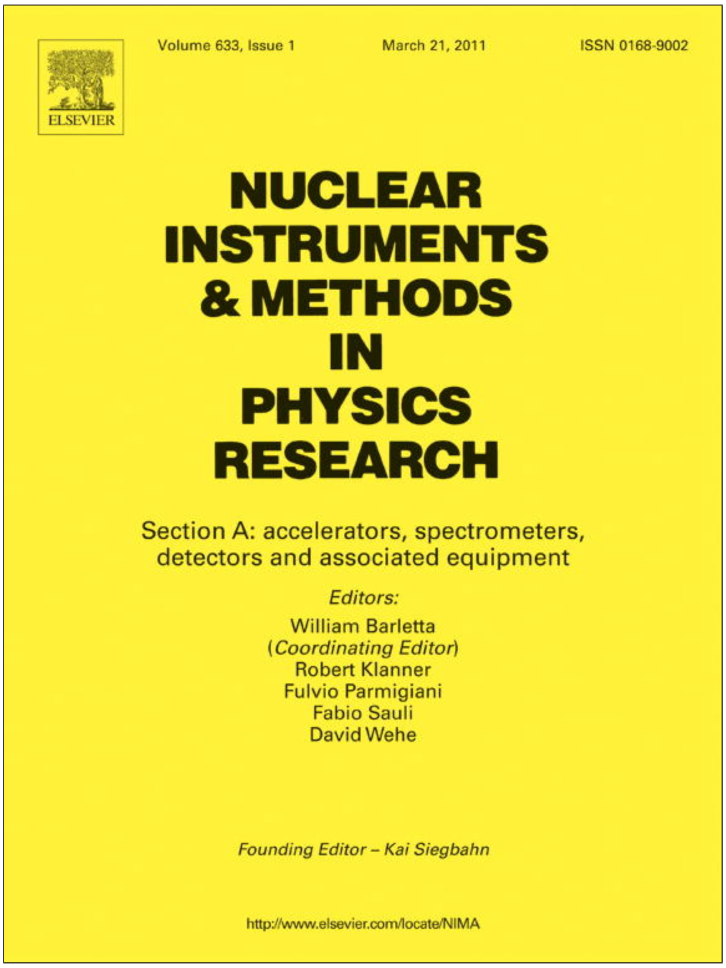
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A method of neutron energy evaluation by using an imaging plate and cone-like acryl converters with a geometrical modulation concept

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ABSTRACT

Cone-like acryl converters have been used for transforming the energy-distribution information of incident fast neutrons into the spatial-distribution information of recoil protons. The characteristics of neutron–proton conversion have been studied up to around 10 MeV by using an imaging plate (IP). A notable and interesting signal enhancement due to recoil protons generated in an acryl converter was observed on IP images for irradiation with a ^{252}Cf source. Similar experiments were also performed in the radiation field of a research nuclear reactor and an accelerator-based neutron generator. A Monte Carlo calculation was carried out in order to understand the spatial distributions of the signal enhancement by recoil protons; these distributions promisingly involve the energy information of incident neutrons in principle. Consequently, it has been revealed that the neutron energy evaluation is surely possible by analyzing the spatial distributions of signal enhancement that is caused by recoil protons.

1. Introduction

The biological effectiveness of neutrons per unit physical dose (absorbed dose [Gy]) significantly depends on the neutron energy. Therefore, the evaluation of the neutron energy spectrum is an obviously essential subject that is commonly related to many research fields such as radiobiological science and radiation protection. On the other hand, however, neutron energy measurement is generally a rather difficult and time-consuming task. The time-of-flight (TOF) technique may be the most accurate and reliable method of neutron spectrum evaluation [1]; it is often used in accelerator experiments but not very common way because sharply bunched pulse neutron beams are used for measuring the flight time of neutrons along a certain fixed path length. The Bonner sphere spectrometer (BSS) is also utilized for measuring neutron energy spectra in various situations [2]. This method is advantageous for the evaluation of wide-range neutron energy spectra from the thermal-energy region up to the mega-electronvolt region. However, rather complicated unfolding calculations are usually unavoidable to accomplish this evaluation. In addition, the dimensions of moderator parts of the detector are usually so bulky that this technique is not appropriate for characterizing the neutron energy spectra in a small field. The activation detectors are another useful tool to evaluate neutron energy by means of various materials (usually tiny metal foils) having different threshold energies of specific nuclear reactions for the neutron activation [3]. After irradiating such foils, the radioactivity induced by neutrons is measured by using any of the conventional methods, such as gamma-ray spectroscopy with germanium detectors. Further, the unfolding calculations are again essentially important in this technique for obtaining the actual energy spectra.

In addition to the methods introduced above, the most common technique of fast neutron detection is based on the elastic scattering of neutrons by light nuclei such as hydrogen. It is well known that incident fast neutrons can be converted into protons by using appropriate hydrogenous materials (so-called "converters"); generated recoil protons have energy information

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on incident neutrons. Thus far, many recoil-proton counter telescopes have been developed and utilized for determining the energy distribution of incident neutrons [4]. Such counter telescopes commonly measure the energies of each recoil proton by some means.

In this study, as an original approach, we have attempted to transform the energy-distribution information of incident neutrons into the spatial-distribution information of recoil protons with the aid of cone-like acryl converters for the purpose of developing a novel and convenient method for evaluating neutron energy spectra. An imaging plate (IP) was used for observing the spatial distributions of recoil proton events [5,6]. Hereafter, we will refer to such a system as "IP–Con^2: imaging plate with cone-like acryl converter". Some fundamental experiments have been performed using a ^{252}Cf source, a research nuclear reactor, and an accelerator-based neutron generator in order to investigate the properties of the IP–Con^2 system. The contributions of the neutron-energy variation to the spatial distributions of recoil protons have been studied by a Monte Carlo calculation while modulating the geometrical shape of the acryl converter. A tentative evaluation of the neutron energy spectra has also been attempted by using the simplified response functions.

2. Principle of neutron-energy evaluation

We used an imaging plate (IP) to record the spatial distributions of protons. Usually, the surface of the IP is covered by a "protective layer" made of a polyethylene terephthalate (PET) film; the thickness of this layer is typically around 10 μm and such a protective layer functions as a neutron converter itself. Here, suppose that an IP without the protective layer such as BAS-TR 2025 (Fuji Film Co. Ltd.) is used. The sensitivity of such a "bare" IP to fast neutrons is very low or almost negligible. By placing an acryl plate only on the phosphor layer of the IP as a converter, we observe that the sensitivity increases because of the emission of recoil protons as the IP detects such protons very efficiently. When a relatively thick acryl plate is placed, a relatively high probability of the H(n, p) reaction is achieved and the total number of recoil protons increases. Therefore, the proton-induced signals on the IP also become relatively large with an increase in the converter thickness. On the other hand, the use of a considerably thick acryl plate leads to an increase in the number of low energy protons whose residual ranges in acryl are not sufficient to reach the phosphor layer on IP when such protons are generated at deep positions from the surface of the converter used. Hence, the increase in IP signals mentioned above may saturate at a certain value and, after that, begin to decrease with a further increase in the converter thickness.

