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# Accelerator-Based Epithermal Neutron Beam Design and Characteristic Analysis for Born Neutron Capture Therapy

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## ABSTRACT

An epithermal neutron beam design study using $^7$Li(p,n)$^7$Be reaction as an accelerator- driven neutron source has been carried out for boron neutron capture therapy (BNCT). To find an useful moderator material for the generation of epithermal neutron, moderation capabilities of $H_2O$, $D_2O$, $^7$LiF, and Al (40%)/$AlF_3$ (60%) were investigated, and several moderator assembly structures consisted of these materials were modeled and evaluated by using MCNP code. The neutron beam characteristics were compared with other reported assemblies. The assembly constructed with two materials, $^7$LiF and Al/$AlF_3$, was found to be a good material structure for epithermal (4 eV ~ 40 keV) neutron beam. The neutron beam produced from this design is more useful for BNCT than from others reported.

## 1. INTRODUCTION

The possibility for use of accelerator-based neutron sources for boron neutron capture therapy (BNCT) has been studied in many countries, since it offers lots of advantage as an alternative to nuclear reactors. Of many possible reactions, the $^7$Li(p,n)$^7$Be reaction has been generally considered due to high neutron yield at low proton energies.

In the 1980s, Ohio State University (OSU) had studied for a moderator assembly composed of BeO cylinder reflected by $Al_2O_3$ using 2.5 MeV protons [1]. Massachusetts Institute of Technology (MIT) had investigated a moderator/reflector for proton energy of 2.5 MeV by using $D_2O$/Pb [2]. Recently, a possibility to use the $^7$Li(p,n)$^7$Be reaction near the threshold proton energy, between 1.93 and 1.99 MeV has been investigated, because of their relatively low projected accelerator cost and the portability of the neutron source/target assembly [3]. Here, $H_2O$ and $Al_2O_3$, were used for the moderator and reflector, respectively. Epithermal neutron beam shaped by three moderators, Al/$AlF_3$, $^7$LiF, and $D_2O$, for proton energies between 2.1 and 2.6 MeV had been analyzed at Lawrence Berkeley National Laboratory (LBNL) [4]. It had been found that the use of Al/$AlF_3$ or $^7$LiF as moderator material could produce superior depth–dose distribution. In these studies, great importance was given to maximizing an epithermal neutron flux and minimizing the treatment time, leading to the choice of materials described above as the moderator.

In this work, a moderator assembly design using two materials is investigated. Attention is paid to maximizing the fraction of the epithermal neutrons between 4 eV to 40 keV from the $^7$Li(p,n)$^7$Be neutron source, and minimizing the fraction of the thermal and fast neutrons. Particularly, it is explored to evaluate the neutron beam spectrum in energy and direction.

## 2. NEUTRON SOURCE SPECTRUM ANALYSIS

The reaction $^7$Li(p,n)$^7$Be displays a large resonance in the forward direction around 2.3 MeV which extends to about 2.5 MeV [4]. It has been generally accepted that to get the highest neutron yield for BNCT one should use a proton bean energy of 2.5 MeV. However, this is a careful tradeoff between neutron yield and neutron spectrum from the target.

In this work, the neutron source spectrum produced from the $^7$Li(p,n)$^7$Be reaction was calculated for 2.0 ~ 2.5 MeV proton energy using a program [5] coded with the $^7$Li(p,n)$^7$Be reaction data [4]. The program was written to calculate neutron double differential (angle and energy) distributions from the target as a function of incident proton beam energy. The neutron energy spectra for various angle bins for various incident proton energies are shown in Figure 1.

## 3. NEUTRON BEAM DESIGN

### 3.1 Preliminary Design

Of various materials tried for the choice of possible moderator, $H_2O$, $D_2O$, $^7$LiF, Al/$AlF_3$, and BeO have the preference.

