International Round Table on Applied Research and Innovations @ NICA

How to get the necessary neutron and ion reaction data for ADTT

Can NICA complex help us?

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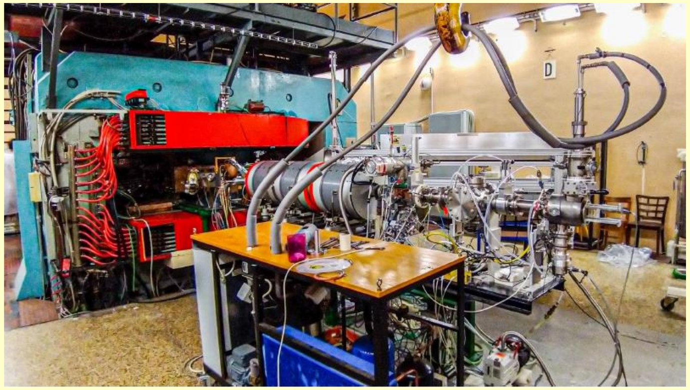
Outline:



1) Introduction (motivation)

2) Measurements of cross-sections
   - 2.1 Neutron reaction cross-sections
   - 2.2 Proton and light ion reaction cross-sections

3) Benchmark studies of complex set-ups
   - 3.1 Different type of thick targets
   - 3.2 Complex set-ups
   - 3.3 Transuranium elements transmutation

4) Summary

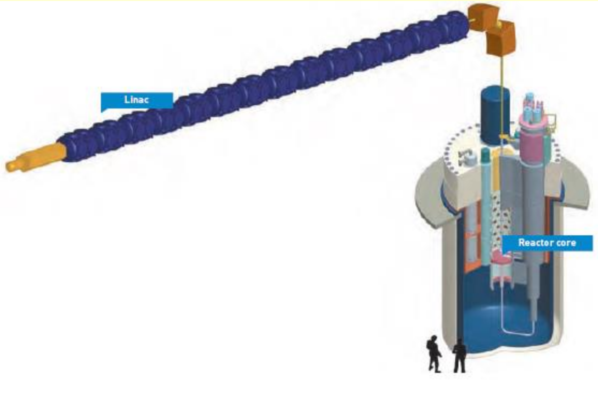
New nuclear technologies – necessity of nuclear data

New fast breeder reactors – **China CEFR, Russian BN-800, Indian Kalpakkam PFBR sodium cooled fast breeder reactors, also other types (lead cooled BREST-300) . Many types of advanced SMR**

ADS test project MYRHA – **European project of accelerated driven system able to operate in sub-critical and critical modes. Proton accelerator of 600 MeV, spallation target and multiplying core with MOX fuel, cooled by liquid lead- bismuth.**

ITER – **fusion reactor, first tokamak which can produce net gain of energy: 50 MW input should produce 500 MW output**

Fast sodium reactor BN800



MYRHA reactore scheme

ITER construction side

Type of nuclear data

Cross-section data

Nuclear modeling lacks accuracy for detailed prediction of cross-sections

Data are needed for developing models, determination of model parameters, benchmark of model parameters, databases and overall model performance

Improvement of code as TALYS

Deuteron source (JINR Dubna Nuclotron) NPI Řež neutron source n-TOF neutron source

Benchmark data

Different complex set-ups simulate parts of ADS systems (different beams, different targets, different blankets – measurement of differential and integral parameters

It is possible to test codes as MCNPX, GENT4 … by comparison of experimental and simulated data

Neutron reaction cross-section studies

1) Quasi-monoenergy neutron sources based on cyclotron and lithium target (NPI Řež, TSL Uppsala)
2) Time of flight system (n-TOF, GELINA, NPI Řež …)
3) Effective integral cross-sections measurement by means of beryllium and heavy water targets

Studied materials (see High Priority Nuclear Data Request List)

1) Materials important for advanced nuclear technologies (construction materials
2) Transuranium elements from nuclear wastes
3) Material used for neutron activation detectors

n-TOF

new NPI Řež cyclotron

spectroscopic laboratory

Cross-sections of (n,x) reactions on different materials

We measured materials useful for activation detectors, construction materials and transmuted elements: Al, Co, Y, Au, Bi, Ta, Cu, Ni, Zn, Fe, In, I, F and Na.

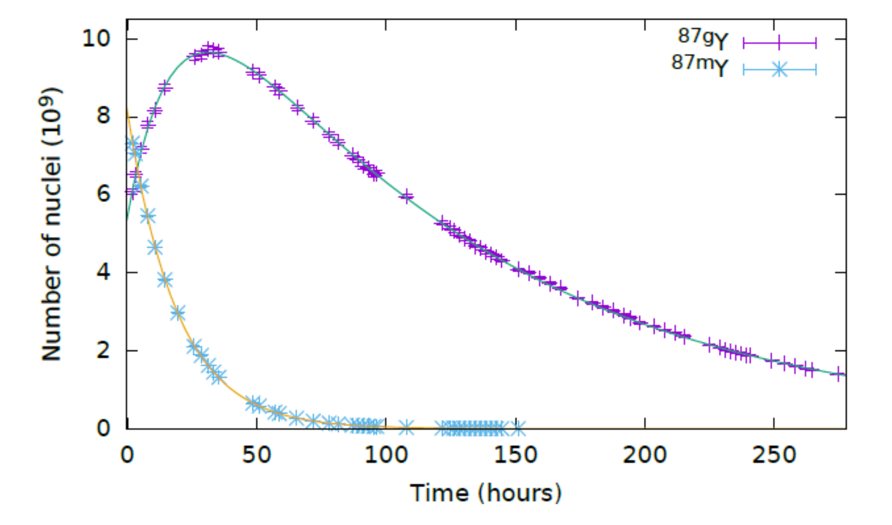
NPI Řež and TSL Uppsala neutron sources were used

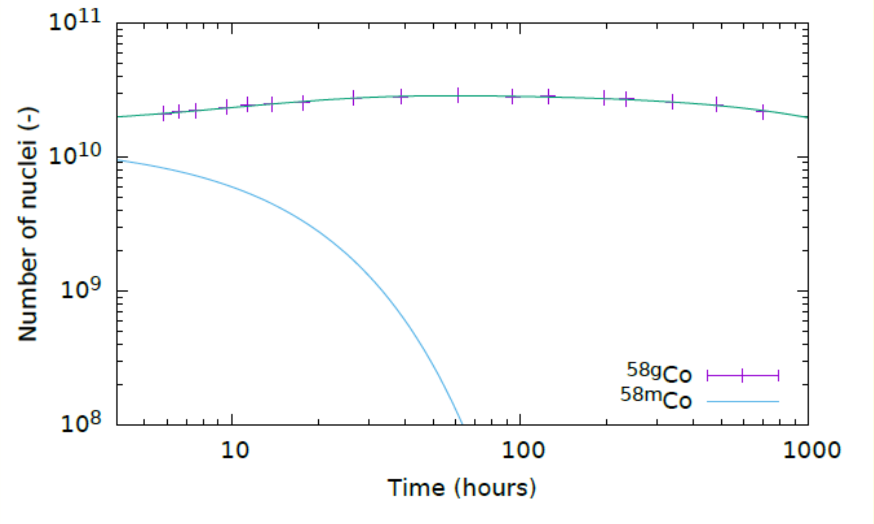
Examples o review of obtained data can be find in journal (they are also in EXFOR):

J. Vrzalová et al: Nuclear Instr. and Meth. in Physics Research A726, (2013) 84-90

P. Chudoba et al: Nuclear Science and Engineering 191(2018)150

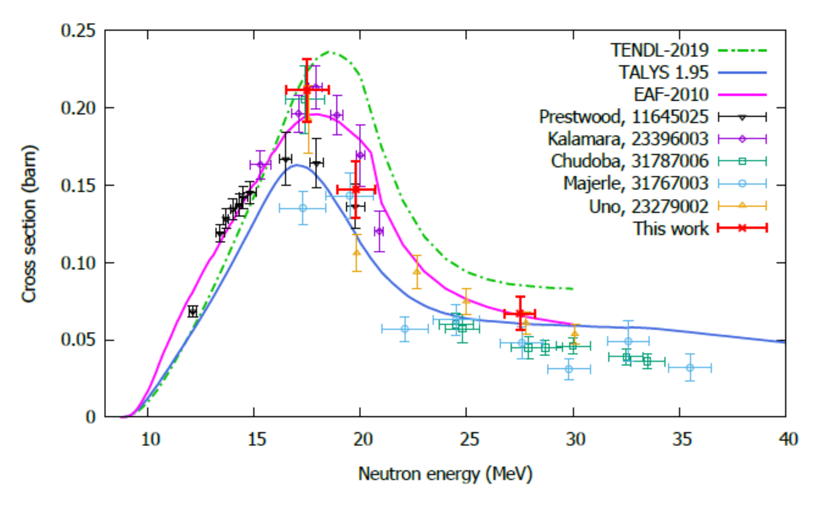
New measurements from last years (publication proces is under way):