When a uniform neutron distribution is achieved in a lateral direction, if an acryl plate is replaced by a cone-like acryl converter, the spatial distributions of protons that appear on the IP should be significantly affected by the energy of the incident neutrons and may indicate a rather complicated dependence on the variation in the neutron energy as schematically shown in Fig. 1. Those spatial-distribution curves are closely related to both the macroscopic cross-sections of H(n, p) reaction, Σ_n, and the ranges of recoil protons, R_p, in acryl (see Fig. 2) [7,8]. Here, Σ_n is calculated as a product of the microscopic cross-section of H(n, p) reaction, σ, and the number density of hydrogen atom, N_H. In most practical situations, neutrons having several different energies exist in the same field. On the basis of an analogy of the conventional unfolding of the pulse-height spectrum of any radiation detectors, we can express such a position distribution of recoil protons (dN/dX) that is recorded by an IP as the convolution of its inherent response function and the energy

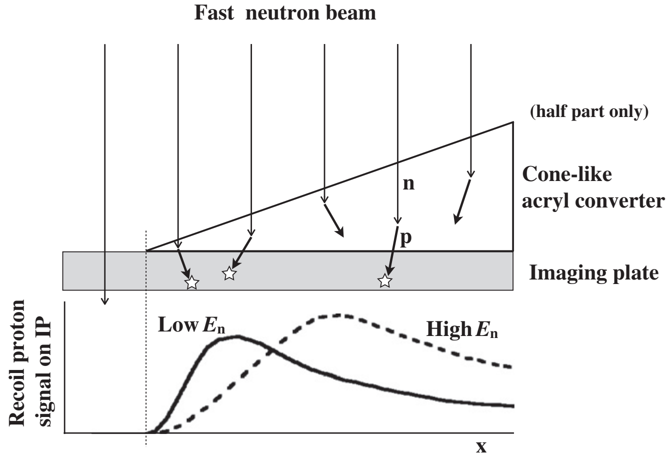

Fig. 1. Schematic representation of the evaluation principle of neutron energy by an imaging plate with a cone-like acryl converter (IP–Con^2). Only half of the converter is drawn here.

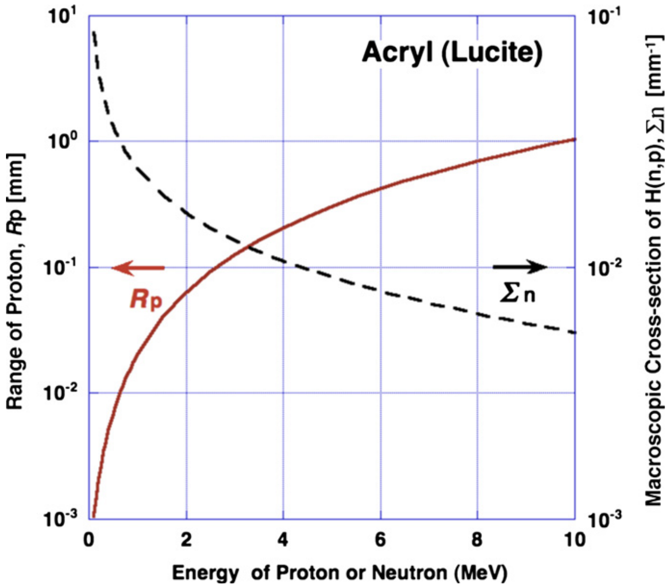

Fig. 2. Proton ranges and macroscopic cross-sections of H(n, p) in acryl for the different particle energies.

distribution of the incident neutrons. Here, we represent the neutron-energy distribution as $S(E)$, where $S(E)dE$ is the differential intensity of an incident neutron with energy within dE about E. The measured position distribution of the recoil protons results from the convolution

$$\frac{dN}{dX} = \int R(X, E)S(E)dE, \quad (1)$$

where $R(X, E)\, dX\, dE$ is the differential probability that a neutron of energy within dE about E is recorded at the position within dX about X. When the position distribution of the recoil protons is recorded by an IP (so-called "digital radiography"), Eq. (1) takes the discrete form of

$$N_i = \sum_j R_{ij} S_j, \quad (2)$$

where N_i is the recorded PSL intensity in the ith position interval, R_{ij} is the response matrix coupling the ith position interval with the jth energy interval and S_j is the radiation intensity in the jth neutron energy interval. If the "response functions" are known for some monoenergetic neutrons, in principle, unfolding calculations may be available to determine the actual neutron energy spectrum [9].

3. Experimental

We used two types of acryl blocks with triangular cross-sections as the cone-like converters (Fig. 3). One is a cone with a base circle diameter of 40 mm and height of 40 mm. The other is a triangular prism with a base square of $50 \times 50\ mm^2$, and height of 40 mm. The imaging plates used were a soft beta-ray type IP (BAS-TR 2025, Fuji Film Co. Ltd.) and an X-ray-type IP (BAS-MS 2025, Fuji Film Co. Ltd.). As already mentioned, BAS-TR does not have a protective layer for the efficient transmission of low-energy beta rays. These imaging plates were scanned by BAS-1800 II (Fuji Film Co. Ltd.) with the fixed scanning parameters of "latitude" = 5, "sensitivity" = 4000 and "resolution" = 50 μm, immediately after the termination of each irradiation. Scanned images were analyzed by using the "Image Gauge" software (Fuji Film Co. Ltd.).

3.1. ^{252}Cf irradiation experiment

The response of BAS-TR to neutron irradiation was investigated using a ^{252}Cf source (2.3 MBq) with the cone acryl converter. The experimental setup is shown in Fig. 4. A diverged beam geometry was used for this measurement. The converter was directly placed on the surface (bare phosphor) of BAS-TR so as to avoid the energy loss of the recoil protons in the existing air layer. In order to reduce the intensity of gamma rays from the ^{252}Cf source, a 50 mm-thick Pb plate was inserted between the source and the IP. Another X-ray-type IP, BAS-MS, was arranged under the BAS-TR in order to measure the gamma rays that penetrated the BAS-TR. During the irradiation of approximately 20 days, the entire IP–Con^2 system, including the ^{252}Cf source, was covered by a shade curtain in order to shield it from the ambient light.

Fig. 5 shows the results obtained from the IP images. Curve A is a profile of the BAS-TR image and the curve B is the profile of the BAS-MS image. The ROI setting width is 20 mm and the position of the acryl cone is also indicated in the same figure. In these plots, PSL stands for "photo-stimulated luminescence", which corresponds to the count of the IP. The broken lines were deduced from an interpolation based on a Gaussian distribution with the data of the region where the acryl cone did not exist. With respect to the results of BAS-TR, a clear enhancement of the PSL intensity was observed at the part where the acryl converter was placed. On the other hand, for BAS-MS, a dip in the PSL intensity appeared at the corresponding part. The enhancement of the PSL signal observed in BAS-TR may be originated from recoil protons emitted by the converter. Further, the dip in the PSL signal that appeared in BAS-MS may be caused from the shielding of gamma

