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60-keV Gamma-Rays Streaming in a Two-Bend Duct

Syuichi BAN[†], Hideo HIRAYAMA and Yoshihito NAMITO

[*] *High Energy Accelerator Research Organization*

Low-energy gamma-rays are linearly polarized after scattering. The 2nd scattering is anisotropic in the azimuth distribution. Two types of rectangular ducts were made. Both were right-angle 2-bend ducts, that is, 3-legged ducts with stainless-steel walls. All legs of the flat type duct were placed on a flat plane. The 3rd leg of the cubic type stood vertically. The length of both ducts was the same. In each duct, Am-241, 60-keV gamma-ray source was placed and the photon fluxes were measured at the exit using a NaI(Tl) scintillator. Gamma-rays transport calculations were made using EGS4 Monte Carlo code. Both the measured and calculated results showed that the fluxes for the flat type were 3-4 times larger than those for the cubic type.

KEY WORDS: Gamma-ray, shielding, duct, 2-bend, streaming, linear polarization, Compton, EGS4

I. Introduction

To consider photon scattering, the linear-polarization effect is important in a synchrotron radiation facility. Originally, gamma-ray sources are not polarized. However, this effect becomes important when low-energy photons are scattered. Exposure buildup factors of gamma-rays below 100 keV become slightly larger due to this effect.(1) In the case of a 90-degree scatter, this effect becomes more evident.

When gamma-ray sources are placed in a 90-degree 2-bend duct, a 3-legged duct, and the photons are measured at the exit, the scattering polar angles are close to 90-degrees. A low-energy photon is linearly polarized after the 1st scatter. In the 2nd scatter, the scattering cross section of the polarized photon depends on the azimuth angle.

There are 2 types of right-angle 2-bend ducts. The flat type is shown in **Photo 1** and the cubic type in **Photo 2**. Each leg of the flat type points in the direction of x, y and x. Another cubic type points in x, y and z direction.

In the former, the gamma-ray fluxes are larger at the exit of the duct. In the latter, the fluxes are smaller. However, a quantitative estimation is rarely made. In this work, measurements were performed using an Am-241 59.5-keV gamma-ray source. A 90-degree 2-bend duct was made. Both the flat and cubic types of 90-degree, 2-bend ducts were constructed, with walls of stainless steel. The gamma-ray fluxes were measured using a 2-inch diameter, 2-mm-thick NaI(Tl) scintillation detector.

Usually, duct streaming is calculated without any linear-polarization effect. It will be shown in this paper that when a 2-bend duct is placed on a flat plane, these calculations underestimate the low-energy photon fluxes and overestimate these for the cubic type. A simple estimation was made using a single scattering approximation in each leg, while considering the polarization effects in both Rayleigh and Compton scattering.(2) Calculations were also made using EGS4(3) Monte Carlo code.

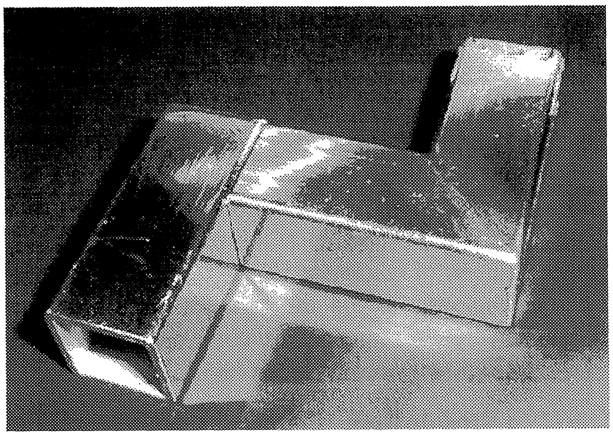

Photo 1 Flat-type duct. The wall is made of stainless steel.

Photo 2 Cubic-type duct. The component is the same as that in Photo 1. The gamma-ray source was placed at the top position.

[*] *Oho, Tsukuba, Ibaraki 305-0801.*
[†] Corresponding author, Tel. +81-298-79-6001, Fax. +81-298-64-4051, E-mail: s.ban@kek.jp

II. Measurements

Measurements were made using a 59.5-keV gamma-rays source, 11.1 GBq Am-241 (Amersham. Code: AMC17. 1.67×10^8 Gamma-rays sr^{-1} s^{-1} from the data sheet). The source was placed at the entrance of the 1st leg, the top position in Photo 2. The active diameter was 12 mm. In **Fig.1**, the experimental setup is shown for the flat type duct in Photo 1. The walls of the duct were made of 304 type stainless steel. The outer cross section of the duct was 19x19 mm and inner size was 16x16 mm. Each leg of the duct was 30-70 mm long. For both cases in Photo 1 and 2, the same components ware used. Around the duct, Pb blocks were placed so as to reduce the photons outside of the duct. The gamma-ray fluxes were measured using a 2-inch diameter, 2-mm-thick NaI(Tl) scintillation detector with a 0.15-mm Be window. To measure the background, the exit of the duct was blocked by a 3-mm-thick Pb plate.