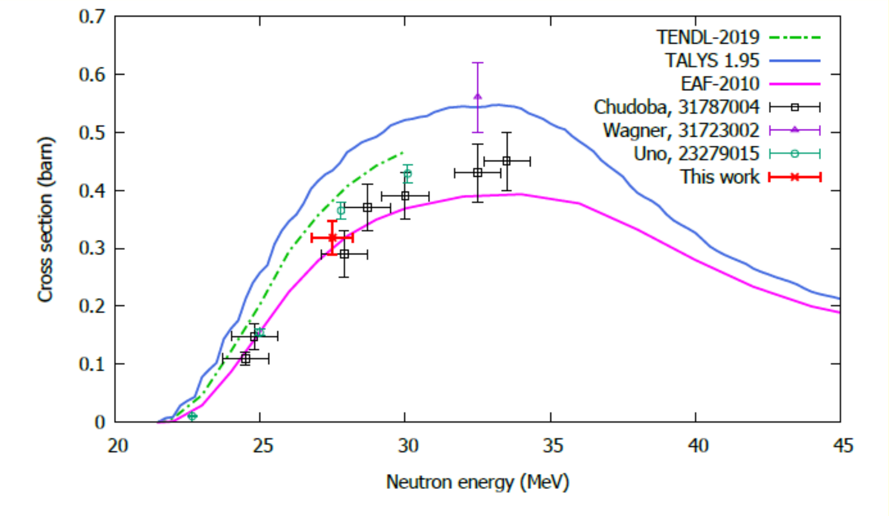




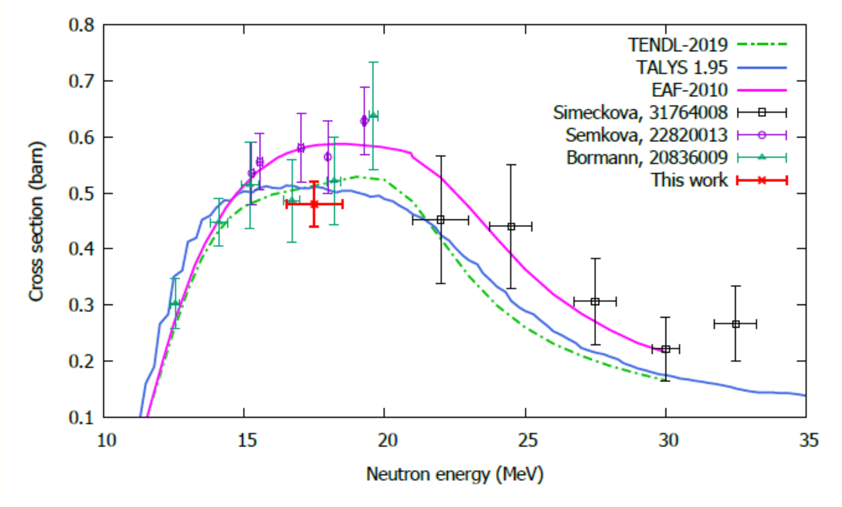
Measurement of cross-sections of isomeric and ground states by means of decay curves, even if transition from isomeric state is not possible to detect

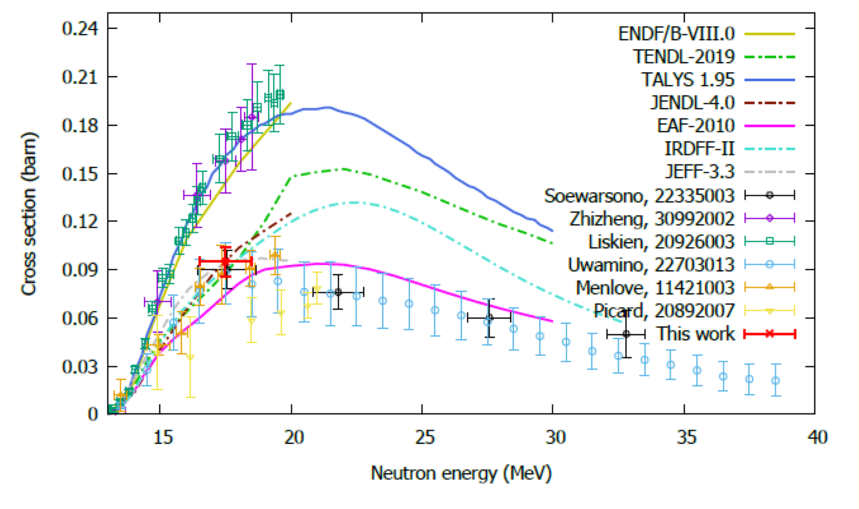
Examples of experimental cross-section measurements





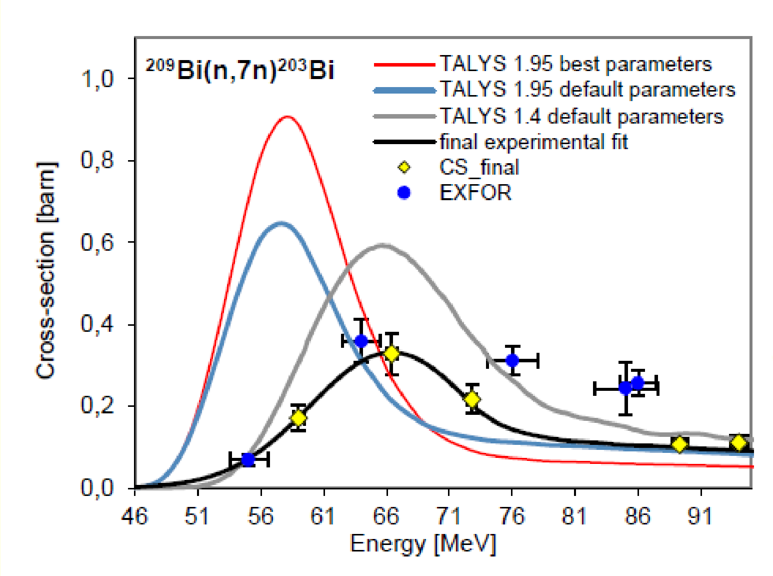
Excitation function of ^{197}Au(n,2n)^{196m2}Au and ^{89}Y(n,3n)^{87m}Y

