Studies of (n,xn) reaction cross-sections and also cross-sections of relativistic deuteron reactions obtained by the activation method

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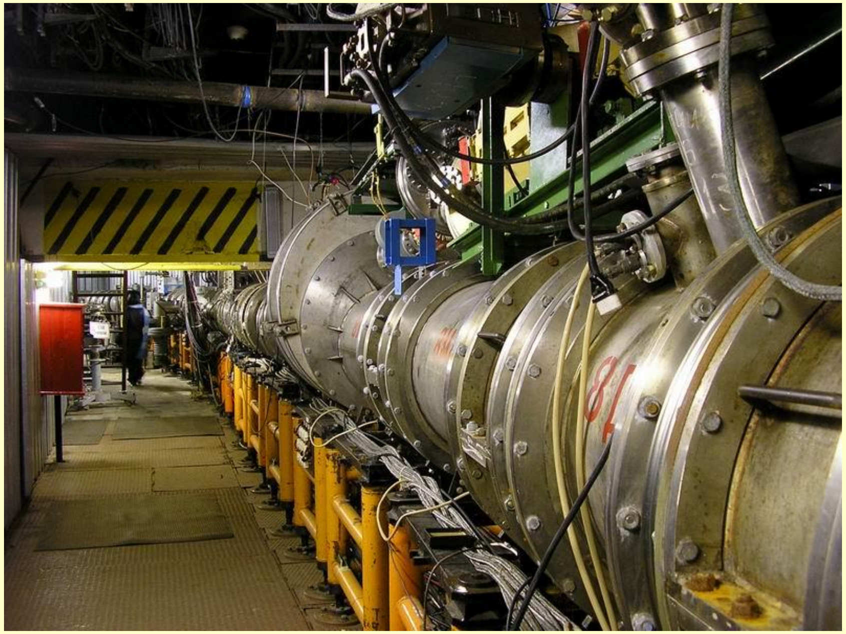
for collaboration "Energy and Transmutation of Radioactive Waste"

(Russia, Belarus, Germany, Greece, Poland, Ukraine, Czech Republic …)



Relativistic deuteron reaction cross-section measurements

Neutron reaction cross-section measurements

Development of ADT systems

Benchmark studies of different set-ups irradiated by relativistic proton and deuteron beams – development of different codes (MCNPX, FLUKA …)

Studies of neutron production and transport

Studies of radioactive materials transmutation

Group "Energy+Transmutation of Radioactive Waste":

Different set-ups irradiated by Nuclotron beams (JINR Dubna)

Activation detectors are used for relativistic beam monitoring and neutron spatial distribution sudies

Lead target + uranium blanket

big uranium target

simple led target +

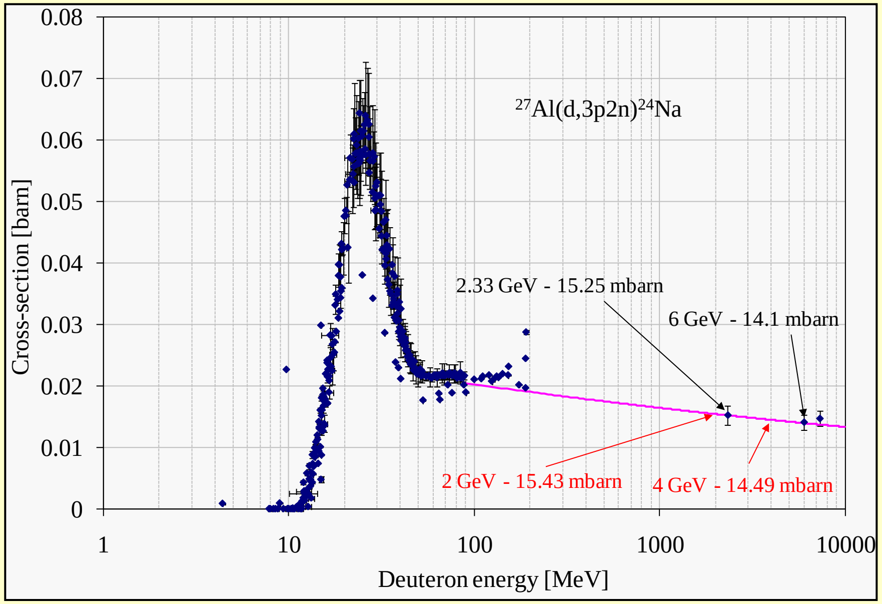
Beam monitoring – aluminum and copper foils

Very scare information about high energy deuteron aluminum reaction cross-sections

Completely no information about high energy deuteron copper reaction cross-sections

We started series of deuteron copper reaction studies by means of JINR Nuclotron

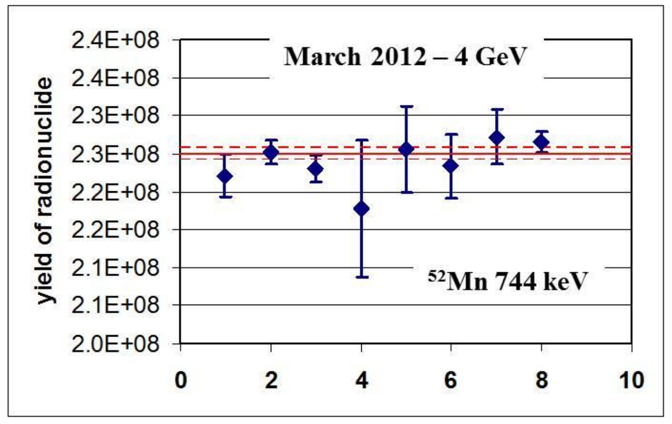
Deuteron aluminum foils were used as beam integral monitor



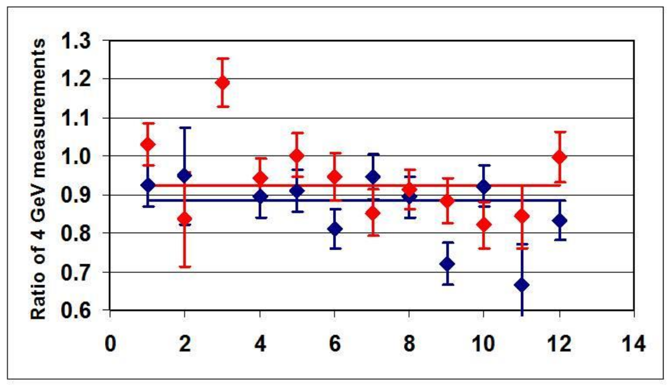
Studies of relativistic deuteron reactions on natural copper

(production of ^{57}Ni, ^{58}Co, ^{56}Co, ^{55}Co, ^{56}Mn, ^{52}Mn, ^{48}Cr, ^{48}V, ^{48}Sc, ^{47}Sc, ^{44m}Sc, ^{43}Sc and ^{43}K)

Energy range of deuteron beam from 1 GeV up to 8 GeV (during QUINTA irradiations)



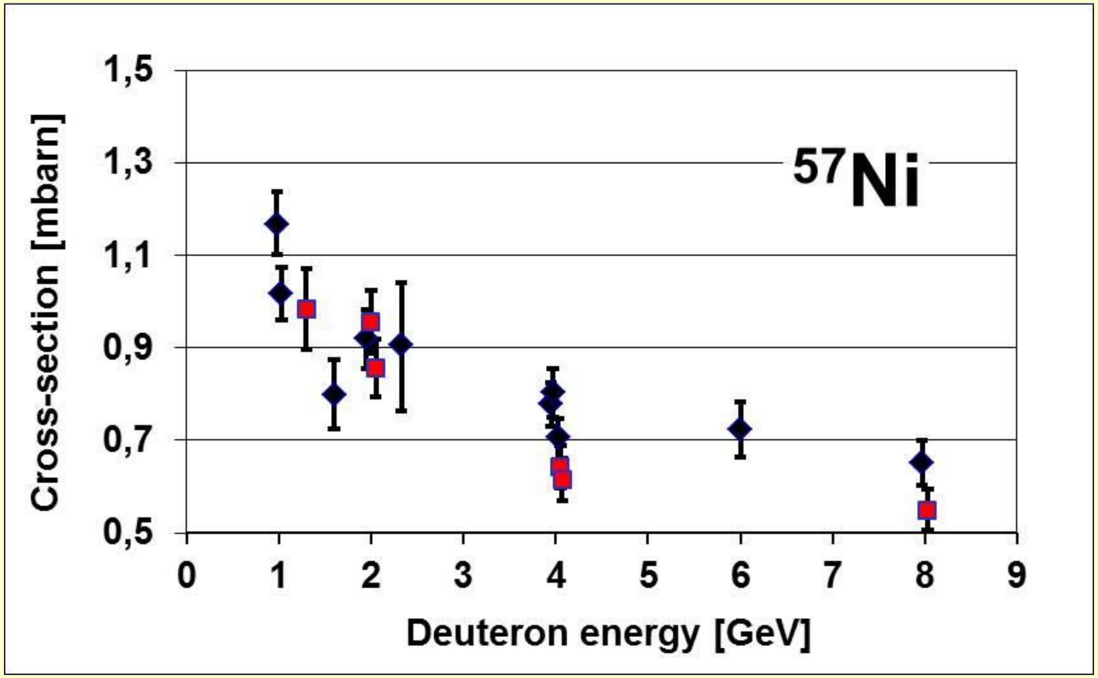
More measurements of activity



More irradioations with same deuteron energy

Five series of irradiations (last two - red signs)

