• Nuclear Physics Institute, Academy of Sciences of Czech Republic
• Department of Nuclear Reactors, Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague

Cross-section Measurements of (n,xn) Threshold Reactions

O. Svoboda, A. Krása, M. Majerle, J. Vrzalová, V. Wagner

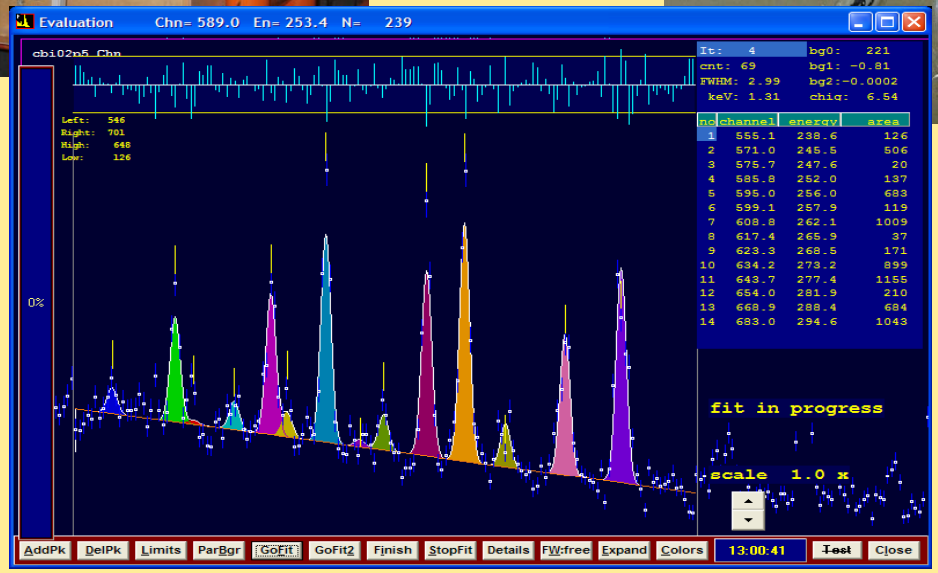
EFNUDAT – scientific workshop on Slow and Resonance Neutrons
23 – 25 September 2009 Budapest

Outline

- **Motivation for σ measurements**
- **Requirements for σ measurements**
- **TSL Uppsala facility**
- **Cyclotron in Řež facility**
- **Evaluation process**
- **Preliminary results**
- **Conclusion**

Motivation for σ measurements – E+T

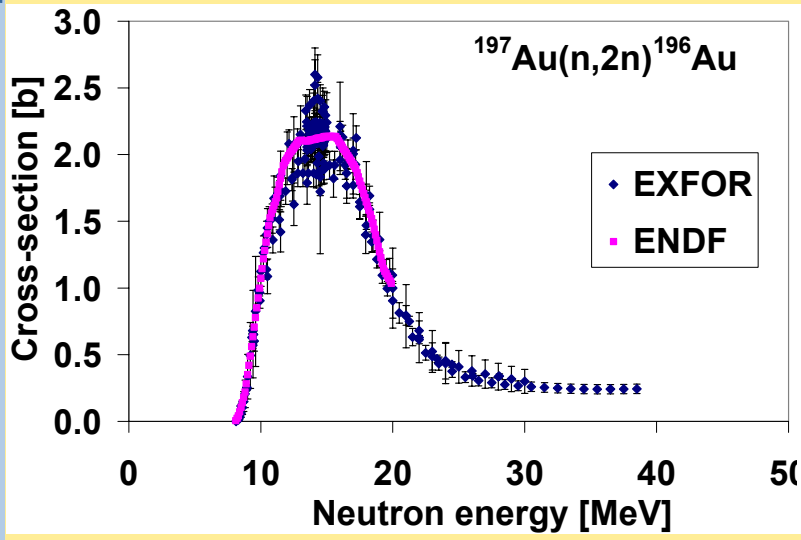
- Motivation for σ measurements
  - *Energy plus Transmutation*
  - EXFOR
- Requirements
- TSL Uppsala
- Cyclotron Řež
- Evaluation
- Results
- Conclusion

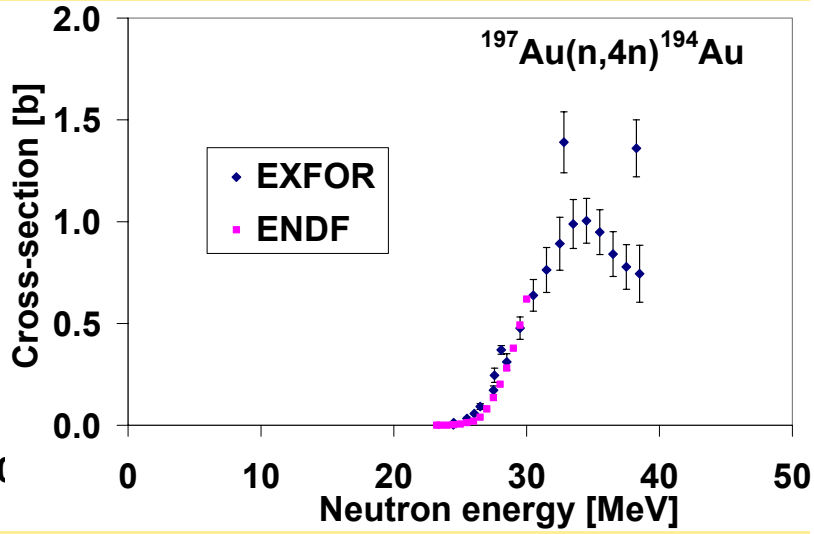


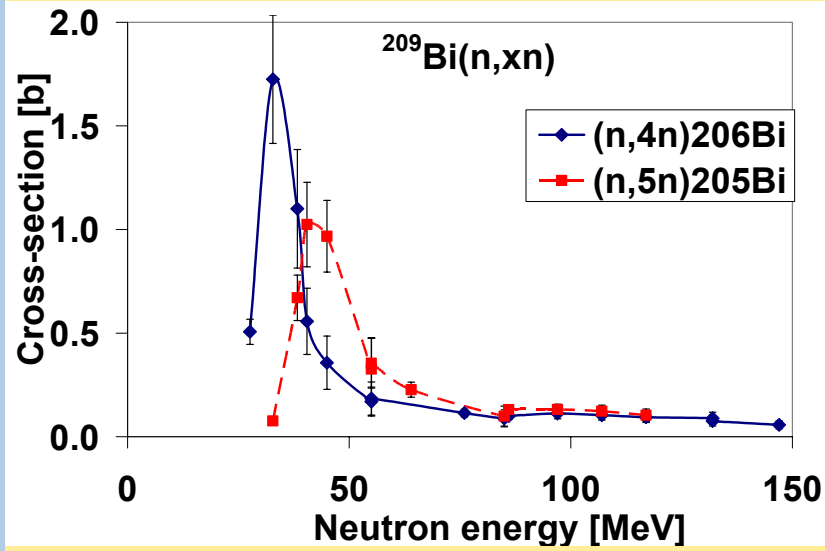
$$N_{yield} = \frac{S_p \cdot C_{abs} \cdot C_{irr}}{I_\gamma \cdot \varepsilon_P(E) \cdot Coi \cdot C_{area}} \frac{t_{real}}{t_{live}} \frac{1}{m_{foil}} \frac{e^{(\lambda \cdot t_0)}}{1 - e^{(-\lambda \cdot t_{real})}} \frac{\lambda \cdot t_{irr}}{1 - e^{(-\lambda \cdot t_{irr})}}$$

