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Neutron Spectrum Unfolding for the Development of a Novel Neutron Detector for Fusion

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Abstract

In future fusion power plants, such as DEMO, the D-T neutron emission rate is predicted to exceed 1×10^{21} n s^{-1}. Accurately monitoring neutron energies and intensities will be the primary method for estimating fusion power, and calculating key nuclear parameters, including the tritium breeding ratio and nuclear heating. The Novel Neutron Detector for Fusion (VERDI) project, implemented under the EUROFusion Enabling Research 2017 program, aims to develop a detector capable of withstanding the harsh environment of a future fusion power plant. The VERDI detector is based on the foil activation technique, which relies on neutron spectrum unfolding methods to process the convolution of gamma-ray measurement and detector response function to infer the neutron energy spectrum. This paper details the experimental method and results collected using six prototype VERDI detectors during an initial experiment performed in July 2017 at the ENEA Frascati Neutron Generator (FNG) under D-T neutrons (14 MeV). The measured activities of product isotopes are compared with equivalent data calculated using the FISPACT-II code to provide an average C/E$_{act}$ agreement of 1.05±0.13. Experimental results from the FNG have been applied to neutron spectrum unfolding techniques using established unfolding codes, MAXED and GRAVEL.

Keywords: neutronics, neutron detector, FNG, unfolding, neutron activation

1. Introduction

The energy spectrum of neutrons in a fusion device is used to infer plasma properties, such as temperature and fuel parameters, and also has impact on nuclear performance and safety parameters. However, measuring neutrons directly is challenging and additional challenges are presented by the fusion environment, such as high temperatures and intense magnetic fields. This paper details recent developments as part of an Enabling Research Project to develop a Novel Neutron Detector for Fusion (VERDI). The project aims to provide a cost effective approach for accurate neutron fluence measurements under the harsh environment conditions encountered in a fusion plant by designing and testing detectors comprising of a low-activation capsule and a range of target elements, and developing methodologies for extracting the neutron energy spectrum.

This paper details an initial experiment performed with six prototype VERDI detector capsules in July 2017 at the Frascati Neutron Generator (FNG) [1], shown in Figure 1. The results of this experiment are compared with simulation data calculated using the FISPACT-II code [2] and MCNP-5 [3] code, and applied to neutron spectrometry methodologies. Neutron spectrum unfolding is a conventional technique for extracting the neutron energy spectrum from activation information derived from gamma spectroscopy measurements of neutron activated products. Many unfolding codes exist, for example see [4–6], each tailored for different environments, this paper details the results obtained from using two such codes, MAXED and GRAVEL (MXDFC33 [7–9] and GRVFC33 [10] UMG version 3.3).

2. Initial FNG experiment

During the experiment performed at the FNG in July 2017 six prototype VERDI detectors, as shown in Fig-

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ure 1, were irradiated under a D-T (14 MeV) neutron field for a total irradiation time of 2.956 hours at a distance of 5.3 cm from the FNG neutron source. The scope of this experiment was to derive reaction rates for the target elements that could be used with the response functions to perform unfolding calculations, and to test the robustness of two different capsule enclosure types in a high neutron flux environment.

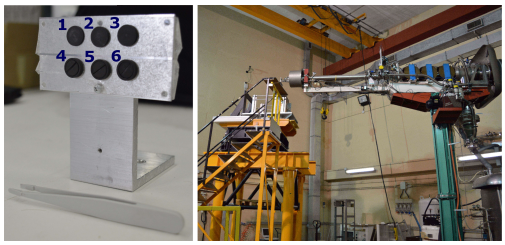

Figure 1: (LHS image) VERDI detector arrangement, showing six detectors mounted onto an aluminium stand. (RHS image) The FNG facility showing the 14 MeV neutron generators with VERDI detector capsules positioned at 5.3 cm from the FNG neutron source.

