Measurement of absolute reaction rates in Be, Pb and Fe spherical systems*

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Abstract The absolute reaction rates in Be, Pb and Fe have been measured by using the activation foil technique with different reaction energy thresholds. Thicknesses of Be, Pb and Fe spheres were 5.3, 19.1 and 31.9 cm, respectively. Eight kinds of activation foils were used for Fe, and four kinds each for Be and Pb. The total experimental error was about 5~7%. The measured results were compared to the values calculated with the 1-D ANISN code and the ENDF/B-VI library data. The average ratio of the experimental to the calculational is less than 7% for Be and Pb, about 5~30% for Fe.

Keywords Be, Pb, Fe, Activation foils, Reaction rates

1 Introduction

In the blanket design of a fusion reactor (e.g. ITER), Be and Pb are the promising neutron multiplication materials, and Fe is the neutron shielding material and constructing material. In the previous measurement of the multiplication and neutron spectra for these materials, the experimental and caluclational values from different laboratories do not coincide.[1,2] In order to further check the evaluated nuclear data of Be, Pb and Fe, it is necessary to carry out the measurement of reaction rates inside these materials. The reaction rates in the Pb sphere, and the blanket mockup and shielding assemblies have been measured by the German, Russian, and Japanese laboratories.[3~5] The differences of some experimental and calculational results are up to 20%, or even larger. The measured reaction rates as neutron spectrum indices in medium provide parameters for checking nuclear data.

2 Method

The reaction rates are measured by using a set of activation foils with different reaction energy thresholds, i.e., threshold detectors. These activation foils are placed along the radial direction of the sphere, and irradiated with a 14 MeV D-T neutron source which was located at the centre of the sphere. The gamma activities of the activated foils are measured with a high-purity germanium (HPGe) gamma spectrometer, and then corrected to obtain the absolute reaction rates.

In the process of the irradiation, the intensity of an accelerator neutron source is not always constant and the radioactivity of the activated foils is decaying. To solve these problems, the irradiation time is divided into N equal t_α intervals. The α-particle counts are recorded at each interval. The total counts are obtained by weighting.

When stopped time is t_0, activation reaction rate can be expressed as:

$$R_i = \frac{N_i(t_0)}{M \cdot b \cdot \phi \cdot g \cdot \varepsilon} \tag{1}$$

$$\phi = \frac{4\pi}{\Omega} \cdot A_\alpha \cdot \sum_{k=1}^{N} \rho_{\alpha k} \cdot e^{-(N-k)\cdot\lambda\cdot t_\alpha} \tag{2}$$

where subscription i represents the different position of a foil in a sample, i=1,2,$\cdots n$. $N_i(t_0)$ is the gamma activity of the foil at the position i-th and at time t_0, and measured by the HPGe detector. M is the number of atoms in a foil. b is the isotope abundance. g is the gamma emission rate of radioactive decay produced. ε is the efficiency of the HPGe detector. ϕ is the absolute intensity of the neutron source and corrected by the decay of the activated foils during

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irradiation. Ω is the solid angle of the α-particle detector to the target. A_α is the anisotropy factor. $\rho_{\alpha k}$ is counts of α particles in t_α period of the k-th record.

3 Setup

3.1 Samples

The Be sphere consisted of three spherical shells with 5.7/6.9, 6.9/9.7, 12.8/14.1 cm in inner/outer radius (IR/OR). To put foils, there was a cavity between 9.7 and 12.8 cm. A set of activation foils was put at the radial positions 5.7, 9.7, 12.8 and 14.1 cm, and 45° direction to D^+ beam.

The Pb sphere was 2.0/25.1 cm in IR/OR. A set of activation foils were put at the radial positions 2, 4, 6, 8, 11, 14, 17, 21 and 25.1 cm, and 60° direction to D^+ beam.

The Fe sphere was 3.1/35 cm in IR/OR, consisted of four spherical shells with 3.1/8.1, 8.1/18.1, 18.1/29.5, 29.5/35 cm in IR/OR. A set of activation foils were put at the radial positions 3.1, 5.1, 7.1, 9.1, 12.1, 15.1, 18.1, 22.1, 26.1, 30.1 and 35 cm. The experiment was conducted at the vertical accelerator, and the target chamber was at the top of the Fe sphere. So the foils were at 90° direction to D^+ beam. The schematic diagram of the foil detector is shown in Fig.1. The foils were put in small chambers with $\phi 2.2 \times 0.1$ cm.