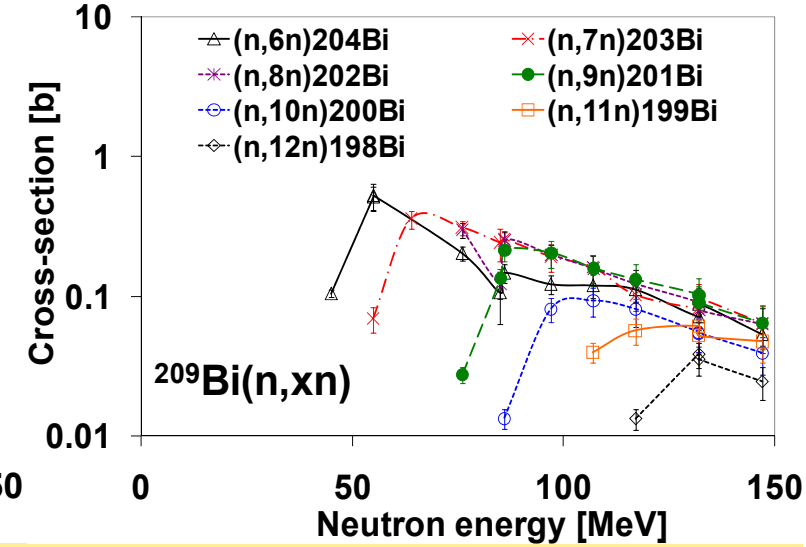
EXFOR cross-sections

- Motivation for σ measurements
  - Energy plus Transmutation
  - *EXFOR*
- Requirements
- TSL Uppsala
- Cyclotron Řež
- Evaluation
- Results
- Conclusion





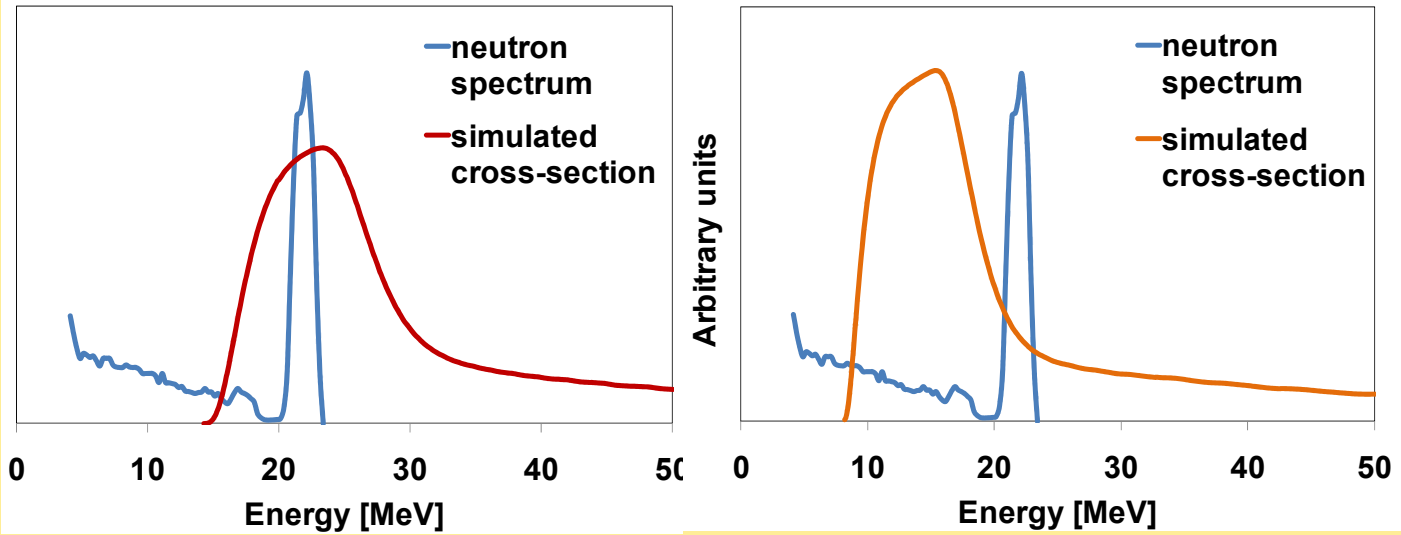




Requirements for σ measurements

Requirements for using activation method of measurement:

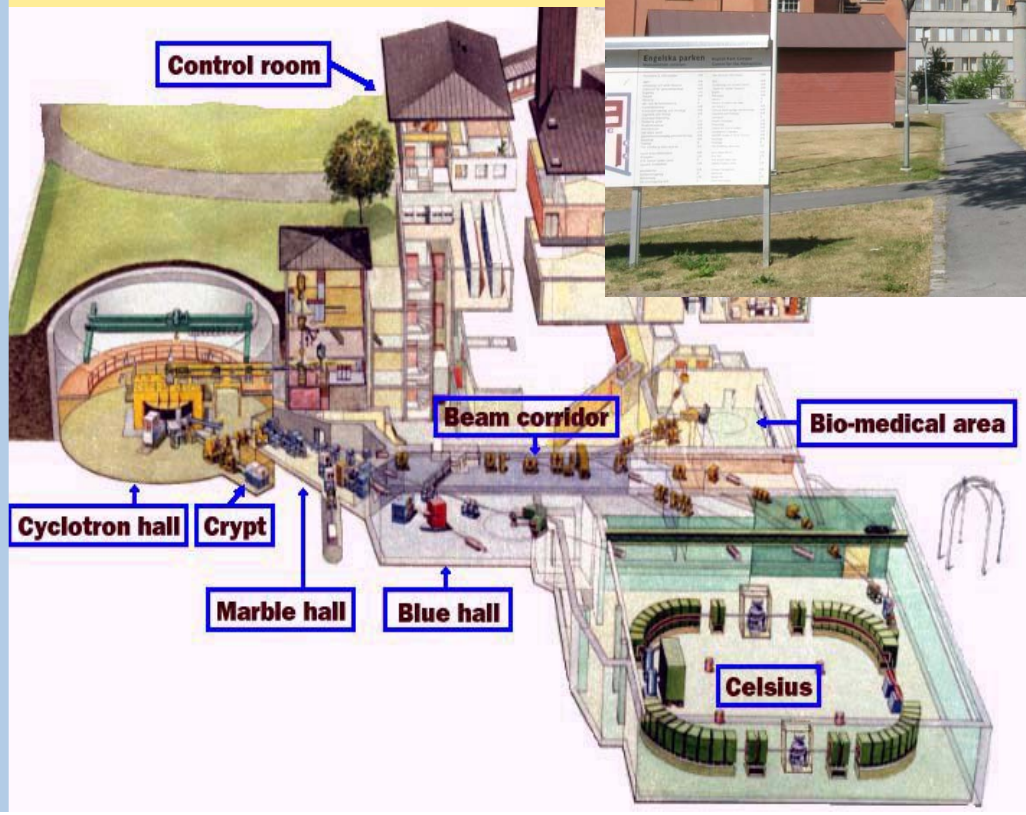
- high energy neutron source with good intensity
- (quasi)monoenergetic neutrons with well known spectrum
- pure monoisotopic samples
- good spectroscopic equipment: γ and X-rays detectors
- knowledge about the corrections on beam fluctuation, self-absorption, non-point like emitters…



