SMALL CYCLOTRON FOR PET FREE FROM HIGH RADIOACTIVITIES

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Abstract

Oxygen-15 is one of the most common radioisotopes in Positron Emission Tomography (PET), and has been utilized to assess regional cerebral blood flow (CBF) and cerebral metabolic rate of oxygen ($CMRO_2$) quantitatively in vivo study. The oxygen-15 can be generated by using a deuteron beam at a relatively low energy of approximately 3 MeV, which enables the use of a small cyclotron, if one intends to produce only this radioisotope. However, a large neutron production requires a large shield, which makes the total size of the system not significantly different from the other cyclotron systems of deuteron energy of 9–10 MeV. We have evaluated a novel approach that reduces the neutron production from the cyclotron to a negligible level by choosing the materials with a large atomic number for the cyclotron parts. Systematic experiments were performed using a Tandem Van de Graaff accelerator to check the feasibility of our approach, in which the neutron production was assessed for realistic energy ranges of deuteron. Neutron production was reduced dramatically in our method, while an enough amount of oxygen-15 was produced. This study suggests that a small oxygen-15 generator is possible and the existing system will be replaced by a new cyclotron based our idea.

INTRODUCTION

Oxygen-15-labeled gases such as $[^{15}O]O_2$, $[^{15}O]CO$ and $[^{15}O]CO_2$ are used for Positron Emission Tomography (PET) to measure oxygen metabolism in acute stroke. However, the preparation time of the sample gases in the PET treatment takes more than 1 hour to raise the temperature of charcoal in an oven used for synthesizing $[^{15}O]CO$ and $[^{15}O]CO_2$ in the conventional method [1]. Therefore, the rapid supply of the gases has been a serious demand for the diagnosis of acute stroke.

Miyake *et al.* have recently developed a new method for synthesis of $[^{15}O]CO$ and $[^{15}O]CO_2$ at the room temperature [2], so that the rapid supply of the gases are achievable. Thanks to its simplicity of the method, the synthesizer can be assembled in smaller dimensions than those of conventional one.

A small cyclotron is an essential ingredient for the miniaturization of the synthesizer system to increase the availability in hospitals. The small cyclotron can be designed by lowering the maximum energy of a beam, because the energy is proportional to the square of a beam extraction radius with a sufficient strong magnetic field. A sufficient quantity of oxygen-15 for the medical purpose can be produced using a low energy beam with an intensity of a few tens of μA [3]. Actually, a small cyclotron which provides the deuteron beam with a maximum energy of 3.6 MeV has been developed only for producing the oxygen-15 [4]. Furthermore, the self-shield of the cyclotron has been developed to be installed in a room which may not have a special thick wall for shielding radiations.

By reducing radiations, we can decrease the amount of the self-shield for minimizing the size of the total system. We have measured neutron dose-equivalent rates from various materials which are used in a small cyclotron for PET. These results are useful as the practical data for designing the self-shield.

EXPERIMENTAL METHOD

The experiment was performed at the Tandem Van de Graaff Accelerator Laboratory, Kyoto University. The positive deuteron beam was transported from the tandem Van de Graaff accelerator to the scattering chamber of the G-course in the laboratory. The deuteron beam energies were 3.5 MeV and 10 MeV. The former corresponds to the maximum beam energy of the small cyclotron which we are designing. The latter is a typical beam energy used in hospitals for PET. The schematic layout of the experimental setup is shown in Figure 1.

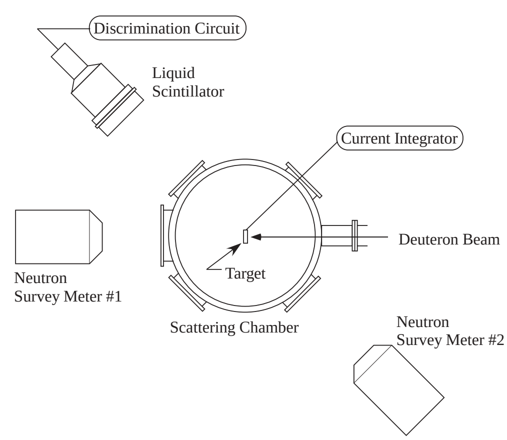

Figure 1: Layout of experiment. Two neutron survey meters were installed at the outside of the scattering chamber to detect neutrons through a thin aluminum plate attached to the flange. A scintillation counter was also mounted for monitoring the yield ratios between neutrons and γ-rays.

The targets used were natural metals of Al, Ti, Fe, Cu, Nb, Mo, Gd, Ta and W with thicknesses of 0.1 mm to 0.5 mm and with the purity of more than 99%. These target materials were purchased from Nilaco Inc. The thickness

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of each target was enough to stop the deuteron beam. The target ladder was electrically insulated from the scattering chamber. To measure the beam currents, a current integrator was connected to the ladder on which the targets were mounted. In order to avoid the emission of secondary electrons from the target, permanent magnets which generated a magnetic field of about 300 G near the target were attached to the ladder perpendicular to the beam.

