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Measurements of Neutron Yield from Deuterium Plasmas at JET by Activation Techniques

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Abstract. The paper reports on experiments carried out at JET to test the possibility of using some activating materials (e.g. ^{89}Y, ^{167}Er, ^{204}Pb, ^{180}Hf, ^{111}Cd, etc.) to perform multi-foil neutron activation measurements. It is shown that apart from indium other materials can be successfully used in these measurements delivering more exact information about fluxes and also energy spectra of the analysed neutrons. These and other materials have threshold energy in the interesting energy range (0.5 – 15 MeV) and relatively large cross sections for the nuclear reactions, but have not been used in the activation measurements supposedly because produce daughter nuclides with a relatively short half-life time. We propose then some modification of the JET activation system mainly in order to convey the activation samples faster to the detector.

Keywords: Neutron diagnostic, Activation method, JET facility, irradiation ends.
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INTRODUCTION

The neutron activation technique has been used at JET for a long time mainly to determine local neutron fluence at certain measuring points. These measurements were supported by neutron transport calculations in order to relate the neutron fluence to the total yield of neutrons from the plasma. Also the calibration of the time-resolved detectors was achieved in this way. However, this method could be more effectively used provided that many different elemental foils (activators) are exposed simultaneously. It is important then to find activation materials with suitable cross section ($\sigma(E_n)$) and threshold energy (E_p) of the activation reactions to cover interesting energy interval 0.5–16 MeV, and especially range close to 2.5 MeV. There exist a few nuclear reactions which have reaction threshold energy in the energy range 0.5 – 3 MeV and relatively large cross-section values, e.g.: ^{89}Y(n,n')^{89m}Y, ^{204}Pb(n,n')^{204m}Pb, ^{167}Er(n,n')^{167m}Er (Table 1 and Fig. 1). Many of these reactions have not been used so far in JET experiments supposedly because their daughter nuclides decay with a relatively short half-life time ($T_{1/2}$).

The paper reports on measurements made at JET to test the possibility of using some activating materials to perform multi-foil neutron activation measurements. The paper demonstrates interesting results obtained with such nuclear reactions as ^{180}Hf(n,n')^{180m}Hf, ^{111}Cd(n,n')^{111m}Cd, ^{27}Al(n,p)^{27}Mg. Hafnium and yttrium have never been used at JET and in other high temperature plasma experiments before. In order to apply at JET reactions producing short-lived nuclides we propose some modifications of the JET activation system.

The neutron activation technique could be also applied to estimate neutron energy spectrum. In principle one activation material (activator) is enough to measure neutron fluence. However, a set of materials with different nuclear reaction cross-sections is needed to determine neutron energy spectrum. The neutron spectrum can be estimated only in the energy range covered by significant cross-section values of the used activators.

The activation method has been commonly used in nuclear fission reactors. Some researchers proposed also to use this method in JET experiments to measure neutron energy spectra but such measurements have never been performed [1]. We have undertaken then an attempt to resume these investigations at JET.

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SELECTION OF THE ACTIVATING MATERIALS

In the first place we selected some materials which physical and chemical properties qualify them to be activators for d-d neutron measurements. In Table 1 there are presented those materials and expected nuclear reactions. Cross-sections for these reactions are demonstrated in Fig. 1. In the considered neutron energy range (0.0 – 15 MeV) mainly neutron inelastic scattering reactions occur. Some of the chosen materials are not dosimetry standards and they have never been used to perform activation measurements, especially in fusion experiments. Therefore, cross-section values for the envisaged nuclear reactions may not be known very well. It was then necessary to check if the theoretically foreseen data are comparable with those obtained experimentally.

The probability of a nuclear reaction induced by neutron in the activating material is expressed by so called nuclear reaction rate $\langle\sigma\cdot\varphi\rangle$. The value of $\langle\sigma\cdot\varphi\rangle$ can be calculated by measuring the intensity of γ-radiation which is emitted from the irradiated sample. Generally the following formula is used:

$$\langle\sigma\cdot\varphi\rangle \equiv \int_0^\infty \sigma(E)\cdot\varphi(E)\cdot dE = \frac{A_0}{N_a\cdot(1-e^{-\lambda\cdot t_a})},$$

where: σ – reaction cross-section, φ – neutron flux density, E – neutron energy, λ –daughter nuclide decay constant, A_0 – sample activity at the irradiation end, N_a – number of activator nuclei, t_a – irradiation time.