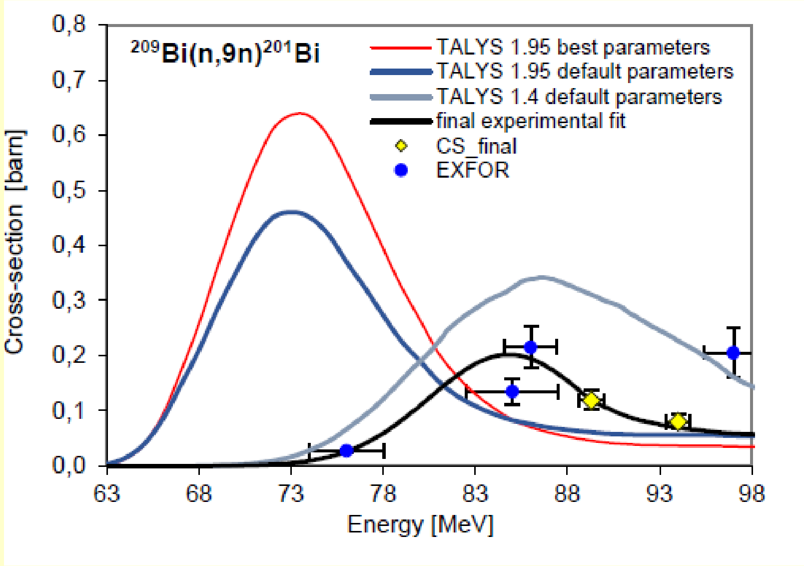


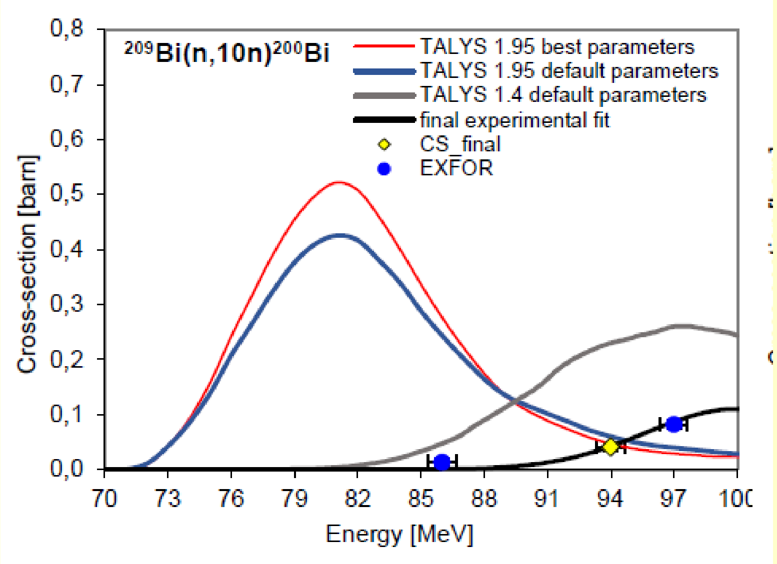


Excitation function of ^{59}Co(n,2n)^{58m}Co and ^{23}Na(n,2n)^{22}Na

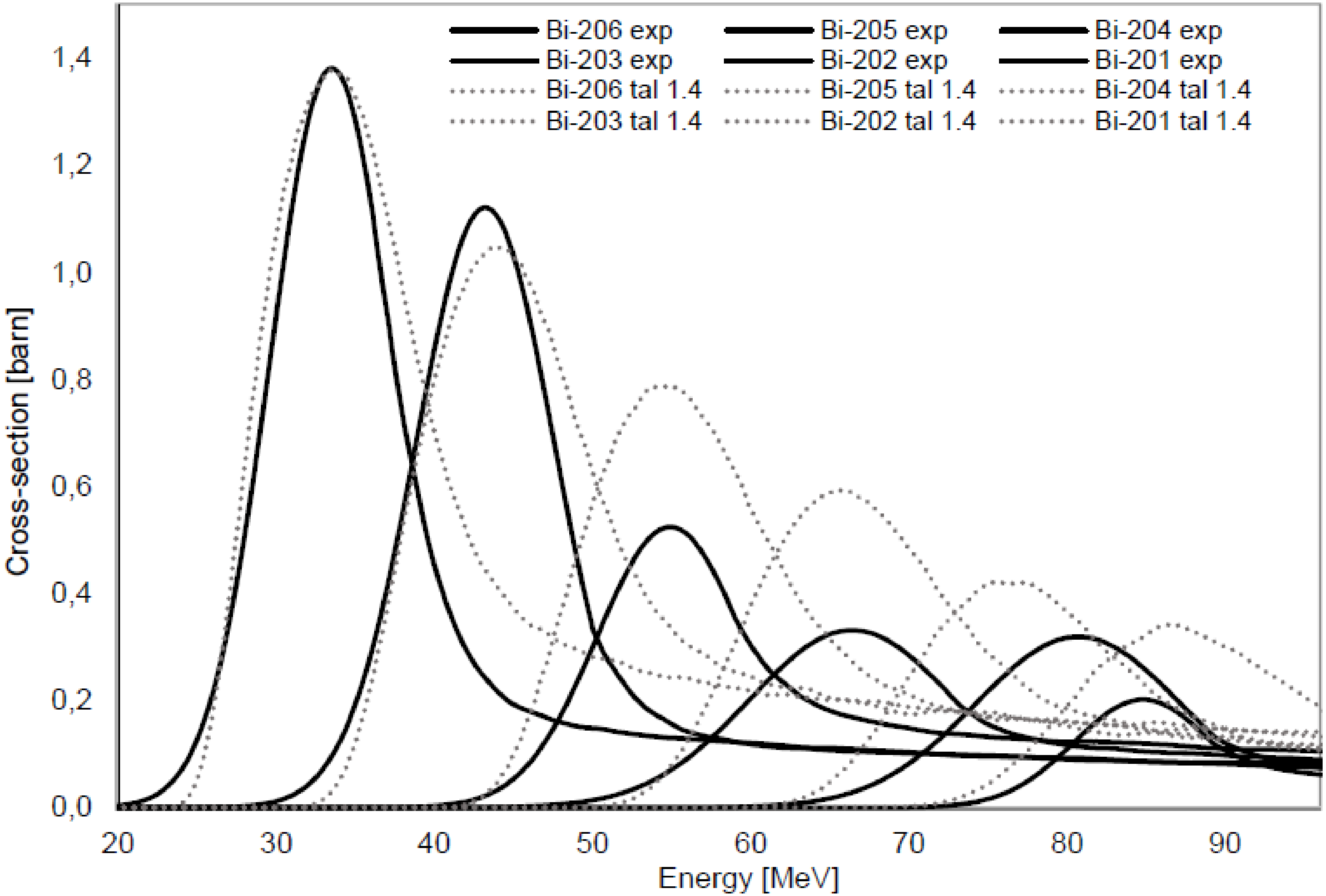
High threshold ^{209}Bi(n,xn) reactions (TSL Upsalla)







1) The agreement between different evaluated excitation functions and variants of TALYS for low threshold reactions
2) Different situation for high threshold reaction –big differences
3) Our data are possible to use for tests of evaluated libraries and improvement of the TALYS code.
4) Description by the TALYS 1.6 looks better



Excitation functions of (n,xn) reactions on bismuth target, comparison of experimental and TALYS 1.4

Cross-sections of relativistc light ion reactions

(Example - relativistic deuteron reactions on copper)

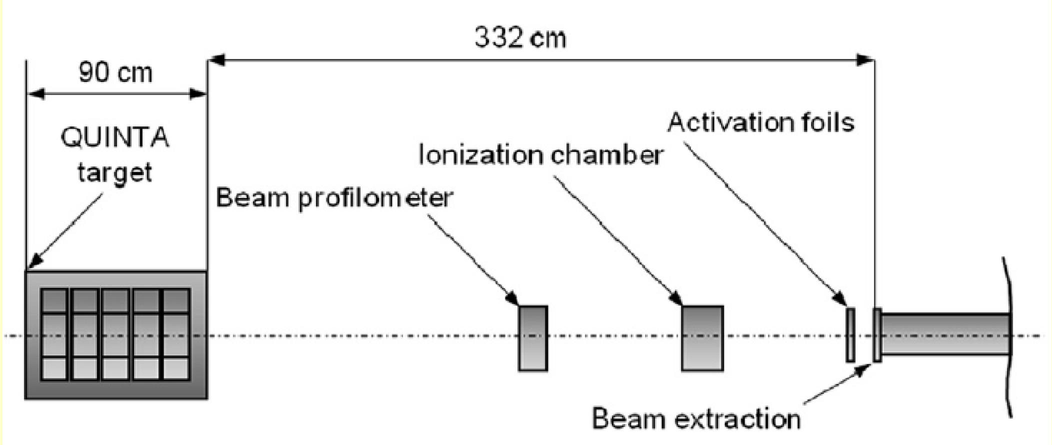
Beams from JINR Dubna Nuclotron were used: energies from 1 GeV up to 8 GeV

Copper is nice material for beam integral and geometry monitoring by means of the activation method

Needed cross-section data were completely missing for deuteron reactions

We started systematic study of cross-sections of relativistic deuteron reactions with copper

