Gamma spectroscopy using two Clover detectors in close geometry

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Abstract

A gamma spectrometer composed of two Clover Ge detectors in close geometry is described. The advantages and drawbacks of the different modes of operation are investigated. The use of offline coincidence analysis for substantial background reduction is presented and an experimental approach for the determination of the summing correction factor is formulated.

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1. Introduction

Increasing interest for high gamma detection efficiencies led the manufacturers of HPGe detectors to build large crystal volumes. Due to limitations in crystal size and due to problems with poor time characteristics, large Doppler broadening and ballistic deficit, recent developments focused on composite detectors like the Clover [1], which consists of four HPGe n-type crystals placed in the same cryostat. Each crystal can be considered as a separate detector with an independent output. Thus, a large total crystal volume (> 470 cm\textsuperscript{3}) is obtained, while preserving the time performance of the individual crystals [2]. For the case of in-beam measurements, Doppler broadening is decreased due to the smaller solid angle covered by each crystal. In addition, the granularity of the detector offers flexible data analysis if the outputs of the individual crystals are registered in an event-by-event mode.

The detection efficiency calibration and the respective simulation results for the case of a “far” geometry, i.e. with the gamma source placed
at \( \sim 25 \) cm from the detectors are discussed elsewhere [1–3]. In this work, the characteristics of a double Clover detector system in close geometry are investigated. The setup (Section 2) furnishes a nearly \( 4\pi \) detection geometry and thus offers relatively high efficiency. However, in such a close geometry, the correction for summing effects becomes important, especially when complex decay schemes are under study. In this paper, the different modes of operation are described in Section 3, including an offline coincidence analysis for substantial background reduction. Extensive Monte-Carlo (MC) simulations with the GEANT4 [4] toolkit were performed and compared with the corresponding experimental data (Section 4). An empirical approach for the determination of the summing correction factor is discussed in Section 5.

2. The gamma detection system

This study has been conducted at the Institut für Kernphysik, Forschungszentrum Karlsruhe. The investigated detection system consists of two Clover detectors from Eurisy Mesures.\(^3\) The detectors are placed face-to-face in close geometry (Fig. 1) and are combined as a single detection unit. The distance between the Al windows of each detector is fixed at 5.2 mm by the sample holder. The sample is placed at an equal distance from both Clovers and positioned at their common axis. The original Clover crystals are 50 mm in diameter and 70 mm long while the final machined geometry is slightly different. In particular, in the first Clover (Fig. 1) the front part of each crystal is tapered as described in Ref. [1], unlike the crystals of the second Clover which are cut only along two faces parallel to the crystal axis to allow for close packing. The whole assembly is shielded against room background with 10 cm of lead.

The output of each single crystal is amplified using ORTEC 672 amplifiers with a shaping time of 6 \( \mu \)s before the signals are digitized through eight Canberra 8715 ADCs. The output file in event-by-event mode of the data acquisition system consists of blocks, called events, each containing eight registers corresponding to the energy signals of the eight individual crystals. If a hit is registered in one ADC, all other ADCs are read within a specified coincidence time (4.1 \( \mu \)s) and the whole sequence is stored as a single event. Thus, one event consists of eight words (16 bytes) and each 2-byte word is related to one single ADC where the lower 13 bits register the channel number (corresponding to 8k analog-to-digital conversion) and the higher 3 bits give the ADC number. This provides flexibility for offline analysis and the detection system can thus be operated in different modes. The corresponding composite spectra are generated offline using a special software called List Mode Data Analysis (LiMDA) written for this purpose [5].

The reproducibility of the detection geometry is an important factor when the source to detector distance is small. For this purpose, both Clover detectors were mounted on rails, thus allowing them to move only in one dimension. The distance between the front windows of the detectors was fixed by a carefully designed sample holder. The diameter of the holder fits the diagonal of the aluminum boxes of the Clovers confining any uncertainty in the lateral placement of the detectors relative to the sample.

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3. Modes of operation

Events in the two-Clover detection system registered in event-by-event mode may exhibit different ‘hit-multiplicities’. Hit-multiplicity 1 means a hit in one crystal with no coincident hits in any of the others. Higher hit-multiplicities correspond to simultaneous hits detected in more than one crystal due to Compton scattering or pair production, or due to cascade coincidences.

The offline software analysis of the event-by-event file described in Section 2 provides flexibility for the operation of the detection system in different modes. If each crystal is considered independently as a single detector, even if the hit-multiplicity is higher than 1, then the composite two-Clover system is said to be operated in the ‘direct’ mode. Thus, the photopeak detection efficiency is simply the sum of the individual photopeak efficiencies of each of the eight crystals.

