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Preliminary study of a cold neutron source using electron linac for Bragg edge imaging

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1. Introduction

Neutron imaging is a powerful and non-destructive tool for testing materials in industrial and research applications. Compact accelerator neutron sources (CANS) are gaining interest in neutron application techniques such as Bragg edge transmission imaging. Because of their low cost and accessibilities for the users, CANS are growing worldwide [1–3]. There is a pressing need for developing a neutron source in Korea for studying the structural materials. In order to develop such technologies, various technological factors need to be taken into account. The neutron production and maximization of the neutron generation, extraction and delivering to the sample position is a fundamental factor for designing a high-flux neutron source. In this work, a preliminary target design calculations are presented.

2. Methods and Results

2.1 Monte Carlo calculations

The calculations were performed using the PHITS-3.1 code [4]. The JENDL-4.0 [5] nuclear data library was used and thermal scattering low was applied to polyethylene and solid methane (CH_4). A simple geometry consisting of a cylindrical target and electron beam was simulated to determine the optimum electron energy, target material and dimensions. However, for determining the optimum moderator and reflector design with sufficiently high statistics with lower CPU time, the calculations were performed in two steps. In the first step, the electron beam with the diameter of 5 mm and energy of 40 MeV was irradiated on the neutron production target and the photoneutrons were scored with their position, direction and energies using DUMP option in the PHITS code. In the second step, the scored neutrons were used as the primary particles. The neutron flux was estimated one meter far from the target.

The suitable neutron energy range for Bragg edge imaging is around 5 meV. The calculations were performed to achieve a high cold neutron flux with energies below 6 meV and short neutron emission time (neutron pulse).

2.2 Neutron production target

Heavy materials are very suitable for photoneutron production as their neutron production cross sections are quite high. In this study, the total generated neutron yields from W, Ta and Pb are investigated. The calculated neutron yields from each material obtained using the PHITS code are shown in Fig. 1(a) for the thickness of 10 radiation length (X_0) as a function of electron energy. It is seen that W generates the highest number of neutrons and Pb produces the smallest number of neutrons. Therefore, W was selected as a candidate for the neutron production material.

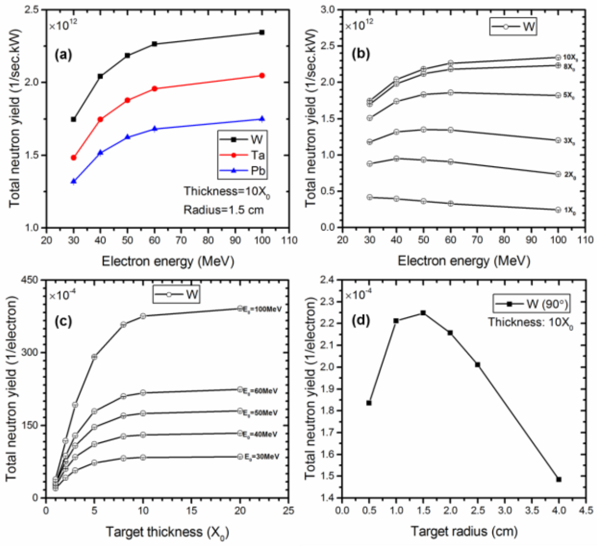

Fig. 1. (a) Total number of neutrons emerging from the targets, (b) variation of neutron yields with electron energy for 1, 2, 3, 5, 8, 10 X_0, (c) neutron yields against W thickness for 30, 40, 50, 60, 100-MeV electrons, and (d) neutron yields against W radius at 90° and E_e = 40 MeV.

The total neutron yields were also estimated as a function of electron energy for different thicknesses of W as shown in Fig. 1(b). The neutron yields increase slightly after around 40 MeV for the thick values of 8 and 10 X_0, thus, the electron energy was selected as 40 MeV. The calculations were also performed in order to determine the optimum target thickness and radius and the results are indicated in Figs. 1(c, d). At different electron energies, the neutron production yields reached a maximum at the thickness of approximately 10 X_0 and after that it remains constant. The results also show that the neutron yields are maximum for the target radius of 1.5 cm. Hence, the target thickness and radius were selected to be 10 X_0 and 1.5 cm, respectively.

