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Technical note

Photon energy conversion efficiency in gamma-ray spectrometry

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HIGHLIGHTS

- Photon energy conversion efficiency as a ratio of registered signal to emitted photon energies.
- An efficiency parameter not affected by coincidence phenomena.
- Particularly useful for calibration and measurement of radionuclide samples at close geometries.
- Suitable mainly for radionuclide assays.

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ABSTRACT

Photon energy conversion efficiency coefficient is presented as the ratio of total energy registered in the collected spectrum to the emitted photon energy. This parameter is calculated from the conventional gamma-ray histogram and in principle is not affected by coincidence phenomena. This feature makes it particularly useful for calibration and measurement of radionuclide samples at close geometries. It complements the number of efficiency parameters used in gamma-ray spectrometry and can partly change the view as to how the gamma-ray spectra are displayed and processed.

1. Introduction

Technical means and procedures used in gamma-ray spectrometry are well known and described in the literature. Acquired gamma-ray spectra represent a form of statistical evaluation of a number of events in which photons emitted by a source interact with the detector material and its surroundings. Individual photons transfer and deposit their energy in the detector in the form of electric charge, the magnitude of which is proportional to the energy deposited. This charge is subsequently converted into voltage pulses. These pulses are digitised by a pulse height analyser (PHA) and stored in a multichannel analyser (MCA) for further processing. The simplest form of the gamma-ray spectrum evaluation consists in displaying it as an histogram with the registered photon energies on the horizontal axis and registered number of such events taking place within some energy interval on the vertical axis. The amount of stored information is huge and the number of counts stored in individual channels or channel groups may differ considerably. Vertical range switching or a logarithmic transformation is used to facilitate the display. Sophisticated computer codes help users to display the spectrum and to extract required data.

Contemporary gamma-ray spectrometry is performed mostly using large volume high purity germanium (HPGe) crystals with samples in close geometry. This arrangement increases the measuring efficiency by increasing the counting rates, which is required for low activity or fast sample measurements. However, it also enhances the coincidence summing effect, considered as a major problem in the correct evaluation of gamma-ray spectra (Hult, 2007). The worst situation is encountered when using a well detector, which offers the highest possible detection efficiency (Gilmore, 2008). This detector geometry has the highest probability of true coincidence summing effects in the case of cascade photon emitting nuclides, which are considered the main drawback of these measurements (Sima, 2000).

The process of spectra acquisition and evaluation is based on counting photons that are sorted by their energy. The existence of coincidence summations is a consequence of limited capability of the device to distinguish photon interactions overlapping in time. Although individual photons interact with the detector independently, the resulting charge deposit is a superimposed sum of these interactions and the PHA and MCA electronics registers these almost simultaneously occurring events as a single event. Consequently, the registered number of interacting photons in the

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full energy peak is reduced but their common total deposited energy is registered correctly.

To calculate the number of interacting photons and their deposited energies back from the summed spectrum is an extremely difficult task that requires additional information about the interaction processes and about the environment in which they take place. (Lépy et al., 2012). Available information is usually only approximate and therefore also are the results. The sum of events cannot be correctly reconstructed without detailed instructions how to do it. And whatever exact instructions are available, the best of which are obtained by Monte Carlo simulations, they require equally correct input data which are often hard to obtain. It is the purpose of this contribution to show an alternative method for quantitative spectra analysis and activity determination using the total deposited energy of photons that is free of coincidence effects. An analytical proof of this statement is given in the Appendix A.

2. Photon energy conversion spectra

When the number of registered photon events n_i in each channel i is weighted (multiplied) by its mean energy E_i, a photon energy spectrum can be obtained instead of the conventional histogram. The absorbed energy rate (the signal power) $\dot{E}_{abs,i}$ corresponding to individual channels can be calculated by an equally simple operation according to the formula

$$\dot{E}_{abs,i} = \frac{n_i E_i}{T_L} \tag{1}$$

where T_L is the live time of the measurement. Unfortunately, this elementary operation is generally not available in commercial gamma-ray spectroscopy software and presently needs to be performed separately. Multiplying the channel contents by corresponding energies slightly changes the overall appearance of the spectra display. Both spectra are shown in Fig. 1 for comparison for the case of a ^{60}Co source measured at close geometry. The appearance of the energy spectrum calculated using Eq. (1) differs from the original most significantly in the lowest energy region, where the weighting transformation causes noise and Bremsstrahlung suppression. This brings a more realistic view to the detector response, including the low level discrimination (LLD) setting. Pulses in usual gamma-ray spectra are registered as equal events not accounting for their significance and so the low energy noise level may overweigh the number of pulses from the source in other energy regions. The usual suppression of noise by LLD brings difficulties with the total counts estimation that is required for calculating corrections of the true coincidence summation (TCS) effect.

