The improvement of the energy resolution in epi-thermal neutron region of Bonner sphere using boric acid water solution moderator

H. Ueda[a], H.Tanaka[b], Y.Sakurai[b,*]

[a] *Graduate School of Engineering, Kyoto University, Kyoto daigaku-Katsura, Nishikyo-ku, Kyoto 615-8530, Japan*
[b] *Research Reactor Institute, Kyoto University, Asashiro-nishi 2-1010, Kumatori-cho, Sennan-gun, Osaka 590-0494, Japan*

Abstract

Bonner sphere is useful to evaluate the neutron spectrum in detail. We are improving the energy resolution in epi-thermal neutron region of Bonner sphere, using boric acid water solution as a moderator. Its response function peak is narrower than that for polyethylene moderator and the improvement of the resolution is expected. The resolutions between polyethylene moderator and boric acid water solution moderator were compared by simulation calculation. Also the influence in the uncertainty of Bonner sphere configuration to spectrum estimation was simulated.

Keywords: boron neutron capture therapy, Bonner sphere, thermal neutron absorber, activation detector, neutron spectrometry, spectrum unfolding

1. Introduction

In epi-thermal neutron irradiation fields for boron neutron capture therapy (BNCT), the neutron energy spans over a wide range. Because neutron biological effectiveness on tissue greatly vary depending on its energy (Blue et al., 1993), it is necessary to evaluate the energy dependency of neutron flux. Thereby, it is important to obtain the detailed information for the neutron energy spectrum before clinical irradiation.

Activation detectors are suitable for neutron spectrometry compared to active detectors which suffer from dead time problem and gamma ray background in the BNCT irradiation field. Combined with a neutron moderator, they can be used to perform neutron spectrometry on a wide energy range including the keV region (Liu et al., 2013). So, the Bonner Sphere Spectrometer(BSS), which consists of a set of moderating spheres housing a thermal neutron deterctor at their centre, is useful to evaluate the neutron energy spectrum in BNCT irradiation field. Activation foils were used as thermal neutron detectors in this work.

Usually, neutron spectrometry based on Bonner sphere of polyethylene moderator has poor energy resolution in the keV region because of its broad response peaks (Alevra and Thomas, 2003). The energy resolution is improved using moderators including thermal neutron absorbers which make the Bonner sphere response peaks narrower (Aroua et al., 1997).

We are improving the energy resolution of Bonner sphere in epi-thermal region, using boric acid water solution (^{10}B 0.14wt%) as a moderator. Its response function peak is narrower than that for polyethylene moderator and the improvement of the resolution is expected. Boric acid water solution moderator has the advantage of its uniform chemical composition. It is easy to change the Bonner sphere response function by changing the ^{10}B concentration and validate the concentration by an analysis(e.g. PGAA) device installed in the BNCT facility.

The energy resoluton depend on a measurement device, pre-information, and an unfolding procedure. In this study, we investigated the dependency only on the moderator. The energy resolution between polyethylene moderator and boric acid water solution moderator were compared by simulation calculation. Also the influence of the detector displacement from the sphere center and the uncertainty of boric acid concentration to the spectrum estimation was investigated.

2. Materials and Methods

Bonner sphere. In this study, Bonner sphere consists of a spherical neutron moderator shell and activation foils placed in the sphere center as thermal neutron detector. Manganin (^{55}Mn) and gold (^{197}Au) are used as activation foil material. The specific saturated activities per neutron flux for each energy group were calculated as the response function of Bonner spheres. Calculations were performed for the sphere diameter of 10, 15, 20 cm, with the MCNP5 radiation transport code (X-5 Monte Carlo Team, 2003).

