



BSI Standards Publication

Nuclear instrumentation — Measurement of activity or emission rate of gamma-ray emitting radionuclides — Calibration and use of germanium-based spectrometers

National foreword

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The UK participation in its preparation was entrusted to Technical Committee NCE/2, Radiation protection and measurement.

A list of organizations represented on this committee can be obtained on request to its committee manager.

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INTERNATIONAL STANDARD



Nuclear instrumentation – Measurement of activity or emission rate of gamma-ray emitting radionuclides – Calibration and use of germanium-based spectrometers

INTERNATIONAL
ELECTROTECHNICAL
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INTERNATIONAL ELECTROTECHNICAL COMMISSION

**NUCLEAR INSTRUMENTATION – MEASUREMENT OF ACTIVITY
OR EMISSION RATE OF GAMMA-RAY EMITTING RADIONUCLIDES –
CALIBRATION AND USE OF GERMANIUM-BASED SPECTROMETERS**

FOREWORD

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IEC 61452 has been prepared by IEC technical committee 45: Nuclear instrumentation. It is an International Standard.

This second edition cancels and replaces the first edition published in 1995. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

- a) Title modified;
- b) Additional information on digital electronics;
- c) Information on Monte Carlo simulations;
- d) Reference to detection limits calculations.

The text of this International Standard is based on the following documents:

FDIS	Report on voting
45/921/FDIS	45/925/RVD

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this International Standard is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/standardsdev/publications.

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- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

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INTRODUCTION

A typical gamma-ray spectrometer consists of a high purity germanium (HPGe) detector with its liquid nitrogen or mechanically refrigerated cryostat and preamplifier, associated to either analog or digital electronic modules including the detector biasing and signal processing (amplification, multichannel conversion and storage) and data-readout devices. The spectrometers include or are associated with computers and their acquisition software. A radiation shield often surrounds the detector to reduce the counting rate from room background radiation for shield construction guidelines). Primary interactions of the photons (X- and gamma-rays) in the HPGe crystal (by photoelectric absorption, Compton scattering or pair production) impart energy to electrons whose energy is finally released by creation of electron-hole pairs. These electrons and holes are collected to produce a pulse whose amplitude is proportional to the energy deposited in the active volume of the HPGe crystal. These pulses are amplified, shaped and sorted according to pulse height to produce a histogram showing, as a function of energy, the number of photons absorbed by the detector. After the accumulation of a sufficient number of pulses the histogram will display a spectrum with one or more peaks with an approximately normal (Gaussian) distribution corresponding to photons that transferred their entire energy to the detector. These are superimposed on continuum constituted by the events related to the partial deposition of energy.

The recorded peak area depends on the emission rate of the gamma-ray and on the detection efficiency of the detector, which is energy dependent. The emission rate, $R(E)$, for a gamma-ray of energy E is determined by dividing the net area, $N(E)$, in the full-energy peak by the measurement live time, T_L , and full-energy-peak efficiency, $\varepsilon(E)$, of the detector for the counting geometry used. A curve or functional representation of the full-energy-peak efficiency permits interpolation between available calibration points. Corrections may be needed for:

- a) decay of the source during sampling (e.g., with air filters) and counting and/or ingrowth;
- b) decay of the source from a previous time to the counting period and/or ingrowth;
- c) attenuation of photons within and/or external to the source that is not accounted for by the full-energy-peak efficiency calibration;
- d) solid angle correction that is not accounted for by the full-energy-peak efficiency calibration;
- e) true coincidence (cascade) summing;
- f) loss of pulses due to pulse pile-up (at high counting rates).

NUCLEAR INSTRUMENTATION – MEASUREMENT OF ACTIVITY OR EMISSION RATE OF GAMMA-RAY EMITTING RADIONUCLIDES – CALIBRATION AND USE OF GERMANIUM-BASED SPECTROMETERS

1 Scope

This document establishes methods for the calibration and use of high purity germanium spectrometers for the measurement of photon energies and emission rates over the energy range from 45 keV to approximately 3 000 keV and the calculation of radionuclide activities from these measurements. Minimum requirements for automated peak finding are stated. This document establishes methods for measuring the full-energy peak efficiency with calibrated sources.

Performance tests are described that ascertain if the spectrometer is functioning within acceptable limits. These tests evaluate the limitations of the algorithms used for locating and fitting single and multiplet peaks. Methods for the measurement of and the correction for pulse pile-up are suggested. A test to ascertain the approximate magnitude of true coincidence summing is described. Techniques are recommended for the inspection of spectral analysis results for large errors resulting from true coincidence summing of cascade gamma-rays in the detector. Suggestions are provided for the establishment of data libraries for radionuclide identification, decay corrections, the conversion of gamma-ray emission rates to decay rates and Monte Carlo simulations.

The measurement of X-ray emission rates is not included because different functional fits are required for X-ray peaks, which have intrinsically different peak shapes than gamma-ray peaks. Further, X-ray peaks are complex multiplets (e.g., the K X-rays of Tl include 10 individual components that form four partially resolved peaks). This document does not address the measurement of emission rates of annihilation radiation peaks or single- and double-escape peaks resulting from partial energy deposition in the detector from pair production. Escape peaks may require different fitting functions than comparable full-energy peaks. Further, annihilation radiation and single-escape peaks have a different and larger width than a gamma-ray peak of similar energy. Discussion of acceptable methods for measuring the lower limits of detection as they relate to specific radionuclides is beyond the scope of this document.

The object of this document is to provide a basis for the routine calibration and use of germanium (HPGe) semiconductor detectors for the measurement of gamma-ray emission rates and thereby the activities of the radionuclides in a sample. It is intended for use by persons who have an understanding of the principles of HPGe gamma-ray spectrometry and are responsible for the development of correct procedures for the calibration and use of such detectors. This document is primarily intended for routine analytical measurements. Related documents are IEC 60973 and ISO 20042.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60050-395:2014, *International Electrotechnical Vocabulary (IEV) – Part 395: Nuclear instrumentation – Physical phenomena, basic concepts, instruments, systems, equipment and detectors*

IEC 60050-395:2014/AMD1:2016

IEC 60050-395:2014/AMD2:2020

IEC 60973, *Test procedures for germanium gamma-ray detectors*

ISO 11929 (all parts), *Determination of the characteristic limits (decision threshold, detection limit and limits of the confidence interval) for measurements of ionizing radiation – Fundamentals and application*

ISO 20042, *Measurement of radioactivity – Gamma-ray emitting radionuclides – Generic test method using gamma-ray spectrometry*

JCGM 100:2008, *Evaluation of measurement data – Guide to the expression of uncertainty in measurement (GUM)*

JCGM 200:2012, *International vocabulary of metrology – Basic and general concepts and associated terms (VIM), 3rd edition 2008 version with minor corrections*

3 Terms, definitions and symbols

For the purposes of this document, the following terms and definitions apply, as well as those given in IEC 60050-395 and JCGM 200.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia available at: <http://www.electropedia.org/> and IEC Glossary available at: <http://std.iec.ch/glossary>
- ISO Online browsing platform: available at <http://www.iso.org/obp>

3.1 Terms and definitions

3.1.1

accuracy

closeness of agreement between a measured quantity value and a true quantity value of a measurand

[SOURCE: JCGM 200:2012]

3.1.2

activity

A

number dN of spontaneous nuclear transitions or nuclear disintegrations for a radionuclide of amount N produced during a short time interval dt , divided by this time interval

Note 1 to entry: The unit is becquerel (Bq).