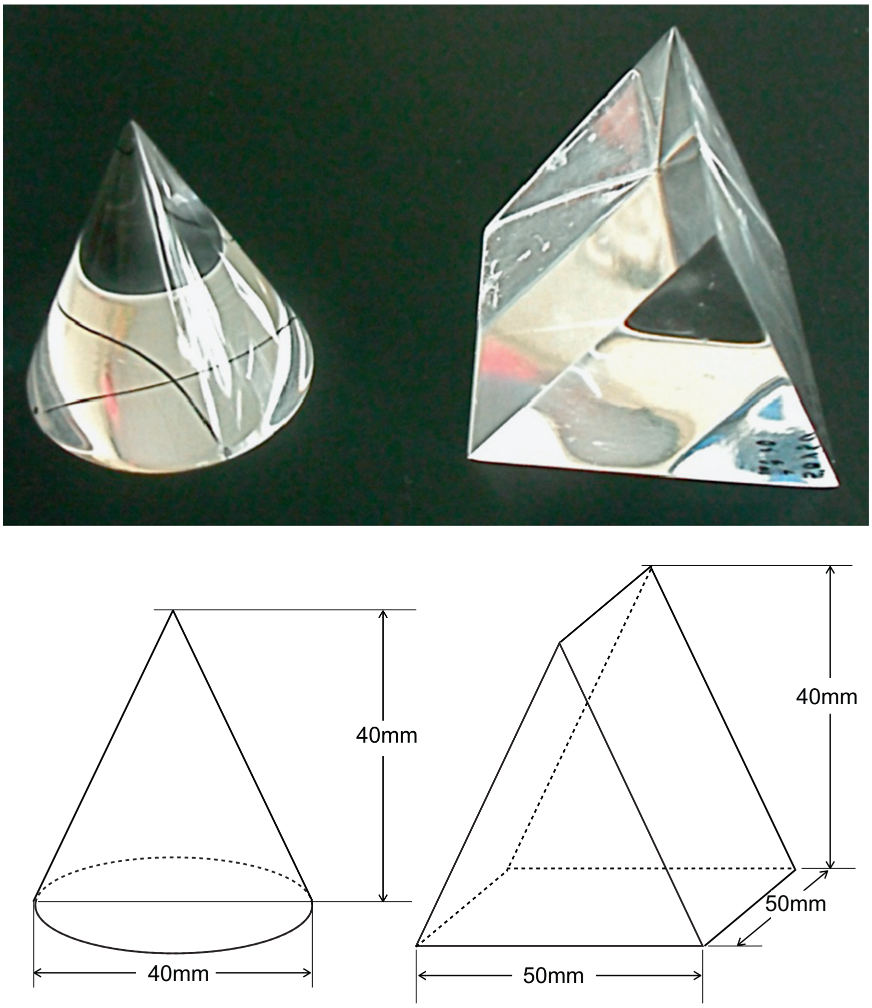

Fig. 3. Cone-like acryl converters used in this study. (Left) Cone, (right) triangular prism.

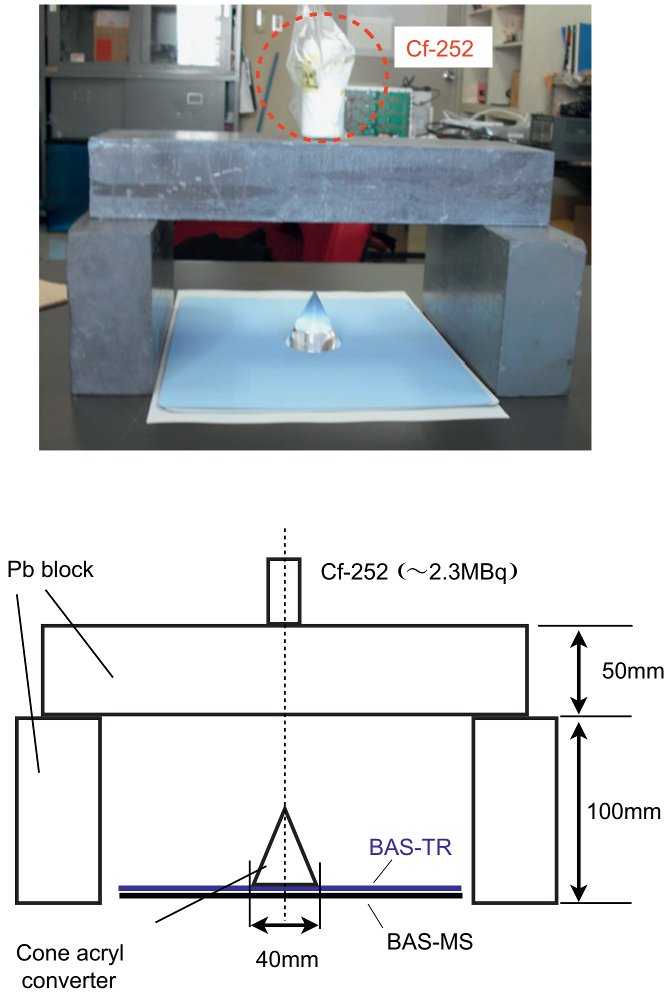

Fig. 4. Experimental setup for ^{252}Cf irradiation.

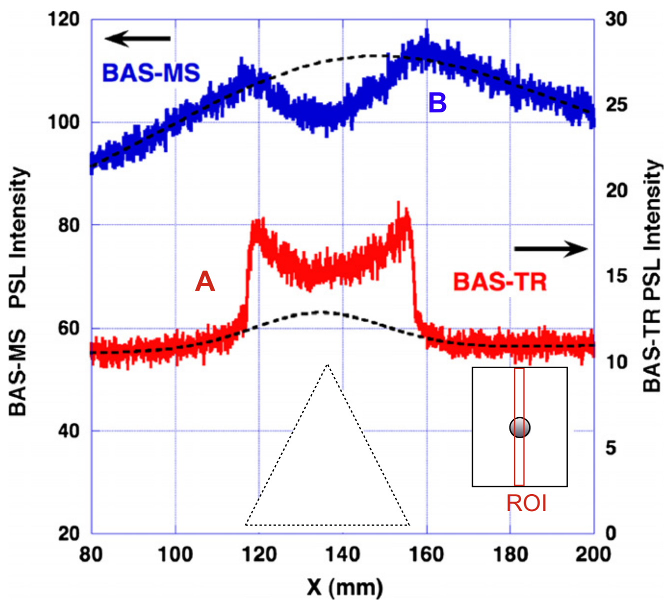

Fig. 5. PSL profiles obtained by IP with a cone acryl converter for ^{252}Cf irradiation.

rays by the converter. Neither the enhancement nor the dip in the PSL intensity was observed when the acryl converter was removed.

The results described above suggest that the BAS-TR is relatively insensitive to gamma rays from ^{252}Cf and chiefly detects recoil protons generated by neutrons from ^{252}Cf. Such a favorable property is significantly attributed to a relatively thin phosphor layer (approximately 50 μm) of BAS-TR, which is carefully designed so as to reduce the gamma-ray contamination for the measurement of soft beta rays; the energy deposition of soft beta rays is very limited near the surface of the phosphor layer only, and therefore, the use of a thick layer is disadvantageous from the view point of the signal-to-noise ratio.

The PSL signal enhancement observed on BAS-TR in Fig. 5 was reproduced as some three-dimensional plots in Fig. 6. These plots clearly display the distinctive signal enhancement around the edge part of the acryl cone converter. When the ^{252}Cf source position was shifted by approximately 50 mm from the original center position, an apparent inclination of the signal distributions was observed as shown in Fig. 7.

3.2. Irradiation experiment by a research nuclear reactor

Neutrons supplied from a research nuclear reactor (UTR-KINKI [10]) were applied to an investigation of the IP–Con^2 system. The experimental set up was similar to that in the case when the ^{252}Cf source was used. A 40 mm-thick Pb plate was used in order to