TSL Uppsala – site

- Motivation for σ measurements
- Requirements
- TSL Uppsala
  - *Site*
  - Blue hall
  - Irradiations
- Cyclotron Řež
- Evaluation
- Results
- Conclusion

User-oriented facility…



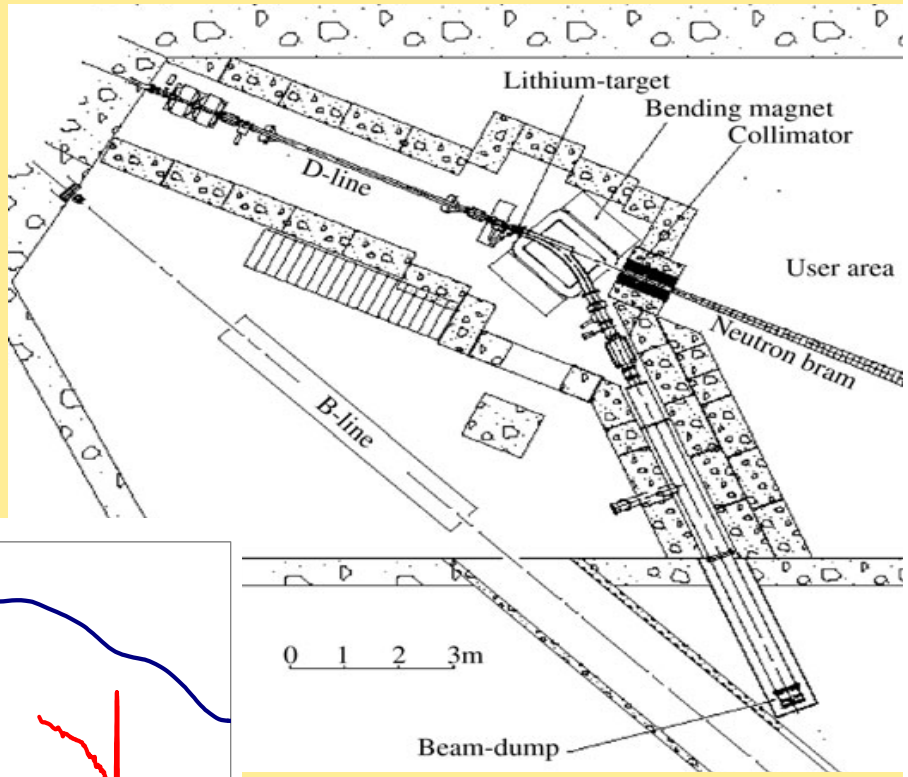
Protons 25 - 180 MeV

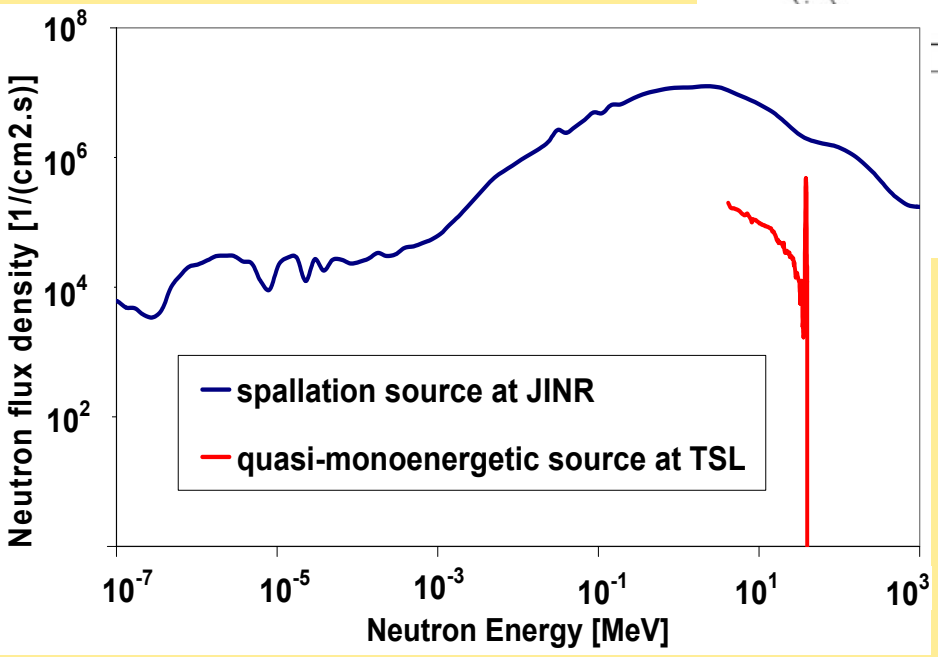
Neutron spectra from $^{7}Li(p,n)^{7}Be$ reaction well known for proton energies 25, 50, and 97 MeV

TSL Uppsala – Blue hall

- Motivation for σ measurements
- Requirements
- TSL Uppsala
  - Site
  - *Blue hall*
  - Irradiations
- Cyclotron Řež
- Evaluation
- Results
- Conclusion