Comparison of energy resolution. For the comparison of energy resolution between polyethylene moderator and boric acid water solution moderator of ^{10}B 0.14wt%, unfolding tests were performed using step-wise neutron spec-

*Corresponding author. Tel.:+81 72 451 2306; Fax: +81 72 451 2658

Email address: `yosakura@rri.kyoto-u.ac.jp` (Y.Sakurai)

trum in epi-thermal neutron energy region. In the tests, the response functions were calculated for aligned and expanded beams in vacuo. The foil activities were calculated using the calculated response functions and the step-wise neutron spectrum. The normally distributed errors, whose deviation is 3%, were added to the calculated activities, which were unfolded into the estimated spectrum using uniform spectrum as the initial by UMG unfolding package (Marcel Reginatto, 2004). We used the uniform spectrum to eliminate the energy resolution dependency on pre-information, considering the case we have no pre-information about the spectrum. We terminated the unfolding procedure iterations when the two different unfolding procedure results began to show some difference. Their results were same and didn't depend on the unfolding procedures. Thus we evaluated only the dependency on the BSSs. The energy resolution comparison was made judging from the peak shapes of the estimated spectrum. The used neutron energy group structure comprised 91 groups in the energy range from 10meV to 10MeV for the same lethargy width of 0.23.

Influence of the uncertaingy of the Bonner sphere configuration to the spectrum estimation. The ^{10}B concentration of 0.14wt% corresponds to the boric acid solubility in water at 20 °C (IUCLID Dataset, 2000). In a prolonged storage of the boric acid water solution, boric acid may precipitate due to evaporation and falling temperature. In addition, it is difficult to place the activation detector exactly in the sphere center, and the displacement of the detector from the sphere center generates measurement error. The uncertainty of the Bonner sphere configuration significantly influences the spectrum estimation accuracy. The influence of the uncertainty for the moderator concentration and the detector placement to the spectrum estimation, was investigated.

In this study, the spectrum estimation was performed for the epi-thermal neutron irradiation mode in the Heavy Water Neutron Irradiation Facility of Kyoto University Reactor (KUR-HWNIF) (Sakurai and Kobayashi, 2000). Water and boric acid water solution (^{10}B 0.14wt%) were used as the moderator material. Each Bonner sphere response function was calculated by MCNP5. Also, the saturated activities were calculated varying the detector placement or the ^{10}B concentration. The calculated activities were unfolded into the estimated spectrum by UMG together with the calculated response functions which have no deviation. The used neutron energy group structure comprised 144 groups in the energy range from 1meV to 16.1MeV.

3. Results

Comparison of energy resolution. Figs. 1 and 2 show the calculated response functions of Bonner spheres using gold activation detector with polyethylene moderator and boric acid water solution moderator, respectively. D10, D15 and D20 represent 10, 15 and 20 cm diameter of the Bonner sphere, respectively. The statistical uncertainties of the simulated response functions are showed with error bars. As expected, the response functions of the BSS loaded with boric acid show a narrower trend in the epi-thermal region. The same trend was observed for the manganin activation foils. From the results, it is expected that the improvement of the energy resolution in the epi-thermal region can be achieved.

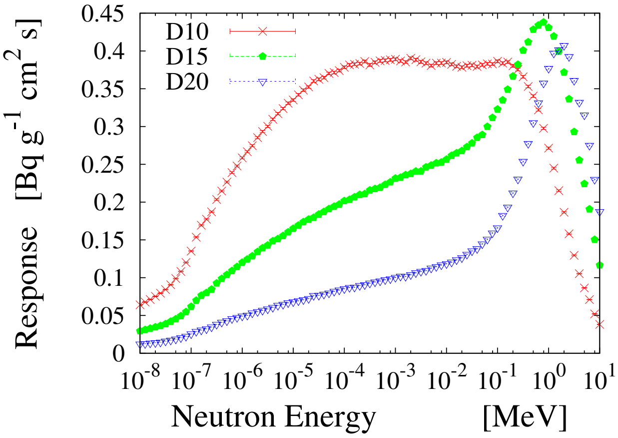

Figure 1: Response functions of Bonner spheres using gold activation detector with polyethylene moderator

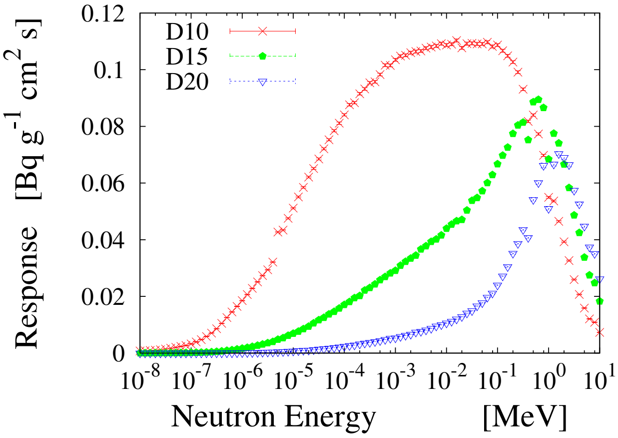

Figure 2: Response functions of Bonner spheres using gold activation detector with boric acid water solution moderator

