ELSEVIER

Applied Surface Science 116 (1997) 68–72

applied surface science

Slow positron beam production by irradiation of p^+, d^+, and He^{2+} on various targets

Y. Itoh [a,*], Z.L. Peng [a], K.H. Lee [a], M. Ishii [a], A. Goto [a], N. Nakanishi [a], M. Kase [a], Y. Ito [b]

[a] The Institute of Physical and Chemical Research, 2-1 Hirosawa, Wako-shi, Saitama 351-01, Japan
[b] Research Center for Nuclear Science and Technology, The University of Tokyo, Tokai, Ibaraki 319-11, Japan

Abstract

Slow positron beams were extracted by irradiating various targets with p^+, d^+ and He^{2+} ion beams from the AVF (azimuthally varying field) cyclotron of RIKEN. The targets were selected considering the large cross section and high maximum energy of the β^+-decay. Two different geometries of the target and moderator (one W sheet) arrangement, reflection-type and transmission-type were used and a yield of $\sim 10^4$ slow $e^+/s/\mu A$ was obtained. However, in both geometries loss of a fraction of the fast positrons by self-absorption in the target is unavoidable. For increasing the number of available fast positrons we have designed a gas target (N_2) system. The estimated slow positron yield is 1.5×10^5 $e^+/s/\mu A$ using a 16 MeV proton beam and a one W foil moderator.

PACS: 78.70

Keywords: Slow positron beam; β^+-decay emitters; AVF cyclotron

1. Introduction

For more versatile and useful applications of slow positron beams such as positron reemission microscopy (PRM), reflection high energy positron diffraction (RHEPD), spin polarized beams and other dynamic measurement systems for the detailed kinetics of the materials, intense slow positron beams ($> 10^8$ e^+/s) should be realized [1]. High intensity slow positron beam production researches have been extensively carried out using linear accelerators [2–7] and cyclotrons [8–10]. So far reasonable intensities of slow positrons (10^6–10^7 e^+/s) have been obtained using LINACs and have been utilized for various applications. However, further research is needed to obtain more intense slow positron beams because slow positron beam intensity is still insufficient.

In this paper we report experimental results on the production of β^+-decay radioisotopes using p^+, d^+, and He^{2+} reactions on various solid targets such as boron nitride (BN), aluminum (Al), carbon (C), nickel (Ni), silicon (Si), copper (Cu), silicon nitride (Si_3N_4) and silicon oxide (SiO_2). In addition, a newly designed gas target system is introduced which will facilitate the production of more intense slow positron beams.

* Corresponding author. Tel.: +81-48-4679423; fax: +81-48-4624662; e-mail: yitoh@postman.riken.go.jp.

PII S0169-4332(96)01030-6

2. Experimental

A schematic drawing of the slow positron beam production system is shown in Fig. 1. The system is composed of three main parts such as the ion target chamber, the slow positron beam guiding line, and the positron detection chamber. Mounted within the target chamber are various target materials which are irradiated with 14 MeV p^+, 8 and 14 MeV d^+, and 35 MeV He^{2+} beams to produce β^+-decay radioisotopes. The slow positrons are extracted using a single foil W moderator of 10 μm thickness. Slow positrons from the moderator are guided to the positron detection chamber through a beam line consisting of a bent solenoid, a straight solenoid, Helmholtz coils and deflector coils. In the center of the detection chamber an MCPA is used to monitor the slow positron beam profile and two BGO detectors and MCPA are aligned colinearly to measure the coincidence of the two annihilation γ-rays. Since the whole system was installed in the same irradiation room of the AVF cyclotron facility, the background radiation was so high that detection of the annihilation γ-rays was impossible during the ion beam irradiation. Hence we had to adopt an intermittent irradiation method, in which the ion beam irradiation was switched on and off intermittently (typically at intervals of several seconds) and the detection of the annihilation γ-rays was performed while the ion beam was off. Two different moderator arrangements, reflection type and transmission type, have been used. In a previous report [8] the reflection type of moderator was described in which slow positrons

