Construction of a surface positronium lifetime spectroscopy apparatus with a spin-polarized low energy positron beam

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Construction of a surface positronium lifetime spectroscopy apparatus with a spin-polarized low energy positron beam

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Abstract. We have developed a surface positronium (Ps) lifetime spectrometer. A spin-polarized slow positron beam is generated by a sodium-22 source and a solid krypton moderator and transported to the sample chamber by electrostatic lenses. The incident energy is adjusted by a retarding potential using a deceleration tube. For the lifetime measurement, the start signal is obtained from a secondary-electron detector installed in front of the sample. The stop signal is detected by a scintillation detector for annihilation gamma rays. As a performance test, Ps lifetime measurements were carried out and clear decay curves derived from ortho-Ps self-annihilation were successfully observed. This system might be used for the estimation of the spin polarization at the surface of ferromagnetic materials.

1. Introduction

As a method to determine surface spin polarization, we have developed a spin-polarized slow positron beam apparatus [1-3]. Positrons, which are implanted near the surface and then diffuse to the surface, are emitted as positronium (Ps) when the work function of Ps is negative. By measuring 3-gamma annihilation ratio of ortho-Ps (o-Ps) decay, the spin polarization at the first surface layer can be determined. Since Ps is formed only at a vacuum region with a low-electron density, the spin polarization obtained by this method is not affected by the bulk condition. Indeed, we successfully observed novel spin phenomena, such as current-induced spin polarization [4].

The intensity of o-Ps decay can be obtained from both an energy spectrum of the annihilation gamma rays and a lifetime spectrum [5]. Since the energy distribution of 3-gamma annihilation is continuous in the range of 0-511 keV, it is not easy to estimate this precisely from the energy spectrum, which is a mixture of some effects, such as Compton scattering. From the lifetime measurement, however, it is easy to extract o-Ps intensity because of its characteristic long lifetime of 142 ns.

To obtain lifetime spectrum using a slow positron beam, a pulsed beam is often used. However, it is difficult to form a pulsed beam in our apparatus using only an electrostatic field to generate the spin-polarized positron beam. Gidley *et al.* show that the Ps lifetime measurement is possible by detecting secondary electrons when positrons with the energy range of 300 - 1600 eV are implanted onto a sample [6, 7]. In this study, to carry out a surface Ps lifetime measurement, we optimised the secondary-electron method for a spin-polarized positron beam with low energy.

