Optimum detector arrangement of a Compton polarimeter using a clover detector for β-delayed γ rays

Y. Kojima[a,*], K. Imai[b], S. Ohno[b], R. Chaya[b], K. Yamamoto[b], M. Shibata[a]

[a] *Radioisotope Research Center, Nagoya University, Nagoya 464-8602, Japan*
[b] *School of Engineering, Nagoya University, Nagoya 464-8603, Japan*

Abstract

Application of a clover Ge detector to the measurement of the linear polarization of β-delayed γ rays was investigated. The spectrometer consists of the clover and coaxial-type Ge detectors, and will be installed at an online isotope separator to measure short-lived nuclei. To evaluate the performance of the spectrometer, the polarization sensitivities were determined using standard radioactive sources in various detector arrangements. During optimization of the detector setup, the figure of merit was found to depend on the solid angles subtended by the detectors.

Keywords: Linear polarization, Polarimeter, Clover Ge detector, Figure of merit

1. Introduction

The multipolarities of γ rays are among the most important properties of nuclei. The experimental data on them and spin-parities of nuclear states are necessary for discussing nuclear structure. The concept of the multipo-

*Corresponding author.
Email address: kojima.yasuaki@f.nagoya-u.jp (Y. Kojima)

larities or multipole radiations is a theoretical framework for the description of transitions between nuclear levels. Using multipole expansion techniques, a γ ray is explained as electric dipole or electric quadrupole,... or magnetic dipole or magnetic quadrupole,... radiation (hereafter referred to as the electromagnetic nature).

The electromagnetic nature of γ rays can be determined by linear polarization of the γ rays. Linear polarization is usually measured by a Compton polarimeter consisting of two or more γ-ray detectors [1–3]. In this technique, a γ ray incoming to a detector is Compton scattered, and the scattered photon is detected by another detector (hereafter called the absorber). The incoming and the scattered photons define the Compton scattering plane. Here, the differential cross section for the Compton scattering depends on the angle of the Compton scattering plane and the polarization plane defined by the direction of the electric field vector of the incoming γ ray [4]. Thus, the polarization can be determined by conducting experiments in which the absorber is placed at various angles with respect to the polarization plane. In actual experiments, the Compton scattering asymmetry A in orthogonal directions is usually determined through coincidence measurements. After correcting the A-value by the polarimeter sensitivity Q, the A/Q value is compared with the degree of polarization P, which has been calculated for various multipolarities. This method is often used in in-beam γ-ray spectroscopies (for example, Refs. [5–8]). On the other hand, however, when we perform the polarization measurement for γ rays following nuclear decay, we need an additional detector. This is because a γ ray (γ_2 in Fig. 1) due to radioactive decay is unpolarized and the direction of the γ ray (and thus the reaction plane) should be defined by measuring its successive γ ray (γ_1 in Fig. 1) [2]. As the detection efficiency of such triple coincidence measurements is very low, the γ rays from the decay of short-lived nuclei are rarely analyzed by this method.

Our group is proposing a clover Ge detector [9] for linear polarization measurements of short-lived β-decaying nuclei produced at the on-line isotope separator of the Kyoto University Reactor KUR-ISOL [10]. The clover detector contains four large, closely packed Ge crystals. In this configuration, the coincidence efficiencies between the neighboring crystals are high and the clover detector corresponds to four conventional polarimeters. Thus, we expect that the clover detector can measure the polarization of β-delayed γ rays. For this purpose, the measuring conditions must be optimized to effectively utilize the limited machine time. This paper introduces our detection system for linear polarization measurements using the clover detector. Based on the figure of merit, we determine the best detector arrangement that minimizes the measuring time required to achieve a certain accuracy.

2. Experiments and data analysis

Fig. 1 is a schematic of the experimental setup. The detection system consists of the clover detector as a polarimeter, a coaxial-type Ge detector (hereafter referred to as the directional detector), and another coaxial-type detector for deducing the correction factors of the detection efficiencies (hereafter called the reference detector). The directional and reference detectors are placed at 90° and 180° relative to the clover detector, respectively. The details of the clover detector are described elsewhere [9]. Briefly, the clover detector contains four n-type Ge crystals (each of diameter 80 mm and length 90 mm), and a 23-mm-diameter through-hole runs along its central axis. The detector housing is made of 3-mm-thick aluminum, and the Ge crystal is set 15 mm from the surface of the housing. The detector is shielded with 10-cm-thick lead bricks except at the side of the incidence window.