Experimental setup in the Blue hall





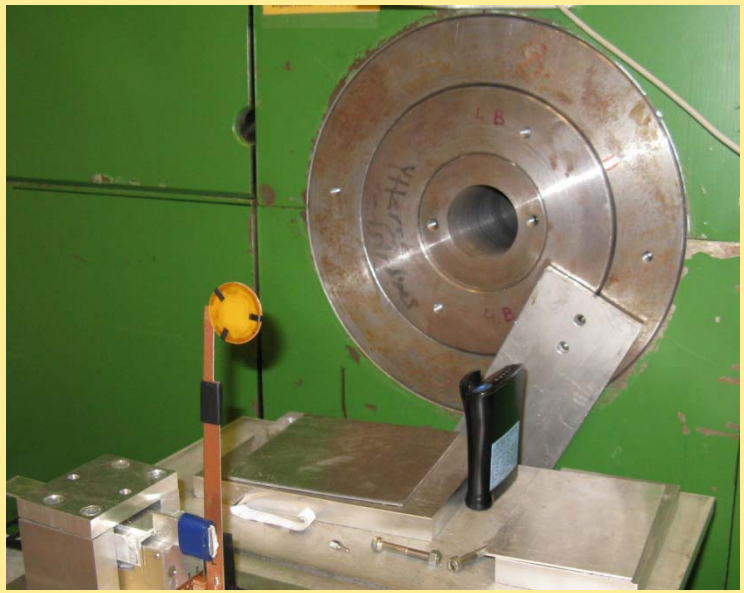
Neutron spectra comparison

TSL Uppsala - irradiations

Proton beam energy [MeV]	25	50	97
^{7}Li-target thickness [mm]	2	4	8.5
Proton beam current [μA]	5	5	2
Average energy of peak neutrons [MeV]	22	47	94
Fraction of neutrons in the peak [%]	50	39	41
Peak neutron flux density [10^{5} cm^{-2} s^{-1}]	6	13	14.5

8 hours irradiation at each energy

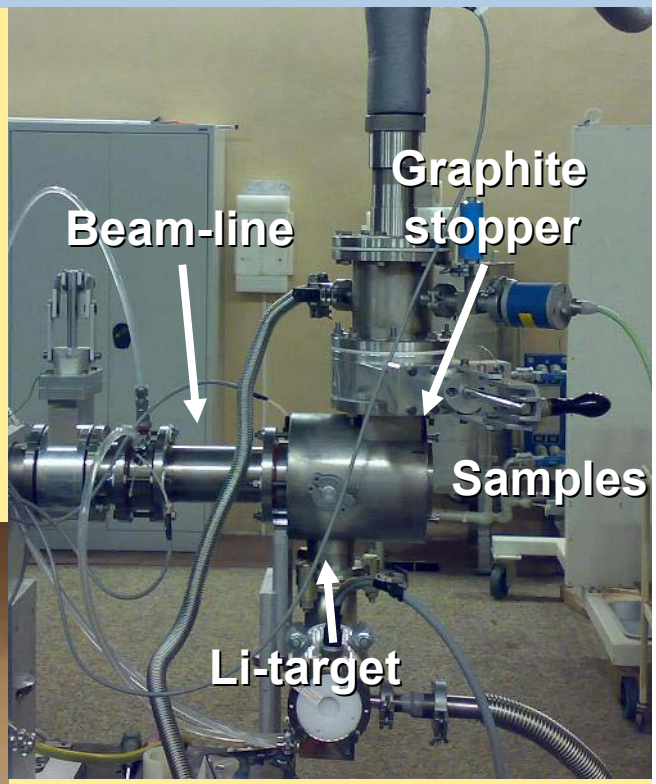
June 2008, supported from the EFNUDAT program



Cyclotron Řež

- Motivation for σ measurements
- Requirements
- TSL Uppsala
- Cyclotron Řež
  - *Facility*
  - Diodes
- Evaluation
- Results
- Conclusion

- Protons 18 – 37 MeV on ^{7}Li target
- Neutron spectra known for 20, 25, 30, and 35 MeV – Y. Uwamino et al., NIM A389 (1997) 463
- High neutron intensities: 10^{8} cm^{-2} s^{-1}
- Well equipped spectroscopic laboratory (NSD-NPI)



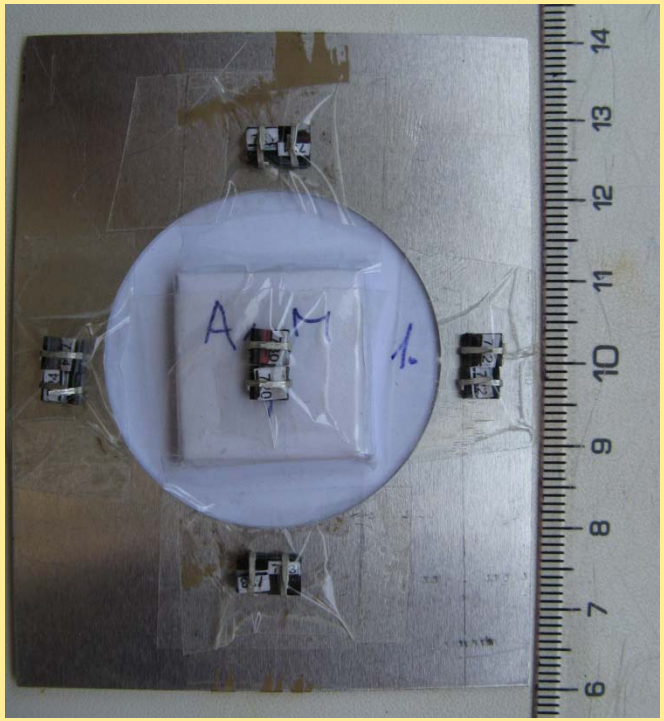
Experiments on 20, 25, 32.5, and 37 MeV p beams

