Some Experiments on Gamma-Ray Backscattering

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The backscattered radiation was observed by a scintillation spectrometer for Co^{60} and Cs^{137} gamma-ray point sources which were in contact with backscatterers of paraffin, aluminum, iron, tin and lead. Contributions to backscattered rays from single and double or multiple Compton scattering of incident gamma-rays were clarified. Intensity of backscattered radiation was measured as a function of scatterer's thickness. Although the experimental arrangement was not so simple that exact analysis of observed data could not be performed, experimental findings were interpreted qualitatively by theoretical predictions. Thus, experimental results obtained may afford some valuable knowledge to design considerations of experimental arrangemments, apparatuses and facilities using gamma-rays.

INTRODUCTION

To estimate the gamma-ray backscattering from a variety of materials is important for shielding problems of nuclear facilities as well as for some experimental researches with gamma-rays. Some investigations, experimental and theoretical, have so far been published by many workers[1~4]. One of the present authors (T.H.) performed experimental researches on some aspects of the gamma-ray backscattering by the use of gamma-ray sources of Co^{60} (1.33 and 1.17 MeV), Cs^{137} (0.662 MeV) and Au^{198} (0.411 MeV) and backscatterers of paraffin, aluminum, copper, iron, tin and lead[5]. In the course of this work, prior to the systematic research on backscattering of gamma radiation it became necessary to clarify what region of the scatterer with which a point gamma-ray source was contacted was effective for this phenomenon.

Heine and McCall[1] published experimental results on the effect of thickness and area of backscatterers on pulse energy spectrum of the backscattered radiation of Hg^{203}, Cs^{137} and Co^{60} gamma-rays. Berger and Doggett[2] calculated, by the Monte Carlo method, reflection build-up factors of collimated gamma-ray beams for different thicknesses of backscatterers of water, iron, tin and lead. Bulatov and Garusov[4] measured the effect of thickness of backscatterers on its energy albedo for gamma-rays from Co^{60} and Au^{198} being incident at angles of 0°, 45° and 60°.

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In the present paper the authors will report some experimental facts concerning the scattered radiation emitted perpendicular from points on a scatterer's surface, being in various distance from a point source placed contact with the scatterer, as well as the observed relation between intensities of scattered rays and thickness of scatterers.

EXPERIMENTAL PROCEDURE

The experimental arrangement of gamma-ray source, scatterer and scintillation detector is shown in Fig. 1. The scintillation detector is composed of a Harshaw 3 inch diameter by 3 inch long NaI(Tl) crystal, DuMont 6363 photomultiplier tube and cathode follower preamplifier. The detector was shielded by a thick lead collimator with a canal of 2 cm diameter as shown in the figure. The pulse-height distribution was measured with a core memory type, 400 channel, pulse-height analyzer, to which output pulses of the detector were fed through a linear amplifier of Argonne A-61 type.

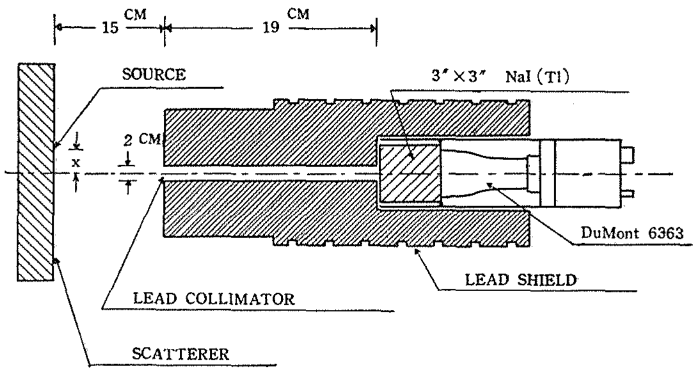

Fig. 1. Experimental arrangement of gamma-ray source, scattering material, NaI(Tl) crystal and lead collimator.

