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Neutronics benchmark experiment on tungsten

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Abstract

In order to validate neutron cross sections for W, a benchmark experiment was carried out at the Frascati Neutron Generator (FNG), that consisted of the irradiation with 14 MeV neutrons of a tungsten block. Neutron flux and gamma heating were measured inside the block. The results were analysed with the Monte Carlo code MCNP-4C using for W, Fe and Ni the cross sections derived from EFF-2.4 and FENDL-2.0. In the neutron flux case, most of the calculations were in agreement with the experimental data within the total uncertainty using EFF-2.4, while they underestimated the fast neutron flux with increasing depth when using FENDL-2 cross sections. A strong discrepancy was found in the photon production data from the EFF-2.4 and FENDL-2 libraries, producing different values for the gamma heating in the two cases. FENDL-2 calculations showed better agreement with the measurements.

1. The experiment

Tungsten is a candidate material for the divertor plates and armour of fusion devices and is a constituent of reduced activation structural materials. In order to provide validation of the neutron cross sections for tungsten, a neutronics benchmark experiment was carried out at the ENEA Frascati using the 14 MeV Frascati Neutron Generator (FNG) [1], in the frame of he European Fusion File Project (EFF, [2]).The experimental set-up consisted of a block of DENSIMET alloy (produced by PLANSEE) in pieces of various shapes, assembled to obtain a size of about 42–47 cm (length) × 46.85 cm (height) and 49.0 cm in thickness (Fig. 1) and located in front of the FNG target, 5.3 cm from the neutron source. Most of the material (about 1.5 ton) was DENSIMET-176 type (93.2%w W, 2.6%w Fe, 4.2%w Ni, density = 17.70 g/cm^3). A layer (about 0.25 ton, 7 cm height) of DENSIMET-180 (95.0%w W, 1.6%w Fe, 3.4%w Ni, density = 18.075 g/cm^3) was used in the central part of the block where the measurements were taken (Fig. 2); it contained lateral access channels (diameter 5.2 cm) for locating detectors of the various types (activation foils, TLD holders, active spectrometers) in four experimental positions at 5.0, 15.0, 25.0 and 35.0 cm penetration depth inside the block.

Eight different reactions: ^{197}Au(n,γ), ^{55}Mn(n,γ), ^{115}In(n,n′), ^{58}Ni(n,p), ^{56}Fe(n,p), ^{27}Al(n,α), ^{58}Ni(n,2n), ^{90}Zr(n,2n) and ^{93}Nb(n,2n) were used to measure the neutron flux, from low neutron energies up to the fusion neutron peak, using the radiometric techniques based upon the use of absolutely calibrated HPGe detectors. During the activation foil measurements, the lateral access channels were completely closed by means of four ad hoc cylinders made of DENSIMET-180 (also shown in Fig. 1). In each cylinder, a thin slot was machined (4.4 mm) to locate activation foils in the exact position, using a thin Al holder. The total experimental uncertainty was due to the HPGe calibration (±2%), measured activity (<±5%) and total neutron yield (±3%).

Gamma heating was measured using TLD-300 dosimeters (CaF_2:Tm, 3.2×3.2×0.9 mm^3 chips). TLDs calibration was performed using a Co-60 secondary standard available at the Institute for Radioprotection (IRP) of ENEA Bologna. The calibration energies ranged from 50 mGy to 4 Gy (air Kerma). The uncertainty on the delivered air Kerma was ±3%. Since the calibration was performed with the TLD-300 in a polyethylene holder, 0.5 mm thick, to ensure the charged

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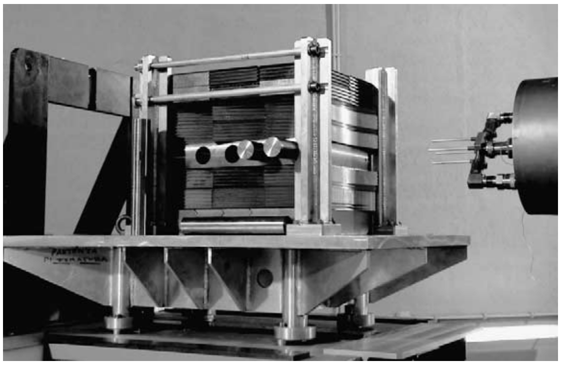

Fig. 1. The tungsten block on the aluminium support in front of the FNG target.