We used irradiation of QUINTA set-up and we put copper foil with aluminum foil



Several complicated decays were analyzed

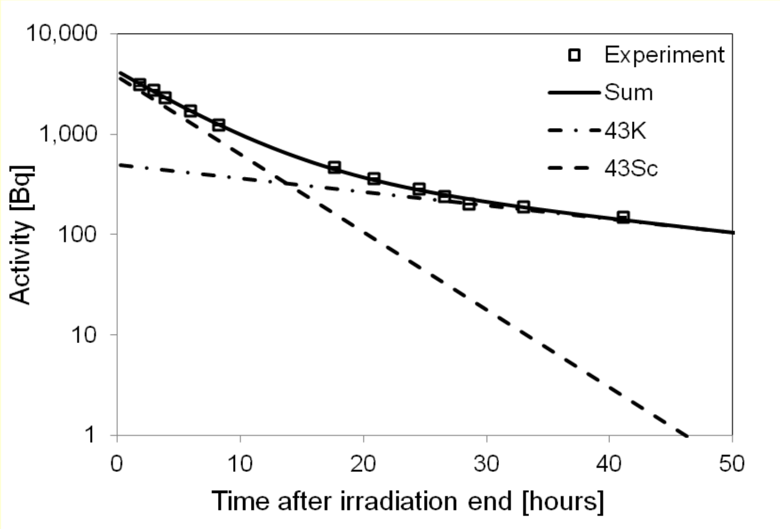
$^{43}K \rightarrow {}^{43}Ca \leftarrow {}^{43}Sc$

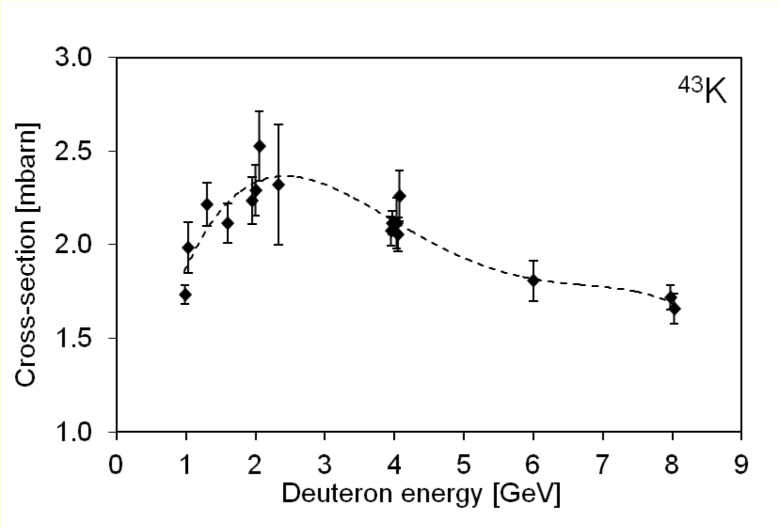
$T_{1/2}$ 22.3 h 3.9 h

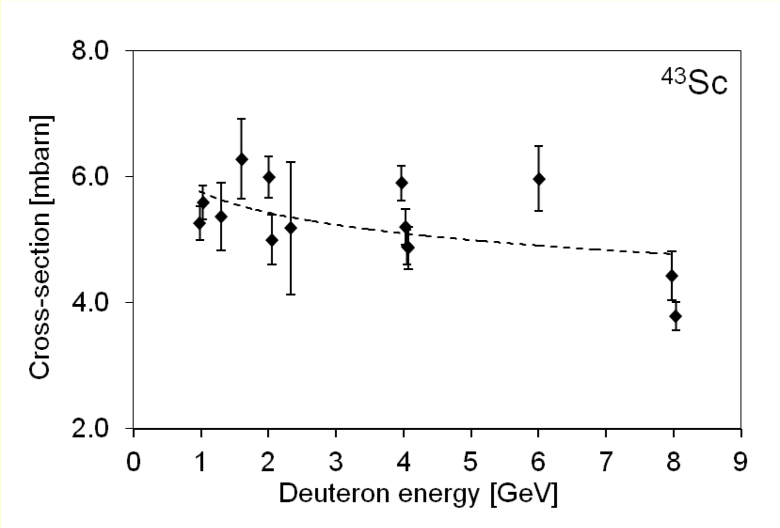
Gamma lines:

^{43}K only: 617.5 keV

^{43}K + ^{43}Sc: 846.8 keV







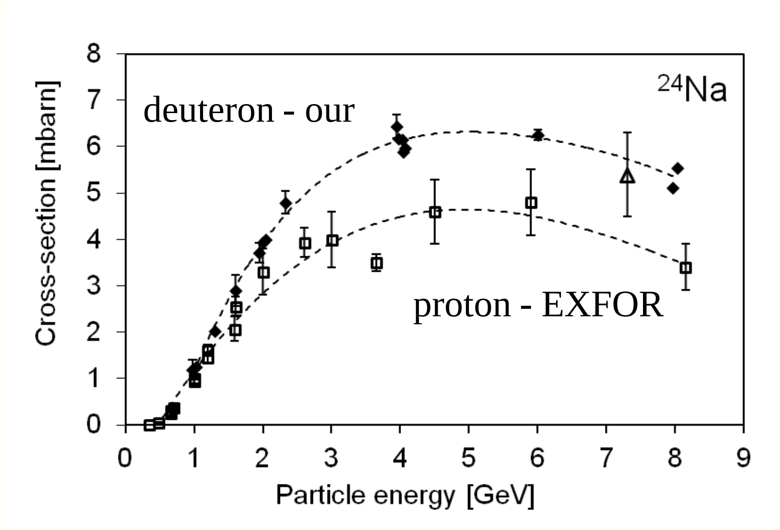
Overall 38 different radioisotopes were identified:

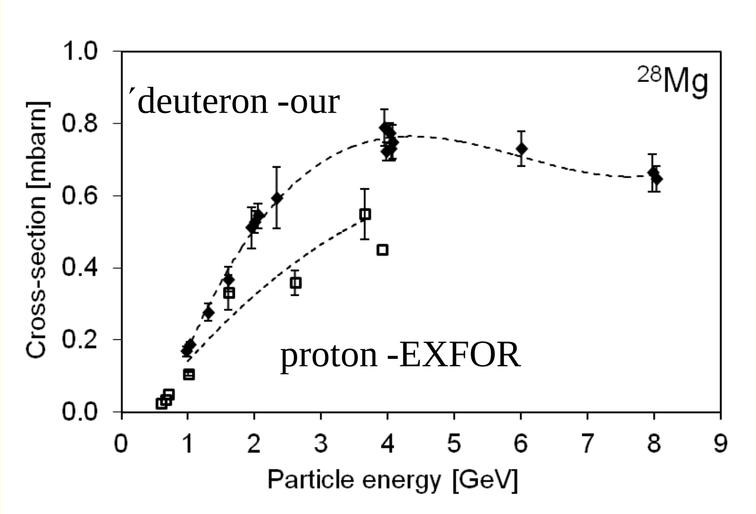
^{7}Be, ^{22}Na, ^{24}Na, ^{28}Mg, ^{28}Al, ^{38}S, ^{38}Cl, ^{39}Cl, ^{42}K, ^{43}K, ^{47}Ca, ^{43}Sc, ^{44}Sc, ^{44m}Sc, ^{46}Sc, ^{47}Sc, ^{48}Sc, ^{48}V, ^{48}Cr, ^{49}Cr, ^{51}Cr, ^{52}Mn, ^{54}Mn, ^{56}Mn, ^{52}Fe, ^{59}Fe, ^{55}Co, ^{56}Co, ^{57}Co, ^{58}Co, ^{60}Co, ^{56}Ni, ^{57}Ni, ^{65}Ni, ^{61}Cu, ^{64}Cu, ^{62}Zn, ^{65}Zn

Their independent or cumulative production cross-sections were obtained.