In the present experiment, the signals from all detectors were recorded in event-by-event mode (along with their time stamp) using a VME-based data acquisition system. The energy thresholds were set just above the noise ($\sim$ 20 keV). The polarimeter spectrum was then deduced from the energy signals of crystals 1–4 of the clover detector. We extracted the events coinciding with the cascade γ ray measured by the directional (or reference) detector, and summed the energies deposited in each crystal for each event. Here, signals recorded within 2 μs were taken as coincident events. The vertically coincident peak counts V were detected in crystal pair 1 and 2 or pair 3 and 4, whereas the horizontally coincident peak counts H were detected in crystal pair 1 and 4 or pair 2 and 3. The V and H were counts of Compton scattering approximately perpendicular to the reaction plane and those in the reaction plane, respectively.

The measured asymmetry $A = (aV - H)/(aV + H)$ is related to the degree of polarization P by $P = A/Q$, where Q is the polarimeter sensitivity. Here, a is a normalization factor corresponding to the efficiency ratio of the horizontal to the vertical crystal pairs. This factor was deduced as $a = H/V$ from the polarimeter spectra gated on the reference detector, because the Compton asymmetry vanishes in this geometry [1]. The sensitivity Q depends on both the γ-ray energy and the detector arrangement. To optimize the

Table 1: Measuring conditions, normalization factors of each setup, and products of the solid angles subtended by the Ge crystal surface of the clover and the coaxial-type detector. The coaxial-type detector was used as the directional and the reference detectors.

Setup	Coaxial detector (relative efficiency)	Source to coaxial detector distance (cm)	Source to clover Ge distance (cm)	Normalization factor $\overline{a}$	product of solid angles
I	60%	20	20	1.004(3)	0.0076
II	60%	10	10	1.020(2)	0.0911
III	38%	10	10	1.005(6)	0.0653
IV	38%	10	5	1.024(6)	0.1746

measuring condition, we repeated the measurements with ^{60}Co (40 kBq), ^{134}Cs (10 kBq) and ^{152}Eu (27 kBq) point-like standard sources, placing the clover and coaxial-type Ge detectors (the relative efficiencies of 38% and 60%) in different geometric arrangements. To avoid γ-ray scattering by a source holder, the source was suspended in the air by a thin string. The total counting rate from each crystal of the clover detector was 0.3–5.7 kcps, of which 70 cps was background radiation. The measuring conditions are summarized in Table 1.

Finally, measurements were performed with and without the reference detector. In both sets of experiments, the radioactive source was placed at a distance of 10 cm from the clover and the directional detector. In the former experiment, the reference detector was also placed at 10 cm from the source. Comparing the ratio of background counts in the peak region to the net peak counts, we discuss the effect of γ-ray scattering by the reference detector.

3. Results and discussion

Fig. 2 shows the polarimeter spectra of ^{60}Co gated on the 1173-keV γ ray measured by the 60% directional detector at 10 cm (setup II). The clear

