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Study of cross-sections of yttrium (n,xn) threshold reactions

P. Chudoba*, **V. Wagner, J. Vrzalova, O. Svoboda, M. Suchopar, M. Majerle, M. Stefanik, A. Kugler**
Nuclear Physics Institute of the ASCR, v. v. i.
Rez 130, 250 68 Rez, Czech Republic
E-mail: chudoba@ujf.cas.cz, wagner@ujf.cas.cz, vrzalova@ujf.cas.cz, svoboda@ujf.cas.cz, suchopar@ujf.cas.cz, majerle@ujf.cas.cz, stefanik@ujf.cas.cz, kugler@ujf.cas.cz

S. Kilim, M. Bielewicz, E. Strugalska-Gola, M. Szuta
National Centre for Nuclear Research
Otwock-Swierk 05-400, Poland
E-mail: s.kilim@cyf.gov.pl, m.bielewicz@cyf.gov.pl, elasg@cyf.gov.pl, mszuta@cyf.gov.pl

Currently the development of the nuclear systems is heading to systems with fast neutrons instead of thermal ones. Such systems are mainly fast reactors of generation IV family and accelerator driven systems. Unfortunately the possibilities of monitoring fast neutrons are limited. One of the possible principles is to use activation detectors. It has shown up that yttrium is very good candidate to act as the activation detector of the fast neutrons. The advantages of yttrium are namely its (n,*x*n) threshold reactions and the fact that its only one naturally occurring isotope. To be possible to use yttrium as the activation detector it is necessary to know the cross-sections of the (n,*x*n) reactions sufficiently good. This condition is fulfilled only in case of the ^{89}Y(n,2n)^{88}Y reaction. For higher orders of reactions there are almost no experimental data.

For this reason a series of experiment were made using quasi mono-energetic neutron source based on the reaction of protons with ^{7}Li target at Nuclear Physics Institute of ASCR in Rez. Special attention was paid to the ^{89}Y(n,3n)^{87}Y reaction. In this case the nuclei are produced both in the ground state and in the isomeric state. The half-lives are 79.8 hours for the ground state and 13.38 hours for the isomeric state. The isomeric state decays mainly through the gamma transition to the ground state. The beta decay of the isomeric state is within our accuracy negligible. The cross-sections of both cases of products were analyzed and compared with existing experimental data, calculated models and evaluated values.

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*Speaker.

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1. Introduction and motivation

Monitoring of neutron fields is an important task for advanced nuclear systems. These systems are mainly Generation IV reactors, accelerator driven systems (ADS) and possibly fusion reactors. Good candidates for such monitoring of the neutron fields are activation detectors. The principle is utilization of (n,*x*n) reactions. In case of a fast reactors of Generation IV and fusion reactors the (n,2n) reaction is suitable and the cross-sections are in many cases well-known. Different situation is in case of the ADS the neutron energy can be in order of hundreds MeV. Therefore it is necessary to know the cross-sections of higher orders of the (n,*x*n) reactions. Unfortunately the knowledge of the cross-sections of higher orders of the reactions is insufficient.
Yttrium is a good candidate for the activation detector of fast neutrons. It has been started to be used within the collaboration Energy&Transmutation of Radioactive Waste. An experimental setup of the ADS is used within the framework of this collaboration . This setup is called QUINTA. Yttrium is widely used to monitor neutron flux in the various places inside the QUINTA setup. Unfortunately the knowledge of the cross-section of yttrium (n,*x*n) reactions are sufficiently known only for the (n,2n) reaction. For the (n,3n) reaction only three points of the cross-section were published in EXFOR. Therefore in cooperation with Polish group we have decided to measure the cross-sections of (n,2n) and (n,3n) reactions with neutron energies 17.4, 24.5, 24.8, 27.9, 28.7, 30.0, 32.5 and 33.5 MeV. Preliminary cross-sections are shown in this article.

2. Irradiation and measurements

The irradiation has taken place at the Nuclear Physics Institute of the ASCR in Řez. The yttrium samples were irradiated using quasi-monoenergetic neutron (QM) source [1] mounted on a cyclotron U-120M. The QM neutron source works on principle of production of the QM neutrons trough reaction ^{7}Li(p,n)^{7}Be and the neutron flux is in order of 10^{8} cm$^{-2}\cdot$s^{-1}. The neutron spectrum is characteristic with its QM peak and the low energy continuum. Each part of the spectrum contains approximately 50% of the produced neutrons. The spectrum is determined by means of an MCNPX [2] simulation. Two samples of yttrium were irradiated during each irradiation. Each yttrium sample was irradiated together with the gold sample in the same geometry. We have evaluated data from both materials and compared the cross-section data from gold samples with data from the EXFOR database. Gold has well measured reaction ^{197}Au(n,2n)^{196}Au and for this reason it has been used to act as neutron monitor.