2.1. Prototype VERDI detector description

Six detectors with graphite capsules were constructed and mounted on an aluminium holder (99% purity, 100 mm width, 50 mm height, 1.5 mm thickness) which was placed 5.3 cm from the FNG neutron source, as shown in Figure 1 along with an illustration of the detector number assignment. In a subsequent experiment performed in March 2018 a Ceramic Matrix Composite (CMC) has been tested as an alternative capsule material, full details are provided in Ref. [11]. In this work two enclosure types were investigated: an inorganic graphite based adhesive was used for capsules 1-3, whereas a mechanical thread was used for capsules 4-6. The determination of the target elements for the prototype detectors was performed using FISPACT-II and the EAF-2010 nuclear data library with VITAMIN-J 175 energy bin group structure [12], target elements were selected for inclusion based on whether the gamma-lines would be measurable and would not interfere with gamma-lines from other product isotopes, further details regarding the foil selection are provided in Ref. [11]. Table 1 details the composition of detectors 2, 4, and 5. In order to check the background radiation induced by the enclosure type and material detectors 3 and 6 did not contain any target elements, and are referred to as blank detectors. Detectors 1 and 4 contained Y_2O_3 powder to check the feasibility of using a mixture of powders instead of foils, however the closure of detector 1 failed while the detectors were being mounted prior to irradiation resulting in the loss of some of the Y_2O_3 powder, therefore the results from detector 1 were not obtained and are not included in this work.

2.2. Experimental method and results

The total neutron yield at the FNG D-T source for the entire irradiation was measured to be 4.96×10^{14} neutrons, determined absolutely by counting the α-particle associated with the neutrons produced by the D-T reaction. Whereas the neutron flux at the detectors' irradiation position ranged from 1.24×10^8 to 1.36×10^8 n cm^{-2} s^{-1}, as calculated using the FNG MCNP-5 model, provided by ENEA [13]. Following irradiation the activities of the prototype detectors were measured approximately 10 days after the end of irradiation using an 80% relative efficiency High-Purity Germanium (HPGe) detector at NCSRD.

The measured activities were compared to activities calculated using FISPACT-II to provide a calculated to experimental (C/E$_{act}$) ratio for detectors 2, 4, and 5, and are presented in Table 1. In the majority of cases the C/E$_{act}$ ratios do not statistically differ from 1. For the case of rhodium, it is noted that two isotopes are produced via the (n,2n) reaction: ^{102m}Rh (t$_{1/2}$ ≈2.9 years) and ^{102}Rh (t$_{1/2}$ ≈207 days). Both isotopes are long-lived and emit photons at exactly the same energies (except at 468.58 keV). In this work, the detected photopeaks are attributed to both isotopes taking into account the different emission probabilities from each isotope. Regarding the blank detectors, no activity due to the neutron irradiation was detected.

3. Neutron spectrum unfolding approach

In this paper, unfolding calculations have been performed using the experimental data collected for detector 4, as it contained the full range of target elements. The weighted average of the C/E$_{act}$ values presented in Table 1 is 1.05±0.13, suggesting a slight overestimation in the total neutron fluence at the irradiation position. The activities measured for 10 reactions from detector 4, listed in Table 2, were used as input to unfolding algorithms to produce an unfolded neutron spectrum that can be used to provide better agreement in the C/E$_{act}$ results.

The unfolding codes employed in this work, MAXED and GRAVEL, require three input files containing *a priori* information (a guessed spectrum), response functions and measured reaction rates. In addition a control file can be used to provide the information needed to run the codes, including file names for the three input files and desired chi-square per degree of freedom

Table 1: Active target elements and masses of the VERDI detectors 2, 4, and 5 irradiated during the initial experiment performed at the FNG in July 2017, along with a C/E_{act} comparison between measured activities for each detector and equivalent simulated results with FISPACT-II. Y_2O_3 was included in powder form, whereas all other elements were included as foils.