[SOURCE: IEC 60050-395:2014, 395-01-05]

3.1.3

analog-to-digital converter

ADC

electronic device used to convert the amplitude of a voltage pulse from analog to digital format

3.1.4

ADC conversion gain

number of channels over which the full amplitude span can be spread

Note 1 to entry: Usually 4 096 to 16 384 channels are used for HPGe gamma-ray spectrometry.

3.1.5**attenuation**

net loss at the detector of primary photons of a given energy resulting from their interaction with matter either due to the occurrence of scattering or absorption in the sample or in material between the sample and the active volume of the detector

3.1.6**background**

spectral data including peaks not caused by the source but rather resulting from radioactive decay occurring in the surrounding environment or from cosmic ray interactions in or adjacent to the detector (see 3.1.11)

3.1.7**calibration**

determination of a value that converts a measured number into a desired physical quantity (e.g., pulse-height into photon energy, or counts per second into emission rate)

3.1.8**cascade transitions**

gamma-rays in the radioactive decay of a single radionuclide that are emitted sequentially and within the resolving time of the spectrometer

3.1.9**true coincidence summing**

simultaneous detection of two or more photons originating from a single radioactive decay that results in only one observed (summed) pulse (also cascade summing)

3.1.10**combined standard uncertainty**

standard uncertainty of the result of a measurement when that result is obtained from the values of a number of other quantities, equal to the positive square root of a sum of terms, the terms being the variances or covariances of these other quantities weighted according to how the measurement result varies with changes in these quantities

Note 1 to entry: See JCGM 100:2008 GUM 1995 with minor corrections.

3.1.11**continuum**

part of the pulse-height distribution lying underneath a peak including contributions associated with the source, detector, and measuring conditions that affect the spectral shape

3.1.12**conventional true value <of a quantity>**

commonly accepted best estimate of the value of that quantity

Note 1 to entry: This and its associated uncertainty will normally be determined by a national or international transfer standard, or by a reference instrument that has been calibrated against a national or international transfer standard.

3.1.13**counting rate**

number of pulses registered by the detector per unit of time being registered in a selected voltage or energy interval (expressed in s^{-1})

3.1.14**crossover gamma-ray**

gamma-ray occurring between two non-adjacent nuclear levels

3.1.15

dead time

time during which a counting system is unable to process an input pulse

3.1.16

direct current (DC) level

input or output voltage level on a DC-coupled instrument when there are no pulses present

3.1.17

direct current (DC) offset

difference between a current or voltage level and a reference level

3.1.18

emission intensity per decay

emission intensity and yield

$P(E)$ or $P_{\gamma}(E)$

probability that a radioactive decay will be followed by the emission of the specified radiation

Note 1 to entry: Gamma-ray emission intensities are often expressed per 100 decays.

3.1.19

energy resolution, full width at half maximum

FWHM

width of a peak at half of the maximum peak height where the baseline is measured from the continuum

3.1.20

energy resolution, full width at tenth maximum

FWTM

width of a peak at one tenth of the maximum peak height where the baseline is measured from the continuum

Note 1 to entry: For a normal (Gaussian) distribution, FWTM is 1,823 times its FWHM.

3.1.21

error

measurement error

measured quantity value minus a reference quantity value

Note 1 to entry: The concept of 'measurement error' can be used both:

- when there is a single reference quantity value to refer to, which occurs if a calibration is made by means of a measurement standard with a measured quantity value having a negligible measurement uncertainty or if a conventional quantity value is given, in which case the measurement error is known, and
- if a measurand is supposed to be represented by a unique true quantity value or a set of true quantity values of negligible range, in which case the measurement error is not known.

Note 2 to entry: Measurement error should not be confused with production error or mistake.

[SOURCE: JCGM 200:2012]

3.1.22

full-energy peak

photopeak

FEP

peak in the spectrum resulting from the complete (total) absorption of the energy of a photon in the active volume of the germanium crystal and collection of all of the resulting charge

3.1.23**full-energy-peak efficiency** $\varepsilon(E)$

ratio between the number of counts in the net area of the full-energy peak to the number of photons of that energy emitted by a source with specified characteristics for a specified measurement geometry (i.e., source-to-detector distance, source type)

3.1.24**gamma-ray branching ratio** $f(E)$

for a given excited nuclear state, ratio of the emission rate of a particular gamma-ray to the total transition rate from that state

3.1.25**gamma-ray emission rate** $R(E)$

rate at which a gamma-ray of a given energy from the decay of a particular radionuclide is emitted from a given source

Note 1 to entry: The gamma-ray emission rate is the activity times the gamma-ray emission intensity.

3.1.26**live time** T_L

time interval of a count during which a counting system is capable of processing input pulses

3.1.27**multichannel pulse-height analyser**

MCA

electronic device that records and stores pulses according to their amplitude. It consists of three function segments:

- an ADC to provide a means of measuring pulse amplitude;
- memory registers (one for each channel of the spectrum) to tally the number of pulses having an amplitude within a given voltage increment; and
- an input/output section that permits transfer of the spectral information to other devices such as a computer, or other display or permanent storage media.

3.1.28**peak-to-Compton ratio for the 1 332 keV ^{60}Co peak**

ratio of the full-energy-peak height, for ^{60}Co measured at 1 332 keV, to the average height of the corresponding Compton plateau between 1 040 keV and 1 096 keV

3.1.29**pole-zero cancellation**

pole-zero adjustment on the shaping amplifier adjusts the zero location of the pole-zero network to exactly cancel the preamplifier output pole and thus provide single-pole (i.e., no under or overshoot) response of the signal pulse at the amplifier output

Note 1 to entry: This operation converts the long-tailed preamplifier pulse to a short-tailed pulse suitable for signal optimization and subsequent pulse-height analysis.

3.1.30**pulse baseline**

average of the level from which a pulse departs and to which it returns in the absence of a following overlapping pulse

3.1.31 pulse pile-up random summing

occurrence of two successive pulses closely associated in time but from separate decays such that they contribute to each other's pulse height and shape

Note 1 to entry: Usually, the system processes the two inputs as a composite single pulse which is stored in a spectral channel different from that at which either of the component pulses would have been stored.

Note 2 to entry: Pulse pile-up is a function of the square of the counting rate and of the amplifier pulse width.

3.1.32 real time counting period

T_r
counting time uncompensated for periods in which an instrument might be unable to respond

Note 1 to entry: Real time of a count equals live time plus dead time.

3.1.33 relative full-energy-peak efficiency <for detector specification>

ε_r
ratio of full-energy-peak efficiency for a point source of ^{60}Co (1 332 keV photons) to that of a NaI(Tl) crystal of 7,6 cm diameter $\times$ 7,6 cm high for a source-to-detector distance of 25 cm (that is $1,2 \times 10^{-3}$).

$$\varepsilon_r = 0,833 \times 10^3 \times \frac{n(1332)}{R(1332)} \quad (1)$$

where

$n(1332)$ is the measured full-energy peak counting rate;
 $R(1332)$ is the 1 332 keV gamma-ray emission rate from the ^{60}Co source;
 $0,833 \times 10^3$ is the reciprocal of the full-energy-peak efficiency of the NaI(Tl) detector at that energy and distance.

