Measurements of High-Energy Gamma Rays by an Organic Liquid Scintillator

By

Kazuo SHIN*, Yoshihisa HAYASHIDA**, Seiji SHIROYA***
and Tomonori HYODO*

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Abstract

An application of an organic liquid scintillator NE-213 to a gamma-ray spectroscopy was studied. Use of a 2-dimension pulse-height analyzer made it easier to separate gamma-ray pulses and neutron pulses. The differential method was used for the unfolding of pulse-height distributions to energy spectra. The response functions and unfolded spectra of ^{137}Cs and ^{60}Co gamma rays, ^{9}Be(α, n)^{12}C, ^{19}F(p, α)^{16}O and ^{9}Be(p, γ)^{10}B reaction gamma rays are shown. The unfolded spectra of reactor gamma rays and those transmitted through an iron barrier of 15 cm in thickness are shown.

1. Introduction

Research on the transport of neutrons and gamma rays through shielding material of nuclear reactors and high-energy accelerators has been done in our laboratory from a macroscopic viewpoint. The production and transport of secondary gamma rays have been the particular interest in the research on this field. Measurements of gamma rays in a mixed field of gamma rays and neutrons are very troublesome because of damage, activation and secondary gamma rays produced by neutrons in detectors.

Measurements of neutrons by organic scintillators using a pulse-shape discrimination method against gamma-ray pulses became possible about fifteen years ago[1]. Many papers have been published on the neutron spectroscopy accompanied by an improvement of the discrimination method [2-6] as well as the progress of unfolding

* Department of Nuclear Engineering
** Present address: Nippon Atomic Industry Group Co., Ltd. 13-12 Mita 3-chome, Minato-ku, Tokyo
*** Present Address: The Research Reactor Institute, Kyoto University.

methods from a pulse-height distribution to an energy spectrum of neutrons[7-11].

Organic scintillators also have been used for the detection of gamma rays, although in general, its application is not for spectroscopy. The reason is that they have no distinct photo-peak in a pulse-height distribution for mono-energy gamma rays, and have broad gaussian distributions for mono-energy electrons.

The possibility of gamma-ray spectroscopy by a stilbene scintillator discriminating against neutron pulses was shown by Cialella and Devanney[12] and Dvukhshers-tnov et al.[13] The former measured gamma-ray spectra from several nucleides emitting gamma rays between 0.322 MeV (^{51}Cr) and 1.84 MeV (^{88}Y) and also those from a Pu-Be neutron source after unfolding by an inverse-matrix method. The latter measured them from ^{137}Cs and the Po-Be neutron source by a differential method.

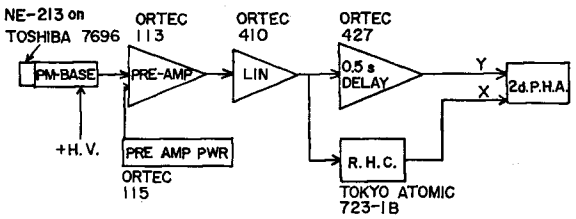
A series of studies on the unfolding from pulse-height distributions to energy spectra has been done by one of the authors (T. H.) for NaI(Tl) scintillators[14),15] and a ^{3}He counter[16].

In this paper, an experiment on the spectroscopy of high-energy gamma rays using an organic liquid scintillator and the differential method is described. Separation between pulses of gamma rays and those of neutrons was improved by using a rise-time to pulse-height converter and a two-dimension pulse-height analyzer (2d. P. H. A.).

2. Measurement of Gamma Rays Discriminating against Neutrons

An organic liquid scintillator NE–213, encapsulated in a glass cylinder 5.08 cm (2 in.) in diameter and 5.08 cm (2 in.) long, with the outside painted white, was used for the measurements of several energies of discrete and continuous gamma rays. Figure 1 shows a block diagram of the measuring system used in this experiment. The difference of the rise-time of pulses was enlarged by a rise-time to pulse-height converter, and its output pulses and those of linear circuits were fed to input terminals of X- and Y-axes of 2d. P. H. A. The pulses were stored in the memory of 2d. P. H. A. in the following category: X-axis for the rise time of pulses, Y-axis for the pulse height and Z-axis for number of pulses. Inspection of the X-Z section at each pulse height made it easy to distinguish gamma ray and neutron pulses. The number of pulses in bits of the memory at the same pulse-height of gamma rays was summed up, and a pulse-height distribution was obtained.