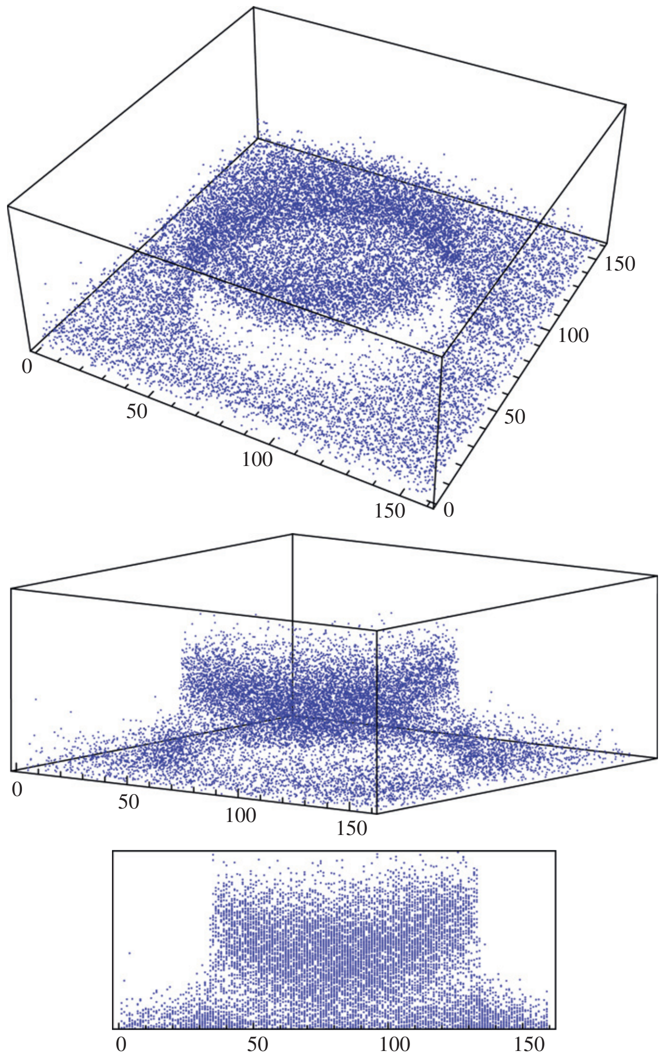

Fig. 6. Three-dimensional plots of PSL intensity observed on BAS-TR for ^{252}Cf irradiation.

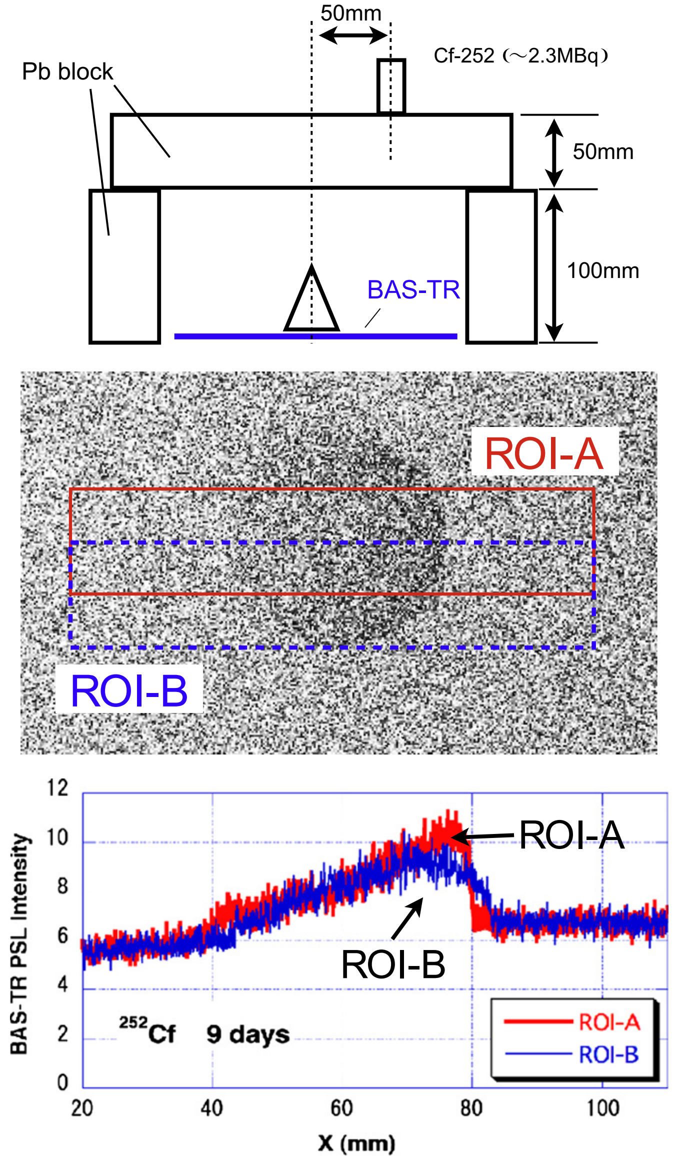

Fig. 7. PSL profiles obtained by BAS-TR with a cone acryl converter for ^{252}Cf in an out-of-center arrangement.

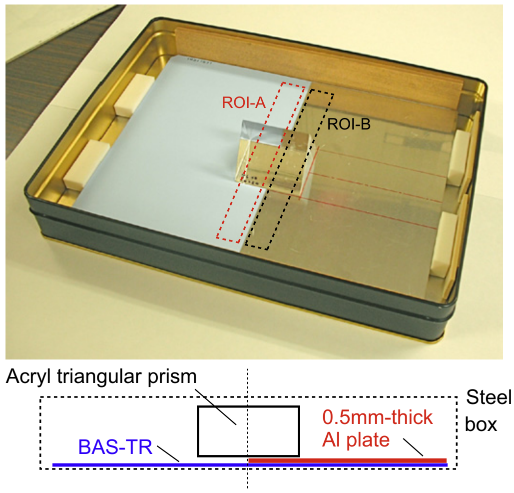

Fig. 8. Arrangement of an acryl triangular prism with an IP.

reduce the gamma-ray contamination. Instead of the acryl cone, an acryl triangular prism was used as a converter. In addition, as shown in Fig. 8, the entire IP–Con^2 system was installed in a rectangular box made of thin steel so that the system could be arranged upside down and neutron irradiation from the bottom side could become available; neutrons were extracted upwards from the reactor core, and the IP–Con^2 system was set in an irradiation port equipped at the top of the reactor, as indicated in Fig. 9. In this measurement, the steel box also played the role of an ambient-light shield. During a 5 h irradiation, the thermal output of this nuclear reactor was maintained at 1 W, and the neutron flux at the irradiation port was approximately 5×10^3 neutrons/cm^2/s ($E_n > 0.01$ MeV) [11].

As shown in Fig. 8, half of the base square of the acryl prism was covered by a 0.5 mm-thick aluminum plate, which was inserted between the surface of BAS-TR and the base of the acryl prism. The aluminum plate was sufficiently thick to stop protons up to approximately 9 MeV; while the maximum neutron energy was at most 10 MeV in this radiation field. After the termination of irradiation, we examined the difference in the PSL intensity between the uncovered part (profile-A) and the covered part (profile-B). The result is shown in Fig. 10. Because of the existence of an intense gamma-ray fluence, a prominent reduction of the PSL intensity was dominantly observed for both profiles at the part where the acryl converter was placed. However, there was a slight difference between both the profile curves; this difference corresponded to the contribution of recoil proton signals. By subtracting profile-B (gamma-ray) from profile-A (gamma-ray+-proton), we obtained the signals of only the recoil protons, as presented in Fig. 10. The resultant proton distribution curve was rather similar to that obtained by the ^{252}Cf source with the acryl cone placed on BAS-TR (curve A in Fig. 5).

3.3. *Irradiation experiment by an accelerator-based neutron generator*

Neutrons generated by a proton accelerator were used for the investigation of the IP–Con^2 system. Eight MeV protons supplied from a Tandem accelerator of *The Wakasa Wan Energy Research Center* were irradiated to a 1 mm-thick Be target in order to obtain energetic neutrons through Be(n, p) reactions [12]. The average beam current on the target was approximately 0.58 μA during the experiment. The range of 8 MeV protons in Be was 0.54 mm, and these protons did not penetrate the target. Therefore, protons with various energies contributed to the neutron production. As the result, generated neutrons were not monoenergetic. The IP–Con^2 system was installed in the steel box in the same way as in the previous experiment with a research nuclear reactor (Fig. 8). As shown in Fig. 11, the steel box was arranged at a distance of 1 m from the Be target. A 50 mm-thick Pb plate was placed in front of the steel box for the purpose of reducing the gamma-ray contamination. During a 10 min irradiation, the neutrons flux at the IP–Con^2 system position was estimated to be approximately 10^5 neutrons/cm^2/s ($E_n > 0.5$ MeV).