On the other hand, the close packing of the crystals facilitates to operate the Clover detector in the so called ‘addback’ mode. In this mode, coincident events in different crystals are summed resulting in the reconstruction of full-energy signals if Compton-scattered or 511 keV annihilation photons escaping from one crystal are detected in a neighboring crystal. The summed signals are stored in the addback spectrum, which results in improved full-energy peak efficiency at the expense of the Compton continuum and escape peaks. Fig. 2 illustrates the photopeak efficiency enhancement in addback mode for the two lines of $^{88}$Y at 898 and 1836 keV and the corresponding reduction of the Compton continuum. However, the disadvantage of the addback mode in such a close geometry becomes clear in the case of coincident cascade photons, leading to pronounced summing effects as can be seen in Fig. 2 where the apparent intensity of the 2734 keV transition (0.71%) and its Compton continuum are extremely overestimated in addback mode, although the addback spectrum shown in the figure is the result of the addition of the two

![Addback and Direct Mode Spectra](image)

**Fig. 2.** Addback and direct mode spectra attained with a $^{88}$Y source. The strong summing effects are clear in addback mode although the spectrum is the sum of the two addback spectra for the individual Clovers and not the total addback of the eight crystals forming the two-Clover system.
addback spectra of the individual Clover detectors and not the total addback of the eight ADCs of the overall detection assembly. In such a case, the detection system could preferably be operated in direct mode, where summing effects are much smaller and can be corrected in a more reliable way (Section 5).

The addback and direct mode spectra considered so far are generated from all the events registered in the raw list file. However, suppression criteria can be set on the original events in order to select relevant hits by setting energy windows on individual ADCs. This coincidence mode of operation allows one to register the coincident hits in the other seven crystals and is useful in the experimental determination of summing effects (Section 5), as well as for background reduction in cases where multiple gamma-rays are emitted during the decay of an excited state [5,6].

In spite of a considerable reduction in detection efficiency, the coincidence mode provides superior peak-to-background ratios of weak features in spectra that are otherwise overwhelmed by the backgrounds. Fig. 3 depicts both singles and coincidence mode spectra for the decay of $^{136}$Cs nuclei activated using a neutron beam generated by the $^{7}$Li(p,n)$^{7}$Be reaction 11 keV above threshold. In the singles spectrum (upper panel), strong $^{137}$Cs contamination in the $^{135}$Cs sample results in complete masking of the $^{136}$Cs lines below 662 keV. Above this energy, ambient background as well as $^{60}$Co contamination allow to distinguish a weak structure only for the strongest transitions at 819 and 1048 keV. The coincidence spectrum in the lower panel is gated on the 1048 keV line and reveals all relevant transitions in the decay of $^{136}$Cs which are in coincidence with this line. Even the weakest transition at 163 keV with 3% intensity can be clearly identified.

On the other hand, it should be noted that artifacts may appear in the coincidence spectrum which originate from photons that are Compton scattered photons (see text).

![Singles and Coincidences](image.png)

Fig. 3. Singles (upper panel) and coincidence (lower panel) modes of operation. Both spectra are in direct mode and generated from the same raw data acquired for the decay of activated $^{136}$Cs nuclei. The strongly improved peak-to-background ratio in the coincidence spectrum allows for clear identification of weak transitions, which are overwhelmed by backgrounds in singles mode. The features labelled “C” correspond to Compton scattered photons (see text).
scattered in one crystal and detected in another. These ghost lines (labelled “C” in Fig. 3) are at energies \( E_c = E_b - E_{gate} \), where \( E_b \) is the full energy of the scattered photon, and \( E_{gate} \) is the energy of the gate. Clearly, the full-energy peak corresponding to these features should be higher than the energy of the gate, and the widths of these lines depend on the width of the gate. The artifacts at 125, 284, 413 and 1566 keV correspond to the two \(^{60}\text{Co} \) lines, \(^{40}\text{K} \) and \(^{208}\text{Tl} \), respectively. This cross-talk among the crystals is more prominent when compared to “standard” coincidence setups due to the close packing of the Ge crystals in the Clover assembly. Since the energy region in which an artifact appears depends on the energy of the gate, the artifacts are easily identified via their shift in energy depending on whether the spectra are gated on the peak or on the continuum below and above the peak. This feature must be taken into account when the coincidence spectrum gated off-peak is to be subtracted from the corresponding spectrum gated on-peak.