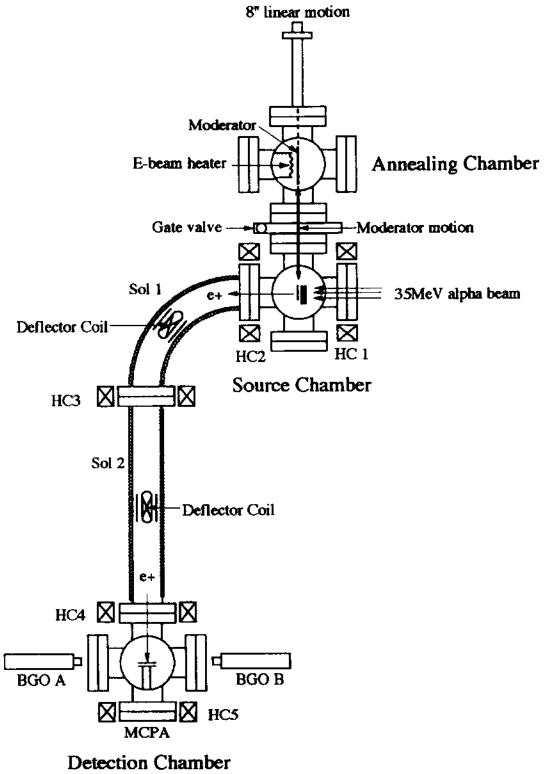

Fig. 1. Schematic diagram of the slow positron beam production system.

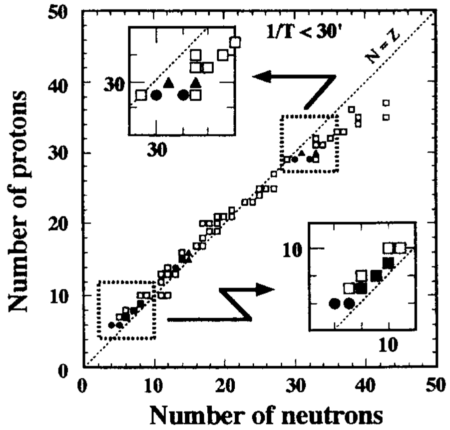

Fig. 2. The list of the β^+-decay isotopes investigated in the present work.

Table 1
Ion beams and target materials for the production of β^+-decay radioisotopes

Incident beam		Target	e^+ emitter	E_{max} (MeV)	Half-life
Proton	14 MeV	BN	^{11}C	1.0	20 min
		Al	^{27}Si	3.9	4.2 s
		Ni	^{58}Cu	8.2	3.2 s
		Cu	^{63}Zn	3.4	38 min
Deuteron	8 MeV	C	^{13}N	1.2	10 min
		SiO_2	^{17}F, ^{29}P	1.8, 4.0	65 s, 4.2 s
		Si_3N_4	^{15}O, ^{29}P	1.7, 4.0	2.0, 4.5 s
	14 MeV	C	^{13}N	1.2	10 min
		SiO_2	^{17}F, ^{29}P	1.8, 4.0	65 s, 4.2 s
		Si_3N_4	^{15}O, ^{29}P	1.7, 4.0	2.0 min, 4.5 s
Alpha	35 MeV	Al	^{26}Al, ^{30}P	3.2, 3.2	6.4 s, 2.5 min
		Si	^{30}P, ^{31}S	3.2, 4.4	2.5 min, 2.7 s
		Ni	^{60}Cu, ^{62}Cu	3.9, 2.9	23 min, 9.7 min

were extracted backward at an angle of 30° to the incident ion beam. In the transmission-type geometry a thin target plate was used and the slow positrons were extracted to the other side of the beam. In both types of moderator, well annealed W has been used as the moderator for the remission of slow positrons. The moderator has been annealed at 2000°C by electron beam heating in a vacuum chamber adjacent to the ion target chamber. The targets were selected from the β^+-decay isotopes listed in Fig. 2 and were chosen because of their large reaction cross sections, high maximum energy and short half-life β^+-decay. The selected targets and reactions using 14 MeV p^+, 8 and 14 MeV d^+, and 35 MeV He^{2+} irradiation are shown in Table 1.