In order to calculate the total yield of neutrons originating from a given source it is necessary to estimate by appropriate modelling (usually by Monte Carlo method) the neutron flux distribution in the surroundings of the activation sample. In general, the probability of provoking a nuclear reaction in the activation material is calculated in this way. The average neutron rate can be then calculated by the comparison of the measured and computed nuclear reaction rates.

Indium activators have been routinely used in many tokamak experiments (also at JET) to determine the total d-d neutron yield in a single plasma discharge. The nuclear reaction $^{115}In(n,n')^{115m}In$ is fully exploited in those measurements. One of our objectives has been then to verify the feasibility of applying other than indium materials as a neutron yield monitor. Using more than one activation material in the same shot one can estimate $\langle\sigma\cdot\varphi\rangle$ for a few nuclear reactions, which are characterised by different E_p and $\sigma(E_n)$. In principle, the neutron flux density for neutrons of different energy can be estimated in this way. It provides the basic data for neutron energy spectrum evaluation.

The Monte Carlo modelling of the neutron flux distribution in the JET facility was done almost twenty years ago (in 1989) [2]. Those calculations were performed under the assumption that the plasma was in a thermodynamic equilibrium (i.e. for a Maxwell ion velocity distribution) [4]. This modelling provided, so called, activation coefficients for some activators in particular irradiation ends [2], [3], [4].

The JET facility is equipped with 8 irradiation ends (KN2 system) [2]. The Monte Carlo simulations were especially conducted for so called 3-Upper irradiation end (3-U) – the only JET irradiation end placed inside the vacuum vessel [3]. Samples located in 3-U are exposed to relatively high neutron flux density and relatively low number of scattered neutrons in comparison to the seven other irradiation ends, which are located behind the tokamak shield. The 3-U irradiation end must be cooled by water mainly because the samples delivered to this end are encapsulated in a polyethylene capsule [2].

The materials selected in our laboratory were irradiated at JET during the C-17 and C-19 experimental campaigns, in general in the 3-U. Usually, a few samples of different materials were placed in one polyethylene capsule and they were transported to the 3-U for irradiation in a single shot. We also used in some shots aluminium samples, which were rather suitable for the detection of d-t neutrons. The set of samples which was used in a given shot always contained one or two indium samples. It made possible to measure the total d-d neutron yield basing on the available activation coefficients.

All the samples were in a cylindrical form, i.e. 18 mm in diameter. We used the following samples: In_1(2.9570 g), In_2(3.8926 g), Hf(2.5355 g), Al_1(0.7270 g), Al_2(0.7254 g), Y(0.7319 g), Cd(2.2072 g), Er(1.3948 g), Au_1(9.9886 g), Au_2(10.000 g), Ni_1(4.6458 g), Ni_2(4.6408 g), Pb(5.3122 g).

EXPERIMENTAL SET-UP

The samples located in the polyethylene capsule (JET standard) were transported to and from the irradiation ends by the JET pneumatic system, which was equipped with so called carousel [5].

The γ-radiation emitted by the irradiated samples was measured by a coaxial high purity germanium (HPGe) detector delivered by Canberra Inc. These measurements allowed to identify nuclear reactions, which were induced by neutrons in the samples as well as to calculate rates of these reactions (Tables 2). However, it is not

feasible at the moment to recalculate the measured reaction rates as long as the activation coefficients for those reactions are not calculated. Nevertheless, most of the expected nuclear reactions (except those producing short-lived nuclides and those induced in nuclides of a low natural abundance) have been identified on the basis of analysis of the γ-radiation spectra, which were taken with the HPGe.