The appearance of the two full-energy peaks of \(^{60}\text{Co} \) in the coincidence spectrum is also plausible. Gating on the Compton continuum of one line allows the full-energy peak of the second to be registered if it was detected in a second crystal.

The main difficulty in the analysis of the coincidence spectrum is the determination of the absolute peak efficiency. This is attributed to the dependence of the coincidence detection efficiency on the details of the decay scheme of the measured isotope, in particular on the angular correlation of the emitted gamma-rays in the cascade. These difficulties can be solved if the ratio of the singles mode to coincidence mode efficiencies can be experimentally deduced. In the case of \(^{136}\text{Cs} \) this ratio can be determined by the activation of the \(^{135}\text{Cs} \) sample with thermal neutrons, where the rate of the \(^{135}\text{Cs}(n,\gamma)^{136}\text{Cs} \) reaction is high and the statistics are sufficient for this purpose. This ratio can then be used in measurements of low neutron capture cross-sections at different neutron energies where no identifiable transitions in the singles mode spectrum are observed. Obviously, this efficiency ratio holds only for the specific decay scheme and the experimental setup used. An alternative but less accurate way to estimate the peak efficiency for this mode of detection is through detailed MC simulations that comprise the whole geometry and the full information concerning angular correlations.

4. Geant4 Monte-Carlo simulations

Weak (10–1350 Bq) point-like radioactive sources with simple decay schemes were used for calibrating the efficiency of the detection system in singles mode, i.e. \(^{109}\text{Cd} \), \(^{203}\text{Hg} \), \(^{137}\text{Cs} \), \(^{54}\text{Mn} \), \(^{65}\text{Zn} \), \(^{88}\text{Y} \) and \(^{22}\text{Na} \). For \(^{88}\text{Y} \) and \(^{22}\text{Na} \), corrections for the summing effects were calculated and applied [7]. One additional calibration point at 412 keV was obtained using a \(^{198}\text{Au} \) sample, 6 mm in diameter and 0.03 mm in thickness, prepared by neutron activation. The activity of the gold sample after the irradiation was measured with a calibrated HPGe detector. The self-attenuation within the sample, as well as the effect of the extended geometry were investigated with MC simulation and found negligible. Fig. 4 depicts the measured efficiency calibration points for the direct mode which are in excellent agreement with the efficiency deduced from extensive Geant4 [4] simulations. For this purpose the rather complex Clover geometry was carefully modeled. For example, the bevels at the front face of each Ge crystal in the first Clover (Fig. 1) generate, on two sides, a
semi-elliptic surface. The other two sides of each crystal are mostly flat to allow for the close packing with the adjacent crystals. The front face of the crystal has thus a quasi-square shape while its rear face is quasi-circular since two sides in the back half conserve the 50 mm diameter of the original Ge cylinder. The geometry of the second Clover is relatively simple (Section 2). These details have been considered in the simulation.

On the other hand, the calculated summing corrections for the $^{88}\text{Y}$ and $^{22}\text{Na}$ spectra mentioned above imply the need for the total efficiencies [7]. For the experimental determination of the total efficiencies, single-line photon emitters are best suited. In practice, this is not possible for the whole energy region under consideration. As an alternative, Geant4 simulations have been performed, which solve the problem of monoenergetic photons as well as for exploring the effect of the surrounding material, especially of the lead shield, on the total efficiencies [5].

In Section 5 an experimental approach is described for the determination of the summing correction factor in direct mode. The results are then compared to simulation and calculation. In the simulation, monoenergetic gamma-rays were first generated in separate runs at the sample position and the energy deposited in each Ge crystal was histogrammed. The decay scheme under consideration was then modeled. Only the gamma-transitions were finally considered since the $\beta^-$ electrons are stopped before reaching the Ge crystals. The summing correction factor for each gamma-transition was then obtained by comparing the intensity of the line in the monoenergetic simulated spectrum to that in the multiple gamma-ray decay spectrum.

5. Summing correction in direct mode using coincidences

Summing effects are important for reliable measurements in such a close geometry, especially when complex decay schemes with high multiplicity of cascade coincidences are involved. In general, these effects for a given gamma-line in the spectrum could yield an increase (summing-in) or decrease (summing-out) in the number of counts under the full-energy peak [5,7]. The summing-in effect is usually less significant but becomes important in the case of a weak cross-over transition in the presence of strong cascade transitions [7]. In this section we deal only with the more common case of summing-out effects and the term “summing” is thus used instead of “summing-out” throughout the paper. Consequently, all the examples given below (Table 1) represent cross-over free transitions.

