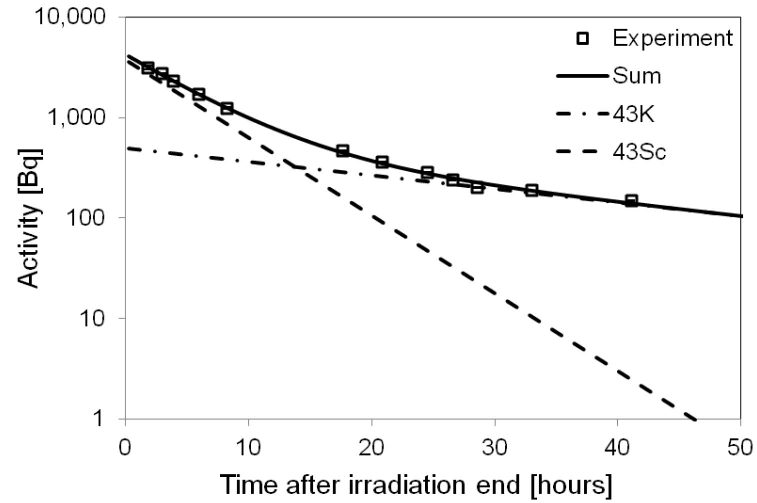
$^{43}K \rightarrow {}^{43}Ca \leftarrow {}^{43}Sc$

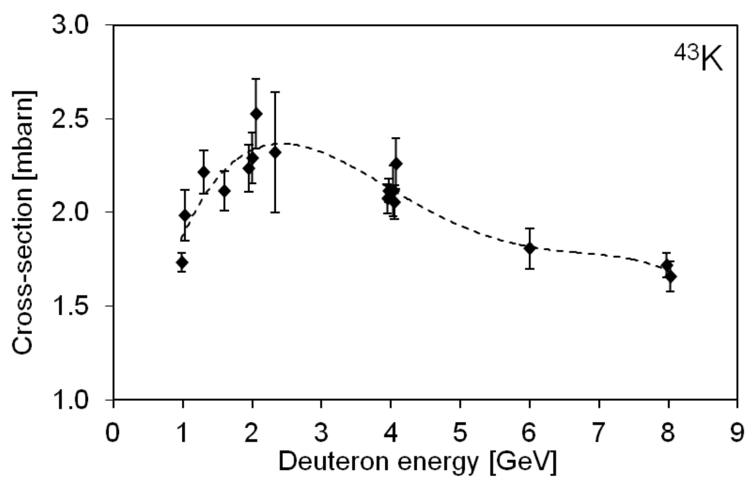
$T_{1/2}$ 22.3 h 3.9 h

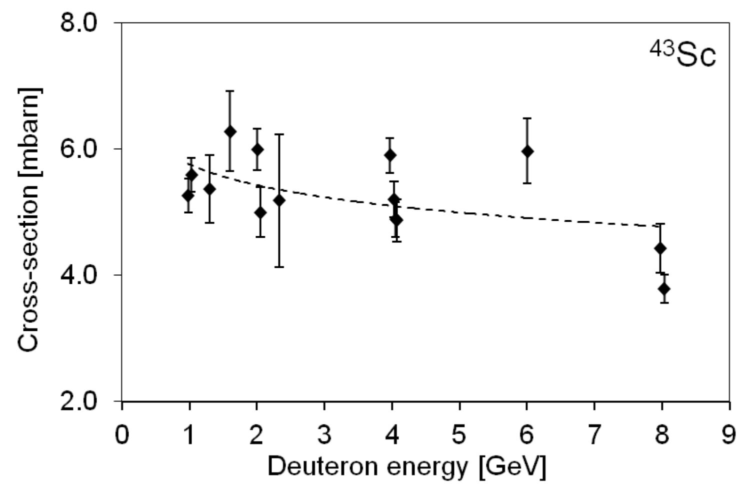
Gamma lines:

^{43}K only: 617.5 keV

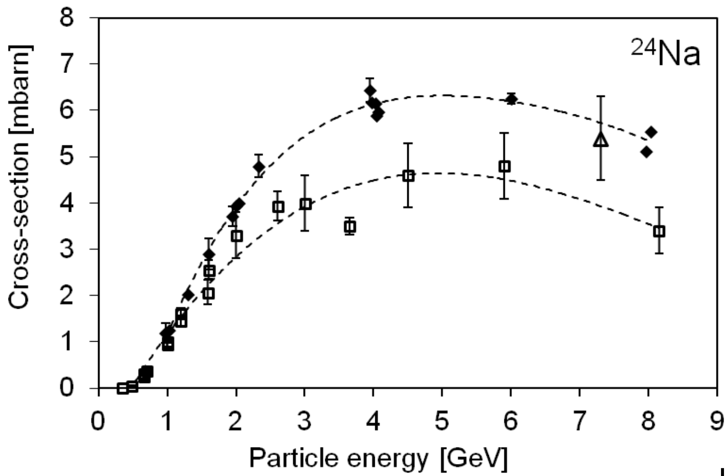
$^{43}K + {}^{43}Sc$: 372.8 keV

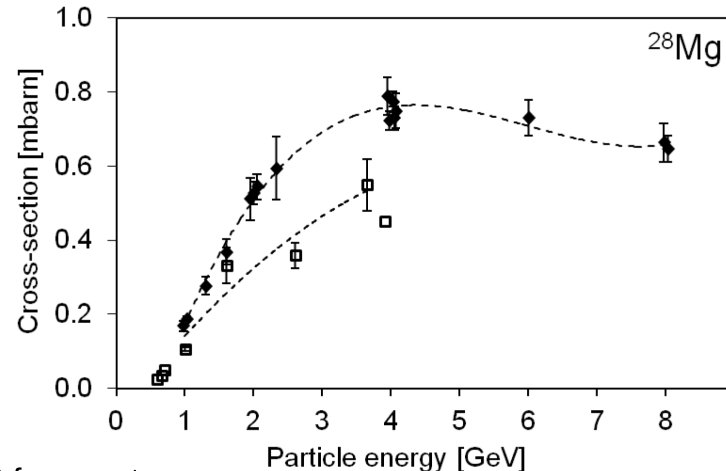




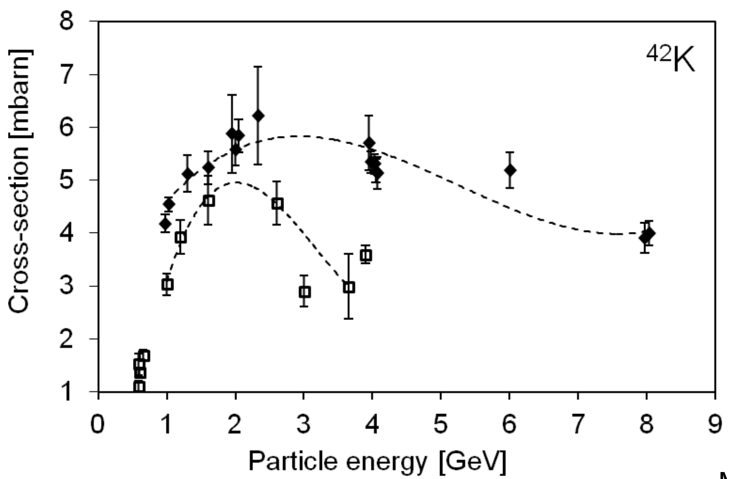


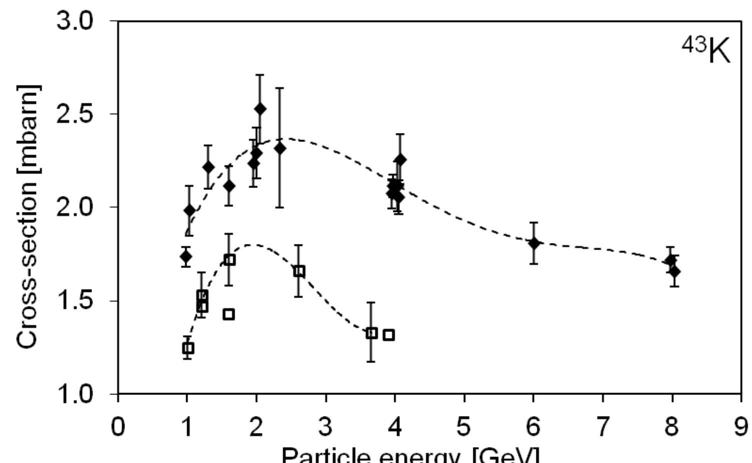