3.2 Neutron source

In the Be and Pb sphere experiments, the D^+ energy was 150 keV. The α-particle detector was in 178.9° direction to the D^+ beam. The Ti-T target was cooled by compressed air.

Another neutron generator with D^+ energy of 250 keV was used in the experiment with the Fe sphere. The α-particle detector was in 178.6° direction to the D^+ beam. The Ti-T target was cooled by water. The measured and calculated angular distributions of neutron flux out of the target chamber are shown in Fig.2. The measured points were obtained by the Al and Fe activation foils.

3.3 Activation foils

The activation foils were 18 and 20 mm in diameter, 0.1~0.5 mm in thickness. Its purity was larger than 99.9%. The activation reactions of foils with its energy thresholds shown in the bracket are as follows: ^{55}Mn(n, γ) ^{56}Mn (thermal neutron), ^{115}In (n, n' γ) ^{115m}In (1.2 MeV), ^{58}Ni(n,p)^{58}Co (2.8 MeV), ^{64}Zn(n, p)^{64}Cu (2.8 MeV), ^{56}Fe(n, p)^{56}Mn (6.3 MeV), ^{24}Mg(n,p)^{24}Na (7.0 MeV), ^{27}Al(n, α)^{24}Na (7.2 MeV), and ^{63}Cu(n,2n)^{62}Cu (12.6 MeV).

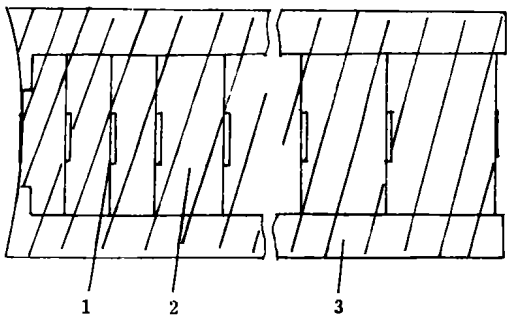

Fig.1 Schematic diagram of activation foil detector: 1 Small chamber; 2 Iron cylinder; 3 Iron sleeve

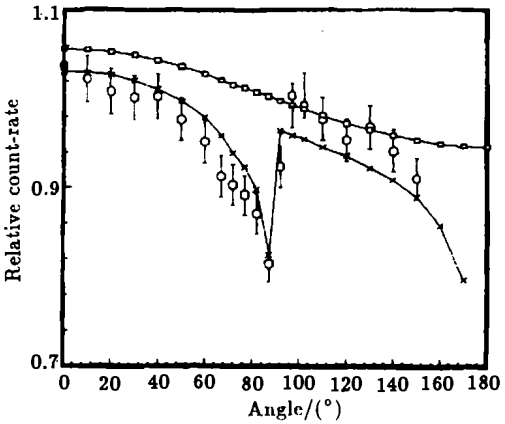

Fig.2 Measured (o) and calculated (×) angular distributions of neutron flux, D-T neutron source (□)

4 Results

In the Be and Pb sphere experiments, the intensity of the D-T neuteon source is about 1×10^9(n/s), which is an order of magnitude less than that for the Fe sphere experiments. The fraction of D-D neutrons is less than 1%. The efficiencies of the HPGe detector were calibrated by a ^{152}Eu, ^{137}Cs and ^{241}Am gamma plane source with 18 mm in diameter.

The gamma spectra from different activation foils were measured in the same condition. When the peak area corresponding to the characteristic gamma-ray energy was calculated, the effects of background, interfering reactions, dead time, etc., were considered in detail. The measured results of reaction rates were normalized to one foil atom and one source neutron according to Eq.(1) and (2).

4.1 Reaction rates in Be and Pb

The absolute activation reaction rates in Be and Pb were measured, respectively, by four kinds of foils: In, Zn Al and Cu with different thresholds. The distributions of the reaction rates in the radial channel are shown in Fig.3 and Fig.4.