3.1.34 sample

radioactive material measured using the HPGe detector to determine the activity and/or emission rate

3.1.35 shaping-time constant index

indicator of shaped pulse width (width of a shaped pulse at 50 % of its peak height). Unless otherwise specified, that width is $f_{1/2}$

3.1.36 source

calibrated radioactive material used to determine the HPGe detector response

3.1.37 standardization coefficient

$S_c(i, E)$
factor used for the direct conversion of the counts contained under a net full energy peak of a given energy, E , and from a specific radionuclide, i , to the activity of the radionuclide

3.1.38**total efficiency** $\varepsilon_t(E)$

ratio of the number of pulses recorded in the entire energy spectrum and the number of photons emitted by the source of a given energy, E , for a specified source-to-detector distance

3.1.39**uncertainty**

non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used

[SOURCE: JCGM 200:2012]

3.2 Symbols

A	activity, or decays per second, of a nuclide (Bq)
$B(E)$	net counting rate of an interfering background peak at energy E
C_i	multiplicative correction factor, where i is: a (attenuation), c (true coincidence summing), d (decay), or r (pile-up)
e	2,71828... base of natural or Napierian (or Napierian) logarithms, $\ln$
$f(E)$	fraction of transitions from a level which produce gamma-rays with energy E
$N(E)$	net counts in a full-energy peak due to a gamma-ray of energy E
$n(E)$	net counting rate in a full-energy peak due to a gamma-ray of energy E
$P(E)$	probability per decay or emission intensity per decay for a gamma-ray with energy E
$R(E)$	emission rate of gamma-rays with energy E by nuclei in a sample
$S_c(i, E)$	fraction of decays of radionuclide, i , in a sample which lead to counts in a full-energy peak corresponding to a gamma-ray of energy E
$f_{1/2}$	shaping-time constant (width of a shaped pulse at 50 % of its peak height)
$T_{1/2}$	half life
λ	decay constant, $\lambda = \ln(2)/T_{1/2}$
T_L	live-time counting period
T_r	real-time counting period
T_d	decay time from a reference time to the start of the counting period
$\alpha_K(E)$	K-shell internal conversion coefficient: the ratio of transitions of energy E that occur by K internal conversion to those that emit gamma-rays
$\alpha_t(E)$	total internal conversion coefficient: the ratio of transitions of energy E that occur by internal conversion to those that emit gamma-rays
$\varepsilon(E)$	full-energy-peak efficiency for gamma-rays of energy E
ε_r	relative full-energy-peak efficiency for detector specification
$\varepsilon_t(E)$	total efficiency for detecting a gamma-ray of energy E and producing a pulse with a height greater than the noise level of the amplifier
ω_K	K-shell fluorescence yield: the fraction of atomic K vacancies which lead to K X-rays
Π	operator that takes the product of the correction factors

4 Installation of instrumentation

Locate the HPGe spectrometer where stable, clean power is available or provide it via a power conditioner or uninterruptable power supply. Assure that the ambient temperature is stable and complies with the operating conditions specified by the manufacturer. Shield the spectrometer from interfering background radiation, including natural radiation emitted from the walls, floor, and ceiling, or resulting from cosmic-rays. The detector should be isolated from vibration producing equipment (see also Annex D).

Precaution – When filling the detector dewar with liquid nitrogen (LN_2), avoid spilling it in the vicinity of the cryostat or preamplifier which could lead to cracks in the vacuum seal rings of the cryostat or damage to the preamplifier. To avoid distortion of the measured spectrum by microphonics, data should not be acquired during the filling process.

Recommendation – Often the instrumentation associated with a HPGe spectrometer is located in more than one equipment rack or in two or more locations so that all components are not plugged into the same circuit or do not share the same ground. This can result in ground loops that adversely affect the detector resolution. To avoid such loops, a single connector box should be used into which all the instruments can be plugged. This box, in turn, should be plugged into a convenient main receptacle. Also, it is desirable to bundle together all the cables leading to the preamplifier, such as the cables from the detector-bias supply, the signal- and test-pulse cables, etc.

Follow the manufacturer's instructions and the procedures in Annex A for installation and preliminary testing of the individual components. Measure the energy resolution (i.e., FWHM, FWTM, FWHM) at 122 keV (^{57}Co) and at 1 332 keV (^{60}Co), and the peak-to-Compton ratio at 1 332 keV as described by the detector manufacturer's user manual. IEC 60973 and Annex A of this document may be useful in performing the above adjustments and measurements.

The experimental conditions recommended by the manufacturer for initial installation of the instrumentation are usually intended to assure that the HPGe spectrometer meets the various specifications (e.g., energy resolution) claimed by the manufacturer. These conditions are often not optimum for routine analyses. Therefore, the user should adjust the various spectrometer settings, including the amplifier shaping-time constant, baseline restorer, pole-zero cancellation, etc., for optimal performance under routine counting conditions before conducting the performance tests in this document. For example, timing of any blanking signals for reset preamplifiers should be checked.

If the measured values do not meet the manufacturer's specifications, the calibration should not proceed until the problem has been investigated and corrected where possible. All settings and experimental conditions shall be documented in a logbook for each specific HPGe spectrometer, and any changes or maintenance shall be so indicated at the time they occur.

5 Peak analysis and calibration procedures

5.1 Energy calibration

The energy calibration (gamma-ray energy as a function of channel number) of the HPGe spectrometer system shall be established by measuring the positions of selected full-energy peaks with large peak-height-to-background ratios and whose energies are known precisely. The energies of the selected peaks should cover the energy range of interest. Laboratories may have detectors that can cover different energy ranges so the ADC zeros and discriminators along with the gains should be adjusted as needed. A procedure to set the ADC zero and gain is described in A.3.3. If all detectors in a laboratory need to cover the same energy range, then it is useful to adjust the ADC zeros and discriminators along with the gains to give the same gain for all spectrometers. This allows the direct comparison of spectra from different detectors.

The calibration source should be counted for a duration that gives sufficient counts (i.e., at least 20 000) in the peaks to permit measurement of the peak positions with a precision of <0,2 keV. The peak positions at the calibration energies should be used to specify the coefficients of the fitting function (linear or quadratic) which are stored for subsequent evaluation of the energies of the measured peaks in the sample spectra. Differences of the order of 0,5 keV in the peak positions of the sample spectra are usually sufficient for correct radionuclide identification. If a linear or quadratic function does not adequately fit the entire energy range, it may be necessary to correct further for the pulse height nonlinearity. Sources that are useful for measuring the pulse-height nonlinearity are ^{152}Eu or $^{110\text{m}}\text{Ag}$ and ^{56}Co or ^{88}Y or $^{144}\text{Ce}/^{144}\text{Pr}$ or a mixed gamma source (see A.8.2).

Recommendation – The calibration of the FWHM and low-energy tail of the peaks is useful for automatic peak finding routines. This calibration can be performed simultaneously with the energy calibration.

5.2 Energy resolution calibration

The energy resolution is an important parameter used in the peak-finding algorithms, and in the peak area determination. The peak width is affected by different factors, such as electronic noise or counting rate, and depends on the deposited energy. The energy resolution calibration shall be established in the same way as the energy calibration, by determining the full-width at half maximum (FWHM) of selected full-energy peaks in the energy range of interest. The experimental conditions should follow the same criteria as for the energy calibration (both calibrations can be performed simultaneously). In a first approximation, the square of the FWHM should be a linear function of the energy.