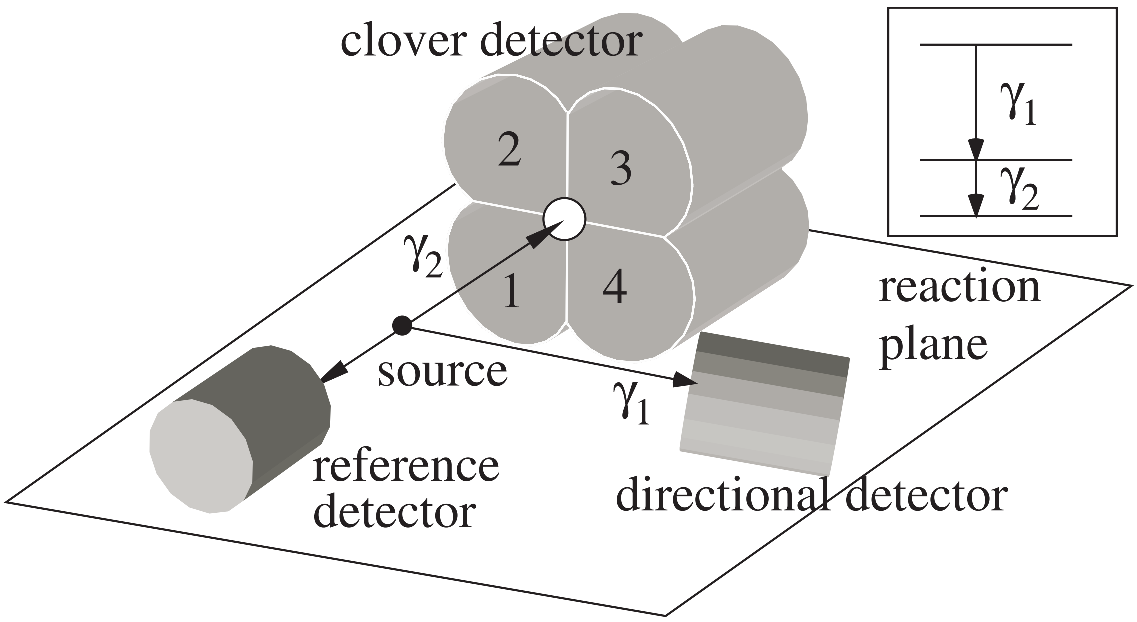

Figure 1: Detector arrangement of the linear polarization measurement of γ rays. The γ_1 is detected by the directional detector to define a reaction plane, and the degree of polarization of the successive γ_2 is measured using the clover detector.

peak at 1332 keV corresponds to Compton scattering events in the clover detector. From these spectra, we evaluated the peak counts V and H.

The normalization factors a were obtained from the spectra gated on the reference detector placed at 180°. As shown in Fig. 3, the normalization factors under each geometrical condition were approximately unity and independent of the γ-ray energy E_γ. The results imply that the four crystals in the clover detector are nearly ideal and symmetrically arranged. For subsequent analysis, the normalization factors were averaged and are listed as $\overline{a}$ in Table 1.

Next, the experimental asymmetry $A(E_\gamma) = (\overline{a}V - H)/(\overline{a}V + H)$ was deduced under each measuring condition. The results are shown in Table 2. As all transitions were $E2$–$E2$ cascades [11], the degree of linear polarization was theoretically known as $P = 0.1667$ [1]. From these values, we deduced the polarization sensitivity $Q(E_\gamma) = A/P$ of our detection system. The sensitivities for various γ-ray energies are summarized in Table 2 and Fig. 4.

For interpolation purposes, the polarization sensitivity was expressed as

$$Q(E_\gamma) \quad = \quad Q_0(E_\gamma) \times (pE_\gamma + q) \tag{1}$$

[5, 12]. Here, $Q_0(E_\gamma)$ is the ideal sensitivity assuming that the polarimeter and directional detector are point-like detectors, and is given by

$$Q_0(E_\gamma) = (1 + \alpha)/(1 + \alpha + \alpha^2), \tag{2}$$

where $\alpha = E_\gamma/m_\mathrm{e}c^2$ is the γ-ray energy in units of electron rest energy [5]. Fig. 4 shows the energy dependence of the polarization sensitivity, together with the fitting parameters p (in keV^{-1}) and q.