Figure 2 shows pulse-height distributions for the gamma rays of ^{137}Cs (0.662 MeV), ^{60}Co (1.172 and 1.333 MeV) and gamma rays from ^{9}Be(α, n) ^{12}C (4.43 MeV), ^{19}F(p, α) ^{16}O (6.13 MeV) and ^{9}Be(p, γ) ^{10}B (7.48 MeV) reactions, respectively. The gamma source of ^{137}Cs and ^{60}Co was a point isotropic source of approximately 10



NE 213 Organic liquid scintillator, 5.08 cmø x 5.08 cm
TOSHIBA 7696 Photomultiplier tube
ORTEC 113 Scintillation Preamplifier
ORTEC 115 Preamplifier Power Supply
ORTEC 410 Linear Amplifier
ORTEC 427 Delay Amplifier
TOKYO ATOMIC 723-1B Rise Time to Height Converter
2d. P. H. A. Two-dimension multi-channel pulse height analyzer

Fig. 1. Block diagram for the measurement of gamma rays discriminating against neutrons. The detector is a liquid scintillator encapsulated in a glass cylinder of 5.08 cm (2 in.) in in.-diameter by 5.08 cm (2 in.) long.

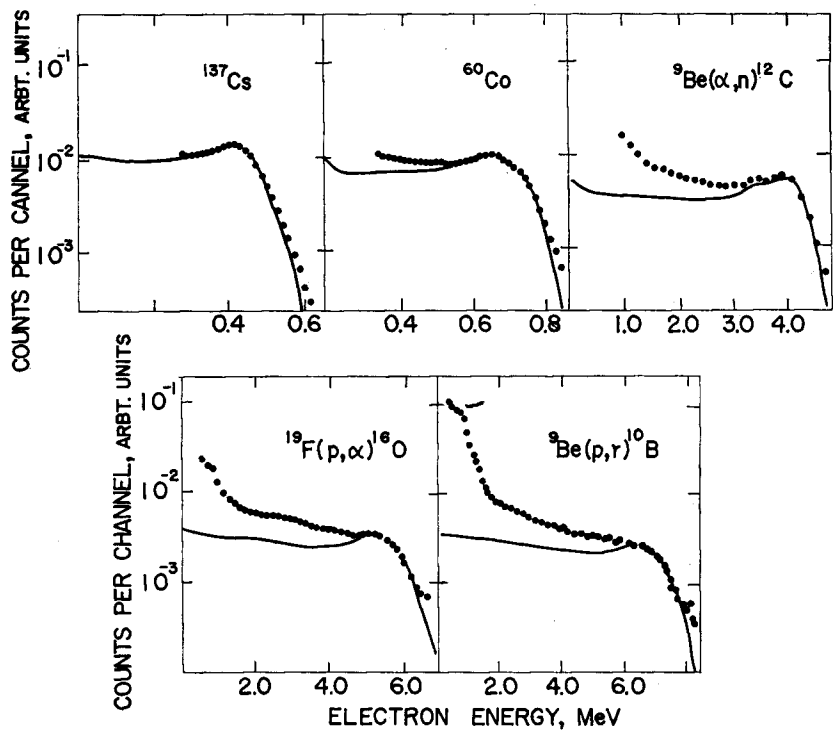


Fig. 2. Pulse height distributions obtained by a liquid Scintillator for gamma rays from ^{137}Cs (0.662 MeV), ^{60}Co (1.172 and 1.333 MeV), ^{9}Be(α, n)^{12}C (4.43 MeV), ^{19}F(p, α)^{16}O (6.13 MeV) and ^{9}Be(p, γ)^{10}B (7.48 MeV)—dotts. Curves are shown calculated value.

mCi. An Am-Be neutron source of 1 Ci was used as a gamma source of ^{9}Be (α, n) ^{12}C reaction. Protons accelerated by a Van de Graaff accelerator were used for the ^{19}F(p, α) ^{16}O and ^{9}Be(p, γ) ^{10}B reactions.

