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Calibration of a low-level anti-Compton underground gamma-spectrometer by experiment and Monte Carlo

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HIGHLIGHTS

- A Compton-suppressed spectrometer using a big n-type HPGe detector was calibrated.
- Coincidence effects on peak efficiency (suppressed and direct modes) were evaluated.
- GESPECOR code was extended for simulation of the Compton-suppressed spectrometer.
- Monte Carlo results are in good accordance with experimental values.
- The code is useful for spectrometer calibration as well as geometrical optimization.

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ABSTRACT

In this work we present the experimental and Monte Carlo calibration of the Compton-suppressed spectrometer of the IAEA's Environment Laboratories, Monaco. For this purpose the GESPECOR code was extended to include the specific geometry and to implement the veto logic, integrated with the coincidence summing module of the code. The simulation results are in good accordance with experimental calibrations. The code is fast and user-friendly, able to evaluate the efficiency and the correction factors for nuclides with arbitrary complex decay schemes.

1. Introduction

Compton-suppressed gamma-ray spectrometers have been used since many years (Euler et al., 1969) for improving the sensitivity of spectral analyses, but the calibration of these spectrometers is still of current interest, especially when nuclides with complex decay schemes are under investigation (McNamara et al., 2012; Fan et al., 2012; Landsberger and Kapsimalis, 2009). Whereas in the case of single photon emitting nuclides the Compton plateau of the spectrum is reduced while the peak count rate is not affected by the anti-Compton system, in the case of the nuclides with complex decay schemes the peak count rate is modified in an intricate way by the anti-Compton system, making the efficiency calibration difficult. The studies presented in this work involve the calibration of the Compton-suppressed spectrometer of the IAEA's Environment Laboratories, Monaco, by combining experimental data with Monte Carlo (MC) simulations. The simulations were carried out with an extended version of the GESPECOR code (Sima et al., 2001).

2. Theory

In the case of a Compton-suppressed spectrometer a count is recorded in the spectrum only if some energy was deposited in the detector but no veto signal was issued by the anti-Compton (guard) system. In the case of nuclides like ^{40}K and ^{137}Cs, emitting a single gamma photon, the probability of recording a count in the peak is the same in the suppressed (anti-Compton, AC) mode and in the unsuppressed (direct, D) mode of operation; the veto signal cannot be generated if the total energy of the photon was absorbed in the main detector. However, the probability of recording a count in the Compton plateau of the spectrum is much reduced in the suppressed mode. The majority of the photons that did not deposit the complete energy in the detector, deposited some energy in the guard detector and thus their contribution to the spectrum is inhibited. The probability of a

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photon to interact with both detectors is the total coincidence efficiency of the main and of the guard detector, ε_T^{D+G}. The counts remaining in the Compton plateau are due to photons which interact in the main detector but do not interact with the guard detector or to photons for which the veto signal is not issued even if the interaction took place in the guard (imperfect time alignment of the signals, presence of lower level discriminators etc.).

The situation is more complex in the case of nuclides which emit photons in cascades. Consider one of the photons from the cascade (the "main" photon). The behavior of the detection system due to the interactions of this photon is exactly the same as presented above. But in addition, the count rate in the peak of this photon will be affected by the interactions of the other photons ("secondary" photons) from the cascade. Consider that the main photon was completely absorbed in the detector. If a secondary photon also interacts in the detector, then coincidence losses occur and the count will be lost from the peak, being moved to a higher energy region of the spectrum; the probability of such an event is proportional to the total efficiency of the detector ε_T^D for the secondary photon. If a secondary photon interacts in the guard detector, the count will also be lost from the peak, due to the veto signal issued; the probability of this event is proportional to the total efficiency of the guard detector, ε_T^G. Of course, the count is lost from the peak also when the secondary photon interacts both with the main detector and with the guard system, with a probability proportional to ε_T^{D+G}. In order to evaluate the probability of removing a count from the peak due to the interactions of the secondary photon it is useful to classify the events corresponding to the secondary photon into independent, mutually exclusive cases: (a) it interacts with the main detector, but not with the guard detector; (b) it interacts with the guard detector, but not with the main detector; (c) it interacts both with the main detector and with the guard detector; (d) it does not interact with the main detector and it does not interact with the guard detector. Clearly the total efficiency of the detector ε_T^D comprises cases (a) and (c), the total efficiency of the guard system ε_T^G comprises cases (b) and (c), while the total coincidence efficiency ε_T^{D+G} comprises case (c). The probability of removing a count from the peak is the sum of the probabilities of cases (a), (b) and (c). By expressing these probabilities in function of the total efficiencies ε_T^D, ε_T^G and ε_T^{D+G}, it is easily seen that the probability of removing a count is proportional to the total efficiency of the complete system, ε_T^{AC}

$$\varepsilon_T^{AC} = \varepsilon_T^D + \varepsilon_T^G - \varepsilon_T^{D+G}, \tag{1}$$

that is the losses of counts from the peak due to the anti-Compton system interfere with the losses due to the usual coincidence summing effects.