$H_2O$ has a large scattering cross section and $\xi$ (the average increase in the neutron lethargy per a collision) for epithermal neutron [1]. Proton of 2.5 MeV injected on $^7$Li target produces neutrons of maximum 785 keV and average 326 keV, thus effective neutron moderation can be expected with small thickness of $H_2O$. There is, however, also a possibility to be too much neutron moderation, which results in poorly shaped neutron spectrum. In addition, $H_2O$ has a larger macroscopic radiative capture cross section ($2.22\times10^{-2}$ cm$^{-1}$) for thermal neutron than the $D_2O$ ($3.00\times10^{-5}$cm$^{-1}$) and BeO ($7.24\times10^{-4}$ cm$^{-1}$), and it can generate a lot of gammas of 2.2 MeV energy. Therefore, it is necessary to shield gamma particle additively. $D_2O$ has smaller $\xi$ (~0.51) for epithermal neutron and can produce neutron spectrum with better shape than that by $H_2O$. The heavier material, $^7$LiF, does not shift the neutron spectrum down as fast as $H_2O$ but let still very effectively neutron slow down in a short distance. Particularly, $^7$LiF has an interesting property of decreasing the neutron energy in a somewhat more controllable way than $D_2O$ of restricting the number of neutrons of energies above 27 keV due to the elastic scattering resonance. Al/$AlF_3$ is also interesting one in the sense that the elastic scattering resonance of Al supplements the ones of F from 27 keV up to high-energy tail. This resonance structure at high energies will preferentially reduce the number of neutrons above 27 keV. BeO has a large neutron scattering cross section and a small capture cross section. It has therefore benefit as a moderator, however it is highly toxic to handle.

Thus, $H_2O$, $D_2O$, $^7$LiF, and Al/$AlF_3$ of them were considered as useful materials and their moderation effects on the 2.5 MeV proton induced neutron source were explored for 30 cm diameter cylinder structure using MCNP code.

As a results, the more increase in the thickness of $H_2O$, the more neutron moderation. Thermal neutron flux exceeds epithermal neutron flux at thickness of 5 cm. $D_2O$ showed significant moderation effect compared with $H_2O$, but the more thickness is required. As fast neutron fraction is decreased, it is shown that the epithermal fraction is also decreased and the thermal neutron fraction is increased a little bit. $^7$LiF makes fast neutrons moderate more effectively, but produce thermal neutrons significantly. Al/$AlF_3$ composition leaves fast neutron of a large value relatively due to small $\xi$. Therefore it can be expected that a moderator structure consisted of more than two materials for compensating properly these under- or over-moderating characteristics of each material would be useful.

## 3.2 Neutron Beam Assembly Design

Three neutron beam assembly models based on previous investigation were introduced. $H_2O$, $D_2O$, and $^7$LiF that have large values of $\xi$ are used to reduce neutron average energy with small thickness structure, and then Al/$AlF_3$ is employed to reduce the rest fast neutrons. The first model is composed of $H_2O$ (1 cm) and Al/$AlF_3$ (25cm) as a moderator and Pb as a reflector. $^6$Li is used in all interface surfaces to eliminate thermal neutrons. The second and third models are composed of $D_2O$ (2 cm) and $^7$LiF (10 cm) as a moderator instead of $H_2O$, respectively.

All three models showed effectively shaped epithermal neutron beam. However, $H_2O$+Al/$AlF_3$ model yielded a large thermal neutron fraction at even small thickness due to large $\xi$ of $H_2O$. Fast neutron fluence in the same epithermal neutron fluence ($2\times10^{-2}$ n/cm$^2$-n) condition was compared with each other. $^7$LiF+Al/$AlF_3$ yielded $4\times10^{-6}$ n/cm$^2$-n and $H_2O$+Al/$AlF_3$ and $D_2O$+Al/$AlF_3$ yielded about $2\times10^{-5}$ n/cm$^2$-n. $^7$LiF+Al/$AlF_3$ assembly configuration is expected to give smaller fast neutrons yield.

At the same epithermal fluence fraction, $^7$LiF+Al/$AlF_3$ model showed 96% epithermal fraction, while other models around 90% fraction. Therefore, it is noted that the $^7$LiF+Al/$AlF_3$ model is superior to other models for effective epithermal beam, though moderator assembly size becomes larger than other models. All the three moderator assembly models have a maximum yield fraction at around the 10 keV. $^7$LiF+Al/$AlF_3$ have broader distribution compared with other two models, while $H_2O$+Al/$AlF_3$ has a narrow beam distribution shifted to thermal energy range. It is considered that $^7$LiF+Al/$AlF_3$ have an advantage for deep-sited tumor within brain.

Forward directed property ($J/\phi$) of neutron beam for each model has been compared. Here, $J$ denotes current per one neutron, and $\phi$ denotes flux. There is no distinct difference between the models, but forward directed property of epithermal neutron for $^7$LiF+Al/$AlF_3$ has a little lower value than other models. Thus $^7$LiF+Al/AlF3 model is useful for epithermal neutron beam.