After the irradiation the samples were measured in γ-spectroscopic laboratory. The measurements were conducted on a spectrometer based on a HPGe detector. Following formula [4] was used for determination of the yields from the peaks areas.

$$N_{yield} = \frac{S_p \cdot C_{abs}(E)}{I_\gamma \cdot \varepsilon_p(E) \cdot COI \cdot C_{area}} \frac{t_{real}}{t_{live}} \frac{1}{m_{foil}} \frac{e^{\lambda \cdot t_0}}{1 - e^{-\lambda \cdot t_{real}}} \frac{\lambda \cdot t_{irr}}{1 - e^{-\lambda \cdot t_{irr}}}, \tag{2.1}$$

where S_p – the peak area, C_{abs} – self-absorption correction, I_γ – γ-line intensity, $\varepsilon_p(E)$ – detector efficiency, COI – true coincidences correction, C_{area} – square-emitter correction, $\frac{t_{real}}{t_{live}}$ – dead time correction, m_{foil} – mass of the sample. The last two fractions represents corrections for decay during cooling and measurement and decay during irradiation respectively. Uncertainty caused

by the used corrections was estimated to be less than 1%. Only the uncertainty coming from the efficiency calibration is not worst than 3%.

An upper limit of a combined uncertainty caused by the neutron spectrum determination and the background subtraction procedure was determined to be 10%.

With the knowledge of the yield (2.1) we can calculate a cross-section using following equation

$$\sigma = \frac{N_{yield} \cdot S \cdot A}{N_n \cdot N_A}, \tag{2.2}$$

where S – the foil area, A – molar weight, N_n – number of neutrons in peak, N_A – Avogadro's number.

3. Low energy neutron background subtraction

Since the neutron spectrum contains besides the QM neutron peak the lower energy tail it is necessary do subtract the contribution of the lower energy neutrons to the yield of measured isotope. For this purpose a background subtraction procedure [3] is used. This procedure is based on a folding of the neutron spectra and the excitation function according to a formula

$$C_{bgr} = \frac{\int\limits_{Peak} \sigma(E) \cdot N(E) \mathrm{d}E}{\int\limits_{Spectrum} \sigma(E) \cdot N(E) \mathrm{d}E} = \frac{\sum\limits_{i \in Peak} \sigma_i \cdot N_i}{\sum\limits_{i \in Spectrum} \sigma_i \cdot N_i} \tag{3.1}$$

where $\sigma(E)$ (σ_i) – excitation function (binned excitation function) and $N(E)$ (N_i) – neutron spectrum (binned neutron spectrum). The binned version of definition is used because the neutron spectrum from the MCNPX simulation is produced in binned form with a bin width of 250 keV. The procedure has an advantage that it is independent on the absolute values of the excitation function. It depends only on the shape in a way that if the shape is wrong, than the results diverge from it in opposite direction. Using this knowledge it is possible to check the validity of the background subtraction. The excitation functions were taken either from EAF-2010 database [5] or calculated with a TALYS-1.4 [6]. From the principle of the procedure, the gold samples and results from reaction ^{197}Au(n,2n)^{196}Au act as validation of the neutron spectra shape.

4. Cross-section results

Preliminary cross-section results are shown in this section. The cross-sections are still preliminary due to discussion about uncertainties within our group. But all necessary corrections were involved. Therefore there shouldn't be any significant changes in the results. The cross-sections of the yttrium and gold (n,*x*n) reactions are shown in the figure 1 and 2 respectively. The graphs shows data from current experiment together with currently known data from the EXFOR database and excitation functions from EAF-2010 and excitation functions calculated by TALYS 1.4.

