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## Development of a spin-polarized positron source

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**Abstract.** We have started the development of a spin-polarized positron beam. In order to obtain a highly spin polarized positron beam, a  $^{68}\text{Ge}$ - $^{68}\text{Ga}$  source will be produced using a nuclear reaction of  $^{69}\text{Ga}(p,2n)^{68}\text{Ge}$ . The optimum proton bombardment energy for  $^{69}\text{Ga}$  target is simulated to be 25 MeV using the Induced Radioactivity Analysis Code (IRAC). A newly designed  $^{69}\text{Ga}$  target holder will also be used as a  $^{68}\text{Ge}$ - $^{68}\text{Ga}$  source capsule.

### Introduction

Possibility of detecting the excess spins of magnetic substances by angular correlation of annihilation radiation with longitudinally spin-polarized positrons was demonstrated [1]. This will be used in the studies of spin-electronics materials such as half-metals, diluted magnetic semiconductors, magnetic surfaces etc., and of spin-dependent phenomena such as the spin Hall effect, the giant Rashba effect etc. The magnetic quenching of surface positronium [2] and spin-polarized positron diffraction will be promising methods to determine the magnetic susceptibilities of the first surface layers. To realize the above applications of spin-polarized positrons, a highly spin-polarized positron source is needed. Positrons generated through  $\beta^+$ -decay are longitudinally polarized because of the parity non-conservation law. Spin-polarized positrons can also be obtained using the spin-orbit interaction between depolarized positrons and some heavy metal targets [3]. However, this method is less efficient. Therefore, in order to obtain highly spin-polarized positron beam, we are developing a newly designed  $\beta^+$ -emitter source.

The longitudinal spin-polarization of positrons from  $\beta^+$ -emitters is given by

$$P = \frac{N_+ - N_-}{N_+ + N_-} = \frac{v}{c} \frac{1 + \cos \alpha}{2}, \quad (1)$$

where,  $N_{+, -}$  denote the numbers of up-spin and down-spin positrons,  $v$  is the positron speed and  $\alpha$  is the open angle from the beam direction (assumed to be the same as the source surface normal direction) [4]. The velocity factor is further given by

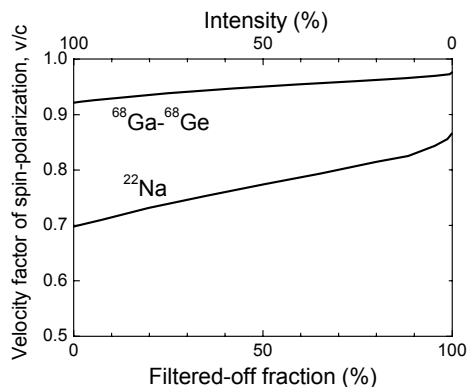
$$\frac{v}{c} = \sqrt{1 - \frac{1}{\{1 + E/(mc^2)\}^2}}, \quad (2)$$

where  $E$  is the positron kinetic energy. Therefore, to obtain highly spin-polarized positrons, it is important to select  $\beta^+$ -emitters with higher endpoint energies. There are two ways to further enhance the spin-polarization. One is to filter-off low energy positrons and the other is to regulate the solid angle of positron emission. For long-term and stable experiments, it is also important to select a  $\beta^+$ -emitter with long half-life.

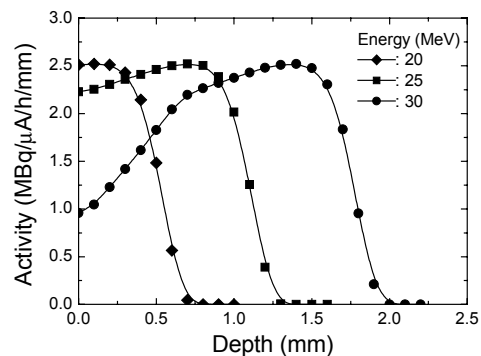
Among a number of  $\beta^+$ -emitters,  $^{22}\text{Na}$  and  $^{68}\text{Ge}$ - $^{68}\text{Ga}$  have relatively long half-lives i.e., 2.6 years and 288 days, respectively. Although  $^{44}\text{Ti}$ - $^{44}\text{Sc}$  has an extremely long half-life (48 years) and hence it is very attractive, the cross section of nuclear reaction ( $^{45}\text{Sc}(p,2n)^{44}\text{Ti}$ ) is very small. We thus compare  $^{22}\text{Na}$  and  $^{68}\text{Ge}$ - $^{68}\text{Ga}$ . Figure 1 shows the velocity factor of the spin-polarization for  $^{22}\text{Na}$  and  $^{68}\text{Ge}$ - $^{68}\text{Ga}$  as a function of filtered-off low energy positron fraction calculated from their energy spectra. Here, we replace the energy in eq. (1) with its mean value. The original spin-polarisation of  $^{68}\text{Ge}$ - $^{68}\text{Ga}$  is 0.92. Whereas, the spin-polarisation of  $^{22}\text{Na}$  is less than that of  $^{68}\text{Ge}$ - $^{68}\text{Ga}$  even after filtering-off low energy positrons. The dump of low energy positrons causes the decrease of intensity. Therefore, to obtain highly spin-polarized positrons with less intensity loss, obviously,  $^{68}\text{Ge}$ - $^{68}\text{Ga}$  is better than  $^{22}\text{Na}$ .