Activation method was used



Example of simple decay results

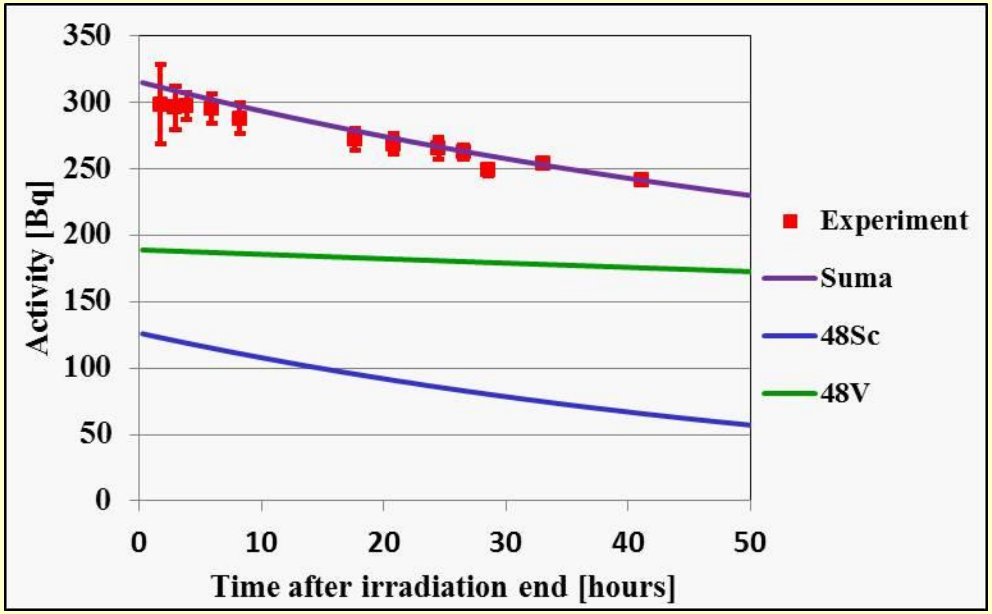
$^{48}Sc \rightarrow {}^{48}Ti \leftarrow {}^{48}V$

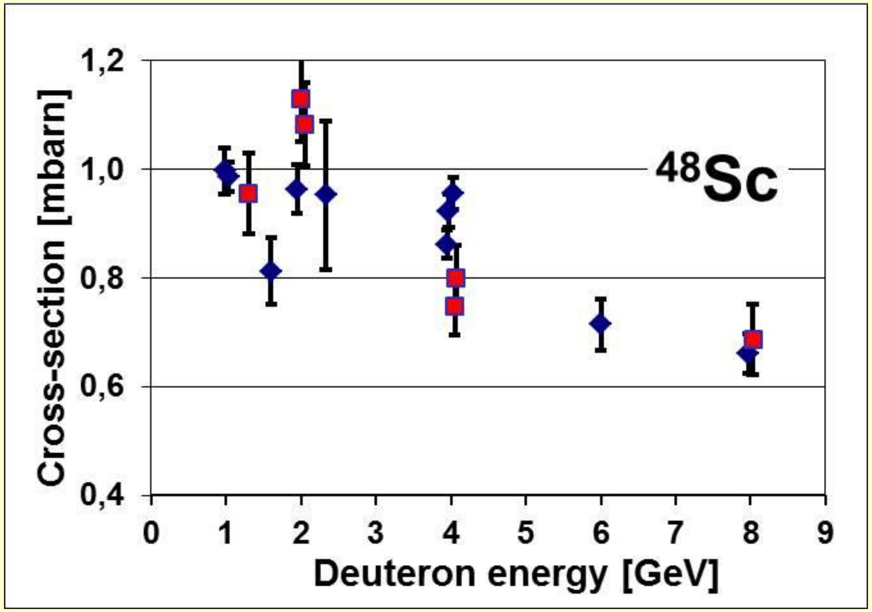
T1/2 **43.7 h** **383.3 h**

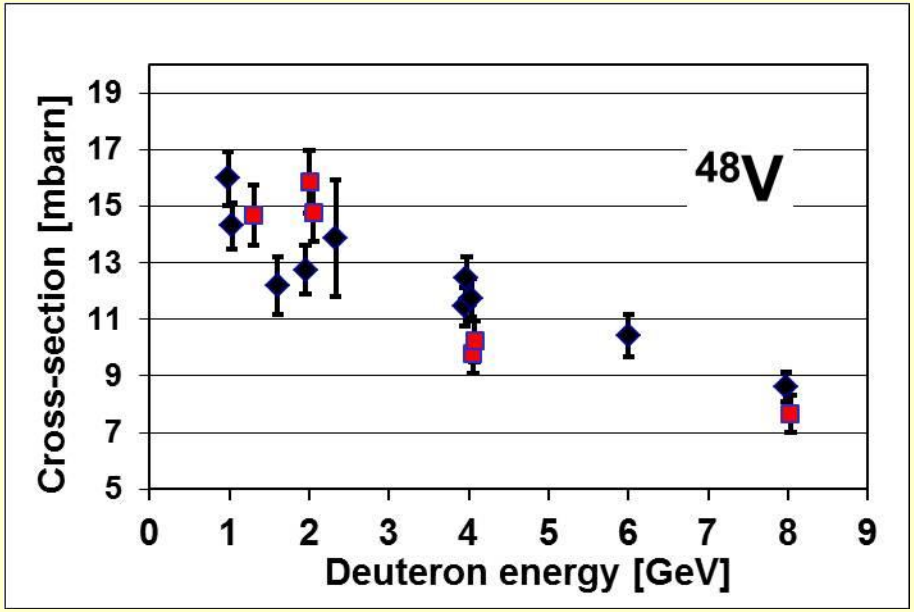
Gamma lines:

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

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







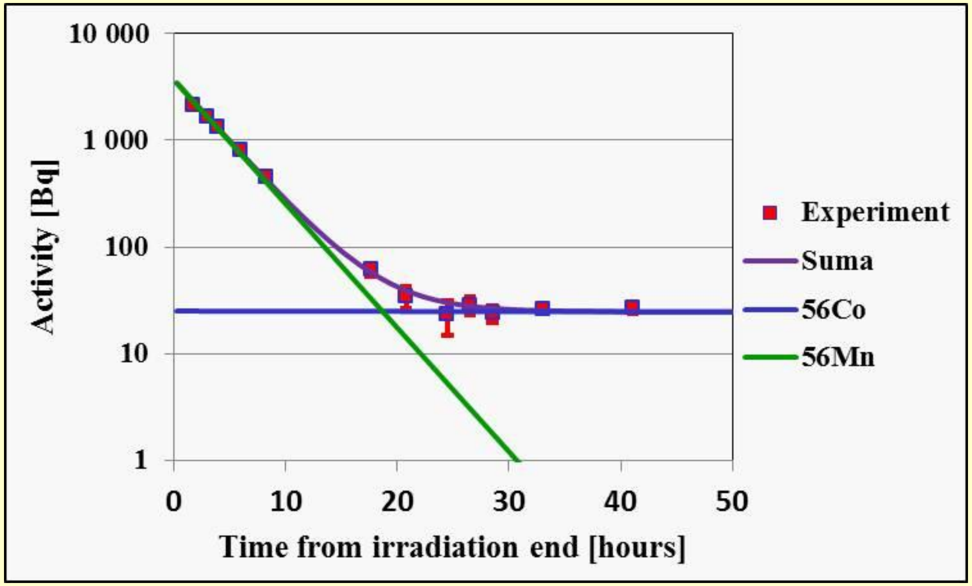
$^{56}Mn \rightarrow {}^{56}Fe \leftarrow {}^{56}Co$

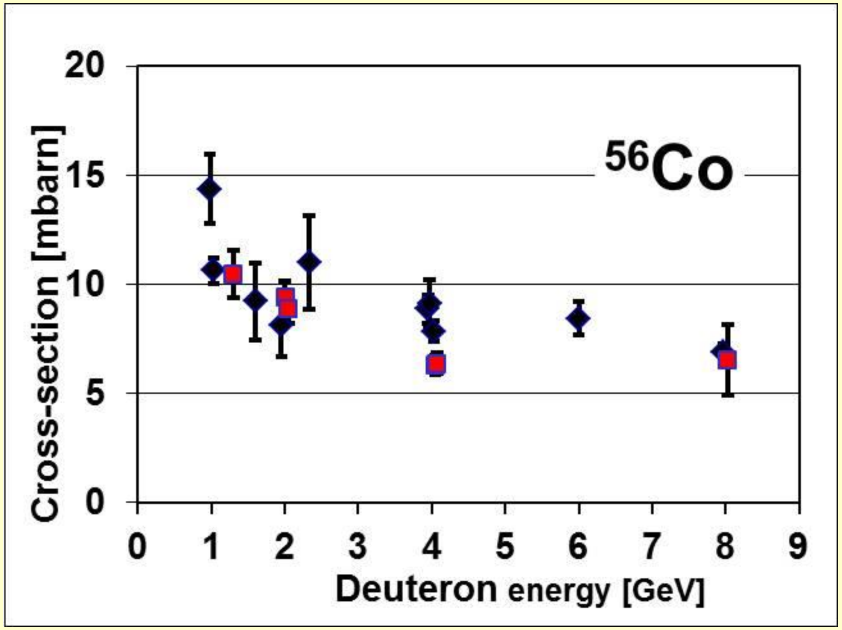
$T_{1/2}$ 2.6 h 1854.5 h

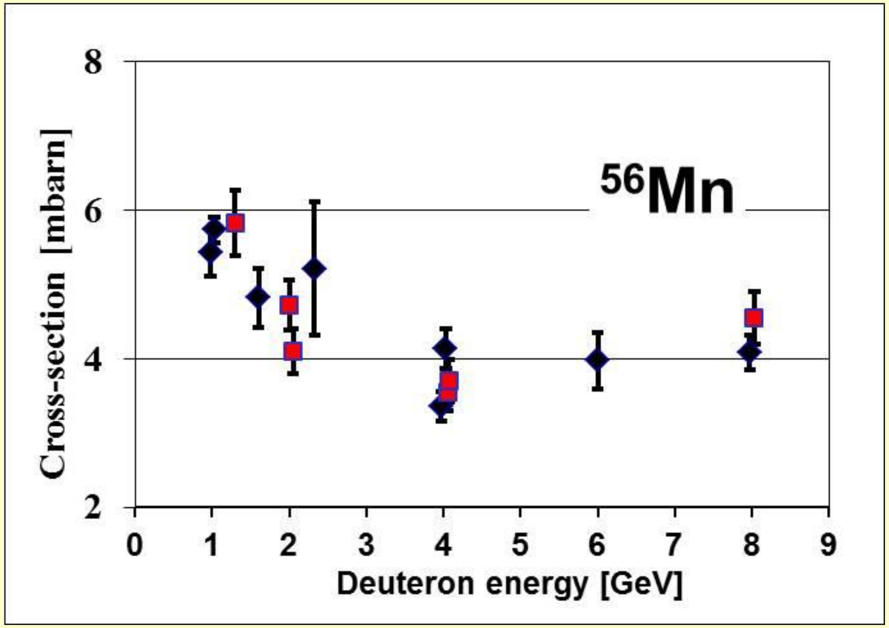
Gamma lines:

^{56}Co only: 1238.3 keV

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







Isomeric state

$^{44m}Sc \rightarrow {}^{44}Sc \rightarrow {}^{44}Ti$

$T_{1/2}$ 58.6 h 3.9 h

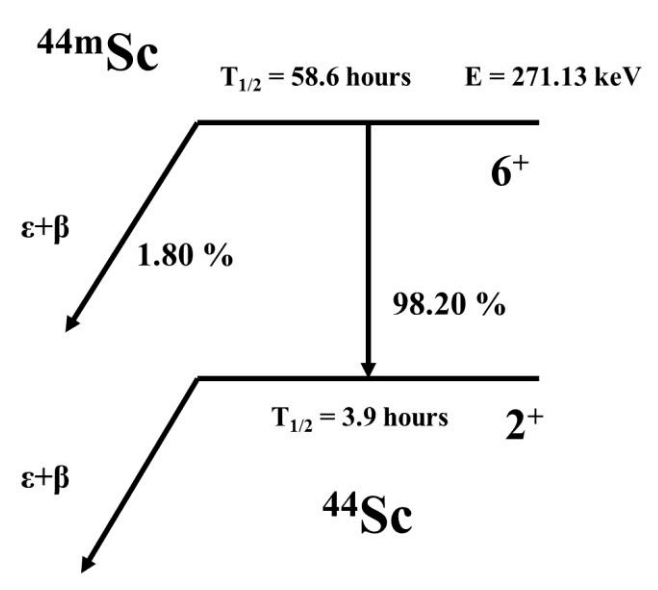
$T_{1/2}(^{44m}Sc) \gg T_{1/2}(^{44}Sc)$

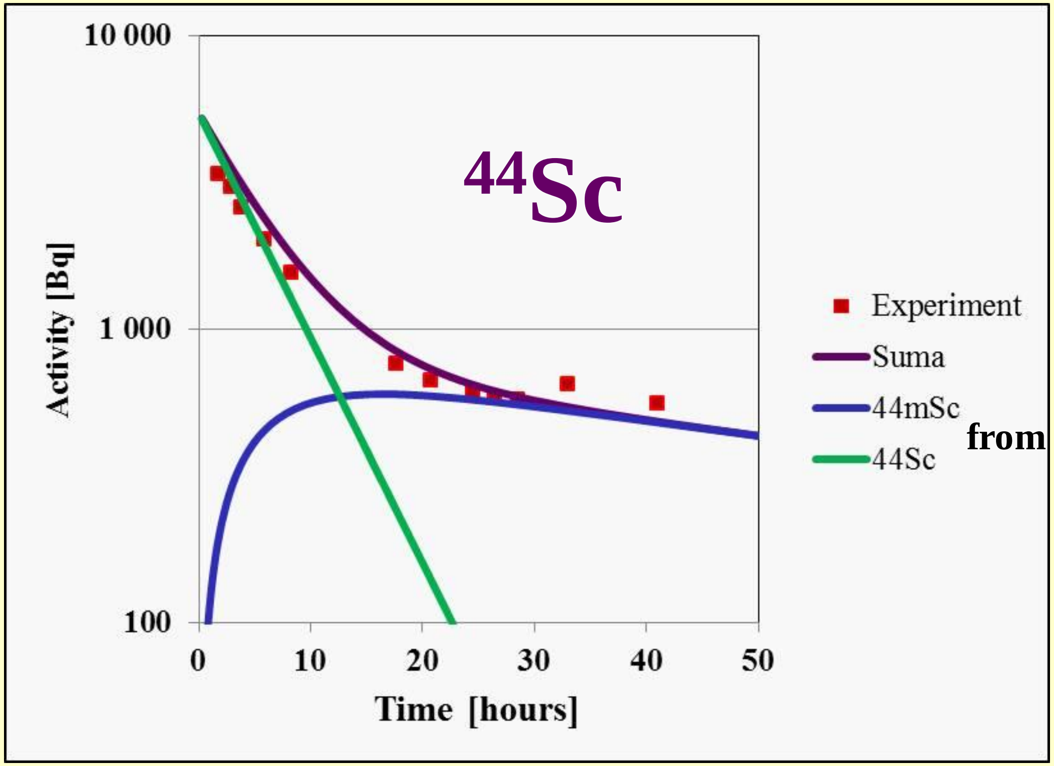
^{44m}Sc $N_1 = N_{01} e^{-\lambda_1 \cdot t}$

^{44}Sc $N_2 = N_{02} \cdot e^{-\lambda_2 \cdot t} + \frac{\lambda_1}{\lambda_1 - \lambda_2} \cdot N_{01} \cdot \left(e^{-\lambda_2 \cdot t} - e^{-\lambda_1 \cdot t}\right)$

$t \rightarrow \infty$ $N_2 = -\frac{\lambda_1}{\lambda_1 - \lambda_2} \cdot N_{01} e^{-\lambda_1 \cdot t}$

only N_{01} information

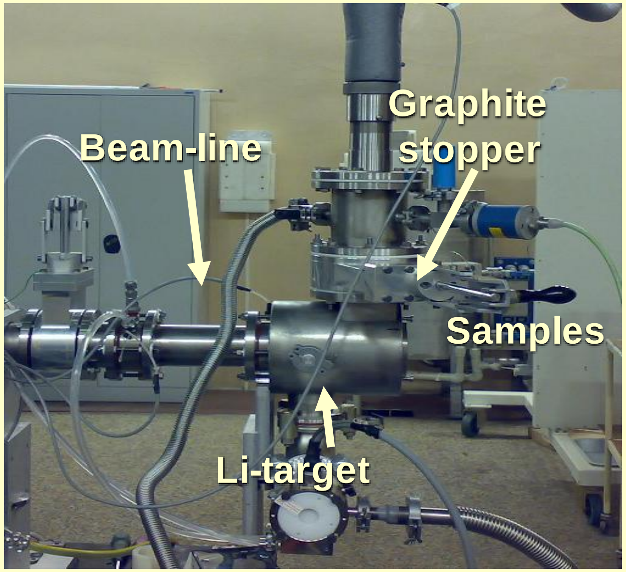




from

Measurement of neutron reaction cross-sections

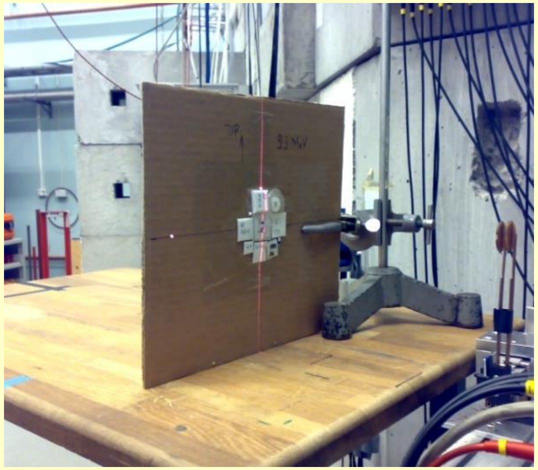
Quasi-monoenergetic neutron source:
protons from cyclotron + lithium target

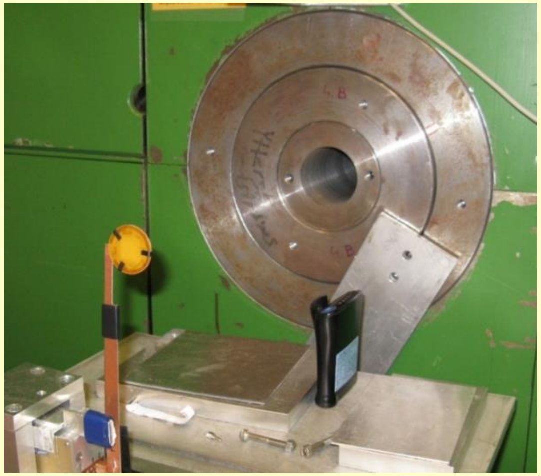


NPI ASCR Řež: Energy range 18 -37 MeV,
neutron intensity ~ 10^8 neutron cm^{-2} s^{-1}

TSL Uppsala: Energy range 25 – 180 MeV
neutron intensity ~ 10^5 neutron cm^{-2} s^{-1}

Advantage of two neutron sources: very wide energy range, partial overlap – better estimation of systematical uncertainties





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Test of single-crystal diamond detectors for fluency measurements

$n+^{12}C$	$\rightarrow ^{9}Be+^{4}He$	-5.70 MeV
	$\rightarrow n'+^{12}C$	-4.44 MeV
	$\rightarrow n'+3a$	-7.27 MeV
	$\rightarrow p+^{12}B$	-12.59 MeV
	$\rightarrow d+^{11}B$	-13.73 MeV

NPI neutron source was used
(80 hours of irradiation)

