Development of Miniature Fast Neutron Spectrometers

By

Kazuo SHIN, Shigeo NUMATA*, and Akira HIGASHINO**
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Abstract

Miniature fast neutron spectrometers are developed. A 1 cm diam. by 1 cm thick stilbene scintillator and a 1 cm radius spherical NE-213 are newly constructed and the detecting system, i. e. the response matrices, proton light data, an unfolding method, and a calibration method for the pulse-height axis, which are fitted to the new detectors are developed.

Verification tests on the detecting system are made by applying the system in a ^{252}Cf neutron field, a graphite transmitted neutron field, and a neutron field of an Am-Be source. The obtained spectra by the developed detectors are compared with the reference spectra obtained by an already established 5 cm diam. by 5 cm thick NE-213 scintillator.

It is concluded through the tests that the developed miniature detector systems are adequate as a fast neutron spectrometer.

I. Introduction

Measurements of fast neutron spectra inside materials are often required in fusion neutronics studies to make a detailed test of neutron cross sections of the materials. Gap streaming is of importance in fusion and fast reactor shielding studies. In the studies, detailed spatial and energy distribution should be measured in the shield system.

A 5 cm diam. by 5 cm thick NE-213 has been widely used as a fast neutron spectrometer. Its response functions to neutrons have been systematically obtained by experiment[1] or by calculations,[2)-6)] and proton light output data have been obtained by experiments.[1),6)-8)] The unfolding method like FERDO[9] was developed for the detector to get better spectra. Through all of these studies the NE-213 of the above size is now accepted as the standard spectrometer by which

* Present Address: Shimizu Construction Co. LTD, 4-17 Etchujima 3-chome, Koto-ku, Tokyo 135

** Present Address: Mitsubishi Heavy Industries LTD, 1-1 Watazuki-cho 1-chome, Hyogo-ku, Kobe 652

one can obtain fast neutron spectra with reasonable accuracy.

However, the detector size, i. e. 5 cm in diameter by 5 cm in thickness, is too large for the detector to be inserted into the material system, or to measure the detailed spatial distribution of neutrons which are, usually in gap streaming problems, sharply peaked at the gap region whose dimension is much less than the detector.

The objective of this work is to develop new detectors which are small enough in dimension to enable one to make spectrum measurements inside the material system.

The efficiency of neutron detectors is nearly proportional to the detector volume, so the efficiency decreases dramatically as the size is reduced. For the spectroscopic purpose, the pulse-height distribution must be given within acceptable statistical errors over a sufficient number of pulse-height channels. This means that the measurement by the miniature detector requires more and more measuring time as the detector size is reduced. Moreover, the reduction in the detector size generates more the wall-end effect, which in turn limits the maximum detectable energy of neutrons. The wall-end effect is more serious for gamma rays than for neutrons due to the larger electron range than the proton range of the same energy. The calibration of the pulse height which is usually made by the Compton edges of well known gamma rays will be more difficult as the detector becomes smaller.

The detector size is determined from the trade off consideration between the merits and the demerits that are caused by decreasing the size. And a 1-cm spherical NE-213 detector is adopted. The reason for the selection of the spherical shaped detector is to avoid variation in the detector response as the neutron incidence direction is changed.

A 1-cm diameter by 1-cm thick stilbene scintillator is also tried, because it is known that the stilbene scintillator has better neutron detection characteristics, i. e. a better n-γ discrimination and a better energy resolution, than the NE-213 scintillator. The cylindrical shape is selected for the detector simply because of the easiness for mechanical shaping.

The response functions for each detector are calculated by the Monte Carlo method.[6] Light output data in literatures[7)-10)] are tried. The energy calibration method is reconstructed by using the gamma ray Monte Carlo code.[11] The FERDO unfolding code is applied for the unfolding of the NE-213 pulse-height spectrum. The SIMPLE method[13] is applied to the stilbene pulse-height data. The method, however, is modified here such that the covariance data[12] of the response functions are included in estimating propagated errors in the unfolded results.