5.3 Peak-finding algorithm

If an automated peak-finding routine is used in the spectral analysis, it should be able to find small, well-formed single peaks whose areas are statistically significant (above continuum). The peak-fitting routine should be able to find multiplet peaks (and discern if there is a single or multiple peaks) that meet the peak-area criterion for a singlet, are of the same intensity and are separated by one full-width-at-half-maximum (see Clause 8 for the test procedures). Optimization of the peak-search parameters of the peak-finding algorithm is left to the user or software vendor (see Annex B). These should be adjusted so that statistically significant peaks are found with a minimum number of false peaks being reported (see performance tests in Clause 8). Alternatively, it is possible to use a library to search for peaks at particular energies in the spectrum.

5.4 Peak position and area measurement

Any method that consistently produces satisfactory results for the measuring conditions and analysis requirements may be used to determine the peak position and area. Nonlinear and linear peak-fitting methods are primarily useful for complex spectra containing multiplet peaks. In general, more experience is required of the person using these more sophisticated peak-fitting methods. Gamma-ray spectroscopists should be thoroughly trained before using nonlinear fitting functions containing both a Gaussian and a tailing function. In all cases the same peak-area measuring technique should be used for the analysis of unknown samples as is used to measure the detector efficiency. Analyses of single gamma-ray peaks (i.e., >3 FWHM separation) are recommended over those with overlapping interferences (i.e., <3 FWHM separation) whenever there is a choice.

Warning – The peak-fitting algorithm may influence the energy dependence of pile-up corrections (see 7.6 and Clause A.7).

Recommendation – It is very helpful to be able to evaluate the quality of any peak fit visually through a display of the spectral counts in the peak region with the fitted function and continuum superimposed. This capability may permit resolution of questionable results. A display of the residuals between the fitted function and data in units of the estimated standard deviation of the data is also recommended.

5.5 Efficiency calibration measurement

5.5.1 General

Three separate approaches are considered for the calibration of the detector efficiency:

- a) measurement of a standardization coefficient for a specific gamma-ray and radionuclide by direct comparison with a standard source of known activity,
- b) measurement of the full-energy-peak efficiency as a function of energy, and
- c) calculations or modelling. These can be used in place of measurements to deduce efficiencies, or to infer efficiencies for one counting geometry from those measured for another; however, satisfactory agreement shall be demonstrated by direct measurement for at least one typical geometry. Monte Carlo simulations may be used to determine the detector efficiency. This will require knowledge of all the detector dimensions that shall be provided by the detector manufacturer. Validation measurements shall be performed to assess the accuracy of the simulations.

For approach b) two cases are considered:

- 1) source-to-detector distances for which essentially no need exists for true coincidence summing corrections, that is, greater than 10 cm, and
- 2) small source-to-detector distances that are required for sensitivity (low-activity samples) but may compromise the accuracy of the source configuration geometry and add the requirement for true coincidence summing corrections.

Clause A.8 contains efficiency measuring procedures for each of these experimental conditions.

5.5.2 Standardization coefficient for specific radionuclides

When the activity or gamma-ray emission rates of a limited number of radionuclides are to be measured, it is most accurate to measure them relative to a standardized sample of the same radionuclide in exactly the same source geometry and matrix. From measurements on the standardized samples, a standardization coefficient can be calculated for a selected gamma-ray emitted from each specific radionuclide. The standardization coefficient converts the net peak area divided by the live time to the activity of the radionuclide being measured. The need to interpolate between measured efficiency values, to correct for true coincidence summing, and to account for the uncertainty in the gamma-ray emission intensity is eliminated with this method. If the counting rates of the samples are low or closely approximate those of the standard, pulse pile-up corrections can also be neglected.

Severe true coincidence summing of cascade gamma-rays or of X-rays from electron capture or from electron conversion with coincident gamma-rays can occur, especially when counting samples located inside the well of a HPGe well detector (also see first precaution in 6.2.5). Therefore, the standardization coefficient method is the efficiency calibration technique recommended for these or similar experimental conditions.

5.5.3 Detector efficiency as a function of energy

5.5.3.1 General

The general method for measuring the emission rates of gamma-rays is by establishing the detector efficiency curve as a function of energy for a defined geometry and energy range. The efficiency values at intermediate energies are determined by interpolation between measured values. With this method, corrections may be required for pulse pile-up and true coincidence summing of gamma-rays. The corresponding radionuclide activities can be calculated from the gamma-ray emission rates when the gamma-ray emission intensities are known.

5.5.3.2 Large source-to-detector distances

At large sample-to-detector distances (typically, a source-to-detector distance >10 cm) the uncertainty in the replication of the sample-detector geometry – and in the correction for true coincidence summing of photon pulses in the detector – can usually be neglected for routine measurements. For these reasons, measurements at large sample-to-detector distances are preferred over measurements close to the detector, provided the source activity is high enough to achieve an acceptable accuracy within the allotted counting time.

5.5.3.3 Small source-to-detector distances

The analysis of low-activity-level samples is performed at many different types of nuclear facilities. Effluent and environmental samples typically require small sample-to-detector distances and long counting times. These experimental conditions can result in large uncertainties/errors due to large background contributions, non-reproducibility of sample-to-detector distance, and large true coincidence summing effects resulting from two or more coincident gamma-rays from the same radionuclide. For example, an uncertainty of $\pm 1,0$ mm in the source-to-detector distance reproducibility at 5 cm results in an additional relative uncertainty of approximately 4 % in the net peak area for a point source and a 5 cm diameter HPGe detector. A similar size or larger uncertainty can result from the true coincidence summing of gamma-rays at a 5 cm source-to-detector distance for a point source depending on the radionuclide decay scheme.

Whenever possible, a sample should be at least 5 cm from the detector. True coincidence summing corrections should be applied to all peaks warranting such corrections. This is especially important when the source-to-detector distance is <5 cm (see 6.2.5). Large sample containers have a large mean source-to-detector distance even when they are in close proximity to the detector. This effect reduces the true coincidence summing effect.

5.5.3.4 Reentrant (Marinelli) beakers

The reentrant (or Marinelli) beaker (IEC 60973) is a beaker with a recessed well in its bottom that allows the beaker to fit over and around the detector housing. This geometry provides high sensitivity for the measurement of gamma-ray-emitting radionuclides. Depending on the size of the reentrant beaker and the detector efficiency, significant true coincidence summing corrections may be required and corresponding corrections should either be estimated or applied. The test described in 9.1 may be useful in demonstrating if true coincidence summing corrections can be avoided.