Size: 4.7x4.7x0.5 mm^3

$E_{deposition} = Q + E_n - E_{n'}$

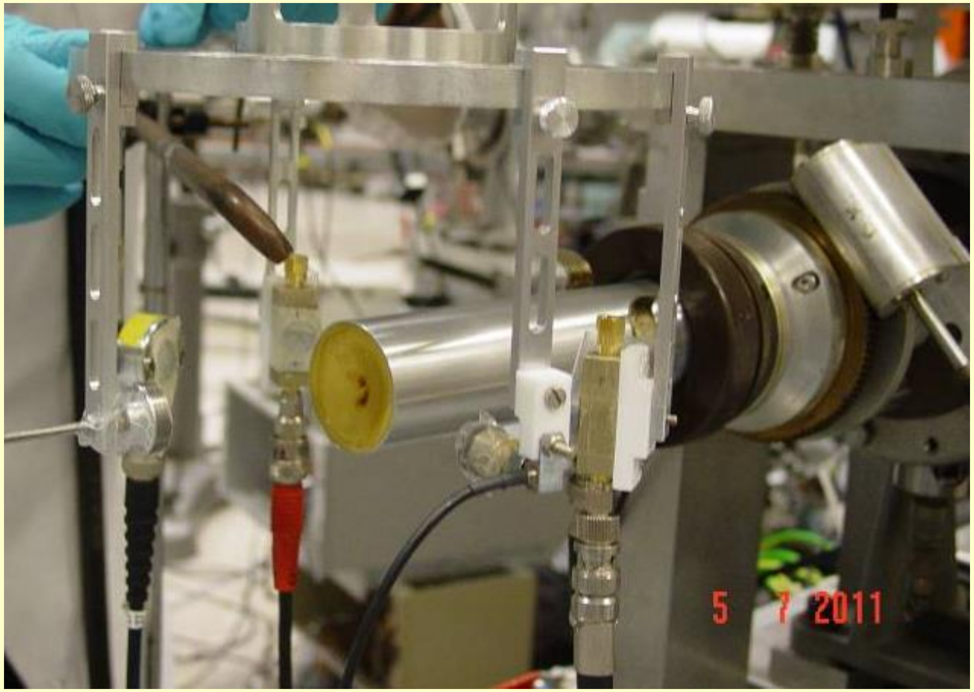
Sharp if no n' emitted:

E_n spectrometer

Antonín Krása
Arjan Plompen

(IRMM-JRC-EC)

ERINDA – PAC 2/3



from Arjan Plompen presentation

Yttrium cross-section measurement (ERINDA project)

Only reactions (n,2n) and (n,3n) for energy up to 38 MeV, systematic study of yttrium reactions using the NPI neutron source were done during last two years

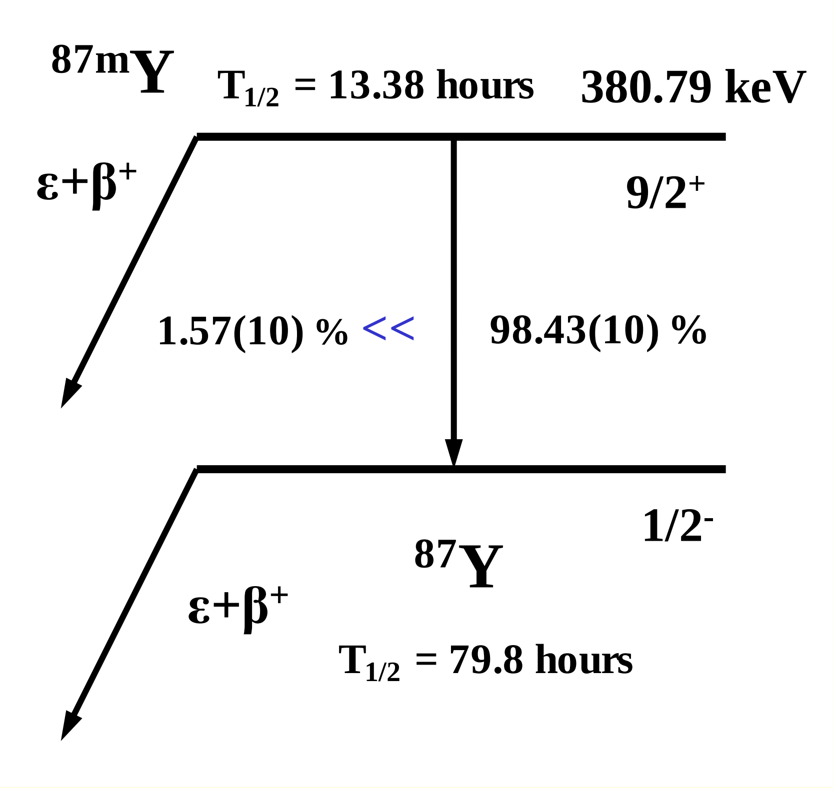
Yttrium – good material for activation detector
Used by "Energy+Transmutation" collaboration

Very scare data about cross-sections

No data about cross-sections of isomeric state production

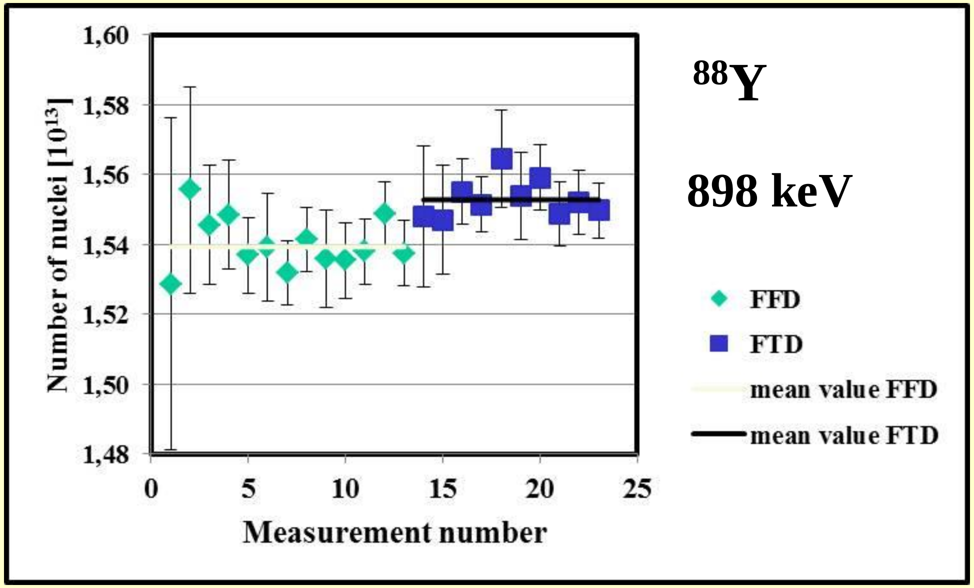
Long irradiation, intensive beam, only limited number of samples → possibility to measure yttrium sample many times to study systematic uncertainties of gamma measurements

Important - isomeric state ^{87m}Y study



Reaction (n,3n) - production of isomeric and ground state of ^{87}Y

Accuracy of gamma spectroscopy measurement



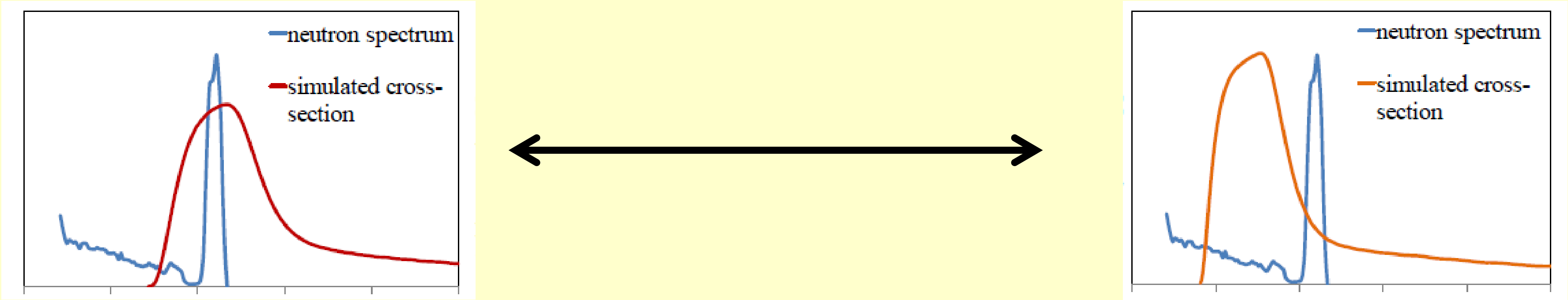
Source detector distance – **50 mm**

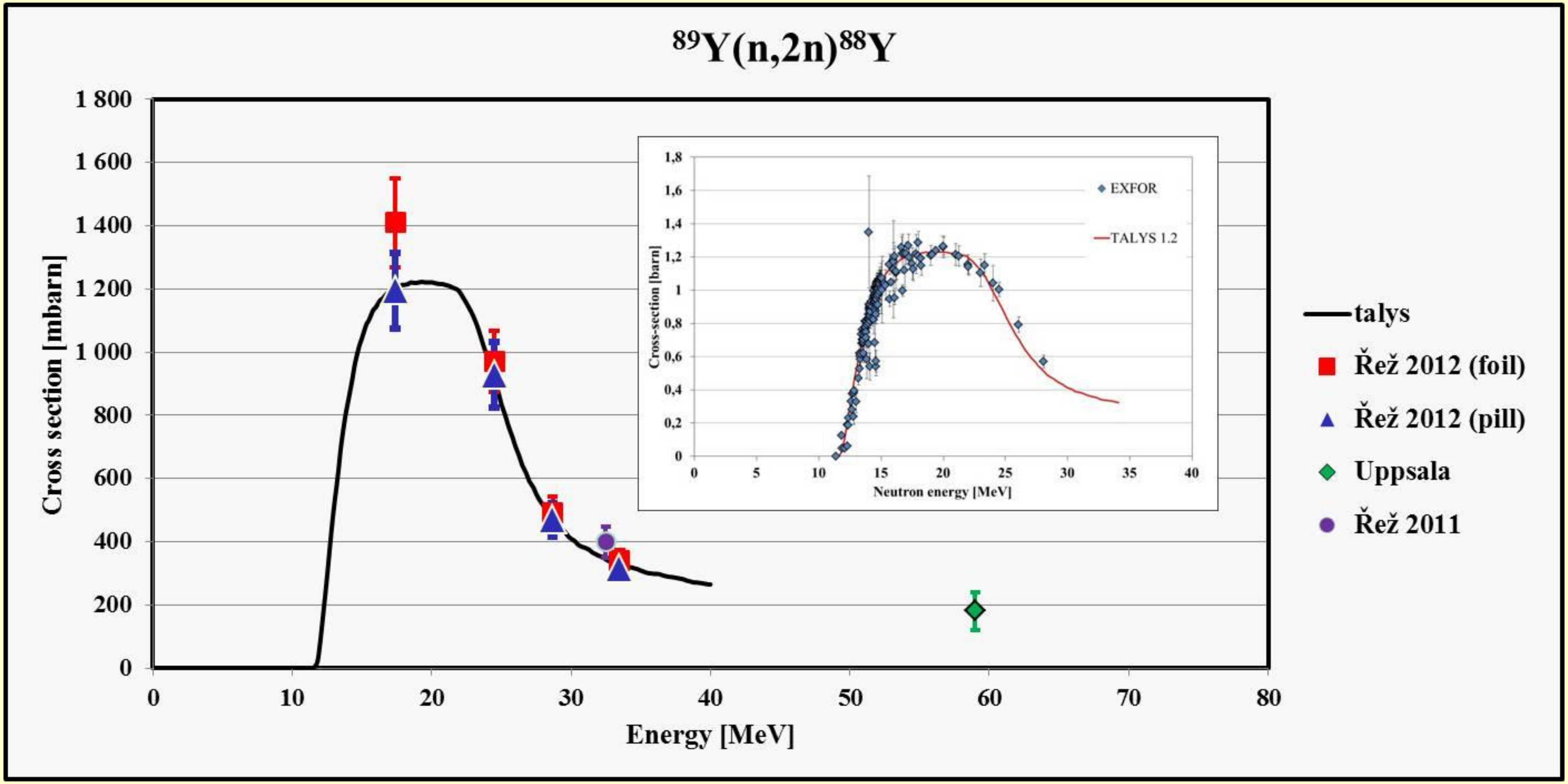
Yttrium – thicker sample (~ mm) →
if different side facing to the detector
→ small difference:

N(FFD) = 1.539(3)·10^{13}
N(FTD) = 1.553(3)·10^{13}
N(all) = 1.546(2)·10^{10}

difference
~ 0.9 %

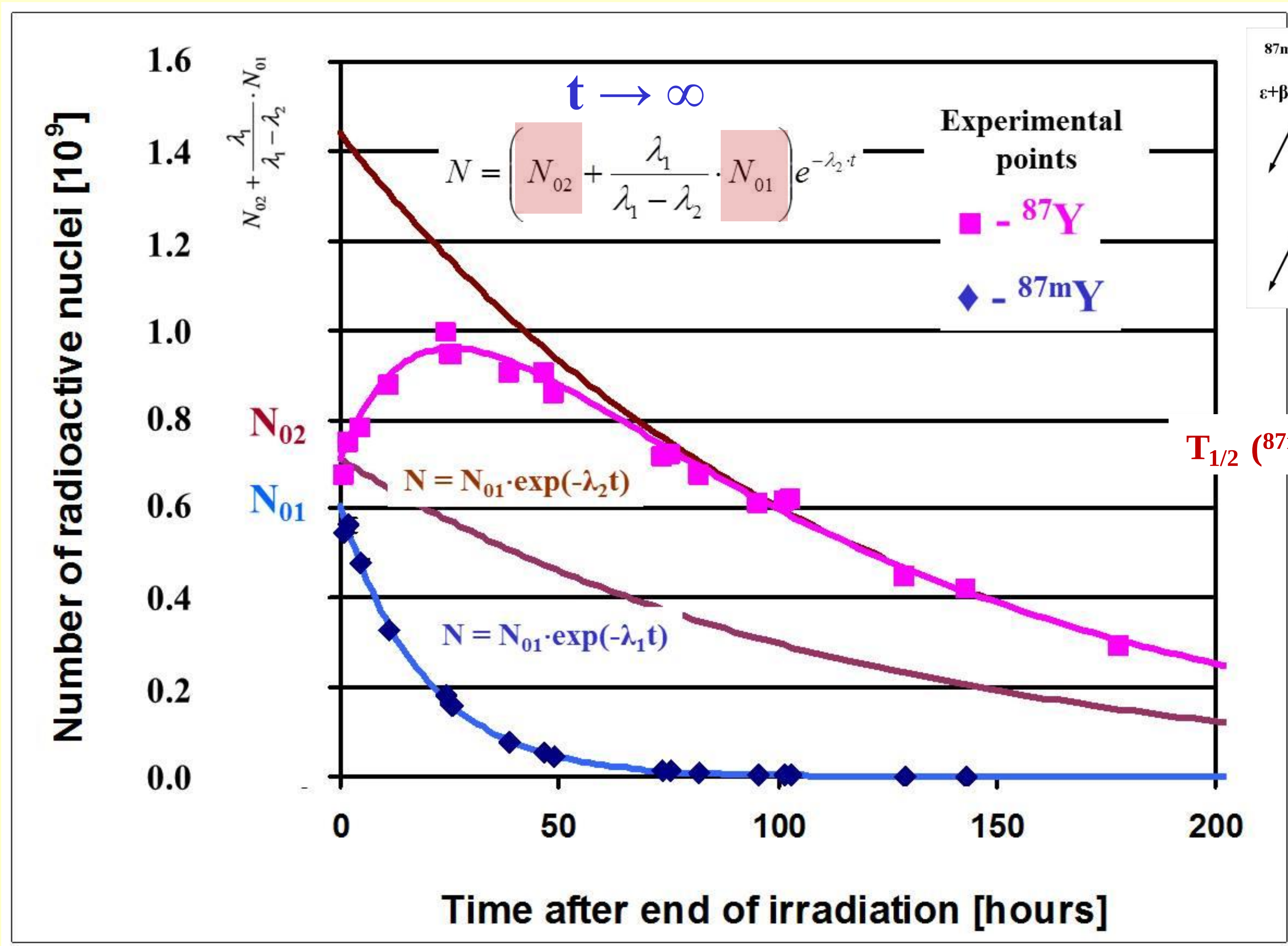
Phenomena is quickly decreasing
with bigger source detector distances

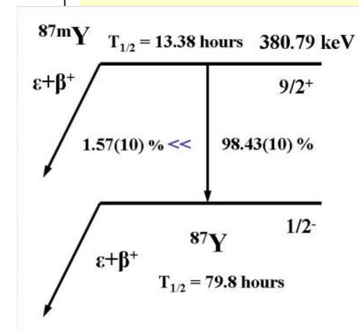

neutron spectrum
simulated cross-section
neutron spectrum
simulated cross-section


89Y(n,2n)88Y
Cross section [mbarn]
Energy [MeV]
0
200
400
600
800
1 000
1 200
1 400
1 600
1 800
0
10
20
30
40
50
60
70
80
Cross-section [barn]
Neutron energy [MeV]
EXFOR
TALYS 1.2
talys
Řež 2012 (foil)
Řež 2012 (pill)
Uppsala
Řež 2011

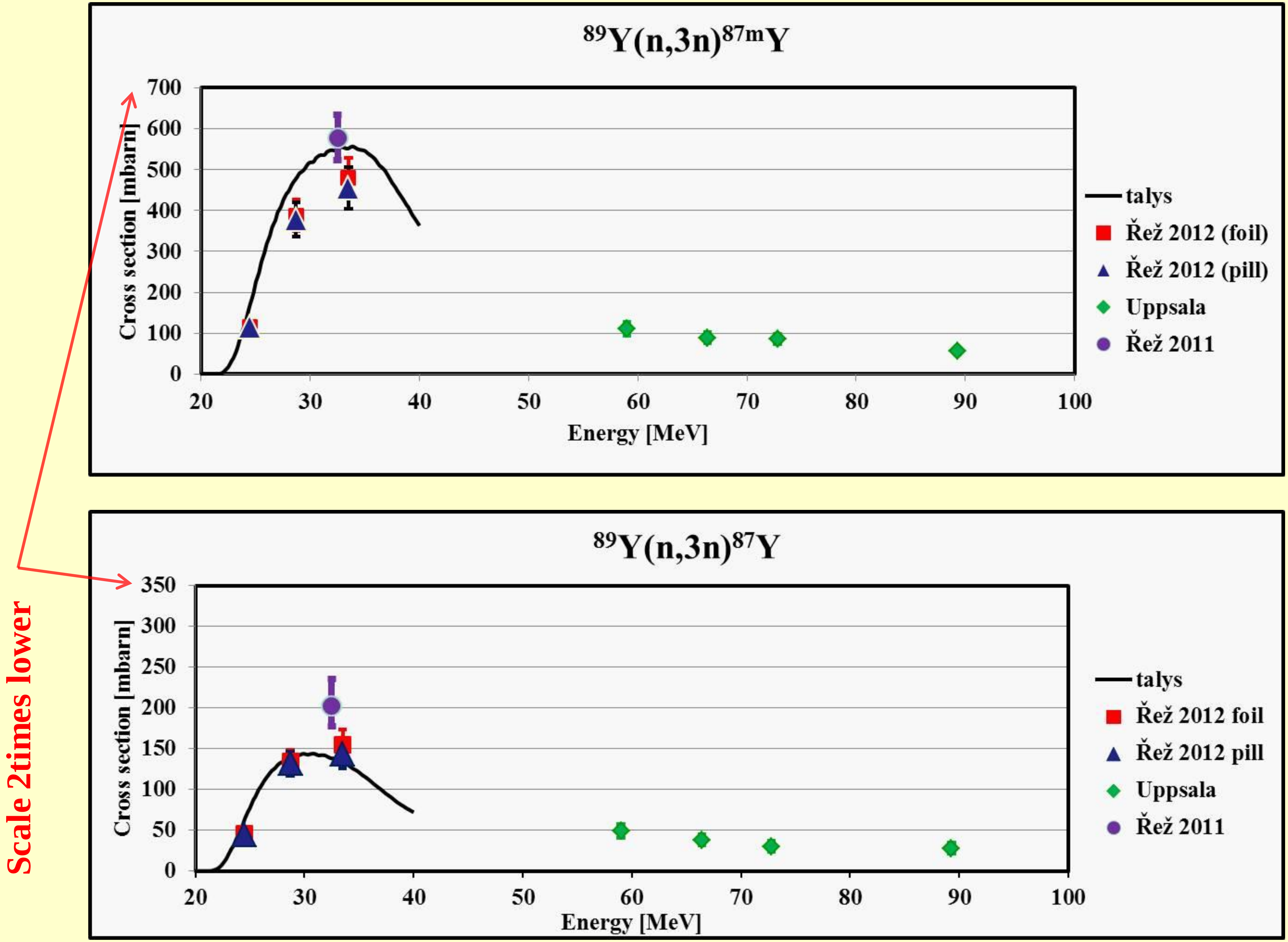
87mY $N_1 = N_{01} e^{-\lambda_1 \cdot t}$

