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Activation Material Selection for Multiple Foil Activation Detectors in JET TT campaign

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In the preparation for the Deuterium-Tritium campaign, JET will operate with a tritium plasma. The T+T reaction consists of two notable channels: (1) T+T → ^{4}He + 2n, (2) T+T → ^{5}He + n → ^{4}He + 2n. The reaction channel (1) is the reaction with the highest branching ratio and a continuum of neutron energies being produced. Reaction channel (2) produces a spectrum with a peak at 8.7 MeV. A particular problem is the ratio between the individual TT reaction channels, which is highly dependent on the energy of the reacting tritium ions. There are very few measurements on the TT spectrum and the study at JET would be interesting.

The work is focused on the determination of the spectral characteristics in the TT plasma discharges, especially on the presence of the 8.7 MeV peak, a consequence of channel (2) of the TT reaction. The possibility to use an optimized set of activation materials in order to target the measurement of the 8.7 MeV peak is studied. The lower limit of detection for the channel (2) ratio within the TT reaction is estimated and the influence of DT source neutrons, which are a consequence of deuterium traces in the plasma, is investigated.

Keywords: JET, TT plasma, spectroscopy, activation measurements

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1. Introduction

A new Deuterium-Tritium campaign (DTE2) is planned at JET in 2019. In preparation for this campaign in 2018 JET will operate, with a tritium plasma. JET has spectrometry capabilities which have been used to study fast ions from both the D(D,n)^{3}He (DD) reaction and the T(D,n)^{4}He (DT) reaction [1-3]. The emission from the T(T,2n)^{4}He (TT) reaction, which has a cross section comparable to the DD reaction, is normally of little importance since it is drowned by neutrons from the much more probable DT reaction. However, the planned operation with a tritium plasma will allow for the possibility to study the TT neutron spectrum.

In contrast to the DT and DD reactions, the TT reaction has three particles in the final state, which results in a continuum of neutron energies being produced, even for mono-energetic reactants. The TT neutron energy spectrum has previously been measured in accelerator experiments [4, 5] and in inertial confinement fusion experiments [6]. In the accelerator experiments, where the centre-of-mass energies were in the 100 keV range, the three-body neutron energy continuum, ranging between 0 and 9.4 MeV, was distorted by a peak around 8.7 MeV, the extent of this peak exhibits, however, an energy dependence [3]. Plasma ions at JET have a different energy spectrum with respect to previously performed experiments and measurements of the presence of interactions between the particles in the final state in a JET TT plasma could be of scientific interest.

The present work is focused on the determination of the spectral characteristics in the TT plasma discharges, especially on the presence of the mentioned 8.7 MeV peak. The standard JET spectroscopic capabilities are routinely used for spectrum determination [7]. The focus in this work is, however, the study of the possibility to use an optimized set of activation materials in order to specifically target the measurement of the 8.7 MeV peak. The optimal choice of these materials is limited by the range of their cross-sections and half-lives and in addition by several constrains, namely that the materials used in irradiations may should not be combustible and should be in solid form. For this reason only standard dosimetry materials from the IRDFF data base [8] were considered.

2. The TT reaction

Only limited literature is available on the study of the TT reaction, especially at the relatively low triton energies, expected in the JET tokamak. The TT reaction consists of three channels:

(1) $T+T \rightarrow {}^4He + 2n$
(2) $T+T \rightarrow {}^5He(GS) + n \rightarrow {}^4He + 2n$
(3) $T+T \rightarrow {}^5He(ES) + n \rightarrow {}^4He + 2n$

GS meaning the ground state and ES the excited state of ^{5}He. The reaction channel (1) is the reaction with the highest branching ratio regardless of the reactant energies [9]. The emitted neutrons have an elliptical energy distribution [10, 11].

Reaction channels (2) and (3), on the contrary, do not produce a continuum of energies. The neutron energies, resulting from these channels, have defined energies, but relatively broad widths at FWHM [9]. The mean energy for the first emitted neutron from reaction (2) is calculated as [9] 8.778 MeV and for reaction (3) as 7.738 MeV.

