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Development of ^{44}Sc high spin-polarized positron source using high energy proton beam

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Abstract. A ^{44}Sc positron source was produced via ^{45}Sc(p, pn)^{44}Sc nuclear reaction by 20 MeV-proton irradiation to a target composed of stacked six Sc plates with each 0.25 mm thick. The production efficiency of ^{44}Sc was determined to be 0.315 GBq/μA/h. Spin polarization of positrons emitted from the irradiated Sc plate was determined to be 52%, which is consistent with the numerical simulation. The efficiency of slow positron beam using tungsten moderator was also determined to be 6.0×10^{3} e^{+}/s/μA/h.

1. Introduction

Spin-polarized positron annihilation spectroscopy (SP-PAS) provides a unique opportunity for selective detection of electron spins localized at specific sites, such as atomic vacancies and the outermost surface [1,2]. We have been developing various spin-polarized positron beams. From a ^{22}Na source of typically ~400 MBq, a slow positron beam with an intensity of ~10^{4} e^{+}/s and a polarization of 30 % can be obtained [3]. For further practical applications, it is necessary to improve both the intensity and spin polarization of positron beam. In this purpose, one effective way may be to produce stronger positron sources than the commercial ^{22}Na source by nuclear reactions. To obtain higher spin polarization, it is essential to exploit sources with high Q-values, since positron spin polarization is given by average helicity, $\langle v \rangle/c$, where $\langle v \rangle$ is the average positron speed and c is the speed of light. So far, we produced ^{68}Ge sources by 20 MeV-proton irradiations to pure Ga and GaN targets. Typical spin polarization and intensity of the positron beam generated with these sources were 47% and 10^{5} e^{+}/s, respectively [4]. However, due to the low production efficiency of ^{68}Ge (0.5 MBq/μA/h) and the half-life of 270 days, to maintain positron beam intensity, proton irradiation (typically with 5 μA beam current for 40 hours) should be repeated once a month. Further serious problems are the destruction of source capsule because of accumulated radiation damage and the alloying reaction with molten Ga target (melting point is 28 °C).

In this study, we focused on ^{44}Sc which can be produced by a nuclear reaction of ^{45}Sc(p, pn)^{44}Sc. One reason is that the melting point of ^{45}Sc is 1540 °C and hence it will be able to withstand high-intensity proton irradiation. Due to the high cross section (0.3-0.6b) [5,6], a higher production efficiency than ^{68}Ge is expected. Although the half-life of ^{44}Sc itself is only 3.93 hours to be decayed into ^{44}Ca, as shown in Fig. 1, metastable ^{44m}Sc is also produced and it decays into

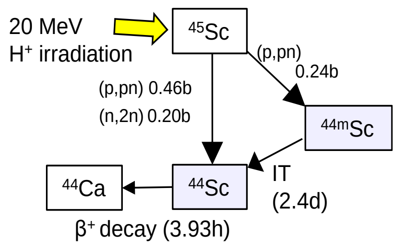

Figure 1. Scheme of nuclear reaction and decay processes.

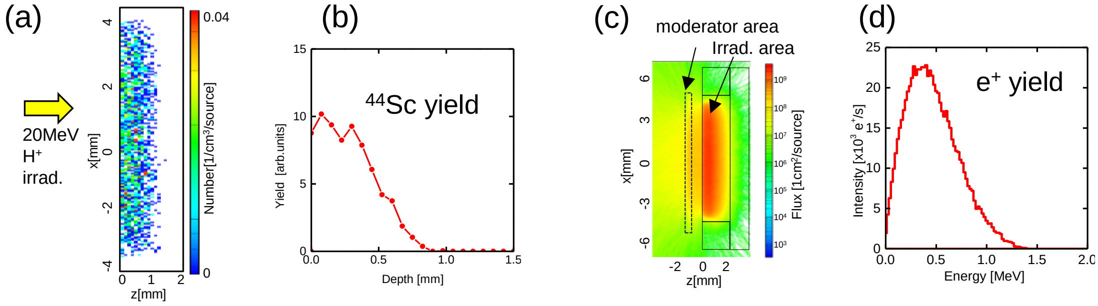

Figure 2. Result of PHITS simulation. (a) Distribution of the produced ^{44}Sc nuclides, (b) depth distribution of ^{44}Sc, (c) trajectories of the emitted positrons, and (d) energy spectrum of positrons stopped in the moderator area.

^{44}Sc by internal transition (IT) with a half-life of 2.4 days. Consequently, some amounts of positrons are continuously emitted for a week. The energy endpoint of emitted positrons from ^{44}Sc is 1.48 MeV, and hence higher beam spin polarization is expected as compared to ^{22}Na.