Excitation Functions





Light fragments





Mid-mass nuclei

Excitation Functions

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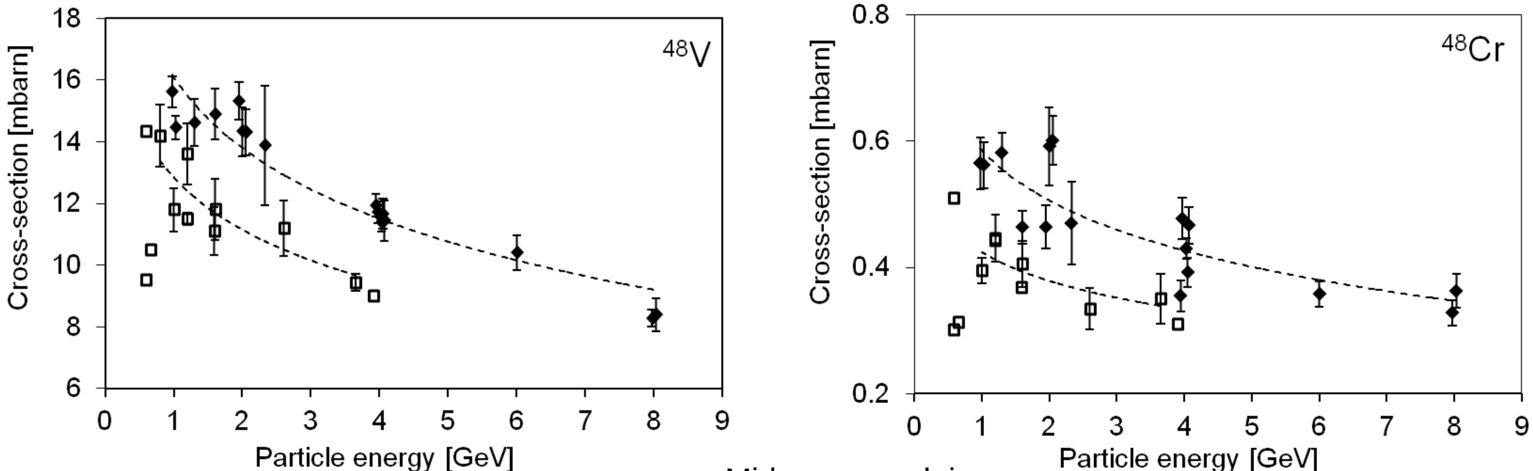
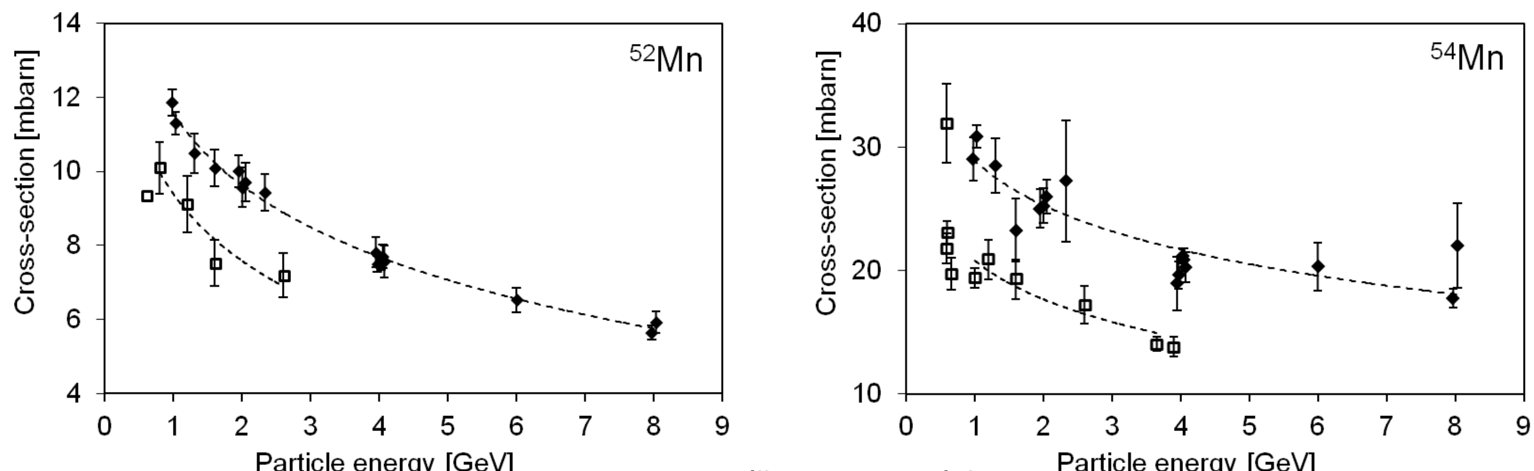