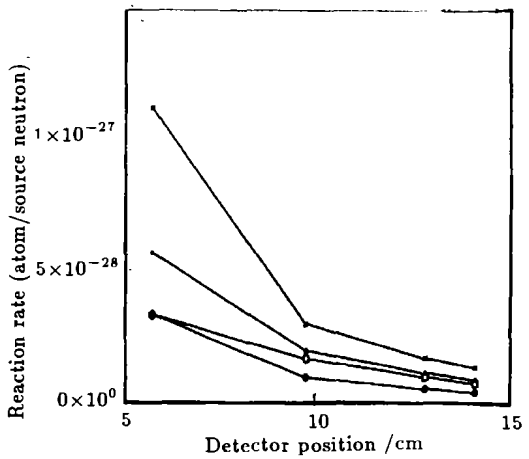

Fig.3 Distributions of absolute reaction rates in Be obtained with In(o), Zn(▲), Al(•) and Cu(×) foils, respectively

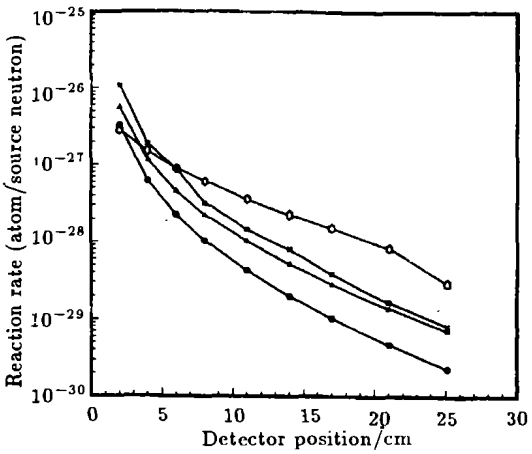

Fig.4 Distributions of absolute reaction rates in Pb obtained with In(o), Zn(▲), Al(•) and Cu(×) foils, respectively

4.2 Reaction rates in Fe

The absolute activation reaction rates in Fe were measured by eight kinds of foils of Mn, In, Zn, Ni, Fe, Mg, Al and Cu with different thresholds. The distributions of the reaction rates in the radial channel are shown in Fig.5(a) and (b).

4.3 Experimental error and calculation

The experimental error was estimated to be 5~7%, which mainly comes from the counting statistics(0.5~ 3%), the absolute intensity of the neutron source (3%), the detecting efficiency (4%), the radial position uncertainty (1%), the foil self-absorption effect (0.1~4%), and the others (1%) including the background effect.

The distributions of reaction rates were calculated by using the 1-D ANISN code and ENDF/B-VI library data.[6] The number of energy group was 33. The low threshold was 1.39×10^{-4} eV.

5 Conclusions

The absolute activation reaction rates in three kinds of spherical samples have been measured. The total experimental error is about 5~7%.

The measured results are compared to the values calculated with the 1-D ANISN code and ENDF/B-VI library data. The measured re-

sults from In, Zn, Al and Cu foils in Be and Pb are generally consistent with the calculated ones within the experimental error. However, there exists differences to different extents between the measured and calculated results in Fe, average E/C about 5~ 30%. Further analysis is needed.

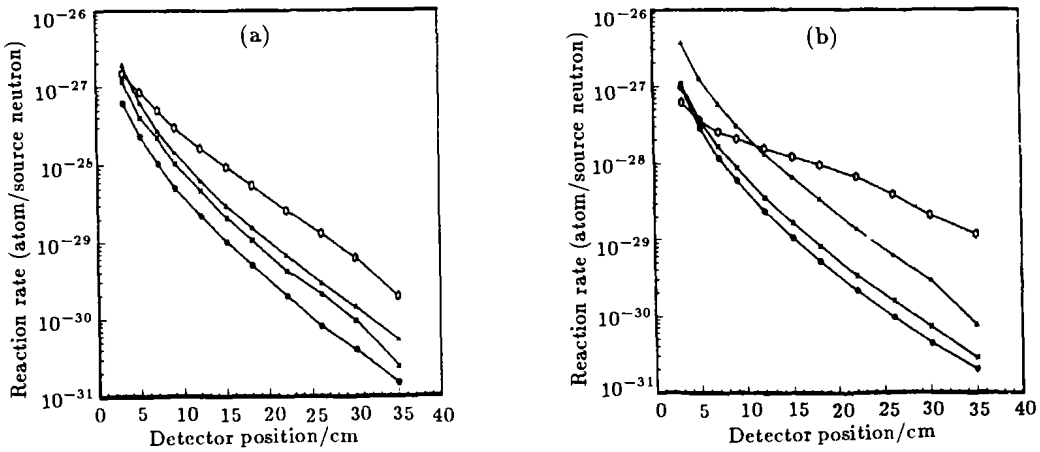

Fig.5 Distributions of absolute reaction rates in Fe obtained, respectively, with In(o), Zn(▲), Al(•) and Cu(×) foils (in Fig.5a); Mn(o), Ni(▲), Fe(•) and Mg(×) foils (in Fig.5b)

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