The review of obtained data can be find in the article (there are also in the EXFOR):

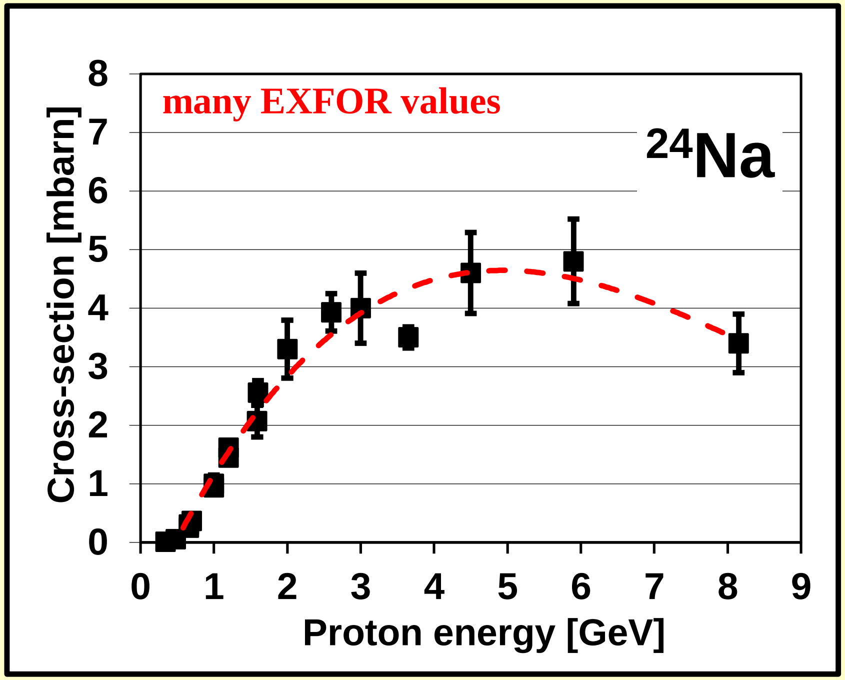
M. Suchopar et al: Nuclear Instr. and Meth. in Physics Research B344, (2015) 63-69



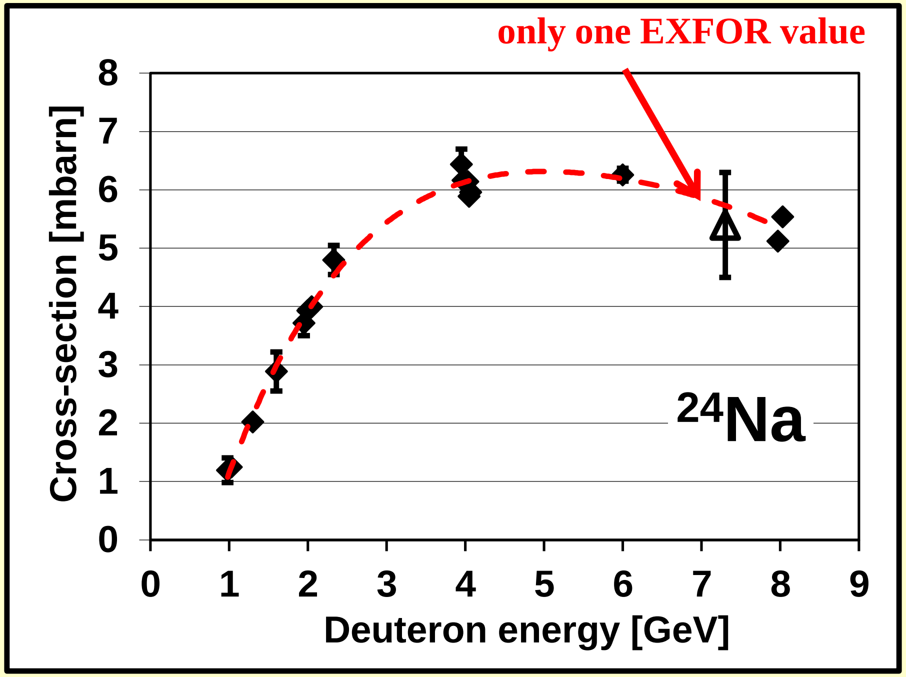


Light products – comparison of protons and deuterons

Only one example of obtained cross-section data



Relativistic protons (EXFOR)

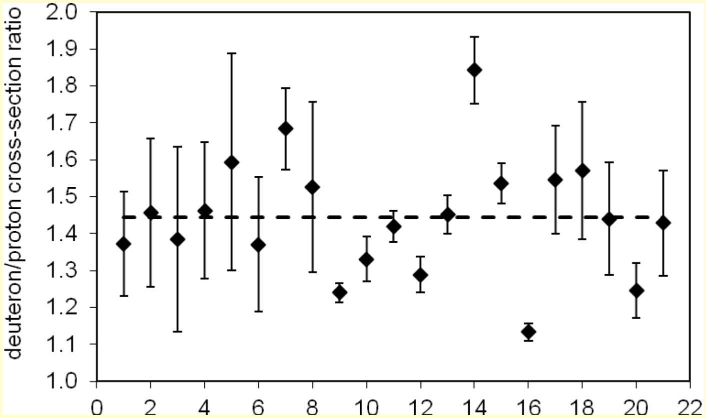


Relativistic deuterons (ours)

The ratio between deuteron and proton cross-sections:

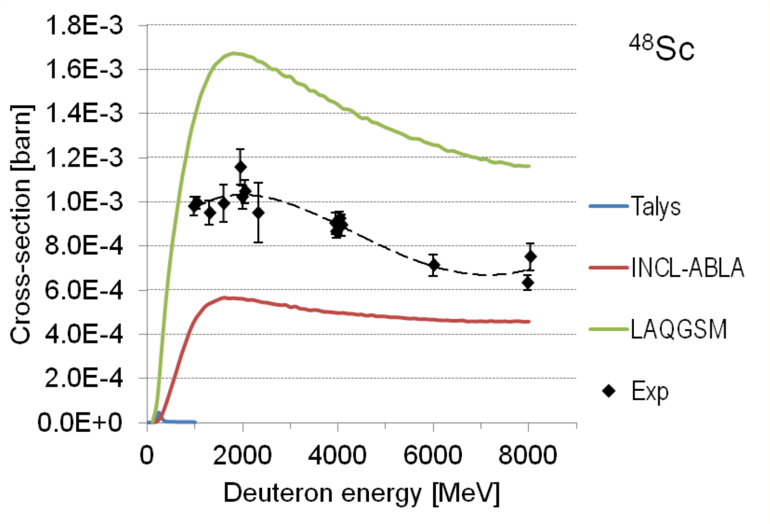
1.3 – 1.6 → deuteron production is about 40 % higher

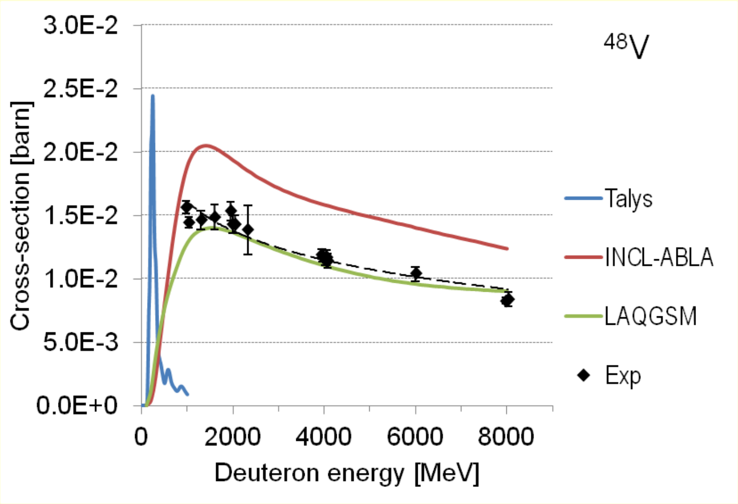
Only ratio for productions of the lightest nuclide (^{7}Be) is different (deuteron reaction cross-section is two times higher)

