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Preliminary Study on Accelerator Based D-D Neutron Generator with Hydrocarbon Liquid Target

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1. Introduction

A neutron generator is very usefully utilized in various field such as neutron activation analysis, neutron radiography, and medical application [1]. Especially, a fast neutron generator based on beam-target fusion reactions is favored at a laboratory level [1]. Because the neutron generator has advantages such as a compact size, flexibility of operation and low establishment cost, in contrast to a research reactor. In addition, the higher neutron energy than the research reactor allows a reaction whose threshold energy is higher than 2 MeV. Thus, more elements can be utilized in a neutron activation analysis. Also, a low specific activity of isotope production by (n, γ) reaction can be improved when (n, p) reaction is utilized [2].

Furthermore, since a conventional deuteron-triton (D-T) neutron generator shows higher neutron energy and yield than deuteron-deuteron (D-D) neutron generator, D-T neutron generator is more widely used. However, D-T neutron generator has tritium handling problem. Thus, this work proposes accelerator based D-D neutron generator whose neutron energy and yield are similar with those of D-T neutron generator. Additionally, a forward flux of the neutron generator is significantly enhanced when the incident deuteron beam is accelerated up to 10 MeV. Therefore, in order to estimate a performance of the accelerator based D-D neutron generator, this work conducted a preliminary study based on a numerical method. Also, a liquid target was introduced to deal with a beam power loaded on the target. Thus, several types of target materials were characterized numerically and compared.

2. Numerical Study on Accelerator Based D-D Neutron Generator

2.1 Neutron Energy and Yield of Accelerator Based D-D Neutron Generator

The neutron yield of the beam target type neutron generator is expressed as [1]

$$Y = \frac{I_b C_t}{q}\int_0^{E_b} \sigma(E)\left(\frac{dE}{dx}\right)^{-1} dE \qquad (1)$$

where Y is the neutron yield, I_b is a beam current, C_t is a deuterium concentration in the target, q is a charge of D^+ ion, E_b is the incident beam energy and dE/dx is energy loss rate of the target material. The target is assumed as a thick target which means that every beam particle is stopped inside the target. Also, the beam is considered as 100% of D^+ ion beam. The target material is set as $TiD_{1.6}$ and $TiT_{1.6}$ and their hydrogen isotope concentrations are regarded as 1.6 times of the solid titanium particle density.

The neutron energy can be obtained from the momentum and energy conservation equation. For D-D neutron, it is simply expressed as

$$E_n(\theta) = 0.13E_b\left[\cos\theta + \sqrt{\cos^2\theta + 1.98 + \frac{19.5}{E_b}}\right]^2 \qquad (2)$$

where θ is neutron emission angle to the incident beam. The neutron energy is shown as a continuum spectrum because the incident beam is slowed down inside the target.

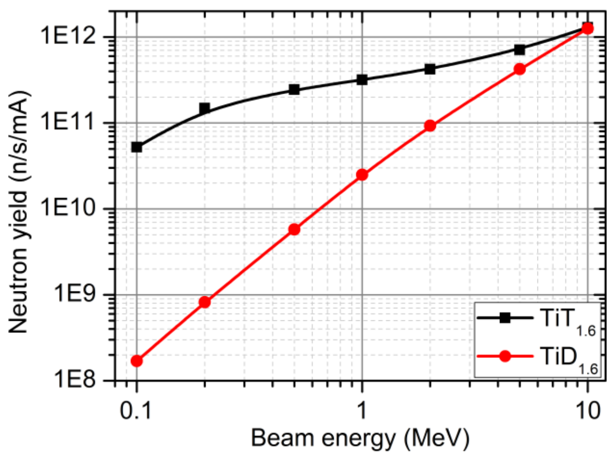

FIG. 1. D-T and D-D Neutron yield per 1 mA of deuteron beam. The targets are the solid titanium target.

The neutron yield of D-T and D-D neutron generator with 1 mA deuteron beam are depicted in Fig. 1. The neutron yield of deuterated target depends on the incident beam energy stronger than the tritiated target. Because the cross section of D-D reaction increases monotonically up to near 2 MeV, while D-T reaction sharply increases up to 0.1 MeV and decrease after 0.1 MeV. Thus, though the yield of D-T neutron generator is about two order of magnitude larger than D-D at conventionally operated region near 0.1 MeV, the neutron yields of both reactions are almost same at 10 MeV.

The neutron energy of accelerator based neutron generator is greatly increased according to Eq. 2. Figure 2 presents the neutron spectrum on parallel direction with incident beam, i.e. θ=0. The energy of D-D neutrons at low beam energy is less than 3 MeV. However, the maximum neutron energy exceeds 13 MeV at 10 MeV deuteron beam case, because the momentum of the incident deuteron is transferred to the neutron. Thus, this neutron generator can be utilized in application field which should be maintained by the D-T neutron generator. However, the energy spread is significantly large because the deuteron beam produces the neutrons during decelerated inside the target.

