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Neutron activation experiments on chromium and tantalum in the NPI p- ^{7}Li quasi-monoenergetic neutron field

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Abstract. The work aims to make the study of neutron activation cross section data up to 35 MeV neutron energy using the reaction ^{7}Li(p,n). This reaction produces the high-energy quasi-monoenergetic neutrons with some tail to lower energies. The cross section data for neutron energies higher than 20 MeV are not well known. The data are needed for the development of the International Fusion Material Irradiation Facility (IFMIF) to test materials for fusion power plants technology and for the comparison to nuclear reaction models as well. The variable-energy proton beam of NPI cyclotron is used for the production of the quasi-monoenergetic neutron field using the thin lithium target. The carbon backing for the Li target is utilized as the beam stopper. The stable operation of the source is achieved under cooling of the Li foil and the carbon backing separately. The system permits to produce neutron flux density of about 10^9 n/cm^2/s in peak at 30 MeV neutron energy. We used the alloy of 70% chromium and of 30% nickel instead of pure chromium foils because of bad mechanical properties of pure chromium material. The chromium and tantalum samples of 15 mm in diameter and of 0.75 mm thickness were activated. All investigated samples were stacked in packets containing the “reference” dosimetry foils of gold. The nuclear spectroscopy methods were used to obtain the activities of produced isotopes. Spectra at HPGe detectors were measured at different cooling times. The most important data obtained for neutron energies of 20 to 35 MeV are described and discussed. The analysis of resulting specific activities and reaction rates is carrying out in terms of C/E ratio (E - measured reaction rate, C - the predicted value of this observable calculated for the neutron spectrum). The neutron flux and spectra across the Cr(+Ni) and Ta samples are calculated using the modified data of the ^{7}Li(p,n) reaction measured by other authors. Activation cross section data for selected reactions of neutrons were taken from EAF-2005 library. The preliminary results are discussed.

1 Introduction

The neutron activation cross section data of reactions at incident energies higher than 20 MeV are needed to improve the accuracy of neutronic calculations for the test of nuclear reactions models and for the various technological applications like IFMIF as well. In the following sections we describe the quasi-monoenergetic neutron source, the activation experiments and the method of data evaluation. The resulting radioactive isotopes were studied by means of gamma spectroscopy methods. The analysis in terms of C/E values was carried out using cross section data from EAF-2005 library [1] and modified neutron spectra [2].

2 Experimental equipment and neutron spectrum

The overall view to the target station of neutron source is shown in figure 1. The proton beam from isochronous cyclotron strikes the Li foil at variable energies from 11 to 38 MeV. The carbon backing serves as a beam stopper.

The neutron spectra [2] were measured at different sets of proton energies. Therefore, we decided to shift the spectra [2] according to our incident proton beam energies. An example is given in figure 2. The spectrum taken for the next analysis is the mean of both shifted spectra.

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Fig. 1. The overall view to the target station of NPI p-^{7}Li neutron source.

3 Experimental procedure and results

The stacks of irradiated foils (CrNi+Au) or (Ta+Au) were activated simultaneously at two distances (48 and 88 mm) from the Li foil. The CrNi alloy is used instead of pure Cr material because of the better mechanical property. The foils were of 14 and 15 mm diameter and thickness of 0.05 mm (Au)to 0.5–0.7 mm (Ta and CrNi). The time profile was

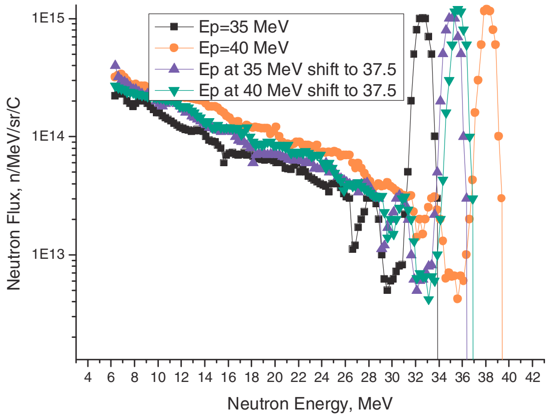

Fig. 2. Neutron spectra of the ^{7}Li+p reaction measured [2] at the proton energies of 35 and 40 MeV. The corresponding spectra shifted to 37.5 MeV proton energy are shown as well.

monitored by the proton beam current. The typical proton beam current was about 3μA. The activation was carried up separately with Li+C and C target only to investigate the contribution of neutrons from carbon stopper.

The set of Ta+Au foil was irradiated at the proton energy of 37.5 MeV. The CrNi+Au foils were irradiated at the proton beam energies 22.0, 27.2, 29.5 and 37.5 MeV.

Irradiated samples were investigated by means of gamma-spectroscopy methods. Two HPGe detectors of 23 and 50% efficiency and FWHM of 1.8 keV at 1.3 MeV were used.

The following reactions were studied.

The reactions given in previous tables include the other open channels, e.g., (n, t) = (n, t) + (n, dn) + (n, p2n). Activated isotopes were identified on the basis of $T_{1/2}$, γ-ray energies and intensities. Resulting isotope activities related to unitary beam current at different Li to foils distances were obtained.

Table 1. Isotopes observed from irradiations of Au foil.

Isotope	$T_{1/2}$	reaction	Threshold (MeV)
Au194	38.02 h	(n,4n)	23.220
Au195	186.09 d	(n,3n)	14.790
Au196	6.183 d	(n,2n)	8.112
Au196m	9.6 h	(n,2n)	8.708

Table 2. Isotopes observed from irradiations of Ta foil. Reactions and thresholds are given for reactions on ^{181}Ta.