The ratio of the probability for the three individual reaction channels is highly dependent on reactant energies [5] with the common feature that channel (2) becomes pronounced with increasing ion CMS temperatures and channel (3) at even higher energies. In the case of ion energies as found in the JET plasma, it is anticipated that in addition to the TT reactions through channel (1) only reactions through channel (2) may appear and that the number of the latter will probably be low or may even approach zero. For this reason the channel (3) reactions are entirely neglected in the continuation and the focus is stressed on the possibility of the presence of the interaction of the TT ions via the channel (2) reaction.

3. Neutron flux at JET

The neutron diagnostics system, positioned closest to the plasma in the JET torus, is the KN2–3U neutron activation system, which penetrates inside the vacuum vessel [12], and is shown in Figure 1. Due to its best position it is also the location of choice for irradiation of activation foils during the TT campaign.

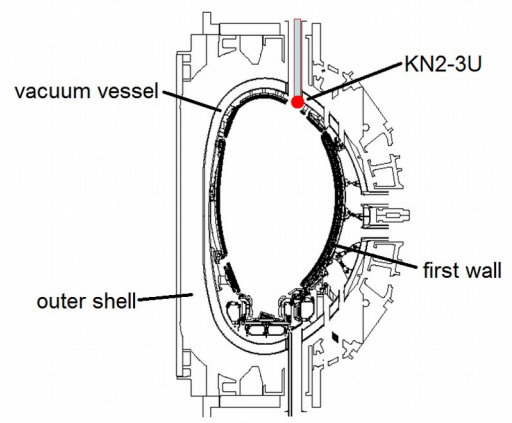

Fig. 1. Location of the KN2-3U activation system in the cross-section of the JET torus (marked with the dot).

3.1 Neutron transport calculations

Neutron spectra are routinely calculated for locations inside and around the JET torus [13, 14]. Experience shows that for the KN2-3U location the uncertainty in the calculated flux values in the higher energy bins is low (typically lower than 3% for direct plasma neutrons), and increases at intermediate and thermal energies.

The source energy dependence of the TT neutrons was simulated using the available data [1-6], while the

source geometry had typical JET characteristics – major radius 300 cm, minor radius 80 cm, elliptical elongation of 1.6 . One free parameter in modelling of the energy dependence of the TT neutron source is the branching ratio of neutrons, born through channel (2) of the TT reaction, noted as α. Results of calculations for neutron spectra with the MCNP6 code [15] at the KN2-3U position for three cases of α, namely α=0, α=1 and α=0.05, are presented in Fig. 2. The last case, α=0.05, is representative of a possible ratio for JET plasmas.

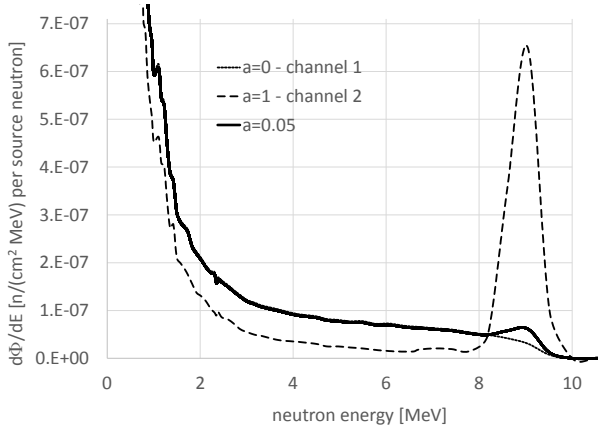

Fig. 2. Calculated spectra at the location of the KN2-3U neutron diagnostics for three cases of α - 0, 1 and 0.05, α representing the branching ratio for channel (2). The 8.7 MeV peak of the TT spectrum is clearly visible also in the curve for α=0.05.