Comparing the pulse-height distributions and calculated response functions of the scintillator obtained by the Monte Carlo method[17], a rather good agreement was obtained in the pulse-height distributions of ^{137}Cs and ^{60}Co gamma rays.

There is, however, considerable discrepancy between them for higher-energy gamma rays. The cause of the discrepancy might be considered as follows. A considerable amount of low-energy gamma rays was produced in the Am-Be neutron source and ^{19}F(p, α) ^{16}O and $_{9}$Be(p, γ) ^{10}B reactions. Scattered gamma rays and secondary electrons from outside the scintillator may be considerable in their energy and amount. These might affect the increase of the number of pulses in the lower part of the pulse-height distributions. The calculation of the response functions was carried out without consideration of these effects.

3. Unfolded Spectra of Discrete and Continuous Gamma Rays

The differential method was applied for the unfolding of the pulse-height distribution to energy spectra because of its simplicity and dispensability of exact response functions. The procedure of the differential method for neutrons[7] was translated to gamma rays. The response functions for mono-energy gamma rays were assumed to be rectangular and their upper edge was identified to the Compton edge of the spectra of recoil electrons. Also, their area was equalized to the total detection efficiency of the scintillator.

$$\frac{dN_e}{dE_e}=\int_{E'}^{\infty}[1-\exp\{-\mu(E_\gamma)x\}]\frac{dN_\gamma}{dE_\gamma}\frac{dE_\gamma}{E_C} \tag{1}$$

where dN_e/dE_e=number of electrons per unit electron interval, dN_γ/dE_γ=number of photons per unit area per unit photon energy interval incident upon the scintillator, E_γ=photon energy, E_e=electron energy, $\mu(E_\gamma)$=attenuation coefficient of gamma rays, x=thickness of the scintillator, E_C=Compton edge, E'=gamma-ray energy corresponding to the Compton edge.

Differentiating formula (1), we obtain,

$$\frac{dN_\gamma}{dE_\gamma}=-\frac{E_C}{1-\exp\{-\mu(E_\gamma)x\}}\left[\frac{d^2N_e}{dE_e^2}\right]_{E_e=E_C} \tag{2}$$

The shape of the response functions for mono-energy gamma rays is not exactly rectangular as shown in Fig. 2, but suggests that it may be applicable for the unfolding by the differential method. Figure 3 shows energy spectra unfolded from the

pulse-height distributions shown in Fig. 2. The spectra of ^{137}Cs and ^{60}Co seem to be satisfactory, excluding negative parts caused by over-correction for concave parts of the distributions. Each spectra of 4.43, 6.13 and 7.8 MeV gamma rays has a distinct peak corresponding to those energies. These spectra also have tails. Two types of contribution to the tails may be considered. One is the contribution of scattered gamma rays and secondary electrons described in the previous chapter. The other is a deviation of the shape of the response function from the exact rectangle. The amount or ratio of the two types of contribution is not known.

For the purpose of testing the applicability of this method to several discrete-energy gamma rays, those from the ^{137}Cs and ^{60}Co source and an Am-Be neutron source were superposed on a one pulse-height distribution and unfolded. The results are shown in Fig. 4 and good isolated peaks sutalbe for the energies of incident