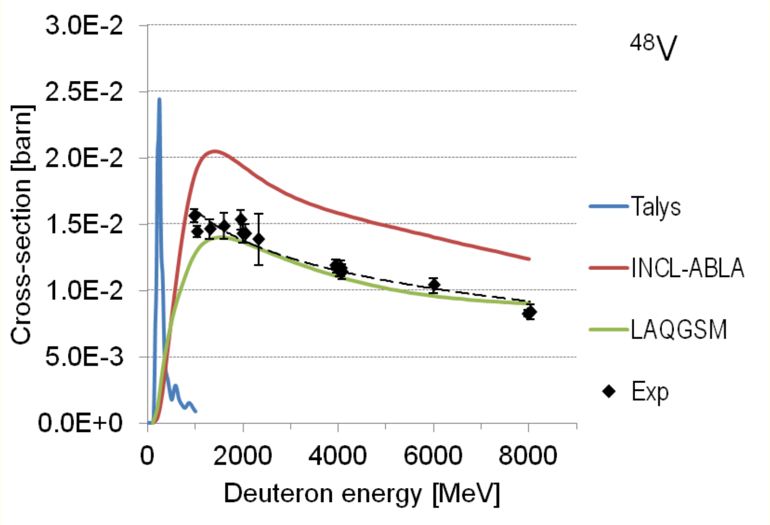


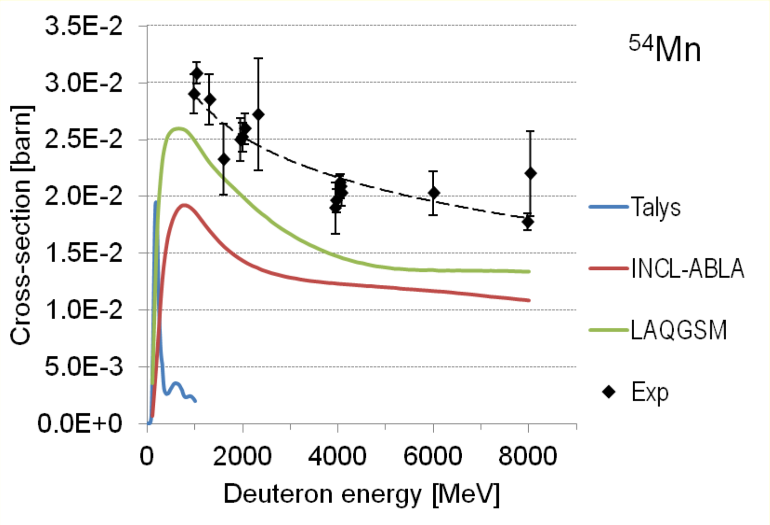
Comparison with models

MCNPX 2.7.0 with two different INC models (INCL-ABLA and LAQGSM)









The obtained data are possible to use for model test and model improvement (description of experimental data by LAQGSM looks better)

Benchmark measurements with the E+T set-up

Energy + Transmutation set-up (JINR Dubna) – lead target with uranium blanket

Irradiated by proton and deuteron beams with different energies

Main tasks: 1) Measurement of neutron fields in different places of the set-up by different activation detectors

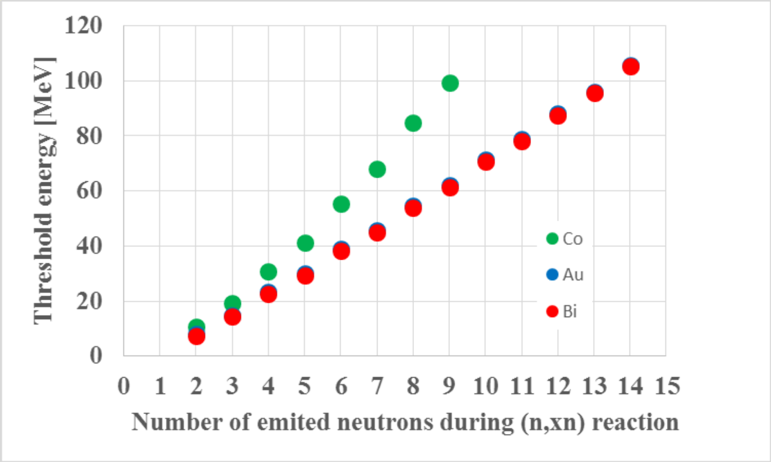
2) Study of transmutation of different samples (actinides, fission products)

Systematic review of proton experiments were published:

A. Krása et al: Nuclear Instr. and Meth. in Physics Research A615 (2010) 70

M. Suchopar et al: Nuclear Instr. and Meth. in Physics Research A908 (2018) 347

Activation neutron detectors - reactions with high threshold

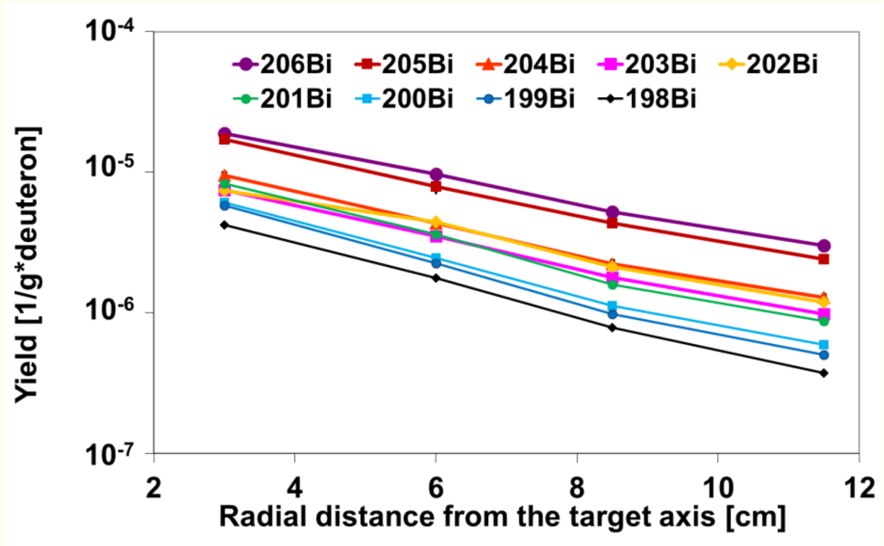


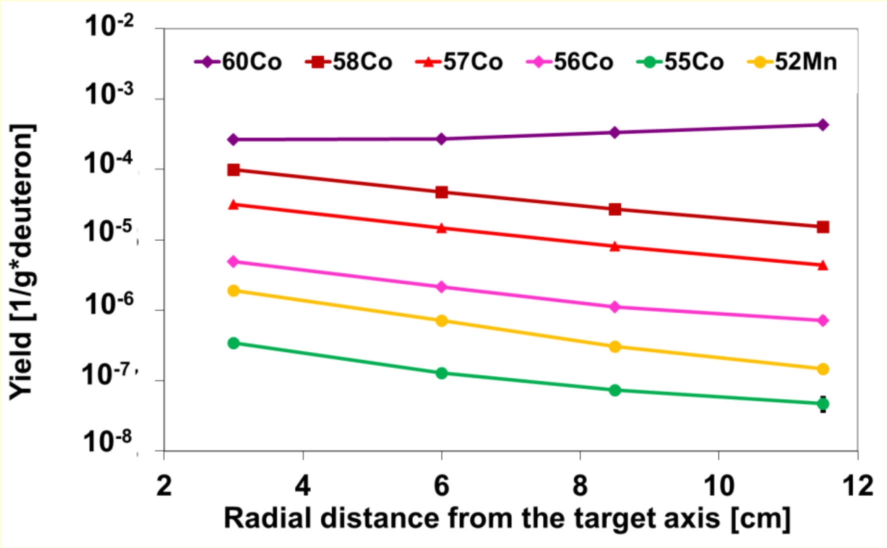
Bi – foil :

^{209}Bi(n,3n)^{207}Bi (31,6y)
^{209}Bi(n,4n)^{206}Bi (6,2d)
^{209}Bi(n,5n)^{205}Bi (15,3d)
^{209}Bi(n,6n)^{204}Bi (11,2h)
^{209}Bi(n,7n)^{203}Bi (11,8h)
^{209}Bi(n,8n)^{202}Bi (1,7h)
^{209}Bi(n,9n)^{201}Bi (1.8h) → ^{201}Pb (9.3h) → ^{201}Tl (72.9h) → ^{201}Hg
^{209}Bi(n,10n)^{200}Bi (0.6h) → ^{200}Pb (21.5h) → ^{200}Tl (26.1h) → ^{200}Hg
^{209}Bi(n,11n)^{199}Bi (0.45h) → ^{199}Pb (1.5h) → ^{199}Tl (7.4h) → ^{199}Hg
^{209}Bi(n,12n)^{198}Bi (0.17h) → ^{198}Pb (2.4h) → ^{198}Tl (5.3h) → ^{198}Hg
^{209}Bi(n,13n)^{197}Bi (0.16h) → ^{197}Pb (0.13h) → ^{197}Tl (2.8h) → ^{197}Hg (64.16h)

Au-foil : ^{197}Au(n,3n)^{195}Au
^{197}Au(n,4n)194Au
^{197}Au(n,5n)193Au
^{197}Au(n,6n)192Au (4.9h)
^{197}Au(n,7n)191Au (3.2h) → ^{191}Pt (2.8d)
^{197}Au(n,8n)190Au (0.7h) → ^{190}Pt
^{197}Au(n,9n)189Au (0.5h) → ^{189}Pt (10.9h) → ^{189}Ir (13.2d) → ^{189}Os
^{197}Au(n,10n)188Au (0.5h) → ^{188}Pt (10.2d) → ^{188}Ir (41.5h) → ^{188}Os