Several trials have been done to optimize the moderator assembly for effective epithermal neutron beam. Final design composed of $^7$LiF (15 cm) and Al/$AlF_3$ (25 cm) with use of $^6$Li as a thermal neutron filter was described in Figure.2.

The beam design introduced in this work was analyzed and compared with the designs by other groups reported. To estimate beam properties at the same condition, the designs by other groups were recalculated using MCNP. It was reported that the energies between 4 eV ~ 40 keV are most suitable epithermal neutron energy range for BNCT [5]. Therefore, whole energy range was divided into three regions, thermal (0 eV ~ 4 eV), epithermal (4 eV ~ 40 keV), and fast (40 keV ~) neutron energy, and then fluence, fraction of fluence, spectrum and forward directed property were evaluated

The results of MIT beam design show high thermal and fast neutron fluences on the exit window of moderator and are displayed in Figure 3. LBNL design shows good results as shown in Figure 4 and it is similar to the results of this work shown in Figure 6. However when thermal/epithermal/fast neutron fluence fractions (0.019/0.961/0.020) are compared with those of this work (0.015/0.968/0.017), thermal and fast neutron fluence fractions in this work are lower than those values of LBNL. The design of the OSU group is not appropriate to use for deep-sited tumor because of too much thermal neutron fluence. The results analyses are displayed in Figure 5.

The energy spectra of neutron beams were analyzed in Figure 7 and can be characterized by three types of distribution. First type is the OSU model that involves a broad range of thermal neutrons, so it is considered to appropriate for shallow sited tumor. Second type is MIT model, which has a broadened distribution. Third type is the LBNL and present work models. They have a similar distribution, however, LBNL model shows harder distribution than this work. Thus it can be considered that the design of this work is better than other beam designs. For forward directed property, significant difference was not found as shown in Table 1.

## 4. CONCLUSIONS

Moderation capability for several recommended materials has been analyzed and evaluated by comparing with other reported assembly designs. A new assembly structure using $^7$LiF and Al/AlF$_3$ showed a good neutron beam quality for BNCT and yielded better results than from others reported. However, approach to optimize epithermal neutron beam with human phantom model added is required as a further study.

## ACKNOWLEGEMENT

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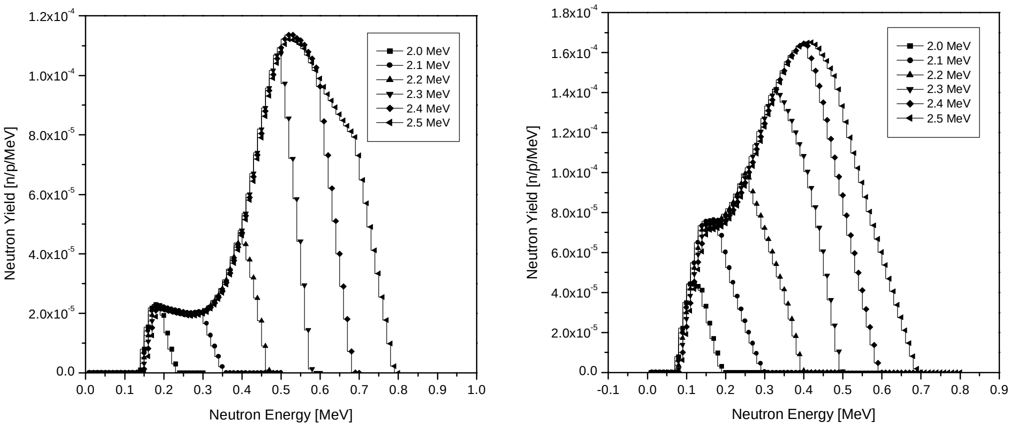
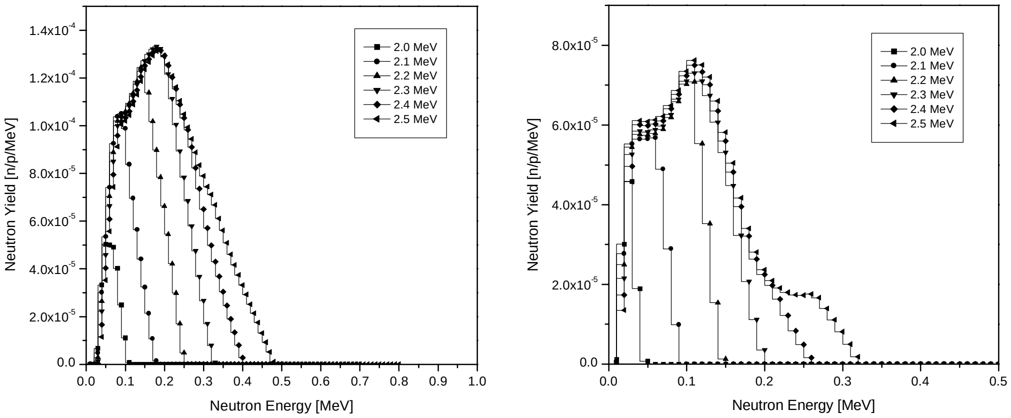