For the test of all the detecting systems described above, detectors are applied to the well known neutron field, i. e. a ^{252}Cf fission field, an Am-Be neutron field, and a transmission neutron field of ^{252}Cf neutrons through a graphite slab.

II. Response Functions

(i) Calculation Method

The response functions of both the miniature stilbene and the miniature NE-213 scintillators are calculated by a Monte Carlo code, which was originally developed for the 5 cm diam. by 5 cm thick NE-213 scintillator. The accuracy of the code was already well verified by experiments[6] for the conventional detector. The code needs certain modifications in geometry routines for the application to the spherical miniature detector. For the stilbene scintillator, the replacement of the proton light output data is needed to fit the code to the detector.

Several proton light output data of the stilbene scintillator have been published in literatures.[7),8),10),14)] However, they are not always consistent with one another. This may be due to the light attenuation effect in the scintillator, since each worker used a detector of a different size. None used the very small size detector that we are attempting to use. Here we picked up two typical data, one from Smith's literature[7)] and the other from Brodsky's formula.[10)] As the number of data points of Smith's data is not enough to directly construct the light curve which is usable in the Monte Carlo code, the data are fitted by Birk's formula[7)] by following the way described in his literature. A light curve is calculated by the formula. Fig. 1 shows the light curve by the formula and Smith's original data, incomparison with Brodsky's curve.

Light curves for other charged particles, e. g. α particles and C nucleus, of the stilbene were not given anywhere. We evaluated these data by Birk's formula based on the same kB and S values that were given for protons by Smith,[7)] and the stopping power data of these charged particles that were compiled by Sugiyama.[15)]

The proton range data in the stilbene, which are needed for the estimation of the wall-end effect, are cited from Brodsky's work.[10)] Other charged particles are assumed to lose their energies at a point where they are generated.

For the NE-213, all the adapted data originally in the Monte Carlo code are used for the calculation.

Usually, the scintillators are encapsulated in a case. However, the case is

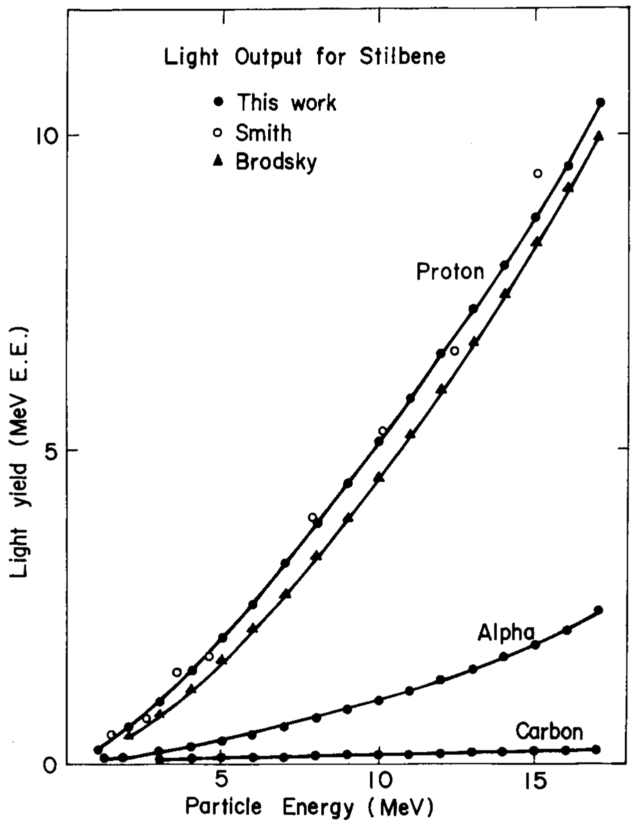

Fig. 1 Comparison of proton light-output data for stilbene scintillator.

neglected in making up the calculational model because, as is written in Ref. 12), its influence on the response function is trivial.

