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Spin-polarization of an electro-static positron beam

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ABSTRACT

We constructed an electro-static positron beam apparatus. We fabricated a simple spin-polarimeter composed of a permanent magnet with a surface magnetic field of 0.65 T and an iron pole piece. The longitudinal spin-polarization of the positron beam was determined to be 0.3 by analyzing the magnetic field dependence of the Doppler broadening of annihilation radiation from a fused silica specimen. The effect of spin rotation was examined using an iron poly-crystal and a simple $E \times B$ filter.

1. Introduction

Positrons emitted through β^+-decay of radioactive nuclei are longitudinally spin-polarized due to the parity non-conservation in weak interaction. Spin-polarization is given by $\langle v \rangle / c$, where $\langle v \rangle / c$ is the average velocity of positrons and c is the velocity of light. The effect of positron spin-polarization was extensively investigated in 1950s concerning the annihilation of positronium atoms [1,2]. Even in condensed matters where positronium state is not formed, if spin-uncompensated electrons exist, positronium-like state may be formed between positrons and spin-uncompensated electrons. In this case, positron spin-polarization has a crucial role to get information on spin-uncompensated electrons. In 1960s, taking advantage of positron spin-polarization, several studies on magnetic substances were carried out with angular correlation of annihilation radiation (ACAR) technique [3]. It is also proposed that at paramagnetic centers such as vacancy defects in insulators and semiconductors, positronium-like state may be formed [4]. This may be useful to detect the charge state of vacancy defects [5]. Furthermore, using spin-polarized positron beam, the magnetic properties of surfaces, interfaces and thin films may be investigated. It was demonstrated that from the positronium annihilation the surface magnetic susceptibility can be determined [6].

In this study, we examined the spin-polarization of a positron beam generated by an electro-static apparatus. For this purpose, we also fabricated a simple polarimeter and spin rotator.

2. Apparatus and experiment

The positron beam apparatus is composed of a modified Soa-gun, five Eintzel lenses and a magnetic deflector as shown in Fig. 1. A ^{22}NaCl source with an activity of 370 MBq and tungsten mesh moderator [7] were installed in the modified Soa-gun. Positron beam with energy of 20 keV is generated by applying the bias voltage to the modified Soa-gun. At the magnetic deflector, the positron beam is bended by 45° in a vertical field. The longitudinal spin-polarization may be rotated by 45° as the similar Larmor precession effect. Thus, the longitudinal spin-polarization may be conserved after passing the magnetic deflector.

Spin-polarization of charged particle is normally measured using the Mott detector, which uses the asymmetric scattering phenomenon of particles due to spin–orbit interaction. However, this manner is rather inefficient in the present beam energy and also weak positron beam flux because of too small scattering cross section. Therefore, we fabricated a polarimeter, which uses the magnetic field dependence of positronium annihilation. It is composed of a permanent magnet with the surface magnetic field of 0.65 T and a pole piece made of pure iron as shown in Fig. 1. The sample is placed on the permanent magnet. From the beam entrance to the sample, a magnetic field parallel to the beam axis is formed. By reversing the permanent magnet, the field polarity is reversed. Here, the positive field direction is defined as the beam axis. The Doppler broadening of annihilation radiation (DBAR) is measured from the fused silica, in which the positronium formation was confirmed in the positron lifetime measurement, as a function of magnetic field. From the asymmetry of the *para*-positronium intensity by reversing the magnetic field the longitudinal spin-polarization is determined.

To examine the effect of spin rotation, we fabricated a spin rotator composed of an electro-static deflector and a Helmholtz

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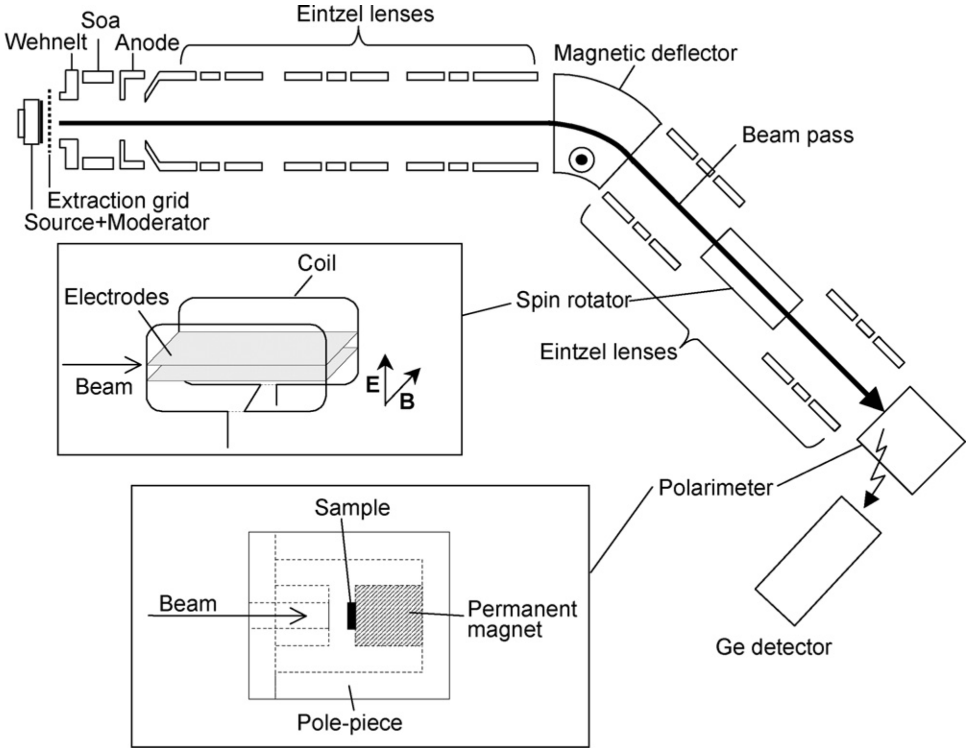