As the first step of the work we had to measure the geometrical efficiency of the experimental arrangement of the source and detector with a collimator. A Cs^{137} source of about 80 μC used for this purpose was in the form of evapolated deposit of about 3 mm diameter of radioactive caesium chloride solution mounted on a very thin mica sheet. By a precision counting-rate meter and linear recorder we followed the variation of counting-rate of photopeak maximum of Cs^{137} gamma-rays when its source was moved laterally on a plane located 15 cm from the front of the collimator.

The observation, presented in Fig. 2, shows the effective aperture of the collimator to be about five quarters of the geometrical aperture. This may be due to the size of the source used and to penenetration of the gamma-rays through the collimator edges and scattering from the inner wall of the collimator. Strict analysis of this counting-rate curve shown in the figure is very difficult. However, it is understood qualitatively by the theory of gamma-ray collimator developed by Mather[6]. Here, we would like only to present the observed result without discussion,

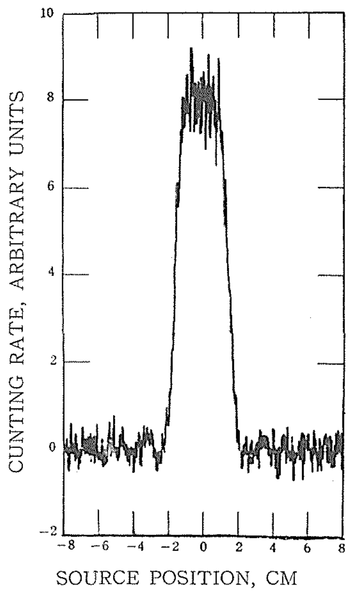

Fig. 2. Geometrical efficiency of the collimator.

because this measured effective aperture would have some meaning for the measured backscattering of the radiation which will be mentioned here after.

In the present experiment, we were only concerned with the backscattered radiation emitted upright from a surface of the backscattering material with a point source in contact with it, by the experimental arrangement as shown in Fig. 1. The gamma-ray sources of Co^{60} of about 50 μC and Cs^{137} of about 100 μC are both 2 mm×4 mm strips of filter paper containing evaporated radioactive cobaltous chloride and caesium chloride solution, respectively, mounted on thin mica sheets of about 10 mg/cm^2 thick.

In the first set of experiments with Co^{60} and Cs^{137} gamma-rays, paraffin, aluminum, iron, tin and lead were used as scatterers, of which thickness and size were chosen as effectively infinite, and relative positions of a gamma-ray point source to the detector were changed; on the scatterer's surface the source was displaced laterally 0, 3, 6, 9 and 12 cm from the centerline of the scintillation detector. Pulse-height spectra of backscattered radiation with different source positions were observed.

As the second set of experiments we observed the intensity of backscattered radiation as a function of thickness of the scatterer, where a point source of gamma-rays was placed just in front of the detector, *i.e.* 0 cm from the centerline of the detector.

The background due to the directly incident gamma-rays from the source was of course subtracted in each experiment. Furthermore, in order to eliminate the effect of obliquely incident radiation which might penetrate lead of the collimator and contribute to the spectrum, a lead plug was used, which could be inserted exactly into a collimator canal. By observing the difference of countings at each channel of pulse-height with and without this plug we could subtract the contribution of

