Contribution of cadmium to the total amount of positron creation in a reactor-based slow positron beamline

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Abstract

In the slow positron beamline at the Kyoto University Research Reactor (KUR), positron creation was enhanced by increasing the gamma-ray intensity at the positron source via the reaction of ^{113}Cd(n,γ)^{114}Cd. To achieve this, a cadmium (Cd) cap was attached to the positron source, surrounding it, and thus, without intentional cooling, the temperature was able to reach near the melting point of Cd via nuclear heating. In this study, the degree to which the Cd cap contributes to the quantity of positron creation was estimated by using the Monte Carlo calculation code PHITS (Particle and Heavy Ion Transport code System), which simulates radiation transportation and interaction with matter. As a result, the number of positrons created was found to become 2.0 ± 0.1 times higher by using the Cd cap at the KUR slow positron beamline. The use of the Cd cap was confirmed to be significantly effective for enhancing positron creation.

Keywords: Reactor-based slow positron beamline, Cadmium, Prompt gamma-ray, Pair creation, Monte Carlo simulation

1. Introduction

Positrons are widely used in the field of materials science as a unique probe that can detect vacancy-type defects in crystalline materials with high sensitivity [1, 2, 3]. It is especially important when observing vacancies in thin films or near the surface regions for many functional materials or ion-irradiated materials. In order to apply positron annihilation spectroscopy in thin films and/or near surface regions, a monoenergetic slow positron beam is useful [2]. However, since the conversion efficiency of moderating high-energy positrons into low-energy (slow) positrons is very low (the efficiency is generally around 10^{-4} using a tungsten (W) positron moderator [4, 5, 6, 7, 8]), intense positron sources are desirable. Thus, positron sources using nuclear reactors [9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23], instead of those using radioisotopes, are explored here.

In reactor-based positron sources, electron-positron pairs are typically created by using fission gamma-rays emitted from the reactor core. At the Kyoto University Research Reactor (KUR) slow positron beamline, a positron source is surrounded by a cadmium (Cd) cap in order to enhance the gamma-ray intensity through a ^{113}Cd(n,γ)^{114}Cd reaction [24] in addition to the fission gamma-rays. ^{113}Cd has a very large neutron-capture cross section of 20600 barns, and it is present in natural cadmium at 12.22% [25]. Figure 1 shows schematic views of the KUR slow positron beamline and its positron source structure. A vacuum duct is inserted close to the reactor core. A W-disk with a diameter of 46 mm and thickness of 1 mm is installed at the top of the vacuum duct as a positron converter. Electron-positron pairs are emitted from the W-disk by irradiating gamma-rays. The emitted high-energy (~MeV) positrons are incident into a W-strip assembly [26] attached as a positron moderator, and a small part of the positrons are re-emitted into a vacuum with an energy of a few eV [27]. The re-emitted slow positrons are extracted by an electric field, guided by a magnetic field excited by solenoid coils, and are then transported about 10 m downstream to a sample position. Details regarding the KUR slow positron beamline have been described elsewhere [28, 29, 30].

A feature of the positron source of the KUR slow positron beamline is that the Cd cap attached to the vacuum duct is housed in two sleeves, called the 'outer sleeve' and 'inner sleeve' which have inner diameters of 200 mm and 178 mm, respectively. The inner sleeve is installed to prevent the collision of the vacuum duct to the outer sleeve, which is part of the nuclear reactor, even if the vacuum duct is shaken significantly by a severe earthquake. The outer side of the outer sleeve faces the reactor coolant water (~50°C during operation); however, the gaps between the outer sleeve, the inner sleeve, and the vacuum duct are filled with air. Such a setup makes it difficult to remove the heat generated at the top of the vacuum duct (including the Cd cap). Without intentional cooling, when the KUR is operated at 5 MW, which is its max-