The neutron dose equivalents were measured by the two survey meters (Aloka Model TPS-451C) at a distance of 66 cm from the target position to the front surface of each detector. The detectors were installed at the angles of 0°, 90°, 135° to the beam direction to inspect dependence of the angular distributions of neutron dose equivalents. A liquid scintillator (Bicron BC501A) was mounted for monitoring the yield ratios between neutrons and γ-rays. The events of neutrons and γ-rays were identified using the pulse shape discrimination method. After the beam exposure, γ-ray dose equivalents were measured by a γ-ray survey meter for estimating the life-time of residual radioactivities.

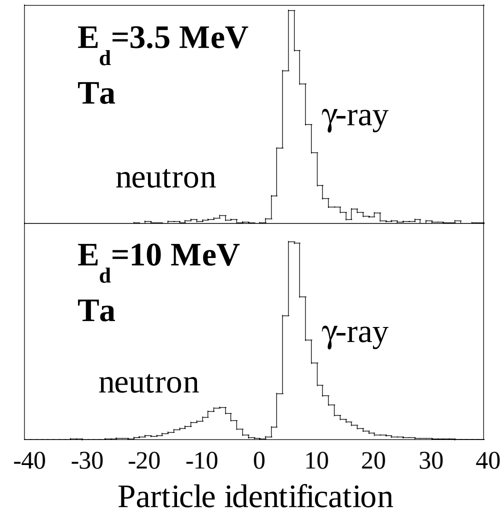

Figure 2: Examples of discrimination spectra between neutrons and γ-rays. The spectra shown in the upper and lower panels were obtained from a thick tantalum target at $E_{\rm d}$=3.5 MeV and 10 MeV, respectively.

RESULTS

Neutron and γ-ray yields

Figure 2 shows spectra for neutrons and γ-rays measured in the pulse shape discrimination method with a liquid scintillator. In this example, the neutron yield ratio at $E_{\rm d}$=3.5 MeV was much smaller than that of $E_{\rm d}$=10 MeV. The counting rates, in which the natural γ-ray backgrounds were included, are shown in Figure 3. Neutrons and γ-rays yields decreased with increasing target atomic number, especially at $E_{\rm d}$=3.5 MeV, as expected from the consideration of the Coulomb barrier which suppresses nuclear reactions.

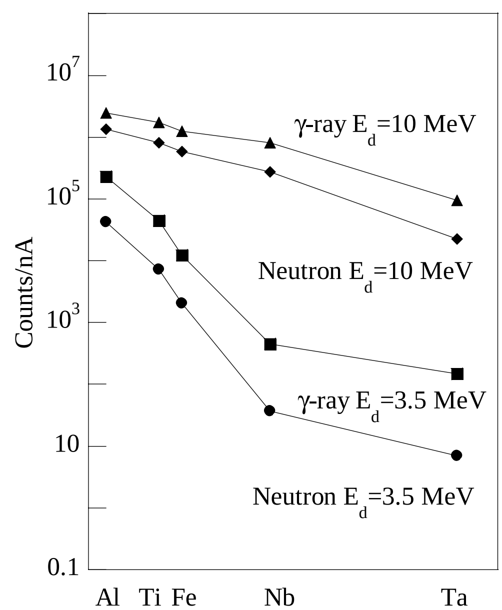

Figure 3: Neutron and γ-ray yields normalized with the beam current.

Neutron dose equivalents

Figure 4 and 5 shows the neutron dose-equivalent rates normalized with beam currents and the detector solid angle at $E_{\rm d}$=3.5 MeV and $E_{\rm d}$=10 MeV. We confirmed that the neutron dose-equivalent rates were proportional to the beam currents. Each dose-equivalent rate at forward angles was larger than those at backward angles. However, the difference was not prominent, especially in large atomic-number targets at $E_{\rm d}$=10 MeV. The dose-equivalent rates of these energies tend to decrease with increasing the atomic number of the targets. Although the dose-equivalent rate for gadolinium showed an interesting enhancement at $E_{\rm d}$=3.5 MeV, we could not confirm whether the neutrons were originated only from the gadolinium or from a stain remained on the surface of the target. In these data, the background originated from other than a target was not evaluated. However, the maximum background level can be supposed to be the same order of magnitude with the dose-equivalent rates from tantalum or tungsten. These rates were less than $1/1000$ of aluminum at $E_{\rm d}$=3.5 MeV.