Neutron cross section data are taken from the ENDF/B-V file.[16]

The resolution function is approximated by the Gaussian functions for the NE-213, while no smearing by the resolution function is applied to the stilbene response functions.

The energy range from 0 to 17 MeV is divided into 34 energy bins. Then, two 34×34 response matrices are generated for the stilbene scintillator, corresponding to the two proton light curves. For the NE-213 scintillator, the same energy range is divided into 42 energy bins and a 42×42 response matrix is generated.

The number of Monte Carlo histories is decided for each incident neutron energy such that the statistical errors in all the response matrix elements are 3

– 4 %, where the statistical error in the (i, j) –element D_{ij} of the response matrix is measured by the equation,

$$\delta D_{ij}=\sqrt{\frac{D_{ij}}{N}}, \tag{1}$$

where N is the history numter.

An error estimation is made for errors in the calculated response functions due to those in the used cross section data. The method for the estimation is described in Ref. 13). The covariance data estimated is,

$$\overline{\delta D_{ij}\delta D_{i'j'}}=\sum_{k}\sum_{k'}\frac{\partial D_{ij}}{\partial \sigma_k}d\sigma_k\cdot\frac{\partial D_{i'j'}}{\partial \sigma_{k'}}d\sigma_{k'}\sum_{l}\gamma_{lk}\gamma_{lk'}\frac{d\sigma_l^s}{d\sigma_k}\frac{d\sigma_l^s}{d\sigma_{k'}} \quad . \tag{2}$$

The quantities $(\partial D_{ij}/\partial\sigma_k)\ d\sigma_k$, $(\partial D_{i'j'}/\partial\sigma_{k'})\ d\sigma_{k'}$ are evaluated by the Monte Carlo method, while r_{lk} $r_{lk'}$, $d\sigma_l^s/d\sigma_k$ and $d\sigma_l^s/d\sigma_{k'}$ are estimated by the way described in Ref. 13) from the error data in the ENDF/B-V file.[16)]

(ii) Example of Response Functions

A calculated response function for a stilbene scintillator of 3 cm diam. by 1 cm thickness is taken from the literature by Doroschenko.[17)] The response is for 14 MeV neutrons. The corresponding calculation for the same detector is performed by the Monte Carlo code described above.

The result is shown in Fig. 2, where the horizontal axis is measured by the proton energy. Because Doroschenko's calculation neglected contributions from charged particles other than protons, his result is very small at the lower pulse height region as compared to the calculated data of this work. Except for this one point, the agreement between the two calculations is excellent.

Ⅲ. Unfolding Method

The SIMPLE method[13)] is utilized for the unfolding of the stilbene pulse-height data. The SIMPLE method described in the previous work[13)] included the propagation of errors to unfolded results due to the statistical errors in the response matrix. The method is extended here to also include the covariance errors in the response functions in estimating the error propagation.