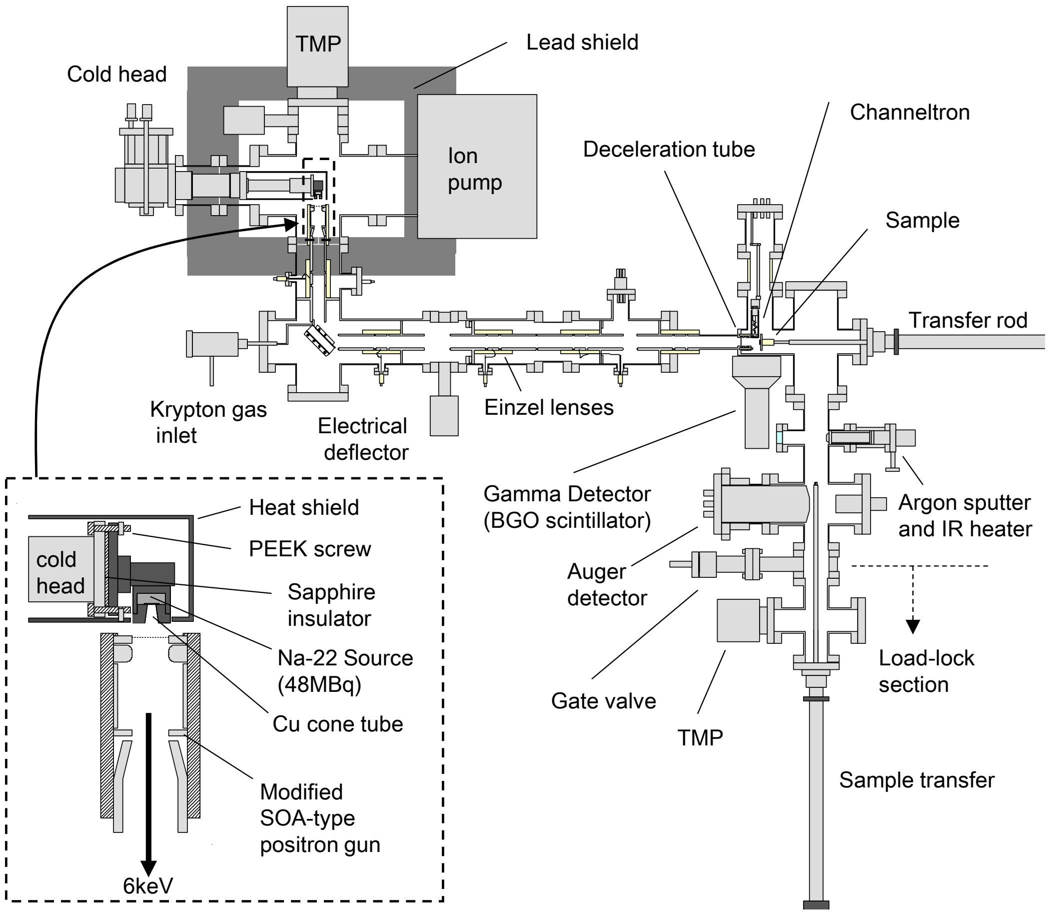

Figure 1. Schematic diagram of the apparatus developed in this work.

2. Construction of apparatus

Figure 1 shows an overview of the newly developed beam apparatus. A 48 MBq ^{22}Na sealed source and a copper cone tube with a bottom diameter of 5 mm and an angle of 5.7 degree are mounted on a 4 K refrigerator. A solid krypton moderator is formed on the inner surface of the copper cone and on the source window [8]. A slow positron beam with an energy of 6 keV is generated by a modified Soa-gun [9]. Since positrons emitted from radioisotopes are longitudinally spin-polarized [10], one can obtain spin-polarized positron beam by the electrostatic beam transportation not to rotate spin direction. The positron beam is transported by five einzel lenses and focused onto the sample. By using an electrostatic deflector, a transversely spin-polarized positron beam is formed. Spin polarization was estimated before to be approximately 27 % using the magnetic quenching method [11].

Figure 2 shows a schematic diagram of the lifetime measurement system. The energy of the incident positron beam is reduced to typically 50 eV by a deceleration tube located in front of the sample. For the detection of secondary electrons that are used as start signals, a channeltron module (Photonis, model 4831) is installed between the deceleration tube and the sample. Since the channeltron module is biased to the same electric potential of the sample, the signals are taken out through a high-voltage fast capacitor (TDK, UHV-241A). Ps which is formed on the sample surface annihilates with the lifetimes of 125 ps (para-Ps) and 142 ns (ortho-Ps). Annihilation gamma rays, which are used as stop signals, are detected by a Bismuth Germanate (BGO) scintillation detector beside the sample. These start and stop signals are collected by a digital oscilloscope (Lecroy, WavePro7100) providing the Ps lifetime spectrum.

With only the channeltron, the secondary electrons are rarely collected because the secondary electrons are pushed back to the sample by a fringing field from the deceleration tube. To collect the secondary electrons efficiently, the fringing field from the deceleration tube, that tends to push back electrons to the sample, is terminated by a tungsten mesh and the space between the mesh and the sample is covered by an electrostatic shielding consisting of an aluminium shroud. Moreover, the entrance of the channeltron is biased to +50 V relative to the sample. Figure 3(a) shows the results of numerical calculations of the electric potential around the channeltron. The trajectories of incident positrons and secondary electrons emitted from the sample surface (the energies are assumed to be 50± 3 eV and 10 ± 5 eV, respectively) are also shown in Figs. 3(b) and 3(c). These confirm that positrons hit the sample and the secondary electrons are collected efficiently at the channeltron entrance. Trajectory of incident positrons are also slightly shifted by this drawing potential, however, it is negligible because the positron beam energy is enough high.