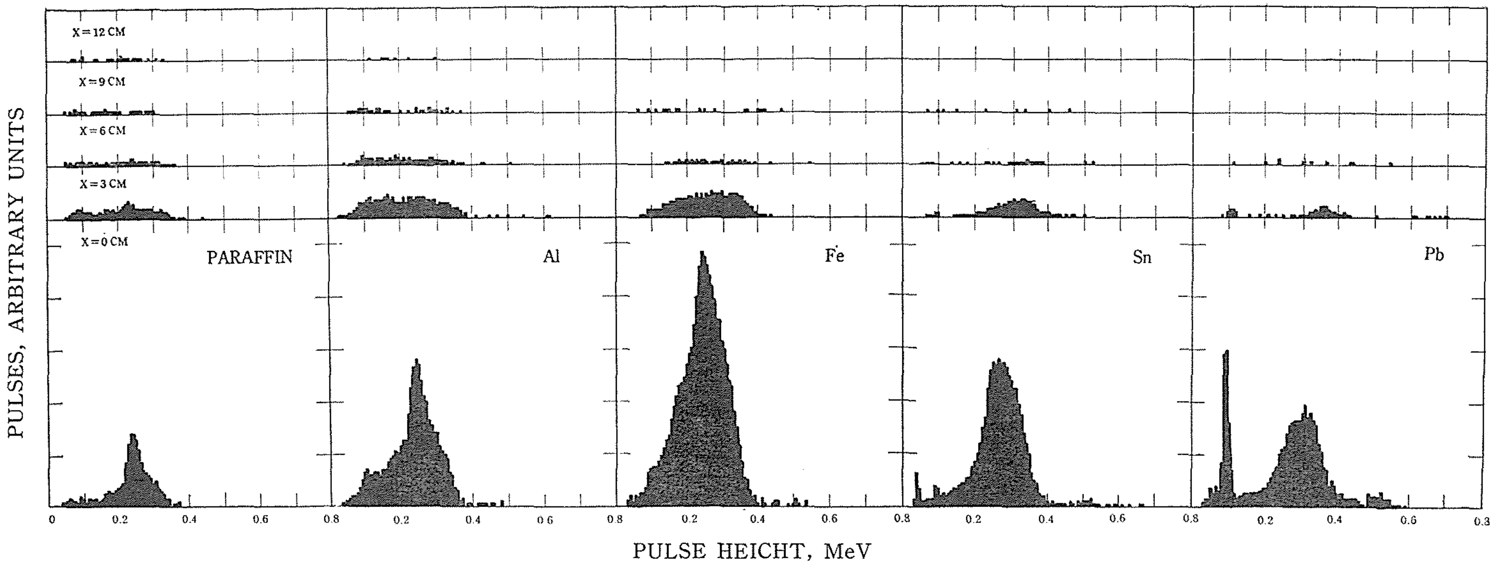

Fig. 3. Pulse energy spectra of backscattered radiation of Co^{60} gamma-rays (1.25 Mev-averaged). A point source is in contact with scatterers. The source position is shifted laterally 0, 3, 6, 9 and 12 cm from the centerline of the detector.