The unfolding is done based on Equation (3) of the matrix form,

$$\boldsymbol{C}=\boldsymbol{D}\cdot\boldsymbol{P}, \tag{3}$$

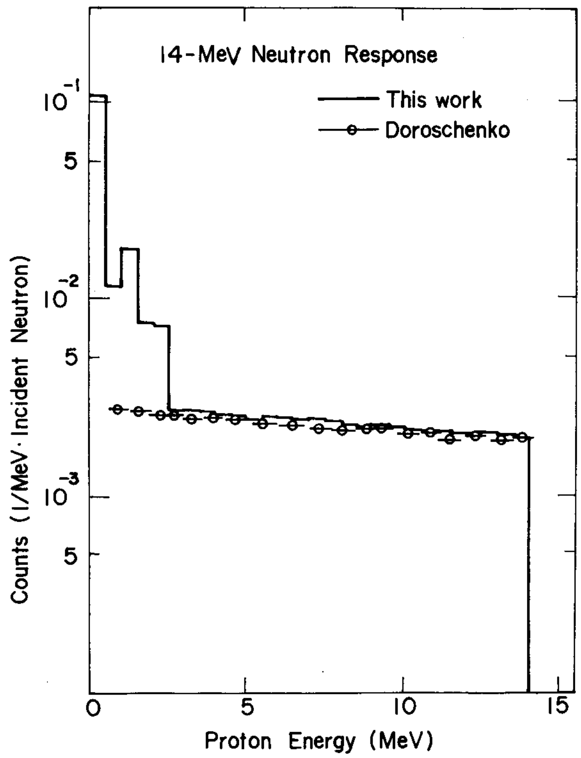

Fig. 2 Comparison of stilbene response functions for 14-MeV neutrons between the calculation of this work and that of Doroschenko's work.

whrer $\boldsymbol{C}$=pulse-height spectrum,
$\boldsymbol{D}$=response function,
and $\boldsymbol{P}$=neutron spectrum.

The procedure to introduce the covariance errors in $\boldsymbol{P}$ is similar to that for the independent errors;

$$\delta P_g = -P^+_{ig}\delta D_{ij}P_{ig} \qquad (i,\ j=1,\ 2,\cdots\cdots)\ , \tag{4}$$

where $P^+_{ig} = {}^tD^{-1}_{ig}$,
and ${}^tD^{-1}_{ig}$=the $(i,\ g)$ element of the inverse matrix of ${}^tD$.
Then

$$\overline{\delta P_g \delta P_{g'}} = \overline{\sum_{i,j}\sum_{i',j'} P^+_{i'j'}P^+_{ij}\delta D_{ij}P_{ig}\delta D_{i'j'}P_{j'g'}}\ ,$$

$$=\sum_{ij}\sum_{i'j'} P^{+}_{i'g'} P_{ig} P_{jg} P_{j'g'} \overline{(\delta D_{ij}\, \delta D_{i'j'})} \ . \tag{5}$$

The factor $\overline{\delta D_{ij}\delta D_{i'j'}}$ is given by Eq. (2).

For the statistical errors in the response functions, Eq. (5) is written as Eq. (6).

$$\begin{aligned}\overline{(\delta P_g)^2} &= \sum_{ij} \overline{(P^{+}_{ig}\delta D_{ij} P_{jg})^2}\ ,\\ &= \sum_{ij} (P^{+}_{ig} P_{jg})^2\ \overline{(\delta D_{ij})^2}\ ,\end{aligned} \tag{6}$$

where δD_{ij} in this case is given by Eq. (1).

Because the count $\boldsymbol{C}$ also includes statistical errors, the error δP^{c}_{gi} is introduced into the g-th group flux P_g due to the error of δC_i in C_i.

$$\delta P^{c}_{gi} = D^{-1}_{gi}\delta C_i\ , \tag{7}$$

where Eq, (7) is directly derived from the following equation,

$$\boldsymbol{P} = \boldsymbol{D}^{-1}\boldsymbol{C}. \tag{8}$$

The sum of the errors in P_g due to the statistical errors in all of the channels is

$$\begin{aligned}\overline{(\delta P^{c}_{g})^2} &= \sum_{i} (\delta P^{c}_{gi})^2\ ,\\ &= \sum_{i} (D^{-1}_{gi}\delta C_i)^2\ ,\end{aligned} \tag{9}$$

where $\delta C_i \fallingdotseq \sqrt{C_i}$.

The total error δp_g is estimated by the square root of the sum of Eqs. (5), (6) and (9).

For the unfolding of the NE-213 pulse-height data, the modified FERDO code[13] is utilized, since the method is considered at this time as the best one for the NE-213 scintillator. However, the covariance errors in the response functions are not considered in the evaluation of the error propagation.

IV. Application to Neutron Measurement

(i) Calibration of Pulse Height

Gamma rays from radioisotopes are used for the calibration of the pulse height of the scintillator output. For this purpose, ^{60}Co, ^{22}Na, and ^{137}Cs sources are available. The energies of these gamma rays cover a range of 0.511 - 1.27 MeV.