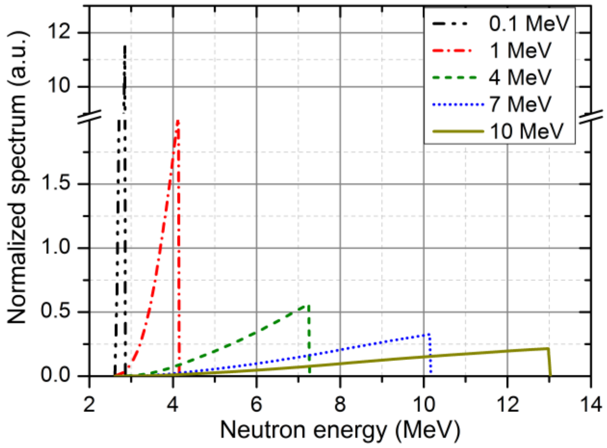

FIG. 2. Calculation results of normalized neutron spectrum according to incident beam energy.

Another important result of the numerical study is an angular flux distribution of the neutron generator. In practice, the neutron flux distribution biased the forward direction is efficient for the neutron generator, because the neutron field behind the target is mainly utilized. The calculated angular neutron flux of $TiD_{1.6}$ target is depicted in Fig. 3. There are 2 reasons of an anisotropic distribution. The differential cross section of D-D reaction is intrinsically anisotropic and the anisotropy is more enhanced according to the incident beam energy.

If a forward yield is defined as the neutron emitted within 15 degrees which occupies 1.7% of the total solid angle 4π, the forward yield is 14% of the total neutron yield with 10 MeV beam, while the forward yield is only 3% with 0.1 MeV beam.

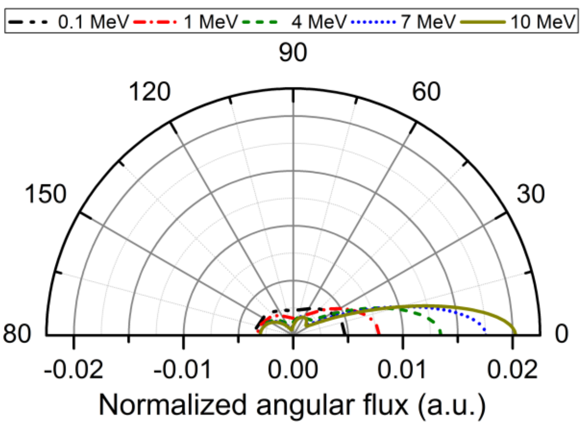

FIG. 3. Calculation results of normalized angular flux according to incident beam energy.

Thus, the accelerator based D-D neutron generator can achieve the performance similar with the D-T neutron generator without the tritium. However, this numerical study considers that the beam energy is 100 times higher than that of the conventional neutron generator. Thus, an appropriate treatment of the beam power loaded on the target becomes important issue. In order to resolve this issue, this work suggests the cryogenically cooled liquid target.

2.2 Cryogenically Cooled Hydrocarbon Liquid Target

2.2.1. Neutron yield of hydrocarbon liquid target

The liquid target can secure a self-cooling and self-healing function with a circulation system. However, since it is operated in a vacuum, a vapor pressure of the liquid target is maintained as low as possible. Also, high deuterium concentration and low energy loss rate of the target material are favorable. Thus, this work numerically and experimentally examined the cryogenically cooled hydrocarbon liquid target.

The performance of the liquid target is compared with other conventional solid target through the numerical study. 4 kinds of the target materials are compared. Titanium and D_2O target are a solid and deuterated propane and ethanol are the liquid target. The basic properties of the target materials are summarized in Table I.

Table I**:** Physical properties of neutron emission target.

Materials	**Deuterium concentration [#/cm^3]**	**Triple point (liquid target)**	
		Pressure [Pa]	**Temperature [K]**
$TiD_{1.6}$	9.07×10^{22}	-	-
D_2O (s)	6.12×10^{22}	-	-
C_3D_8 (liq.)	4.98×10^{22}	1.7×10^{-4}	85.5
C_2D_5OD (liq.)	6.18×10^{22}	4.3×10^{-4}	150

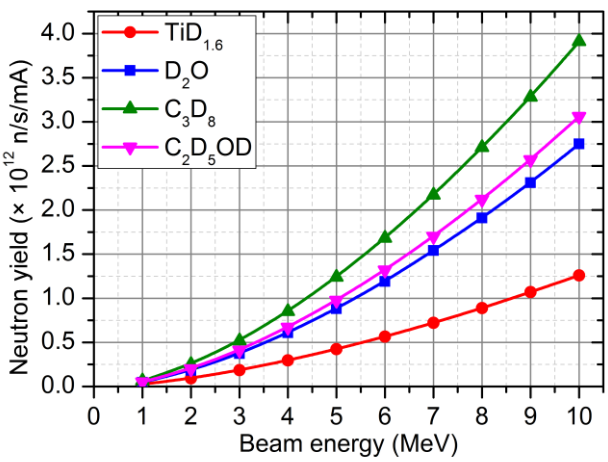

FIG. 4. Neutron yield of various deuterated targets.

