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(Revision of IEEE Std 325-1986)

IEEE Standard Test Procedures for Germanium Gamma-Ray Detectors

Sponsor

**Nuclear Instruments and Detectors Committee
of the
IEEE Nuclear and Plasma Sciences Society**

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Abstract: Terminology and standard test procedures for germanium radiation detectors that are used for the detection and high-resolution spectrometry of gamma rays, X rays, and charged particles that produce hole-electron pairs in the crystal lattice are established so they have the same meaning to both manufacturers and users.

Keywords: gamma rays, germanium radiation detectors, X rays

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Introduction

(This introduction is not part of IEEE Std 325-1996, IEEE Standard Test Procedures for Germanium Gamma-Ray Detectors.)

IEEE Std 325-1996 provides standard test procedures for germanium gamma-ray detectors for ionizing radiation. It is a revision of IEEE Std 325-1986, updated to bring it into line with current practices and technology. The revision was approved by the Nuclear Instruments and Detectors Committee (NIDC) of the IEEE Nuclear and Plasma Sciences Society and by the Accredited Standards Committee on Nuclear Instrumentation of the American National Standards Institute. The previous revision of this standard, published as ANSI/IEEE 325-1986, combined and updated ANSI/IEEE Std 325-1971, ANSI/IEEE Std 645-1987, and ANSI/IEEE Std 680-1980.

Companion documents are IEEE Std 300-1988 (Reaff 1993), IEEE Standard Test Procedures for Semiconductor Charged-Particle Detectors (ANSI); IEEE Std 301-1988 (Reaff 1993), IEEE Standard Test Procedures for Amplifiers and Preamplifiers Used with Detectors of Ionizing Radiation (ANSI); and IEEE Std 759-1984 (Reaff 1990), IEEE Test Procedures for Semiconductor X-Ray Energy Spectrometers (ANSI).

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Contents

CLAUSE	PAGE
1. Overview.....	1
1.1 Scope.....	1
1.2 Purpose.....	1
2. References.....	1
3. Definitions, symbols, and abbreviations and acronyms.....	2
3.1 Definitions.....	2
3.2 Symbols.....	8
3.3 Abbreviations and acronyms.....	9
4. General.....	10
4.1 The interaction of gamma rays with matter	10
4.2 Germanium gamma-ray detector element.....	13
4.3 Detector operating and storage temperatures.....	14
4.4 Operating bias and variations in charge collection time	14
4.5 Detector element classification	15
4.6 Figure of merit	19
4.7 Preamplifiers	19
5. Detector tests.....	21
5.1 General test requirements.....	21
5.2 Test setup for resolution and efficiency measurements	21
5.3 Temperature sensitivity.....	21
5.4 Amplifier pulse shaping	23
5.5 Electromagnetic interference	24
6. Energy resolution measurements	27
6.1 Introduction.....	27
6.2 Resolution specifications and other requirements.....	27
6.3 Errors in determining resolution	31
7. Test procedures and computations.....	32
7.1 Recording a spectrum.....	32
7.2 Sample spectrum, 1332.5 photopeak of ^{60}Co	33
7.3 Noise resolution near 1.2 MeV	34
7.4 Computations	35
8. Energy rate limit	40
9. Peak-to-Compton ratio.....	40

CLAUSE	PAGE
10. Counting efficiency.....	42
10.1 Absolute counting efficiency for a full-energy peak.....	42
10.2 Background correction.....	42
10.3 Relative full-energy peak counting efficiency	44
10.4 Well-Type coaxial detector efficiency	44
10.5 Summing of coincident gamma rays.....	44
10.6 Detector gamma-ray efficiency with a Marinelli reentrant beaker	44
10.7 Marinelli beaker standard source (MBSS).....	46
10.8 Measurement, absolute efficiency, full-energy peak	47
10.9 MBSS documentation	51
11. Window thickness index.....	52
12. Timing.....	52
12.1 Setup for timing measurements.....	52
12.2 Timing measurements	53
13. Temperature-Cyclable detectors	54
14. Annealable detectors.....	54
15. Low-Background detectors.....	55
16. Bibliography	56
ANNEX	
Annex A (informative) Representative Marinelli beakers.....	58

IEEE Standard Test Procedures for Germanium Gamma-Ray Detectors

1. Overview

1.1 Scope

This standard applies to germanium radiation detectors that are used for the detection and high-resolution spectrometry of gamma rays, X rays, and charged particles that produce hole-electron pairs in the crystal lattice. Included are detector endcap and reentrant (Marinelli) beaker standards.

