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Determination of the emission rate for the 14 MeV neutron generator with the use of radio-yttrium

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Abstract. The neutron emission rate is a crucial parameter for most of the radiation sources that emit neutrons. In the case of large fusion devices the determination of this parameter is necessary for a proper assessment of the power release and the prediction for the neutron budget. The 14 MeV neutron generator will be used for calibration of neutron diagnostics at JET and ITER facilities. The stability of the neutron generator working parameters like emission and angular homogeneity affects the accuracy of calibration other neutron diagnostics. The aim of our experiment was to confirm the usefulness of yttrium activation method for monitoring of the neutron generator SODERN Model: GENIE 16. The reaction rate induced by neutrons inside the yttrium sample was indirectly measured by activation of the yttrium sample, and then by means of the γ-spectrometry method. The pre-calibrated HPGe detector was used to determine the yttrium radioactivity. The emissivity of neutron generator calculated on the basis of the measured radioactivity was compared with the value resulting from its electrical settings, and both of these values were found to be consistent. This allowed for a positive verification of the reaction cross section that was used to determine the reaction rate (6.45×10^{-21} reactions per second) and the neutron emission rate (1.04×10^{8} n·s^{-1}). Our study confirms usefulness of the yttrium activation method for monitoring of the neutron generator.

Key words: 14 MeV neutron generator • activation method • yttrium activation

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Introduction

The neutron emission rate (Y_n) is one of the most important parameters defining the emissivity of contemporary neutron sources. It could be determined in different ways but the activation technique still is very popular [1, 2]. The activation method does not affect any of the crucial parameters of plasma generation. Determination of the Y_n value for a large fusion device is necessary in order to predict the neutron budget as well as for monitoring of the total released power. The JET and ITER neutron diagnostics will be calibrated with the use of the 14 MeV neutron generator (NG). In our research the neutron emission rate of the 14 MeV NG was measured by the yttrium activation. The inelastic neutron scattering on yttrium nuclei leads to the creation metastable state of yttrium – ^{89}Y(n,n')^{89m}Y – with a short half-life ($T_{1/2}$ = 15.663 s). The radio-yttrium obtained from the activation process can be easily detected by the γ-spectrometry method with low measurement uncertainty. This is due to the relatively high cross section for the above reaction. The stability of the neutron emission and the homogeneity of the angular neutron distribution are very important, as the tokamak neutron diagnostics will be calibrated on the basis of these parameters.

The aim of this work was to assess the reaction rate (R) and Y_n for the NG installed in the National Centre of Nuclear Research in Swierk, Poland. To this end the nuclear properties of the radio-yttrium were carefully studied, which showed that yttrium nuclide could be accepted as a neutron monitor. Then the yttrium sample was irradiated for a predefined time. Finally, the activity of the yttrium sample was measured by means of γ-spectrometry method.

Materials and methods

Yttrium

Yttrium has only one stable isotope: ^{89}Y. Neutrons interact with yttrium target causing inelastic scattering. As a result, the following nuclear reaction occurs [3]:

$$n + {}^{89}Y \rightarrow {}^{89m}Y(T_{1/2} = 15.663\ s) + n' + \gamma,$$
$$(E_\gamma = 908.96\ keV;\ I_\gamma = 99.16\%).$$

An isotope produced in this reaction has a relatively short half-life, and returns to the ground state with the intensive emission of the monoenergetic γ radiation.

The yttrium sample used for measurements had diameter of 80 mm and thickness of 5 mm. The optimization of the geometry of the sample for its optimal activation and high detection efficiency was the subject of our earlier work [4].

Figure 1 shows the cross section for the considered nuclear reaction as given by the TENDL-2013 nuclear data library. The n + ^{89}Y reaction is a threshold reaction and occurs when neutron energy exceeds ~919 keV [5]. The cross section assumes its maximum value (i.e. 1.8 barn) for the neutron energy 7.80 MeV. The cross section for 14.14 MeV neutrons is approximately half of the maximum value (0.7 barn) and lies on the descending part of the curve. The reaction does not occur for slowed down and scattered neutrons with energy below the threshold.

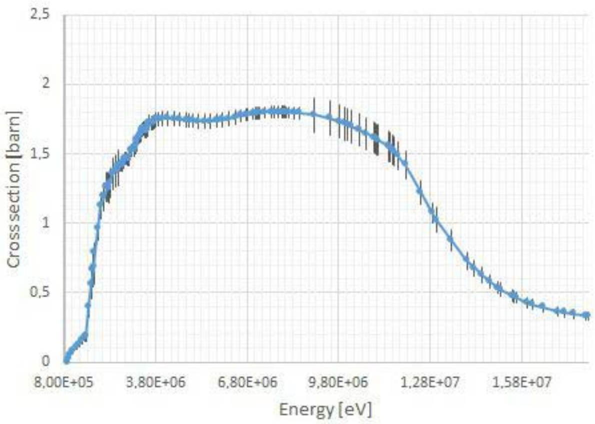

Fig. 1. The cross section for activation of ^{89}Y (TENDL-2013 nuclear data library) [5].