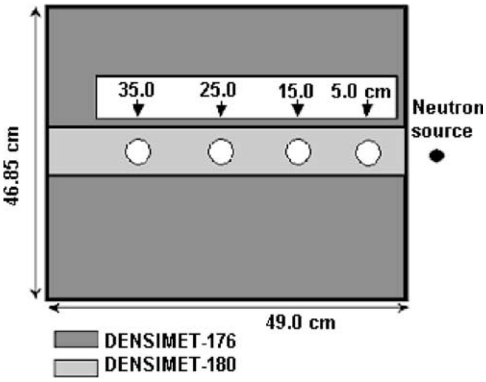

Fig. 2. Schematic view of experimental set-up (vertical section) showing the experimental positions. DENSIMET are high W alloys containing Fe and Ni.

particle equilibrium, the air Kerma was converted into absorbed dose in TLD-300 using the photon energy attenuation coefficients (μ_{en}/ρ) from [3]. Seven TLDs chips were located in each experimental position, using the same experimental arrangement as for the activation foils, and enclosed in a perspex holder 1 mm thick. The TL-signal was converted into absorbed dose by using the measured calibration curve. The associated total errors in the four experimental positions were ±10%, ±12%, ±14% and ±15%, respectively. They include the statistical error on TL-signal reading (<8% in the first three positions and ±10% in the last one), the uncertainty on the calibration and on the total neutron yield, summed using the quadratic law.

2. Analysis

The experimental results (E) were analysed using the Monte Carlo code MCNP-4C [4] using for W, Fe and Ni the point-wise cross sections derived from EFF-2.4 [1], and FENDL-2.0 [5] for comparison. In both libraries, only data for natural W (no isotopes) are available. In the case of EFF-2.4, W data come from an EFF, rather old evaluation, while in the case of FENDL-2, W data are taken from JENDL-FF evaluation. In the case of EFF calculation, the Fe cross section was taken from EFF-3.0. A detailed model of the experimental set-up was prepared for the calculation, in which the activation foils and the TLD detectors, including holders, were accurately described. Track length estimator was used (tally 4 of MCNP) for fluxes and reaction rates calculation, while the gamma heating was calculated from the gamma energy deposition over the TLD cells (tally 6 of MCNP). All dosimetric reactions needed for the calculation of reaction rates were taken from IRDF-90.2 library [6].

The calculated to the experimental data ratios (C/E) have been grouped according to the energy threshold, E_{th}, of the activation reactions involved: they are plotted in Fig. 3 for ^{58}Ni(n,2n), ^{90}Zr(n,2n) and ^{93}Nb(n,2n) ($E_{th} > 10$ MeV), in Fig. 4 for ^{56}Fe(n,p), ^{27}Al(n,α) ($E_{th} > 4.5$ MeV), in Fig. 5 for ^{115}In(n,n′), ^{58}Ni(n,p) ($E_{th} > 0.5$ MeV), and in Fig. 6 for ^{197}Au(n,γ), ^{55}Mn(n,γ) reaction rates ($E_{th} > 1$ keV). The neutron flux density is very low in the thermal energy range, especially in deep positions, due to the high capture cross section of W. The error bars (1σ) shown in figures represent the total uncertainties in the comparison: they include experimental and MCNP statistical uncertainties summed using the quadratic law.