3. Calculation of slow positron yield

The activity of a source $A(t)$, that can be formed after an activation time t depends on its decay constant λ. For a production rate R one obtains:

$$A(t) = R(1 - e^{-\lambda t})$$

In order to produce high activities the activation time should be of the order of the half-life. If it is long enough, the activity equals the production rate. In a nuclear rearrangement process the production rate depends on the cross section for the process, σ, the intensity of the projectiles, i, the density of the target, ρ, and the activation range, Δx:

$$R = N_a i \rho \sigma(E) \Delta x$$

where N_a is the Avogadro constant.

When the positrons are emitted from the produced positron source, their energy ranges from zero to the end-point energy E_{max}. Considering the absorption of positrons in the targets, the intensity of the slow positrons extracted from the moderator can be expressed as:

$$Y = \eta \varepsilon \kappa N_a i \rho \times \int_0^{R_{max}} e^{-\mu \xi} \sigma(x)\, dx \quad \text{(reflection type)}$$

$$Y = \eta \varepsilon \kappa N_a i \rho \times \int_l^{l-R_{max}} e^{-\mu \xi} \sigma(x)\, dx \quad \text{(transmission type)}$$

where η is the conversion efficiency from fast to slow positrons of the tungsten moderator ($\approx 10^{-4}$), ε is the geometry efficiency, κ is the branching ratio of β^+-decay, l is the target thickness and R_{max} is the maximum range of the injected particles in the target. The absorption coefficient μ of the target material is related to its density ρ and to the end-point energy E_{max} by the relationship $\mu = 17 \rho E_{max}^{-1.43}$ [11]. ζ is the thickness that positrons should pass through in the target. For the reflection type, $\zeta =$

Table 2
Slow positron intensities for various targets

Incident beam		Target	Slow e^+ intensity reflection type e^+ (s)		Slow e^+ intensity transmission type e^+ (s)	
			calculated	measured	calculated	measured
Proton	14 MeV	BN	2.1×10^4	1.4×10^4	1.2×10^4	—
		Al	2.6×10^4	1.3×10^3	7.8×10^4	—
		Ni	2.4×10^4	1.1×10^3	4.7×10^4	—
		Cu	3.0×10^4	—	5.4×10^4	5.0×10^3
Deuteron	8 MeV	C	2.0×10^4	1.3×10^4	6.9×10^4	—
		SiO_2	0.5×10^4	1.2×10^4	2.1×10^4	—
		Si_3N_4	1.3×10^4	8.4×10^3	5.1×10^4	—
	14 MeV	C	2.1×10^4	—	8.9×10^4	1.7×10^4
		SiO_2	1.1×10^4	—	3.5×10^4	—
		Si_3N_4	2.3×10^4	—	7.2×10^4	—
Alpha	35 MeV	Al	1.5×10^4	—	5.8×10^4	1.3×10^4
		Si	2.4×10^4	—	9.4×10^4	5.5×10^3
		Ni	1.8×10^4	—	5.9×10^4	1.4×10^4

$x \cos \theta$, for the transmission type, $\zeta = l - x$ where x is the ion penetration depth in the target; θ is the angle at which positrons was extracted to the incident ion beam. It was assumed that each cross section is constant within each 1 MeV division of irradiation beam energy, thus allowing the cross section $\sigma(E)$ to be calculated using the ALICE program [12] from which it was converted to the function of the depth x using the stopping power data from the TRIM program.