Irradiation of an yttrium sample by neutrons from the Sodern 14 MeV neutron generator

A 14 MeV NG SODERN Model: GENIE 16 was used as a source of neutrons for determination of the neutron production rate using yttrium sample. The maximum neutron yield of the generator is 2×10^8 n·s^{-1}. During the NG life cycle the Y_n decreases. Different manufacturers give limited guarantee for the stable value of Y_n over the working time in the range of hundreds to thousands of hours. The NG construction allows for up to 4000 hours of permanent generator work with neutron emission rate approximately 1×10^8 n·s^{-1}, or 8000 hours with emission rate of 5×10^7 n·s^{-1}. The neutron energy spectrum is strongly dependent on NG's environment and neighborhood. This is due to the neutron interactions with walls, floor and other massive elements that are close to the NG. The NG used in this experiment was permanently fixed to the floor. The configuration of shields and other massive objects was preserved. Therefore it is expected that the neutron spectrum in the particular location does not change in time.

Table 1 presents the current of the deuterium ions on the target and the neutron emission rate for some of the electrical settings of the NG used in this experiment. The main operating parameters of the NG were as follows: the acceleration voltage 90 kV and the current of the deuterium ions on the target 40 μA. The total working time for the NG in this experiment was less than 500 hours.

The yttrium sample was fixed 30 cm from the center of the neutron source along the direction perpendicular to the main axis of the NG. The sample was put into the thin nylon foil attached to the arm of the metal stand. It was assumed that the saturation time of yttrium is $t_s \approx 6\ T_{1/2}$ and the irradiation time was taken as twice the saturation time and equal to t_i = 200 s. The sample was activated, then manually transferred to the measuring stand. The samples cooling time ranged from 12 to 14 s.

Figure 2 shows the 14 MeV SODERN neutron generator model: GENIE 16.

Radiometry of the activated yttrium sample

The n-type HPGe detector with relative efficiency of 30% and resolution 1.80 keV (for the 1332 keV peak of ^{60}Co) supplied by Canberra was used for

Table 1. Basic parameters of the 14 MeV neutron generator for various values of the acceleration voltage

Acceleration voltage [kV]	Current of the deuterium ions on the target [μA]	Neutron emission in 4π [n·s^{-1}]
75	30	0.39×10^8
90	20	0.51×10^8
85	35	0.70×10^8
90	35	0.88×10^8
90	40	1.00×10^8

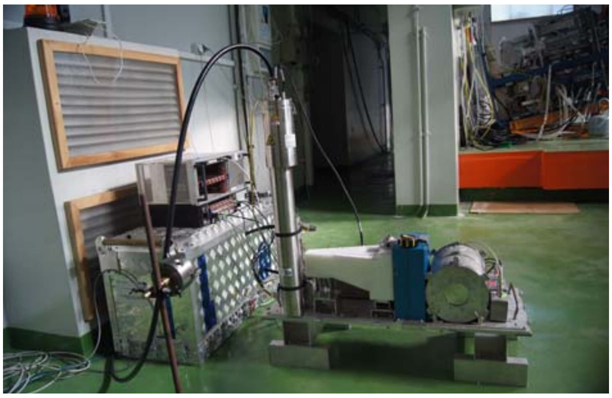

Fig. 2. The 14 MeV neutron generator.

the determination of the radioactivity induced in the yttrium sample by neutrons from the NG. The measurement was performed using the Inspector 2000 Multichannel Analyzer and analyzed with use of the Genie PC software. The detector was supplied with its numerical characteristic (pre-calibration). LabSOCS® software (Laboratory Sourceless Object Calibration Software) allows for the mathematical energy efficiency calibration without the use of calibration sources for practically arbitrary measurement geometries as well as sample geometry. The efficiency of registration is understood as the efficiency determined for the absolute full energy peak efficiency (AFEPE). The standard deviation of the mathematical energy efficiency calibration is in the range of 3.0÷7.1% [6, 7].

The energy efficiency calibration was based on the numerical characteristic of the HPGe detector. Figure 3 shows the energy efficiency calibration curve for the considered geometry of the yttrium sample.

After activation of the sample and its cooling the γ-spectrum was recorded for 100 s. The resulting spectrum is shown in Fig. 4.

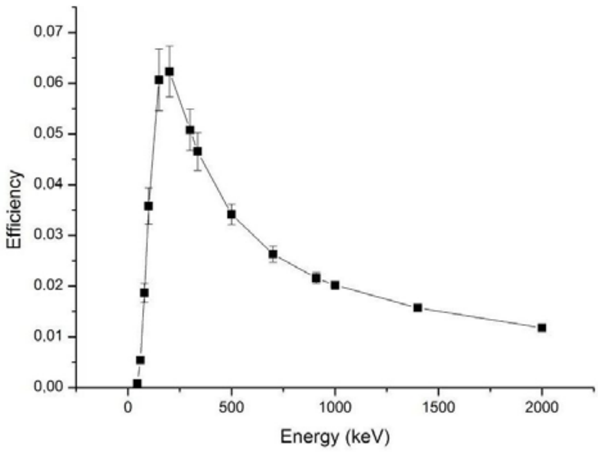

Fig. 3. Energy efficiency calibration curve for the considered geometry of the yttrium sample.

