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^{nat}Cu and ^{nat}V cross-sections measured by quasi-monoenergetic neutrons from p+^{7}Li reaction in the energy range of 18–34 MeV

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Abstract. ^{nat}Cu and ^{nat}V samples were irradiated several times with quasi-monoenergetic neutrons from the p+^{7}Li reaction in the energy range of 18–35 MeV. The activities of the samples were measured with the HPGe detector and the reaction rates were calculated. Time-of-flight measurements of the produced neutron spectra and the measurements of the residual ^{7}Be activity in the Li target were performed to improve the knowledge of the neutron spectra. The cross-sections were extracted using the SAND-II procedure with the reference cross-sections from the EAF-2010 database. The uncertainties of the final results are discussed.

1. Introduction

The experimentally measured neutron data above 20 MeV are becoming increasingly important in the future energy production. New reactor concepts, fusion and accelerator driven systems (ADS) utilize faster neutron spectrum than conventional reactors. The experimentally measured cross-sections data for neutrons with energies above 20 MeV are rare and many dedicated facilities are operating or are in construction for this purpose.

In the past decades, several procedures to gather knowledge on neutron reactions were standardized. Irradiation with the known neutron spectrum (quasi-monoenergetic neutrons based on the p+^{7}Li reaction) and the subsequent activity measurement is commonly used to determine the reaction cross-section in the neutron energy range above 20 MeV.

The NPI neutron laboratory is working on the program for the measuring and analysis of such cross-sections [1,2]. In paralell, the cross-sections for some materials that are not directly connected to fusion/ADS are measured and presented in this paper.

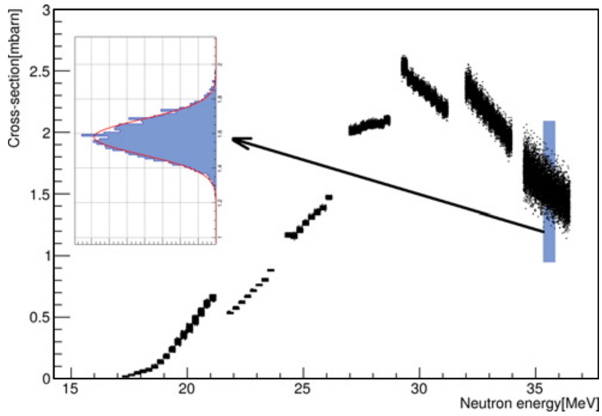

Figure 1. Two dimensional distribution of the extracted cross-section curves for the reaction ^{nat}Cu(n,p+α)^{59}Fe. The input parameters of the iterative procedure were varied, in this histogram the multiplicative factor for the neutron spectrum below the monoenergetic peak. The distribution of the extracted cross-section values is gaussian with the maximum value of σ=0.1mbarn at the energy of 35 MeV.

2. Experimental setup

The neutron irradiations have been performed with the quasi-monoenergetic neutron generator, based on the p+^{7}Li reaction. Protons with energies 20–35 MeV were directed at a 2 mm thick lithium foil with a 1 cm carbon backing, which fully stopped the protons, see [1].

The irradiated samples were made from high purity (99.9%) metallic Cu and V, and had the disc shape with a 15 mm diameter and a thickness of 0.1–0.15 mm for Cu and 0.05-0.5 mm for V. The masses of the samples were determined by weighing with an relative accuracy below 0.5%. New samples were used at each irradiation. In every experimental run the samples were irradiated at distances of 42 mm and 86 mm from the neutron source. The distance of 42 mm was used for short irradiations (5 minutes) and quick transport of the samples to the HPGe detector with the pneumatic post system (ca. 20 seconds). The distance of 86 mm was used for long irradiation (8 hours). Several radioactive products were detected in the irradiated foils by the offline γ-spectroscopy employing two calibrated HPGe detectors with the efficiency around 50% and the energy resolution 1.8–1.9 keV at 1332 keV. The decay γ spectra were measured during the cooling period from tens of seconds up to tens of days.