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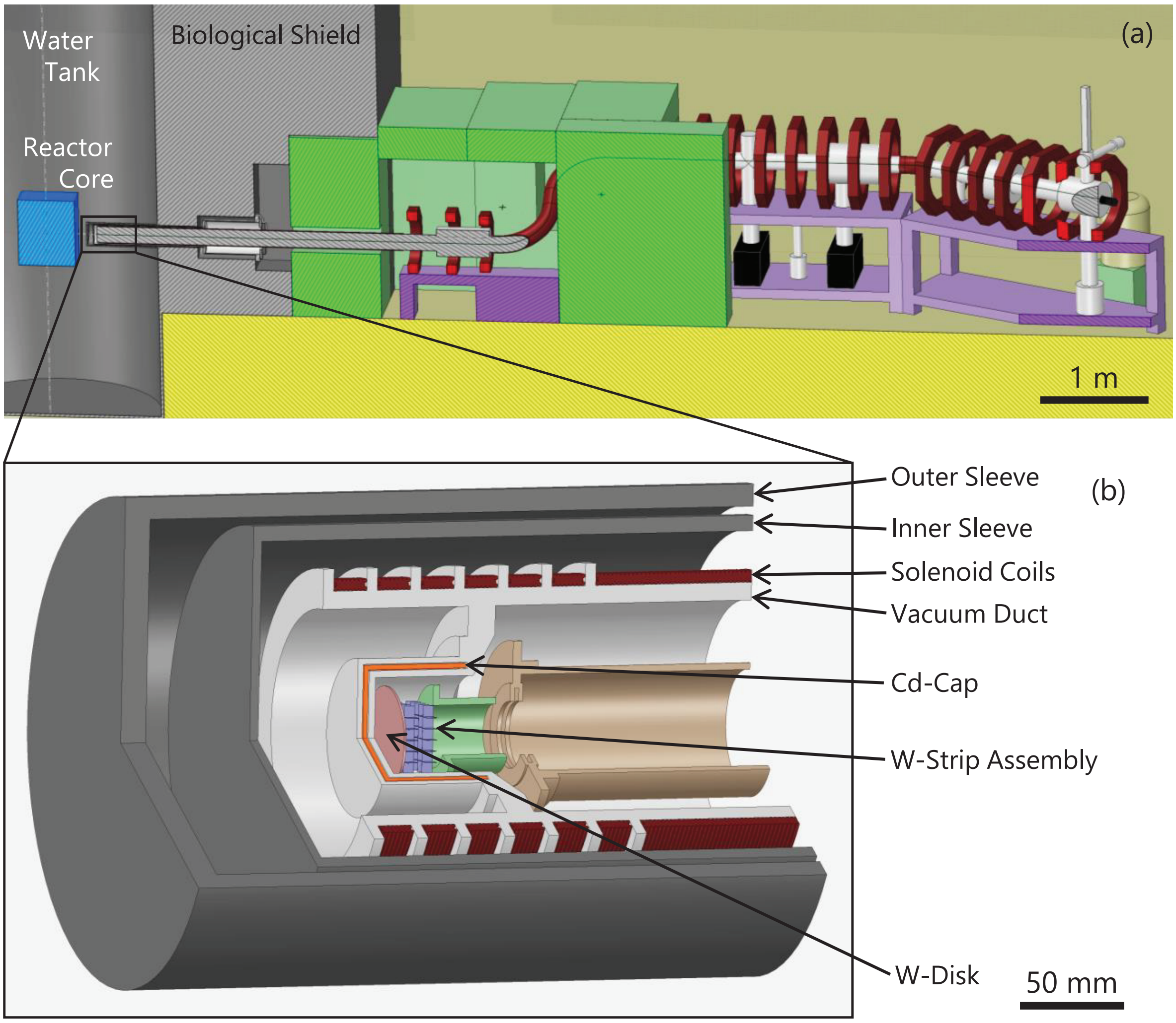