2. Numerical Simulation

The amount of ^{44}Sc produced by 20 MeV proton irradiation to ^{45}Sc was simulated using the Particle and Heavy Ion Transport code System (PHITS, ver. 3.26) and DCHAIN code [7]. The result shows that ^{44}Sc is generated within a depth of 1.0 mm from the surface (Fig.2(a) and (b)). Also, the production rate per unit irradiation current and time was obtained to be 0.33 GBq/μA/h. After proton irradiation for 3 hours with the current of 3 μA, the initial activity of ^{44}Sc, 3.0 GBq, at the end of irradiation, decreases to 250 MBq within 24 hours. Even after one week, it keeps 60 MBq. The effective half-life of activity taking into account of the production of ^{44m}Sc was evaluated to be 9.29 hours, which is longer than that of ^{44}Sc, 3.93 hours.

Figure 2 (d) shows the intensity of positrons implanted from the above ^{44}Sc source of 3 GBq activity into the tungsten moderator (thickness 5 μm) in Fig. 2(c). The intensity of the slow positrons is expected to be 5×10^4 e$^+$/s, which is comparable to that of ^{68}Ge produced by proton irradiation with the same current (3 μA) as above, but for ~300 hours. Thus, the slow positron intensity per unit irradiation current and time is 5.5×10^3 e$^+$/s/μA/h. Lastly, the average spin polarization of the slow positrons was estimated to be 58 %.

3. Development of ^{44}Sc positron source and slow positron beam

3.1 Source production

Figure 3(a) shows the schematic of the source capsule. The scandium metal target was cut from the commercial scandium plate with a thickness of 0.25 mm. In this experiment, six plates were stacked and placed in a carbon capsule. The capsule was installed in an irradiation stage equipped with a water-cooled jacket (Fig.3 (b)) to protect against heat damage during irradiation [4]. The irradiation chamber was evacuated to a base pressure of 5×10^{-4} Pa. The target was irradiated with 20 MeV protons with an average current of 1 μA for 2.4 hours using the cyclotron. After irradiation, the energy spectrum of the gamma rays emitted from the top scandium plate on the incident side was measured using a high-purity germanium (HPGe) detector, as shown in the Fig. 3(c). The peaks corresponding to ^{44}Sc, ^{44m}Sc and annihilation gamma rays are observed. A small amount of ^{45}Ti appeared as a byproduct. The activity of ^{44}Sc just after irradiation was determined to be 0.75

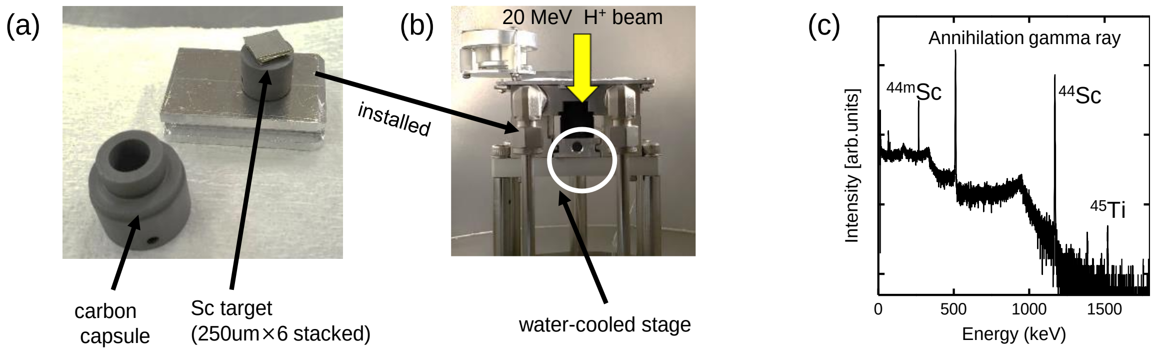

Figure 3. Picture of (a) the scandium target and source capsule and (b) the proton irradiation stage. (c) The gamma-ray energy spectrum from the top scandium plate on the incident side.

GBq. Based on this result, the production rate of ^{44}Sc was determined to be 0.315 GBq/μA/h, which is in good agreement with the above simulation.