The calculation of the summing correction factor based on the total efficiency and emission probability [7] which is readily applicable for simple decay schemes, requires more perseverance in cases when the measured photon is in coincidence with a high multiplicity cascade. In these cases special computer codes based on general formulae are usually used. This requires, in addition to the peak and total efficiencies for the

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>Transition energy (keV)</th>
<th>Standard calculation</th>
<th>Geant4 simulation</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{88}\text{Y}$</td>
<td>898</td>
<td>$1.0610 \pm 0.0001$</td>
<td>$1.058 \pm 0.004$</td>
<td>$1.0769 \pm 0.0002$</td>
</tr>
<tr>
<td>$^{88}\text{Y}$</td>
<td>1836</td>
<td>$1.0678 \pm 0.0004$</td>
<td>$1.071 \pm 0.005$</td>
<td>$1.0851 \pm 0.0003$</td>
</tr>
<tr>
<td>$^{22}\text{Na}$</td>
<td>1274</td>
<td>$1.1557 \pm 0.0005$</td>
<td>$1.152 \pm 0.002$</td>
<td>$1.1622 \pm 0.0005$</td>
</tr>
<tr>
<td>$^{54}\text{Mn}$</td>
<td>835</td>
<td>1</td>
<td>1</td>
<td>$1.0015 \pm 0.0001$</td>
</tr>
<tr>
<td>$^{136}\text{Cs}$</td>
<td>819</td>
<td>—</td>
<td>$1.137 \pm 0.002$</td>
<td>$1.165 \pm 0.006$</td>
</tr>
<tr>
<td>$^{140}\text{La}$</td>
<td>1596</td>
<td>—</td>
<td>$1.099 \pm 0.006$</td>
<td>$1.110 \pm 0.001$</td>
</tr>
<tr>
<td>$^{140}\text{La}$</td>
<td>487</td>
<td>—</td>
<td>$1.111 \pm 0.003$</td>
<td>$1.127 \pm 0.001$</td>
</tr>
</tbody>
</table>
relevant energy range, detailed information on the
decay into the different levels of the nuclide [7].

As an alternative, a conceivable experimental
approach is proposed for the determination of the
correction factor. For this purpose, an offline
coincidence analysis has been investigated and
compared to MC simulations for the complex
decay of $^{136}$Cs and $^{140}$La nuclei produced by
neutron activation. For the radioactive sources,
the results are compared to calculated correction
factors as well (Table 1).

Since the summing effect in direct mode, unlike
the case of addback mode, involves simultaneous
hits of more than one photon on one single crystal,
the main objective is to experimentally determine
the probability for such coincidences. Gating on
any single crystal with an energy window centered
at a selected gamma-transition in the cascade, a
suppressed list file is generated which contains for
each event all coincident hits in the other seven
crystals. From this new list file, the coincidence
spectrum is constructed.

In addition to the sought coincidences with the
selected transition, the suppressed spectrum in-
cludes coincidences associated with the back-
ground continuum under the peak as well.
Accordingly, two additional coincidence spectra
are needed for background subtraction, namely by
gating with equivalent energy windows below and
above the original gate centered at the peak.

In this coincidence analysis, the number of
“gate” signals is registered for the peak position
$G_p$, as well as for the “left” $G_L$ and “right” $G_R$
background gates, at lower and higher energies,
respectively. The total number of counts $S_P$, $S_L$
and $S_R$ in the corresponding coincidence spectra
(in direct mode) are also determined. The net
number of gate counts in the singles spectrum for
the gamma-line under consideration is

$$G = G_p - \frac{G_L + G_R}{2}$$  \hspace{1cm} (1)

whereas the total number of coincidences recorded
in the other seven crystals is

$$S = S_P - \frac{S_L + S_R}{2}. \hspace{1cm} (2)$$

Since the summing correction in direct mode is
associated with the net number of cascade coin-
cidences in one crystal, and because of the nearly
4$\pi$ solid angle covered by the eight crystals, the
adoption of $S/7$ as an average value of coinci-
cences per crystal moderates the effect of angular
correlations. The summing correction factor in
direct mode can finally be written as