The background was 24 % of the flat case and 56 % of the cubic case. Subtracting the background, gamma-rays were measured which streamed inside the duct.

The measured spectra are shown in **Fig. 2**. The photons were both due to Rayleigh and Compton scattering, and contribution of each was not known. The measured counts between 40 and 60 keV are given in **Table 1**. They were normalized per one source gamma-ray, 59.5-keV gamma-ray intensity shown in the data sheet. Only statistical errors were estimated. The detection efficiency of the NaI(Tl) detector was simply assumed to be equal to 1, though small escape peaks of iodine K-Xrays from the detector are shown in Fig.2. Because the detector was larger than the cross-sectional area of the duct, the measured counts are close to number of gamma-rays through the duct. The number of photons was 3-4 times larger for the flat-type duct, compared to the cubic case, though the total length of the duct was kept the same for both cases.

III. EGS4 Simulation

EGS4 was improved in low-energy photon transport(4) by including linearly polarized photon scattering(2) and Doppler broadening of the Compton-scattered photons. In this simulation, the former(2) was included, but the latter was ignored. The particle-splitting technique was applied(5) at region boundaries. Four splitting points were set and 5×10^7 case histories were used at each point. There were two media: stainless steel and air. The calculated number of photons through the duct are given in Table 1. They are 1.5 times larger than measured number of photons because all photons were scored at the exit of the duct in the simulation. The ratio of flat/cubic is in good agreement with the measured ones.

IV. Simple Estimation

Because the fluxes become 10^9 times smaller at the exit, such a simulation is not easy using a Monte Carlo photon-transport code.

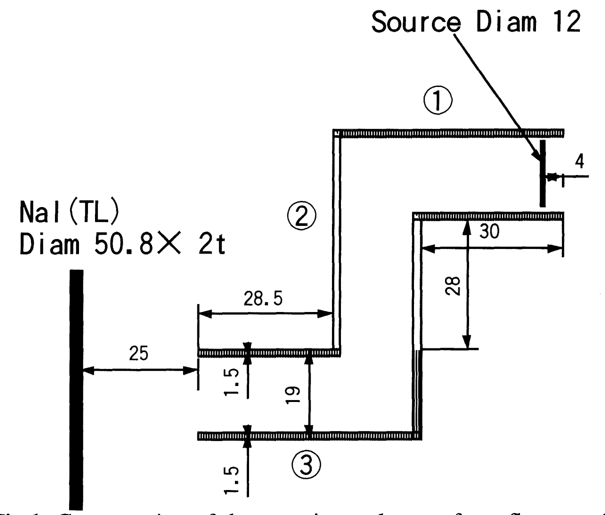

Fig.1. Cross section of the experimental setup for a flat-type duct in Photo 1. The dimensions are in mm. For the cubic type in Photo 2, the size is the same and the 1st leg stands vertically.

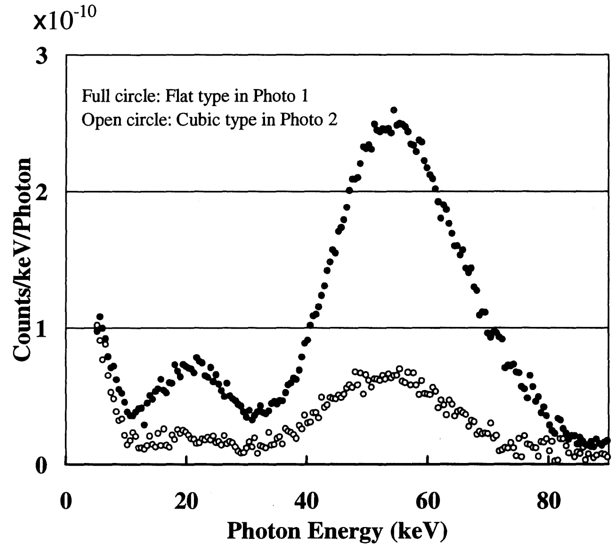

Fig. 2. Measured photon spectra. A background was subtracted and only photons streaming inside the ducts are shown. The spectra were normalized per keV and per one source gamma-ray.