Mid-mass nuclei



Target-like mass nuclei

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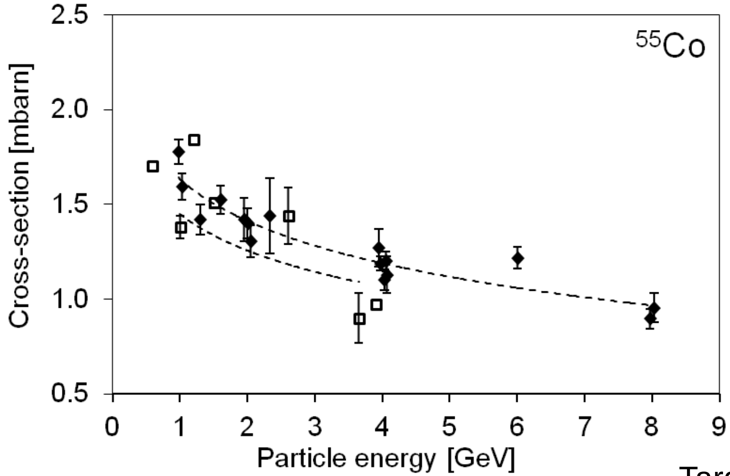
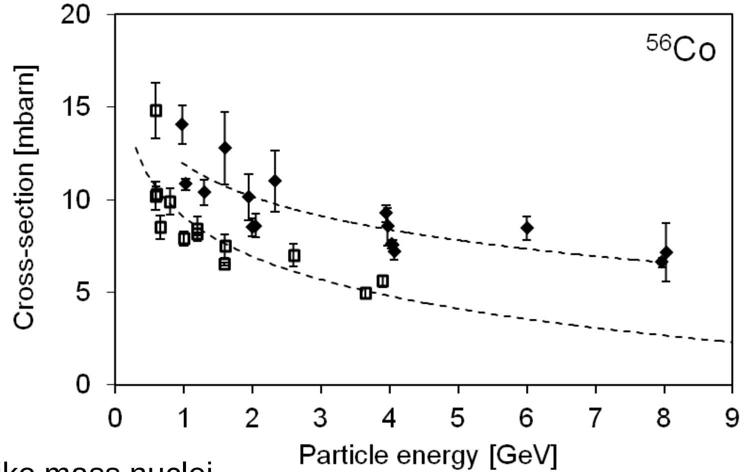
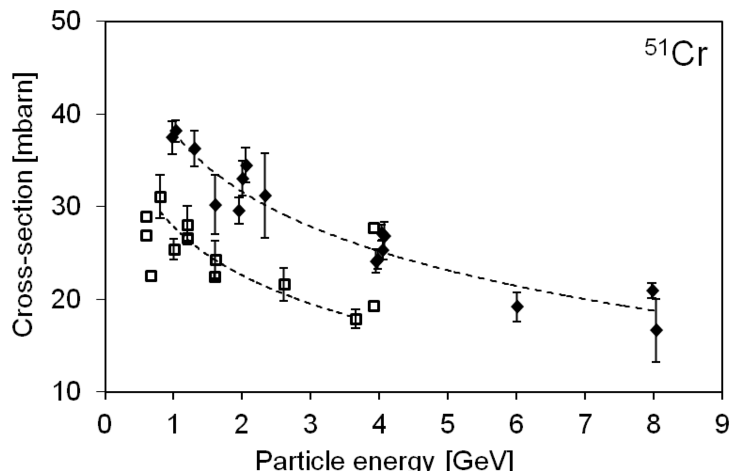
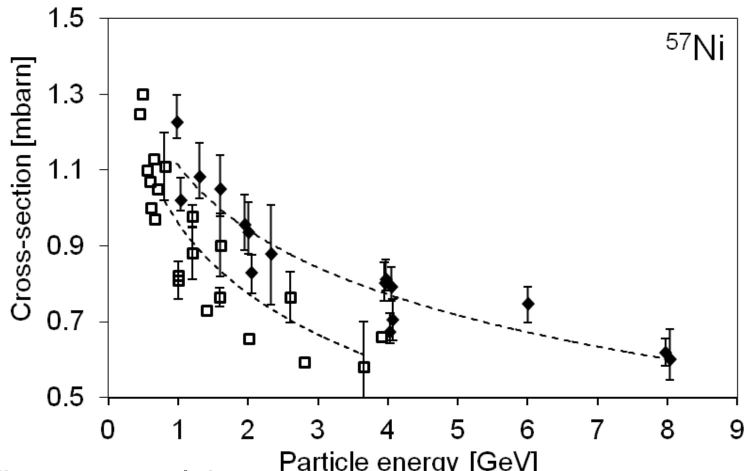