Figs. 3 and 4 show the examples of the unfolding results for the step-wise spectrum of 10^{-3}MeV in the lethargy center, using polyethylene moderator and boric acid water solution moderator, respectively. The width of this step-wise spectrum was 2.3 in lethargy. GRV and MXD were unfolded results by Gravel and Maxed unfolding codes in UMG unfolding package. A uniform energy spectrum was used as pre-information in the unfolding procedures. From these figures, we can see that the unfolded spectrum using boric acid water solution moderator tends to have narrower shapes and be closer to the true spectrum than those using polyethylene moderator. This result signals that the BSS energy resolution could be improved in the epi-thermal region by using a boric acid solution.

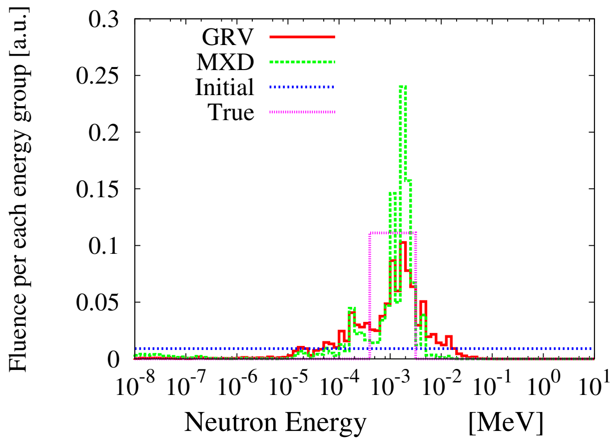

Figure 3: Unfolding results for the step-wise spectrum of 10^{-3}MeV in the lethargy center using polyethylene moderator.

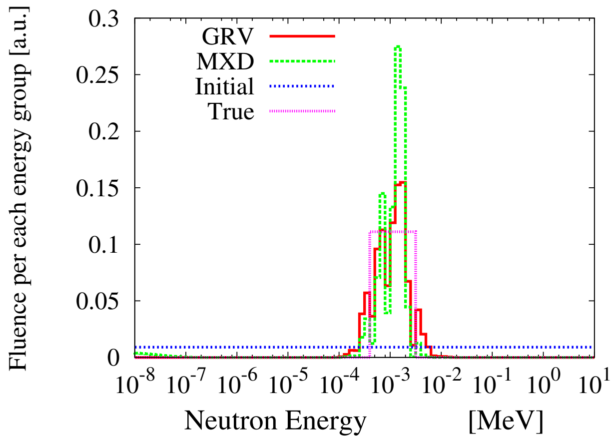

Figure 4: Unfolding results for the step-wise spectrum of 10^{-3} MeV in the lethargy center using boric acid water solution moderator.

Although the resolving power depends on the unfolding procedure, we quantified the resolving power to show the improvement numerically. We used the approach of Backus and Gilbert. See the reference paper (Reginatto, 2002). For the lethargy L_0=-4, -3, -2 and -1, the resolving power ΔLs are 1.63, 1.46, 1.50 and 1.18 respectively using boric acid water solution moderator. They are 2.01, 1.94, 1.53, 1.37 respectively using polyethylene moderator. These results also show the improvement of the energy resolution.

Influence of the uncertainty of the Bonner sphere configuration to the spectrum estimation. Figs. 5 and 6 show the calculated response functions by MCNP5 for the epi-thermal neutron irradiation field in KUR-HWNIF. The statistical uncertainties of the simulated response functions are showed with error bars.