It can be seen that the C/E ratio is close to unity within the total uncertainty for all reaction rates calcu-

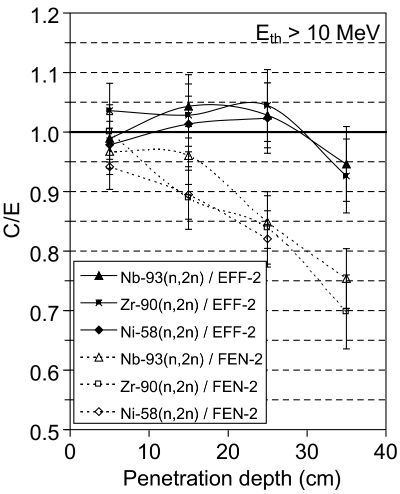

Fig. 3. C/E ratios for reactions with high energy threshold reactions, i.e. $E_{th} > 10$ MeV, as a function of penetration depth using EFF-2.4 and FENDL-2.0.

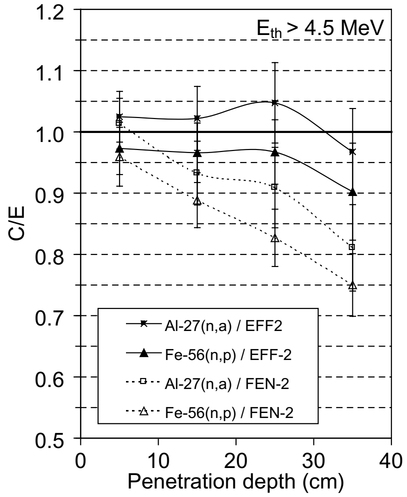

Fig. 4. C/E ratios for $^{27}Al(n,\alpha)$ and $^{56}Fe(n,p)$ reaction rates as a function of penetration depth, obtained using nuclear data libraries EFF-2.4 and FENDL-2.0 nuclear data libraries.

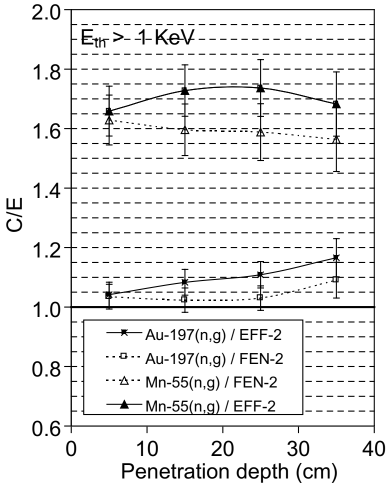

Fig. 6. C/E ratios for $^{197}Au(n,\gamma)$ and $^{55}Mn(n,\gamma)$ reaction rates as a function of penetration depth in the DENSIMET block, obtained using EFF-2.4 and FENDL-2.0 nuclear data libraries.

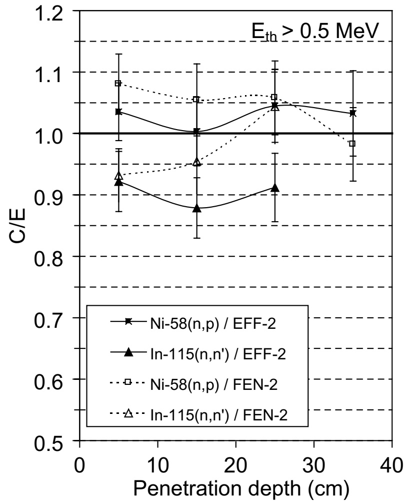

Fig. 5. C/E ratios for $^{58}Ni(n,p)$ and of $^{115}In(n,n')$ reaction rates as a function of penetration depth, obtained using EFF-2.4 and FENDL-2.0 nuclear data libraries.