4. Neutron spectroscopy and activation foil response

Several methods for neutron spectroscopy are employed at the JET torus [7] including high resolution diamond detectors, which will not be discussed here. Neutron spectroscopy using activation foils is broadly developed [16, 17] and could be used as a method complementary to other spectroscopic systems. One of the important decisions before each measurement is the choice of activation materials to be used. Neutron spectrum unfolding, or adjustment, is then usually performed through the use of computer codes and a proper choice of guess spectra used as pre-information.

In the present work explicitly the presence and extent of the channel (2) peak of the TT reaction (i.e. the α value) in a JET TT plasma with a *pair* of activation foils, positioned in the KN2-3U diagnostics, is described. This technique may be used in addition to other measurement techniques. The simpler approach is used also due to the limited availability of the KN2-3U diagnostics and consequently a low number of JET pulses, possibly available for the particular experiment. The choice of suitable activation materials is investigated. Further the lower measurable limit for α is estimated. As foundation for the analyses the calculated neutron spectra in the JET tokamak are used.

4.1 Determination of α

In case the energy dependent neutron flux in a diagnostic position as a function of the plasma neutron source can be calculated with a high precision, it is in principle possible to determine the ratio α with a measurement using only two suitable activation foils. The number of activation reactions per target atom in each of the foils in a TT plasma discharge with arbitrary α can be written as::

$$A_I = Y\left((1-\alpha)\int_E \Phi_1(E)\cdot\sigma_I(E)dE + \alpha\int_E \Phi_2(E)\cdot\sigma_I(E)dE \right)$$

(1) and

$$A_J = Y\left((1-\alpha)\int_E \Phi_1(E)\cdot\sigma_J(E)dE + \alpha\int_E \Phi_2(E)\cdot\sigma_J(E)dE \right)$$

(2)

in which case the quantities are defined as

A_I , A_J – number of activation reactions per target atom in detector foils *I* and *J* exposed during the plasma discharge,

Y – total JET neutron yield during the plasma discharge,

$\sigma_I(E), \sigma_J(E)$ - energy – dependent cross-sections for the dosimetry reaction for materials *I* and *J*,

$\Phi_1(E), \Phi_2(E)$ - neutron spectra for channel (1) or channel (2) of the TT neutron source at the location of the KN2-3U detector per one plasma source TT neutron of the respective TT reaction channel.

The set of equations (1) and (2) can be combined in order to eliminate the unknown yield *Y* of a specific JET pulse to find the unknown ratio α as

$$\alpha = \frac{\mu_{I1} - \frac{A_I}{A_J}\mu_{J1}}{\frac{A_I}{A_J}(\mu_{J2}-\mu_{J1}) - (\mu_{I2}-\mu_{I1})}$$

(3)

introducing the quantity μ_{XZ} as

$$\mu_{XZ} = \int_E \Phi_Z(E)\cdot\sigma_X(E)dE \quad , \qquad (4)$$

i.e. the partial reaction rates for material *x* and spectrum z. α can thus be calculated with the use of any two foils with the constrain that $\mu_{I2}/\mu_{I1} \neq \mu_{J2}/\mu_{J1}$ [1]. In reality the values for μ_{XZ} and the ratio A_I/A_J are subject to uncertainties, reflected also in the accuracy of the value

[1] The constrain is derived from Eq.'s 1-4 by noting that if $\mu_{I2}/\mu_{I1} = \mu_{J2}/\mu_{J1}$, i.e. the ratio of the sensitivity to channel (2) neutrons with regards to channel (1) neutrons is equal for materials I and J, $\frac{A_I}{A_J} = \frac{(1-\alpha)\mu_{I1}+\alpha\mu_{I2}}{(1-\alpha)\mu_{J1}+\alpha\mu_{J2}}$ can be rewritten as $\frac{A_I}{A_J} = \frac{(1-\alpha)\mu_{I1}+\alpha\mu_{I2}}{(\mu_{J2}/\mu_{I2})(1-\alpha)\mu_{I1}+\alpha\mu_{I2})}$ and consequently $\frac{A_I}{A_J} = \frac{\mu_{I1}}{\mu_{J1}} = \frac{\mu_{I2}}{\mu_{J2}}$. It is easy to derive that in this case the denominator and numerator in Eq. 3 both equal to 0 .

for α. The most extensive part of the work was dedicated to estimation of these uncertainties.