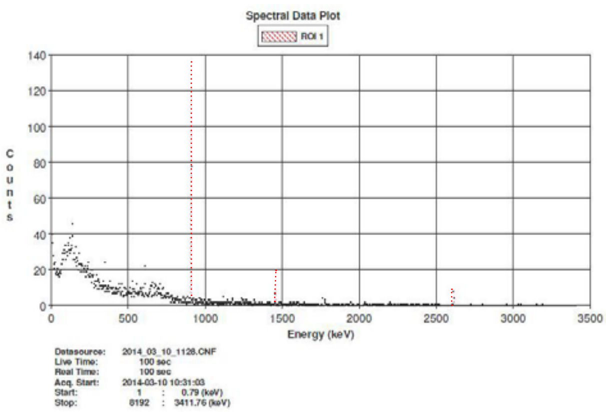

Fig. 4. The spectrum measured for the yttrium sample. The subsequent peaks 909 keV (^{89m}Y), 1460 keV (^{40}K), 2614 keV (^{208}Tl) are labeled with red marker.

Calculation of the reaction rate and Y_n

The yttrium radioactivity was determined by means of γ spectrometry method. Activation of each sample was determined for the moment when activation was completed. It is expressed by Eq. (1).

$$A = \frac{\lambda N_p}{I_\gamma \cdot eff \cdot \left(e^{-\lambda t_c} - e^{-\lambda(t_c + t_m)}\right)} \quad (1)$$

where: λ – decay constant ^{89m}Y [s^{-1}], N_p – the number of counts [unitless], $eff(E_\gamma)$ – AFEPE [unitless] for γ quanta with energy E_γ = 909 keV, I_γ – emission intensity [unitless], t_c – cooling time [s], t_m – measurement time [s].

Let A be the yttrium radioactivity [Bq], A_{rel} – the atomic mass of the target nucleus [g·mol^{-1}], m – mass of irradiated sample [g], f_i – the abundance of particular nuclide in the sample [unitless], N_{Av} – the Avogadro constant [mol^{-1}], t_{irr} – irradiation time [s]. Then the reaction rate R is given by:

$$R = \frac{A \cdot A_{rel}}{m \cdot f_i \cdot N_{\text{Av}} \cdot (1 - e^{-\lambda t_{irr}})} \quad (2)$$

The neutron emission rate Y_n is expressed by the Eq. (3):

$$Y_n = \frac{R \cdot 4 \cdot \pi \cdot d^2}{\sigma(E_n)} \quad (3)$$

where: d – the distance of the sample from the detector [cm], $\sigma(E_n)$ – the value of the cross section for 14.14 MeV neutrons [cm^2].

The values of the parameters used in calculation of the neutron emission rate with the use of the yttrium activation are shown in Table 2.

Table 2. The values of the parameters used in the calculation of the neutron emission rate using the yttrium activation method

Parameter	Value	Relative error [%]
A [Bq]	5010	5.77
A_{rel} [g·mol^{-1}]	88.91	NA
σ [cm^2]	7.20×10^{-25}	8.60
m [g]	114.74	0.01
f_i	1	NA
N_A [mol^{-1}]	6.022×10^{23}	4.48×10^{-6}
λ [s^{-1}]	0.0443	0.03
t_i [s]	200	NA
d [cm]	30	3.33

Results

The value of AFEPE for the E_γ = 909 keV γ – quanta used for the radioactivity calculation was 2.15 ± 5%. The spectra from the activated samples were measured using the γ-spectrometer and then the radioactivity of each sample was determined. The average activity of yttrium was $A = 5.01 \pm 0.29$ kBq (value calculated on the basis of four measurements obtained from Genie 2000). The calculated reaction rate was $R = 6.45 \times 10^{-21} \pm 5.77\%$ reactions · s^{-1} and the neutron emission rate was found to be $Y_n = 1.04 \times 10^8 \pm 10.88\%$ $n \cdot s^{-1}$.

Conclusions

The NG (SODERN Model: GENIE 16) yield was determined for one of the many of its electrical settings i.e. the beam current and the acceleration voltage. The measured Y_n is close to the expected value for a given electrical set presented in the Table 1. The calculated uncertainty of our method is 11%. Another source of uncertainty is the assumed monoenergetic character of the neutron emission and the fact that neutron scattering in the laboratory environment was neglected. The impact of the slowed down neutrons with energies lower than 14.14 MeV also was not taken into consideration. But they could distort the final result due to their higher value of cross section as compared to 14.14 MeV neutrons. It is the disadvantage of described method. The spatial and energetic anisotropy of the emitted neutrons has also influence on the uncertainty of this process. Another limitation of the method is the relatively low energy threshold of the reaction. The most important advantage of the applied method is the short half-life of ^{89m}Y. It means that the testing measurements could be performed very frequently. The yttrium activation method can efficiently diagnose the stability of operation of a stationary NG and that fact was confirmed. For that kind of measurements aimed at the verification of the stability of operation it is important that the configuration of equipment in the vicinity of the generator is not changed. That guaranties comparability of the obtained neutron energy spectra.

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