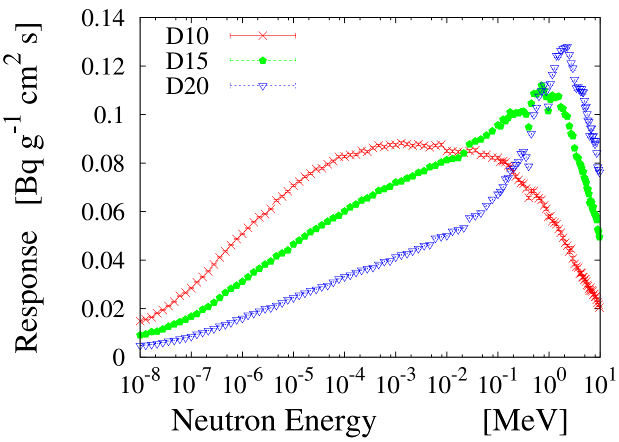

Figure 5: Calculated response functions of Bonner spheres for the epi-thermal neutron irradiation mode of the KUR-HWNIF using gold activation detector with water moderator

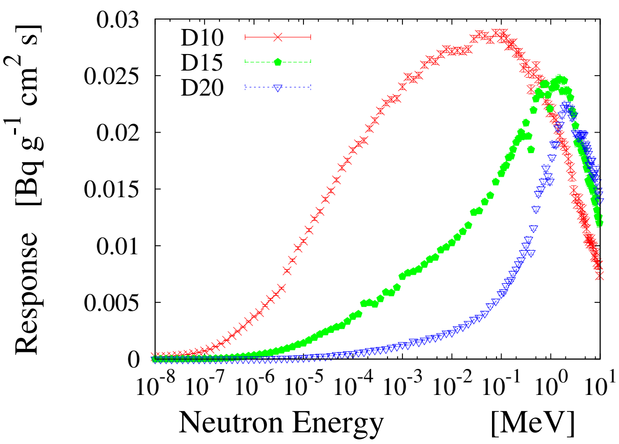

Figure 6: Calculated response functions of Bonner spheres for the epi-thermal neutron irradiation mode of the KUR-HWNIF using gold activation detector with boric acid water solution moderator.

The response of Bonner sphere varies extremely depending on the degree of neutron moderation and the boric acid concentration. In this calculation, the saturated activities change by about 11–24% if the ^{10}B concentration changes from 0.14 wt% to 0.12 wt%. If the displacement of the activation detector from the sphere center is 3mm, saturated activities change by about -18–26% for the boric acid solution water solution and about -11–14% for pure water. If these errors are not considered, the neutron spectrum may be evaluated inaccurately.

Fig. 7 shows the unfolding results using boric acid water solution moderator without the displacement of the activation detectors from the sphere center. Fig. 8 show the results in the case that the activation detector displacement of 3mm occurs only on the 10-cm diameter Bonner sphere and the error is not considered in the unfolding procedure. The true spectrum is used as the initial spectrum. Fig. 9 shows the unfolding results in the same case as Fig. 8, except the error is considered. In Fig. 8, the neutron spectrum was estimated wrongly. In Fig. 9, the neutron spectrum was estimated more adequately, but the errors of the estimated spectrum are large. For the case of using water moderator, it was confirmed that the unfolding results were in the same tendency.

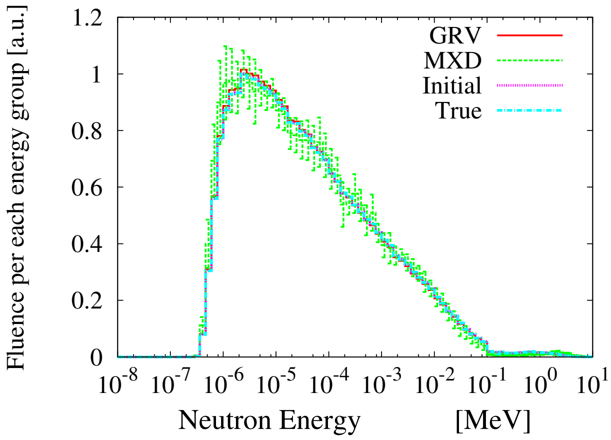

Figure 7: Unfolding results using boric acid water solution moderator for the epi-thermal neutron irradiation mode of the KUR-HWNIF in the case of without the displacement of the activation detectors from the sphere center.

