MEASUREMENTS OF CROSS-SECTIONS OF THE NEUTRON THRESHOLD REACTIONS AND THEIR USAGE IN HIGH ENERGY NEUTRON MEASUREMENTS AT “ENERGY PLUS TRANSMUTATION”

O. Svoboda\textsuperscript{1,2}, A. Krása\textsuperscript{1,2}, M. Majerle\textsuperscript{1,2}, V. Wagner\textsuperscript{1,2}

from collaboration „Energy plus Transmutation“

\textsuperscript{1} Nuclear Physics Institute of the Academy of Sciences of the Czech Republic, 250 68 Řež, Czech Republic
\textsuperscript{2} Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Czech Republic

svoboda@ujf.cas.cz

Abstract

We measured neutron cross-sections of various threshold reactions using different quasi-monoenergetic neutron sources. Our motivation for the cross-section measurements comes from the "Energy plus Transmutation" project. In this international project we use neutron activation foils for measurements of high energy neutron field, which is produced during the proton or deuteron irradiation of a thick lead target surrounded by a natural uranium blanket. Au, Al, Bi, In and Ta foils are used as activation detectors, but unfortunately almost no experimental cross-section data for observed threshold (n,xn) reactions are available for higher neutron energies.

We prepared a few studies to measure the (n,xn) cross-sections using neutron sources on NPI ASCR cyclotron in Řež and on TSL cyclotron in Uppsala (EFNUDAT program). In these experiments we irradiated above mentioned foils, iodine samples and SSNTD with quasi-monoenergetic neutrons from p+Li reaction. First experiments on the Li target were already carried out at NPI with 20 and 25 MeV protons, next irradiations are planned for near future to cover whole available neutron energy region (10-37 MeV) from this source. On June 2008 a measurement at TSL was carried out with energies 25, 50, 100 MeV protons on Li. Activated foils were measured on HPGe detectors and a wide range of spectroscopic corrections was applied. First results of these measurements and their practical importance for the Energy plus Transmutation project will be shown.

Finally, complex overview of the results from the last two deuteron experiments on the Energy plus Transmutation setup measured on Nuclotron at JINR by our group from Řež will be provided. Yields of the threshold activation detectors and MCNPX simulations of the setup will be discussed in more detail.

State-of-the-art of the (n,xn) cross-section libraries

The present status of knowledge of cross-sections for the (n,xn) reactions is poor. Fig1 and 4 show measured cross-sections for (n,xn) reactions in Bi and Au.

In the case of bismuth, reactions from (n,4n) until (n,12n) were measured already (Fig1) \cite{1}, but there are values from one experiment only \cite{2}. There are no evaluated data available.
In the case of gold, only \((n,2n)\) reaction was measured in detail and by more authors (Fig 4 left), \((n,4n)\) reaction was measured only for small neutron energies (Fig 4 right). Other \((n,xn)\) reactions were not studied at all. The situation for Al, In, and Ta is similar to Au.

Therefore, it is still necessary to perform new cross-section measurements to fill in the gaps and estimate possible systematic errors at already measured values.

![Graph showing neutron cross-sections for Bi (n,xn) threshold reactions. Data are from EXFOR [1].](image1)

**III Cross-section measurements**

For cross-section measurements by the means of activation analysis one need firstly a good high energy neutron source with quasi-monoenergetic well known spectrum. Due to low cross-section values and limited weight of the samples these sources must furthermore be quite intensive. This reduces the number of suitable neutron sources to a few in the whole world. For measurements of activated samples one need a spectroscopic laboratory with \(\gamma\) and X-Ray detectors of suitable resolution and efficiency. Finally, wide range of spectroscopic corrections must be applied.

**III.1 Cross-section estimation**

During planning of the irradiation it was necessary to have at least some knowledge about the possible cross-section course and values. We calculated the threshold energies (Fig 2) and roughly estimated the course of cross-sections. It is necessary to stress that these \(E_{\text{thresh}}\) are only illustrative and \(\sigma(E)\) reaches its maximum at energy about 10 MeV bigger than \(E_{\text{thresh}}\) and can have important influence even at energy of 20 MeV bigger, see for example Fig 1, 4.