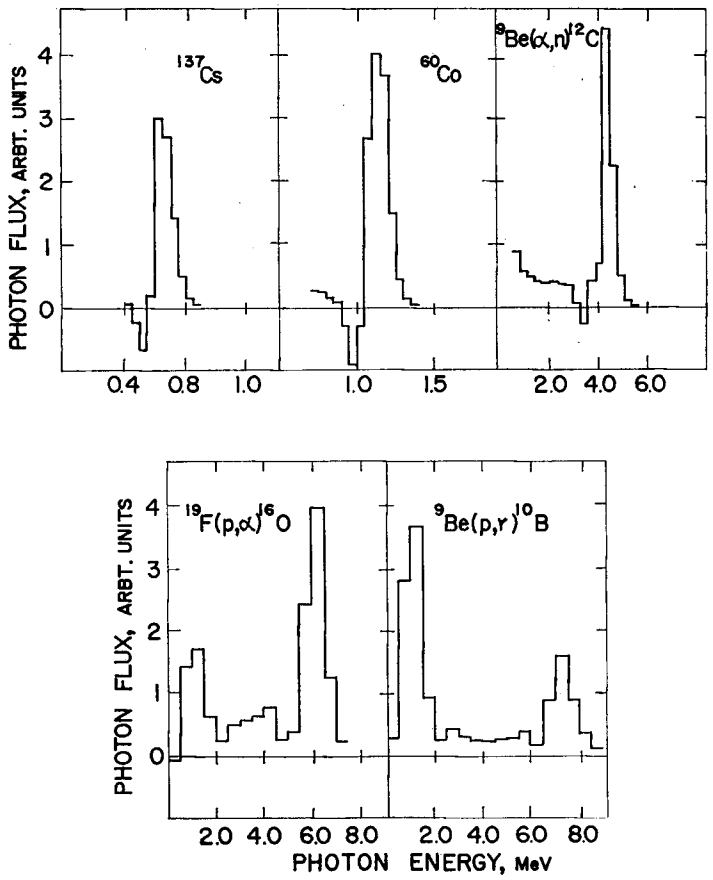


Fig. 3. Energy spectra unfolded from the pulse height distributions shown in Fig. 3.

gamma rays were obtained.

The gamma rays from the reactor core of the Fast Neutron Source Reactor "Yayoi" of the University of Tokyo were measured by this scintillator and unfolded by this method. Figure 5 shows the geometry of the experiments. The gamma rays accompanied by neutrons, passed through a heavy concrete collimator 5 cm in diameter and 150 cm long, were incident to the detector. Figure 6 shows the gamma rays from the reactor core and incident directly to the detector. It shows the gamma-ray spectrum is in good shape for the semi-empirical formula obtained by Goldstein[18] for prompt fission gamma rays,

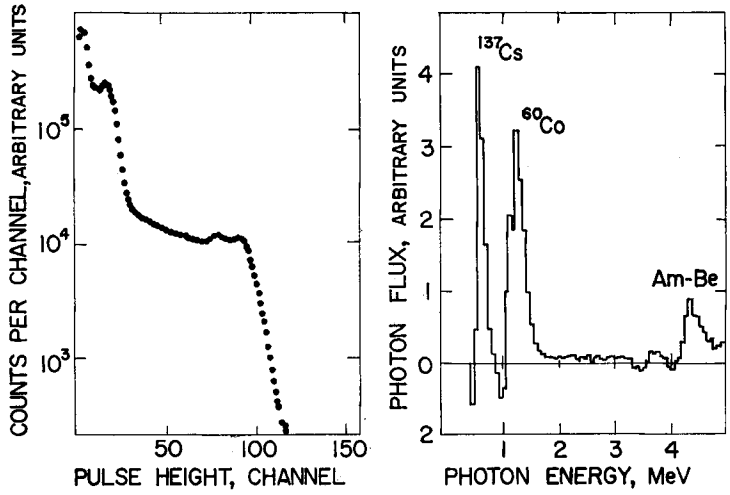


Fig. 4. Pulse-height distribution and unfolded energy spectrum for superposed gamma rays from ^{137}Cs, ^{60}Co and Am-Be neutron source.

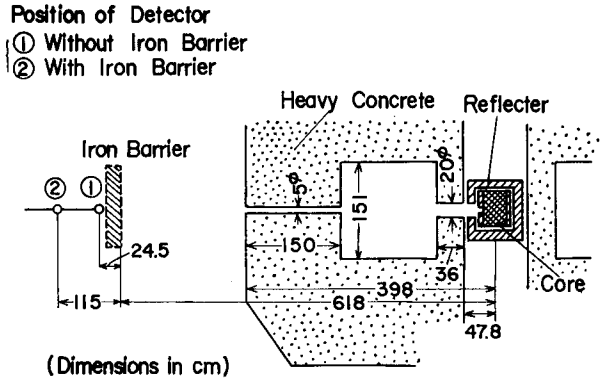


Fig. 5. Geometry of measurements at the Fast Neutron Source Reactor "Yayoi".