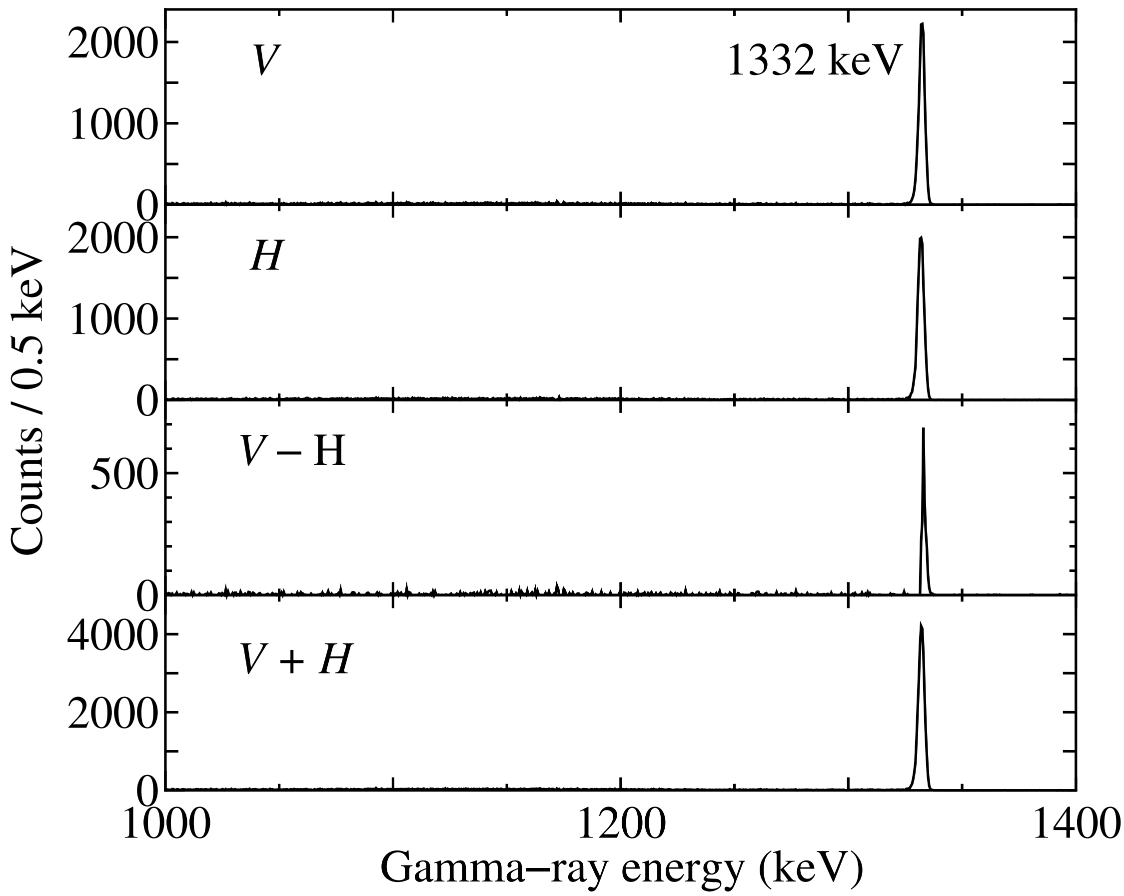

Figure 2: Polarimeter spectra obtained using a ^{60}Co standard source gated on the 1173-keV γ ray. Top to bottom: Vertical coincidence (V), horizontal coincidence (H), asymmetry ($V - H$), and summed ($V + H$) spectra.