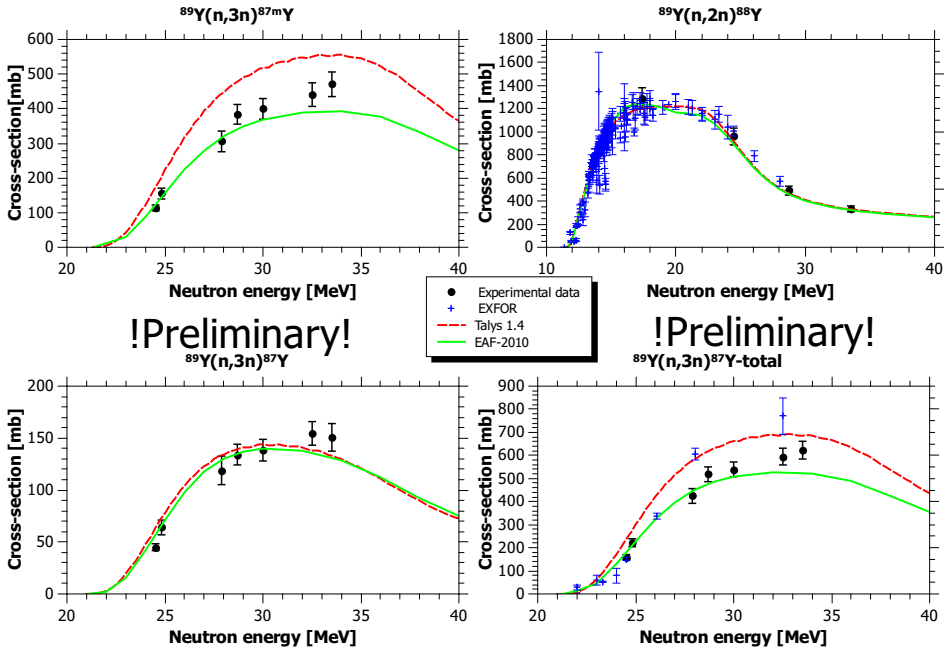

Figure 1: Preliminary results of the ^{89}Y(n,2n)^{88}Y and ^{89}Y(n,3n)^{87}Y reactions.

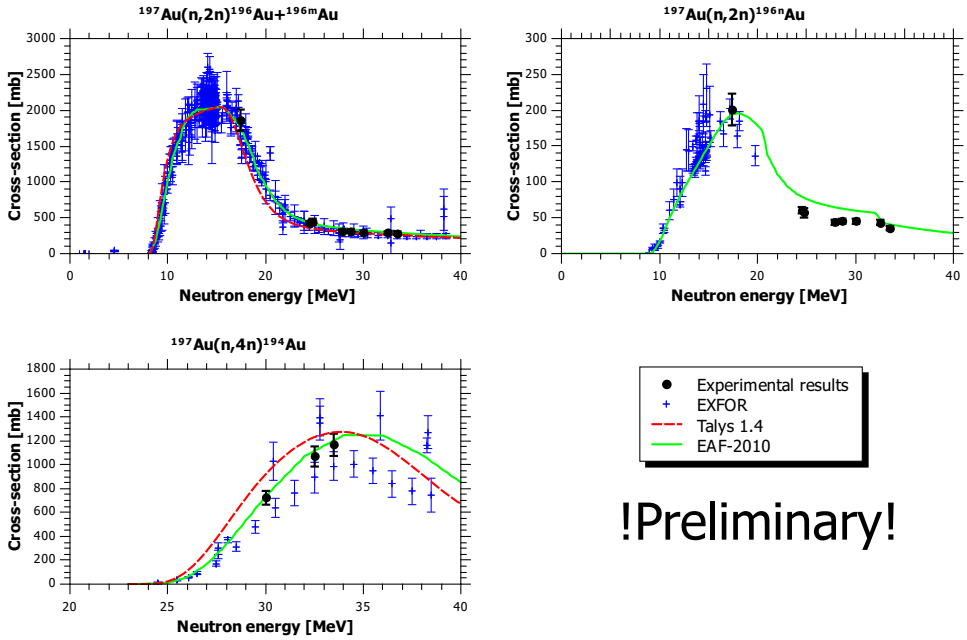

Figure 2: Preliminary results of the ^{197}Au(n,2n)^{196}Au and ^{197}Au(n,4n)^{194}Au reactions.

In both cases the data shows good agreement with the existing experimental data. In case of the ^{89}Y(n,3n)^{87m}Y reaction there is possible to see differences in absolute values between the experimental, calculated and database data, however the shapes are again in a good agreement.

5. Conclusion

We have measured cross-sections of the (n,2n) and (n,3n) reactions on yttrium and (n,2n) and (n,4n) on gold. In case of the (n,3n) reaction on yttrium and (n,2n) reaction on gold we have separated the cross-sections of isomeric states. These data are unique in the measured energy region. The agreement of our results with currently known data shows good applicability of described method and good knowledge of the neutron spectra of the QM neutron source. It is possible to see it mainly in the cases of ^{197}Au(n,2n)^{196}Au+^{196m}Au and ^{89}Y(n,2n)^{88}Y reactions where for the highest neutron energies the yield produced by the background neutrons exceeds the yield produced by the QM peak.

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