4.2 Uncertainty propagation

The values of μ_{XZ}, as calculated with MCNP via equation (4), are subject to uncertainties originating from the Monte Carlo method and uncertainties due to the used nuclear data. The former are in calculations for JET reasonable low, in order to minimize the latter, only evaluated dosimetry materials from IRDFF 1.05 [8] were considered. Since μ_{XZ} are found in equation (4) the mentioned uncertainties are propagated also to the calculated value of α. In addition the A_I and A_J values are subject to measurement uncertainties, also reflected in the accuracy of α. Both types of uncertainties are discussed.

Uncertainty due to Monte Carlo calculations

The accuracy of the spectra, calculated in the KN2-3U position of the JET tours, is dependent also on the neutron energy. Typically the calculations are more precise in the higher energy range; the uncertainty of the model ranges from 2% – 6% above 3 MeV, while it is higher below 1 MeV. The uncertainty in the model, MCNP statistical uncertainty and the uncertainty in nuclear data all contribute to the overall uncertainty of the calculated values. For each of the μ_{XZ} values for a particular activation material the uncertainty is calculated individually by performing the integral of eq. (4) with evaluation of the uncertainties. These uncertainties in the μ_{XZ} values due to the uncertainties in the nuclear data and the in the calculated neutron spectra were calculated using the RR_unc code [18] and are listed in Table 1 for all considered activation reactions. In addition to the total uncertainty, the uncertainty contributions due to the nuclear data and the spectra are listed separately.

Experimental uncertainty of KN2-3U measurements

The derived value of α is subject also to the experimental uncertainty of the measured activities of the activation foil pair, or more precisely to the uncertainty in the ratio A_I/A_J (Eq. 4). The irradiations are performed with a pneumatic system, which delivers the samples to an HPGe gamma spectrometer [17]. The uncertainty of an activity measurement is typically lower than 10%, provided that sufficient activity is induced during neutron irradiation. In case of low count rates, as a consequence of low activation cross-sections and/or long decay times of the activation materials the statistical uncertainties in the measured activities are important. The statistical uncertainties for all considered activation reactions have been calculated for the KN2-3U measurement system and for a maximum allowable mass of 10 g of irradiated material and a maximum counting time of 1 day. These uncertainties are listed in Table 1.

4.3 Activation foil material selection

The International Reactor Dosimetry and Fusion File (IRDFF) features 76 different nuclear reactions [8]. The focus of this work was to determine which reactions are suitable for the goal of distinguishing the spectra of channels (1) and (2) of the TT reaction. For a simple differentiation, one of the materials should be responsive primarily to neutron energies around 8.7 MeV (i.e. primarily to channel (2) TT neutrons), while the other should be responsive primarily to lower energies (this is the case in which the ratio μ_{I2}/μ_{I1} for the first dosimetry material and μ_{J2}/μ_{J1} for the second material differ by a large factor, preferably 5 or more). Due to the very similar shape of the spectra for channels (1) and (2) in the lower energy part of the spectrum (visible in Fig. 1), an effective differentiation is possible only with the effective elimination of this part of the spectrum by using threshold dosimetry reactions with threshold energies of a few MeV. Considering only threshold reactions is advantageous also from the viewpoint of lowering the calculation uncertainty, which is higher for energy bins below 3 MeV (Section 4.2). On the other hand no neutrons with energies above 10 MeV, originating from the TT reaction are expected and materials with a threshold above 10 MeV would yield zero response. For this reason only dosimetry materials with lower threshold energies above approximately 3 MeV and below 10 MeV were considered. The set of possible threshold reactions, filtered from the IRDFF library [8], is presented in Table 1. Table 1 includes the uncertainties in the reaction rates due to the uncertainties in the nuclear data and the calculated spectra for both TT reaction channels, and the statistical uncertainty due to the counting process after irradiation.