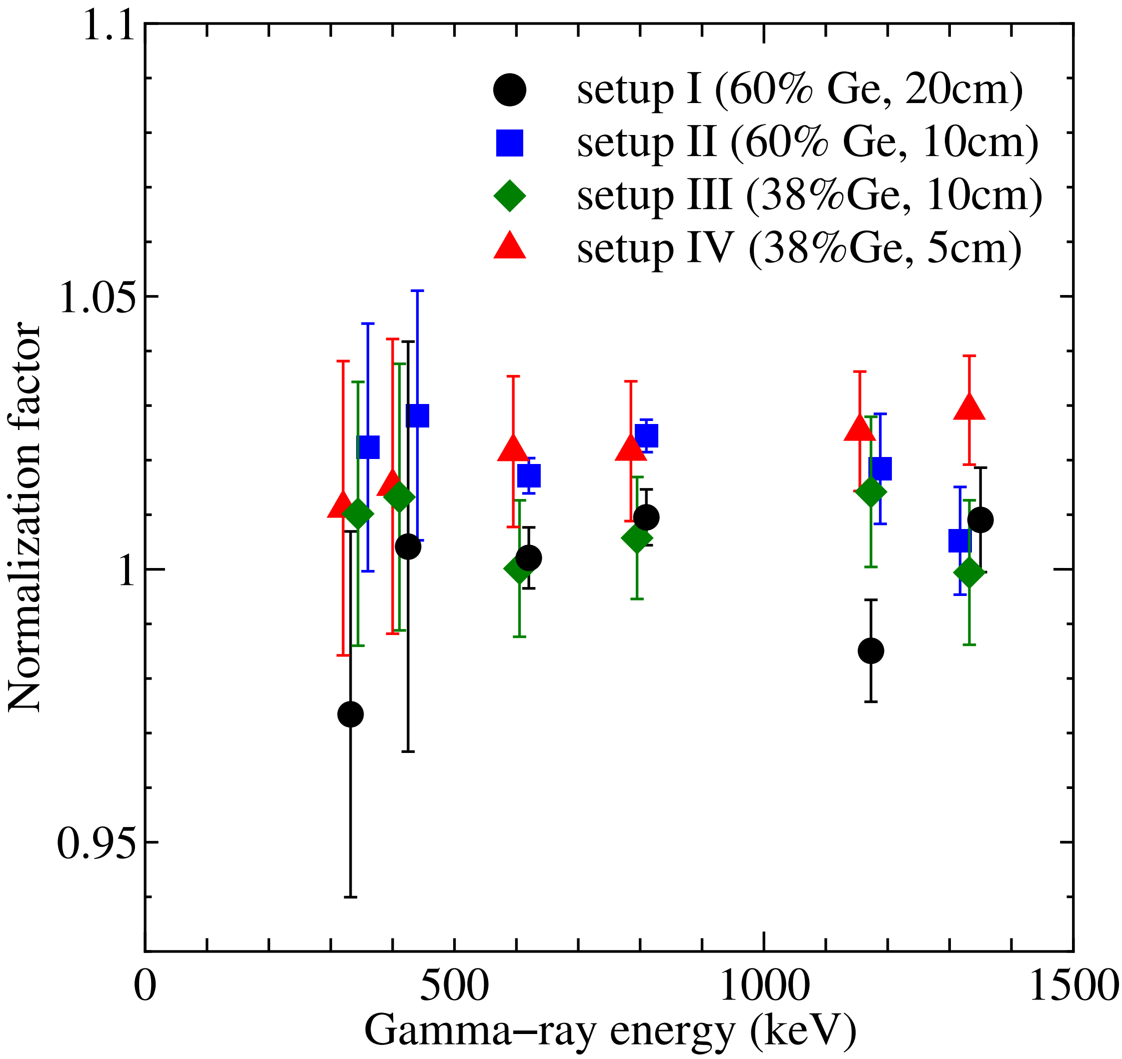

Figure 3: Normalization factors of the polarimeter. The detector setup conditions are summarized in Table 1. Some data points other than closed diamonds are plotted slightly displaced in the horizontal direction to make them easier to read.

Table 2: Degrees of asymmetry A and polarization sensitivities Q obtained in our experimental setup using the ^{152}Eu (344–411 keV γ cascade), the ^{134}Cs (605–795 keV cascade) and the ^{60}Co (1173–1332 keV cascade) sources.

Energy	Setup I		Setup II		Setup III		Setup IV	
(keV)	A	Q	A	Q	A	Q	A	Q
344	0.068(20)	0.41(12)	0.051(15)	0.31(9)	0.0344(12)	0.23(7)	0.017(17)	0.10(10)
411	0.048(22)	0.29(13)	0.058(14)	0.35(8)	0.304(12)	0.18(7)	0.028(16)	0.17(10)
605	0.0342(38)	0.205(22)	0.0419(39)	0.251(23)	0.0310(40)	0.186(24)	0.021(8)	0.13(5)
795	0.0347(35)	0.208(21)	0.0402(34)	0.241(20)	0.0281(37)	0.169(22)	0.017(8)	0.104(45)
1173	0.022(6)	0.129(37)	0.030(7)	0.181(42)	0.027(6)	0.163(39)	0.015(7)	0.087(40)
1332	0.022(6)	0.134(36)	0.033(7)	0.197(42)	0.024(7)	0.144(39)	0.009(7)	0.052(40)

