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Photon emission induced by fusion neutrons on optical window materials

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Abstract

In situ 14 MeV neutron, ^{60}Co gamma-ray and ion beam irradiation experiments were performed to analyze photons emitted from sapphire and quartz. Wavelength spectrum of photons emitted from sapphire during 14 MeV neutron irradiation had luminescence peaks around 330, 410 and 690 nm, and the spectrum from quartz had luminescence peaks around 450 and 650 nm. These spectra were compared with those measured for gamma-ray and ion beam irradiations. The luminescence intensity was proportional to the 14 MeV neutron flux. As for window materials at low damage levels, it has been found from the comparison of the spectra that there is no large difference in the luminescence mechanism between 14 MeV neutron, gamma-ray and ion beam. However, the number of photons per unit absorbed energy for 14 MeV neutrons in the visible range was one order smaller than that for ^{60}Co gamma-rays. The data on the luminescence of window materials for 14 MeV neutron and gamma-ray irradiations should be useful for the design of D–T fusion plasma diagnostic system. © 1998 Elsevier Science B.V. All rights reserved.

1. Introduction

Vacuum windows used for a fusion plasma diagnostic system are required to maintain vacuum integrity and to transmit light spectrum from core plasma to the various spectrometers without distortion, though a large flux of neutrons may cause transmission loss and photon emission noise [1]. In an ITER conceptual design, the windows are shielded against neutrons and gamma-rays with shielding blocks [2]. The life requirement for the windows is, for instance, 40,000 h. The neutron flux at the position of the windows should be lowered with shield below 10^7 n/cm^2/s. In this condition, the transmission loss through the windows may not occur thanks to the shield, however, the neutrons and secondary gamma-rays may induce photon emission noise during the running of a fusion reactor. Therefore, it is necessary to examine the neutron- and gamma-ray- induced photon emission on the window materials. Several works with particle accelerators and fission reactors have already been done for the research of photon emission [3–6]. It has been found that the photon emission strongly depends on the irradiation conditions; the specimen temperature, dose rate, type and energy of incident particles, etc. Fourteen MeV neutrons release high energy charged particles of protons, α-particles, recoils, etc, and these particles cause the large ionization effects and complex defects in materials. However, there is little data on the 14 MeV neutron induced photon emission. Irradiation experiments with a 14 MeV neutron source are essential, and data on 14 MeV neutron effects are directly useful for design of the fusion diagnostic systems. Hence, a photon detection system has been developed to measure the photons emitted from the window materials during 14 MeV neutron irradiation. The photon emission rate for 14 MeV neutrons and ^{60}Co gamma-rays was obtained by the in situ experiments and related dose calculations. This paper describes the experimental method and data on the photon emission for 14 MeV neutrons and gamma-rays for the design of fusion diagnostic system. Tentative ion beam irradiation experiments were also carried out with the similar

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photon detection system. And some data from ion beam experiments are shown for the comparison with the data for neutrons and gamma-rays.

2. Experimental

The in situ 14 MeV neutron irradiation experiments on the window materials were performed utilizing a deuteron accelerator type fusion neutron source, FNS [7]. At the FNS facility, 400 kV and 20 mA deuteron beams produce 3×10^{12} D–T neutrons per second at the tritium target. A photon detection system has been developed to measure photons emitted from the window sample during the 14 MeV neutron irradiation [8]. The system was composed of a sample holder, a radiation-resistant optical fiber, a multi-channel spectrometer and other electronic devices. The sample holder was set near the neutron target, and the spectrometer and other electronic circuits were placed in the working room. Fig. 1 shows the construction and arrangement of the sample holder together with the absorbed dose rate for the sample. The sample holder included a sample and two focusing lenses, and it was connected with the optical fiber. Quartz and sapphire were prepared as the irradiation samples, and their size was 5∼8 mm thick and 10∼25 mm in diameter. The samples were irradiated at room temperature and their temperature scarcely changed during irradiation. The lenses effectively transmitted photons from the sample to the optical fiber. The lenses and optical fiber were made of high pure silica to cope with the radiation damage. The fluxes and energy spectra of neutrons and gamma-rays at the position of the sample were calculated by the neutron gamma transport code MCNP [9] with nuclear data library JENDL-3.2 [10]. The absorbed doses for the samples were calculated using the energy spectra of neutrons and gamma-rays and KERMA library [11], and these dose rate D (Gy/s) are summarized in Table 1. The 14 MeV neutron flux at the position of the sample was 10^6–10^{11} n/cm^2/s and the calculated dose rate was 10^{-5}–1 Gy/s. The visible wavelength spectrum of the emitted photons was measured with the multi-channel spectrometer with an image intensifier. In addition, experiments with the sample holder not including samples was carried out to measure background photons emitted from the lenses and the optical fiber during the neutron irradiation. Finally, the number of photons emitted from the sample was determined by the subtraction of the data without the sample from the data with the sample. The 14 MeV neutron yield at the target was determined from the measurement of α-particles associated with D–T neutrons. The α-particles were measured with a silicon surface barrier detector. The measured data were all auto-stored in the personal computer.

