Positron beam facility at Kyoto University Research Reactor

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Abstract. A positron beam facility is presently under construction at the Kyoto University Research Reactor (KUR), which is a light-water moderated tank-type reactor operated at a rated thermal power of 5 MW. A cadmium (Cd) – tungsten (W) source similar to that used in NEPOMUC was chosen in the KUR because Cd is very efficient at producing $\gamma$-rays when exposed to thermal neutron flux, and W is a widely used in converter and moderator materials. High-energy positrons are moderated by a W moderator with a mesh structure. Electrical lenses and a solenoid magnetic field are used to extract the moderated positrons and guide them to a platform outside of the reactor, respectively. Since Japan is an earthquake-prone country, a special attention is paid for the design of the in-pile positron source so as not to damage the reactor in the severe earthquake.

1. Introduction
Positron annihilation spectroscopy is a powerful tool for detecting vacancy-type defects in condensed matter. Monoenergetic positrons are widely used to study thin layers, surfaces and near surface effects in solids. There are three methods for the generation of positron beam [1]. $\beta^+$ active isotopes such as $^{22}$Na are mainly employed as the positron source in slow positron beam facilities. The beam intensity depends on the radio activity of isotopes and the high beam intensity is not easy to be gotten because of the difficulty for obtaining high activity isotopes. The linac-based positron source can increase the positron beam intensity [2, 3]. Positrons are generated in a high-Z target, which is bombarded by electrons with energies of several tens of MeV. This system, however, is cost a lot for the construction of high energy and high intensity electron accelerator.

The in-pile positron source can provide a monoenergetic positron beam of high intensity, where positrons are generated by pair production of high energy of $\gamma$-rays [4, 5]. Though the beam is continuous one, it is possible to make high intensity pulse beam using beam buncher. The application of positron beam can be expanded with increasing the beam intensity. For example, the microstructural changes in deformed and irradiated materials can be dynamically measured. These factors motivated the development of a high-intensity positron beam facility at Kyoto University Research Reactor (KUR). In this paper, the design of a reactor-based slow positron beam facility is...
described, and the safety assessment of the in-pile positron source is also discussed because Japan is earthquake country.

2. Positron source and positron beam facility at KUR

In order to promote materials science research using positron beams, an in-pile positron source is now in production at the B-1 hole (20 cm in diameter) of KUR, which is a light-water moderated tank-type reactor operated at maximum thermal power of 5 MW. The cross sectional view of the reactor is shown in Figure 1 [6]. The thermal neutron flux and the $\gamma$-ray flux at the positron source position are about $1.5 \times 10^{12}$ n/cm²s and $10^{5}$ Gy/h, respectively, at 5 MW. Figure 2 shows the draft of positron beam line and material irradiation chamber.

![Figure 1. Cross sectional view of KUR.](image1)

![Figure 2. Draft of positron beam line and material irradiation chamber.](image2)
Figure 3 shows a schematic view of the in-pile positron source. A W foil capped with a Cd shroud is used to generate a positron beam. In addition to the $\gamma$-rays from the reactor core, high energy $\gamma$-rays are generated by the $^{113}\text{Cd}\ (n, \gamma)^{114}\text{Cd}$ reaction, since the cross-section of thermal neutron capture in $^{113}\text{Cd}$ (the abundance of $^{113}\text{Cd}$ in natural Cd is 12.22%) is up to 26000 barns. On average, 2.3 photons with energies above 1.5 MeV are emitted per captured neutron [7]. The present design, a 1-mm-thick Cd cap covered by an Al plate is used. Though $^{113}\text{Cd}$ in natural Cd burns up by neutron capture, enough $^{113}\text{Cd}$ remains even after five years of KUR operation of 1500 h with an average power of 2 MW per year. According to reference 7, the optimal thickness for positron production in the W converter is about 0.2 – 0.8 g/cm$^2$, which corresponds to a W thickness of 0.1 – 0.4 mm. The peak energy of positrons produced by pair production is 800 keV. Well-annealed W foils with a mesh structure are used as a moderator to moderate the positrons with high energy. Figure 4 shows a depth profile of stopping probability for positrons with an energy of 800 keV. The depth profile was calculated by the following equation [8, 9].

$$ P(x, E) = -\frac{d}{dx} \exp(-x^m / x_0^m) \quad (1) $$

Here, $x_0 = (\alpha / \rho)E_0$, $\rho$ is the material density in g/cm$^3$, $E$ is the incident positron energy in keV, and $x$ is the distance from the surface in cm. We used the Makhovian parameters of $\alpha = 4.0 \mu g/cm^2/keV^{1.6}$, $m=2$, and $n=1.62$ determined by Vehanen et al [9]. The calculation indicated that the optimum thickness of W foils is about 250 $\mu$m for positron moderation. But 0.2 mm in thickness of W foil is selected as converter shown in Figure 3 in consideration of heat generation of W induced by $\gamma$ radiation. As described above, the thermal neutron flux at positron source is $1.5\times10^{12}$ n/cm$^2$s at 5 MW. $\gamma$ ray flux with energy higher than 1.022 MeV needed for pair production is estimated to be $8.4\times10^{11}$ photos/cm$^2$s using the model calculation code (MCNP: Monte Carlo N-Particle-transport-calculation [10]). Though we have not estimated the slow positron flux yet, the $\gamma$ ray flux is almost the same as that at the Hoger Onderwijs Reactor in the Reactor Institute Delft [$8.8\times10^{12}$ photos/cm$^2$s]. A positive voltage of several tens of eV is applied at the electrical lens to extract the moderated positrons. Then, the positron beam is magnetically guided in a solenoid field of 7 mT and compensation fields. In order to reduce the background of fast neutrons and $\gamma$-radiation from the reactor core, the positron beam passes two bends in shields consisting of polyethylene, concrete and lead block. The former two materials are to moderate the fast neutrons, and the latter is to shield the $\gamma$-radiation. After passing these bends, the beam is guided to samples in the irradiation chamber and accelerated up to 30 keV.

3. Safety assessments of positron beam facility

Earthquake resistant beam lines, especially in-pile positron sources, are required in KUR. Therefore, we design an in-pile positron source with a tough structure and ensure that the positron source would not damage the reactor in a severe earthquake. The beam line is fixed using more than twenty anchor bolts of 16 mm in diameter. Furthermore, in order to maintain the allowable stress of the Al alloy tube of the positron source, the temperature of the Al tube was designed to be below 473 K at in-pile position. Finally, to decrease the production of $^{41}\text{Ar}$ by absorption of neutrons ($^{40}\text{Ar}\ (n, \gamma)^{41}\text{Ar}$) in air and reduce the background $\gamma$-radiation in the reactor room, the composition and configuration of the shield are designed based on calculations using the MVP2 code (Monte Carlo Codes for Neutron and Photon Transport [11]). Figure 5 shows positron beam facility at Kyoto University Research Reactor.
4. Summary and outlook

The main parts of the positron beam facility at KUR were made in the last year. After adjustment of the magnetic coils, the in-pile components will be installed in the B-1 hole at KUR by the end of 2013. Positron generation tests and coincidence Doppler broadening measurements will be carried out in early 2014. Then beam buncher is introduced for the production of pulse positron beam, and the positron annihilation lifetime and age-momentum correlation can be measured in the facility within two years.
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