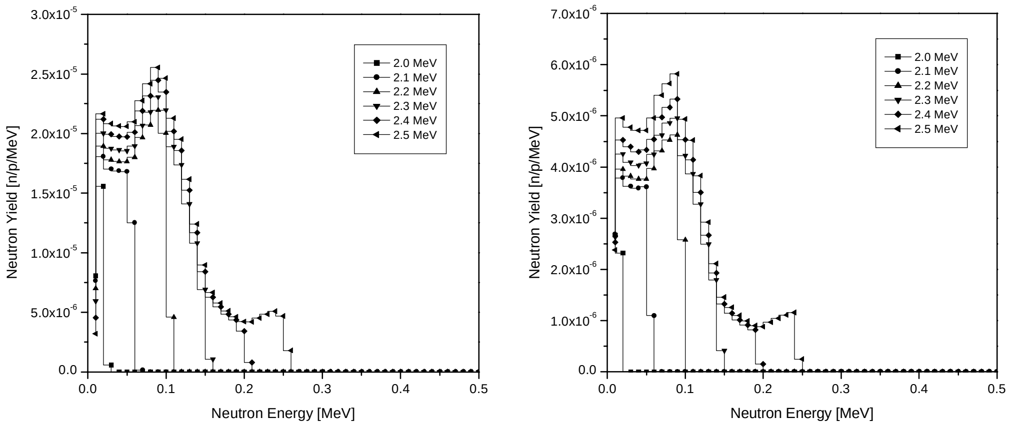
(a) 0° ~ 30° (LAB)

(b) 30° ~ 60° (LAB)



(c) 60° ~ 90° (LAB)

(d) 90° ~ 120° (LAB)



(e) 120° ~ 150° (LAB)

(f) 150° ~ 180° (LAB)

Figure 1. Neutron Yields as a Function of Neutron Energy for Different Angle Bins and Various Incident Proton Energy for the $^{7}$Li(p,n)$^{7}$Be

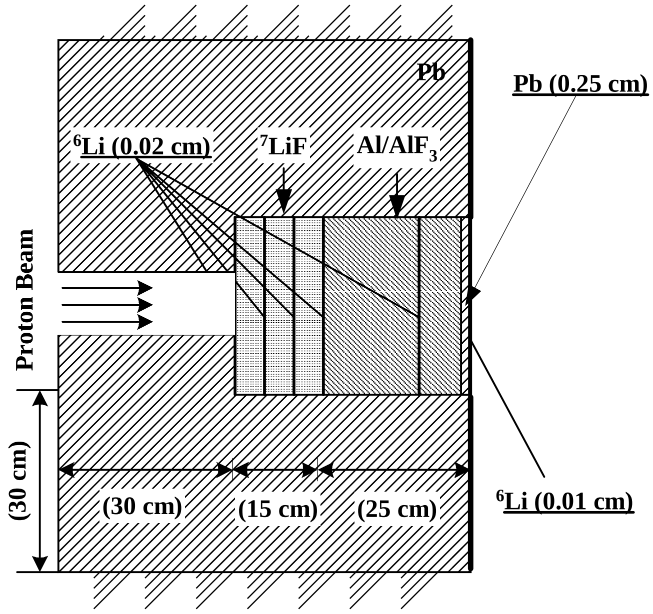
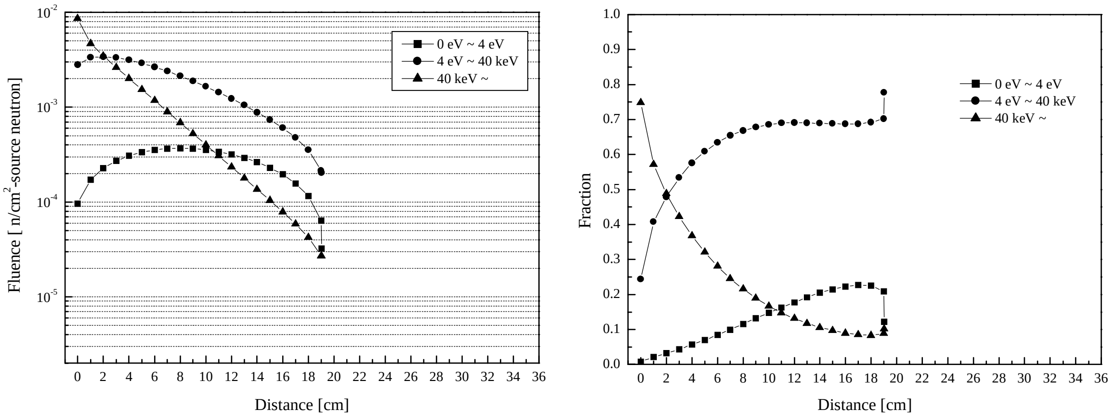