Some materials e.g. indium, had to be cooled immediately after the irradiation before being analysed with the HPGe. It means that indium samples after exposing to the neutrons were kept far away from the detector for 2.5 hours to reduce activity of the ^{116}In isotope, which was rather produced by thermal neutrons. Soon after the exposition the activity of ^{116}In was much more intense than activity of ^{115m}In isotope.

Among materials selected in our laboratory yttrium seems to be especially relevant for measuring 2.5 MeV neutrons. We used this material in campaign C-19 and it appeared that only nuclear reactions of the type ^{89}Y(n,n')^{89m}Y were induced by neutrons in the yttrium samples. Excited ^{89m}Y nuclei emitted only one γ-line of energy 909 keV and a half-live of 16 sec. It seems than that yttrium could be better monitor of 2.5 MeV neutrons than commonly used indium. Moreover, it is easier to measure the only one excited γ-line (909 keV), and it could be done even by means of a NaI(Tl) detector. We also used hafnium. A few radioactive isotopes were produced in this material. We decided to measure the activity of ^{180m}Hf isomer. Hafnium samples had to be cooled in order to reduce the activity of the short-lived isotopes. Cadmium was also used in the recent campaign. This material was rather not recommended for the activation measurements because it has very large cross section values for thermal neutrons (~10^4 barn). However, the induced activity was not extremely high, so we used this material together with other samples. Also γ-activity from the ^{27}Al(n,p)^{27}Mg reactions was registered in spite of the fact that cross-section value for this reaction is very low for 2.5 MeV neutrons. Probably the measured activity was induced by 14 MeV neutrons, which originated from tritium burn-up. Also activity induced in a gold sample was the result of radiative capture of neutrons. Cross-section values for such nuclear processes are very high and probably it was impossible to reveal in this way other nuclear reactions induced by neutrons in gold.

The activities connected with transportation of the capsule and with removing a sample from the capsule and putting it on the HPGe detector took at least 70 sec. For this reason the short-lived nuclides (like ^{167m}Er) could not be observed. To apply at JET the materials producing short-lived nuclides it is necessary to transport the samples from the irradiation ends to the HPGe detector as fast as possible. The activation materials applied in such kind of experiment do not need to be removed from the capsule to analyse them by the HPGe detector. Especially, the materials producing short-lived nuclides could be measured without removing them from the capsule. It could shorten the cooling time. We propose to select one of the irradiation ends and to connect it directly with the γ-detector through a by-pass evading the carousel. The HPGe detector should be recalibrate to measure the samples located inside the capsule.

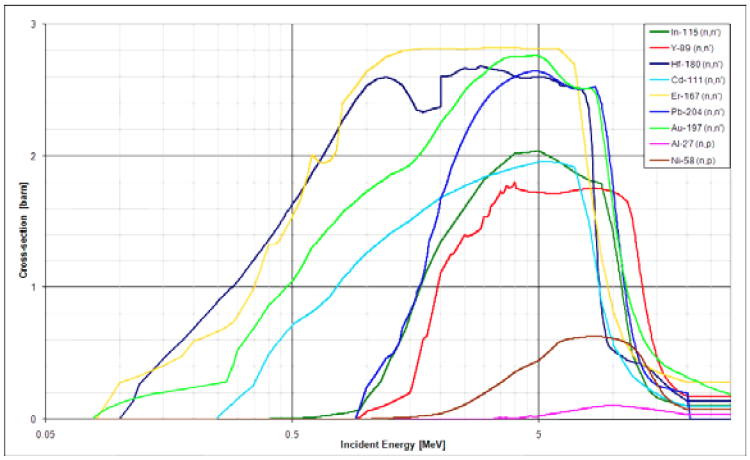

FIGURE 1. Cross-sections for the selected reactions.

CONCLUSIONS

1. Some new materials have been applied to neutron activation measurements at JET.
2. In those measurements there were observed many nuclear reactions induces by D-D fusion neutrons.
3. Among applied materials yttrium seems to be especially useful for 2.5 MeV neutrons measurements.
4. A new Monte Carlo modeling is necessary to analyze neutron yield and spectrum measurements performed by means of the new activation materials.

TABLE 1. The selected materials and expected reactions.