Target-like mass nuclei





Target-like mass nuclei

Experimental Data vs. Talys+MCNPX Simulations

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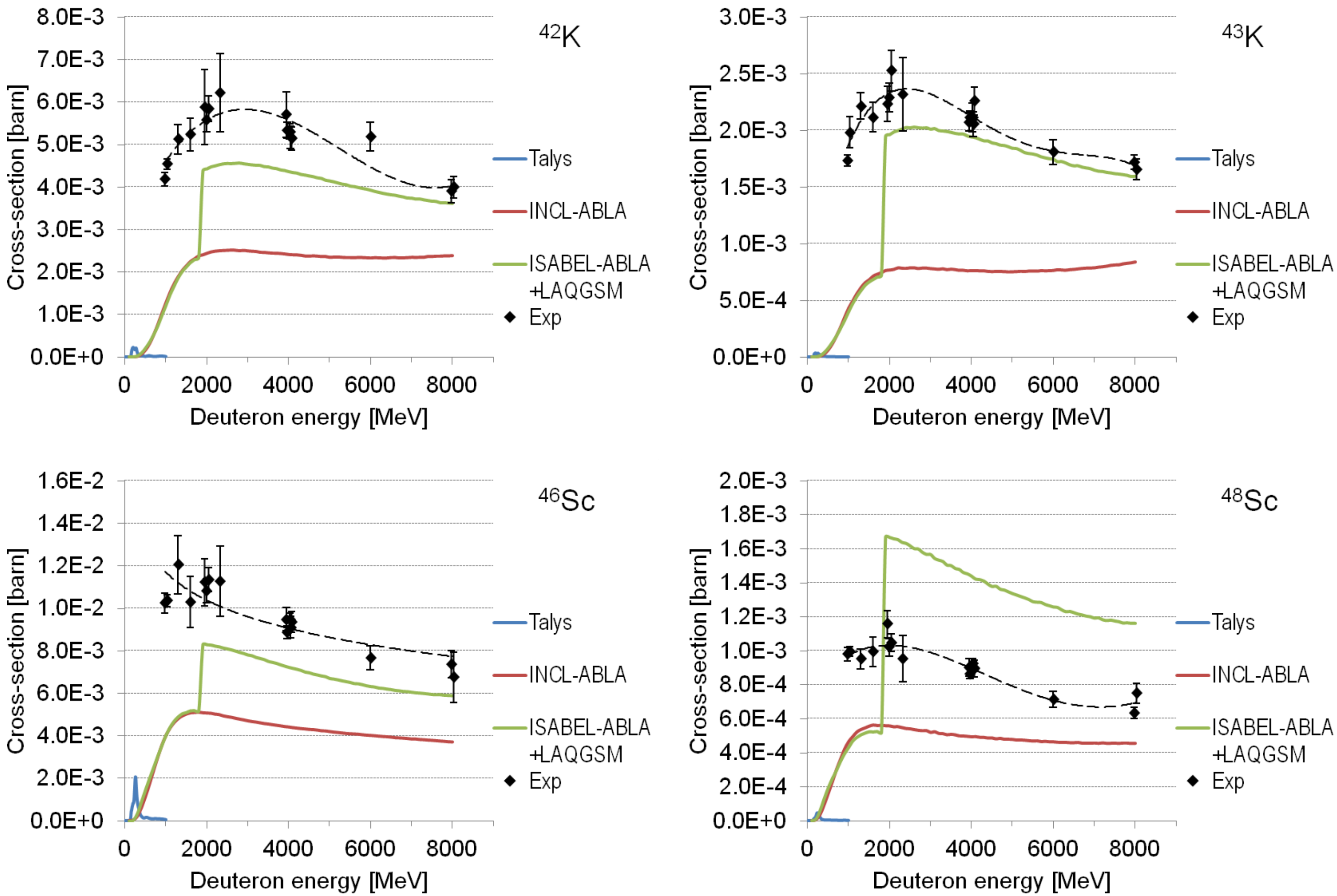
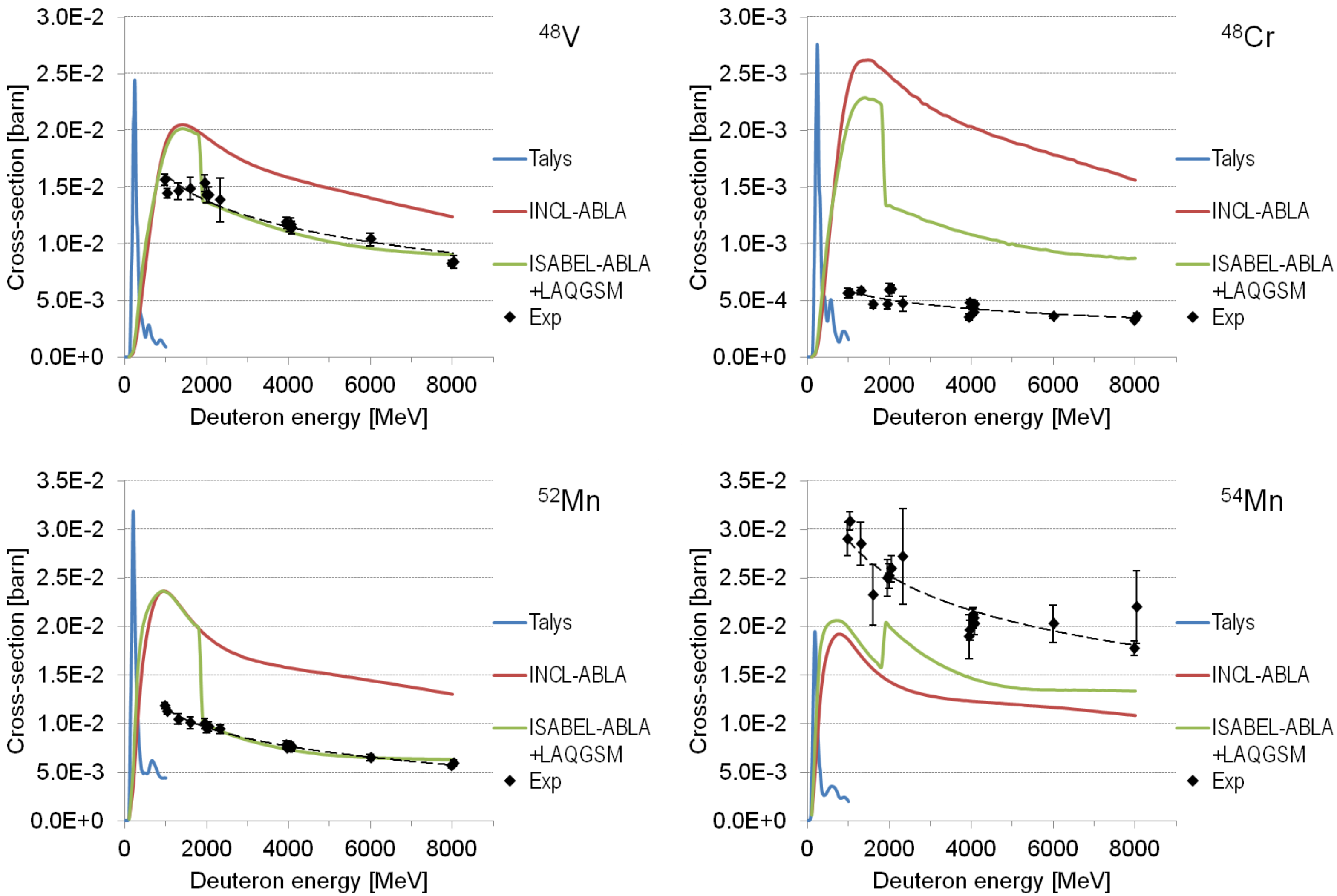