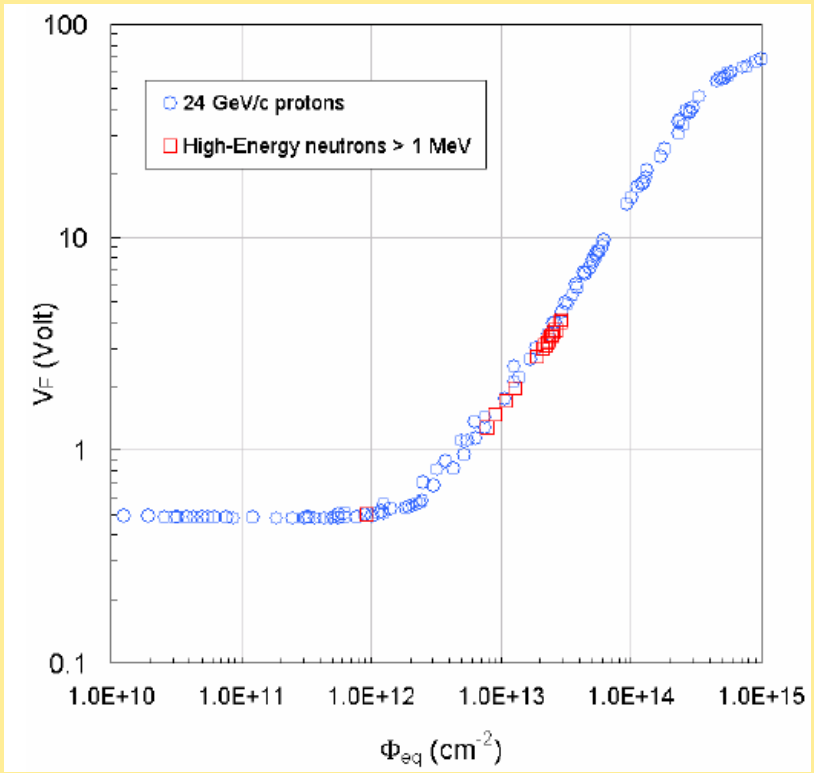
~ 15 hours of irradiation

Silicon diods for neutrons monitoring

- Motivation for σ measurements
- Requirements
- TSL Uppsala
- Cyclotron Řež
  - Facility
  - *Diodes*
- Evaluation
- Results
- Conclusion

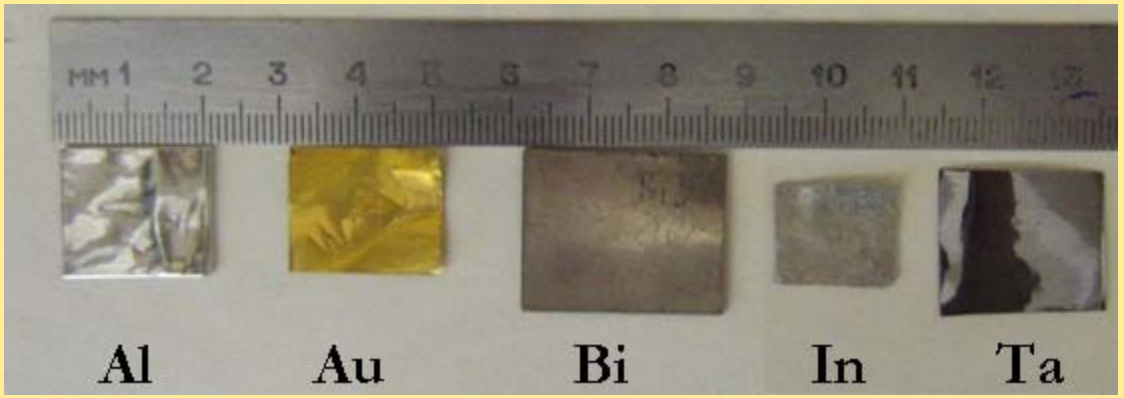
- **BPW 34F, CMRP and Si-1 silicon diods tested at Řež**
- **Originally proposed as dosimeters (CERN), but can be also used as high-energy neutron monitors**
- **Irradiation with fast neutrons causes shift of the current-Voltage curve (measurement at constant current few mA for a period of hundreds of ms)**
- **Neutron intensity range 2.10^{12} – 4.10^{14} cm^{-2} at BPW 34F, respectively 1.10^{8} – 2.10^{12} cm^{-2} at CMRP**





Measured materials

- Motivation for σ measurements
- Requirements
- TSL Uppsala
- Cyclotron Řež
- Evaluation
  - *Materials*
  - Process
  - Corrections
  - Background
- Results
- Conclusion



iodine (KIO_4)

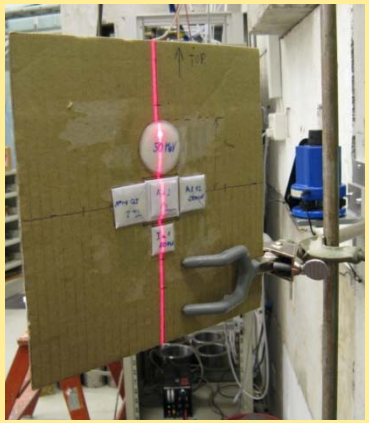
Reaction	E_{thresh} [MeV]	Half-life
$^{197}Au\ (n,2n)^{196}Au$	8.1	6.183 d
$^{197}Au\ (n,3n)^{195}Au$	14.8	186.1 d
$^{197}Au\ (n,4n)^{194}Au$	23.2	38.02 h
$^{197}Au\ (n,5n)^{193}Au$	30.2	17.65 h
$^{197}Au\ (n,6n)^{192}Au$	38.9	4.94 h
$^{197}Au\ (n,7n)^{191}Au$	45.7	3.18 h
$^{197}Au\ (n,8n)^{190}Au$	54.5	43 min
$^{197}Au\ (n,9n)^{189}Au$	61.8	29 min
$^{197}Au\ (n,10n)^{188}Au$	70.9	9 min

In Řež also measured:

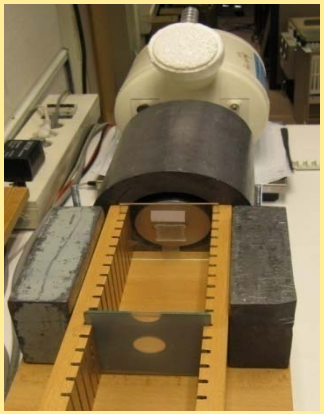
Mg, Ni, Fe, Zn

Evaluation process

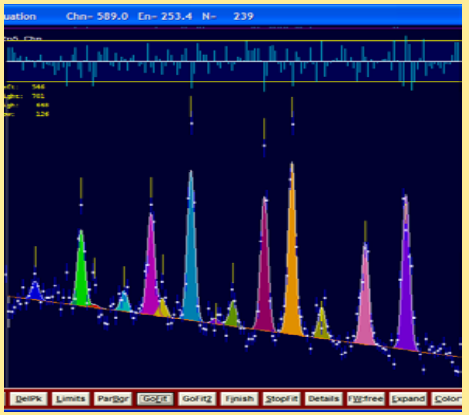
- Motivation for σ measurements
- Requirements
- TSL Uppsala
- Cyclotron Řež
- Evaluation
  - Materials
  - *Process*
  - Corrections
  - Background
- Results
- Conclusion