Figure 1: (a) Schematic view of KUR reactor-based slow positron beamline. A vacuum duct is inserted close to the reactor core. Positrons are created at the top of the vacuum duct, indicated as a rectangular frame in the panel. (b) Magnified drawing of positron source structures of the KUR slow positron beamline. W-disk and W-strip assembly are installed as a positron converter and positron moderator, respectively. A Cd cap is installed at the top of the vacuum duct in order to enhance the gamma-ray intensity at the positron converter by using neutron-capture-induced prompt gamma-rays. The Cd cap is covered and sealed with an outer Al cap. The vacuum duct, inner sleeve, and outer sleeve are made of Al alloy. The outer side of the outer sleeve faces the reactor coolant water. The gaps between the outer sleeve, inner sleeve, and vacuum duct are filled with air. Note that although solenoid coils are drawn in brown, they actually consist of Al-wires to reduce the effect of radioactivation.

imum thermal power, the temperature of the Cd cap in its mounted position reaches nearly 300°C due to nuclear heating, which is close to its melting point (321°C). For this reason, an additional cooling system of the positron source has been installed to enable safe extraction of a slow positron beam during 5 MW operation [30], and special attention must be paid to its temperature to avoid melting. Using the Cd cap as the positron source is the same as the other reactor-based slow positron beam facilities. However, removing heat from the Cd cap in the KUR positron source is difficult because of its structure [30], described above. Therefore, estimating how much the Cd cap contributes to positron creation becomes an interesting matter.

PHITS (Particle and Heavy Ion Transport code System) [31, 32, 33], which is a radiation behavior simulation code based on the Monte Carlo technique, is used not only in the nuclear field but also in various fields such as accelerator, medicine, radiation protection, and aerospace. The radiation behavior simulation makes it possible to evaluate the contribution of neutrons and gamma-rays in positron creation separately. In this study, the quantity of positron creation in the KUR slow positron beamline was simulated by using the PHITS code, and the differences between the setups with and without using a Cd cap were compared.

2. Simulation method

Figure 2 shows the constructed simulation model used in this study. The model was constructed in the x-y-z coordinate space of -60 cm $\leq x \leq 60$ cm, -60 cm $\leq y \leq 60$ cm, and -13.3 cm $\leq z \leq 60$ cm (only part of the

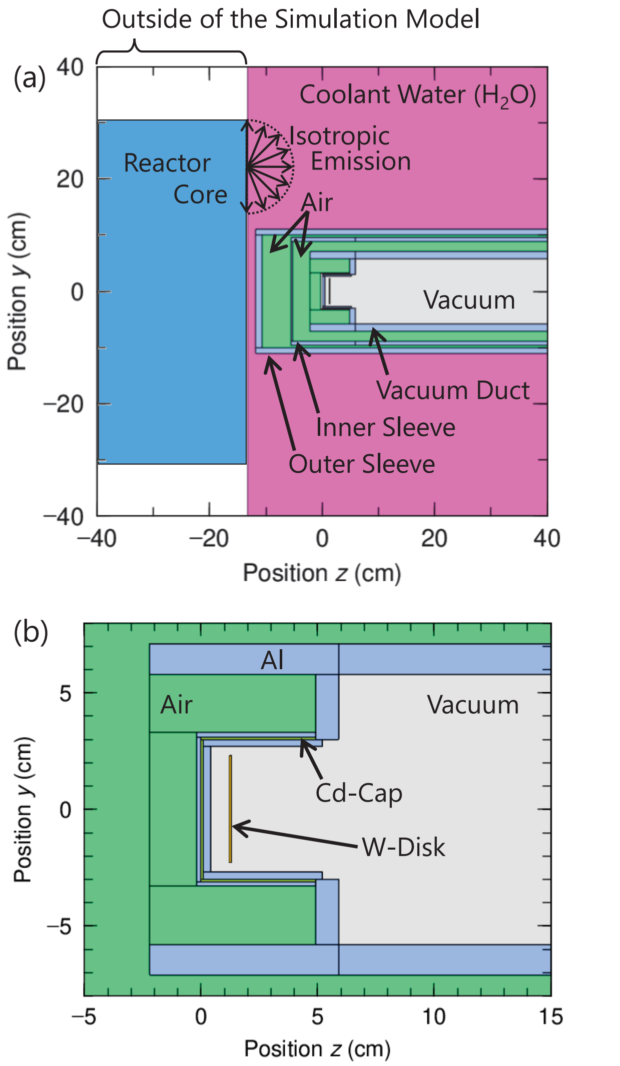

Figure 2: (a) Schematic diagram of a simulation model at an $x = 0$ cm cross section. A rectangular planar source, emitting particles isotropically into the outer halfspace, is placed on the x-y plane at $z = -13.0$ cm instead of the reactor core. (b) Enlarged schematic diagram of the model around the top of the vacuum duct. In the case of the non-Cd cap configuration, the cap region was replaced by air.