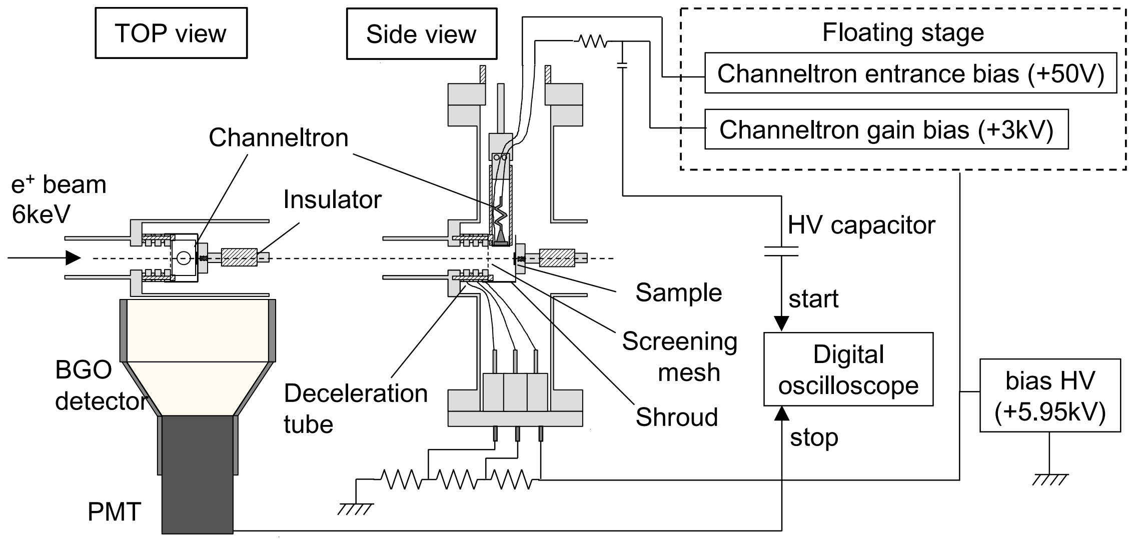

Figure 2. Schematic of the lifetime measurement system.

3. Lifetime measurements

Positonium lifetime measurements were carried out using the above apparatus. The beam intensity provided by the solid Kr moderator was estimated to be 1×10^4 e^+/s at the sample position and final counting rate of lifetime measurement was ~30 cps. By decreasing the incident energy, the counting rate was slightly increased. This is because the emission efficiency of secondary electrons tends to be higher at lower incident particle energy. Two samples were used for the test measurements. The first one was a silica aerogel block (Panasonic, SP-15) with a size of 10×15 mm and thickness of 2 mm. Figure 4(a) shows lifetime spectra when the positron beam energy was decelerated to 500 eV. Nearly the same spectrum was obtained even for an incident positron energy of 50 eV. The total spectrum area contained more than 1×10^6 events. The signal-to-noise ratio is ~50000. Short and long lifetime components are seen. From a two components analysis using the PATFIT code, the lifetimes and its intensities were estimated to be τ_1 = 20 ns (51%) and τ_2 = 120 ns (49%), respectively, with the time resolution of 11 ns. However, the lifetime of this τ_2 component tends to be underestimated due to the thermalization process [12]. From an exponential-decay fitting only in the time region of 500 ~ 1600 ns, where the thermalization effect is small enough, a lifetime of 140 ns was obtained [13, 14]. The intensity of o-Ps lifetime components for some aerogels are reported to be 40~50 % [15]. From these results, the long lifetime component is attributed to o-Ps decay. The short component τ_1 is not only from p-Ps decay because τ_1 is longer than the p-Ps lifetime convoluted with the time resolution. This component might be mixture of the o-Ps thermalization process and o-Ps pick-off annihilation on grain surfaces [16]. These results show that the apparatus is sufficient to measure the o-Ps lifetime spectrum.