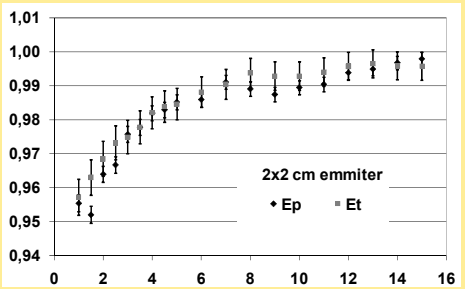
Irradiation



HPGe

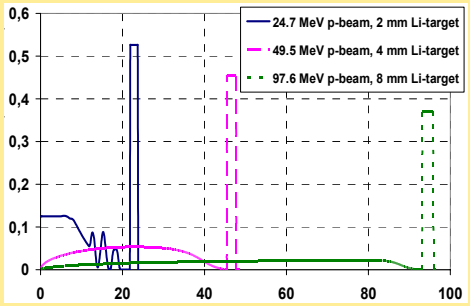


Spectra evaluation

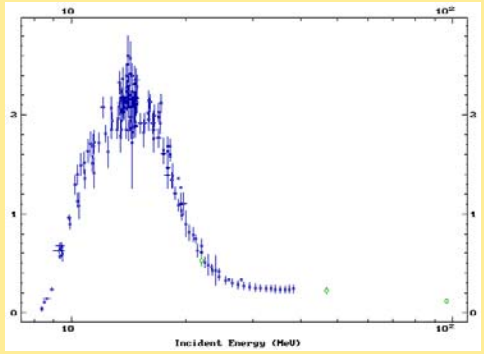


Corrections

N_{Yield}



Production in peak Talys1.0

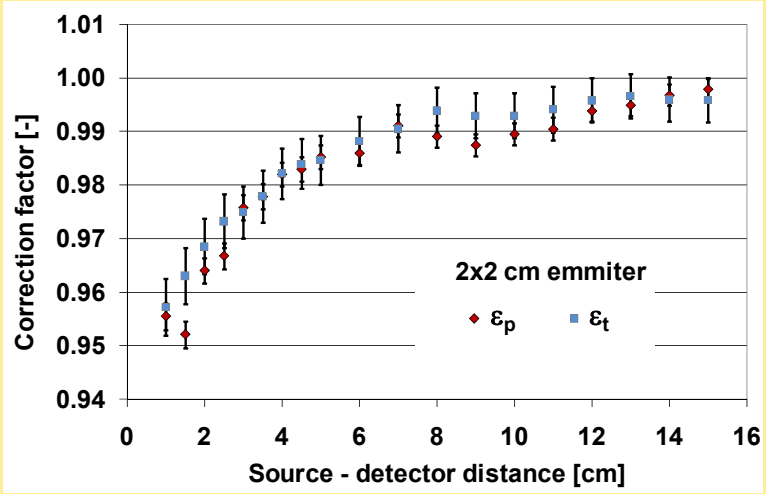


Cross-section

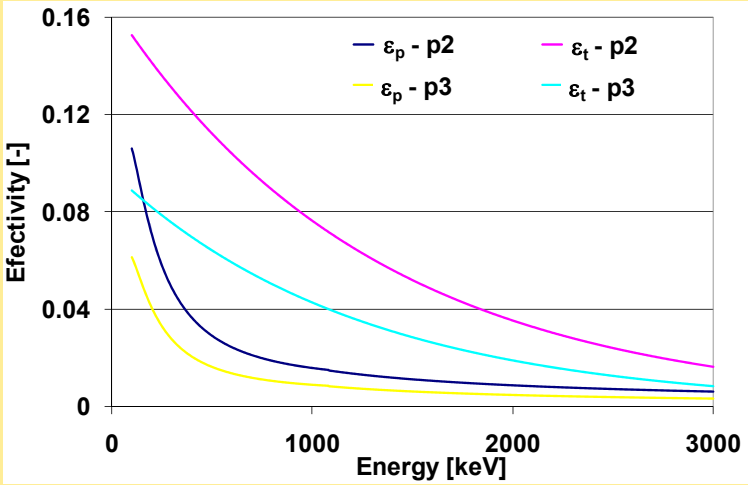
Spectroscopic corrections

- Motivation for σ measurements
- Requirements
- TSL Uppsala
- Cyclotron Řež
- **Evaluation**
  - Materials
  - Process
  - *Corrections*
  - Background
- Results
- Conclusion

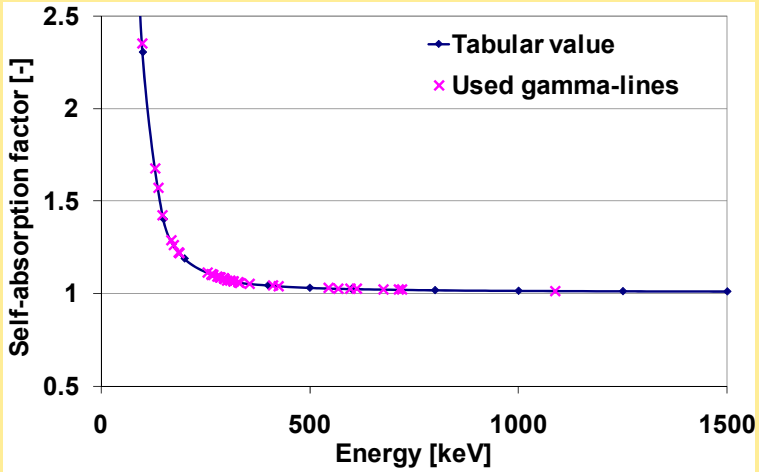
Non-point-like emitters



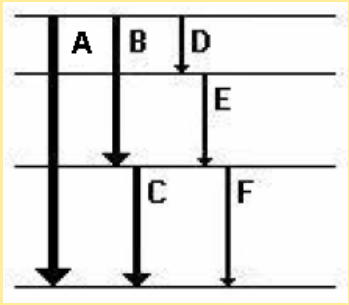
Detector efficiency



Self-absorption



Real γ-γ cascade coincidences



Beam instability correction

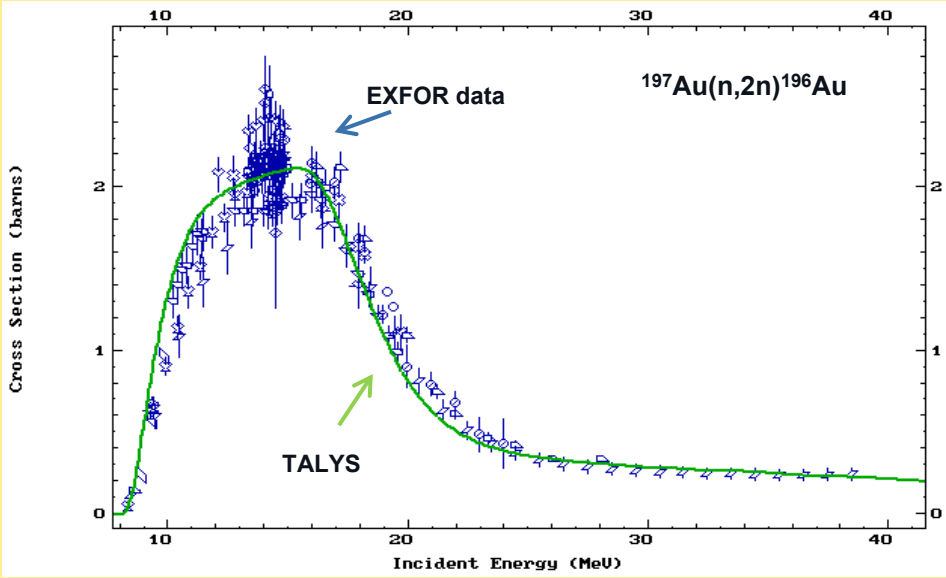
...