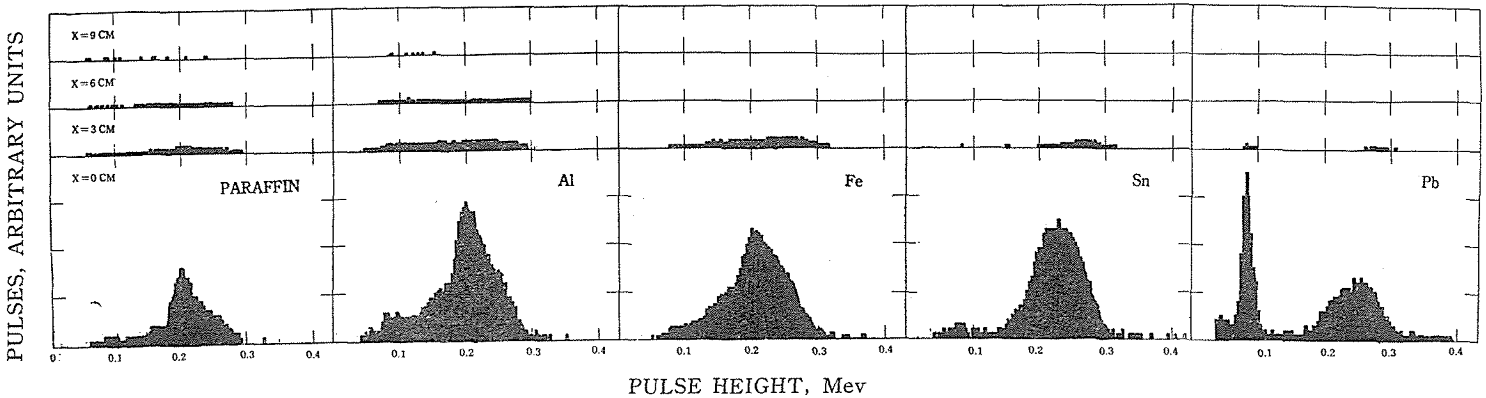

Fig. 4. Pulse energy spectra of backscattered radiation of Cs^{137} gamma-rays (0.662 MeV). A point source is in contact with scatterers. The source position is shifted laterally 0, 3, 6 and 9 cm from the centerline of the detector.

such undesirable radiation from the observed pulse energy distribution.

RESULT AND DISCUSSION

The pulse-height distribution of backscattered gamma-rays with various scatterers and with Co^{60} and Cs^{137} gamma-ray sources, of which relative positions to the detector were varied, are shown in Figs. 3 and 4. In the low energy parts of the spectra, especilly in the case of the lead scatterer, there is a very sharp peak by the lead K X-rays (76 keV) in addition to the backscattered radiation.

The energy of a gamma-ray photon after a Compton scattering is given by

$$h\nu' = \frac{h\nu}{1+\frac{h\nu}{mc^2}(1-\cos\theta)}, \qquad (1)$$

where $h\nu$ = energy of the primary photon, $h\nu'$ = energy of the scattered photon, θ = angle between directions of primary and scattered photons, and mc^2 = 0.511 Mev = rest energy of the electron. Eq. (1) is shown graphically for Co^{60} and Cs^{137} gamma-rays

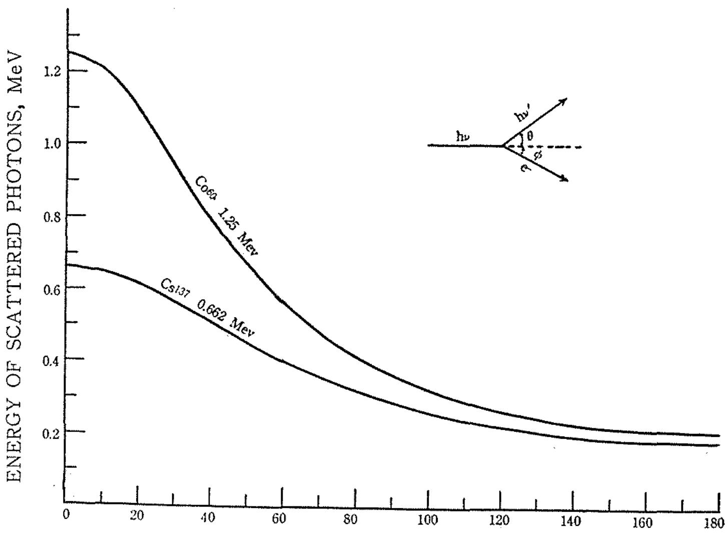

Fig. 5. Energy of the Compton scattered photons as a function of scattering angle θ for primary gamma-rays from Co^{60} and Cs^{137}.

in Fig. 5. Even though the gamma-rays from Co^{60} consist of two lines emitted in equal numbers with energies of 1.17 and 1.33 MeV, in the present case it is assumed practically to be monochromatic of being 1.25 MeV.

The observed peaks of the spectra shown in Figs. 3 and 4 are resonably explained as to be due to the scattered radiation by the single Compton scattering. The scattering angles corresponding to the peak maxima of the observed spectra can be calculated by Eq. (1), if the observed distribution of the backscattered radiation is assumed to be due to a single scattering. Table 1 gives the result of this calculation.

Table 1. Single Compton scattering angles corresponding to the peak maxima of observed spectra of backscattered radiation.