Improvement of our knowledge of the neutron reaction excitation function for high energy threshold reactions is needed



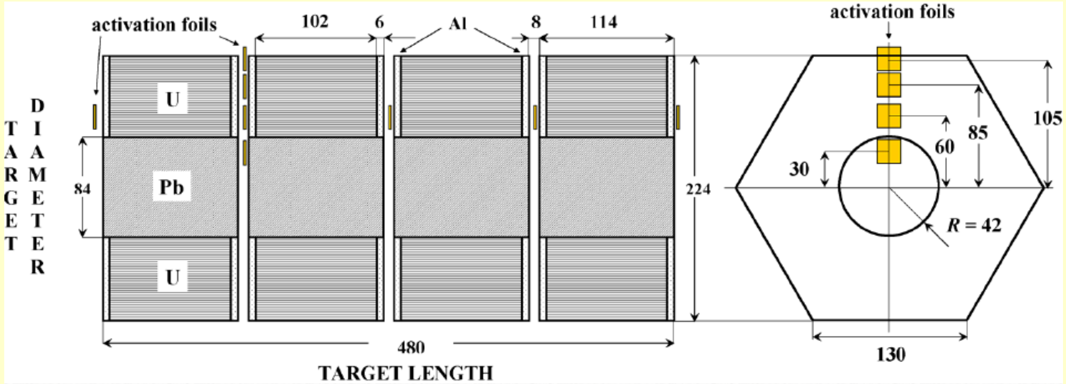


Irradiation of E+T set-up by the 4 GeV deuterons

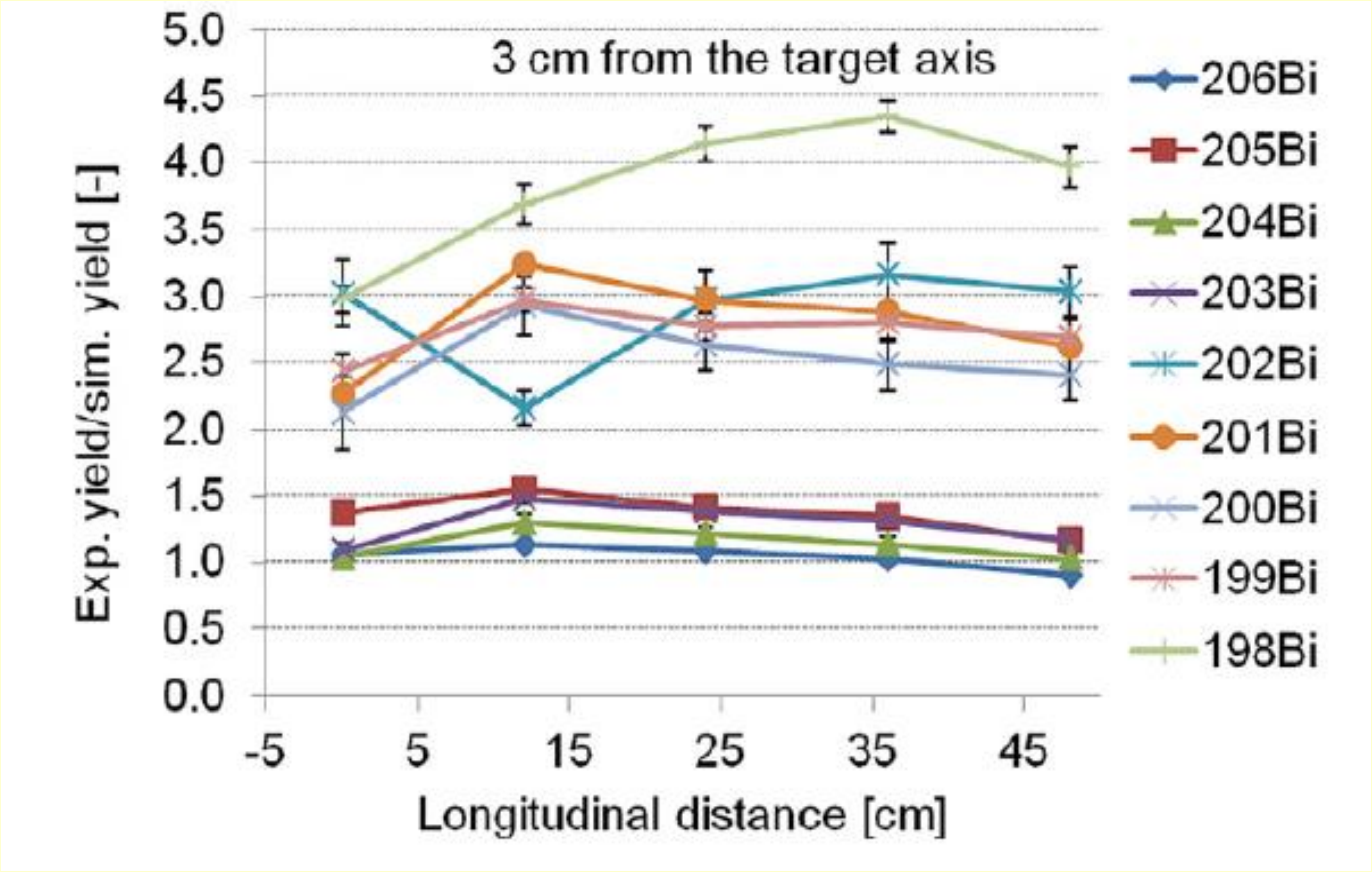
Inside the lead target also high energy neutrons (up to 100 MeV and more are produced)

Activation detectors are used for spatial neutron flux distribution

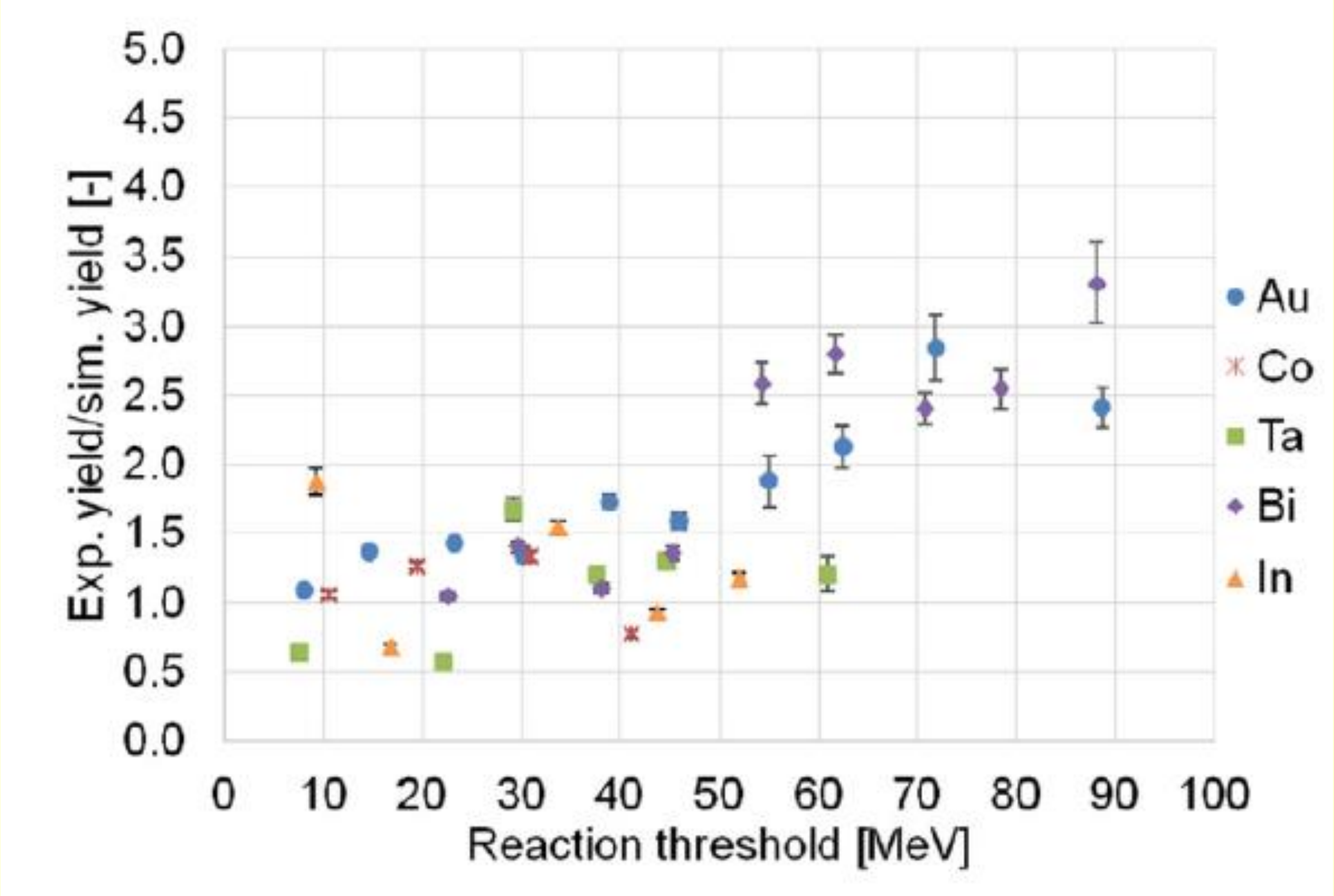
Production of different radionuclides shown number of neutrons with different energies