87Y $N_2 = \left(N_{02} + \frac{\lambda_1}{\lambda_1 - \lambda_2} \cdot N_{01} \right) e^{-\lambda_2 \cdot t} - \frac{\lambda_1}{\lambda_1 - \lambda_2} \cdot N_{01} e^{-\lambda_1 \cdot t}$





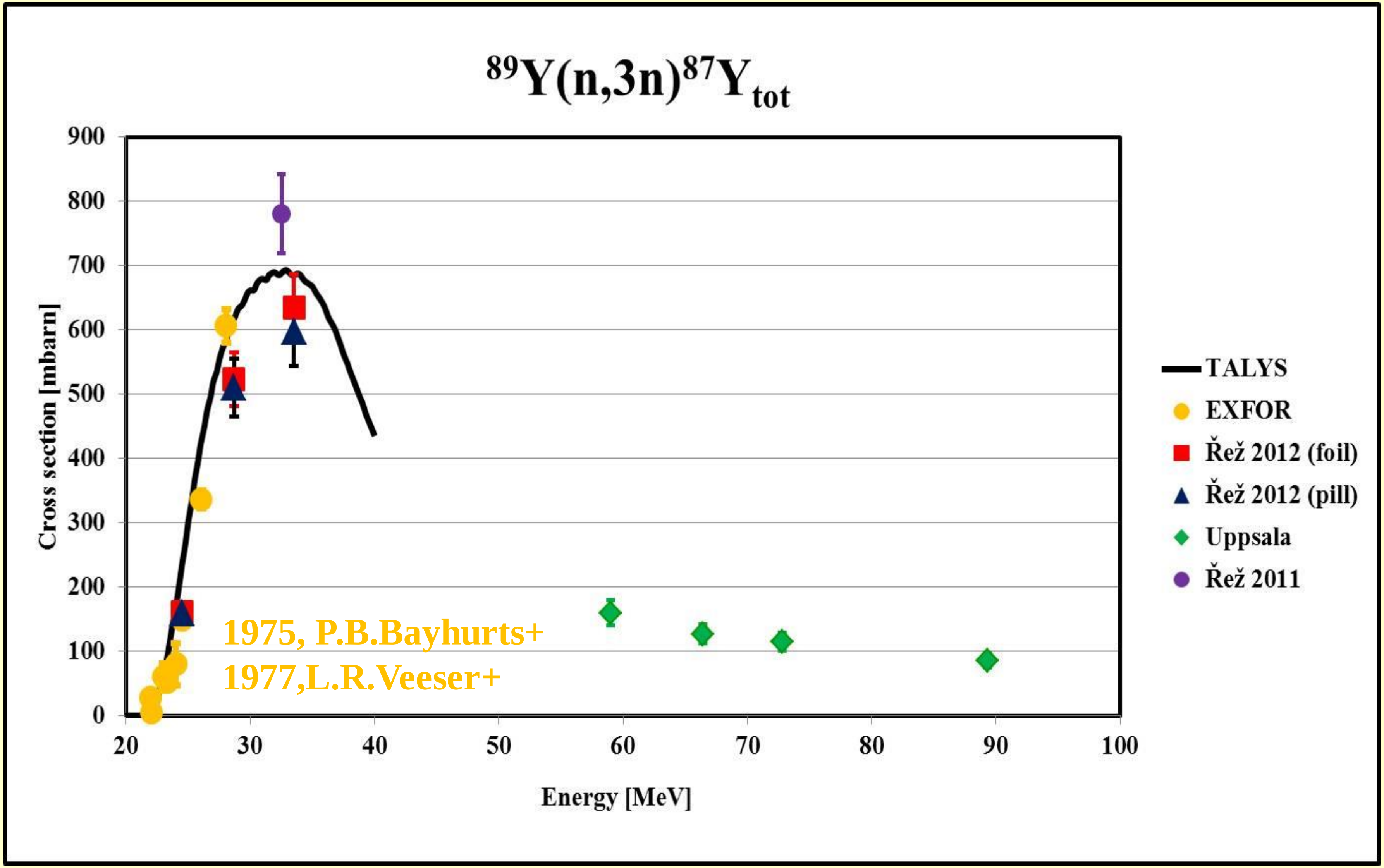
$T_{1/2}$ (^{87m}Y) << $T_{1/2}$(^{87}Y)



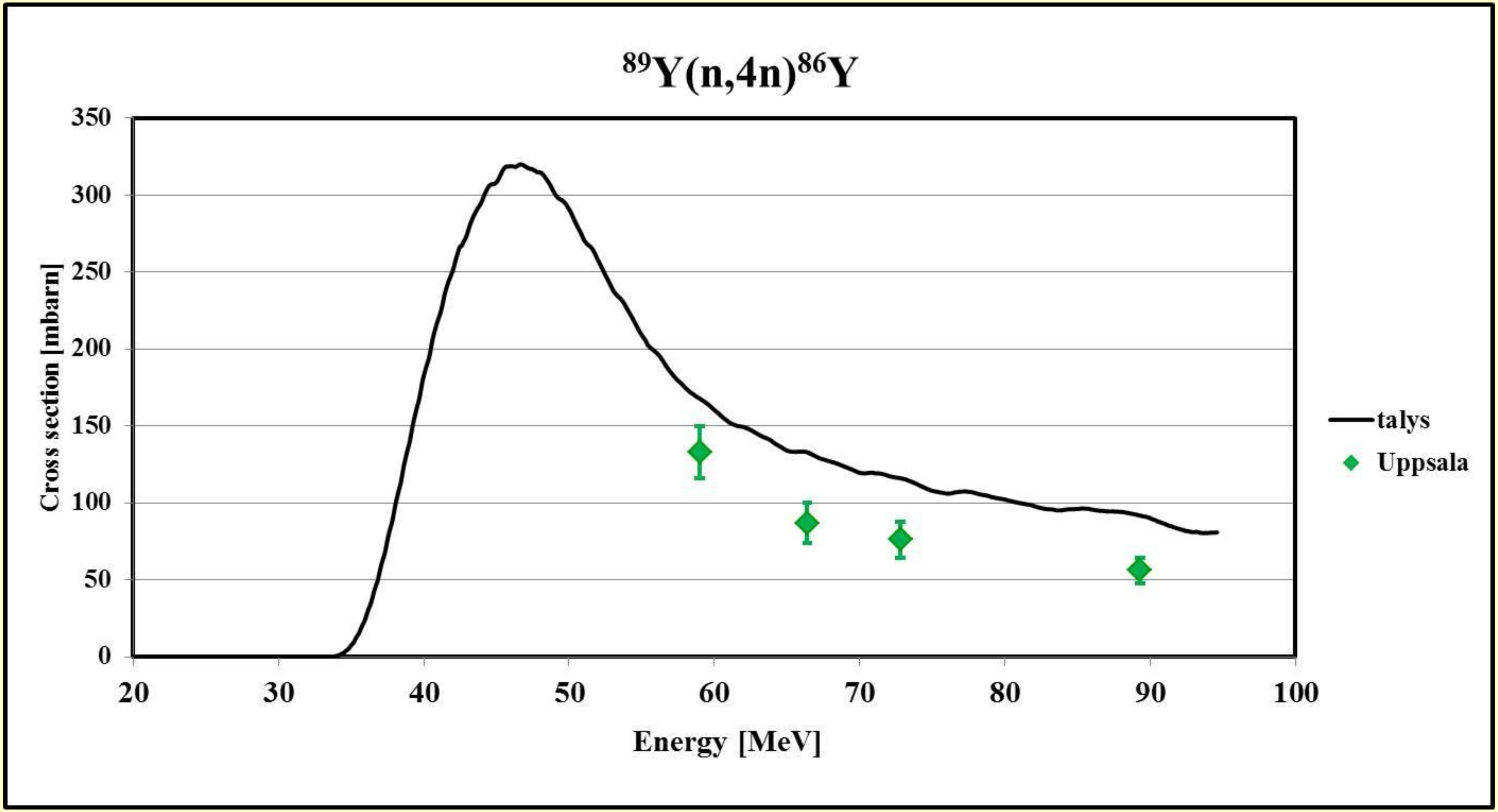
$^{89}Y(n,3n)^{87m}Y$
Cross section [mbarn]
Energy [MeV]
talys
Řež 2012 (foil)
Řež 2012 (pill)
Uppsala
Řež 2011
$^{89}Y(n,3n)^{87}Y$
Cross section [mbarn]
Energy [MeV]
talys
Řež 2012 foil
Řež 2012 pill
Uppsala
Řež 2011
Scale 2times lower