Gamma-rays (Source Position, x=0 cm)	Scatterer	Peak maxima of observed spectra (MeV)	Calculated scattering angle, by Ep. (1)
Co^{60}, 1.25 MeV (Averaged)	Paraffin	0.24	135°
	Aluminum	0.24	135°
	Iron	0.24	135°
	Tin	0.26	123°
	Lead	0.31	104°
Cs^{137}, 0.662 MeV	Paraffin	0.20	142°
	Aluminum	0.20	142°
	Iron	0.21	131°
	Tin	0.23	117°
	Lead	0.25	106°

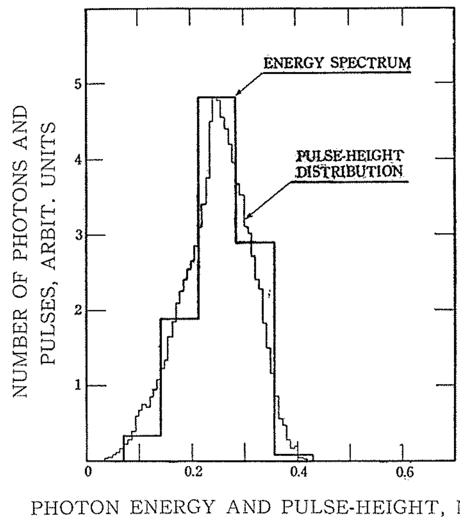

Fig. 6. Response corrected energy spectrum of backscattered radiation with an iron scatterer for gamma-rays from Co^{60}. Position of the gamma-ray source is x=0 cm.

Figure 6 shows an example of the energy spectrum of backscattered radiation obtained by applying a 20×20 inverse response matrix covering photon energies from 0 to 1.44 Mev for 3″×3″φ NaI(Tl) crystal[5] to the observed pulse-height spectrum.

From Fig. 5 it can be seen that the energy of the scattered radiation is nearly constant for θ greater than 150°, about 0.21 and 0.19 MeV for Co^{60} and Cs^{137} gamma-rays, respectively. Thus, the low energy parts of scattered radiation smaller than those values, with the exception of K X-ray peaks, may be concluded to be due to double or multiple Compton scattering. By examining Figs. 3 and 4, it may also be seen that the peak maxima of the observed spectra when the source position x is greater than 0 cm are shifted slightly to higher energy region, although this tendency could not be measured exactly by the present observation.

It was of interest to find that under the present experimental arrangement the integrated intensity of backscattered radiation decreases very rapidly as x increases according appproximately to a simple empirical formula, $I(x)=I(0)e^{-ax}$, where x is measured by units of Compton mean free paths of primary gamma-rays for backscatterers concerned and a is a constant characterized by gamma-rays and scatterer used. This empirical relation is shown in Figs. 7 and 8. The integrated

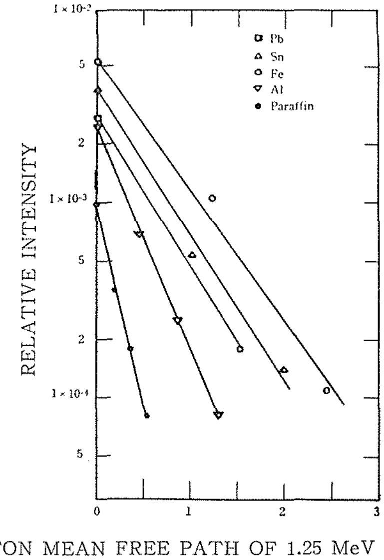

Fig. 7. Integrated intensity of backscattered radiation as a function of the source position, x. A Co^{60} gamma-ray source is shifted laterally from the centerline of the detector.