In summary, in the case of single gamma nuclides the count rate in the peak is not affected, while the Compton plateau is much reduced in the suppressed mode. This enhances the sensibility of detection of a nuclide with lower energy photons in the presence of a nuclide with higher energy photons; a typical example is the detection of low activities of ^{137}Cs in samples with a higher activity of ^{40}K. In contrast, in the case of nuclides with cascade emission both the Compton and the peak count rates are diminished by the anti-Compton system (coincidence summing effects in the main detector can increase the count rate due to summing in, but the guard system will never increase the count rate in a peak). The peak efficiency for the main photon depends on the decay scheme of the nuclide, so a nuclide-specific calibration is required.

The expression of the full energy peak efficiency can be easily derived by adapting the formalism developed in (Sima and Arnold, 2000), which is briefly recalled.

Consider a source of volume V, containing the nuclide X with a total activity A, uniformly distributed within V. The nuclide emits several photons γ_i (energy E_i) in fast cascades. Denote by p_i, $p_{i,j}$, $p_{i,j,k}$… the emission probability of γ_i, of the pair (γ_i, γ_j), of the triplet (γ_i, γ_j, γ_k)… in one decay. In the absence of coincidence summing and of Compton-suppression effects, the count rate N_i in the peak at the energy E_i would be

$$N_i = \frac{A}{V} p_i \int_V \varepsilon(E_i, \vec{r})dV = Ap_i\varepsilon(E_i; V) \tag{2}$$

here $\varepsilon(E_i;V)$ is the full energy peak (*FEP*) efficiency for the extended source, and $\varepsilon(E_i, \vec{r})$ is the *FEP* efficiency for an elementary source located at $\vec{r}$. These efficiencies depend on the source and main detector, but do not depend on the guard detector (as far as coherent scattering is negligible). Thus Eq. (2) is valid both in the AC and in the D modes.

The rate $N^{loss,\ AC}$ of losses from the γ_i peak due to the interactions of the γ_j photon in the main detector (usual summing out effects) and in the guard detector (Compton-suppression) is:

$$N_{i;j}^{loss,AC} = \frac{A}{V} p_{i,j} \int_V \varepsilon(E_i, \vec{r})\varepsilon_T^{AC}(E_j, \vec{r})dV \tag{3}$$

where $\varepsilon_T^{AC}(E_j, \vec{r})$ (see Eq. (1)) is the total detection efficiency in the suppressed mode for an elementary source of photons with energy E_j located at $\vec{r}$. Terms of the type $N_{i;j}^{loss,\ AC}$, involving the effect on the E_i peak of a single secondary radiation, are called first order correction terms. The second order terms, e.g. $N_{i;j,k}^{loss,AC}$, resulting from the simultaneous interactions of three photons, are defined by

$$N_{i;j,k}^{loss,AC} = \frac{A}{V} p_{i,j,k} \int_V \varepsilon(E_i, \vec{r})\varepsilon_T^{AC}(E_j, \vec{r})\varepsilon_T^{AC}(E_k, \vec{r})dV \tag{4}$$

The total coincidence losses from the peak at energy E_i should be computed by evaluating the contributions of the appropriate terms produced by any radiation which may be emitted together with the γ_i photon.

Similarly with the case of coincidence summing in a single high efficiency detector, also in the case of Compton-suppressed spectrometers it is possible to observe sum peak effects. If the photons γ_p, γ_q are totally absorbed in the detector simultaneously they add a count in the peak at the energy E_p+E_q; the corresponding count rate N_{p+q} is:

$$N_{p+q} = \frac{A}{V} p_{p,q} \int_V \varepsilon(E_p, \vec{r})\varepsilon(E_q, \vec{r})dV \tag{5}$$

This count rate is the same in the AC and D modes. It should be corrected further due to coincidence losses of the types presented above, e.g. $N_{p+q;j}^{loss,\ AC}$ in the case when the photons γ_p, γ_q are totally absorbed in the detector but simultaneously the γ_j photon interacts in the main or in the guard detector.

Finally, the actual count rate $N_i^{c,\ AC}$ in the peak at energy E_i in the presence of coincidence summing and Compton-suppression is given by

$$N_i^{c,AC} = (N_i - N_{i;j}^{loss,AC} - N_{i;k}^{loss,AC} - \ldots + N_{i;j,k}^{loss,AC} + \ldots) + (N_{p+q} - N_{p+q;j}^{loss,AC} - \ldots) + \ldots \tag{6}$$

The second parenthesis represents the sum peak contribution of the γ_p and γ_q photons; for each different sum peak combination contributing to the E_i peak a similar parenthesis should be added. Note that in each parenthesis from Eq. (6) the terms of successive orders have alternating signs; for example, the first order terms are subtracted, whereas the second order term $N_{i;j,k}^{loss,\ AC}$ should be added, because it was included in each of the loss terms $N_{i;j}^{loss,\ AC}$, $N_{i;k}^{loss,\ AC}$.

The apparent efficiency in the suppressed mode is given by

$$\varepsilon^{app,AC}(E_i,V) = \frac{N_i^{c,AC}}{p_i \cdot A} \tag{7}$$