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Development of spin-polarized positron source using high energy proton beam

M Maekawa, Y Fukaya, Y Yabuuchi and A Kawasuso
Advanced Science Research Center, Japan Atomic Energy Agency
1233 Watanuki, Takasaki, Gunma, 370-1292, Japan

E-mail: maekawa.masaki@jaea.go.jp

Abstract. To obtain a highly spin polarized positron beam, ^{68}Ge isotope have been produced using a nuclear reaction of ^{69}Ga(p,2n)^{68}Ge. As target materials, we examined a metal form ^{69}Ga stable isotope and a GaN substrate. By 20 MeV proton irradiation, the production of ^{68}Ge source was confirmed in both targets. The production rates of ^{68}Ge were 0.16 and 0.53 MBq/μA/h for the metal Ga and GaN target, respectively. The spin polarizations of positrons emitted from ^{68}Ge was estimated to be approximately 50 to 70%.

1. Introduction

Using spin-polarized positrons, the excess spins in magnetic substances can be detected in positron annihilation measurements [1]. This will be useful in the studies of spin-electronics materials such as half-metals, diluted magnetic semiconductors and so on. Positrons emitted from β^+-decay nuclei are longitudinally polarized because of the parity non-conservation law. The longitudinal spin-polarization of positrons from β^+-emitters is given by $(v/c)\times(1+\cos\alpha)/2$, where, v is the positron speed, c is the light speed and α is the open angle from a specific direction. To obtain highly spin-polarized positrons, it is important to use β^+-emitters with higher endpoint energies. Sodium 22 source is widely used in the positron annihilation spectroscopy method. However, the maximum longitudinal spin polarization of positron emitted from sodium 22 is estimated to be 70 % from its endpoint energy [2]. For sufficient measurements with spin-polarized positrons, a strong enough source emitting highly polarized positrons is needed. For this purpose, we focus on a ^{68}Ge isotope. This isotope decays to ^{68}Ga with a half-life of 280 days. When ^{68}Ga decays with a half-life of 68 min, a positron (89 %) is emitted. The endpoint positron energy is 1.9 MeV and hence the theoretical maximum longitudinal spin polarization is approximately 94%. This radioisotope can be produced though the nuclear reaction of ^{69}Ga(p,2n)^{68}Ge. The threshold energy of this reaction is 11 MeV. By multiple irradiations, ^{68}Ge isotope for the generation of the slow positron beam can be accumulated. In this study, we report the production of ^{68}Ge by proton irradiation using some target materials.

Stable isotopes of Ga are ^{69}Ga(60.1 %) and ^{71}Ga(39.9 %). The cross sections of the production of ^{68}Ge isotope for ^{69}Ga and ^{71}Ga are 0.465×10^{-28} and 0.137×10^{-28} m^2, respectively. If isotope-separated ^{69}Ga was used as a target material, the production of ^{68}Ge is effective. During the high-energy proton irradiation, metal Ga is expected to melt because of the low melting point (29 ^{o}C). Therefore, to prevent the leakage of the melt Ga, a source structure to seal the melt Ga is required. When the gallium compound having a high melting point is used, such a difficulty can be avoided.

However the production efficiency of ^{68}Ge isotopes decreases because the content of ^{69}Ga decreases. In this study, we examined two types of targets; a metal form ^{69}Ga stable isotope and a GaN substrate.

2. Simulation

First we carried out a simulation to determine the optimum condition of proton irradiation to produce ^{68}Ge isotope by the Induced Radioactivity Analysis Code (IRAC) [3]. Figure 1(a) shows the depth profile of ^{68}Ge isotope at the proton energy of 20 and 25 MeV for the pure ^{69}Ga target. Total amounts of ^{68}Ge isotope were estimated to 1.1 MeV/μA/h and 2.3MeV/μA/h for the 20 and 25 MeV protons, respectively. Considering the transmission of positrons from the inside of target materials, more positrons are obtained in the case of the 20 MeV irradiation [2]. Figure 1(b) shows the depth profile of ^{68}Ge isotope for the GaN target with the proton beam of 20 MeV. Total amount of ^{68}Ge isotope was estimated to 0.56 MeV/μA/h. The total amount of ^{69}Ge for the metal ^{69}Ga target is approximately 2 times higher than that of GaN.

3. Experimental

Figure 2 shows the schematics of the source capsule. To avoid leakage of melted ^{69}Ga during irradiation, metal ^{69}Ga was put into a carbon tray (diameter:8mm, depth:0.5 mm or 1.0 mm) with a beryllium cap, which are rarely corroded by the Ga metal. The source capsule is finally capped by the Ti window. The thicknesses of Ga targets are 0.5 mm and 1 mm. These were irradiated with 20 MeV and 25 MeV protons, respectively, though the bdellium window. The thickness of GaN target is 0.475 mm. This target was directly irradiated with 20 MeV protons. Proton irradiation was carried out using the cyclotron at Japan Atomic Energy Agency. During the irradiation, the above targets were cooled by running water. The irradiation chamber was evacuated with a base pressure of 6×10^{-4} Pa.