Tab. 1: Set of dosimetry materials from IRDFF 1.05 [8] with energy thresholds between 3 MeV and 10 MeV including the notation of the approximate threshold energy. Evaluated uncertainties in the reaction rate values (Eq. 4) due uncertainties in nuclear data, spectral characteristics and counting statistics.

dosimetry reaction	Appr. threshold energy [MeV]	uncertainty [%]				
		nuclear data		calculated spectra		Measure-ment stat. unc.
		Ch1	Ch2	Ch1	Ch2	
24Mg(n,p)24Na	5	0.87	0.86	3.15	2.06	0.02
27Al(n,p)27Mg	2	2.40	3.31	3.47	2.07	0.02
27Al(n,a)24Na	6	0.78	0.83	2.84	2.04	0.03
28Si(n,p)28Al	4	2.50	2.89	3.64	2.09	0.02
46Ti(n,p)46Sc	2.8	3.12	2.95	3.59	2.08	0.11
48Ti(n,n'p)47Sc	9.5	6.21	6.53	3.01	2.05	0.10
51V(n,a)48Sc	6	4.91	4.61	2.46	2.02	0.42
54Fe(n,a)51Cr	4	3.20	3.14	3.33	2.07	0.22
56Fe(n,p)56Mn	5	3.08	3.31	3.27	2.06	0.04
59Co(n,a)56Mn	5	3.12	2.77	2.95	2.04	0.10
93Nb(n,2n)92^{m}Nb	9	6.58	7.62	3.56	2.17	3.47
115In(n,2n)114^{m}In	9.3	17.9	17.9	8.38	3.71	27.07
127I(n,2n)126I	9.2	19.0	18.8	4.58	2.46	5.19
141Pr(n,2n)140Pr	9.5	27.6	27.6	33.7	13.2	126.42
169Tm(n,2n)168Tm	8	6.46	5.61	2.20	2.01	0.57

197Au(n,2n)196Au	8.1	3.71	3.72	2.19	2.01	0.19
204Pb(n,n')204^{m}Pb	3	4.44	4.58	3.59	2.08	0.02
238U(n,2n)237U	6.2	1.91	2.02	2.98	2.05	0.05

4.4 Lower limit of detection of channel (2) presence

The main goal of the present study is the determination of the lowest value of α, which could still be detected with a suitable pair of activation foils. The criterion used for this purpose is that the uncertainty in α, noted as α_{unc}, be three times smaller than the value of α itself, i.e.:

$$\alpha > 3 \cdot \alpha_{unc} \quad (5)$$

An analyses of the uncertainty for all pairs of foils, listed in Tab. 1, was performed using forward uncertainty propagation. The results for the lowest values of α complying with Eq. (5), are presented in Tab. 2. In the table the ratios the μ_2/μ_1 for both dosimetry materials are also presented.

Tab. 2 . The lowest measurable value of □ as a function of the pair of activation foils used. The criterion is that □ > 3□□$_{unc}$. n.m. means that the measurement is not possible with the specific activation foil pair regardless of the value of □. In the top row or and in the first column the values for □$_2$/□$_1$ for the specific reaction are listed.

	μ_{I2}/μ_{I1}	3.7	2.9	4.5	17.3	16.6	2.7
μ_{J2}/μ_{J1}	Foil material /reaction	28Si(n,p)28Al	46Ti(n,p)46Sc	54Fe(n,α)51Cr	169Tm(n,2n)168Tm	197Au(n,2n)196Au	204Pb(n,n')204^{m}Pb
3.2	27Al(n,p)27Mg	n.m.	n.m.	n.m.	0.09	0.09	n.m.
3.7	28Si(n,p)28Al		n.m.	n.m.	0.11	0.11	n.m.
2.9	46Ti(n,p)46Sc			n.m.	0.09	0.09	n.m.
4.5	54Fe(n,α)51Cr				0.17	0.17	n.m.
17.3	169Tm(n,2n)168Tm					n.m.	0.07
16.6	197Au(n,2n)196Au						0.07

For a pure tritium plasma the lowest detectable value of α is around 7% with the use of the most favourable activation foil pairs. As anticipated the lowest measurable α is found for material pairs with the largest difference in the μ_2/μ_1 ratio. It turns out that α can not be measured at all for pairs with a similar ratio.