3.2 Beam generation

After 20 hours from the period of irradiation, the scandium plate was installed into the test positron beam apparatus shown in Fig.4(a). Fast positrons were moderated by a tungsten-mesh moderator composed of 16 tungsten meshes with a wire diameter of 10 μm [8], which was annealed at above 1800 °C for 30 minutes using an electron gun in a vacuum. The extracted slow positrons with an energy of 1 keV were transported in a magnetic field. Figure 4(c) shows the change in count rate measured with the HPGe detector as a function of the time elapsed after irradiation. The decay rate changes from the initial half-life of ^{44}Sc to that of ^{44m}Sc. Figure 4(b) shows the beam image obtained by a microchannel plate after 24 hours from the period of irradiation. The beam intensity was also determined to be 1.2×10^3 e^+/s. The positron beam intensity just after proton irradiation is expected to be 1.4×10^4 e^+/s and hence its efficiency per unit proton current and time is 6.0×10^3 e^+/s/μA/h. This is also consistent with the above simulation.

3.3 Spin Polarization

The longitudinal spin polarization of the emitted positrons was determined through the magnetic field dependence of the S parameter in SiO_2, which is related to the self-annihilation of spin-singlet

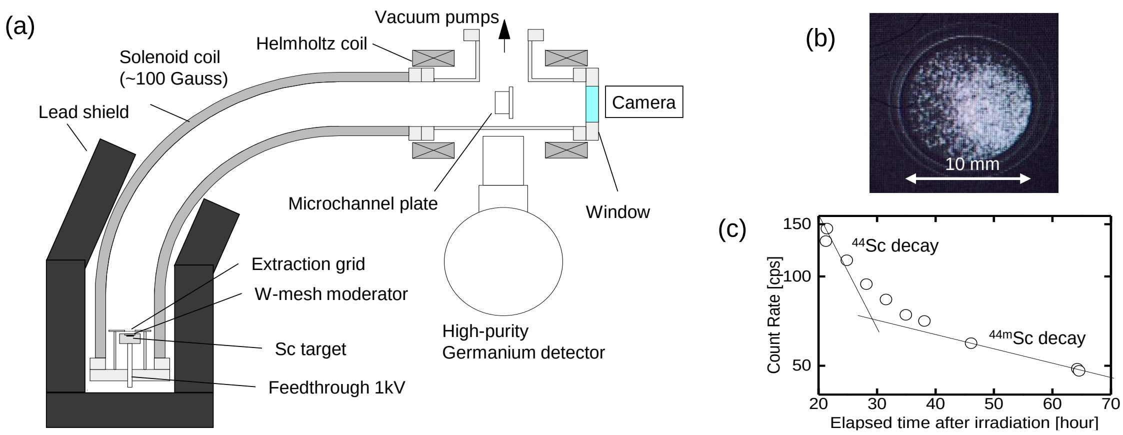

Figure 4. (a) Schematics of the test positron beam apparatus. (b) Image of slow positron beam observed by the microchannel plate. (c) Beam intensity (count rate) as a function of elapsed time after irradiation.

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positronium [9,10]. The details of this method have been described elsewhere [4,11]. Figure 5 shows S parameters in SiO_2 as a function of the magnetic field. By fitting theoretical curve, the spin polarization was determined to be 52 %. This value is comparable to the above-prediction (58 %). The spin polarizations of positrons emitted from the ^{22}Na and ^{68}Ge sources measured using the same measurement system are 39 % [11] and 65 % [4], respectively. The spin polarization obtained for the ^{44}Sc source is situated between these two values, reflecting the average emission energies of positrons of 0.2 MeV (^{22}Na), 0.45 MeV (^{44}SC) and 0.99 MeV (^{68}Ge).

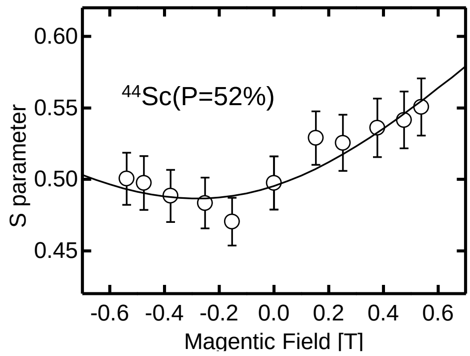

Figure 5. Magnetic field dependences of S parameters in SiO_2 using the ^{44}Sc source. Solid line denotes the fitting curves calculated from the equations (see, text).

4. Summary

A ^{44}Sc source was produced by irradiating the Sc metal target with 20 MeV protons. The production rate and average spin polarization of positrons were determined to be 0.33 GBq/h/μA and 52%, respectively. The yield of slow positron beam per unit proton current and time using a tungsten moderator was determined to be 6.0×10^3 e^+/s/μA/h. Assuming a rare-gas solid moderator, which has one-order of magnitude higher efficiency as compared to the tungsten moderator, and 300 μA proton current that is a typical value for cyclotron designed for source production, a slow positron beam intensity of more than 5×10^7 e^+/s is feasible. This may open the further applications of spin-polarized positron beam.

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