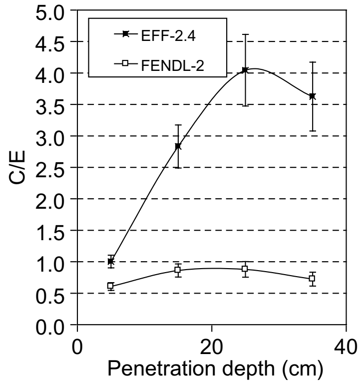

Fig. 7. C/E ratios for gamma heating in TLD as a function of penetration depth in the DENSIMET block, obtained using nuclear data libraries (EFF-2.4, FENDL-2.0).

lated using EFF-2.4, with the exception of the C/E values for $^{55}Mn(n,\gamma)$ reaction for which C/E $\sim$ 1.7 is found. The C/E ratio obtained using FENDL-2 are significantly lower than those obtained using EFF-2.4 with the only exception of the $^{115}In(n,n')$ reaction ($\sim$1 MeV). For $^{55}Mn(n,\gamma)$ reaction, a very high C/E value is found also with FENDL-2.

The calculation of $^{55}Mn(n,\gamma)$ reaction rates was repeated using the transport cross sections from EFF-2.4 and FENDL-2 as dosimetric cross sections instead of IRDF-90.2, but the results did non change. The spectral analysis showed that >90% of reaction rates for both $^{55}Mn(n,\gamma)$ and $^{197}Au(n,\gamma)$ occur in the same range, i.e. 10^{-3}–1 MeV. As far as the $^{197}Au(n,\gamma)$ cross section is concerned, the large resonance region falls below this energy range, while it corresponds to the reaction high probability region in the case of the $^{55}Mn(n,\gamma)$. The C/E discrepancy found in the $^{55}Mn(n,\gamma)$ case can then be attributed either to the difficulty of calculating the neutron flux in the Mn sample or to $^{55}Mn(n,\gamma)$ cross section in this specific range.

The gamma fluxes were calculated using EFF-2.4 and FENDL-2.0: a difference by a large factor was observed in the photon productions from the two libraries (of about 1.6, 3, 4.1 and 4.8 in the four positions respectively). The same discrepancy was found in the gamma heating in TLD using EFF-2.4 and FENDL-2.0 nuclear data, and in the C/E values, as shown in Fig. 7. The analysis of W data in the EFF-2.4 and FENDL-2.0, show that the (n,γ) and (n,n′) reactions are very similar, but the photon yield is significantly higher in EFF2.4. The C/E values relative to the gamma heating show that the FENDL-2 data have better agreement with the measurements, although an underestimation up to 40% is observed, while the EFF-2.4 shows a large overestimation up to a factor of 4.

3. Conclusions

As far as the neutron flux measurement is concerned, the C/E ratios are close to unity within the total uncertainty for all reaction rates calculated using EFF-2.4 with the exception of the C/E values for ^{55}Mn(n,γ) reaction (C/E $\sim$ 1.7). The C/E ratios obtained using FENDL-2 decreases with increasing depth for all the high energy threshold reactions, and show a good trend for ^{115}In(n,n′), and ^{197}Au(n,γ) reactions. For ^{55}Mn(n,γ) reaction, a very high C/E value is found also with FENDL-2 as with EFF-2.4. However, from the spectral analysis it was concluded that the ^{55}Mn(n,γ) reaction is not a good dosimetric reaction in this experiment because, given the neutron spectrum in tungsten, more than 90% of the reaction rate falls in the large resonance region of the ^{55}Mn(n,γ) cross section.

There is a strong discrepancy in the photon production data from the EFF-2.4 and FENDL-2 libraries, producing different values for the gamma flux and the gamma heating in TLD's in the two cases. FENDL-2 calculations show better agreement with measurements, although an underestimation up to 40% is observed, while the EFF-2.4 calculation overestimate the gamma heating up to a factor of 4.

From the above results we conclude that EFF-2.4 satisfactorily predicts the neutron transport in W up to 35 cm depth, while FENDL-2.0 underestimates the fast neutron flux. The photon production data in EFF-2.4 need to be revised.

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