Total cross section of ^{87}Y production

ERINDA Rez
EFNUDAT Uppsala

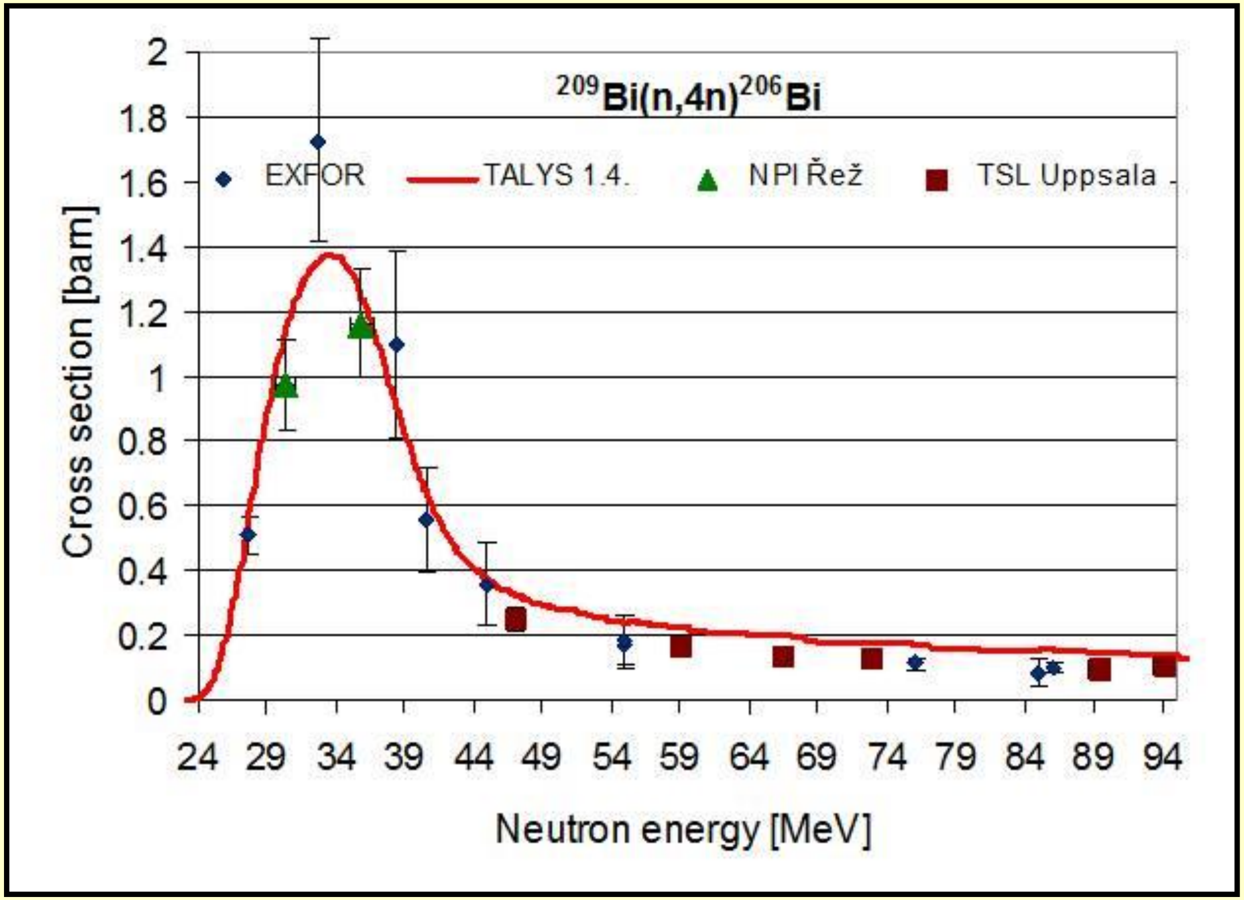


Cross section of ^{86}Y production EFNUDAT Uppsala

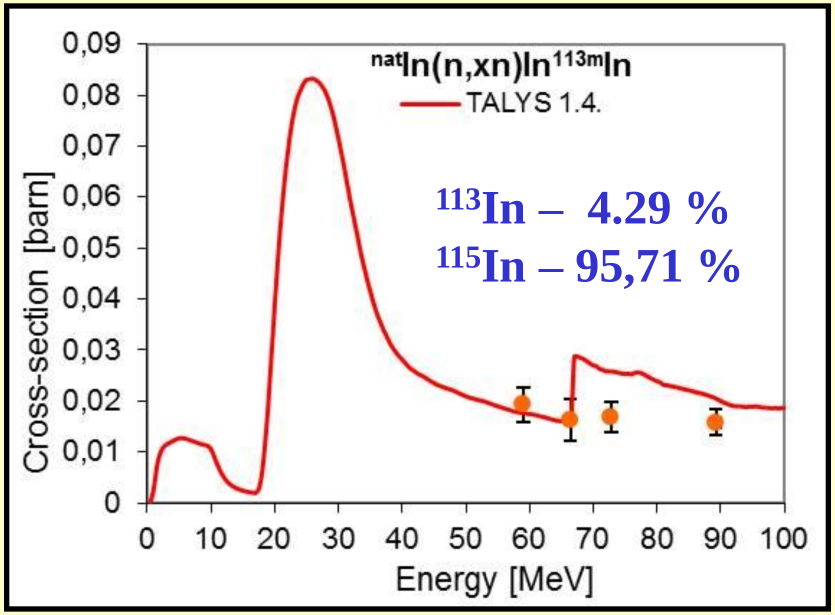


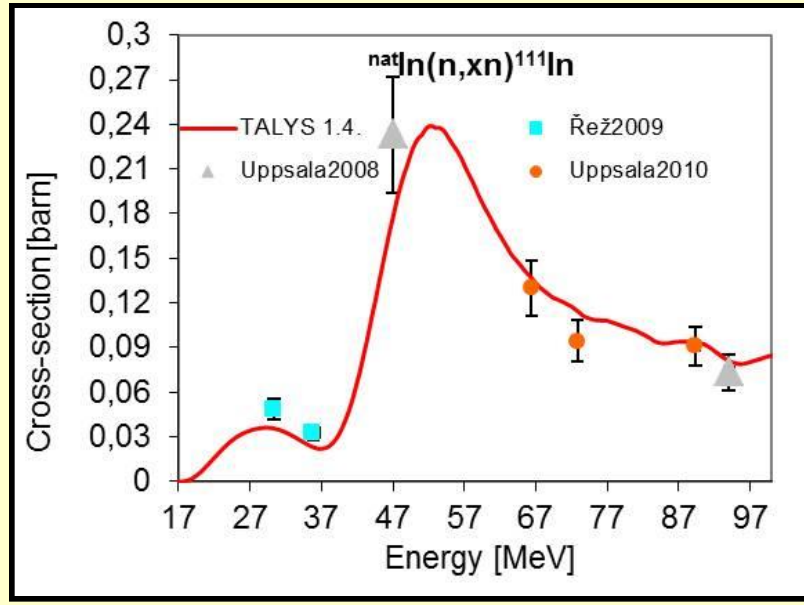
Systematic study of neutron cross sections (EFNUDAT)

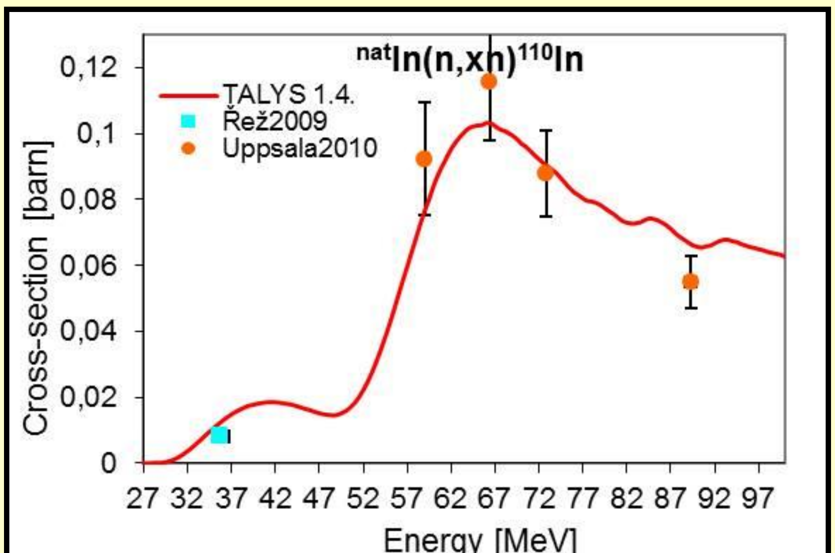
We measured threshold reactions on Au, Al, Bi, In, Ta, Ti, Y commonly used for such purposes and we also studied other materials: Cu, Fe, I, Mg, Ni, Zn.