Element	Isotope	Abundance	Reaction	Daughter $T_{1/2}$
In	^{115}In	95.7%	^{115}In (n,n') ^{115m}In	4.5 h
Hf	^{180}Hf	35.1%	^{180}Hf (n,n') ^{180m}Hf	5.5 h
Er	^{167}Er	23.0%	^{167}Er (n,n') ^{167m}Er	2.3 s
Cd	^{111}Cd	12.8%	^{111}Cd (n,n') ^{111m}Cd	48.5 m
Y	^{89}Y	100%	^{89}Y (n,n') ^{89m}Y	15.7 s
Ni	^{58}Ni	68.1%	^{58}Ni (n,p) ^{58m}Co→ ^{58}Co	9 h → 71 d
Au	^{197}Au	100%	^{197}Au (n,n') ^{197m}Au	7.7 s
Pb	^{204}Pb	1.4%	^{204}Pb (n,n') ^{204m}Pb	67.2 m
	^{207}Pb	22.1%	^{207}Pb (n,n') ^{207m}Pb	0.8 s

TABEL 2. Results of activation measurements including the measured nuclear reaction rates.

Shot No and Total Neutron Yield	Irradiated sample	t_c [s]	t_m [s]	Identified reaction	$\langle\sigma\cdot\varphi\rangle$ [s^{-1}]
70337 ($3.46\cdot10^{16}$)	In_1	11 316	3 000	^{115}In (n,γ) ^{116}In	$6.4\cdot10^{-15}$ ± 8%
				^{115}In (n,n') ^{115m}In	$7.8\cdot10^{-16}$ ± 8%
	Al_1, Al_2	171	600	^{27}Al (n,γ) ^{28}Al	$1.5\cdot10^{-17}$ ± 9%
				^{27}Al (n,p) ^{27}Mg	$2.1\cdot10^{-18}$ ± 14%
	Hf	14 926	5 400	^{180}Hf (n,n') ^{180m}Hf	$3.7\cdot10^{-16}$ ± 10%
				^{180}Hf (n,γ) ^{181}Hf	$3.0\cdot10^{-14}$ ± 12%
	Au_1	20 978	600	^{197}Au (n,γ) ^{198}Au	$3.9\cdot10^{-14}$ ± 8%
70460 ($1.28\cdot10^{16}$)	In_1	9 958	1 800	^{115}In (n,γ) ^{116}In	$3.6\cdot10^{-15}$ ± 8%
				^{115}In (n,n') ^{115m}In	$3.5\cdot10^{-16}$ ± 8%
	Al_1, Al_2	108	600	^{27}Al (n,γ) ^{28}Al	$6.7\cdot10^{-18}$ ± 9%
				^{27}Al (n,p) ^{27}Mg	$1.4\cdot10^{-18}$ ± 15%
	Hf	17 294	5400	^{180}Hf (n,n') ^{180m}Hf	$1.2\cdot10^{-16}$ ± 14%
				^{180}Hf (n,γ) ^{181}Hf	$3.2\cdot10^{-14}$ ± 11%
	Au_1	25 260	3600	^{197}Au (n,γ) ^{198}Au	$2.1\cdot10^{-14}$ ± 8%
		84 180	1800	^{197}Au (n,γ) ^{198}Au	$1.8\cdot10^{-14}$ ± 8%
70627 ($1.25\cdot10^{16}$)	In_1, In_2	7 259	2 400	^{115}In (n,γ) ^{116}In	$2.2\cdot10^{-15}$ ± 6%
				^{115}In (n,n') ^{115m}In	$3.4\cdot10^{-16}$ ± 6%
	Al_1, Al_2	314	600	^{27}Al (n,γ) ^{28}Al	$1.6\cdot10^{-18}$ ± 8%
				^{27}Al (n,p) ^{27}Mg	$8.5\cdot10^{-19}$ ± 9%
	Y	75	180	^{89}Y (n,n') ^{89m}Y	$1.1\cdot10^{-17}$ ± 7%
	Cd	975	1 200	^{111}Cd (n,n') ^{111m}Cd	$6.1\cdot10^{-16}$ ± 7%

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