The calculated neutron yields of four deuterated targets are presented in Fig. 4. Although the deuterium concentrations of the solid targets are higher than the liquid targets, the neutron yields of the liquid targets are higher. Because the energy loss rate of the deuteron beam is different for each target. The energy loss rate determines the beam range which is a practical target thickness and is maximum penetration depth in Fig. 5. Therefore, the liquid propane target with about a fourth of the beam current and power, can achieve the same neutron yield of the titanium target.

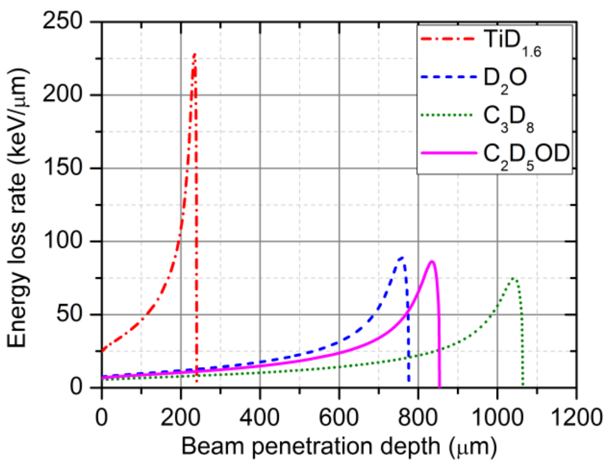

FIG. 5. Energy loss rate of deuterated targets when the incident beam energy is 10 MeV.

The hydrocarbon target is favorable for the intensive neutron generator. In addition, the hydrocarbon target can be operated with self-cooling and healing effects when it is liquefied at low temperature. However, since the neutron emission target is emerged in vacuum condition, a vacuum compatibility of the liquid target should be examined. Thus, this work conducted a proof-of-principle experiment.

2.2.2. Proof-of-principle experiment of hydrocarbon liquid target

The pressure inside the neutron generator should be maintained lower than 10^{-1} - 10^{-3} Pa for stable operation [3]. Thus, a vacuum compatibility is a key parameter for the liquid target. The liquid phase cannot exist at vacuum pressure lower than the pressure of the triple point. Thus, triple point pressure must be lower than 10^{-3} Pa.

According to the neutron yield and triple point pressure in Table I, the propane is most plausible candidates of the liquid target in this work. However, the ethanol was utilized in the experiment because the propane is highly flammable material.

The liquid target system is presented in Fig. 6(a). The system consists of a vacuum chamber, a liquid target injector and a cold trap. The cryogenically cooled liquid ethanol is injected into the vacuum via stainless steel tube. The liquid target is exposed to the vacuum and recovered as the solid phase by the cold trap. Figure 6(b) is the picture of the liquid target fabricated at Seoul national university. The vacuum pressure was 6.7×10^{-2} Pa during the liquid target injected [4].

Thus, the concept of the liquid target is experimentally confirmed in this study. The liquid target is expected to be applied to the neutron generator with improvement of cooling, recovery, injector design and vacuum system in an engineering design phase.

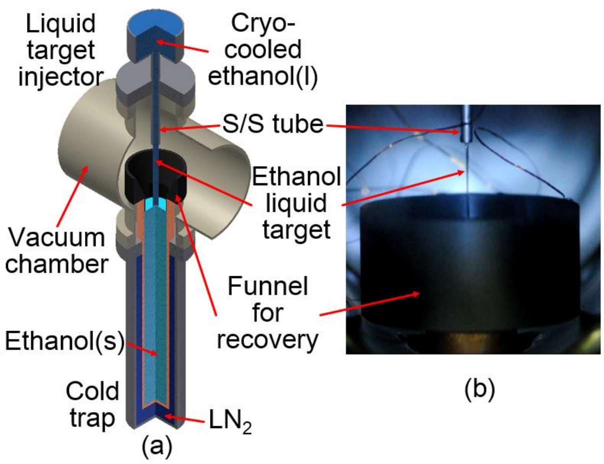

FIG. 6. (a) Schematic view of liquid target system. (b) Picture of liquid ethanol target fabricated in vacuum.

3. Conclusions

This study suggests new concept of the D-D neutron generator which can achieve the high neutron yield and energy without tritium. The highly accelerated beam up to 10 MeV will enhance not only the total neutron yield but also the forward yield and the neutron energy. Also, the hydrocarbon liquid target is expected to reduce the required beam current by its low energy loss rate, and treat the high energy beam by the self-cooling and healing function.

This study is useful to develop the intensive neutron generator which is applicable for the fusion material irradiation test as well as the neutron activation analysis, neutron radiography, medical application and so on.

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