Fig. 1. Schematic view of the electro-static positron beam apparatus, spin rotator and polarimeter.

coil ($E \times B$ filter) is inserted in between two Eintzel lenses after the magnetic deflector. The angle between the beam axis and spin-polarization is determined by $\theta = l\omega/v = 1.76 \times 10^{11} Bl/v$, where l is the drift length of the spin rotator, ω is the Larmor frequency, v is the speed of positrons and B is the magnetic field. The electric field E and B are correlated by $E = vB$. In the present spin rotator, l = 10 cm and the gap of electro-static deflector is 1 cm. Thus, $\theta = \pi/2$ is obtained at B = 0.0073 T and E = 5.84 kV/cm for the beam energy of 20 keV.

The above positron beam was injected into fused silica and iron poly-crystal samples and the DBAR spectra were measured using a Ge detector. The energy windows of S and W parameters were 510.2–511.8 keV and 512.3–518.2 keV, respectively.

3. Results

3.1. Spin-polarization

Fig. 2(a) shows the dependence of S parameter obtained from the fused silica sample on the magnetic field. It is found that the S parameter increases with the presence of magnetic field. Also, the increase of S parameter is asymmetric to the reverse of magnetic field. This may be ascribed to the longitudinal spin-polarization of the positron beam. *para*-Positronium and one of the *ortho*-positronium states are no longer the eigen states and perturbed states appear in a magnetic field. The two-gamma annihilation probability of the perturbed positronium is known to be enhanced in the magnetic field. The behavior is asymmetric to the reverse of magnetic field if positrons are spin-polarized. Having the pick-off annihilation rate of *ortho*-positronium (0.63 ns^{-1}), the self-annihilation rate of *para*-positronium (8 ns^{-1}) and the contact density (0.95), we calculated the fraction of two-gamma annihilation of perturbed positronium as a function of magnetic field and positron spin-polarization [8]. The results are plotted in Fig. 2(b). Without spin-polarization, the magnetic field dependence is symmetric. Contrarily, the asymmetric field dependence appears with the finite spin-polarization. The two-gamma annihilation of perturbed positronium causes a narrow momentum distribution and hence enhancement of S parameter as the self-annihilation of

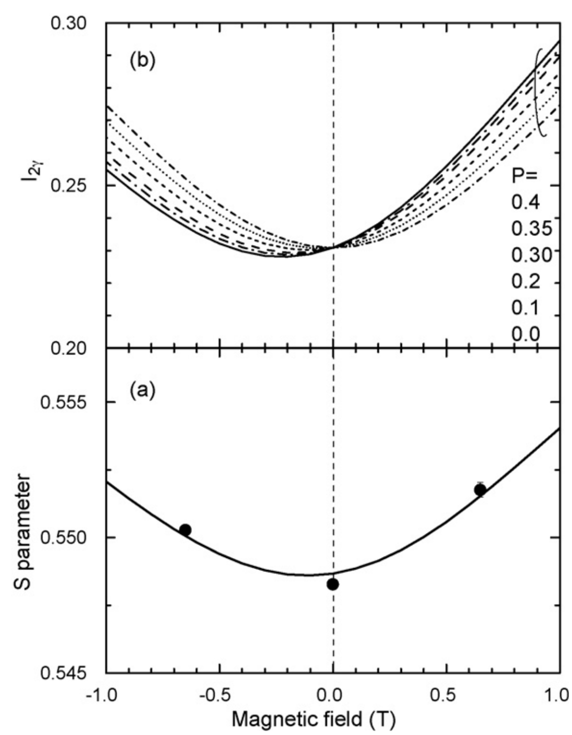

Fig. 2. (a) S parameter obtained from the fused silica as a function of magnetic field. Incident positron beam energy is 20 keV. (b) Calculated two-photon annihilation rate of perturbed positronium state as a function of magnetic field and positron spin-polarization.