model region is shown). The x-y plane at $z = -13.0$ cm corresponds to the surface of the square-pillar-shaped reactor core. The reactor coolant water (light water), outer sleeve, inner sleeve, vacuum duct, solenoid coils, W-disk, and Cd cap are incorporated into the simulation model. The concentrations of each cadmium isotope were specified by their natural abundance ratios. The region of $z < -13.3$ cm, where the reactor core is located, is outside of the simulation model. In the simulation, a rectangular planar source with a size of 51×61 cm^2 is placed on the x-y plane at $z = -13.0$ cm instead of the reactor core. Neutrons or gamma-rays were isotropically emitted into the outer halfspace. A W-disk, with a diameter of 46 mm and a thickness of 1 mm, and a cylindrical Cd cap with a diameter of 62 mm, length of 48 mm, and thickness of

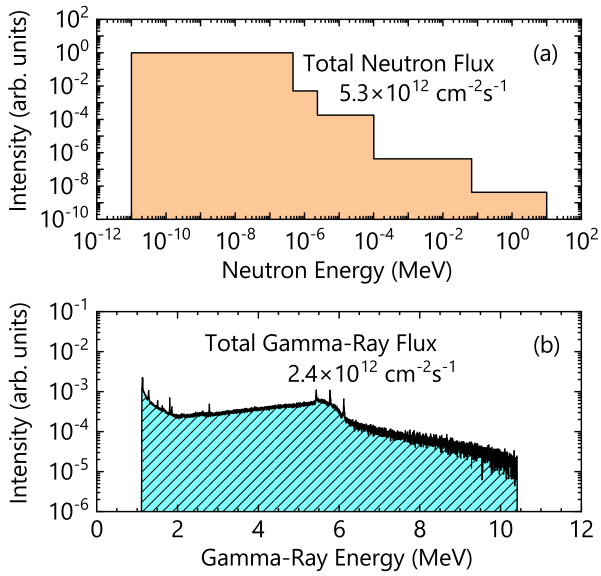

Figure 3: Energy spectra of (a) neutrons and (b) gamma-rays emitted from the planar source (instead of the reactor core) used in the simulation. The total fluxes of neutrons and gamma-rays used for the calculation, corresponding to the values at 5 MW KUR operation, are also indicated, respectively.

1 mm are placed, as shown in Fig. 2(b). (The reactor-core-side surface of the cylindrical Cd cap corresponds to the x-y plane at $z = 0$ cm.) The thickness of the solenoid coils (aluminum (Al)-wires) is included as the thickness of the vacuum duct. In the non-Cd cap configuration, the cap region was replaced by air, in this study. The positron moderator (W-strip assembly) and the structure supporting it in the vacuum duct were omitted in the simulation model.

Figure 3 shows energy spectra of neutrons and gamma-rays emitted from the planar source used in the simulation. The neutron and gamma-ray fluxes at the planar source used for calculation were 5.3×10^{12} neutrons/(cm^2·s) and 2.4×10^{12} photons/(cm^2·s), respectively, corresponding to the fluxes in the 5 MW KUR operation. The neutron energy spectrum and its flux were determined based on another Monte Carlo simulation [34], whereas the gamma-ray energy spectrum and its flux were based on measurement data [34]. Since gamma-rays below 1.022 MeV do not contribute to positron creation, they were cut off from the gamma-ray source in this work.