An Am-Be neutron source is sometimes used as a 4.43 MeV gamma ray source, when high energy neutrons like D-T neutrons are measured by the conventional size detectors. However, in the miniature scintillators developed here, the range of the electrons which correspond to the Compton edge of the 4.43 MeV gamma rays is much longer than the detector size. Consequently, the energy of these electrons is not measurable by miniature detectors. This is a drawback of the miniature detectors. The pulse-height calibration curve must be extrapolated to a higher pulse height region from the experimental points at the low pulse-height region.

The way of the pulse-height calibration is decided by the following process. First, the gamma-ray response functions are calculated by the Monte Carlo code

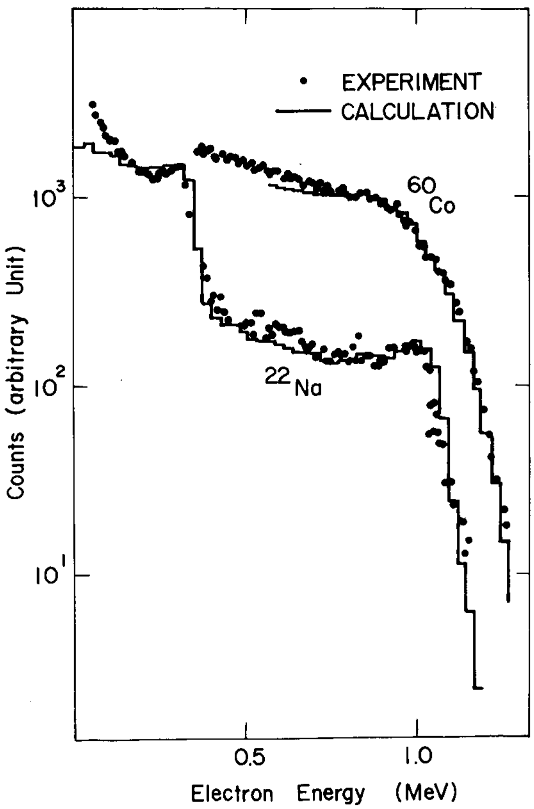

Fig. 3 Examples of stilbene pulse-height spectra obtained for ^{60}Co and ^{22}Na gamma rays.

TAURUS[11] for the gamma rays from the above radioisotopes. Then, the resolution function is multiplied to the calculated results. The width of the resolution function is decided so that the smeared calculated results agree best with the measured ones in the spectral shape at the Compton edge region. Fig. 3 shows examples of the comparison of the pulse-height spectrum between the experiment and the calculation for the stilbene scintillator. Then, a standard energy is determined for each gamma ray at the edge part. The ratio of the count at the standard energy to the count at a peak in the Compton edge region is computed by using the calculated pulse-height spectrum. By these ratios, one can easily