By regulating the solid angle of positron emission, the geometrical factor of spin polarization  $((1+\cos\alpha)/2)$  in eq. (1) increases, but it causes the loss of positrons. For example,  $(1+\cos\alpha)/2=0.93$  for  $\alpha=\pi/3$ , but the available positron fraction is only 13% compared to the case of  $\alpha=\pi/2$ , where all positrons in the forward solid angle can be used. Hence,  $^{68}\text{Ge}$ - $^{68}\text{Ga}$  is again better than  $^{22}\text{Na}$ , because of less intensity loss by filtering-off low energy positrons.

In this study, we carried out a simulation to determine the optimum condition of proton bombardment to produce  $^{68}\text{Ge}$ - $^{68}\text{Ga}$  source and a design of its capsule.



**Figure 1.** Velocity factor of the spin-polarization ( $v/c$ ) for  $^{68}\text{Ge}$ - $^{68}\text{Ga}$  and  $^{22}\text{Na}$  as a function of filtered-off low energy positron fraction.



**Figure 2.** IRAC simulation of depth profiles of  $^{68}\text{Ge}$ - $^{68}\text{Ga}$  produced by proton bombardment with energies of 20, 25 and 30 MeV.

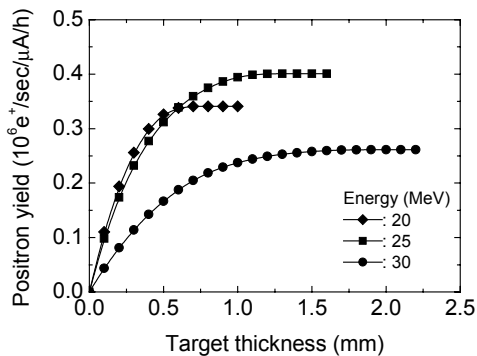
### Simulation

To produce  $^{68}\text{Ge}$ - $^{68}\text{Ga}$  by proton nuclear reaction, a plausible target would be Ga since this material is placed just before Ge in the periodic table. The stable isotopes of Ga are  $^{69}\text{Ga}$ (60.1%) and  $^{71}\text{Ga}$ (39.9%). The total amount of  $^{68}\text{Ge}$ - $^{68}\text{Ga}$  produced by  $^{69}\text{Ga}(p,2n)^{68}\text{Ge}$  and  $^{71}\text{Ga}(p,4n)^{68}\text{Ge}$  continuously increases when proton energy ( $E_p$ ) from 15 to 150 MeV. However, net positron number emitted from the target is reduced for higher proton energies since  $^{68}\text{Ge}$ - $^{68}\text{Ga}$  is produced in deeper region of the target. As shown later, the optimised proton energy to obtain a high positron emission efficiency from the target surface is ranging from 20 to 30 MeV. The cross section of  $^{69}\text{Ga}(p,2n)^{68}\text{Ge}$  is three orders of magnitude greater than that of  $^{71}\text{Ga}(p,4n)^{68}\text{Ge}$  for  $E_p=30$  MeV. Therefore, it is better to use high purity

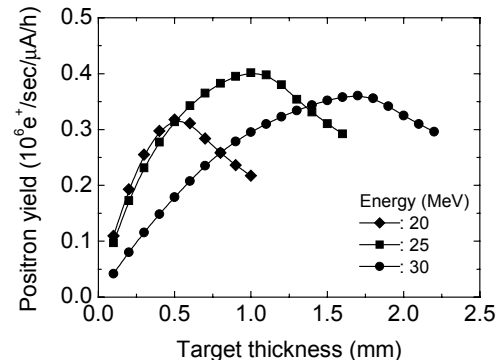
of  $^{69}\text{Ga}$  as a target material. Figure 2 shows the depth profile of  $^{68}\text{Ge}$ - $^{68}\text{Ga}$  simulated by the Induced Radioactivity Analysis Code (IRAC) [5] at various proton energies. Assuming the proton current of 10  $\mu\text{A}$  and the irradiation duration of 10 hours, the total activities of  $^{68}\text{Ge}$ - $^{68}\text{Ga}$  are estimated to be 140, 280 and 370 MBq for  $E_p=20, 25$  and 30 MeV, respectively. Net positron intensity emitted outside from the target is roughly estimated by