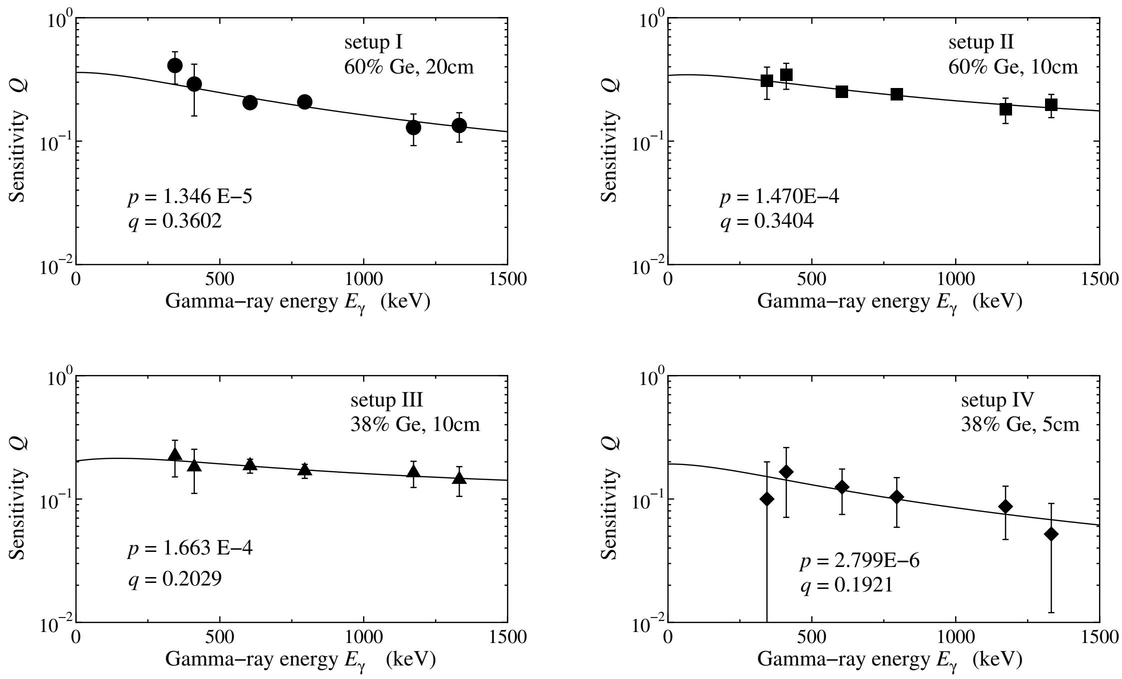

Figure 4: Polarization sensitivities $Q(E_\gamma)$ as functions of γ-ray energy E_γ in the four setups (see Table 1). The lines are fitted to the equation $Q(E_\gamma) = Q_0(E_\gamma) \times (pE_\gamma + q)$.

Fig. 5 shows the ratio of background counts in the peak region to the net peak counts observed in the polarization spectra. The large ratio in the low energy region was caused by Compton scattering of high energy γ rays. The maximum ratio was observed at 411 keV in the spectrum gated on the directional detector at 344-keV γ ray. As the 344-keV γ ray is in cascade with high energy γ rays such as 779, 1090 and 1299 keV, the relatively large background counts were naturally expected. Note also that all ratios were similar in the experiments with and without the reference detector. To understand these results, we performed calculations using the Geant4 simulation tool kit [13]. Assuming that the 344-keV γ ray was detected by the directional detector, we calculated the background counts around 411 keV caused by γ rays scattered from the reference detector. In these calculations, the background counts due to scattered γ rays comprised fewer than 0.1% of the total background counts. The experimental and computational results clarify that the effect of γ-ray scattering by the reference detector was negligibly small.