2.3 Moderator and reflector

Graphite (1.7 g/cm^3) was selected as the reflector material because it is composed of light atoms, and it has low neutron absorption, and is easy to handle. The size of the reflector is 60 × 60 × 60 cm^3 so that it can provide the neutron with saturated intensity [2]. The target geometry is shown in Fig. 2. The neutron extraction beam line was selected at 90° with respect to the electron beam because the generated photons are much lower than the forward direction. Polyethylene (PE) is one of the most widely used materials as a neutron moderator at ambient temperature. However, to achieve high cold neutron flux, solid CH_4 is used as the main moderator [1,2]. Therefore, the PE (0.94 g/cm^3) and solid CH_4 (0.493 g/cm^3 at 20 K) with different thicknesses were used in the simulation and the neutron flux was estimated and compared.

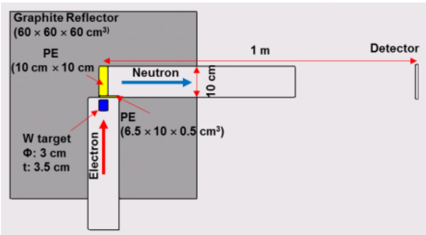

Fig. 2. The target geometry simulated in the PHITS code.

The neutron spectrum, that was scored using the DUMP option, is shown in Fig. 3(a) and it was used as the source for the second step. The number of cold neutrons after moderators at 1 m from the target is listed in Table 1.

Table 1. Comparison of the neutron yields by using PE and solid CH_4 as the moderators at 1 m from the target (E_n < 6 meV).

Moderator size (cm)	Cold neutron flux (n/cm^2/electron)	
	PE	Solid CH_4
10×10×2	8.82×10^{-10}	3.93×10^{-9}
10×10×3	9.11×10^{-10}	4.78×10^{-9}
10×10×4	8.86×10^{-10}	5.23×10^{-9}
10×10×5	9.68×10^{-10}	5.45×10^{-9}

3 cm-thick PE shows a large cold neutron flux. Solid CH_4 indicates quite higher cold neutron flux so that for 3 cm-thick solid CH_4 the number of cold neutrons is higher than that of PE by a factor of 5.2. The neutron spectra after using PE and solid CH_4 at 1 m from the target are shown in Fig. 3(b). Solid CH_4 shifts the spectrum down to more cold neutrons. Another factor that affects the neutron imaging is the emission time or pulse shape for neutrons coming out at the moderator surface. For PE and solid CH_4 the cold neutron emission time distributions (at 5 meV) are shown in Figs. 3(c, d). The neutron intensity increases as the thickness of the moderator increases, the emission time also increases, resulting in lower resolution imaging. It seems that 3 and 4 cm of PE and solid CH_4, respectively, are suitable thicknesses of moderator for this target geometry.

3. Conclusions

A preliminary design of a cold neutron source using an electron linac is presented. W produced higher neutron yields than Ta and Pb. The optimum

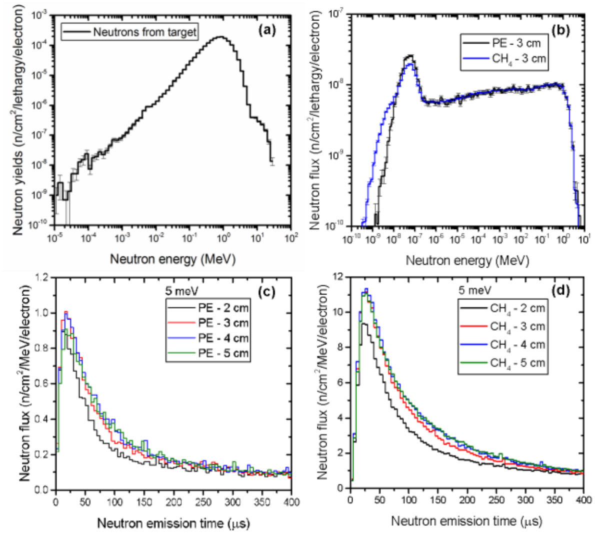

Fig. 3. (a) Neutron spectrum generated in the target, (b) neutron spectra after PE and solid CH_4 moderators at 1 m from the target, (c) neutron time emission for PE, and (d) for solid CH_4.

electron energy was 40 MeV. The W dimensions that generated highest neutron yields were 3 cm in diameter and 3.5 cm thick. These data are not fixed and might change by considering the heat effects on the target. For PE, the thickness of 3 cm generated the high cold neutron flux with reasonable neutron emission time. Solid CH_4 showed a good capability in cold neutron production. The 4 cm-thick solid CH_4 showed high neutron flux and acceptable neutron emission time compared to the other thicknesses. Although, using solid CH_4 is quite difficult as it must be kept at low temperatures of around 20 K. Different material shapes and combinations need to be considered to optimize target-moderator-reflector design to achieve a high cold neutron flux as well as narrow neutron pulse shapes.

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