			Detector No. 2		Detector No. 4		Detector No. 5	
Foil	**Measured Isotope**	**γ Energy (keV)**	**Foil Mass (g)**	**C/E_{act}**	**Foil Mass (g)**	**C/E_{act}**	**Foil Mass (g)**	**C/E_{act}**
Au	^{196}Au	332.98	0.0069	1.05 ± 0.09	0.0063	1.17 ± 0.10	0.0063	1.06 ± 0.09
	^{196}Au	355.68		1.09 ± 0.09		1.21 ± 0.10		1.12 ± 0.10
	^{198}Au	411.80		0.83 ± 0.24		0.85 ± 0.27		0.75 ± 0.30
Nb	^{92m}Nb	934.46	0.0008	0.91 ± 0.20	0.0007	0.83 ± 0.18	0.0008	0.97 ± 0.21
Ni	^{57}Co	122.06	0.0049	1.01 ± 0.17	0.0053	1.13 ± 0.19	0.0051	1.14 ± 0.19
	^{57}Co	136.47		0.87 ± 0.25		0.81 ± 0.30		–
	^{58}Co	810.78		0.76 ± 0.13		0.97 ± 0.17		0.86 ± 0.14
Rh	^{102}Rh	468.58	0.0241	1.11 ± 0.29	0.0243	1.38 ± 0.42	0.0240	–
	^{102}Rh	475.10		1.15 ± 0.15		1.28 ± 0.17		1.16 ± 0.16
	^{103}Rh	497.08		1.09 ± 0.63		1.11 ± 0.64		1.27 ± 0.74
	^{102}Rh	628.05		1.38 ± 0.32		1.16 ± 0.20		1.14 ± 0.22
	^{102}Rh	1103.16		0.88 ± 0.25		–		–
Ti	^{47}Sc	159.38	0.2448	0.79 ± 0.38	0.2456	0.96 ± 0.46	0.2447	0.89 ± 0.43
	^{48}Sc	175.36		0.78 ± 0.49		0.92 ± 0.58		0.90 ± 0.57
	^{46}Sc	889.28		0.99 ± 0.24		0.97 ± 0.17		0.86 ± 0.14
	^{48}Sc	983.52		0.93 ± 0.58		1.06 ± 0.66		1.00 ± 0.63
	^{48}Sc	1037.60		0.92 ± 0.58		1.05 ± 0.66		0.99 ± 0.62
	^{48}Sc	1212.88		0.96 ± 0.60		1.04 ± 0.66		1.09 ± 0.69
	^{48}Sc	1312.10		0.91 ± 0.57		1.05 ± 0.66		0.98 ± 0.61
Y_2O_3*	^{88}Y	898.06	–	–	0.0403	1.16 ± 0.27	–	–
	^{88}Y	1836.00		–		1.12 ± 0.26		–
Zn	^{69m}Zn	438.63	0.0833	1.15 ± 0.23	0.0833	1.29 ± 0.26	0.0834	1.14 ± 0.25
	^{63}Zn	669.62		0.67 ± 0.58		–		–
	^{63}Zn	962.06		0.70 ± 0.60		–		–
	^{65}Zn	1115.55		0.83 ± 0.25		0.92 ± 0.28		0.86 ± 0.26
	^{64}Cu	1345.84		1.07 ± 0.93		–		–
	^{63}Zn	1412.08		1.01 ± 0.88		–		–

*Y_2O_3 was included in powder form, whereas all other elements were included as foil discs.

(χ^2 pdf). The MAXED algorithm applies the maximum entropy method [14] to infer the most likely spectrum for a given data set. Whereas the GRAVEL algorithm, a modification of SAND-II [10], is an iterative non-linear least squares algorithm with the added constraint of non-negative particle fluence, details of the approach used in GRAVEL is provided in Ref. [10]. Both codes ran to minimise the χ^2 pdf.

3.1. A priori information

The *a priori* information used in this work was calculated at the irradiation position of detector 4 using the FNG MCNP model, the spectrum was provided by ENEA [13]. The *a priori* spectrum was provided to MAXED and GRAVEL in units of n cm^{-2} in 175 energy bin group structure. The spectrum is shown together with the final unfolded spectra (discussed later) in Figure 3.

3.2. Response functions

The response function for the nth reaction type as a function of neutron energy was calculated using:

$$R_n(E) = N_d V \sigma_n(E), \tag{1}$$

where N_d is the number density (atoms barn^{-1}cm^{-1}), V is the volume of the activation foil (cm^3), and σ_n is the cross-section data extracted from the IRDFF-v1.05 library, where the data exists, otherwise from the TENDL-2017 library. The response functions are calculated in the VITAMIN-J 175 energy group structure, and are shown in Figure 2.