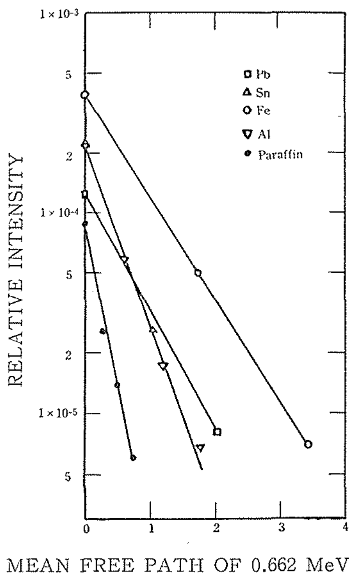

Fig. 8. Integrated intensity of backscattered radiaton as a function of the source position, x. A Cs^{137} gamma-ray source is shifted laterally from the centerline of the detector.

intensity of the backscattered radiation, shown in ordinates of the figures, is expressed in units of ratio of integrated intensity of scattered rays to that of directly incident rays from a source being at x=0 cm and without any backscatterer. The integrated intensities of radiation were obtained by the observed pulse-height distribution and by the use of a 20×20 inverse response matrix of the NaI(Tl) crystal used in the present work.

Since the present geometry of detector, scattering material and gamma-ray source is not so simple, no exact conclusion can be derived. However, from these observed data it may be seen qualitatively that the surface layer of a scatterer responsible for backscattering of gamma-rays should be thinner for a material with higher atomic number.

A set of experiments was performed to check this fact by measuring the intensity of backscattered radiation as a function of thickness of the scatterer. Measurements were carried out for gamma-rays from a point source in contact with aluminum and lead scatterers of different thickness, where the source position is x=0 cm. The results obtained are given in Figs. 9 and 10. For lead scatterers our results are in consistent with the theoretical predictions of other workers[7,8] and the observations by Bulatov and Garusov[4], who measured total gamma-ray energy albedo as a function of thickness of scatterers. But, it is noted that for aluminum the intensity curves obtained by isotropic source under the present geometry

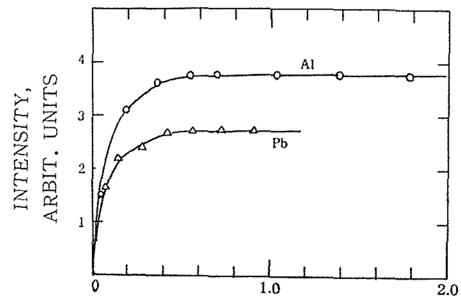

Fig. 9. Measured intensiiy of backscattered radiation of Co^{60} gamma-rays as a function of scatterer thickness. The source position is x=0 cm.

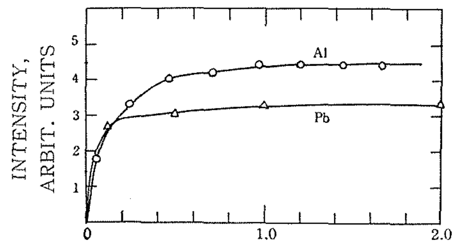

Fig. 10. Measured intensity of backscattered radiation of Cs^{137} gamma-rays as a function of scatterer thickness. The sourceposition is x=0 cm.

become saturated at much smaller thickness than the values obtained by other workers with normally incident parallel beams. Since the Compton scattering cross section is proportional to the number of electrons per unit volume, while the photoelectric absorption cross section increases very rapidly with increasing atomic number and decreasing photon energy and scattered photons suffer a photoelectric absorption before they can escape from a scatterer of high atomic number, high atomic number materials like lead are poor scatterers for gamma-rays of all energies, as one can see from the measuring data we obtained.

The present experimental arrangement was rather complicated and observed pulse-height distribution of scattered radiation was so weak that the observed data seemed to endure no exact analysis. However, the present series of measurements allowed us to distinguish between single and multiple scattered radiation and to get some qualitative findings such as the region of a scatterer responsible for this phenomenon, as expected by theoretical considerations, which would be valuable for further work on backscattering of gamma-rays as well as for design considerations of the gamma-ray experimental facility.

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