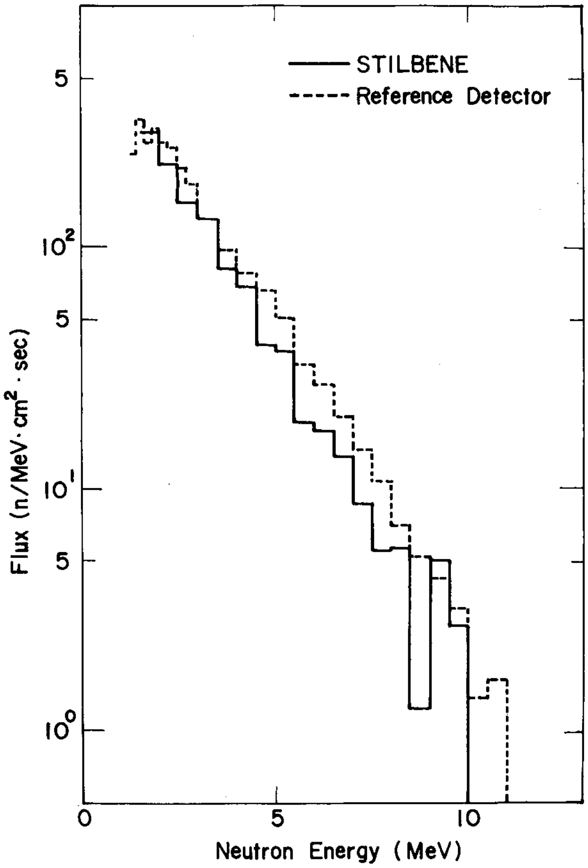

Fig. 4 Comparison of measured spectrum for ^{252}Cf neutrons by the miniature stilbene scintillator with Smith's light output data with that by the reference NE-213 scintillator.

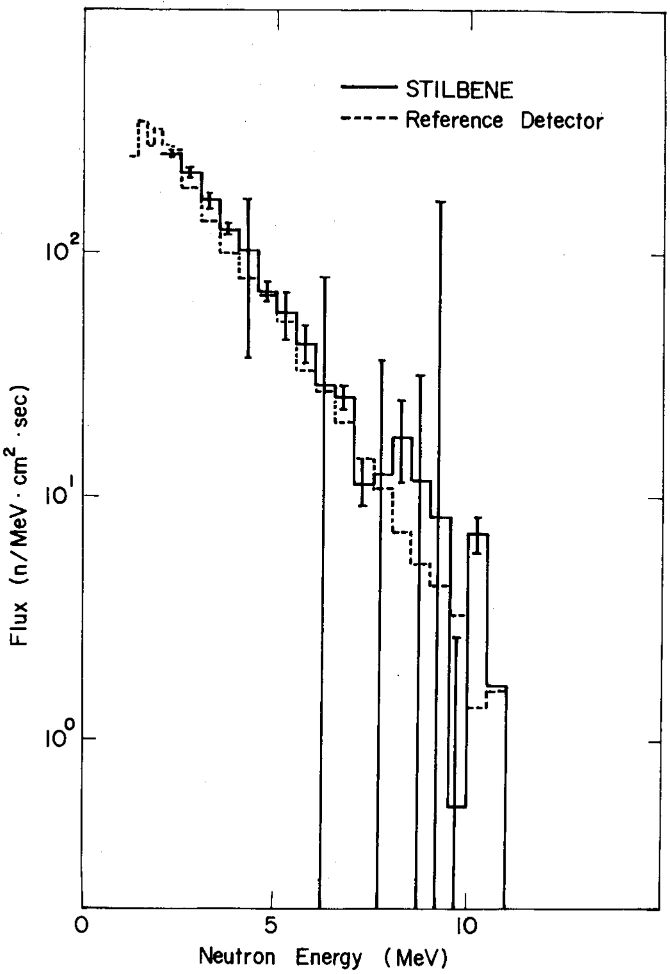

Fig. 5 Comparison of measured spectrum for ^{252}Cf neutrons by the miniature stilbene scintillator with Brodski's light output data with that by the reference NE-213 scintillator.

decide the channel number which corresponds to the standard energy, in measured pulse-height spectra of the radioisotope gamma rays.