As mentioned in the previous section, after the termination of irradiation, we examined the difference in the PSL intensity between the uncovered part (profile-A) and the covered part (profile-B). In this experiment, the IP was scanned by BAS-5000 (Fuji Film Co. Ltd.), instead of BAS-1800II, with almost equivalent scanning parameters which were used for BAS-1800II. As indicated in Fig. 12, the obtained profile of the recoil protons prominently showed a tendency that was considerably similar to that obtained in the case of the ^{252}Cf source (curve A in Fig. 5).

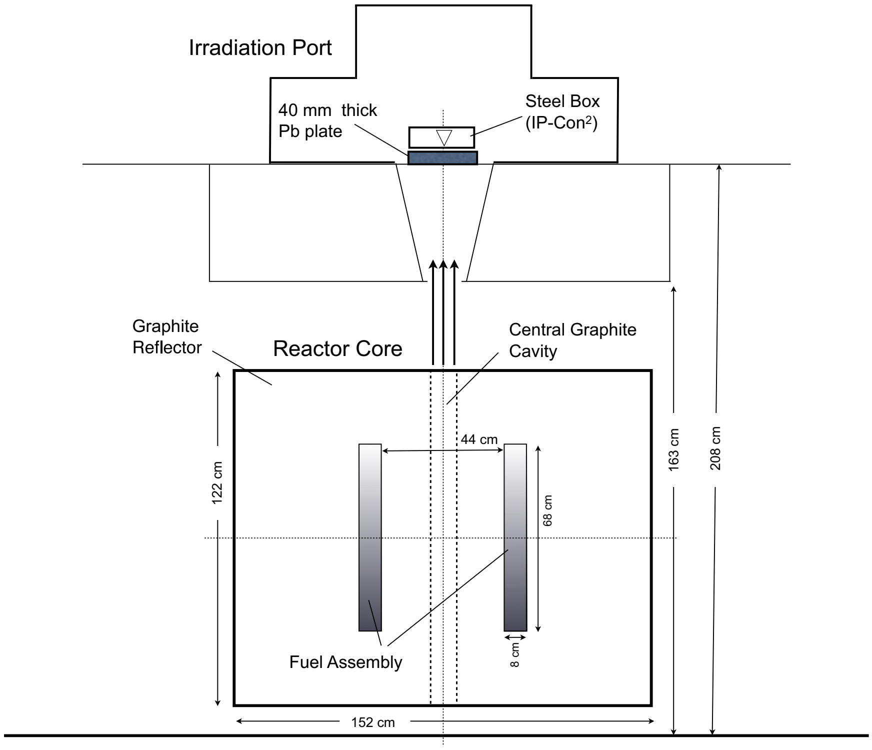

Fig. 9. Experimental setup for the reactor irradiation.

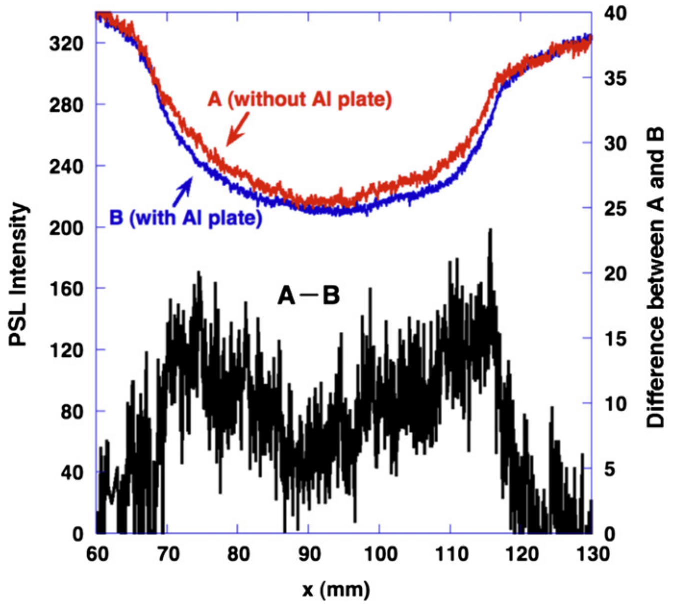

Fig. 10. Profiles obtained by BAS-TR with a triangular acryl converter for the reactor irradiation.

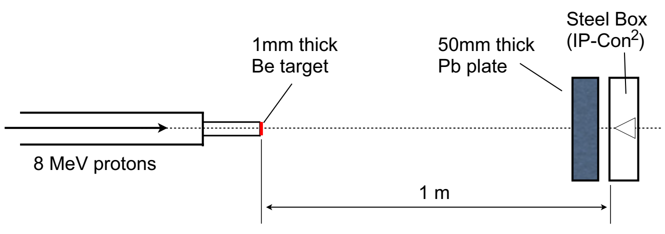

Fig. 11. Experimental setup for the accelerator-based neutron generator.

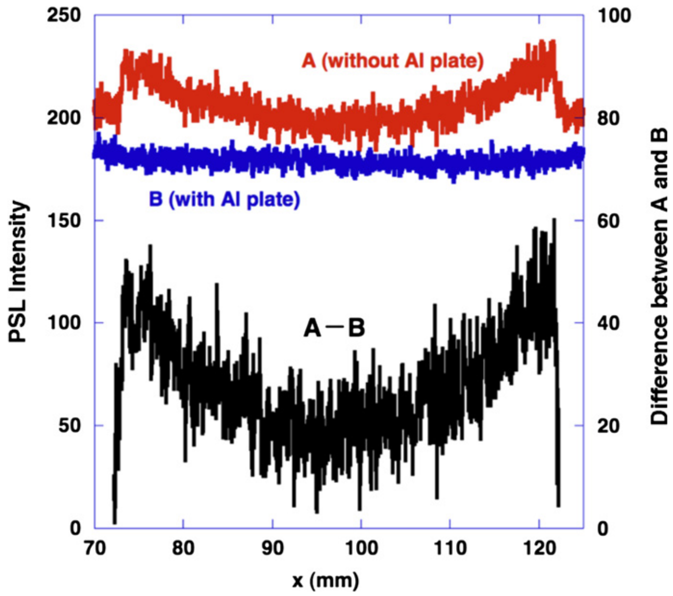

Fig. 12. Profiles obtained by BAS-TR with a triangular acryl converter for the accelerator-based neutron generator.

4. Monte Carlo studies of the IP–Con^2 system

In order to understand the spatial distributions of the recoil protons described above, we developed a simple computer program. The program merely calculates the position distribution of recoil protons that reach the IP surface by using the Monte Carlo method for different geometries, instead of the PSL intensity distribution related to their energy deposition in the phosphor layer of the IP. In the calculation, (1) H(n, p)-reaction cross-sections were obtained from JENDL-3.3 [8], (2) the scattering process was assumed to be isotropic in the center-of-mass coordinate system for low-energy neutrons (<10 MeV), (3) residual ranges of the recoil protons in acryl were evaluated on the basis of Janni's table [7], (4) the contribution of secondary neutrons was ignored and (5) the direction of neutron incidence was set to be perpendicular to the IP surface. Although such a simple calculation based on some approximations may not accurately explain the actual IP observations, it is still advantageous to quickly examine the various properties of the IP–Con^2 system.