Threshold reactions up to 100 MeV threshold will be possible to use if excitation functions will be known

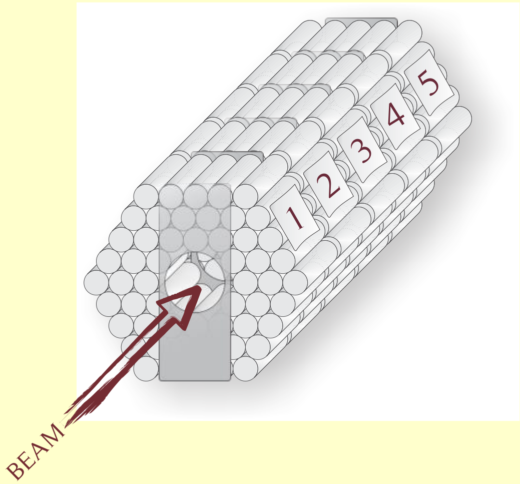


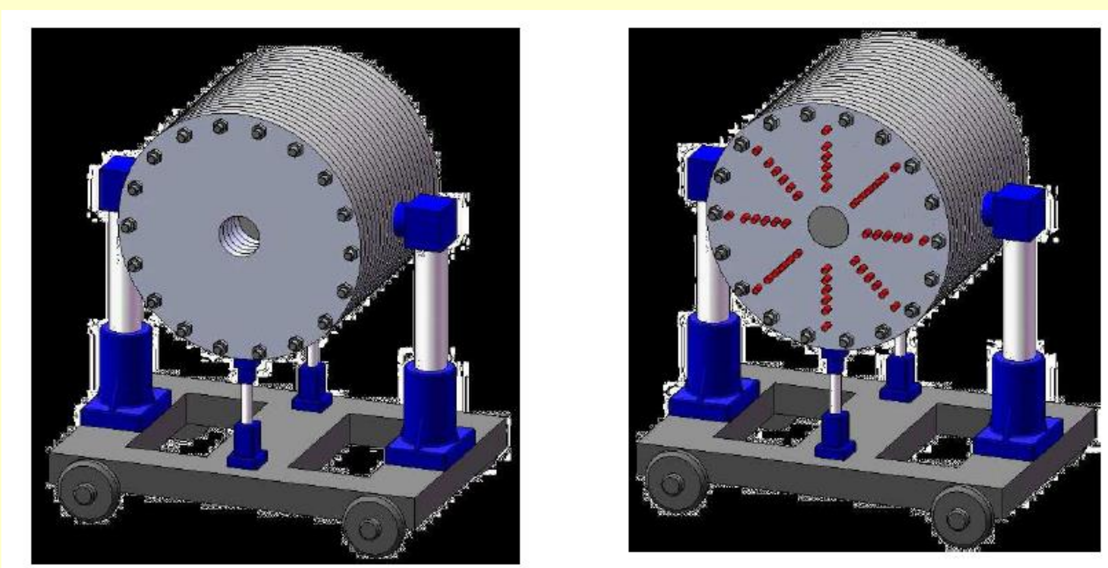
Ratios of experimental and simulated (MCNPX INCL4+ABLA) yields in the Bi samples in longitudinal direction 3 cm over the target axis



Average experimental to simulated yield ratios as a function of reaction threshold energy folded with TALYS v1.6, calculations performed in MCNPX v2.7

Big uranium targets - QUINTA and BURAN





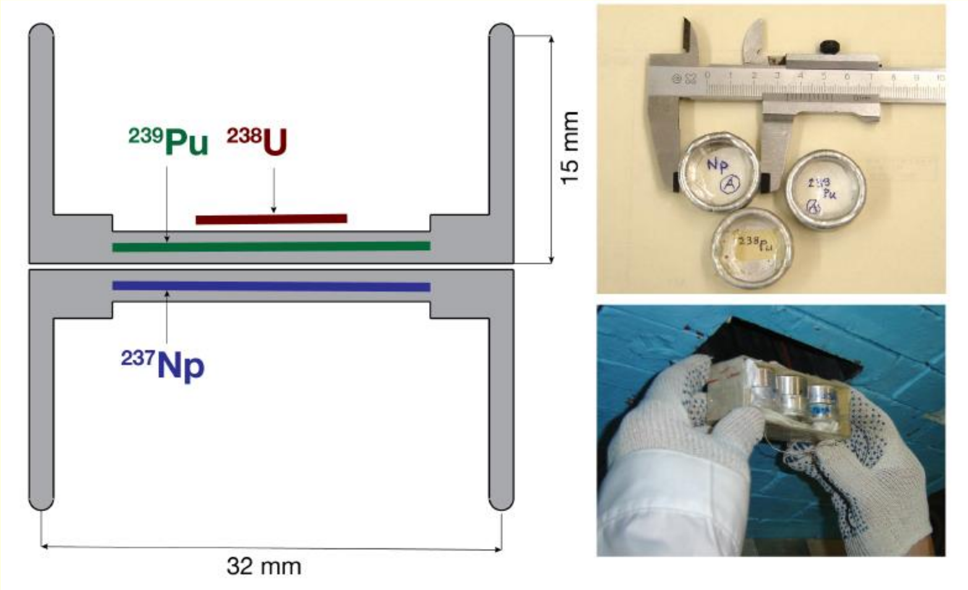
QUINTA (512 kg of the natural uranium was irradiated by deuteron beams on the Nuclotron and high intensive proton beam on the Phasotron
High energy neutrons were measured

BURAN (infinite uranium target – 19.5 t of depleted U)

E+T and QUINTA studies

1) Distribution of neutron fields by means of activation detectors
2) Escape neutrons measurement
3) Integral neutron production
4) Transmutation of uranium and transuranium elements (U, Pu, Am, Cm, Np)
5) Heat distribution by thermocuples

QUINTA set-up without lead shielding



Transuranium samples

How can NICA complex help us?

1) Proton and deuteron unpolarized beams with energy from hundreds MeV up to GeV units (maybe also other light ions)
2) Thin targets – studies of relativistic ions reactions with different materials
3) Thick targets – spallation reaction studies, benchmark studies, produced neutron field is possible to use for transmutation studies
4) More complex set-ups – need space

Possible synergies:

1) With space study of cosmic ray radiation
2) Radiobiological studies
3) Dosimetry studies – use of produced neutron field

We will go from

Phasotron to NICA

Summary

- **Experimental nuclear data are needed for different applications (fast breeder reactors, Accelerator Driven Transmutation systems, fusion systems, spallation sources ….)**
- **Improvement of models, libraries and code is necessary**
- **We can provide cross-sections neutron reactions on different materials and of relativistic proton and deuteron reactions on copper**
- **Such data help us improve our benchmark studies of different uranium set-ups - E+T, QUINTA, BURAN. Possibility to test and improve not only MCNPX code**
- **Transmutation of transuranium elements studies by means of ´produced neutron fields**
- **NICA complex – excellent possibility for continuation and extension of such studies**
- **All you need is a quality beam of protons and deuterons with energy from hundreds of MeV to GeV units.**