After the irradiation, the amount of ^{68}Ge was measured using intensities of photopeaks of 511 keV and 1.07MeV. The former is from the annihilation of positrons emitted from ^{68}Ga. The later is derived from the decay of ^{68}Ge. The spin polarization of emitted positrons was estimated from the magnetic field dependence of *S*-parameter arising from two-gamma self-annihilation of positronium in a fused silica [4, 5]. The magnetic field was applied by SmCo permanent magnets. By changing the distance of pole gap, the strength of the magnetic field was controlled. Schematic of the measurement system is shown in figure 3.

4. Results and discussions

Figure 4 shows the estimated amounts of ^{68}Ge isotope for the different targets and irradiation energies.

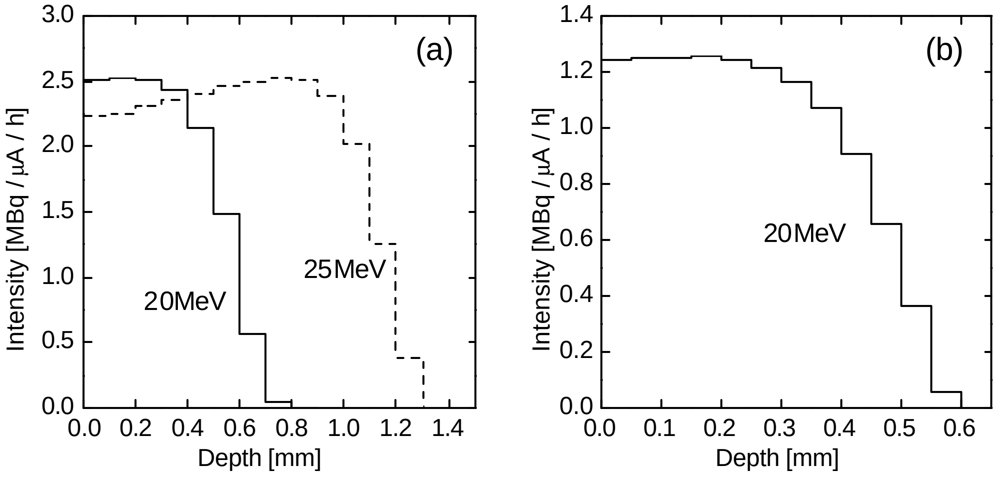

Figure 1. Simulation of depth profiles of ^{68}Ge source produced by proton irradiation. (a) Metal Ga target with energies of 20 and 25 MeV, (b) GaN target with energy of 20 MeV.

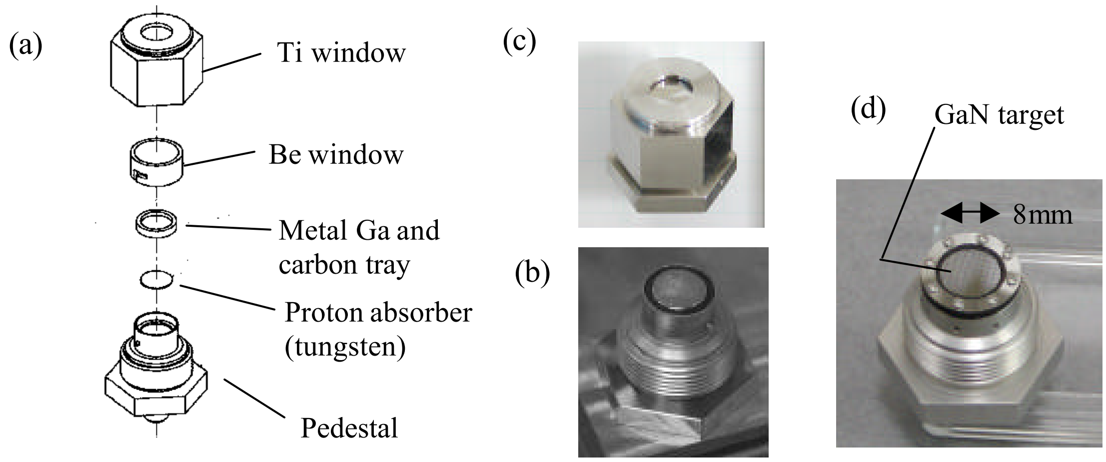

Figure 2 Schematics of the source capsule. (a) Structure of the capsule, (b) source capsule with metal Ga, (c) Ti window and (d) source capsule with GaN target.

When the metal ^{69}Ga targets were used, the production rates of ^{68}Ge were 0.16 and 0.14 MBq/µA/h for 20 and 25 MeV, respectively. These values are one order of magnitude lower than those expected from the simulation. After the irradiation, the metal Ga targets were melted and shrunk to spherical shapes of 2~3 mm in the capsule. Probably, only a part of protons were irradiated to the metal ^{69}Ga targets. In the case of the GaN target, no physical change was observed after the irradiation. The efficiency was estimated to be 0.53 MBq/µA/h. This value is in good agreement with the simulated value. Thus, the production of the ^{68}Ge isotope was confirmed in both targets, while an improvement to avoid the change of the shape due to the irradiation is needed in the case of metal targets.