Fig. 13 shows the calculated results for an acryl converter having a triangular cross-section (base length: 50 mm; height: 40 mm) for different neutron energies from 0.5 to 10 MeV. The calculations considerably reproduce the experimental trends, although observations were not for monoenergetic neutrons but for those with a broad energy spectrum of up to around 10 MeV. It should be kept in mind that the actual neutron beam was not exactly parallel but diverged to some extent. The detection efficiencies obtained from the same calculations of the IP–Con^2 system are plotted in Fig. 14 as a function of the neutron energy. Those for Fig. 15 are also arranged in the same figure in advance.

In the calculated results of Fig. 13, it is noticeable that the gradual increase in the signal intensity is not evident around the edge part of the converter as schematically expressed in Fig. 1. This may be because of the considerably steep gradient of the edge of the acryl converter used. Hence, as a demonstration, the shape of the acryl converter was geometrically modulated in the following calculation. The simple triangle was replaced by a couple of exponential decay curves reversed in left and right each other (as found in Fig. 15), which allows a very moderate gradient around the edge part. Consequently, the calculated results displayed in Fig. 15 clearly indicate two specific responses related to the adoption of this peculiar converter with an increase in the incident neutron energy, i.e. a decrease in the recoil proton

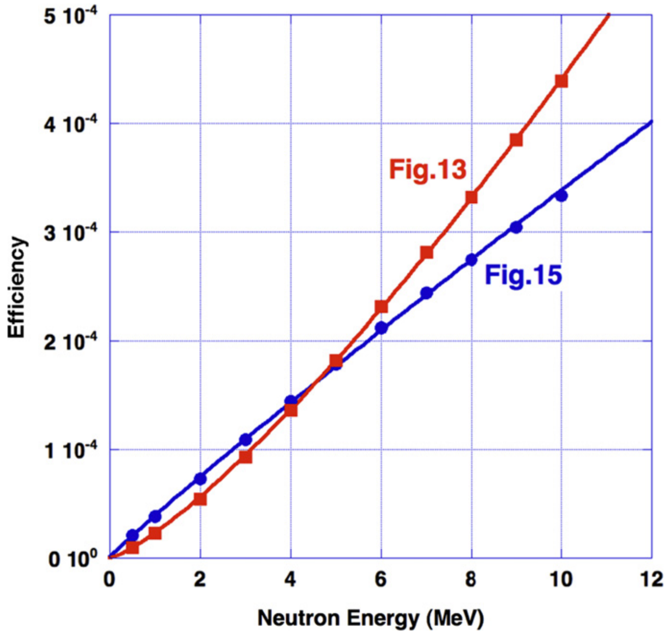

Fig. 14. Calculated detection efficiencies of IP–Con^2 system. The lines are fitted by linear quadratic functions just as a guide to the eye.

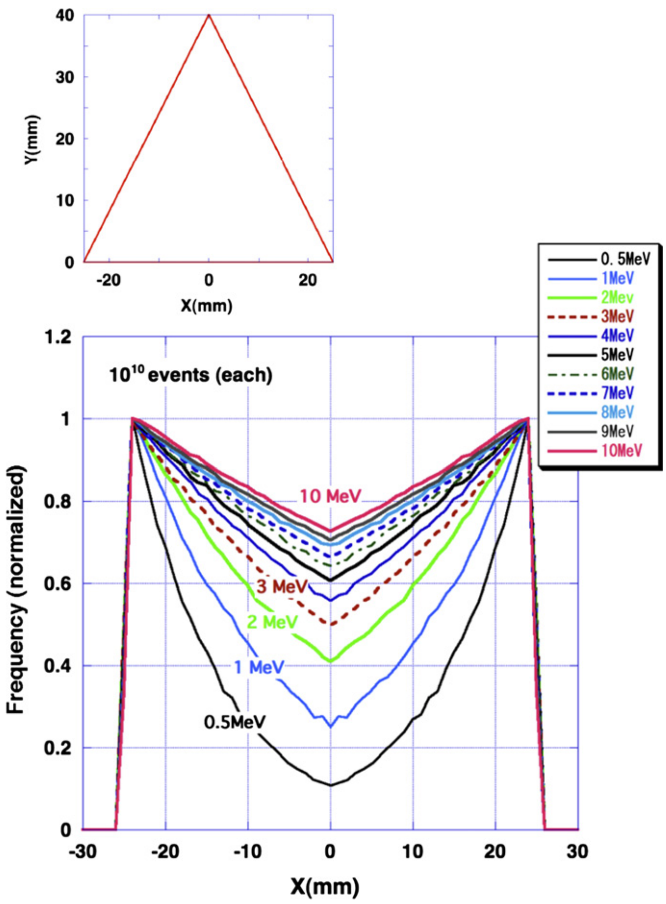

Fig. 13. Calculated responses of a triangle-shaped converter for monoenergetic neutrons.

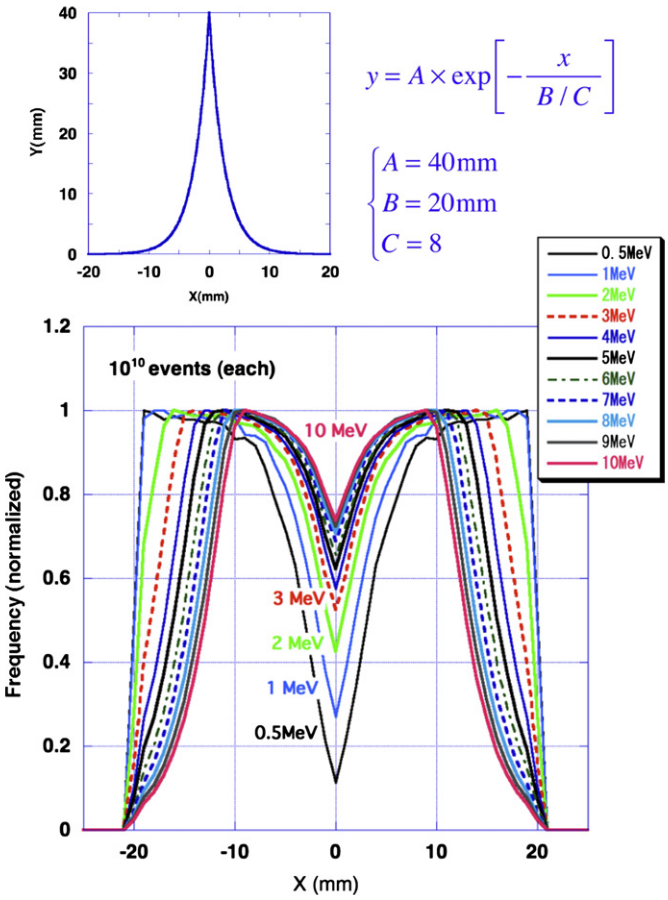

Fig. 15. Calculated responses of a geometrically modulated converter for monoenergetic neutrons.

generation near the edge part of the converter due to the relatively small cross-sections of the H(n, p) reaction for the relatively high-energy neutrons and an increase in the energetic protons that penetrate the thick converter at the center.

5. Tentative evaluation of neutron energy spectra

For checking the practical possibilities of the proposed method, we tentatively tried to evaluate the neutron energies of the fields described in Section 3. By using the simplified response functions calculated in Fig. 13, the position distributions of recoil protons obtained by the acryl triangular prism, i.e. Fig. 10 (a research nuclear reactor) and Fig. 12 (an accelerator-based neutron generator), have been analyzed; as far as the irradiation with the ^{252}Cf source was concerned, an additional measurement was carried out by using the acryl triangular prism.