Table 1
Calculated absorbed dose rates for samples
(DT neutron intensity: 3.0×10^{12} n/s)

Sample	D_n (Gy/s)	D_γ (Gy/s)	D_{total} (Gy/s)
Silica (SiO_2)	1.0	0.07	1.1
Sapphire (Al_2O_3)	0.92	0.11	1.0

The photon detection system was calibrated for the determination of the photon emission rate of the sample,

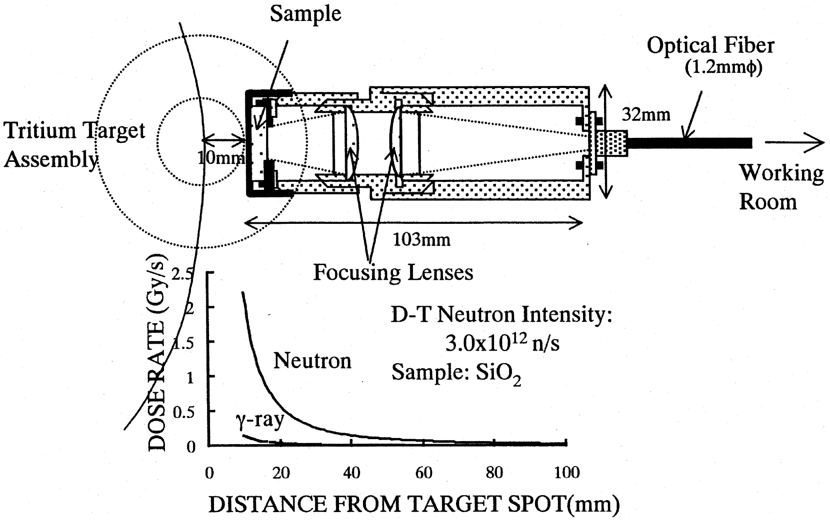

Fig. 1. Construction and arrangement of a sample holder, including a window material sample and focusing lenses, placed near the tritium target.

i.e. the number of photons emitted from the sample per unit absorbed energy. A computer program based on the data of lens optic was made to determine the geometrical efficiency of the focusing lens system. The transmittance of optical fiber was measured with a calibrated light source. The spectral power calibration of the spectrometer was carried out with the light source. The specification of the spectrometer gave the spectral bandwidth of 10 nm and the wavelength precision of ±1 nm. The errors in the efficiencies were estimated from the uncertainty of the light source. The photon detection efficiency of the total system in visible range amounted to $(8.9 \pm 1.2) \times 10^{-3}$. The luminescence efficiency of a plastic scintillator obtained by the present system with a ^{60}Co gamma-ray source was agreed approximately with the known efficiency determined by Clark [12].

Similar gamma-ray irradiation experiments on the same samples were also performed using a 110 kCi ^{60}Co source. The gamma-ray absorbed dose rate for the samples was also calculated by the MCNP code and was 0.1–5 Gy/s in the ^{60}Co gamma-ray irradiation. In addition, tentative ion beam irradiation experiments were carried out for the comparison with the neutron and gamma-ray irradiation experiments. The photons emitted from the same sapphire sample irradiated with 20 keV ions of H^+, He^+ and Ar^+ were observed with the similar photon detection system. The sapphire sample was placed in a vacuum chamber below 1×10^{-6} Torr. The beam current was adjusted as low as possible to minimize the damage of the sample. The spectrum of the photons emitted from the sample was measured with the spectrometer for a short time. The beam current was less than 100 pA and the beam spot size was about 1 mm in diameter.

3. Results and discussion

Fig. 2 shows a wavelength spectrum of photons emitted from a sapphire sample (SA-100, Kyocera Inc.) during 14 MeV neutron irradiation and its impurities are listed in Table 2. The dose rates at the position of the sample for the 14 MeV neutrons and secondary gamma-rays were 0.4 and 0.04 Gy/s, respectively. The spectrum had the luminescence peaks around 330, 410 and 690 nm. The luminescences around 330 and 410 nm are considered to be concerned with excitation and relaxation of F^+- and F-center, i.e. oxygen vacancies with one and two trapped electrons, respectively [4,6]. Also, the photon emission around 690 nm is concerned with impurity of Cr in the sapphire sample. The luminescence intensity was proportional to the 14MeV neutron flux in this experiment. It has been reported that the F-center concentration in a typical sapphire is about 10^{16} F-centers/cm^3 [13]. According to data by B.D. Evans et al., the amount of the F-centers induced with 14 MeV neutron fluence of 1×10^{14} n/cm^2 is estimated to be about 7×10^{14} cm^{-3} [14]. This means that the maximum neutron fluence of 1×10^{14} n/cm^2 was too low to damage the sample and the photon emission rate depended on the initial concentration of the F-centers in the present experiments.