Experimental Data vs. Talys+MCNPX Simulations



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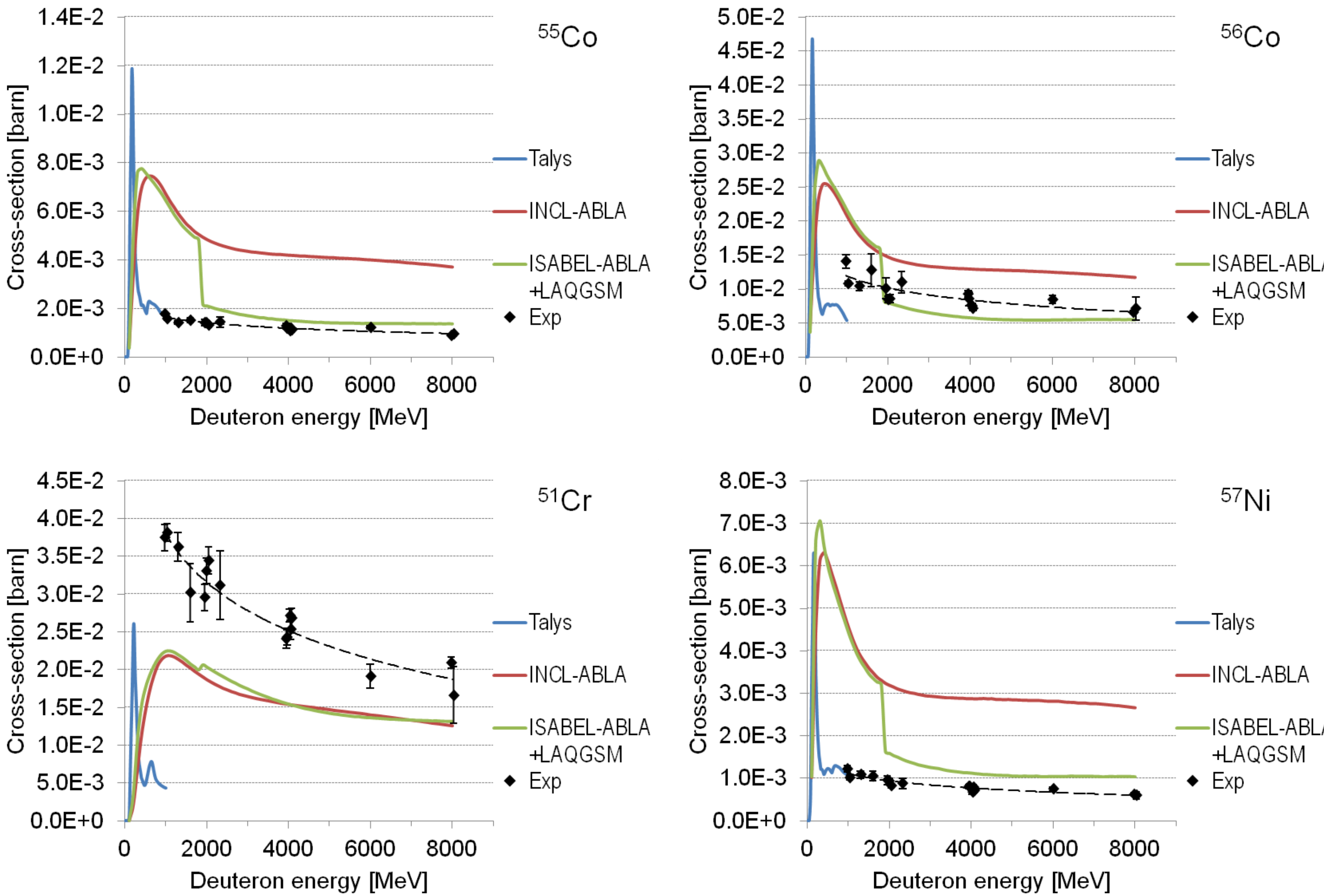

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Summary

- Cross-sections of relativistic deuterons reactions on natural copper were studied in the energy range 1-8 GeV
- Production cross-sections of 38 different radioisotopes created in copper samples were obtained
- Different shape of cross-sections for light, medium, and target-like mass nuclei
- Cross-sections vary in the range ~0.1 – ~10 mbarn
- Compared cross-sections of relativistic deuterons and protons on ^{nat}Cu (data from EXFOR library) – similar shape but 30-40% higher absolute value in general
- Simulated excitation functions in certain cases differ significantly from experimental data in shape and absolute value → need further improvement

Thank you for your attention