Production by background neutrons

- Motivation for σ measurements
- Requirements
- TSL Uppsala
- Cyclotron Řež
- Evaluation
  - Materials
  - Process
  - Corrections
  - *Background*
- Results
- Conclusion

• σ comparisons between EXFOR and TALYS – mostly good agreement

• We believe the simulated σ shape is OK, only the absolute value can be shifted



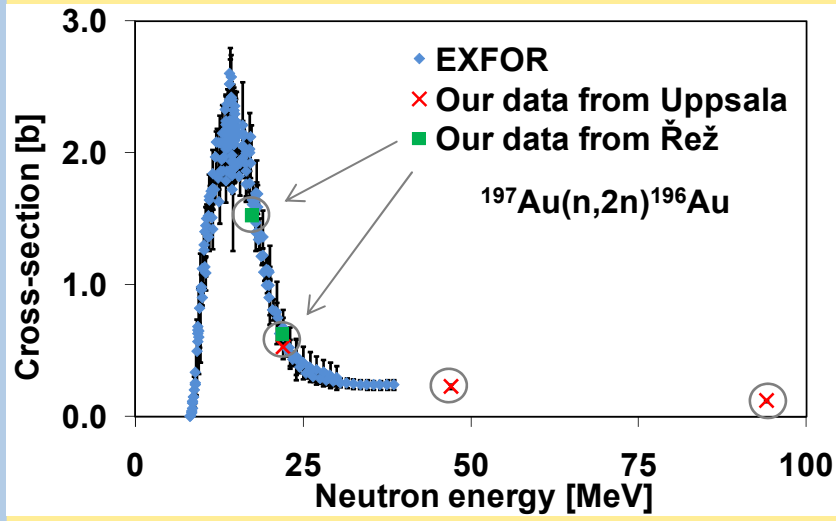
•Following the neutron spectrum knowledge, we calculated ratio between production in neutron peak and total production

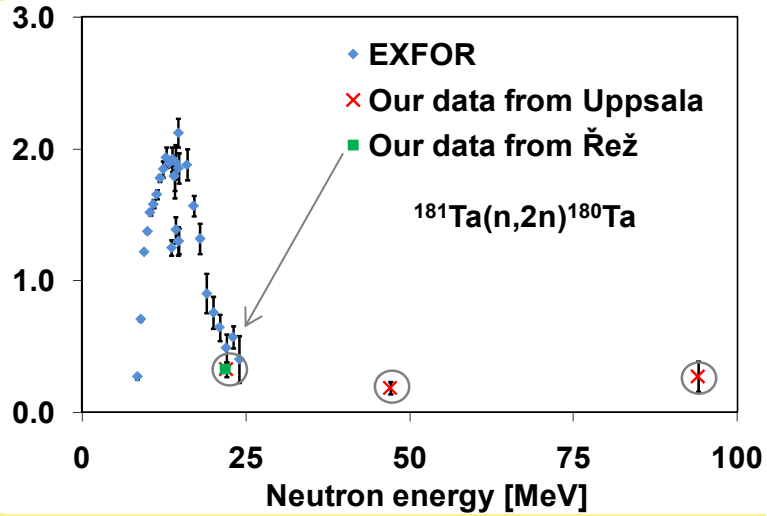
• With this ratio we multiplied the yields to subtract background production

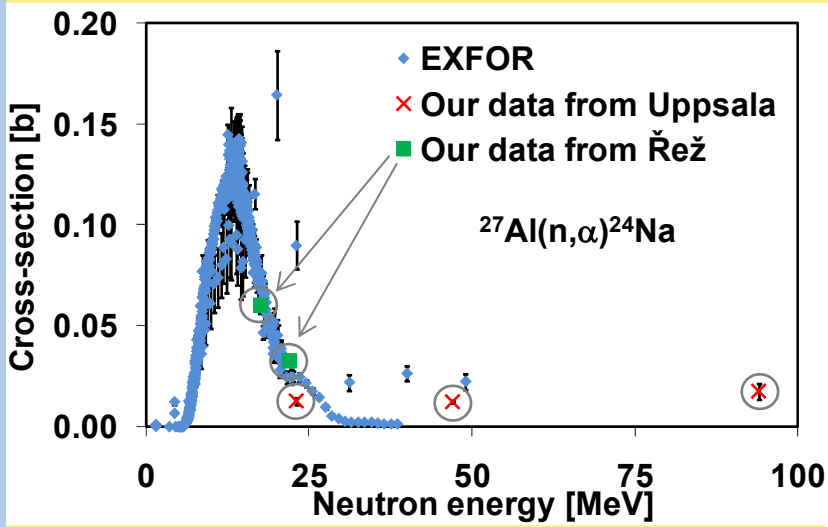
Experimental results – Au, Al, Ta

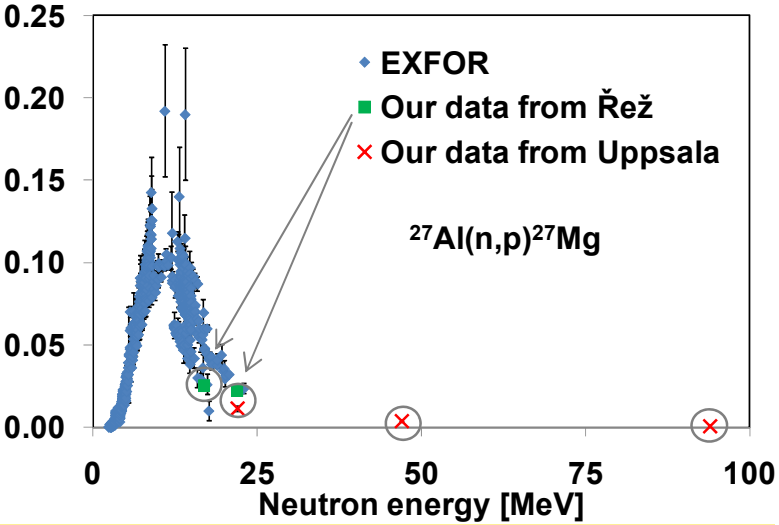
- Motivation for σ measurements
- Requirements
- TSL Uppsala
- Cyclotron Řež
- Evaluation
- **Results**
  - *Au, Al, Ta*
  - Bi
- Conclusion