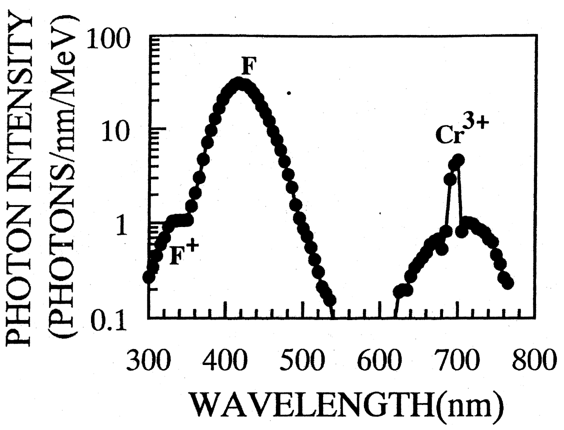

Fig. 2. Wavelength spectrum of photons emitted from sapphire sample in 14 MeV neutron irradiation experiment.

Table 2
Impurities of sapphire sample, (SA-100) (ppm)

Si	10	K	1	Zr	<1
S	4	Ca	1	Cr	<1
Fe	2	Ti	<1	Total	<28
Na	1	Y	<1		

Similar photon emission spectra were observed in the gamma-ray experiments. Fig. 3 compares luminescence spectra from the same sample between 14 MeV neutron and ^{60}Co gamma-ray irradiations. A large luminescence peak around 410 nm was observed in both experiments.

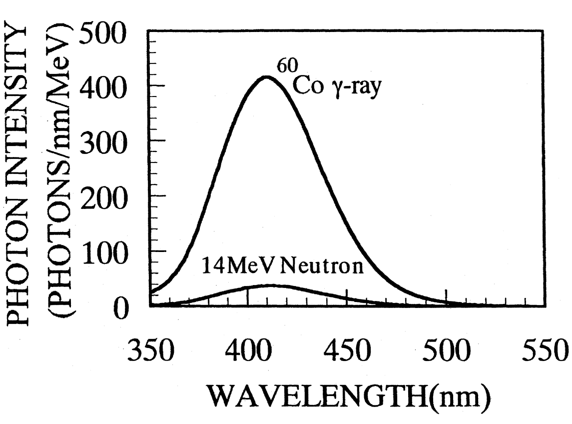

Fig. 3. Wavelength spectra of photons emitted from sapphire sample in 14 MeV neutron and ^{60}Co gamma-ray irradiation experiments.

Similar spectra have been reported in other experiments with ion and electron beams and fission neutrons [4,6,15]. As for this low-damaged sample, there seems to be no large difference in the luminescence mechanism between 14 MeV neutron and other radiations, though the photon emission rate for 14 MeV neutrons was much smaller than that for ^{60}Co gamma-rays in the present experiments. The reason of the smaller rate for 14 MeV neutrons is that the charged particles such as protons, α-particles and recoils released by 14 MeV neutron reactions induce the luminescence less efficiently than high energy electrons due to gamma-ray reactions. It should be noted that the amount of the photons measured in the 14 MeV neutron experiment includes the photons due to the secondary gamma-rays.

Fig. 4 shows an example of wavelength spectra of the emitted photons from the sapphire sample obtained in 20 keV He$^+$ beam irradiation experiments. The spectrum of the emitted photons had the same luminescence peaks of F- and F$^+$-center as shown in Figs. 2 and 3 at the beginning of the He$^+$ beam irradiation. However, a drastic change in the luminescence spectrum was observed with increasing He$^+$ fluence. The luminescence spectrum had not only peaks around 330 and 410 but also a peak around 390 nm in higher fluence irradiation. This change may be due to the creation of the defects with optical absorption and the formation of aggregated defects such as a pair of anion vacancies described by Ghamdi et al. [15]. Such effects were also observed in H$^+$ and Ar$^+$ beam irradiation experiments.