$$C = 1 + \frac{S}{7G}. \hspace{1cm} (3)$$

Preliminary verification of this technique has been
carried out using $^{22}$Na and $^{88}$Y sources, where the
calculation of the correction factor can be readily
performed using the standard approach that
depends on the total efficiencies and emission
probabilities [7]. As a third cross check of the
above procedures, Geant4 simulations have been
also carried out (Section 4). The results obtained
from the three approaches for the determination of
the summing correction factor have been found to
be consistent within 2% (Table 1). This can be
considered as the combined systematic uncertainty
($\delta C/C$) in the experimentally deduced correction
factor together with the MC deduced total
efficiencies used in the standard calculation. The
uncertainties listed in Table 1 were computed using
the uncertainties in the decay probabilities and
total efficiencies ($\text{Standard calculation}$), the statis-
tical uncertainties in the simulated monoenergetic
and cascade peaks as described in Section 4
($\text{Geant4 simulation}$), and the statistical uncertain-
ties in the number of gate counts and the number
of coincidences ($\text{Experiment}$).

As a trivial test, the same procedures were
applied to the 835 keV monoenergetic gamma-
transition in the decay of $^{54}$Mn, where no summing
effects are expected. It should be noted that due to
the higher multiplicity in the case of $^{22}$Na ($M = 3$
compared to $^{88}$Y ($M = 2$), the correction factor is
correspondingly higher (Table 1). Conceptually,
the higher multiplicity does not necessarily mean
that more photons hit the same crystal, but rather
that there is higher probability for simultaneous
hits. The two annihilation photons in the case of
$^{22}$Na are emitted in opposite directions, which
implies only single or double hits on any crystal.
This is exactly the same number of hits expected in
the case of $^{88}$Y. Nevertheless, the probability for
coincident hits is higher for $^{22}$Na due to the larger number of emitted photons.

For a more rigorous validation of the proposed approach, the summing correction factor has been also investigated for $^{136}$Cs and $^{140}$La which exhibit relatively complex decay schemes. Both the experimental coincidence technique as well as Geant4 simulations have been applied. All results are summarized in Table 1.

Fig. 5 provides an example for the different spectra generated from a single file in order to determine the summing correction for the 1596 keV first excited state transition in the decay of $^{140}$La. The top panel shows the singles spectrum in direct mode, where the prominent gamma-transitions are indicated. The raw data are then gated on- and off- the 1596 keV line. Thus, two suppressed event files are generated from which the corresponding direct mode spectra are obtained (middle and bottom panels, respectively). According to the decay scheme [8], the 1596 keV line is in coincidence with all the other lines labeled in the top panel. Thus, the spectrum gated on the 1596 keV line displays all these transitions (middle panel). This spectrum includes coincidence data with the 1596 keV transition as well as with the background continuum under the peak. This background contribution is depicted in the lower panel where the gate was set off-peak with an equivalent energy window.

Unlike the case of the 1596 keV transition, which is in coincidence with all the prominent lines, the 487 keV transition in the decay of $^{140}$La is in coincidence only with three lines, namely at 328, 432, and 1596 keV [8]. By gating on this line, the resultant spectrum (Fig. 6, lower panel) shows only those coincident transitions. The features labelled “C” in the coincidence spectrum again correspond to gating on the Compton continuum of higher energy lines as described in Section 3.

It should be noted that the applicability of this method is determined by the count rate. The time window for coincidences should be small enough to minimize random coincidences at high count rates. The relatively weak tendency towards higher correction factors in the experimental approach (Table 1) can be attributed to such accidental coincidences. The range of the observed count rates during the measurements listed in Table 1 was between 100 and 1200 events/s.

6. Conclusions

In this work the use and the modes of operation of a system of two Clover detectors in close
geometry are described. The almost \(4\pi\) geometry results in a high detection efficiency, but particular attention must be paid to the summing effects and to the reproducibility of the detection geometry. For the latter purpose a carefully designed setup has to be used.

The summing correction factor cannot always be readily obtained by standard calculations either due to the complex geometry or due to the lack of relevant data (e.g. total efficiency and angular correlations). Therefore, an experimental determination of the correction factor has been investigated and compared with results obtained from calculations and simulations. The offline software coincidence analysis of the event-by-event data not only provides flexibility in the operation of the detection system in different modes, but also facilitates this experimental determination of the summing correction factor. The setup thus enables maximizing the detection efficiency while at the same time accounts for the associated summing effects.

In addition, the significant improvement in the peak-to-background ratio achieved in the coincidence mode allows for the clear identification of extremely weak features in the spectrum which are overwhelmed by ambient backgrounds in singles mode.

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