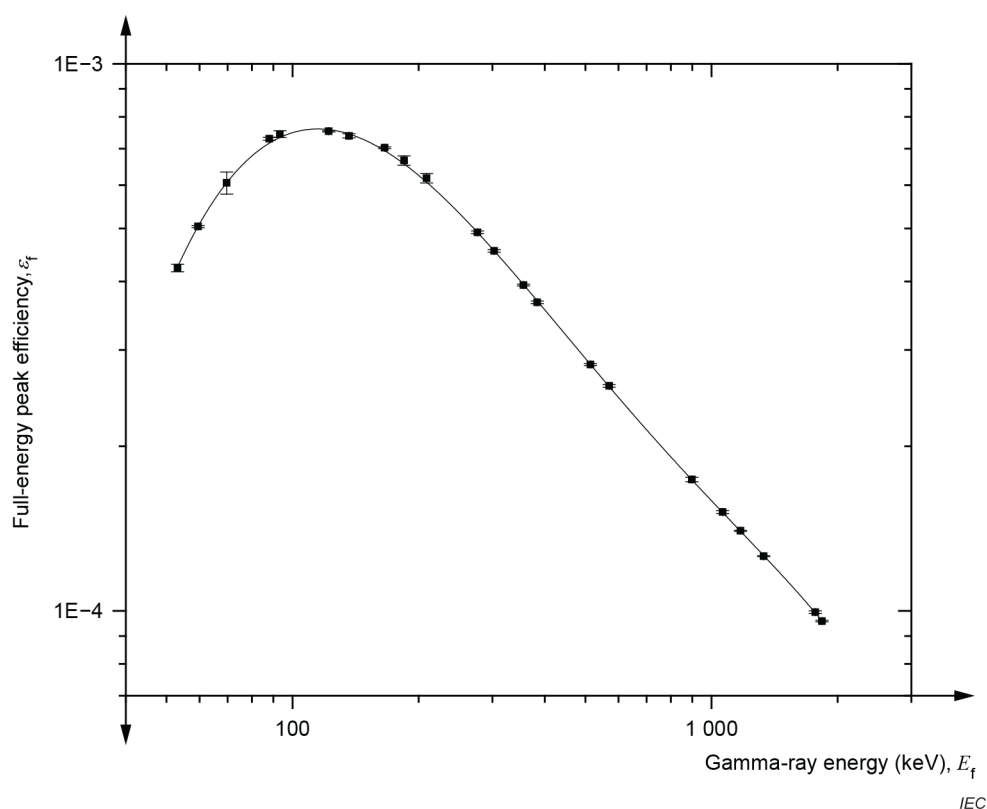
5.5.4 Efficiency function

The full-energy-peak efficiency values, $\varepsilon(E)$ for energy E , should be plotted either a) as $\varepsilon(E)$ on a log-log graph (see Figure 1) or b) as the function $Y = \varepsilon(E) \times E^a$ on a linear plot (a is a normalizing constant as shown in Figure 2); this latter function provides better resolution of the efficiency data when plotted.

There should be no large energy gaps between the efficiency values (especially below 300 keV) that would cause a large efficiency-interpolation uncertainty. Efficiency values for energies below the lowest measured energy efficiency point shall not be used to measure gamma-ray emission rates. Above approximately 300 keV the efficiency, as a function of energy, approximates a straight line to a few percent when plotted on a graph with a log-log scale. For many detectors, only a small deviation from this straight line exists between 500 keV and 1 000 keV. For $2 \text{ MeV} < E < 4 \text{ MeV}$ efficiency values may be estimated, with some loss in accuracy, by linear extrapolation beyond the highest measured efficiency value. However, it is best to avoid extrapolation beyond the highest measured efficiency.

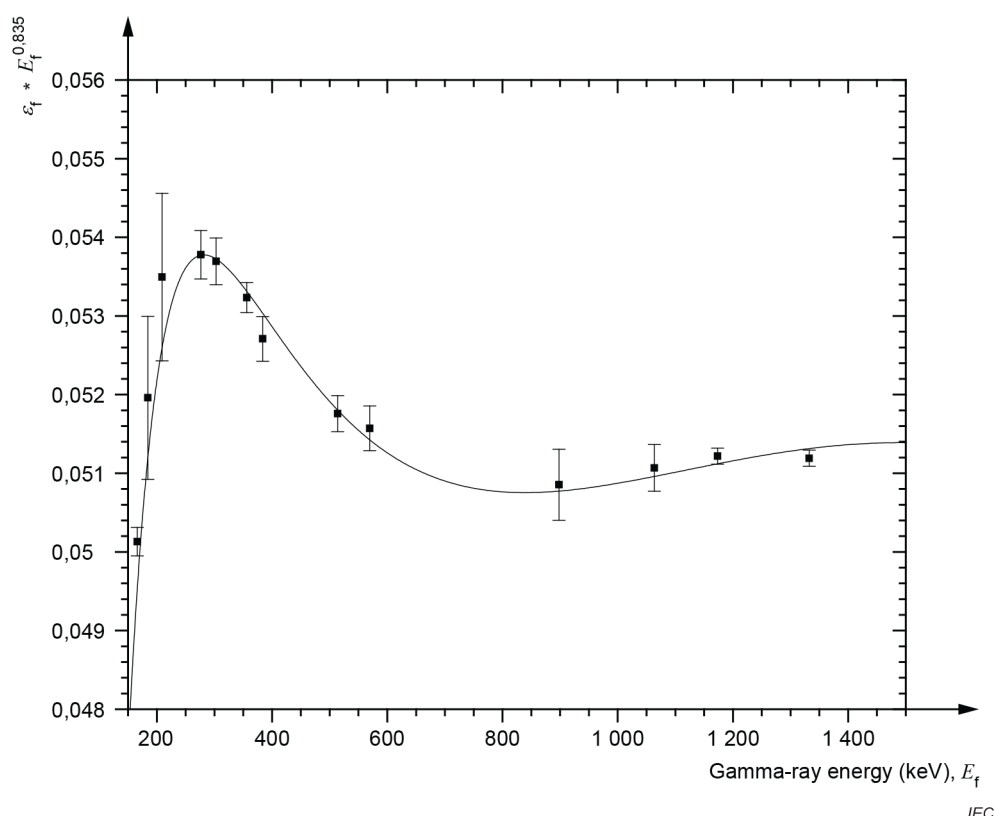
When fitting efficiency data with a function, the number of data points being fitted should exceed the number of functional parameters to be determined by about a factor of two and no large gaps should be present within the energy range being fitted if oscillations in the fitted function are to be avoided. Extrapolation of a fitted function beyond the measured efficiency data is subject to large biases.

Recommendation – Different functions may be used for the fit. The residuals of the fit and χ^2 divided by the degrees of freedom can provide information about the goodness of the fit. Comparing different fits can provide information that could allow for the selection of the best possible fit for the efficiency data. The user can define two (or more) energy regions to fit the efficiency data: the consistency between the set of fits should be checked around the cross points.



NOTE Efficiency as a function of energy on a log-log plot for a point source at a 45 cm source-to-detector distance for a coaxial HPGe spectrometer.

Figure 1 – Full-energy-peak efficiency as a function of gamma-ray energy



NOTE Part of the data in Figure 1 plotted as $\varepsilon_f E_f(\text{keV})^{0.835}$ versus gamma-ray energy $E_f(\text{keV})$, where ε_f is the full-energy peak efficiency at $E_f(\text{keV})$ and where $E_f(\text{keV})$ is the gamma-ray energy.

Figure 2 – $\varepsilon_f E_f(\text{keV})^{0.835}$ as a function of gamma-ray energy

6 Gamma-ray measurements with HPGe spectrometers

6.1 Measurement of gamma-ray energies

The gamma-ray energies are normally derived from a previous energy calibration (see 5.3 and 5.4). Sometimes it is desirable to derive the energies directly from the spectrum. In this case, calibration shall be performed using identified gamma-rays having accurately known energies.