Fig. 5 shows a wavelength spectrum of the photons emitted from a quartz sample (KU-Quartz, made in Russia) during 14 MeV neutron irradiation. The impurities in the sample are listed in Table 3, and the OH content was about 800 ppm. The spectrum had the large peaks around 450 and 650 nm. The intensity of the peaks was proportional to the 14 MeV neutron flux, though the radiation dose was considered to be too low to damage the sample. Moreover, a notable reduction of the transmission was not observed in the visible range of 350–750 nm at the neutron irradiation of 1 × 10^{15} n/cm^2. The luminescence around 450 nm is considered to be concerned with the decay of self-trapped excitons in oxygen vacancies [16]. The other peak is also considered to be concerned with dissolved O_2 in the silica, and to be caused by the radiative relaxation of $O(^1D)$ to $O(^3P)$ [17]. The luminescence efficiency depended considerably on the type of samples. For example, the luminescence peak around 650 nm was not observed for a silica sample with low OH content, which is described in our previous paper [8].

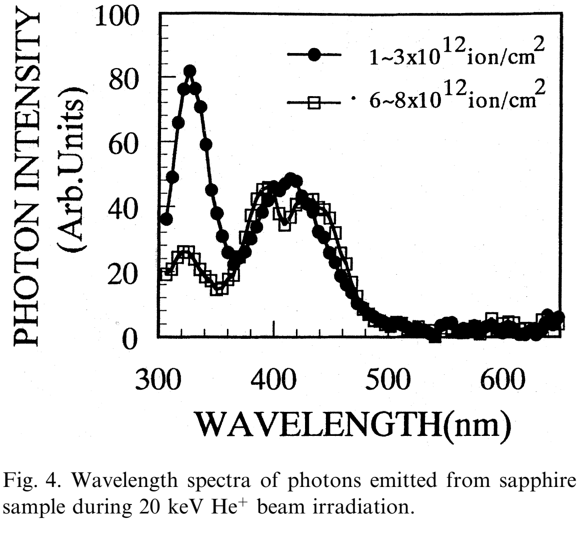

Fig. 4. Wavelength spectra of photons emitted from sapphire sample during 20 keV He$^+$ beam irradiation.

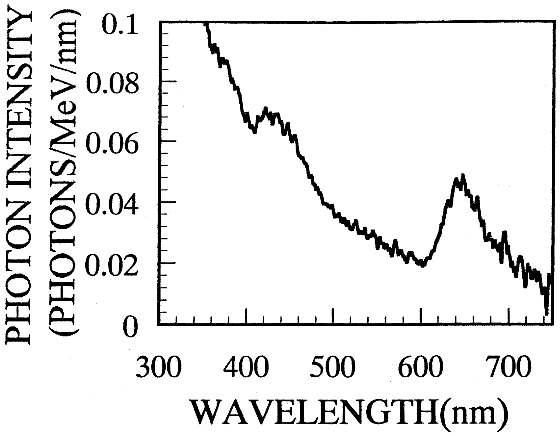

Fig. 5. Wavelength spectrum of photons emitted from quartz sample in 14 MeV neutron irradiation experiment.

Table 3
Impurities of quartz sample, (KU-Quartz) (ppm)

OH	821	Ca	1.0	Mn	0.02
Fe	1.6	Al	0.4	Ti	0.01
K	1.4	Mg	<0.4		
Na	1.0	Cu	<0.1		

4. Conclusions

The in situ 14 MeV neutron irradiation experiments were performed to measure photons emitted from the window samples. The number of the photons per unit absorbed energy was determined by the irradiation experiments and calculations. The wavelength spectrum of photons emitted from sapphire had the luminescence peaks around 330, 410 and 690 nm, and the spectrum of photons emitted from the quartz sample had the large peaks around 450 nm and 650 nm. The similar photon emission spectra were also observed in gamma-ray and ion beam experiments. It has been found from these experiments that there is not much difference in the luminescence mechanism between 14 MeV neutron and other radiations. The luminescence intensity was proportional to the 14 MeV neutron flux from 10^6 to 10^{11} n/cm^2/s and the neutron fluence was too low to damage the sample. In addition, it has been found that the photon emission rate for 14 MeV neutrons is much smaller than that for ^{60}Co gamma-rays. This suggests that photons induced by secondary gamma-rays may become the photon noise problem in the fusion diagnostic system. In addition, the ion beam irradiation experiments were carried out with the similar photon detection system. The drastic change in the luminescence spectrum was observed and this is probably because of the creation of defects with optical absorption and the formation of the aggregated defects by the collision cascades. It is not easy to compare the irradiation effects between neutrons and ion-beams due to the difference between the bulk and surface effects. The luminescence spectrum may be changed owing to the complex defects in heavier fusion neutron irradiation, which is one of the subjects to be studied. The present data on the photon emission obtained in 14 MeV neutron and gamma-ray experiments should be useful for the estimation for photon-noise level from the optical windows used for the fusion plasma diagnostic system.

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