Table 1 Number of Gamma-rays between 40 and 60 keV. The counts were normalized per one source gamma-ray.

	Flat[a]	Cubic[b]	2nd Leg[c]
Fig.1[d]	$6.77 \pm 0.03 \times 10^{-9}$	$1.81 \pm 0.02 \times 10^{-9}$	1.1×10^{-5}
Cal[e]	$1.01 \pm 0.04 \times 10^{-8}$	$2.9 \pm 0.2 \times 10^{-9}$	$1.7 \pm 0.2 \times 10^{-5}$
Long[f]	$1.96 \pm 0.02 \times 10^{-9}$	$4.9 \pm 0.2 \times 10^{-10}$	4.0×10^{-6}

[a] Flat type, as shown in Photo 1.
[b] Cubic type, as shown in Photo 2. The total length of the duct was kept the same as that in Photo 1.
[c] At the exit of the 2nd leg. The 3rd Leg was removed.
[d] Measured using NaI(Tl). The duct sizes are shown in Fig.1.
[e] Calculated using EGS4 for the duct in Fig.1.
[f] Measured using NaI(Tl). The 2nd leg was 20 mm longer than that in Fig. 1

To estimate the ratio of gamma-ray fluxes in both types of ducts, a very simplified estimation was made. Photon absorption was ignored. Compton- and Rayleigh-scattering were considered. For the former, any electron-binding effects were ignored, and the angular distribution was used based on the free-electron Klein-Nishina cross section:

$$\left(\frac{d\sigma}{d\Omega}\right)_C = \left(\frac{d\sigma_{II}}{d\Omega}\right)_C + \left(\frac{d\sigma_T}{d\Omega}\right)_C \quad (1)$$

$$\left(\frac{d\sigma_{II}}{d\Omega}\right)_C = \frac{1}{4} r_0^2 \left(\frac{k}{k_0}\right)^2 \left(\frac{k}{k_0} + \frac{k_0}{k} - 2 + 4\left(1 - \sin^2\theta\cos^2\varphi\right)\right) \quad (2)$$

$$\left(\frac{d\sigma_T}{d\Omega}\right)_C = \frac{1}{4} r_0^2 \left(\frac{k}{k_0}\right)^2 \left(\frac{k}{k_0} + \frac{k_0}{k} - 2\right) \quad (3)$$

$$k = \frac{k_0}{1 + k_0(1-\cos\theta)/511} \quad (4)$$

r_0 : Classical Electron Radius
k_0: Incident Photon Energy (keV)
k: Compton Scattering Photon Energy (keV)
θ: Scattering Polar Angle
φ: Scattering Azimuth Angle from the Plane of Incident Photon Polarization Vector

Polarization vectors of the incident and scattered photons are in the same plane for σ_{II} and perpendicular for σ_T. For Rayleigh scattering:

$$\left(\frac{d\sigma}{d\Omega}\right)_R = \left(\frac{d\sigma_{II}}{d\Omega}\right)_R + \left(\frac{d\sigma_T}{d\Omega}\right)_R \quad (5)$$

$$\left(\frac{d\sigma_{II}}{d\Omega}\right)_R = F^2(x,Z) r_0^2 \left(1 - \sin^2\theta\cos^2\varphi\right) \quad (6)$$

$$\left(\frac{d\sigma_T}{d\Omega}\right)_R = 0 \quad (7)$$

$F(x,Z)$: Atomic Form Factor

The polar angle (θ) was close to 90 degrees. Two angles represented the azimuth angles: one close to 90 degrees and the other close to 0 degree. The source gamma-ray is not polarized, and the photon fluxes in the 2nd leg were represented by the average of two scatters:

$$F_{2nd} = \text{Const.} \times [F_V + F_H] \quad (8)$$

$$F_V = \left[\frac{d\sigma_{II}}{d\Omega}\left(\theta = 90^\circ - \Delta\theta, \varphi = 90^\circ - \Delta\varphi\right)\right] + \left[\frac{d\sigma_T}{d\Omega}\left(\theta = 90^\circ - \Delta\theta, \varphi = \Delta\varphi\right)\right] \quad (9)$$