4.5 Disturbance due to DT neutrons

The above analyses has been performed with the assumption that the plasma neutrons originate solely from the TT reaction. In a realistic JET tritium plasma a small amount of deuterium will always be present. Even if the D fraction is only 1 percent, the neutron yield originating from DT reaction will be comparable to that originating from TT reactions due to its much higher fusion cross-section.

The possible influence of the presence of deuterium in the plasma has been investigated for a most favourable case, i.e. by repeating the previous analyses with the inclusion of a yield of DT neutrons equal to 20% of the total neutron yield, assuming that this may be achieved at JET towards the end of the TT campaign. The relative uncertainty, with which this yield can be measured, was estimated to be 7% in accordance with the above results for the similar TT channel (2) case. The MCNP simulation of the additional DT neutrons are treated in a similar way as described in Section 4 for the TT neutrons. They are also subject to the same sources of uncertainties (Section 4.2). DT neutrons would typically be measured by employing additional higher energy threshold reactions ^{59}Co(n,2n)^{58}Co or ^{90}Zr(n,2n)^{89}Zr [17].

The uncertainty of α in equation (3) increases due to the additional uncertainty in neutron spectra as a consequence of DT neutron disturbance. The calculations presented in Tab. 2 were repeated for a realistic plasma with the ratio of the TT and DT yields of source neutrons of Y_{TT} : Y_{DT} = 0,8 : 0,2 .

In this case the lowest measurable values α are larger, therefore the criterion of Eq. (5) was relaxed slightly to $\alpha > 2 \cdot \alpha_{unc}$. The results are presented in Tab. 3.

Tab. 3. Lowest measurable value of □ as a function of the pair of activation foils used; Y_{TT} : Y_{DT} = 0,8 : 0,2 . The criterion is that □ > 2□□$_{unc}$. Subset of reactions, listed in Tab. 1.

Foil material	Al-27 (n,p)	Al-27 (n,a)	Ti-46 (n,p)	Pb-204 (n,n')	U-238 (n,2n)
Mg-24(n,p)	n.m.	n.m.	0.45	0.35	n.m.
Al-27(n,p)		0.44	n.m.	n.m.	0.45
Al-27(n,a)			0.36	0.29	n.m.
Ti-46(n,p)				n.m.	0.35
Pb-204(n,n')					0.24

With the addition of the disturbance due to the DT component the detection of the TT reaction channel (2) neutrons becomes more difficult and the lowest value of detectable α increases to over 24%. The detectability can be improved with a low deuterium fraction in the plasma and exact measurements of the DT component.

The above analyses has been performed to estimate the lower limit of α, which should easy be measurable in the subsequent TT campaign at JET. By using several

pairs of activation foils, presented in Tab. 2 and Tab. 3, and cross-check of the results, this values can possibly be lowered.

5. Conclusions

The possibility for determining the channel (2) reaction path branching ratio in a TT plasma neutron spectrum at JET, with an activation foil pair was investigated. The input data consisted of Monte Carlo calculated spectra for individual TT reaction channels and DT plasma neutron sources. A crucial part was the uncertainty propagation due the computational, measurement and nuclear data uncertainties.

In case of a pure TT plasma the estimated lowest detectable TT channel (2) branching ratio was less than 7%. The disturbance of the measurements due to DT neutrons, originating form deuterium traces in the tritium plasma, will significantly increase the lowest detectable branching ratio; in case of the yields of TT to DT source neutrons of Y_{TT}: Y_{DT} = 4 : 1 , to over 24%.

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