(ii) Measurements of Fast Neutron Spectra

(a) ^{252}Cf Fission Spectrum

A ^{252}Cf neutron source is located in a heavy concrete container. Fast

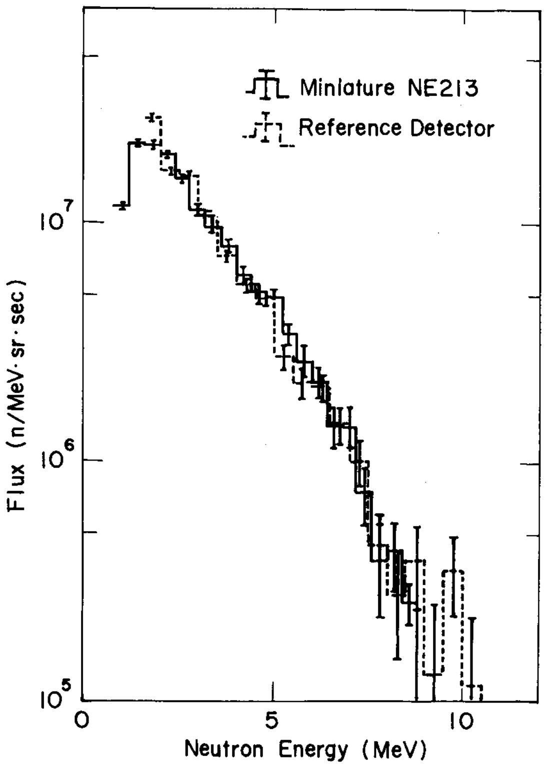

Fig. 6 Comparison of ^{252}Cf neutron spectrum measured by the miniature NE-213 scintillator with that by the reference detector.

neutrons are pulled out through a collimator. The neutron spectrum is measured by the miniature stilbene scintillator in the beam. The unfolding of the pulse-height spectrum is made by the SIMPLE method with the two proton light output data, i. e. Smith's data and Brodski's data.

Fig. 4 shows the comparison of the obtained spectrum by the stilbene with Smith's light output data with the reference spectrum which was given by the 5 cm diam. by 5 cm thick NE-213 (reference detector) with the aid of the FERDO unfolding code. The spectrum unfolded by Smith's data is shifted slightly to a lower energy as compared to the reference spectrum by a certain fraction of reduction in the horizontal axis. Fig. 5 shows the spectrum obtained with Brodski's light output data in comparison with the reference spectrum. Brodski's data gives a better agreement with the reference in the spectrum shape. We

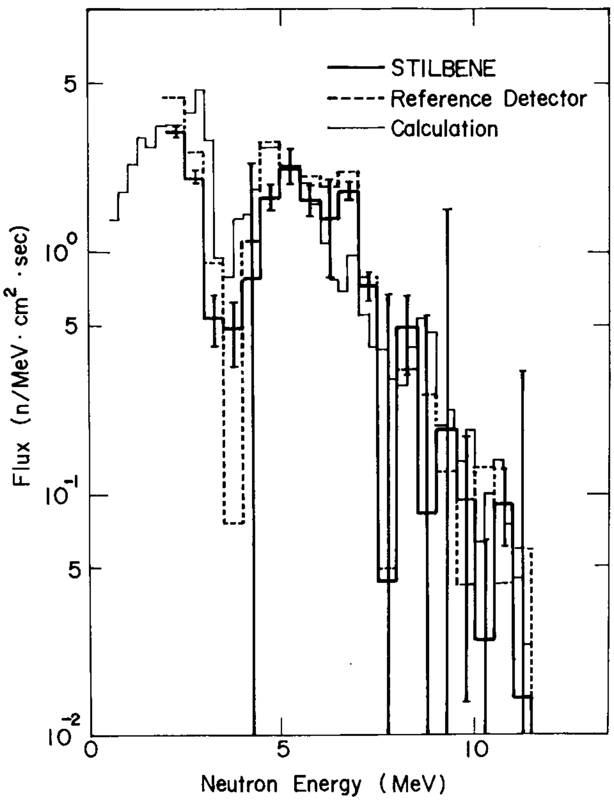

Fig. 7 Comparison of graphite transmitted neutron spectrum obtained by the miniature stilbene scintillator with those by the reference detector and the calculation.

conclude that, for our detector, Brodski's data are more suitable.

Brodski's data and the corresponding response matrix will be used for the stilbene scintillator in the unfolding described below.

Fig. 6 shows a similar comparison between the reference spectrum and the spectrum obtained by the miniature NE-213 scintillator. The two spectra are in excellent agreement.