The number of positrons emitted from the W-disk into the vacuum was counted for each case, where only neutrons or only gamma-rays were emitted from the planar source. The calculations were performed by using the PHITS 3.04 code. In each calculation, 3×10^8 neutrons or 1×10^8 gamma-rays were emitted from the planar source. Neutron and gamma-ray transport calculations were carried out until the energy of each particle became less than 10 μeV. Electron and positron transport calculations were also performed until the energy of each particle became less than 1 eV.

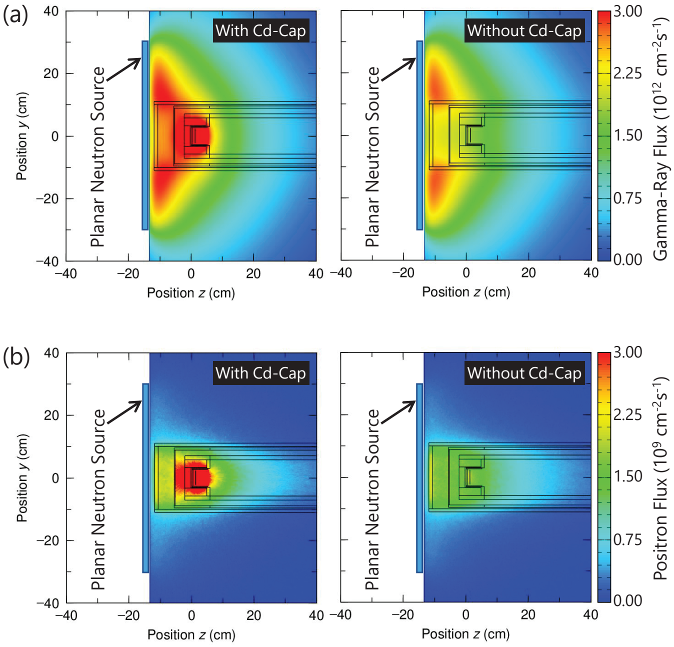

Figure 4: Distributions of (a) gamma-ray and (b) positron fluxes when only neutrons are emitted from the planar source. The left and right panels show the cases with and without using a Cd cap, respectively. In all of the panels, the values in the x-axis direction are integrated with the range of -10 cm $\leq x \leq 10$ cm.

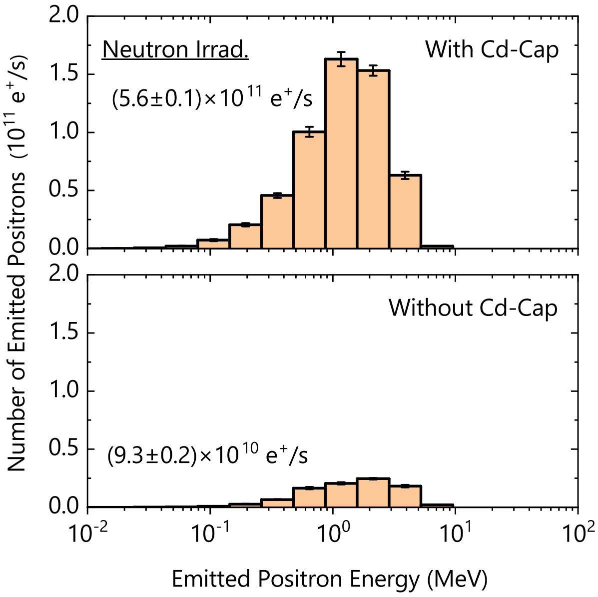

Figure 5: Numbers of positrons emitted from the W-disk into a vacuum when only neutrons were emitted from the planar source. The upper and lower panels show the cases with and without using the Cd cap, respectively. Total numbers of emitted positrons in both cases are also indicated.