Table 2 gives the calculated intensities of the slow positron beams for the transmission and reflection arrangements. The transmission type of the target geometry provides approximately several times higher collection efficiency than the reflection type. This results from the poorer geometry of the reflection type of target holder. The calculation suggests that the geometry efficiency is about 50% for transmission-type system and only 10% for reflection-type system. Thus we conclude that the transmission type of moderator has the better geometrical configuration between the target and moderator.

4. Results and discussion

Table 2 shows the comparison of emitted slow positron counts from each target with different experimental conditions. For all of the cases the irradiation time was longer than 5 times the half-life of β^+-decay source to get saturation activity. The relationship between the yield of low energy positrons and the coincidence count rate was determined by use of a small calibrated ^{22}Na source. We obtained best counts of 1.7×10^4 e^+/s from the carbon target irradiated with a 1 μA, 14 MeV deuteron beam. The experimental results did not parallel the estimated ones, being very close to the estimation for BN, carbon and Al, and substantially smaller for Si. For SiO_2 irradiated by 8 MeV deuterons the experimental value was much higher than the expected one. Uncertainty of the excitation function is one of the reasons. Fig. 3 shows the comparison of the cross section between the literature and that from the ALICE code. We notice that the two values are close each other for the large mass number products. For ^{17}F, the calculated value is much smaller than the literature data. Since ^{17}F is the main product by

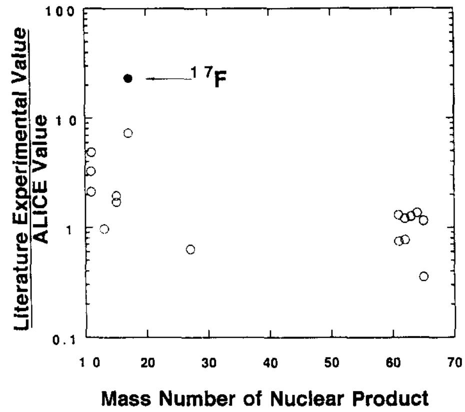

Fig. 3. Comparison of the cross sections obtained from the literatures and those obtained from the ALICE code.

irradiating SiO_2 with 8 MeV deuterons, the value from the ALICE code causes a substantially smaller estimation of the e^+ emitter yield. Problems associated with materials science are also involved in the difference between the experimental and calculated values. For example, for Si there is a charge-up effect which will result in a loss of the ion beam intensity and a decrease of the ion beam energy. In fact we noticed unstable fluctuation of the slow positron yields during the experiment with the Si target. On the other hand, the condition of the moderator is one of the most important factors for the emission of slow positrons. In the case of the proton beam irradiation, the same moderator was used for targets BN, Al and Ni. For the reflection type target system, there was a noticeable problem caused by the decrease in the slow positron beam intensity due to radiation damage in the moderator. This may be seen from the big difference between the estimated and experimental values for the Al and Ni targets. In the transmission type geometry the experimental value is very close to the estimated value.

Based on the presented calculations and experimental results, if the beam current is increased to 100 μA which is almost the maximum value obtainable in most commercially available cyclotrons, a flux of $\sim 10^6$–10^7 e^+/s could be achieved. This slow e^+ intensity is still not very high. One reason is that the positrons must pass through a thickness of the target in both geometries causing the slower positrons to be stopped. The loss of a fraction of positrons by self-absorbtion in the target is unavoidable providing we continue to employ solid targets.