Preliminary results from Uppsala and Řež





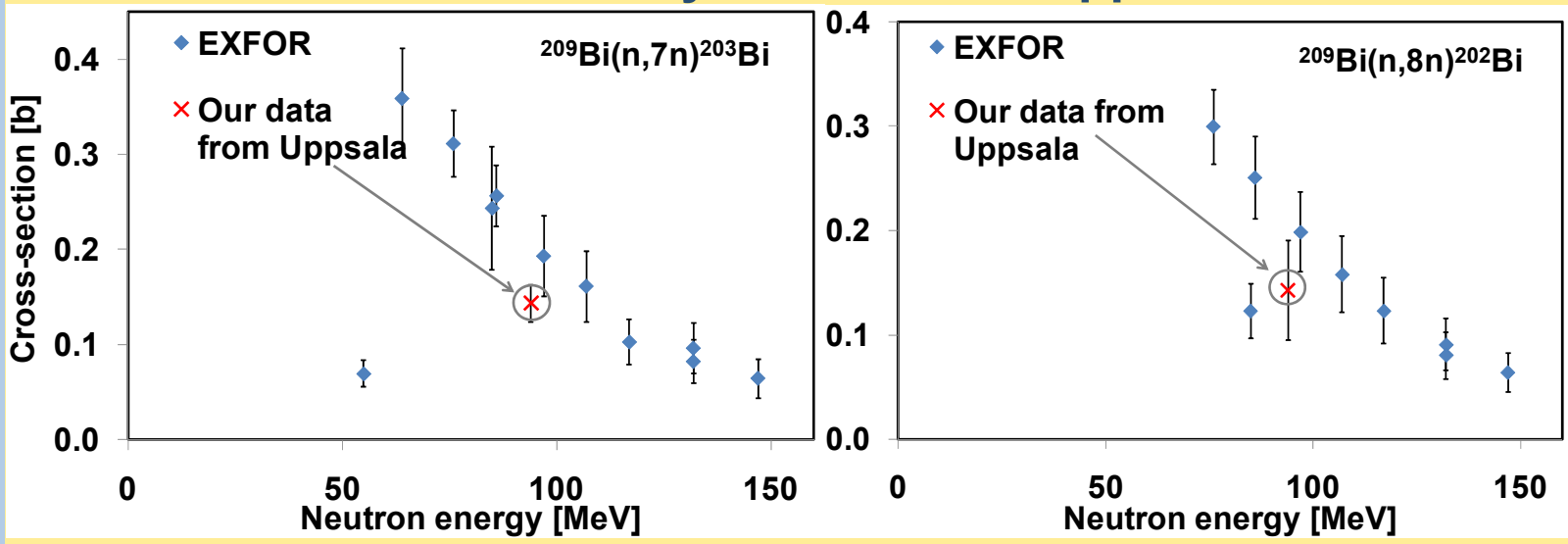


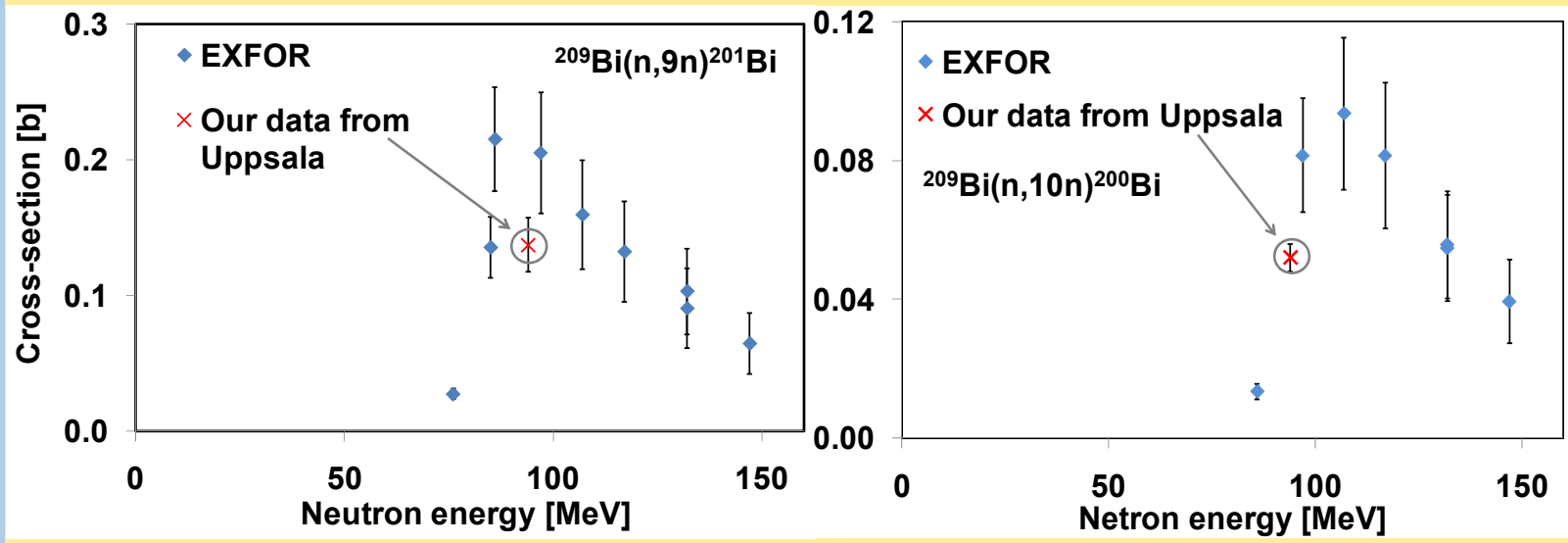


Experimental results – Bi

- Motivation for σ measurements
- Requirements
- TSL Uppsala
- Cyclotron Řež
- Evaluation
- **Results**
  - Au, Al, Ta
  - *Bi*
- Conclusion

Preliminary results from Uppsala





Conclusion

- Our cross-section measurements cover wide range of neutron energies (17 - 94 MeV)
- New cross-sections measured in neutron energy region, where no data available so far (40 - 94 MeV)
- Measured even cross-sections of reactions that have not been measured yet at all (e.g. I)
- Preliminary results show that we are close to known cross-section values
- This method of σ measurements can be used also for other materials
- Plans for future – finalize Řež experiments analysis
  – next experiments at Uppsala
  – uncertainty analysis
  – publish final results
  – complete comparison with TALYS

Acknowledgements

We would like to thank to Dr. Bém and his colleagues for the possibility to joint their irradiations on cyclotron in Řež!

This work was supported from the EFNUDAT and from the grant CTU0808214.

Thank you for your attention..