(b) Transmission Spectrum through Graphite

A 30-cm thick graphite slab is inserted in the ^{252}Cf fission neutron beam between the detector location and the collimator exit. The spectrum of transmitted neutrons is measured by the stilbene and the reference NE-213 detector. Moreover, a Monte Carlo calculation is carried out by the pointwise Monte Carlo

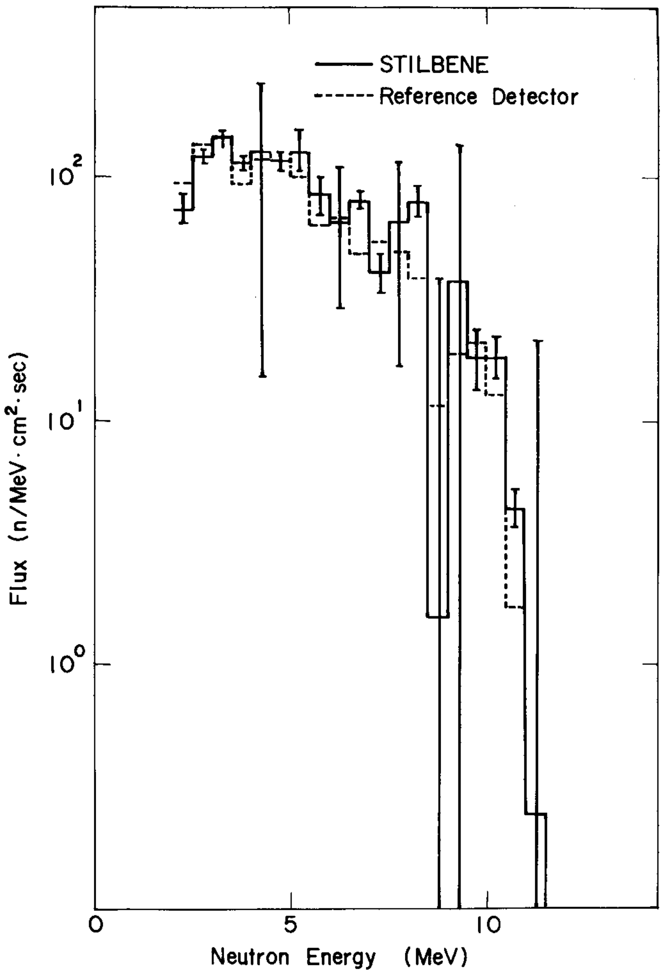

Fig. 8 Comparison of Am–Be neutron spectrum obtained by the miniature stilbene scitillator with that by the reference NE-213 detector.

code BUCCUS,[18] the geometrical model of which simulates as closely as possible the experimental one.

The results of the experiments and the calculation are compared with one another in Fig. 7. Both experimental spectra agree fairly well with each other, while the calculated one dffers from the measured spectrum. Due to some inaccuracies in the cross section data, the calculated spectrum probably includes some errors. However, since the error estimation is not done for the BUCCUS calculation, it is not known how large the errors are.

It is concluded from the agreement of the spectra by the two detectors that the miniature stilbene scintillator reproduces the graphite transmitted neutron spectrum as accuratly as does the reference detector.

(c) Am-Be Neutron Spectrum

Neutrons from an Am-Be source are measured by the stilbene scintillator and the reference detector. The results are shown in Fig. 8. Since the source strength is not enough, and since the efficiency of the miniature detector is very small, the statistics in counts are not enough for the miniature detector. Consequently, the spectrum by the miniature detector oscillates at high energies around 10 MeV. The oscillation is still seen in the intermediate energy range of 5-8 MeV, although the strength of the oscillation decreases as the neutron energy goes down. Except for this one point, the spectrum by the miniature detector agrees in general with the spectrum by the reference detector.

V. Conclusions

Application of the miniature detectors to the neutron spectrum measurements indicated that (a) the detectors in general reproduced the spectra as well as the reference detector did, (b) Brodski's proton light data for the stilbene fitted better to the small size detector than Smith's data did, and (c) the response matrices as well as the parameters for the pulse height calibration of the two miniature detectors developed in this work were verified by the test.

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