3. Results

Figure 4 shows the distributions of the gamma-ray and positron fluxes when only neutrons are emitted from the planar source, for the cases with and without the Cd cap. Even for the case without using the Cd cap, a slight increase in gamma-ray flux was observed in the W-disk and in the water near the planar source. However, the gamma-ray flux around the W-disk was significantly enhanced by using the Cd cap, as shown in Fig. 4(a). Along with the enhancement of the gamma-ray flux, the positron flux around the W-disk was also significantly increased by using the Cd cap, as shown in Fig. 4(b). Figure 5 shows the difference in the number of positrons emitted from the W-disk into a vacuum, for the cases with and without using the Cd cap when only neutrons were emitted from the planar source. Even for the case without using the Cd cap, a total of $(9.3 \pm 0.2) \times 10^{10}$ positrons/s were estimated to be emitted from the W-disk. However, for the case using the Cd cap, the total number of emitted positrons increased to be $(5.6 \pm 0.1) \times 10^{11}$ positrons/s. That is, for the case of neutron emission from the planar source, the use of the Cd cap increases the number of emitted positrons by a factor of 6.0 ± 0.2.

Figure 6 shows the distributions of the gamma-ray and positron fluxes when only gamma-rays are emitted from the planar source, for the cases with and without the Cd cap. In these cases, the distributions of the gamma-ray and positron fluxes are not affected by the presence of the Cd cap. Figure 7 shows the difference in the number of positrons emitted from the W-disk into a vacuum between the cases with and without using the Cd cap when only gamma-rays were emitted from the planar source. The total number of positrons emitted from the W-disk was $(3.6 \pm 0.1) \times 10^{11}$ positrons/s in both cases, which is the same regardless of the presence of the Cd cap.

Figure 8 shows the sum of the number of positrons emitted from the W-disk into a vacuum for each case shown in Figs. 5 and 7. This corresponds to the number of positrons obtained when neutrons and gamma-rays are emitted from the planar source, as in the actual reactor core. In these cases, the total numbers of emitted positrons with and without using the Cd cap are $(9.2 \pm 0.1) \times 10^{11}$ positrons/s and $(4.5 \pm 0.1) \times 10^{11}$ positrons/s, respectively. When both neutrons and gamma-rays are emitted from the planar source, the use of the Cd cap increases the number of emitted positrons by a factor of 2.0 ± 0.1.

4. Discussion

For the case of neutron irradiation from the planar source, an increase in the gamma-ray flux is observed in the water near the planar source, even without using the Cd cap, as shown in Fig. 4(a). This increase can be attributed to the gamma-rays emitted through the ^{1}H(n,γ)^{2}H reaction. In addition, gamma-rays will be emitted from the vacuum duct and two sleeves through the ^{27}Al(n,γ)^{28}Al reaction. The neutron-capture cross sections of ^{1}H and ^{27}Al are 0.33 barns and 0.23 barns, respectively [25]. Although these cross sections are very small compared with those of ^{113}Cd (20600 barns), gamma-rays are expected

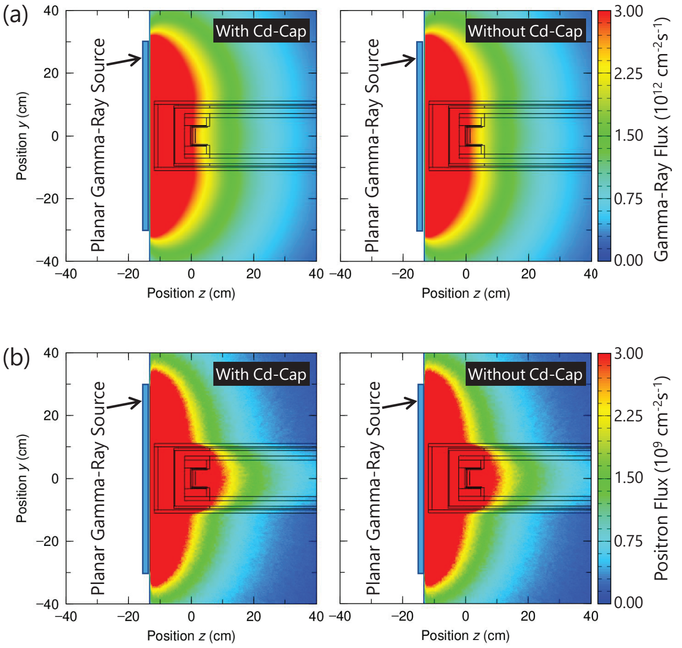

Figure 6: Distributions of (a) gamma-ray and (b) positron fluxes when only gamma-rays are emitted from the planar source. The left and right panels show the cases with and without using a Cd cap, respectively. In all of the panels, the values in the x-axis direction are integrated with the range of -10 cm $\leq x \leq 10$ cm.