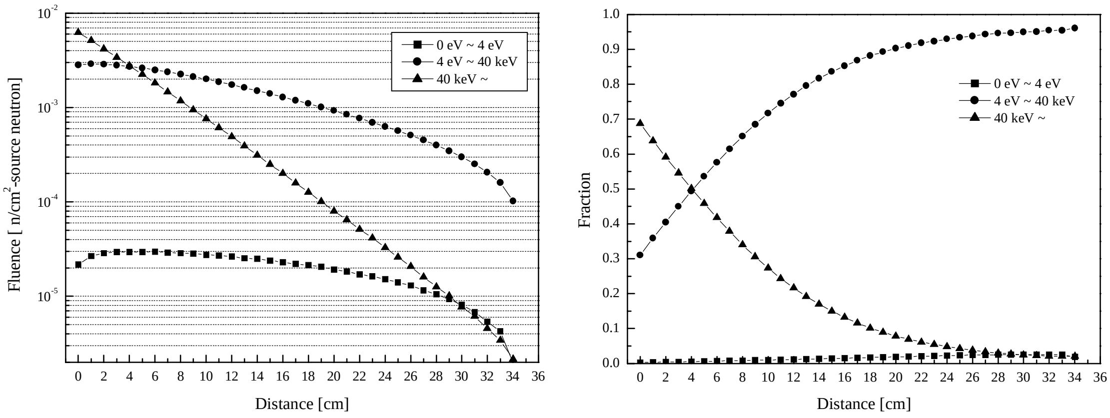
Figure 2. New Moderator Assembly Design



(a) Neutron Energy Fluence Distribution

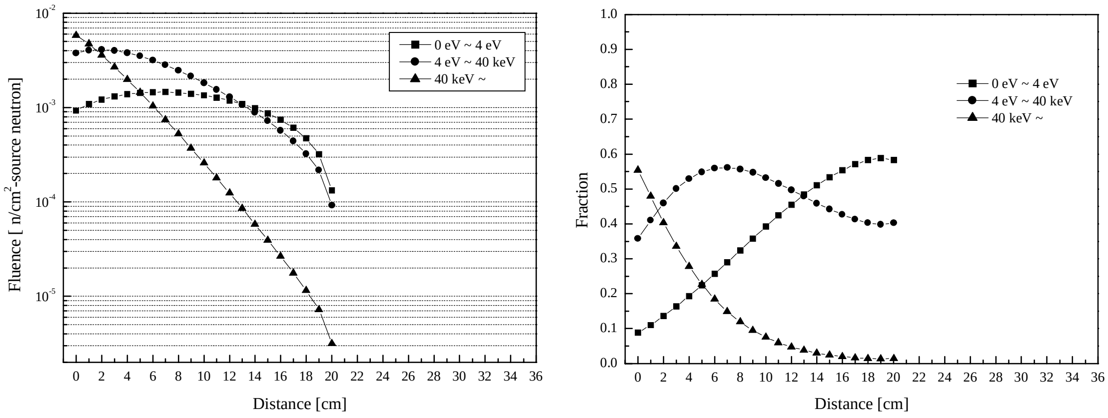
(b) Neutron Energy Fraction Distribution