Isotope	$T_{1/2}$	reaction	Threshold (MeV)
Ta180	8.152 h	(n,2n)	7.619
Ta178m	2.36 h	(n,4n)	22.245+x
Ta177	56.56 h	(n,5n)	29.164
Hf181	42.39 d	(n,p)	0.246
Hf180m	5.5 h	(n,d)	3.737+1.14
Hf179m	25.05 d	(n,t)	4.874+1.106
Lu177	6.734 d	(n,nα)	0

4 Comparison of experimental results and calculated values

The comparison is based on the usual C/E ratio, where C and E correspond to the calculated and experimental activity, respectively. In the calculations, the cross section data were taken from EAF-2005 [1], the neutron spectra were taken from ref. [2] with shifts described in the previous part. The data on C/E values for different incident proton energies are in the next tables. Experimental uncertainties includes statistical part of errors only.

Table 3. Isotopes observed from irradiations of Cr isotopes.

Isotope	$T_{1/2}$	reaction	Threshold (MeV)
Cr49	42.3 m	Cr50(n,2n)	13.264
Cr48	21.56 h	Cr50(n,3n)	24.058
V48	15.974 d	Cr50(n,t)	12.914
Sc46	83.79 d	Cr50(n,pα)	10.343
Sc47	3.3492 d	Cr50(n,p^{3}He)	20.477
		Cr52(n,dα)	18.931
Sc48	43.67 h	Cr50(n,3p)	19.952
		Cr52(n,pα)	12.807

Table 4. C/E values (including exp. uncertainty in %) for the isotopes observed from irradiations of Au at proton energy Ep.

Isotope	Ep (MeV)	C/E 48 mm	C/E 86 mm
Au196	22.0	1.092 (4)	1.015 (4)
	27.2	1.085 (4)	1.047 (4)
	29.5	1.023 (3)	0.978 (4)
	37.5 a)	0.933 (3)	0.923 (3)
	37.5 b)	1.081 (4)	1.051 (4)
Au196m	22.0	1.200 (6)	1.146 (6)
	27.2	1.307 (5)	1.245 (5)
	29.5	1.294 (5)	1.232 (5)
	37.5 a)	1.044 (7)	0.991 (7)
	37.5 b)	1.218 (5)	1.124 (5)
Au195	27.2	0.802 (10)	0.819 (18)
	29.5	0.705 (11)	0.629 (20)
	37.5 a)	0.446 (12)	0.416 (13)
	37.5 b)	0.816 (15)	0.688 (30)
Au194	29.5	1.088 (3)	0.943 (4)
	37.5 a)	0.837 (3)	0.731 (3)
	37.5 b)	0.970 (3)	0.838 (3)

a) Experiment CrNi + Au. b) Experiment Ta+Au.

Table 5. C/E values (including exp. uncertainty in %) for the isotopes observed from irradiations of Cr at proton energy Ep.

Isotope	Ep (MeV)	C/E 48 mm	C/E 86 mm
Cr49	22.0	0.763 (4)	0.815 (3)
	27.2	0.618 (6)	0.615 (3)
	29.5	0.583 (5)	0.542 (3)
	37.5	0.608 (4)	0.633 (3)
V48	27.2	2.072 (12)	1.852 (6)
	29.5	0.875 (4)	0.763 (6)
	37.5	1.035 (3)	0.875 (3)
Sc46	27.2	0.630 (10)	0.542 (13)
	29.5	0.547 (8)	0.448 (8)
	37.5	0.452 (4)	0.375 (4)
Sc48	27.2	1.159 (6)	0.840 (6)
	29.5	0.720 (6)	0.562 (6)
	37.5	0.642 (12)	0.571 (3)
Cr48	29.5	2.118 (8)	2.319 (8)
	37.5	1.199 (4)	1.121 (3)

Table 6. C/E values (including exp. uncertainty in %) for the isotopes observed from irradiations of Ta at proton energy Ep.

Isotope	Ep (MeV)	C/E 48 mm	C/E 86 mm
Ta178m	37.5	0.180 (4)	0.161 (3)
Hf181	37.5	1.157 (4)	1.083 (3)
Hf180m	37.5	2.405 (4)	2.314 (3)
Hf179m	37.5	30.407 (5)	27.227 (3)
Lu177	37.5	0.207 (15)	0.109 (40)
Ta180	37.5	0.894 (4)	1.126 (5)

The possible difference between spectral yield (measured in the point-like geometry [2]) and the form of spectra in the sample position (due to the integration over space and energy) was not taken into account.

The C values are obtained on the basis of the convolution integral of neutron spectrum and cross section function as in the "benchmark" experiments. It means that not only quasi-monoenergetical peak is taken into account. But, assuming the dependence of cross section vs. energy as more or less correct, we can come to the conclusion that the influence of quasi-monoenergetic part is dominant in most cases.

There are no cross section data [1] of the reaction Ta181 (n,5n)Ta177 at 35 MeV neutron energy. The cross section value of 24 mb (uncertainty 12%) could be determined under assumptions that the effect comes from the quasi-monoenergetic spectrum part only and the cross section is constant in the region of quasi-monoenergetic peak.

Similarly, we can estimate the cross section of the reaction Cr(n,x)Sc47(normalized to the sum of stable Cr isotopes) at 35 MeV. The value of 1.50 mb (uncertainty 5%) could be determined under same assumptions as in the reaction described above.

5 Conclusions

The isotope activities produced in Cr, Ta and Au isotopes by neutrons with energies up to 37 MeV were measured using the quasi-monoenergetic p-^{7}Li neutron source. The obtained data were compared with the calculations. The C/E values for Au support the reliability of our procedure. The neutron-source reaction of p +^{7}Li is a powerful tool to study high energy neutron data.

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