$$I = \frac{1}{2} \int_0^d N(z)T(z)dz, \quad (3)$$

where  $N(z)$  is the depth profile of  $^{68}\text{Ge}$ - $^{68}\text{Ga}$ ,  $T(z)$  is the transmission probability of positrons from the depth  $z$  to the vacuum and  $d$  is the source thickness. The transmission probability may be given by  $T(z)=\exp(-\alpha z)$ , where  $\alpha=17\rho/E_{\text{max}}^{1.43}$ ,  $\rho$  is the target density and  $E_{\text{max}}$  is the energy endpoint. Figure 3 shows the net positron number emitted from the source as a function of the thickness considering the depth profile shown in Fig. 2. Figure 4 shows the case assuming uniform depth profile. Thus, in any cases, more positrons are obtained with  $E_p=25$  MeV and source thickness of 1 mm. Whereas, a higher emission efficiency to the total activity is obtained for  $E_p=20$  MeV and target thickness of 0.5 mm. The positron emission rate obtained in a feasible proton beam condition (10  $\mu\text{A}$ , 10 hours) is of the order of  $10^7$   $e^+$ /sec. By repeating proton bombardment, this value could be enhanced owing to the long half-life of  $^{68}\text{Ge}$ - $^{68}\text{Ga}$ .



**Figure 3.** Net positron emission rate from  $^{68}\text{Ge}$ - $^{68}\text{Ga}$  produced by proton bombardment with energies of 20, 25 and 30 MeV as a function of target thickness assuming non-uniform depth profile.

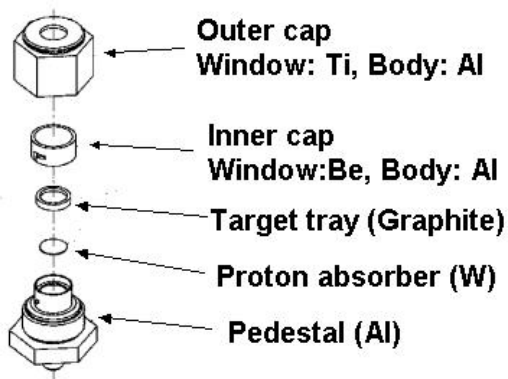


**Figure 4.** Net positron emission rate from  $^{68}\text{Ge}$ - $^{68}\text{Ga}$  produced by proton bombardment with energies of 20, 25 and 30 MeV as a function of target thickness assuming uniform depth profile.

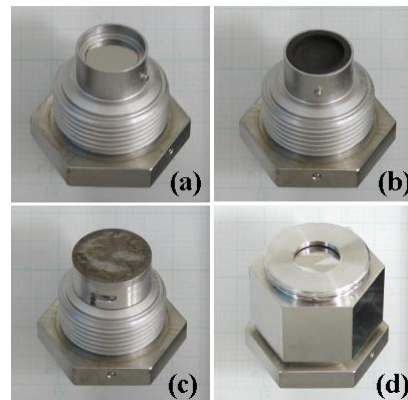
### Source capsule

We designed the source capsule as shown in Fig. 3. The basic concept is similar to that designed by the Halle group [6] and some points are modified considering proton bombardment to Ga target. A proton absorber (tungsten disc) and a graphite tray filled with source material ( $^{69}\text{Ga}$ ) are put into an aluminium pedestal. These are covered with an aluminium inner cap with a beryllium window (25  $\mu\text{m}$  thick) and by an aluminium outer cap with a titanium window (5  $\mu\text{m}$  thick). For avoiding unintentional activation and for cooling efficiently by running water during proton bombardment, the source capsule components are basically made of aluminium. The source tray and the inner cap can not react with melted Ga. Also the source tray should be made of low-Z materials to reduce the backscattering

probability of positrons. Therefore, the source tray and the inner cap window are made of graphite and beryllium, respectively. During proton bombardment with the inner cap, protons transmit the Ga target and the graphite tray and eventually stop at the surface of the tungsten disk as an absorber. When the source is taken outside from the irradiation chamber, it is covered with the outer cap. The air leak is prevented by rigid contact of the edges of pedestal and outer cap. Thus, the source can be used in a vacuum condition. Figure 4 shows the pictures of fabricated source capsule components.



**Figure 3.** Schematic view of the source capsule components.



**Figure 4.** Pictures of fabricated source capsule components: (a) Pedestal, (b) Graphite tray where Ga is put into, (c) Inner cap with a Be window and (d) Outer cap with Ti window.

## Conclusions

In the present work, we estimated the optimum condition to produce a highly spin-polarized positron source ( $^{68}\text{Ge}$ - $^{68}\text{Ga}$ ) by means of  $^{69}\text{Ga}(p,2n)^{68}\text{Ge}$  nuclear reaction. A practical  $^{68}\text{Ge}$ - $^{68}\text{Ga}$  source could be produced by proton bombardment with energies of 20-25 MeV to high purity of  $^{69}\text{Ga}$  targets of 0.5-1 mm thick. We also made a newly designed  $^{69}\text{Ga}$  target holder, which is also used a sealed  $^{68}\text{Ge}$ - $^{68}\text{Ga}$  source capsule. Proton bombardment will be conducted using a Cyclotron accelerator at Japan Atomic Energy Agency.

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