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Development of intense ^{7}Be and ^{22}Na beam for wear diagnostics application

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The industrial cooperation team in RNC and SHIEI Ltd. are developing a new method for wear diagnostics of industrial material using RI beams as tracers. RI nuclei are implanted in a near surface of the machine parts within depth of 100 μm, and its wear-loss is evaluated by the decrease in the measured radioactivity. Continuous γ-ray detection from the outside of the machine enables real-time diagnostics of wear in running machines. For this purpose, RI nuclei having appropriately long lifetime are desired. At present, we can provide an intense ^{22}Na ($T_{1/2}$ = 2.6y) beam at RIPS separator [1] using a fragmentation reaction of ^{23}Na. As the produced ^{22}Na beam has an adequate energy of 26.6 MeV/u, it enables to implant in atmosphere and to control the depth profile easily. However, the RI beam production at RIPS needs the RRC cyclotron whose beam time scheduling is very tight. The beam production cost using RRC and RIPS is expensive, also. These two drawbacks were practical issues of developing and promoting industrial applications using RI beams.

On the other hand, CRIB group has developed a cryogenic gas target system [2] and reported production of intense ^{7}Be ($T_{1/2}$ = 53d) and ^{22}Na beams using the system. The RI beam energy produced by CRIB is low as 4 MeV/u, approximately. Accordingly, it becomes difficult to implant in atmosphere environment. But from the point of view of beam cost and beam-time flexibility, the low energy RI beam production at CRIB using the compact AVF cyclotron independently is favorable. With the aim to utilize these intense RI beams for the wear diagnostics, beam studies managed by the industrial cooperation team collaborating with the CRIB group was performed.

The ^{7}Be beam was produced via $p(^{7}\mathrm{Li},^{7}\mathrm{Be})n$ reaction. A primary beam of $^{7}\mathrm{Li}^{2+}$ with the energy of 5.7 MeV/u and intensity of 1.2 particle μA (pμA) was introduced to the cryogenic gas target. The H_2 target gas was confined in a gas cell (8 cm long and 2 cm in diameter) sealed by 2.5-μm-thick Havar foils. The H_2 gas at a pressure of 760 *Torr* was cooled by liquid N_2 in a vessel at 90 K and circulated to the gas cell at a rate of 55 *slm*. The primary beam was focused on a Havar foil placed at entrance of the gas cell with the spot size of 1 mm in diameter. The calculated energy loss in the gas target was 1.0 and 4.6 W at the entrance Havar foil and the target gas, respectively. The target was very stable during this experiment. The produced ^{7}Be beam was introduced to the F2 focal plane without degrader foil at F1. In order to enable ^{7}Be implantation under air pressure condition, the vacuum chamber at F2 was modified so that a vacuum-separation foil could be attached. First, under a vacuum condition, the profiles of secondary beams were measured at F2 using a PPAC and a silicon detector. The energy and radius of the $^{7}\mathrm{Be}^{4+}$ beam was 28.7 MeV (4.1 MeV/u) and σ = 6.1 mm, respectively, with a momentum slit of $\pm$ 3.1% ($\pm$ 50 mm) at F1. The calculated range of this ^{7}Be beam into an aluminum material is 67 μm. A contaminant nuclide of $^{7}\mathrm{Li}^{3+}$ was observed with a fraction of 20 % and energy of 18.8 MeV. Secondly, a Kapton vacuum-separation foil (50 μm thick and 5 cm in diameter) was assembled, and He gas at 1 *atm* was filled in the F2 chamber. The distance from the foil to the irradiation position was 14 cm. The ^{7}Li contaminant was stopped in the He gas, completely. The remainder of the ^{7}Be beam was 100 % in purity and its peak energy was 13.5 MeV, with a width of σ = 1.6 MeV. The intensity of the ^{7}Be beam was 1.9×10^{8} pps obtained by the following γ-ray measurement, which reproduced the reported value in the Ref. 2.

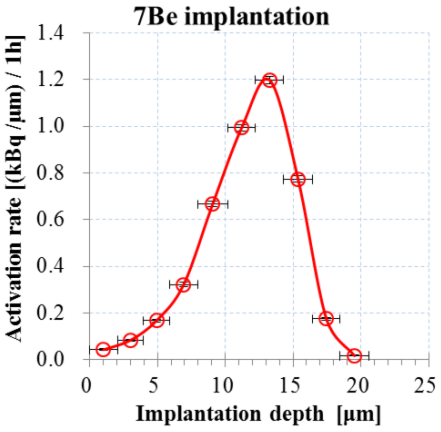

Figure 1. Implantation-depth profile of ^{7}Be beam into aluminum material under He gas of 1 *atm* environment.