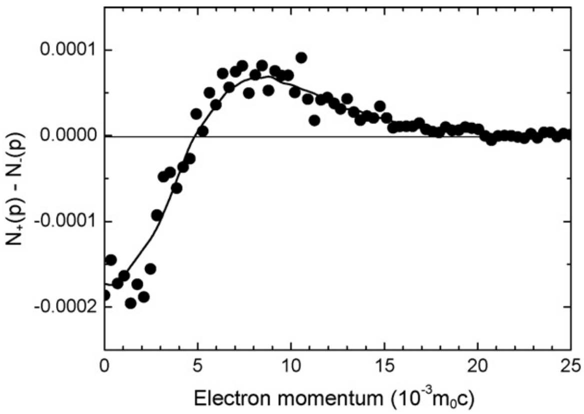

Fig. 3. Differential DBAR spectrum obtained from the magnetically saturated iron poly-crystal. The saturated magnetic field is 0.65 T.

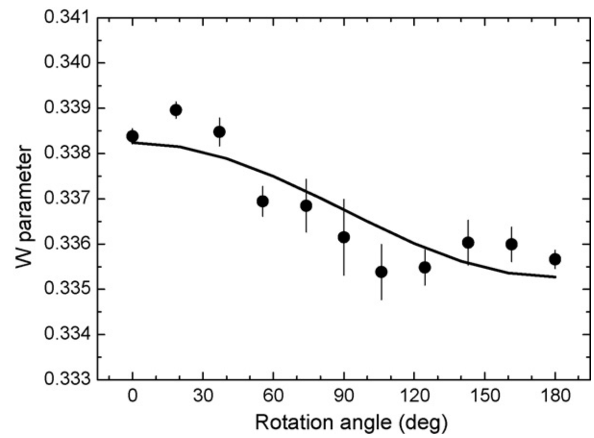

Fig. 4. *W* parameter obtained from the magnetically saturated iron poly-crystal as a function of the angle between the direction of magnetic field and positron spin-polarization. The saturated magnetic field is 0.65 T.

para-positronium. Thus, *S* parameter can be given by $S = \alpha I_{2\gamma} + \beta$, where α and β are the constants and $I_{2\gamma}$ is the fraction of two-gamma annihilation of perturbed positronium [9]. As shown by the solid line in Fig. 2(b), the magnetic field dependence of *S* parameter is well reproduced assuming $P = 0.3$, $\alpha = 0.09995$ and $\beta = 0.5256$.

The ideal average longitudinal spin-polarization of positrons emitted from ^{22}Na is $P = 0.5\langle v\rangle/c = 0.335$. The above spin-polarization is less than the ideal value suggesting that positrons are depolarized in the slow-down processes and/or diffusion processes in the moderator and/or sample. It was demonstrated that the above method can be used to determine the spin-polarization of incident positron beam.

3.2. Spin rotation

The electron–positron momentum distribution from a magnetic substance changes depending on the magnetic field polarity if the incident positrons are spin-polarized [3]. This is because the formation probabilities of perturbed *para*- and *ortho*-states and two *ortho*-states of positronium-like state between positrons and spin-uncompensated electrons and hence their two-gamma annihilation rate changes with the field strength and field direction accompanying the reverse of electron spin-polarization. Fig. 3 shows the differential DBAR spectrum (i.e., $N_+(p) - N_-(p)$, where $N_+(p)$ and $N_-(p)$ are the spectra obtained with the positive and negative fields, respectively) of an iron poly-crystal. At $p < 5 \times 10^{-3} m_0 c$, the intensity is suppressed while at $p > 5 \times 10^{-3} m_0 c$, the intensity is enhanced. This reflects the fact that the annihilation probability of positrons with 3d-band electrons is enhanced when positive field. We simply define the intensity of the DBAR spectrum at $p > 5 \times 10^{-3} m_0 c$ to be *W* parameter.

The above *W* parameter can be used to determine the direction of spin-polarization [10]. That is, if the spin-polarization is parallel to the field the *W* parameter should be the highest. Oppositely, if the spin-polarization is anti-parallel to the field the *W* parameter should be the lowest. Fig. 4 shows the *W* parameter as a function of spin rotation angle. It is found that the *W* parameter decreases with increasing the angle between the field direction and spin-polarization. The solid line is the fitting by a cosine function, which reproduces the experimental result.

4. Summary

In summary, we investigated the spin-polarization of the positron beam generated by the electro-static apparatus. Analyzing the magnetic field dependence of *S* parameter from the fused silica sample, we determined the longitudinal spin-polarization to be ~0.3. We also examined the effect of spin rotation by the $E \times B$ filter and iron poly-crystal sample.

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