The observed position distributions of the recoil protons seem to suffer from rather serious fluctuations mainly because of the “low counting statistics”. Therefore, before the unfolding process, the data were smoothed by some operations for an adjustment that include the moving average. Then, the smoothed data were re-arranged into 1 mm-wide intervals (Fig. 16). The unfolding of the resultant position spectra was simply performed by using the “Solver for Excel 2008 for Mac” software (Microsoft Corporation). To seek a minimum in the sum of residuals (ε^2), the “solver options” were set to be the same values for a series of all analyses: i.e. “precision”$=10^{-6}$, “convergence”$=10^{-4}$ and “assume non-negative”=true. Here the value of ε^2 is given by

$$\varepsilon^2=\sum_i\left(N_i-\sum_j R_{ij}S_j\right)^2. \tag{3}$$

The evaluated solutions of $S(E)$ are displayed in Fig. 17 for the different radiation fields. In Fig. 17(a), a typical fission spectrum is also indicated for comparison, which is approximated by the expression of

$$\frac{dN}{dE}=C\sqrt{E}\exp\left(-\frac{E}{T}\right), \tag{4}$$

where E is the neutron energy and C is a normalized constant. The constant T in Eq. (4) is chosen to be 1.42 MeV for Fig. 17(a) [13]. In Fig. 17(b), the neutron energy spectrum at the central graphite cavity of UTR-KINKI is also displayed, which was evaluated by the unfolding of the multi-foil activation data [3]. In Fig. 17(c), the neutron energy spectrum at a point 1 m away from the Be target on the 0° beam axis is also indicated, which was calculated on the basis of the ENDF/B-VII Nuclear Data [14].

6. Discussion

As already explained in Section 2, the unfolding procedure is essential to the evaluation of the neutron energy spectra by the IP–Con^2 system. The results of a Monte Carlo study indicate that the shapes of the “response functions” for a simple triangle converter evidently depend on the change in the incident neutron energy from 0.5 to 10 MeV (Fig. 13). On the other hand, however, the neutron energy spectra in Fig. 17, which were tentatively evaluated on the basis of the response functions in Fig. 13, seem to be rather poor in reproducing the reference spectra obtained by using other methods. A reason for such discrepancy may lie in the fact that the experimental conditions are not identical or the assumptions for the calculation between the present evaluation and the reference spectra are not identical; for example, the insertion of a considerably thick Pb plate for the gamma-ray

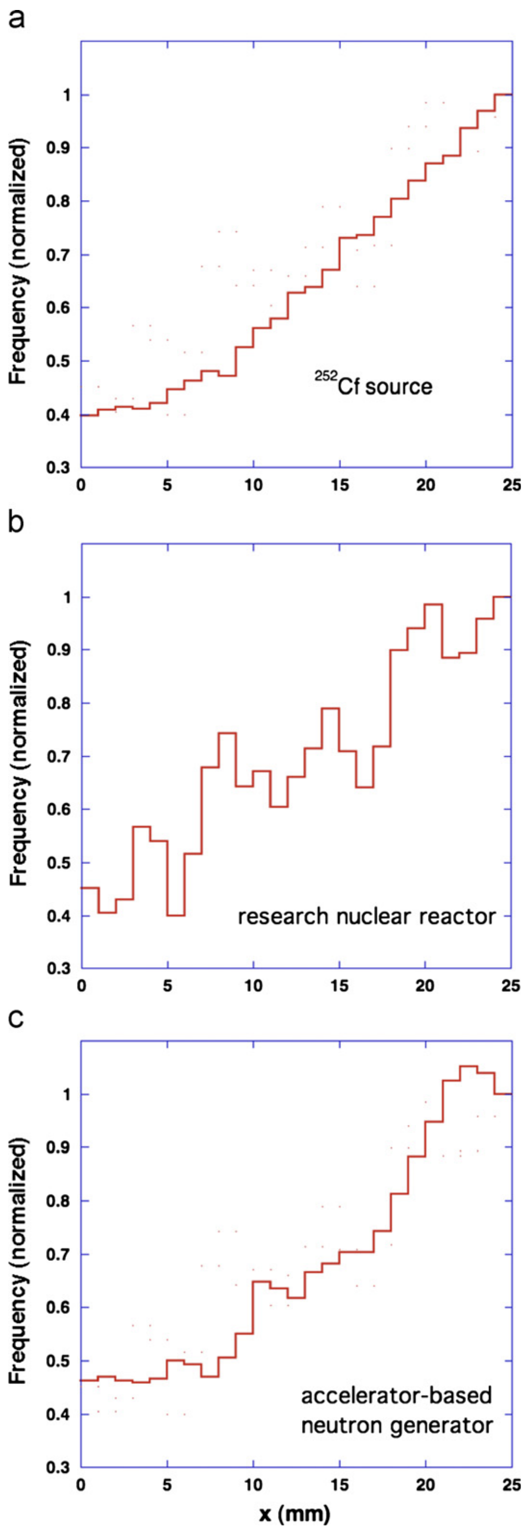

Fig. 16. Position spectra of recoil protons used for unfolding.

shielding may also affect the neutrons and the evaluated neutron spectra would be distorted from the original one more or less. In addition to this, the other reasons of such a discrepancy may be related to some experimental limitations (and not the principle limitations) of the present evaluation, such as low counting statistics due to the weak neutron fields and difficulties in the appropriate subtraction of the considerable gamma-ray backgrounds (including the activation of aluminum plate due to the neutron flux). One

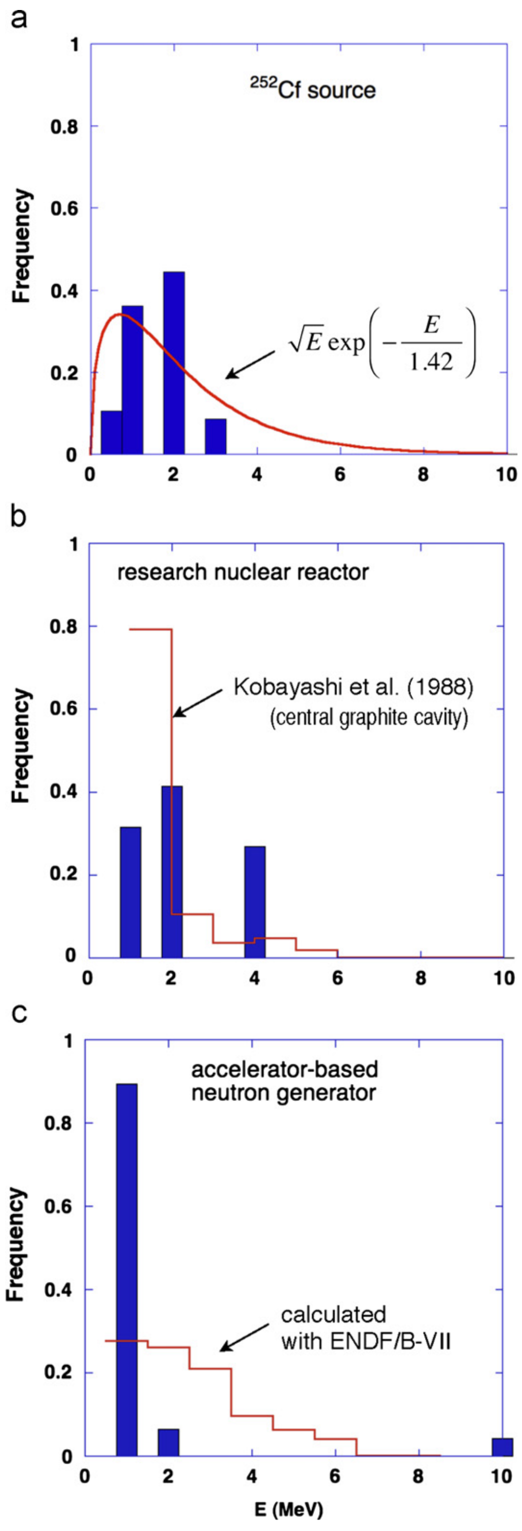

Fig. 17. Evaluated neutron energy spectra.

possible way to overcome such unfavorable situations is the use of response functions that are considerably sensitive to even a subtle change in the incident neutron energy. As already pointed out in Fig. 15, it has been clarified that the sensitivity can be drastically improved by using an appropriate geometrical modulation. Such facts encourage us to apply this technique to the actual evaluation of unknown neutron fields. It is apparent that the achievable energy resolution of the IP–Con^2 system significantly depends on the adoption of an appropriate shape of the converter.