6.2 Measurement of gamma-ray emission rates and radionuclide activities

6.2.1 General

The sample shall be counted in the same source-to-detector geometry as used for the establishment of the efficiency unless the differences can be accurately compensated for by calculation. The gamma-ray spectrum shall be accumulated at the same gain as used in the energy calibration and for a counting time sufficient to give an acceptable statistical uncertainty. The energies of the gamma-ray peaks present in the spectrum shall be identified by use of the energy calibration described above.

Warning – If the sample geometry (e.g., source-to-detector distance, source type) is not the same as for the source used to establish the efficiency, then additional corrections to account for differences in solid angles, source area/volume and/or matrices are needed.

Obtain the net area counting rate in each of the gamma-ray peaks of interest as described in 5.4. Obtain the full-energy-peak efficiency for each of the peaks of interest from the efficiency function as described in 5.5.4. Calculate the number of gamma-rays emitted per second, $R(E)$, for each of the full-energy peaks as follows:

$$R(E) = (n(E) - B(E)) \frac{\prod C_i}{\varepsilon(E)} \quad (2)$$

where

- $n(E)$ is the net counting rate in the full-energy peak at energy E ; $N(E)/T_L$, where $N(E)$ is the net peak area and T_L is the counting live time;
- $B(E)$ is the net counting rates of any interfering peaks in the background;
- $\varepsilon(E)$ is the full-energy peak efficiency;
- C_i are the multiplicative correction factors (where $i = d, r, c$ and a , as defined below); and
- Π is the operator that takes the product of the correction factors.

The correction factors, C_i include correction for decay during the counting period ($i = d1$) and from the start time of counting period to a reference time ($i = d2$), pulse pile-up ($i = r$), true coincidence summing ($i = c$), and differences in the attenuation of the sample counting geometry from that in the standard ($i = a$). Each correction factor shall be applied whenever its magnitude is expected to exceed one third of the acceptable inaccuracy in the resulting gamma-ray emission rate.

If there is only one nuclide contributing to the full energy peak, the nuclear decay rate or activity (in units of becquerel, Bq) is calculated by dividing the gamma-ray emission rate (in units of s^{-1}) by the appropriate gamma-ray emission intensity, $P(E)$, see formula (3).

$$A = \frac{R(E)}{P(E)} \quad (3)$$

6.2.2 Subtraction of interference peaks in the background

Large samples may shield the detector from the ambient background radiation, causing a lower counting rate than if an instrumental background (no sample present) were obtained. In addition, all soils contain some natural ^{40}K , Th and U radioactivity. Thus, whenever large low-activity samples are counted, a background spectrum shall be obtained with a "blank" sample in the same geometry and of the same density. The background count shall be accumulated for at least the same counting time as used in counting the samples to be analysed.

The "blank" sample background spectrum, normalized for the same counting time, could be subtracted from the sample spectrum, channel-by-channel, or preferably, the background spectrum should be analysed to obtain the background-peak counting rates, $B(E)$, at energies E . If the latter method is used (it is preferred), the background-peak counting rates are then subtracted from the respective net peak area counting rates, $n(E)$, in the sample spectrum (see formula (2)). By subtracting the respective background peak counting rates from those of the sample, the statistics of each count are preserved. This method is also less sensitive to small changes in the energy calibration. If possible, the "blank" spectrum should be scanned to be sure that all background peaks are identified and that no false peaks are reported.

6.2.3 Radioactive decay

6.2.3.1 General

The correction factor that normalizes for radioactive decay is normally composed of two components:

- a) decay during the counting interval, and
- b) decay from a previous time, usually a sample-irradiation time (e.g., neutron-activation analysis) or a sample-collection time or reference time.

When sampling radioactivity or performing an irradiation over a time period comparable to the half-lives of the radionuclides of interest, a third correction factor shall be applied. These correction factors will be designated C_{d1} , C_{d2} , and C_{d3} , respectively. The combined correction factor for radioactive decay can be expressed as:

$$C_d = C_{d1} \times C_{d2} \times C_{d3} \quad (4)$$

Figure 3 illustrates the time to which each correction is made for the decay correction formulas given in 6.2.3.2, 6.2.3.3 and 6.2.3.4.

6.2.3.2 Radioactive decay during the counting period

If significant decay occurs during the counting time (>10 %) it will be necessary to correct the net peak area so that the gamma-ray emission rates or the radionuclide activities are determined at the start time of the count. If this correction is not applied when decay during the counting time is significant, the measured gamma-ray emission rates will apply to sometime after the start of the count. The following formula gives this multiplicative correction:

$$C_{d1} = \frac{\lambda T_r}{1 - e^{-\lambda T_r}} \quad (5)$$

where

- C_{d1} is the correction factor for decay during the count;
- λ is the decay constant, $\lambda = \ln(2)/T_{1/2}$ in which $T_{1/2}$ is the radionuclide half-life;
- T_r is the real time of the count; and
- e = 2,71828..., base of the natural logarithm.

This correction assumes a constant dead time during the acquisition period. A bias will be introduced if the dead time varies significantly.

6.2.3.3 Radioactive decay from the start time of counting period to a reference time

The correction for radioactive decay to a reference time from the start time of a count is determined from the following formula:

$$C_{d2} = e^{\lambda T_d} \quad (6)$$

where

- C_{d2} is the correction factor for decay from the reference time to the start time of the count period;
- T_d is the decay time from a reference time to the start of the counting period.

6.2.3.4 Correction during the sampling time or the irradiation period

Two options may be used to calculate the correction to the start of a sample activation at a constant rate during irradiation or a constant rate of activity collection (see Figure 3). If one is interested in the number of atoms in the unirradiated sample that are available for activation during an irradiation such as for neutron-activation analysis, then a saturated activity is useful (i.e., number of atoms which would be activated at saturation). In this option:

$$C_{d3} = \frac{1}{1 - e^{-\lambda T_i}} \quad (7)$$

where

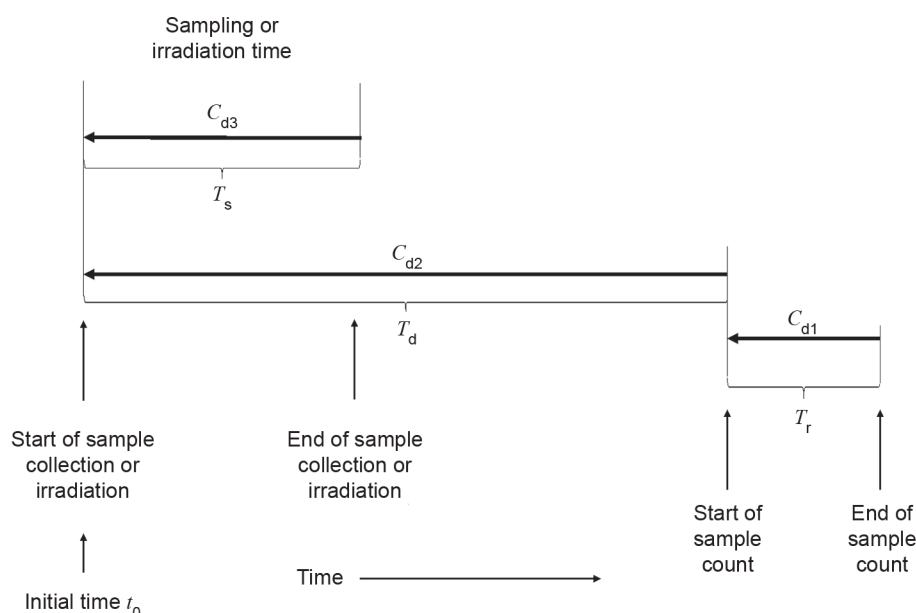
T_i is the irradiation duration.