3.3. Measured reaction rates

Seven foil elements, shown in Table 1, were irradiated in detector 4, spanning 10 reaction types as listed in Table 2. The measured reaction rates M_{0n} were calculated from the measured activities for the nth reaction

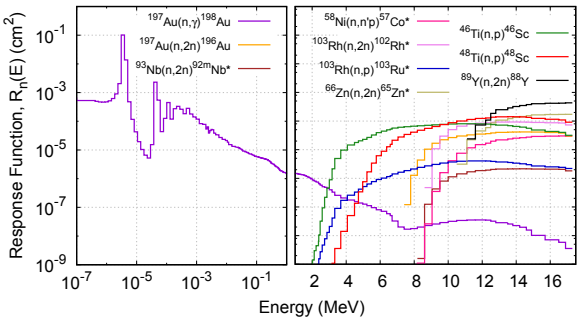

Figure 2: Response functions plotted as a function of energy for each reaction considered in this work. Cross-sections used to calculate these response functions were extracted from the IRDFF-v1.05 library except those reactions marked (*) which were extracted from TENDL-2017. Note the split logarithmic-linear x-axis.

type and decay corrected to the end of the irradiation period, A_n, using the equation:

$$M_{0n} = \frac{A_n}{1 - \exp^{-\lambda_n T}}, \quad (2)$$

where λ_n is the product nuclide decay constant, and T is the total irradiation time of 2.956 hours.

Table 2: Reaction rates and uncertainties calculated from the experimentally measured activities using Equation 2.

Reaction	Reaction Rate (s^{-1})	Uncertainty (s^{-1})
^{197}Au(n,γ)^{198}Au	124.02	18.23
^{197}Au(n,2n)^{196}Au	4337.90	359.01
^{93}Nb(n,2n)^{92m}Nb	350.09	51.90
^{58}Ni(n,n'p)^{57}Co	3358.30	1408.30
^{103}Rh(n,2n)^{102}Rh	14964.00	4327.20
^{103}Rh(n,p)^{103}Ru	335.96	27.61
^{46}Ti(n,p)^{46}Sc	7575.80	583.27
^{48}Ti(n,p)^{48}Sc	15902.00	2504.80
^{89}Y(n,2n)^{88}Y	27487.00	2401.70
^{66}Zn(n,2n)^{65}Zn	15109.00	1793.80

4. Unfolded Spectrum Results

MAXED and GRAVEL were both run to minimise the χ^2 pdf of 3.14 to the same final χ^2 pdf of 1. In the case of MAXED this was implemented as a termination criteria, whereas for GRAVEL this equated to 23 iterations. Figure 3 shows the *a priori* spectrum (purple data set) and the final unfolded spectra output from MAXED (green data set) and GRAVEL (red data set). The total neutron fluence in detector 4 following irradiation was 1.29×10^8 n cm^{-2} s^{-1}, calculated using the *a priori* spectrum. Following the unfolding methodology described previously the total fluence calculated using the final unfolded MAXED spectrum was 1.35×10^8 n cm^{-2} s^{-1}, and was 1.37×10^8 n cm^{-2} s^{-1} when calculated using the final unfolded GRAVEL spectrum, a factor of 1.05 and 1.05 higher than the *a priori* spectrum respectively.

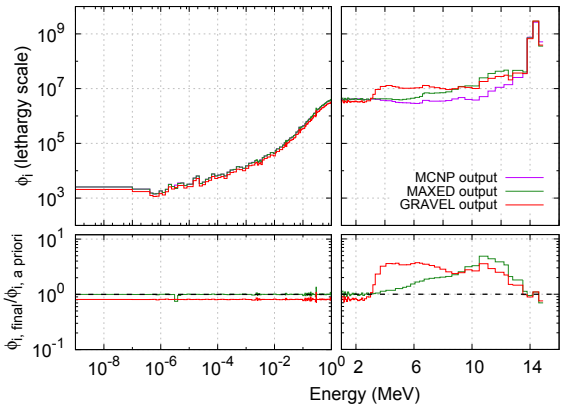

Figure 3: (top) *a priori* neutron spectrum (purple data set) and the final unfolded spectra output from MAXED (green data set) and GRAVEL (red data set). (bottom) the ratio between the unfolded MAXED spectrum and the *a priori* spectrum (green data set) and the ratio between the unfolded GRAVEL spectrum and the *a priori* spectrum (red data set). Note the split logarithmic-linear x-axis.