At a first glance, the original and transformed spectra resemble each other in a way similar to those displayed in linear and logarithmic scales. Both diagrams show the presence of coincidence summing peaks. The gamma-ray spectra of cascade (multiphoton) emitters are not simple superpositions of responses to equivalent single photon emitters and their mutual coincidences resulting in changes in the channel contents must be accounted for when processing a usual gamma-ray histogram. However, it is not only the spectrum appearance that has changed by the proposed transformation, but its information content that changed significantly from a simple number of counts to a real physical quantity – the energy absorbed in the detector and analysed by the PHA. The number of particles involved in the primary photon interaction with matter varies, but the proposed operation ensures that both axes are calibrated in meaningful energy units. The photon energy conversion spectrum displayed in Fig. 1b is a more realistic representation of the gamma-ray interactions with matter than the conventional histogram in Fig. 1a.

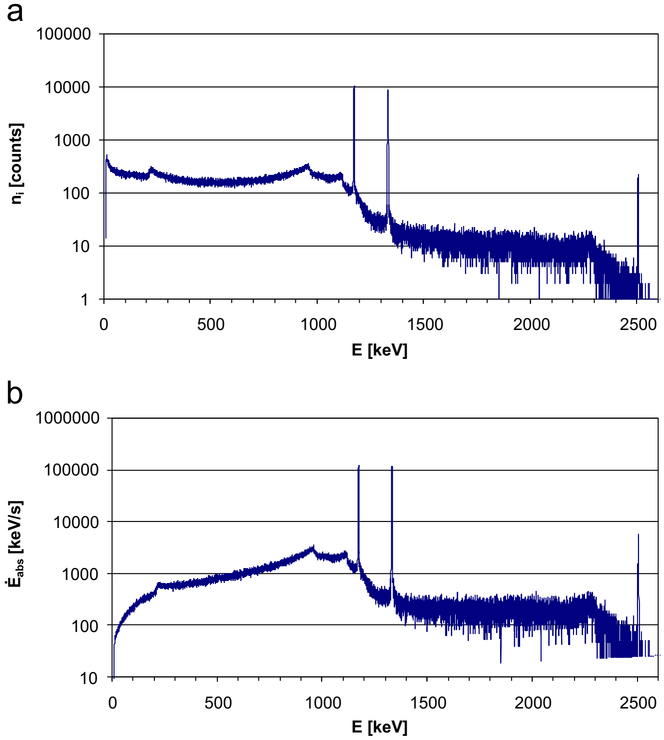

Fig. 1. Comparison of two spectra of a Ge detector response to ^{60}Co gamma rays. (a) – a conventional histogram, (b) – deposited energy spectrum calculated from the former one.

Both diagrams in Fig. 1 illustrate several (not all) characteristic features of gamma-ray spectra: first of all the full-energy peaks, the Compton continuum, a backscatter peak and bremsstrahlung continuum, then the piled-up continuum and a coincidence peak at the high-energy end. It is important to keep in mind that each of the significant interaction processes results in the transfer of gamma-ray energy to electrons in the detector and this energy represents the energy absorbed in the detector and related to the electric output from the detector (Gilmore, 2008). Therefore it is the amount of photon energy that is the information carrier, not the number of photons sorted by energy. In fact, a photon that entered the detector may be registered as a single event anywhere in the spectrum. The full-energy peak corresponding to the initial energy of a gamma ray is seldom created by the photoelectric effect but it mostly consists of a series of fast consecutive interactions by which the full-energy peak is gradually built-up. In a detector with sufficiently large volume, all the response will be concentrated in a peak with the energy corresponding to the emitted photon energy (Gilmore, 2008), not accounting for the existence of isomeric (metastable) states.

If a real detector of medium size is used, some of the photons after a few interactions may leave its active volume and the rest of their energy is lost for registration. On the other hand, even these few interactions may coincide with some others and register themselves in a wrong energy channel (from the point of view of the first photon observer) and as a wrong (reduced) number of events. However, if the PHA is correctly set, it is the total energy of these combined interactions that is correctly registered.

The obtained total absorbed energy can be further compared with total energy emitted by the source and the real energy efficiency of the photon energy conversion into pulses of electric charge can be calculated. If a source of activity A emits photons with energies E_j with corresponding emission probabilities (yields)