When comparing the performance of different detector arrangements, the most important quantity is the figure of merit F. In this work, we set $F = \overline{\epsilon} Q^2$ (similarly to Refs. [14–16]), where $\overline{\epsilon}$ is the coincidence efficiency $\overline{\epsilon} = (V + H)/(2N)$, and N is the number of γ rays emitted during the measurements. This figure of merit is approximately inversely proportional to the time required for the asymmetry measurement to reach a given precision. Here, we emphasize that decreasing the source-to-detector distance increases the coincidence efficiency $\overline{\epsilon}$ but reduces the sensitivity Q, because as the source approaches the detector, the solid angle subtended by the detector increases. Therefore, the figure of merit should be maximized at a certain

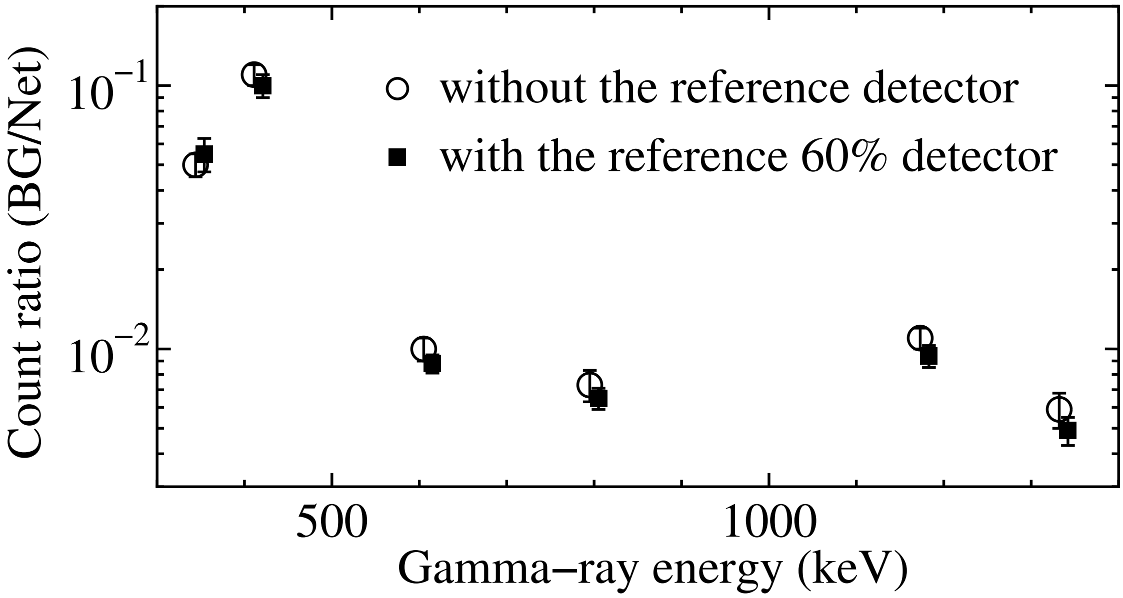

Figure 5: Ratios of background counts to peak net counts observed in the peak regions of the polarization spectra. Closed squares are plotted slightly displaced in the horizontal direction to make them easier to read.

solid angle. Fig. 6 plots the figure of merit versus the product $\Omega_{\rm clover} \times \Omega_{\rm dir}$, where $\Omega_{\rm clover}$ and $\Omega_{\rm dir}$ are the solid angles of the Ge crystal surface of the clover and the directional detector, respectively (see Table 1). The figure of merit was highest in the measuring setup II, meaning that the detector arrangement was optimized by placing the clover Ge detector and the 60% Ge detector at 10 cm from the radioactive source.

4. Conclusions

To determine the electromagnetic nature of γ rays following β decays, we constructed a detection system consisting of a clover Ge detector and coaxial-type Ge detectors. Within this system, the degree of linear polarization can be deduced from the measured asymmetry of the Compton scattering. The optimal detector arrangement was examined for several standard radioactive sources. The performance was maximized by placing the clover and 60% (relative efficiency) Ge detectors at 10 cm from the source. In future work, the polarimeter will be applied to on-line measurements of short-lived nuclei at KUR-ISOL.