To increase the number of available fast positrons, we have designed a gas target method, in which N_2 gas is irradiated with a p^+ beam causing the β^+-decay positron source $^{11}CO_2$ to be produced through the reaction $^{14}N(p, \alpha)^{11}C$. The radioactive $^{11}CO_2$ is then transported away from the target chamber and deposited on to a cold spot near the moderator. In our preliminary experiment, a 16 MeV proton beam from cyclotron was used to irradiate gas target N_2 (30 mm diameter, 300 mm length and 7 kg/cm^2 pressure), more than 40% of produced positron activity can be trapped on the cold window and about 1.5×10^5 e^+/s positron beam is estimated to be obtained using one W foil moderator, a flux which is one order of magnitude higher than that of the solid target. Also in the gas target system the produced $^{11}CO_2$ is easily transported to an experimental room where there is no background radiation from the cyclotron. Furthermore, this method does not require strong focusing of the primary ion beam, hence it is possible to work under high beam power so as to obtain even larger positron activities. By using a far more intense proton beam ($\sim$ 1 mA) and a rare gas moderator (efficiency $\sim 10^{-3}$) [13], it may be possible to achieve a more than $10^9/s$ slow positron beam.

5. Conclusions

We have succeeded in developing a slow positron system using the RIKEN AVF cyclotron. The present technique is based on the production of short-lived β^+-decay isotopes by using 14 MeV p^+, d^+ and 35 MeV He^{2+} irradiation on various targets. In the current stage, the intensity of slow positrons extracted reaches $\sim 10^4$ $e^+/s/\mu A$. In order to avoid the problem self-absorption of positrons in the target material, a gas target has been designed. We estimate that a 1.5×10^5 e^+/s positron beam can be produced with a 1 μA, 16 MeV proton beam using a single W foil moderator.

Acknowledgements

The authors are grateful for the contributions of RIKEN AVF cyclotron personnel. This research was supported by the Nuclear Cross-over Research Funds and the Special Grant for Promotion of Research from the Institute of Physical and Chemical Research (RIKEN).

References

[1] P.J. Schultz and K.G. Lynn, Rev. Mod. Phys. 60 (1988) 701.
[2] R.H. Howell, R.A. Alvarez and M. Stanek, Appl. Phys. Lett. 40 (1982) 751.
[3] R. Ley, K.D. Niebling, A. Osipowicz, A. Picard and G. Werth, in: Proc. 7th Int. Conf. on Positron Annihilation, New Delhi, 1985, p. 996.
[4] G. Gräff, R. Ley, A. Osipowicz and Werth, Appl. Phys. A 33 (1984) 59.
[5] T. Akahane, T. Chiba, N. Shiotani, S. Tanigawa, T. Mikado, R. Suzuki, M. Chiwaki, T. Yamazaki and T. Tominasu, Appl. Phys. A 51 (1990) 146.
[6] Y. Ito, M. Hirose, S. Takamura, O. Sueoka, I. Kanazawa, K. Mashiko, A. Ichimiya, Y. Murata, S. Okada, M. Hasegawa and T. Hyodo, Nucl. Instr. Meth. A 305 (1991) 269.
[7] A. Asami, A. Enomoto, H. Kobayashi, T. Kurihara and T. Shidara, in: Proc. 9th Int. Conf. on Positron Annihilation, Hungary, 1992, p. 1832.
[8] Y. Itoh, K.H. Lee, T. Nakajyo, A. Goto, N. Nakanishi, M. Kase, I. Kanazawa, Y. Yamamoto, N. Oshima and Y. Ito, Appl. Surf. Sci. 85 (1995) 165.
[9] M. Hirose, M. Washio and K. Takahashi, Appl. Surf. Sci. 85 (1995) 111.
[10] R. Xie, M. Petrov, D. Becker, K.F. Canter, F.M. Jacobsen, K.G. Lynn, R. Mills and L.O. Roelling, Nucl. Instr. Meth. B 93 (1994) 98.
[11] S. Dannefaer, in: Defect Control in Semiconductors, Ed. K. Sumino (Elsevier, Amsterdam) p. 1561.
[12] ALICE/Livermore/85/300, Some discussion of code physics may be found in M. Blann and H.K. Vonach, Phys. Rev. C 28(1983)1475 and LLNL Report UCID 19614 (1982).
[13] A.P. Mills, Jr., S.S. Voris, Jr. and T.S. Andrew, J. Appl. Phys. 76 (1994) 2556.