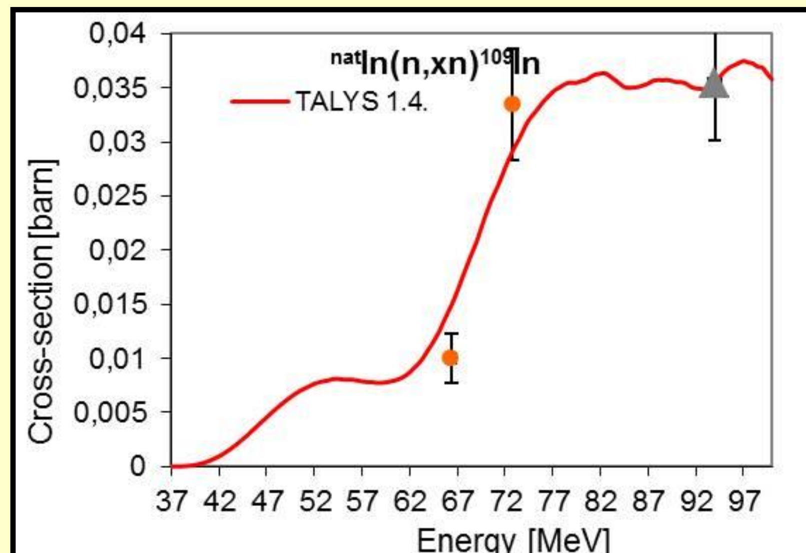


Comparison of cross-sections (n,xn) reactions on natural indium with TALYS

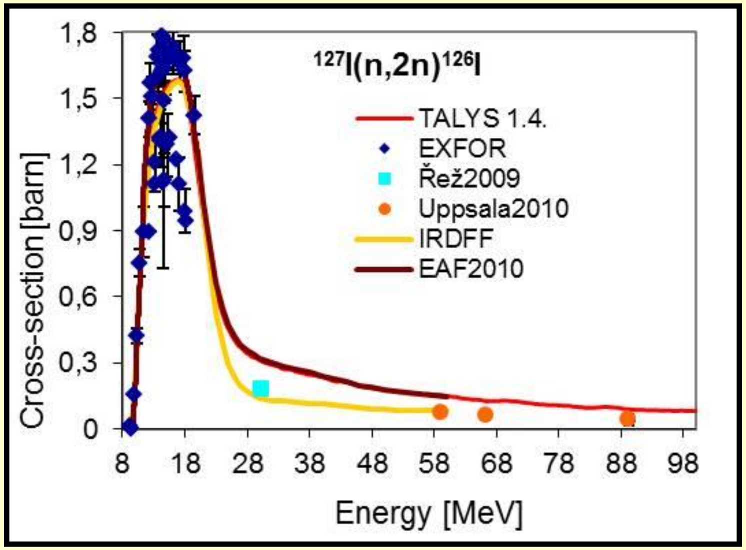


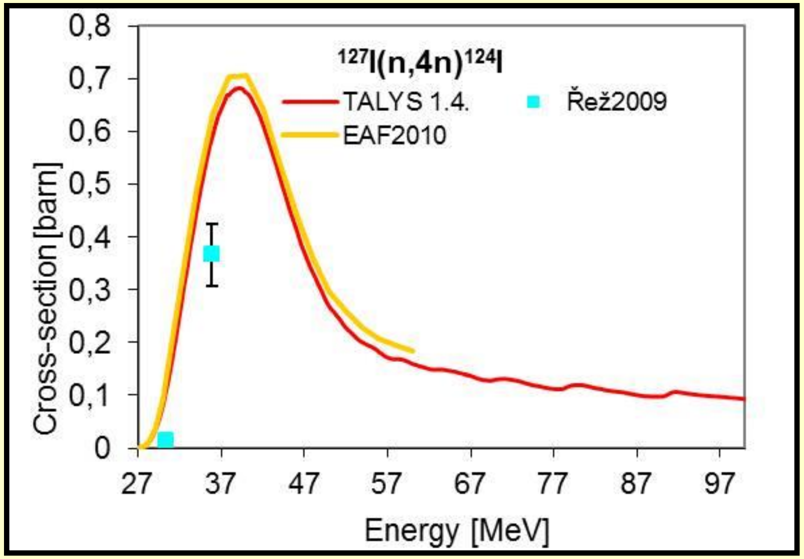


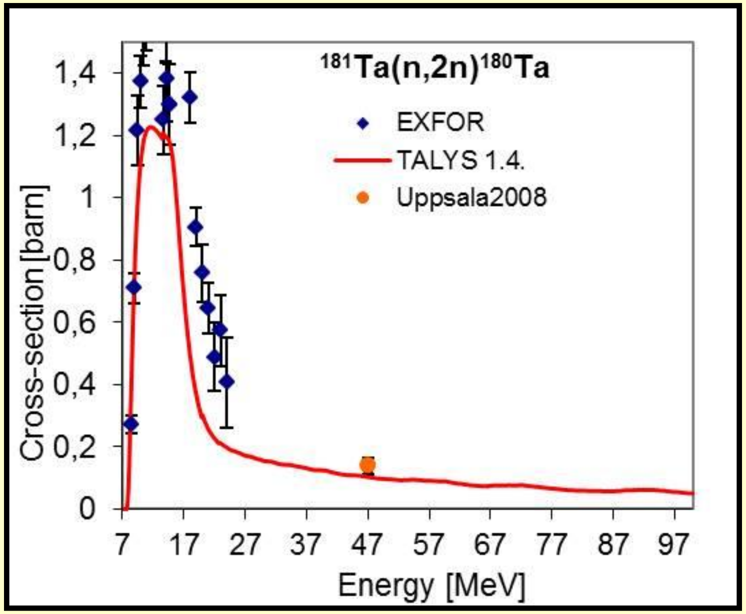


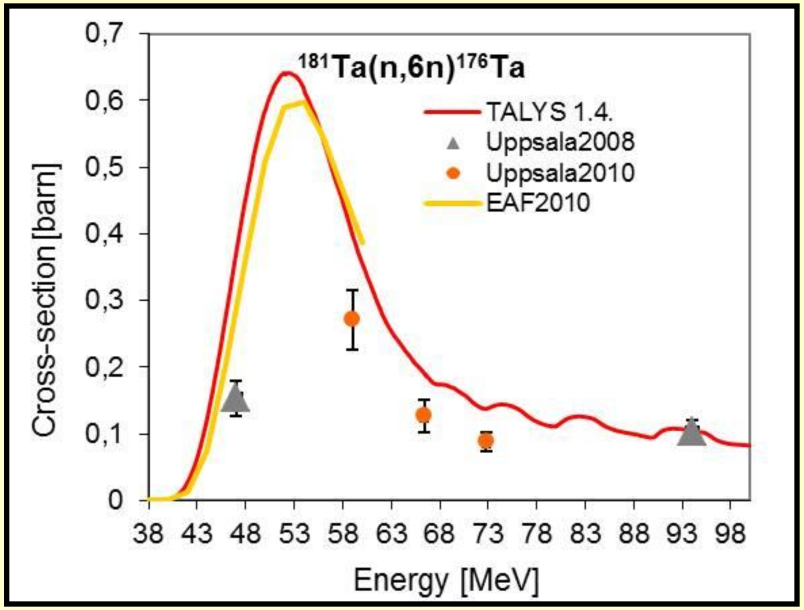


Comparison of cross-sections (n,xn) reactions on iodine and tantalum with EXFOR, TALYS and libraries of evaluated data

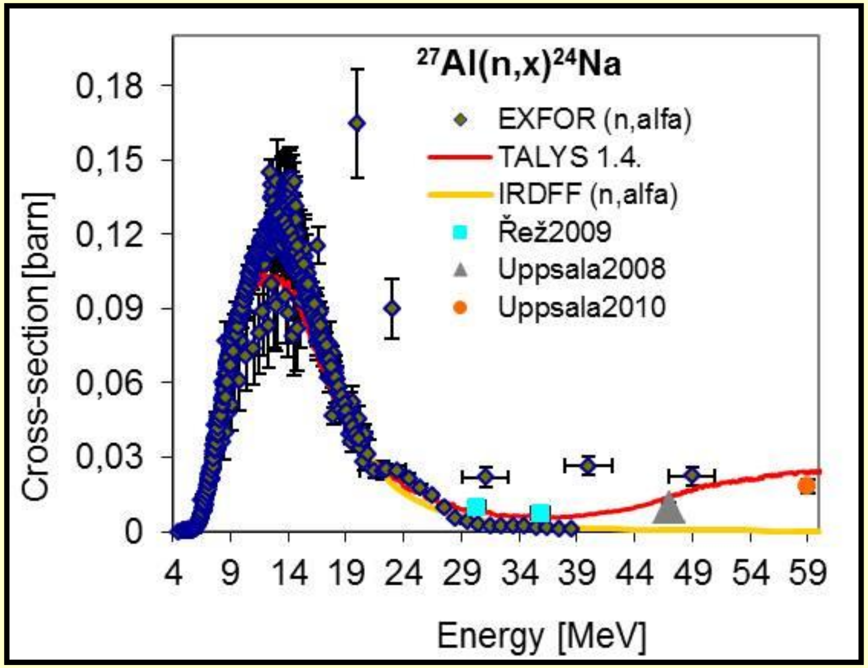


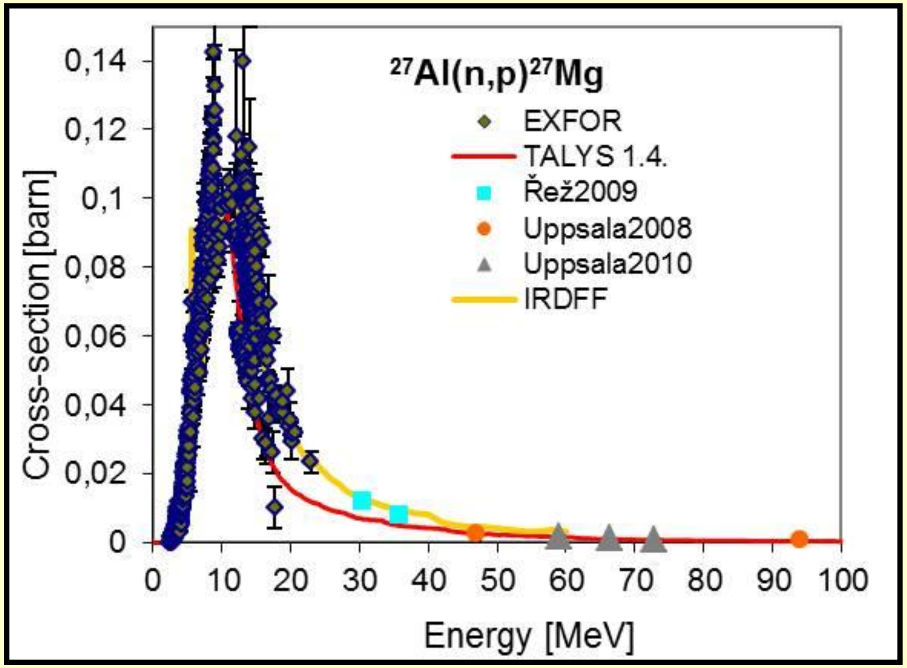






Comparison of cross-sections (n,x) reactions on aluminum with EXFOR, TALYS and libraries of evaluated data





Review of obtained data can be find in journal:

Nuclear Instruments and Methods in Physics Research - Vol.726, (2013) 84-90

Nice data obtained thanks to EFNUDAT, ERINDA and Řež and Uppsala neutron sources

CHANDA will be next opportunity

Conclusions

- Experimental nuclear data for different applications (fast breeder reactors, Accelerator Driven Transmutation systems, fusion systems, spallation sources ….
- European transnational access projects (European neutron sources for European users). Present ERINDA and new CHANDA. Neutron sources of NPI of ASCR Řež are open for users.
- Benchmark studies by means different set-ups irradiated by relativistic proton and neutron beams. “Energy+Transmutation of RAW” collaboration uses Nuclotron beams (JINR Dubna).
- The reactions of relativistic deuterons important for beam monitoring were studied using Nuclotron deuteron beam.
- The quasimonoenergetic neutron sources are good tool for neutron cross-sections measurements, perfect knowledge of these cross-sections is important for measurements of neutron field by means of activation detectors. Neutron reactions on yttrium samples were studied.
- The understanding of all sources of systematic uncertainties is necessary
- Such cross-section data are very important step to more effective usage of activation neutron detectors - we will continue such measurements