3. Neutron spectra

The neutron spectra produced by the NPI neutron generators in forward direction were measured by the Time-Of-Flight method and normalized using the procedures proposed by Schery [3] and Uwamino [4]. These procedures are based on residual ^{7}Be activity

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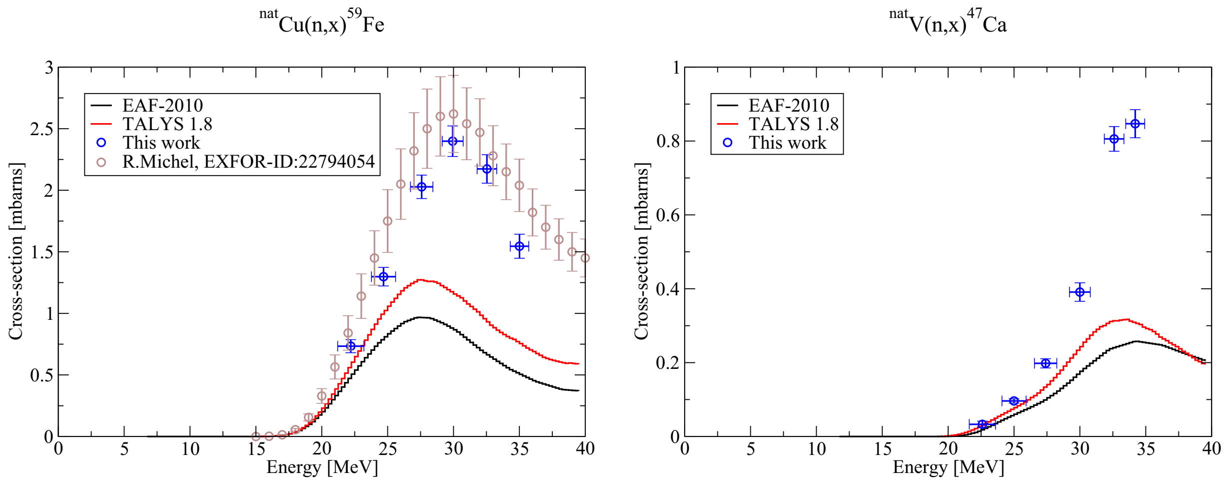

Figure 2. Cross-sections of two (n,x) reactions on ^{nat}Cu and ^{nat}V extracted from the NPI/Řež experimental data versus the evaluated data in EAF-2010 database, model calculations by TALYS-1.8 code and experimental values [10]. The main reaction channel is (n,p+α), the contribution of other reactions is negligible. The experimental values are significantly underestimated by the evaluation.

Table 1. Cross-sections of ^{nat}Cu(n,x) reactions extracted from the NPI/Řež experimental data with the estimated uncertainties. All the irradiations were performed at the target-sample distance of 86 mm.

E_n[MeV]	Cross-section [mbarn]				
	^{nat}Cu(n,x)^{56}Mn	^{nat}Cu(n,x)^{59}Fe	^{nat}Cu(n,x)^{61}Cu	^{nat}Cu(n,x)^{61}Co	^{nat}Cu(n,x)$^{58g+m}$Co
17.1 ± 2.5				1.3 ± 0.6	
19.7 ± 2.2				3.5 ± 1.7	
22.6 ± 2.0	0.09 ± 0.02	0.7 ± 0.1	3.8 ± 0.4	11 ± 1	
25.0 ± 1.8	0.28 ± 0.04	1.3 ± 0.2	31 ± 5	12 ± 1	1.8 ± 0.7
27.4 ± 1.7	0.50 ± 0.05	2.0 ± 0.2	81 ± 7	15 ± 2	15 ± 2
30.0 ± 1.6	0.72 ± 0.08	2.4 ± 0.2	110 ± 10	13 ± 2	34 ± 3
32.6 ± 1.5	0.75 ± 0.08	2.2 ± 0.2	140 ± 10	13 ± 2	60 ± 5
35.5 ± 1.4	0.43 ± 0.05	1.5 ± 0.2	95 ± 10		60 ± 5

of the Li target and the formula for the ratio of forward directed peak neutrons. Absolute measurements of the peak neutrons using a calibrated 2″ × 2″ NE213 scintillator were performed and the preliminary results agree well with the predicted number of neutrons. The neutron spectra which were used for the extraction of cross-sections were calculated at the place of the activation foils by the MCNPX code and were normalized and modified according to the experimental measurements, details are described in [5].