In order to control the implantation depth near to the surface, a rotating energy degrader was introduced. An 8-μm-thick aluminum foil was set on the beam path at 50° (corresponding to a thickness of 10.4 μm) and 90°, alternatively, relative to the beam axis with a time fraction of 5:1. To investigate the implantation-depth profile of ^{7}Be, a stack of 2-μm-thick aluminum foils with a diameter of 16 mm were irradiated. After irradiation, the stack was disassembled and the intensity of the γ ray (E_γ = 478 keV) was measured using a Ge detector. The obtained implantation-depth profiles are shown in Figure 1. In this figure, the vertical axis is in the unit of (kBq/μm)/1h irradiation with a full primary beam intensity of 1.2 pμA. X-error bars indicate the thickness of each foil. We achieved the total activity rate of 10 kBq/1h, approximately.

The ^{22}Na beam was produced via the $p(^{22}\mathrm{Ne},^{22}\mathrm{Na})n$ reaction. A primary beam of $^{22}\mathrm{Ne}^{7+}$ with energy of 6.1 MeV/u and intensity of 0.3 pμA was introduced to the cryogenic gas target. The H_2 gas at a pressure of 400 *Torr* was cooled as 90 K and circulated to the gas cell at a rate of 70 *slm*. The calculated energy loss in the gas target was 2.2 and 5.3 W at the entrance Havar foil of 2.5 μm in thickness and at the target gas, respectively. The target was very stable during this experiment. The produced ^{22}Na beam was introduced to the F2 focal plane without degrader foil at F1. To investigate optimum parameters for ^{22}Na beam,

		CRIB		RIPS
RI beam		^{7}Be	^{22}Na	^{22}Na
Energy	MeV/u	4.1	3.69	26.6
Intensity	cps	1.9×10^{8}	3.1×10^{7}	1.5×10^{8}
Purity		80%	78%	100%
Activation rate	kBq/1h	∼10	∼0.9	∼5
Irradiation environment		He 1 *atm*	Vaccuum	Air 1 *atm*
max. Range in Al	μm	67	38	685
Primary beam		$^{7}Li^{2+}$	$^{22}Ne^{7+}$	$^{23}Na^{11+}$
Energy	MeV/u	5.7	6.1	63.4
Intensity	pμA	∼1.0	∼0.3	∼1.0
Target		H_2 760*Torr*	H_2 400 *Torr*	Be 1.5 mm

Table 1. Avialable RI beams for wear diagnostics.

the magnetic rigidity of CRIB separator was scanned in the range of 0.53 - 0.59 Tm. Contaminant nuclei of $^{19}F^{9+}$ (stable) and $^{22}Ne^{10+}$ (primary beam) were observed. The ^{22}Na beam had two components with different charge state as q=10^{+} and 11^{+}. Because the $^{22}Na^{10+}$ component had fudge $^{22}Ne^{10+}$ contamination, we have searched an optimum magnetic rigidity for $^{22}Na^{11+}$ beam. At the optimum condition, the energy and radius of the $^{22}Na^{11+}$ beam was 81.2 MeV (3.7 MeV/u) and σ = 1.6 mm, respectively, with a momentum slit of $\pm$ 3.1 % ($\pm$ 50 mm) at F1. The ^{22}Na beam was 78 % in purity. The intensity was 3.1×10^{7} pps obtained by the following γ-ray measurement. This beam study was performed under a vacuum condition at F2 irradiation chamber. The implantation-depth profile was measured using the same method mentioned above, observing the γ ray (E_γ = 1274 keV) from ^{22}Na. The obtained profile is shown in Figure 2, here the activation rate indicates (kBq/μm)/1h irradiation with a full primary beam intensity of 0.3 pμA. We achieved the total activity rate of 0.9 kBq/1h, approximately.

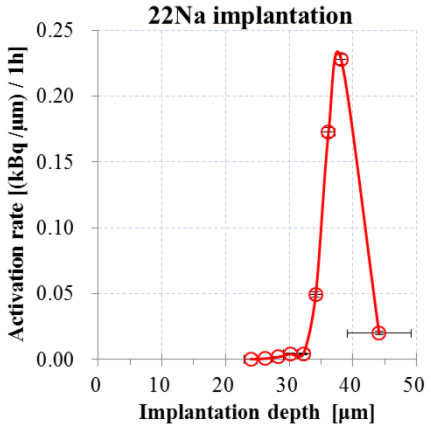

Figure 2. Implantation-depth profile of ^{22}Na beam into aluminum material under vacuum environment.

The obtained results of these beam studies are summarized in the Table 1 including the result of ^{22}Na production in RIPS. For the case of ^{22}Na beam, the total activation rate using RIPS was 5 kBq/1h irradiation, which is 5 times larger intensity than CRIB. However, this difference is nearly compensated with the difference of beam production cost between RIPS+RRC and CRIB+AVF.

References

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