![Graph showing the threshold energies of (n,xn) reactions in Au, Bi, In, Ta. The values of threshold energies were calculated as the difference between outgoing and incoming particles masses (using mass excesses values from [3]).](image2)
For most of the isotopes it was possible to make a convolution of evaluated (estimated) cross-sections and neutron spectra. We roughly calculated yields of most isotopes and with the knowledge about the detector efficiency we planned the weights of the foils in order to get enough activated nuclei.

### III.2 Neutron sources

Within the frame of the EFNUDAT program [4] we performed cross-section measurements at The Svedberg Laboratory (TSL) in Uppsala. In this laboratory quasi-monoenergetic 11 - 175 MeV neutron source based on the $^7\text{Li}(p,n)^7\text{Be}$ reaction is available [5]. High energy protons from the cyclotron at TSL are directed to a thin, lithium target, the neutron flux density can be up to $5 \times 10^5$ cm$^{-2}$s$^{-1}$. The half of intensity is in the peak with FWHM = 1 MeV (corresponds to the ground state and first excited state at 0.43 MeV in $^7\text{Be}$) and half of intensity is in continuum in lower energies (corresponds to higher excited states, multiple-particle emission etc.) Fig3-left. Proton energy loss in the target amounts to 2-6 MeV depending on the incident beam energy and target thickness. Downstream the target, the proton beam is deflected by a magnet and guided onto a graphite beam dump. The neutron beam is formed by an iron collimator (50 cm in diameter and 100 cm long) with a hole of variable size and shape.

Second neutron source that we use is in Nuclear Physics Institute – Academy of Sciences of the Czech Republic in Řež. Protons from the cyclotron are directed to the lithium target and quasi-monoenergetic neutrons in the range 10 – 37 MeV can be produced (Fig3-right).

![Fig3: Quasi-monoenergetic neutron spectrum from $^7\text{Li}(p,n)^7\text{Be}$ at the TSL (left) and cyclotron Řež (right).](image)

### III.3 Yield of produced isotopes

We used Au, Al, Bi, In, I and Ta samples. Materials were except the iodine in form of foils with dimensions of 20x20x0.05-1 mm$^3$, weights of the foils were from 0.2–7 grams depending on the foil type and beam energy. Foils were wrapped in paper to avoid isotope transport between foils and detector contamination. Iodine samples were in form of solid KIO$_4$ tablet packed hermetically in plastic. Samples were irradiated by neutrons in Uppsala with proton beam energies 25, 50, and 100 MeV and in Řež with proton beam energies 20 and 25 MeV. Typical irradiation time was 8 hours, transport from the irradiation hall to the spectrometer took approximately 2 minutes in Uppsala, 10 minutes in Řež.

After irradiations, activated foils were measured on HPGe detectors in Uppsala and Řež. Gained gamma-spectra were evaluated in the DEIMOS-32 code [6]. Yields of observed isotopes were calculated according to equation (1) (scaled to one gram of target material).
We applied various spectroscopic corrections to catch up all possible systematic errors. Beside the standard ones we included following corrections: the self absorption correction was determined to be in extreme case up to the factor of 2 because of big thickness of some foils and low energy of some γ-lines (at most cases typically 1.05). Square-emitter correction was determined with the help of MCNPX to be up to the factor of 0.96 because of the close detector geometry.

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

With the knowledge of yield we calculated cross-section value \( \sigma = \frac{N_{\text{yield}} \cdot S \cdot A}{N_n \cdot N_A} \) for respective beam energy (S – foil area, A – molar weight, \( N_n \) – number of neutrons in peak, \( N_A \) - Avogadro's number). This was purposeful only for such isotopes, where most of their amount was produced by the peak neutrons (isotope production by the background neutrons is zero or could be neglected).