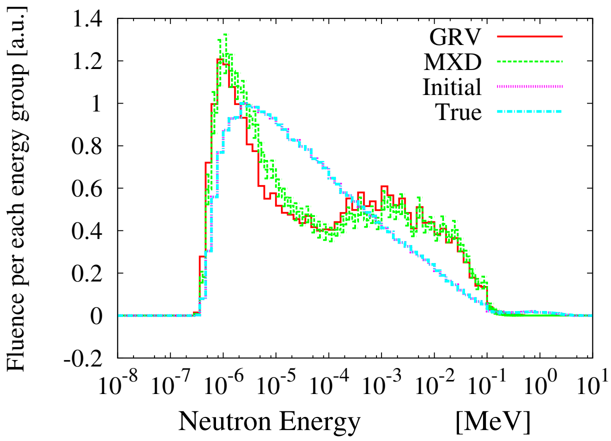

Figure 8: Unfolding results in the case that the activation detector displacement of 3mm occurs only on the 10-cm diameter Bonner sphere and the error is not considered in the unfolding procedure.

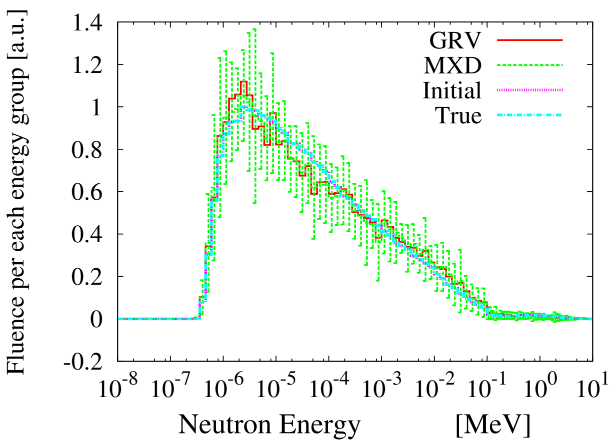

Figure 9: Unfolding results in the same case as Fig. 8 except the error is considered.

4. Conclusion

The improvement of the energy resolution of Bonner sphere using boric acid water solution moderator was confirmed. However, the reduction and evaluation of the errors due to the uncertainty of Bonner sphere configuration are necessary for the adequate neutron spectrometry. While the ^{10}B concentration is easy to validate by the ^{10}B analysis device installed in the BNCT facility, the displacement of the activation detector from the sphere center is hard to reduce in mm order. Bonner sphere needs the modification of the geometry or the method of accurate placement.

Acknowledgement

This work has been carried out in part under the Visiting Researcher's Program of the Research Reactor Institute, Kyoto University.

References

Alevra, A.V., Thomas, D.J., 2003. Neutron spectrometry in mixed fields: Multisphere spectrometers. Radiation Protection Dosimetry 107, 37–72.

Aroua, A., Grecescu, M., Prêtre, S., Valley, J.F., 1997. Improved Neutron Spectrometer Based on Bonner Spheres. Radiation Protection Dosimetry 70, 285–289.

Blue, T.E., GUPTA, N., WOOLLARD, J.E., 1993. A calculation of the energy dependence of the RBE of neutrons. Physics in medicine and biology 38, 1693–1712. doi:10.1088/0031-9155/38/12/002.

IUCLID Dataset, 2000. Boric acid, crude natural, containing not more than 85 percent of H3BO3 calculated on the dry weight. Technical Report 10043-35-3. European Commission, European Chemicals Bureau.

Liu, Y.H., Chen, W.L., Jiang, S.H., 2013. Improvement of Activation-Detector-Based Spectrum Unfolding Technique for BNCT. Nuclear Science, IEEE Transactions on 60, 783–791. doi:10.1109/TNS.2012.2235463.

Marcel Reginatto, 2004. The 'Few-Channel' Unfolding Programs in the UMG Package: MXD_FC33 and GRV_FC33 and IQU_FC33. Technical Report. Physikalisch-Technische Bundesanstalt (PTB). Braunschweig, Germany.

Reginatto, M., 2002. Resolving power of a multisphere neutron spectrometer. Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 480, 690–695. doi:10.1016/S0168-9002(01)01207-4.

Sakurai, Y., Kobayashi, T., 2000. Characteristics of the KUR Heavy Water Neutron Irradiation Facility as a neutron irradiation field with variable energy spectra. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 453, 569–596. doi:10.1016/S0168-9002(00)00465-4.

X-5 Monte Carlo Team, 2003. MCNP - A General Monte Carlo N-Particle Transport Code, Version 5. Technical Report LA-UR-03-1987. Los Alamos National Laboratory. Los Alamos, New Mexico, USA.