The most notable advantage of the IP–Con^2 is that we can select and arrange the shape of the converter very flexibly depending on the energy region of interest. Further, if necessary, it is possible to calculate many “response functions” at the arbitrarily small steps of neutron energy as a function of the position along *X*-axis; it should be strongly emphasized that, with respect to the conventional energy evaluation by the BSS, only one response function is available for each setting of the detector (sphere diameter) as a function of the neutron energy. Moreover, for the IP–Con^2 system, owing to an appropriate binning of the proton profile along *X*-axis, we can virtually divide the region into arbitrary sub-groups; each sub-group corresponds to each single detector of BSS. According to this point of view, as a demonstration, in Fig. 18, the same data as those shown in Fig. 15 are plotted as a function of neutron energy for the respective positions.

In addition to the advantages mentioned above, we can simultaneously obtain information on the change in the neutron energy spectra inside a small neutron field by installing some acryl converters at the different positions on an IP. Furthermore, as demonstrated in the experiment by the ^{252}Cf source, the recoil proton distribution is obviously sensitive to even a slight change in the incident direction of neutrons. Therefore, hopefully, two-dimensional unfolding on both the incident energy and the incident angle of neutrons may be possible by using advanced mathematical techniques, which allow us to evaluate the angle distributions of incident neutrons when such information is unknown.

The elimination of gamma-ray contamination is a practically important issue for the application of the IP–Con^2 system. Although we used an IP as the two-dimensional detector of recoil protons in this study, IP is not the most suitable choice from this point of view because IP is essentially very sensitive to gamma rays. A position sensitive gas detector, such a micro-strip gas chamber (MSGC), is another promising candidate for this purpose owing to its low sensitivity to gamma rays because of the capability for discriminating the pulse heights. Further, the on-line readout capability of such an active detector is highly preferable. Some solid track detectors like CR-39 are also

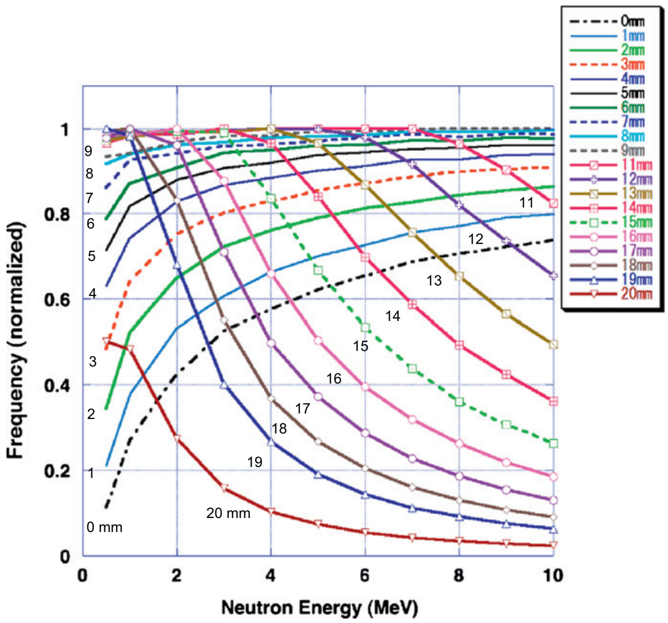

Fig. 18. Calculated responses of a geometrically modulated converter for mono-energetic neutrons. The same data as those shown in Fig. 15 are plotted as a function of neutron energy at different positions along the *X*-axis.

attractive because they have almost no sensitivity to gamma rays, although their sensitivity to protons is not as high as that of IP.

In order to accomplish the ideal performance of an IP–Con^2 system, converters with rather complicated geometrical modulations may often be preferable. For such fine fabrications, a stereolithography technique, which is based on the hardening of an epoxy resin with laser light scanning, is remarkably useful [15].

7. Conclusion

With the aim of developing a novel and convenient method for evaluating neutron energy spectra, we used cone-like acryl converters with different geometrical modulations for the detection of fast neutrons up to around 10 MeV. An imaging plate was successfully used for detecting the recoil protons emitted from an acryl converter. By using the obtained position spectra, a tentative evaluation of neutron energy spectra was attempted. As a result of the experimental examinations and calculation studies, it was revealed that the neutron energy evaluation is surely possible by analyzing the spatial distribution of the signal enhancement that originates from the recoil protons. This new concept may open a possibility to realize an unconventional neutron-energy spectrometer without the time-of-flight (TOF) measurement. Because the present work is just a proof-of-principle study, for the development of a practical system, further investigations need to be carried out on the following subjects: the experimental verification of the total response of IP–Con^2 system by using some monoenergetic neutrons, the development of an imaging detector suitable for the proton distribution measurement under intense gamma-ray backgrounds, the calculation of accurate response functions by full Monte Carlo code, as well as the establishment of an unfolding technique that is applicable to practical situations.

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References

[1] M. Igarashi, Y. Kiyanagi, M. Ohshima, Nucl. Instr. and Meth. A 600 (2009) 332.
[2] R.L. Bramblett, R.I. Ewing, T.W. Bonner, Nucl. Instr. and Meth. 9 (1960) 1.
[3] K. Kobayashi, S. Yamamoto, I. Kimura, R. Miki, T. Itoh, Ann. Rep. Kinki Univ. At. Energy Res. Inst. 25 (1988) 21.
[4] G. Wakabayashi, et al., IEEE Trans. Nucl. Sci. Ns-48 (2001) 320.
[5] T. Sanami, M. Baba, K. Saito, T. Yamazaki, T. Miura, Y. Ibara, S. Taniguchi, A. Yamadera, T. Nakamura, Nucl. Instr. and Meth. A 458 (2001) 720.
[6] A. Nohtomi, T. Terunuma, R. Kohno, Y. Takada, Y. Hayakawa, A. Maruhashi, T. Sakae, Nucl. Instr. and Meth. A 424 (1999) 569.
[7] J.F. Janni, At. Data Nucl. Data Tables 27 (1982) 147.
[8] K. Shibata, et al., J. Nucl. Sci. Technol. 39 (2002) 1125.
[9] G.F. Knoll, Radiation Detection and Measurements, third ed., John Wiley and Sons, Inc., New York, 2000, p. 704.
[10] Kinki University Atomic Energy Research Institute, ⟨http://www.kuaeri.ned.kinda.ac.jp/⟩.
[11] Y. Ogawa, Research on the neutron dosimetry around nuclear facilities, Doctoral Thesis, Nagoya University, Nagoya, Japan, 2007, [in Japanese].
[12] T. Takata, et al., Ann. Rep. Wakasa Wan Energy Res. Center 12 (2009) 25 [in Japanese].
[13] Hambsch, et al., Ann. Nucl. Energy 32 (2005) 1032.
[14] M.B. Chadwick, et al., Nucl. Data Sheets 107 (2006) 2931.
[15] T. Sakae, A. Nohtomi, A. Maruhashi, M. Sato, T. Terunuma, R. Kohno, Y. Akine, Y. Hayakawa, Y. Koike, Med. Phys. 27 (2000) 368.