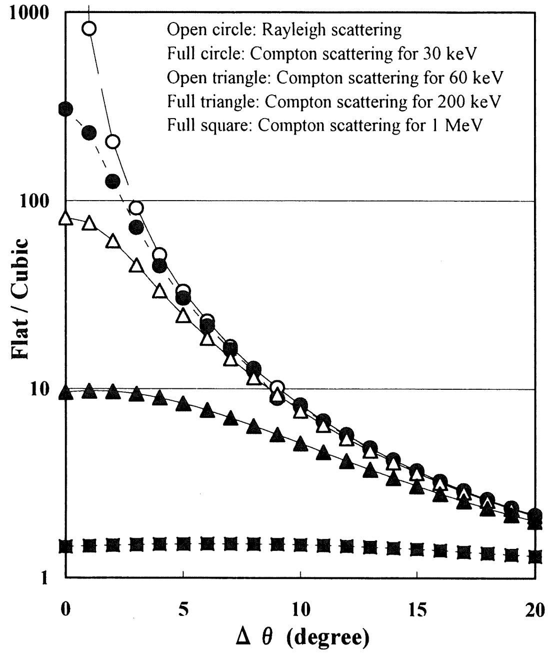

Fig. 3. Simply estimated ratio of the photon fluxes in a 90-degree 2-bend duct. The ratio of the flat-type duct to the cubic type is shown as a function of the divergence of the scattering angle from 90 degrees

$$F_H = \left[\frac{d\sigma_{II}}{d\Omega}\left(\theta = 90^\circ - \Delta\theta, \varphi = \Delta\varphi\right)\right] + \left[\frac{d\sigma_T}{d\Omega}\left(\theta = 90^\circ - \Delta\theta, \varphi = 90^\circ - \Delta\varphi\right)\right] \quad (10)$$

$\Delta\theta$: Divergence of angle from 90 degree

F_V was larger than F_H and the photons were lineally polarized. From the source to the exit of the 3rd leg, only two scatters were considered.

For a flat-type duct, F_V was scattered vertically and F_H was scattered horizontally at the 2nd scatter. The flux at the exit was:

$$F_{Flat} = \text{Const.} \times \left(F_V \times \left[\frac{d\sigma}{d\Omega}\left(\theta = 90^\circ - \Delta\theta, \varphi = 90^\circ - \Delta\varphi\right)\right] + F_H \times \left[\frac{d\sigma}{d\Omega}\left(\theta = 90^\circ - \Delta\theta, \varphi = \Delta\varphi\right)\right]\right) \quad (11)$$

For a cubic type, F_V were horizontally scattered:

$$F_{Cubic} = \text{Const.} \times \left(F_V \times \left[\frac{d\sigma}{d\Omega}\left(\theta = 90^\circ - \Delta\theta, \varphi = \Delta\varphi\right)\right] + F_H \times \left[\frac{d\sigma}{d\Omega}\left(\theta = 90^\circ - \Delta\theta, \varphi = 90^\circ - \Delta\varphi\right)\right]\right) \quad (12)$$

Next, it was simply assumed that $\Delta\theta = \Delta\varphi$, and $\Delta\theta$ was the same in both the 1st and 2nd scatter. The ratio F_{Flat} / F_{Cubic} was calculated as a function of $\Delta\theta$ (**Fig.3**). Both for Compton and Rayleigh scattering, Eqs. 8-12 were calculated using Eqs. 1-4 and 5-7. The photon energy was assumed to be the same in the 2nd leg.

When each leg is long and $\Delta\theta$ is small, the ratio F_{Flat} / F_{Cubic} becomes larger. It is larger in the case of Rayleigh scattering. For Compton scattering, it becomes smaller at higher energy.

The measured ratio of F_{Flat} / F_{Cubic} was between 3 and 4 for 60 keV gamma-rays. The measured ratio corresponds to this simple estimation when $\Delta\theta$ lies around 10-15 degrees.

V. Summary

The streaming of Am-241 59.5-keV gamma-rays was measured in a 90-degree, 2-bend duct. Because the duct was short, gamma-rays were not well collimated, and the linear-polarization effect was not large. Even in such a case, the measured fluxes at between 40 and 60 keV were 3-4 times larger for the flat-type duct, compared to a cubic type, whose 3rd leg stands vertically. Calculations without any linear-polarization effect underestimate the fluxes by about a factor 2 for the flat duct and overestimate these for the cubic type.

The calculated results using EGS4 were in good agreement with the experimental results. For a longer duct and lower energy gamma-rays, the effect became larger, because the photon-scattering angle was close to 90-degrees and the photons were well linearly polarized.

—References—

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