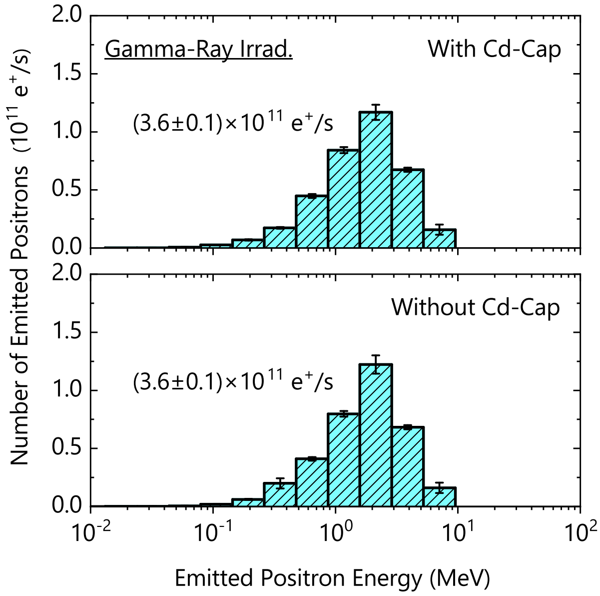

Figure 7: Numbers of positrons emitted from the W-disk into a vacuum when only gamma-rays were emitted from the planar source. The upper and lower panels show the cases with and without using the Cd cap, respectively. The total numbers of emitted positrons in both cases are also indicated.

to be emitted from these materials because of their large absolute amount. As a result, positrons are emitted to some extent from the W-disk even without using the Cd cap, as shown in Fig. 5. However, installing the Cd cap drastically increases the gamma-ray flux around the W-disk, and the total number of emitted positrons increases by about six-fold. When only the gamma-rays are emitted from the planar source, the gamma-ray flux distribution hardly changes, even without using the Cd cap, as shown in Fig. 6. This seems natural, because the Cd cap, with a thickness of 1 mm, hardly shields the gamma-rays. Therefore, the positron flux distribution does not change, and the total number of emitted positrons is also unchanged, as shown in Fig. 7. According to the results shown in Fig. 8, about 60% of the positrons emitted from the W-disk are attributed to neutrons in the case of the result with Cd cap. Figure 8 also indicates that the total number of emitted positrons becomes halved when the Cd cap is removed.

In this work, the number of positrons emitted from the whole surface of the W-disk (*i.e.*, the front, back, and side surfaces) was counted. As shown in Fig. 8, the number of positrons emitted from the whole surface area of 34.7 cm^2 was estimated to be $(9.2 \pm 0.1) \times 10^{11}$ e^+/s when using the Cd cap at 5 MW KUR operation. However, since the positron moderator (W-strip assembly) is mounted on supporting structures with a 28-mm-diameter window (6.15 cm^2) in front of the W-disk, the number of positrons that can be incident on the positron moderator from the W-disk will be $(6.15/34.7) \times (9.2 \times 10^{11}) = 1.6 \times 10^{11}$ e^+/s. (Actually, not all positrons emitted from the 28-mm-diameter area of the W-disk are incident on the moderator, and a part of positrons emitted from the supporting structures are also incident on the moderator, but they are not considered here.) On the other hand, the moderation efficiency of the high-energy ($\sim$MeV) positrons of the W positron moderator is speculated to be lower than that of the relatively low-energy positrons of less than $\sim$500 keV emitted from the ^{22}Na radioisotopes. Therefore, assuming that the positron moderation efficiency of the W-strip assembly is 5×10^{-5}, the number of slow positrons is estimated to be $\sim 8 \times 10^6$ slow e^+/s. The actual beam intensity of the slow positrons obtained during 5 MW KUR operation has been confirmed to be 6.2×10^6 slow e^+/s at the end of the beamline [30]. The above-estimated value seems to be reasonable compared to the measured value. The moderation efficiency of the positron moderator actually varies greatly depending on its surface conditions and internal crystalline defects. Furthermore, the transport efficiency of slow positrons also needs to be considered for comparison with the measured value.