Figure 3. Neutron Characteristic Analyses for MIT Design



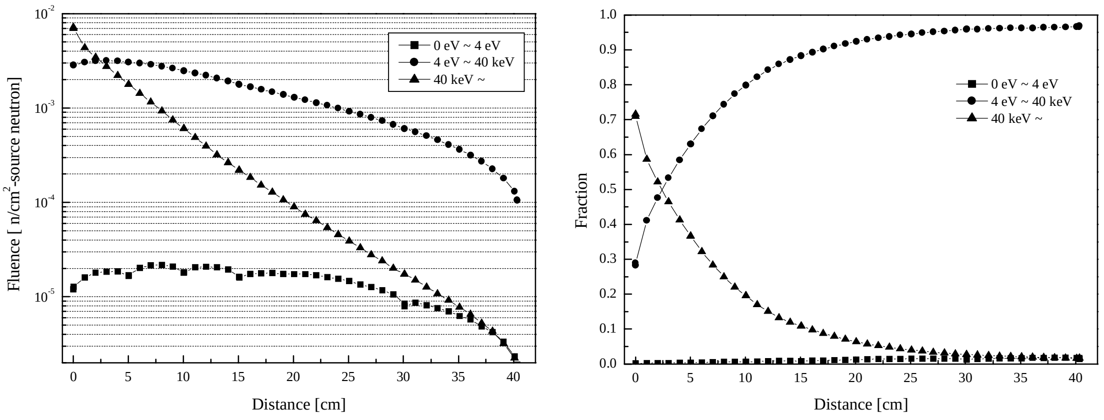
(a) Neutron Energy Fluence Distribution (b) Neutron Energy Fraction Distribution

Figure 4. Neutron Characteristic Analyses for LANL Design



(a) Neutron Energy Fluence Distribution (b) Neutron Energy Fraction Distribution

Figure 5. Neutron Characteristic Analyses for OSU Design



(a) Neutron Energy Fluence Distribution (b) Neutron Energy Fraction Distribution

Figure 6. Neutron Characteristic Analyses for This Work Design

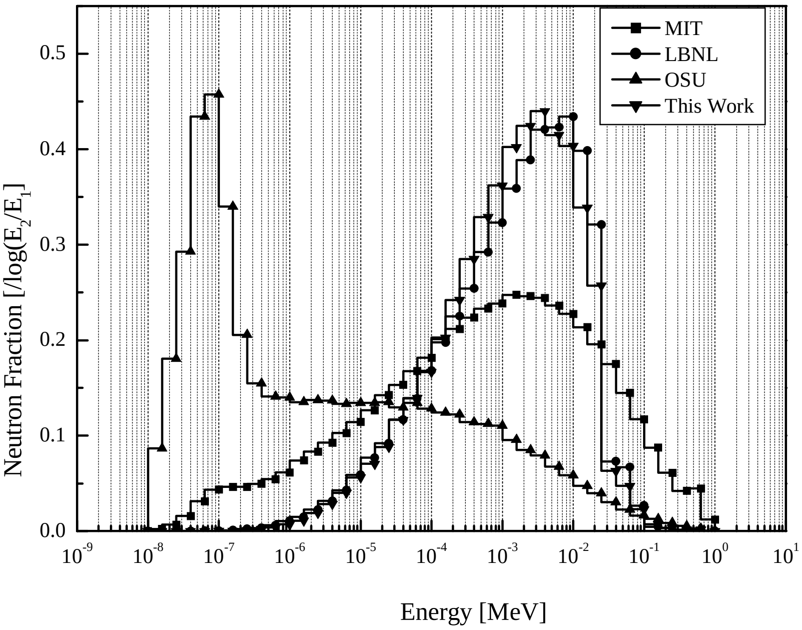


Figure 7. Energy Spectra of Neutron Beams

Table 1. Forward Directed Property of Neutron Beam ($J/\phi$)

| | MIT | LBNL | OSU | This Work |
|---|---|---|---|---|
| 0 eV ~ 4 eV | 0.6757 | 0.6376 | 0.5715 | 0.6193 |
| 4 eV ~ 40 keV | 0.6057 | 0.6010 | 0.5782 | 0.5913 |
| 40 keV ~ | 0.6568 | 0.6489 | 0.6111 | 0.5881 |
| Total | 0.6195 | 0.6029 | 0.5748 | 0.5917 |