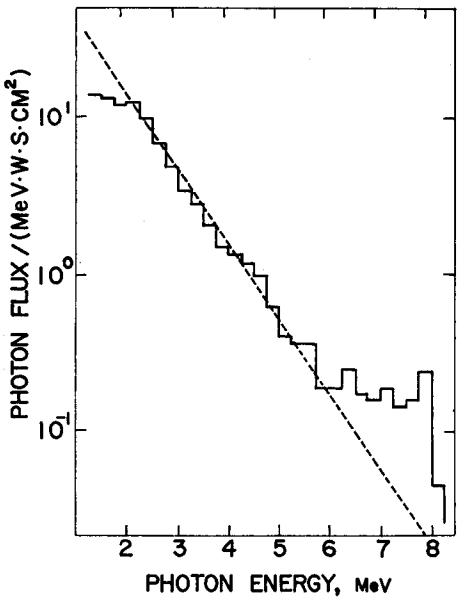


Fig. 6. Energy spectrum of gamma rays from the Fast Neutron Source Reactor "Yayoi" and Semi-Empirical formula for fission gamma rays obtained by Goldstein[18].

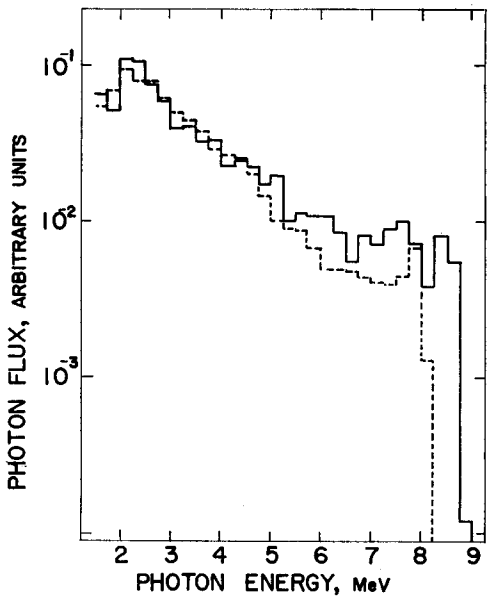


Fig. 7. Spectrum of gamma rays from the reactor core of "Yayoi" and passing through iron barrier of 15 cm in thickness (solid line). Estimated spectrum considering the attenuation in the iron barrier for gamma rays shown in Fig. 6 (dotted line).

$$N(E) = 8.0 \exp(-1.10\,E) \qquad \text{MeV}^{-1} \tag{3}$$

were E=gamma-ray energy. There is a large discrepancy between the higher part of the experimental value and the formula. These high-energy gamma rays may be emitted mainly from lead and iron composing the reflector of the reactor.

Figure 7 shows the gamma rays from the reactor core, and passed through an iron barrier of 15 cm in thickness. The dotted-line histogram shows an estimated spectrum obtained by multiplication of the histogram shown in Fig. 6 by $\exp(-\mu(E)x)$, where $\mu(E)$=linear attenuation coefficient, E=energy of gamma rays, x=thickness of iron barrier. Good agreement was obtained between these spectra, excluding two peaks in the high-energy part and a peak in the low energy part. The former peaks may be neutron capture gamma rays of ^{57}Fe in the iron barrier, 7.64, 6.12 and 6.06 MeV, and the latter those from hydrogen nucleus in the scintillator.

4. Conclusion

The unfolded spectra show that the differential method is satisfactorily applicable for the first approximation of unfolding from a pulse-height distribution to an energy spectrum without knowledge of the response functions of the scintillator of this size of NE–213. Figures 6 and 7 show that the scintillator is one of the superior detectors of high-energy gamma rays being produced in a large scale of material of reactor shielding and a reactor core.

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