4. Extracted cross-sections, uncertainties

To extract the activation cross-section curves in the complex neutron spectra (monoenergetic peak + continuum, which contributes to the production), a modified version of the SAND-II [6] code was used (details in [1]) with the EAF-2010 [7,8] evaluated data used as the input cross-sections. The input cross-section curves were iteratively adjusted so that their product with the neutron spectra corresponded to the measured reaction rates. The average values of the extracted cross-section curve in the energetic regions covered by the monoenergetic peaks were taken for the experimental cross-section values.

The uncertainty on the energy scale was set to the width of the monoenergetic peak (ca. 1.5 MeV at 35 MeV and 2.5 MeV at 20 MeV). On the cross-section scale the sensitivity analysis was performed. The estimated uncertainties of the input parameters were used to randomly sample each input parameter according to the normal distribution and perform the extraction procedure. The distribution of the extracted cross-sections was analyzed and the resulting sigma for each parameter was extracted, Fig. 1. The resulting sigmas for all parameters were summed in square to obtain the cross-section uncertainty.

5. Conclusion

The resulting cross-sections (Tables 1, 2) are in good agreement with the EAF-2010 evaluated data. The exception are the cross-sections for the (n,p+α) reaction which are underestimated by the evaluation (Fig. 2). Similar behavior of the cross-sections for the (n,p+α) reaction was observed also in the case of ^{nat}Cr and ^{nat}Fe [2] and reported by other experimenters [10]. Model calculations with the TALYS-1.8 code [9] were also performed and show similar underestimation of the experimental cross-sections.

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Table 2. Cross-sections of ^{nat}V(n,x) reactions extracted from the NPI/Řež experimental data with the estimated uncertainties. The results marked with (*) were obtained from the irradiation at the target-sample distance of 42 mm, the rest at the target-sample distance 86 mm.

E_n[MeV]	Cross-section [mbarn]			
	^{nat}V(n,x)^{51}Ti (*)	^{nat}V(n,x)^{50}Sc (*)	^{nat}V(n,x)^{48}Sc (*)	^{nat}V(n,x)^{48}Sc
17.1 ± 2.5	14 ± 2		17 ± 2	16 ± 2
19.7 ± 2.2	11 ± 2		14 ± 2	13 ± 1
22.6 ± 2.0	8 ± 3		8 ± 2	8 ± 1
25.0 ± 1.8	15 ± 3	0.27 ± 0.07		8 ± 1
27.4 ± 1.7	7 ± 3	0.23 ± 0.03		9 ± 2
30.0 ± 1.6	10 ± 2	0.23 ± 0.03	8 ± 3	5 ± 1
32.6 ± 1.5		0.33 ± 0.03	6 ± 2	7 ± 2
34.2 ± 1.4				4 ± 1

E_n[MeV]	Cross-section [mbarn]			
	^{nat}V(n,x)^{47}Sc	^{nat}V(n,x)^{46}Sc	^{nat}V(n,x)^{47}Ca	^{nat}V(n,x)^{48}V
17.1 ± 2.5	1.8 ± 0.3			
19.7 ± 2.2	8.5 ± 1	0.3 ± 0.2		
22.6 ± 2.0	22 ± 2	0.2 ± 0.1	0.03 ± 0.02	
25.0 ± 1.8	27 ± 2		0.10 ± 0.01	
27.4 ± 1.7	29 ± 3	0.9 ± 0.3	0.20 ± 0.02	0.20 ± 0.05
30.0 ± 1.6	47 ± 4	0.7 ± 0.2	0.39 ± 0.05	0.30 ± 0.05
32.6 ± 1.5	48 ± 4	15 ± 2	0.81 ± 0.07	0.51 ± 0.07
34.2 ± 1.4	44 ± 4	22 ± 2	0.85 ± 0.08	0.63 ± 0.1

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