Then, by focusing our attention on the energy spectrum of the positrons emitted from the W-disk, large part of positrons were indicated to be emitted with energies above 100 keV, as shown in Fig. 8. In other words, estimating the total number of emitted positrons without counting the positrons having energies below 100 keV does not become a significant problem. In addition, gamma-rays with energies below 100 keV cannot create electron-positron pairs. Therefore, if the transport calculations of electrons,

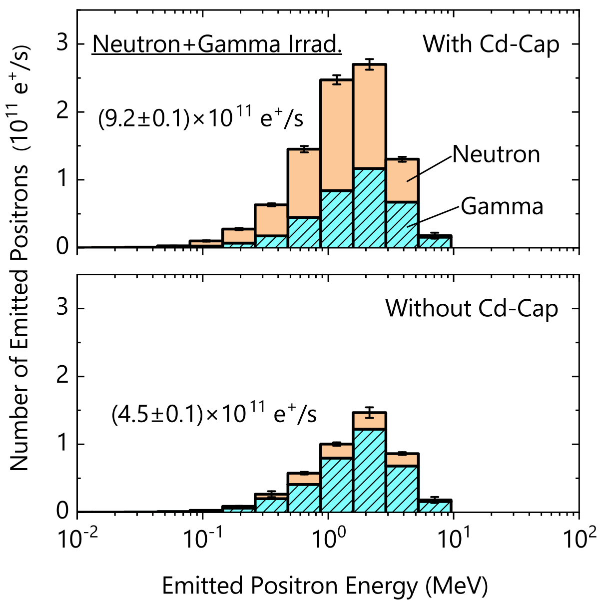

Figure 8: Numbers of positrons emitted from the W-disk into a vacuum when both neutrons and gamma-rays were emitted from the planar source. The upper and lower panels show the cases with and without using the Cd cap, respectively. "Neutron" and "Gamma" represent the numbers of positrons attributed to neutron-capture-induced prompt gamma-rays and fission gamma-rays, respectively. The total numbers of emitted positrons in the cases with and without using the Cd cap are also indicated.

positrons, and gamma-rays are cut off when their energies fall below 100 keV, the calculation cost will be significantly reduced.

Although prompt gamma-rays emitted from Cd are used in the KUR slow positron beamline to enhance the quantity of positron creation, the use of other materials having large neutron-capture cross sections is also worth consideration [17, 35, 36]. The ^{157}Gd(n,γ)^{158}Gd, ^{155}Gd(n,γ)^{156}Gd, and ^{149}Sm(n,γ)^{150}Sm reactions may be effective, since the neutron-capture cross sections of ^{157}Gd, ^{155}Gd, and ^{149}Sm have large values of 254000 barns, 60900 barns, and 40140 barns, respectively [25]. In addition, ^{157}Gd, ^{155}Gd, and ^{149}Sm are sufficiently present in natural gadolinium (Gd) or samarium (Sm) at 15.65%, 14.80%, and 13.82%, respectively [25]. Therefore, Gd and Sm, which have melting points of 1312°C and 1072°C, respectively, may be two of the candidate materials for enhancing the quantity of positron emission. The PHITS calculations will also be useful in estimating the suitability of such materials.

5. Conclusion

In this study, positron creation at the KUR slow positron beamline was simulated by using the PHITS code. As a result, the quantity of positron creation was estimated to become 2.0 ± 0.1 times higher by installing a Cd cap to the positron source. Thus, the use of the Cd cap was confirmed to be significantly effective although special attention must be paid for cooling. The Monte Carlo simulation used in this study will also be helpful in exploring other gamma-ray-enhancing materials for increasing the quantity of positron emission.

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