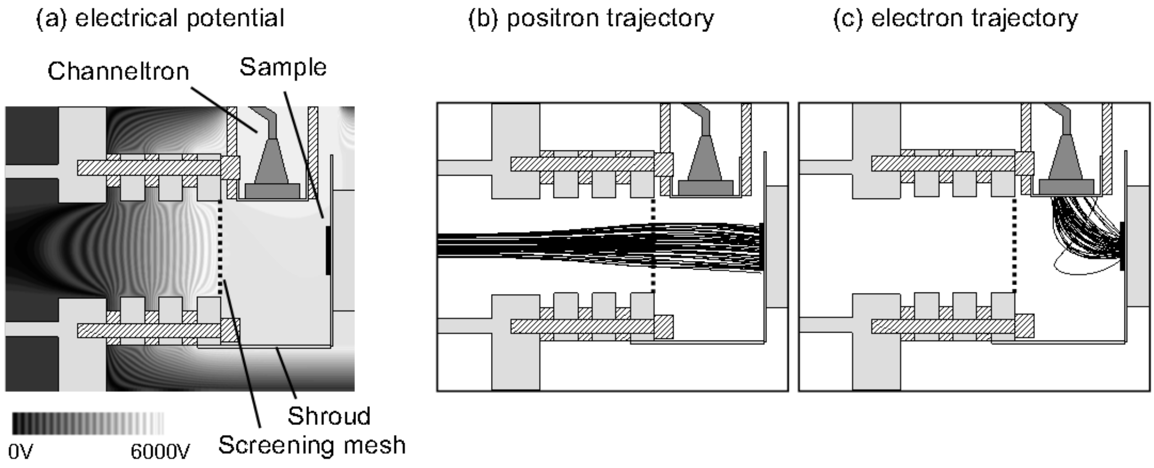

Figure 3. (a)Numerical calculations of the electric potential around the channeltron, (b)(c) simulated trajectories of the incident positron beam and secondary electrons.

The second sample was well-annealed copper plate. Figure 4(b) shows the spectrum when the positron beam energy was set to 6000 eV. The intensity of o-Ps component was decreased to ~ 6 %. For incident positron energy of E = 50 eV, the o-Ps component appears again. Its intensity was estimated to be 19 %. These results show the same tendency with the previous works [17].

4. Summary

A spin-polarized positron beam generated using a ^{22}Na source, a solid Kr moderator and electrostatic lenses was developed. A lifetime measurement system using secondary electrons as start triggers was also developed. Using this system, the lifetime spectra of o-Ps were obtained. This system will be used to determine the surface spin polarization of some ferromagnets.

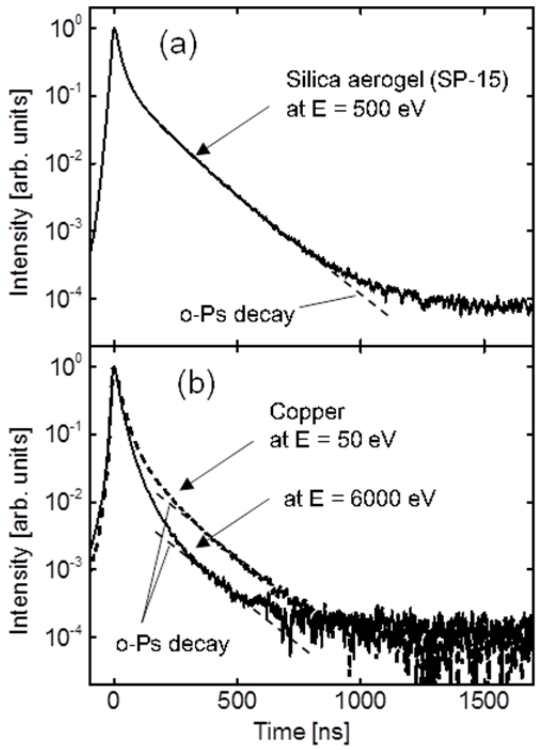

Figure 4. Positronium Lifetime spectra of (a) silica aerogel and (b) well-annealed copper.

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