### III.4 Preliminary results

Irradiations in Řež took place on the 17. May and the 8. August 2008, irradiations in Uppsala were in days 23.-25.6 2008. Up to now we have determined basic yields without some corrections and we are starting to calculate the cross-sections.

![Graph](image)

**Fig4**: Comparison of EXFOR [2] data and our tentative values for (n,2n)\(^{196}\text{Au}\) (left) and (n,4n)\(^{194}\text{Au}\) (right).

Well-known \( \sigma(E) \) for \(^{197}\text{Au}(n,2n)^{196}\text{Au}\) will be used to check if we get appropriate results. When we divide the yield of \(^{196}\text{Au}\) only by the number of neutrons in the main peak, we get
the results like in Fig6-left ($^{196}$Au production by the background neutrons cannot be fully neglected), but we are still near to EXFOR data. On the other hand, $^{194}$Au is produced only by neutrons from the peak and its value corresponds with the EXFOR data very well (Fig4-right). These results are only tentative!

**IV “Energy plus Transmutation” at 1.6 GeV deuterons**

In the December 2007 we took part in the Energy plus Transmutation (E+T) [7] experiment, in which was the lead-uranium setup irradiated by 1.6 GeV deuterons for 8 hours. We used ~90 activation detectors made of Au, Al, Bi, In, and Ta foils to measure the neutron field in the setup. Activated detectors were measured on HPGe detectors at JASNAP (JINR Dubna), code DEIMOS32 was used for gauss-fit of the $\gamma$-peaks in the spectra. Yields of the (n,xn) reaction products were calculated with respect to spectroscopic corrections shown above in the section III.3.

Experimental results show a maximal neutron flux near the first gap of the setup (Fig5), as in MCNPX simulations (Fig6). Weighted average from the $^{198}$Au yields over all used Au detectors is $(3.3\pm0.7)\cdot10^4$ (for previous experiments $(3.8\pm0.3)\cdot10^4$ for 2.52 GeV deuterons, $(0.7\pm0.5)\cdot10^4$ for 0.7 GeV protons).

**Fig5:** Relative comparison between the 0.7 GeV proton, 1.6 and 2.52 GeV deutron E+T experiment, yields of $^{198}$Au (non-threshold reaction) and $^{196}$Au (n,2n). Data are normalized to the second point.

**Fig6:** Absolute experiment/simulation comparisons, radial distance from the target axis 3 cm (left) and 10.7 cm (right). Bigger error-bars in the right figure are caused by the lower statistics in this distance from the target axis.
We performed MCNPX (version 2.6.E) simulations of the setup with the beam parameters same as measured in the experiment. We calculated separately neutron, proton, deuteron and pion spectra in the detector volumes and cross-sections (TALYS+MCNPX). Manual convolution was done in Excel.

**IV Conclusion**

During the “Energy plus Transmutation” project we realized there are significant voids in the cross-section libraries of (n,xn) threshold reactions. We performed a few experiments, in which we measured (n,xn) cross-sections at Au, Al, In, Bi, Ta, and I under the neutron energies 20, 25, 50, and 100 MeV. Preliminary results show we are close to the known cross-section values, but the data processing is still in progress. In the future we will continue with these measurements to cover whole available energy interval. We took part on the E+T experiment with 1.6 GeV deuterons. We used activation detectors to measure the neutron field in the lead-uranium setup. Gained experimental results were compared with the MCNPX simulations. All results fits well in the systematic gained in previous E+T experiments.

**Acknowledgement**

Uppsala cross-section measurements were supported by the EFNUDAT program [4]. E+T measurements were supported by the Řež-Dubna funds.

The authors are grateful to the staff of the Dubna Nuclotron accelerator for providing a good deuteron beam and to the staff of TSL Uppsala for neutron beams. We would like also to thank to Mr. Pavel Bém for the possibility to joint their irradiations on the cyclotron at Řež.

**References**