The neutron energy spectrum was divided into three coarse energy groups to identify which parts of the spectrum present the largest differences to the *a priori* spectrum. For MAXED, the ratio between the unfolded spectrum and the *a priori* spectrum in the 0-2 MeV, 2-13 MeV, and 13-16 MeV ranges were 1.00, 1.95, and 0.98 respectively. Whereas, for GRAVEL, the ratios were 0.81, 2.30, and 0.99 respectively. For both MAXED and GRAVEL the largest differences occurred in the 2-13 MeV range, with the greatest difference in the GRAVEL results.

Figure 4 shows the ratio for the calculated reaction rates to the experimentally measured reaction rates (C/E_{RR}) for all 10 reactions. The calculated reaction rates were obtained by folding the response functions, shown in Figure 2, with *a priori* neutron spectrum (purple data set), unfolded MAXED spectrum (green data set) and the unfolded GRAVEL spectrum (red data set). Following the unfolding process the C/E_{RR} ratios have not changed, except for ^{197}Au(n,γ)^{198}Au and ^{46}Ti(n,p)^{46}Sc which have been pushed further from one and ^{103}Rh(n,p)^{103}Ru which has moved closer to one. However, the average C/E_{RR} has remained the same with a value of 1.02 prior to unfolding and values

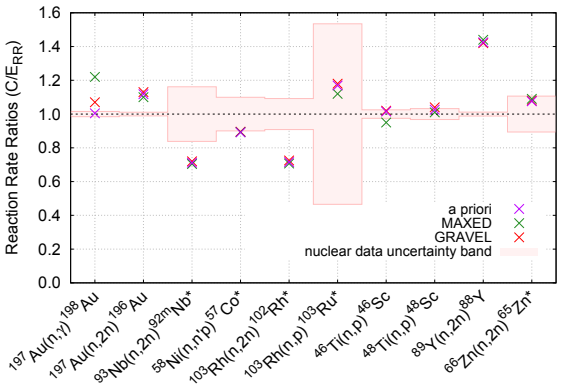

Figure 4: C/E_{RR} plot showing the ratio of the calculated reaction rates to the measured reaction rates for all 10 reactions considered for VERDI detector 4. Nuclear data uncertainties were extracted from the IRDFF-v1.05 library except those reactions marked * which were extracted from TENDL-2017. Error bars are not shown here but uncertainties on the measured reaction rates can be found in Table 2.

of 1.03 and 1.02 following the use of MAXED and GRAVEL respectively, supporting the earlier statement that the the FNG MCNP model provided an accurate calculation of the neutron field during this experiment.

5. Discussion and conclusions

Six prototype VERDI detectors were irradiated at the FNG under a D-T neutron field to examine two enclosure types, a graphite adhesive and a mechanical thread, and to derive reaction rates for a selection of target elements. Neither enclosure type produced additional activity due to neutron irradiation leading to the conclusion that the adhesive used does not affect the neutron activation results.

Derived reaction rates for 10 reactions measured in detector 4 were input to MAXED and GRAVEL and both codes achieved a factor of ≈3 reduction in the χ^2 pdf. When comparing the outputs of MAXED and GRAVEL, although a large difference in flux occurred in the 2-13 MeV region the majority of the flux lies in the 14 MeV region where the differences were small. This resulted in a small difference in the total neutron fluence, suggesting the MCNP model provided an accurate calculation for the neutron field in this experiment.

Due to the larger uncertainty bands associated with the TENDL-2017 library, as illustrated in Figure 4, it is desirable to use the IRDFF-v1.05 library where the data exists to derive response functions. Future experiments to irradiate modified VERDI detectors are planned as part of the 2018-2019 D-D campaign at the Joint European Torus (JET). Pre-analysis work suggests the addition of Ag and Mn foils will provide information from a second capture reaction, ^{109}Ag(n,γ)^{110m}Ag, and a further threshold reaction ^{55}Mn(n,2n)^{54}Mn, both available in the IRDFF-v1.05 library. This will provide more information in the lower energy region of the neutron energy spectrum and is expected to enhance the unfolding capabilities of MAXED and GRAVEL.

6. Acknowledgements

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