Figure 5 shows the magnetic field dependences of S parameters from a fused silica obtained using the ^{68}Ge and ^{22}Na sources. As compared to the case of ^{22}Na source, a larger asymmetry is observed for the case of ^{68}Ge isotope suggesting a higher spin polarization. Theoretical curves for several spin polarizations are also shown. From these results, the spin polarizations of positrons emitted from ^{68}Ge and ^{22}Na were estimated to be 50 to 70 % and 25 to 30 %, respectively. Although the theoretical maximum spin polarization is 94%, the average spin polarization of positrons emitting to 2π direction

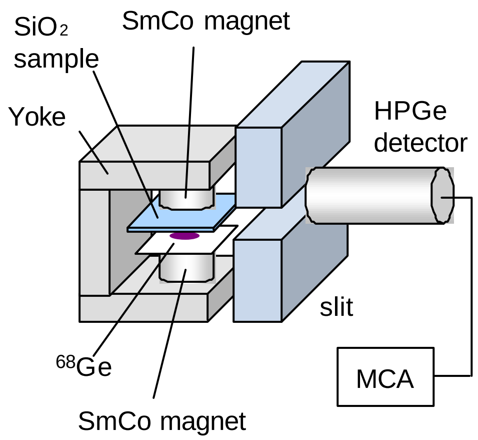

Figure 3. Schematics of the spin polarization measurement system.

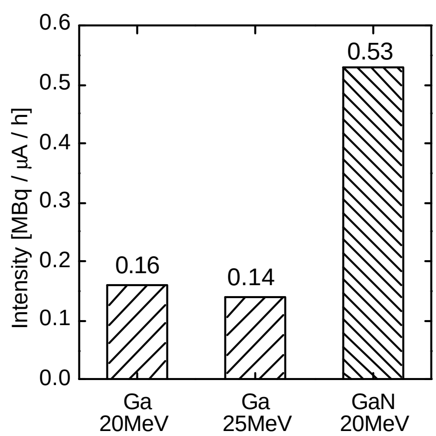

Figure 4. Amount of produced ^{68}Ge source with different targets and irradiation energies.

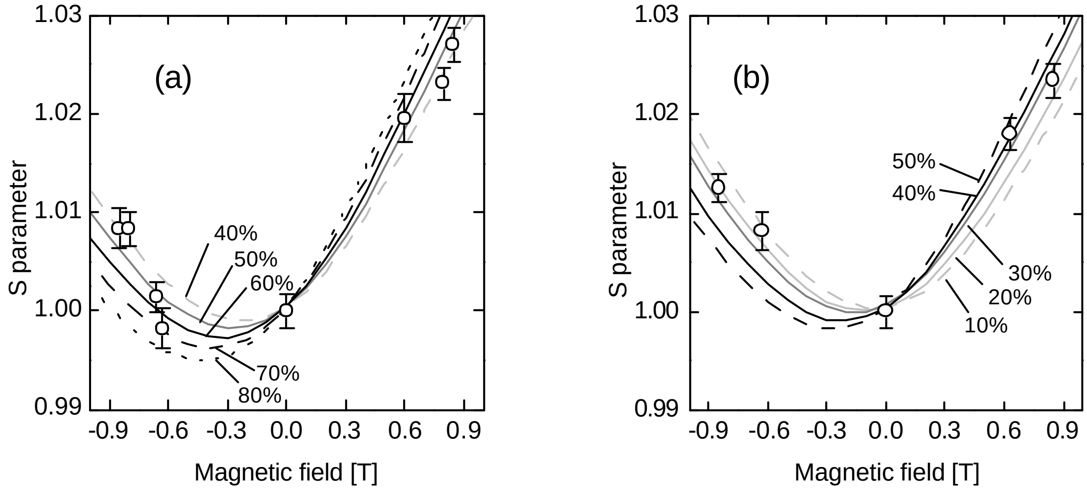

Figure 5. The magnetic field dependences of S parameters from a fused silica obtained using the (a)^{68}Ge and (b)^{22}Na sources. Theoretical curves for several spin polarizations are also shown.

become half of the theoretical value. In these measurements, the sample size was 20 mm square, the gap width of the pole piece was 3 mm and the diameter of the source was 5 mm. The open angle α was limited within 75 degree. From this geometrical reason, the measured spin polarization might have been decreased to 63 % of the maximum theoretical value ((1+cos(75^{o})/2)).

4. Summary

By the proton irradiation to the metal Ga and the GaN targets, production of ^{68}Ge was confirmed. Spin polarization of positrons emitted from the ^{68}Ge isotopes was found to be higher than that from ^{22}Na. The amount of ^{68}Ge isotope can be increased by multiple irradiations. For instance, ten successive proton irradiations with the proton current of 10 μA and irradiation duration of 10 hours could yield approximately 500 MBq activity which is a feasible intensity for generating a spin-polarized slow positron beam.

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