If one is collecting at a uniform rate already activated nuclides, such as in the collection of radionuclides in reactor effluent studies, then a value representing the disintegration rate of the sampled stream at time T_s may be of interest (see Figure 3). In this case:

$$C_{d3} = \frac{\lambda T_s}{1 - e^{-\lambda T_s}} \quad (8)$$

where

T_s is the sampling duration.



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NOTE Specification of various events expressed in units of time, where t_0 is the initial time, T_s is the sampling or irradiation time, T_d is the decay time of the sample, and T_r is the real time. The arrows point to the times to which the respective decay corrections apply.

Figure 3 – Specification of times for decay corrections

6.2.4 Pulse pile-up (random summing)

The pulse pile-up correction shall be applied whenever the desired accuracy of the measurement requires it. The pulse pile-up correction, C_r , may be measured by one of several methods. Three popular methods are:

- method 1: use of a movable intense low-energy gamma-ray source and a fixed higher-energy source, or alternatively, use of a set of sources whose relative activities are precisely known with source counting rates ranging from about 300 s^{-1} up to about $40\,000 \text{ s}^{-1}$;
- method 2: use of live-time extension techniques whereby the live time is extended to compensate for displaced pile-up pulses; and
- method 3: the use of a precision pulser of known repetition rate (injected into the preamplifier test input).

Although each method gives a slightly different correction, the difference between methods is typically less than 20 % of the correction. The type of ADC and the type of peak-area measurement algorithm can affect the amount of energy dependency in the pulse pile-up correction.

A description of the source-set method is given in A.7.2. Descriptions of methods 2 and 3 for measuring the pulse pile-up correction can be found in A.7.3 and A.7.4, respectively, and the literature. The use of these or other types of electronic circuitry to correct automatically for pile-up is permitted if validated by passing the test in Pulse pile-up (random summing) described in 7.6.

Recommendation – Follow manufacturer provided recommendations when setting up the system. When analog electronics are used, the amplifier shaping-time constant should be selected to optimize the overall performance of the spectrometer when high counting rates are to be recorded (i.e., balance the energy resolution against counting rate performance). Larger shaping-time indices ($f_{1/2} > 5 \mu\text{s}$) typically yield better energy resolution but poorer counting-rate performance. For amplifiers operating at an unipolar shaping-time constant of $f_{1/2} = 5 \mu\text{s}$, the pulse width at the 1 % pulse-level is approximately $12 \mu\text{s}$; at input counting rates $< 1\,000 \text{ s}^{-1}$, the pulse pile-up correction is usually $< 1 \%$ and may be neglected.

Warning – High counting rates can lead to dead-time inaccuracies in the ADC and to pile-up of pulses in the amplifier. Although the live timer of the multichannel analyser only records time while the pulse-processing circuitry is able to accept pulses, at very high rates ($> 10\,000 \text{ s}^{-1}$), differences in the live timer can be significant ($> 5 \%$). For digital electronics, use the pile-up rejection provided by the manufacturer and verify that the peak area and resolution is not affected for the entire counting range needed.

Warning – Pile-up rejectors may be useful at high counting rates because they prevent the storing of piled-up pulses in the spectrum and thereby reduce the continuum between and underlying the spectral peaks. However, if the pile-up rejection process is amplitude dependent, unacceptably large errors in the correction of the net peak-area counting rates could result. Therefore, the use of pile-up rejection with or without live-timing or loss-free techniques is permitted only if the user demonstrates that it does not introduce an unacceptable error to the measurement, see 7.6. Available commercially are loss-free counting modules and programs that monitor the dead-time during data acquisition to compensate for a varying dead-time. The reader is referred to the manufacturer's manuals, brochures and catalogues for further information. The performance of these systems shall be verified prior to use for constant counting rates with the performance test in Pulse pile-up (random summing) described in 7.6. The principles upon which some loss-free counting modules work may cause them to distort counting statistics.

6.2.5 True coincidence (cascade) summing

True coincidence summing corrections shall be applied whenever counting conditions result in significant coincident summing of gamma-rays associated with the radionuclides of interest. It should be assumed that these corrections are necessary for all counting geometries in which the mean sample-to-detector distance is <10 cm unless demonstrated otherwise.

Coincidence summing depends on the radionuclide decay scheme and on the detector efficiency. There are two kinds of effects: "summing-out" which results in the removal of counts from the full energy peak (FEP) and "summing-in" which results in adding counts in the FEP (e.g., the low-probability 2 734 keV crossover peak in the decay of ⁸⁸Y can contain counts from the summing of the high-probability 898 keV and 1 836 keV cascade gamma-rays). Programs developed for use in determining true coincidence summing corrections, C_c , for specific radionuclides and source-detector geometries are described in the literature ([2]¹, [28], [29], [42], [43]). A brief description of true coincidence summing, and the equations needed to determine the loss or gain of counts to a gamma-ray peak is provided in Annex C.

Precaution – Characteristic X-rays produced from electron-capture and internal-conversion transitions also can sum with gamma-rays when thin-window detectors are used to measure both low-energy X-rays and gamma-rays. One alternative to reduce this effect is to place an absorber (e.g., 0,5 mm thick copper, 1 mm thick tin) between the source and the detector if this practice does not interfere with the basic intent of the measurement. Photon attenuation corrections shall be applied when using an absorber (including beta absorbers) if the efficiency curve was not obtained with the absorber in place. If software is used to perform the coincidence summing corrections, there is no need to add the absorbers.

Precaution – Beta particles and associated bremsstrahlung emitted in the decay of beta-emitting radionuclides can contribute significantly to the spectral continuum. Further, the gamma-ray transitions promptly follow the beta radiation (assuming no isomeric transitions). The coincidence summing of beta particles and associated bremsstrahlung with gamma-rays is not included in most true coincidence summing correction programs. Under these circumstances, insertion of a low-atomic-number absorber between the source and the detector can significantly reduce the detection of beta particles and thereby reduce their summing with gamma-rays. The correction for gamma-ray attenuation in the beta-particle absorber shall be included in the efficiency or provided as a separate correction.

6.2.6 Efficiency transfer corrections

6.2.6.1 General

Whenever counting geometrical conditions are different from the calibration ones, efficiency transfer corrections shall be introduced, these corrections should consider:

- changes in the sample-to-detector distance,
- differences in shape, matrix and density of the sample,
- external absorbers.

Efficiency transfer methods (numerical or Monte Carlo) can be used to compute these corrections (see Clause 12). In simple cases, where there is no change in the geometry, the attenuation correction can be computed as the product of two components which take account of external absorbers, C_{a1} , and differences in the matrix or density of identically shaped samples, C_{a2} . These corrections are then combined as:

$$C_a = C_{a1} \times C_{a2} \quad (9)$$

where

C_a is the attenuation correction.

¹ Numbers in square brackets refer to the Bibliography.

6.2.6.2 Attenuation external to the sample

When an absorber is inserted between the sample and the detector, the correction for attenuation in the absorber is given by:

$$C_{a1} = e^{\mu \rho d} \quad (10)$$

where

μ is the mass attenuation coefficient (depending on the energy and the absorber material);

ρ is the density of the absorber; and

d is the mean thickness of the absorber.