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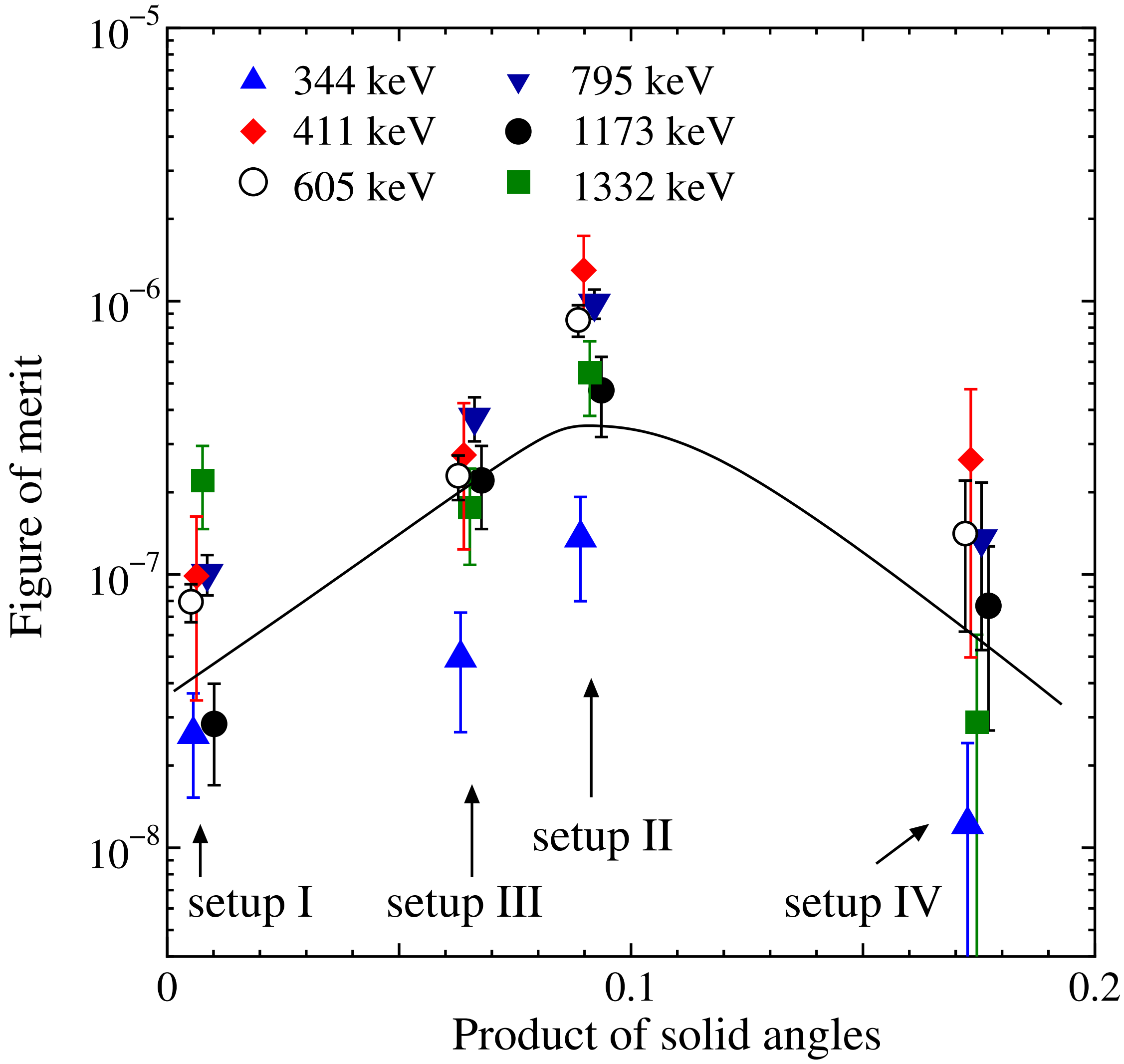

Figure 6: Figures of merit of the polarimeter versus the solid angle subtended by the clover and the coaxial-type Ge detectors. Data points other than closed squares are plotted slightly displaced in the horizontal direction to make them easier to read. The solid line is only a guide for the eye.

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