The Coulomb force between the target nuclei and the deuteron suppresses nuclear reactions such as a proton transfer or a break-up of a deuteron for emitting a neutron. This effect is stronger at $E_{\rm d}$=3.5 MeV than at $E_{\rm d}$=10 MeV using large atomic-number targets. Consequently, the strong neutron reductions were found in the large atomic number targets at $E_{\rm d}$=3.5 MeV compared with $E_{\rm d}$=10 MeV as shown in Figures 4 and 5.

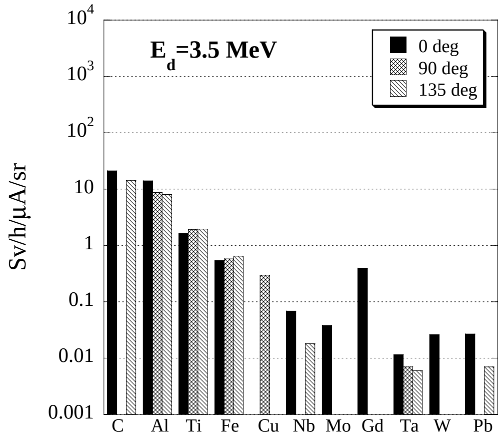

Figure 4: Neutron dose equivalent at $E_{\rm d}$=3.5 MeV.

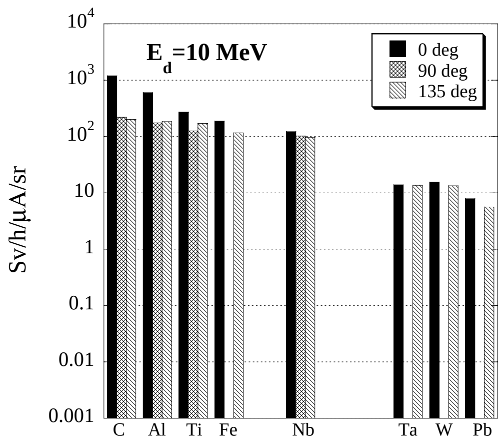

Figure 5: Neutron dose equivalent at $E_{\rm d}$=10 MeV.

Residual γ-ray activities

The residual γ-ray dose equivalents were measured several times for estimating the life-times of the radioactivities in C, Al, Ti, Mo and Ta targets. The results are shown in Figure 6. The life-times obtained from the fitting with the exponential function are enough for choosing cyclotron and the self-shield materials. Each life-time measured from the carbon and aluminum targets were relatively short compared with those of titanium and tantalum.

DISCUSSION

The results of neutron dose equivalents from several targets indicate that generating neutrons will be reduced by utilizing a metallic sheet with a large atomic number to which the beam or the scattered deuteron with the energy of less than 3.5 MeV may hit in a cyclotron. By this simple device, the quantity of the self-shield will be small in comparison with the existing one. Therefore, we propose to apply thin large atomic-number materials such as tantalum or tungsten to the deflector, the chamber, the target cell and some other parts where the beam or scattered deuteron may hit.

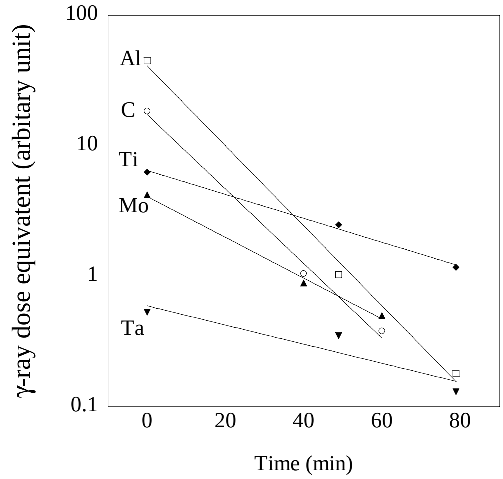

Figure 6: Residual γ-ray activities after beam irradiation.

As an example of the materials, a tantalum sheet with a thickness of 32 μm in consideration of the longitudinal straggling can stop a deuteron beam of 3.5 MeV. While the life-time of radioactivity of tantalum target irradiated by deuteron beam was long compared with light nuclei such as carbon and aluminum, so that further practical experiment using a demonstration cyclotron accelerating deuteron with a maximum energy of 3.5 MeV will be useful to design the self-shield by considering residual radioactivities. For more precise investigation of radiation sources in a cyclotron for PET, construction of a demonstration cyclotron is required to reduce the total size of the PET system.

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REFERENCES

[1] Michael J. Welch and Michael M. Ter-Pogossian, Radiation Research. 36, 580 (1968).

[2] Miyake *et al.*, presented at International Workshop on Quantitation in Biomedical Imaging with PET and MRI (2004).

[3] M. Sajjad, R. M. Lambrecht and A. P. Wolf, Radiochim. Acta 38, 57 (1985)

[4] Product Description: The oxygen generator system, IBA.