For small sample-to-detector distances this formula may need to be modified or the correction measured directly.

Recommendation – The mass attenuation coefficient for different elements, compounds and mixtures can be determined experimentally [51] and can also be found, for example, at: <https://physics.nist.gov/PhysRefData/Xcom/html/xcom1.html>

6.2.6.3 Attenuation within the sample (self-attenuation)

6.2.6.3.1 General

When it is not possible to measure the full-energy-peak efficiency with a standard of the same matrix and density as the sample, an attenuation correction beyond that included in the full-energy-peak efficiency may be required (physical configurations of the standard and sample shall be the same). When the error resulting from no correction is expected to be significant, a correction shall be made. This correction is most important for low-energy gamma-rays or X-rays and samples containing high-atomic-number elements.

6.2.6.3.2 Calculation for uniform plane sample

The correction for self-attenuation in a homogeneous, extended sample may be calculated by numerical integration (of the transmission through a material layer, according to Beer-Lambert law) over the sample thickness. For source-to-detector distances that are large relative to the dimensions of a uniform plane sample, the relative correction for self-attenuation (not included in the measured efficiency) may be estimated to be:

$$C_{a2} = \frac{\mu_u(E) \rho_u d}{1 - e^{-\mu_u(E) \rho_u d}} \times \frac{1 - e^{-\mu_s(E) \rho_s d}}{\mu_s(E) \rho_s d} \quad (11)$$

where

$\mu_u(E)$ is the mass attenuation coefficient at energy E of sample;

$\mu_s(E)$ is the mass attenuation coefficient at energy E of efficiency-measuring standard;

ρ_u is the density of sample;

ρ_s is the density of efficiency-measuring standard; and

d is the thickness of the standard/sample.

6.2.6.3.3 Measured correction

The attenuation correction (relative to that of the efficiency-measuring standard) for samples of the same shape but composed of a different matrix/density may be measured. A standard of the same shape but different matrix/density with gamma-rays covering the energy range of interest should be counted under the same conditions as used to determine the efficiency curve. The emission rates of the gamma-rays from the original efficiency-measuring standard and from the present attenuation-correction standard shall be known with sufficient accuracy to determine the attenuation correction with adequate precision.

The relative attenuation correction, C_{a2} , can be calculated from:

$$C_{a2} = \frac{R(E) \varepsilon(E)}{(n(E) - B(E)) \prod_{i \neq a} C_i} \quad (12)$$

where

- $R(E)$ is the emission rate of the gamma-ray at energy E in the attenuation-correction standard;
- $\varepsilon(E)$ is the full-energy-peak efficiency at energy E ;
- $n(E)$ is the net peak-area counting rate for the attenuation-correction standard of a gamma-ray of energy E ;
- $B(E)$ is the net peak-area counting rate of any background peak at energy E ;
- Π is the operator that takes the product of the correction factors; and
- C_i are the corrections for counting rate ($i = r$); true coincidence summing ($i = c$); and decay prior to and during the count ($i = d$) for the attenuation-correction standard.

An alternative and probably more accurate method to measure the relative attenuation correction is with two uncalibrated samples identically shaped but with different matrices and with each uniformly spiked with an accurately measured aliquant, M , of a gamma-ray emitting radionuclide (see Clause A.9 for the preparation of working standards). The matrix/density of one sample, s , is identical to that of the standard used to measure the detector efficiency and the other sample, u , is the same as the samples whose density is different from the efficiency-measuring standard. Assuming corrections for pulse pile-up can be neglected, for a given energy, E , the relative attenuation correction, C_{a2} , is given by:

$$C_{a2}(E) = \frac{(n_s(E) - B_s(E)) M_u}{(n_u(E) - B_u(E)) M_s} \quad (13)$$

where

- $n_s(E)$ and $n_u(E)$ are the net counting rates in the peak areas of the standard and sample, respectively, at energy E ;
- $B_s(E)$ and $B_u(E)$ are the net counting rates in the peak areas of the associated background spectra;
- M_s is the mass of aliquant used to prepare the working standard whose matrix is identical to that of the standard used to measure the detector efficiency;
- M_u is the mass of aliquant used to prepare the sample whose matrix is identical to that of the unknown samples to be measured.

7 Performance tests of the spectrometry system

7.1 General

The spectrometer tests enumerated in 7.2 to 7.6 shall be performed on a regularly scheduled basis. The frequency for performing each test should depend on the long-term stability and maintenance record of the particular system. A range of typical frequencies for noncritical applications is recommended with each test. In addition, the performance tests shall be made after an event (e.g., change of the settings of an electronic module, repair to the detector or the pulse-processing circuitry) that might result in changes to the system. The results of these performance tests shall be maintained as plots, tables or both. When the measured parameter falls outside reasonable limits, either the cause of failing the test shall be found and corrected or the uncertainty associated with the tested parameter shall be increased sufficiently to avoid quoting unrealistically small uncertainties in the reported gamma-ray emission rates. Actions taken and corrections made should be appropriately documented.

Some hardware allows for direct readout of, for example: leakage current from the preamplifier or cooling power from an electrically cooled detector. These parameters can be logged and tracked for assessing the state-of-health of the detection system.

7.2 Multichannel-analyser and digital signal processing clocks

The real-time clock shall be checked at the time the acquisition electronics is installed and after any maintenance. Follow the instructions in the manufacturer's user manual (also see Clause A.4).

Recommendation – It is possible to synchronize the computer clock associated with the multichannel-analyser using an atomic clock synchronization tool.

7.3 DC offset and pole-zero settings

The DC offset and the amplifier pole-zero settings shall be checked periodically (preferably quarterly or yearly) and after any related maintenance performed on the spectrometer. Follow the instructions in the manufacturer's user manual (also see Clause A.2).

7.4 Energy calibration

The system energy calibration shall be checked periodically (typically daily to semi-weekly) by counting a source(s) emitting gamma-rays whose energies are precisely known and cover the low-energy and high-energy regions of interest (e.g., ^{57}Co and ^{60}Co). A spectrum shall be acquired, and the peaks centroids determined. Compare the gamma-ray energies of interest with the peak centroids, if the peak centroids are outside the desired accuracy (usually, $\pm 0,5$ keV) from the expected gamma-ray energies then perform the energy calibration procedure as described in 5.3.

NOTE Some software packages use a gamma line in the energy spectrum to stabilize the system to maintain the energy calibration by adjusting the gain.

7.5 Spectrometer efficiency and energy resolution

The reproducibility of the full-energy-peak efficiencies and energy resolution shall be checked periodically (daily to weekly checks are recommended) using a radioactive source with a long half-life emitting at least a low-energy (about 100 keV) and a high-energy ($>1\,300$ keV) gamma-ray (e.g., mix of ^{125}Sb , ^{154}Eu and ^{155}Eu , or ^{57}Co and ^{60}Co , or ^{152}Eu sources). The same counting geometry shall be used each time for these checks with a reproducible source-to-detector distance (preferably >10 cm). A spectrum with at least 20 000 counts in the full-energy peaks of interest (approximately 0,7 % counting uncertainty in the net peak areas) shall be acquired. Deviations in the peak counting rates, corrected for decay, of reference peaks that lie more than two estimated standard deviations outside of the mean shall be investigated. An alternative test is to apply a chi-square (χ^2) test to the measured net area counting rates of the reference peaks over time (see [4] and [5]).