Measurements that depend upon phonon production are outside the scope of this standard.

1.2 Purpose

The purpose of this standard is to establish terminology and standard test procedures so they have the same meaning to both manufacturers and users.

Not all tests described in this standard are mandatory, but tests that are used to specify performance shall be performed in accordance with the procedures described herein.

2. References

This standard shall be used in conjunction with the following publications:

IEEE Std 194-1977, IEEE Standard Pulse Terms and Definitions.¹

IEEE Std 300-1988 (Reaff 1993), IEEE Standard Test Procedures for Semiconductor Charged-Particle Detectors (ANSI).

IEEE Std 301-1988 (Reaff 1993), IEEE Standard Test Procedures for Amplifiers and Preamplifiers Used with Detectors of Ionizing Radiation (ANSI).

IEEE Std 759-1984 (Reaff 1990), IEEE Test Procedures for Semiconductor X-ray Energy Spectrometers (ANSI).

¹IEEE Std 194-1977 has been withdrawn; however, copies can be obtained from Global Engineering, 15 Inverness Way East, Englewood, CO 80112-5704, USA, tel. (303) 792-2181. Other IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

IEEE Std 1160-1993, IEEE Standard Test Procedures for High-Purity Germanium Crystals for Radiation Detectors (ANSI).

DOE Report DOE/ER-0457T, Standard NIM Instrumentation System (May 1990).²

3. Definitions, symbols, and abbreviations and acronyms

3.1 Definitions

Of the following definitions, several are “distributed”; that is, terms are used that are themselves defined in other definitions in this clause.

3.1.1 active region: A region of a detector in which charge created by ionizing radiation contributes significantly to the output signal.

3.1.2 amplifier noise: *See:* noise referred to the input.

3.1.3 amplifier shaping time: A nonspecific indication of the shaped-pulse width issuing from a linear pulse amplifier. *See:* shaping index.

3.1.4 amplifier time constant: A misnomer for the width of the shaped pulse issuing from a linear pulse amplifier. *See:* shaping index.

3.1.5 avalanche breakdown: A breakdown caused by the cumulative multiplication of charge carriers through electric-field-induced impact ionization.

3.1.6 background (ambient): The spectrum of X or gamma rays originating from materials other than the radionuclide being measured.

3.1.7 background (under a peak): The background from all sources under a peak being measured, including Compton and degraded-energy counts from higher energy and ambient background events.

3.1.8 ballistic deficit: The loss in signal amplitude that occurs when the charge collection time in a detector is a significant fraction of the amplifier’s differentiating time constant.

3.1.9 band gap: The energy difference between the bottom of the conduction band and the top of the valence band.

3.1.10 baseline (of an electrical pulse): The average of the levels from which a pulse departs and to which it returns in the absence of an overlapping pulse (IEEE Std 194-1977³).

3.1.11 baseline restorer (BLR): A circuit that rapidly restores the baseline following an amplifier’s output pulse (or train of pulses) to the level that existed before the pulse.

3.1.12 bias, detector: The voltage applied to a detector to produce the electric field that sweeps out the signal charge.

3.1.13 bias resistor: The resistor through which the bias voltage is applied to a detector.

²Available from Louis Costrell, NIM Committee Chairman, National Institute of Standards and Technology, Radiation Physics Division, or from the National Technical Information Service, U.S. Dept. of Commerce, Springfield, VA 22161.

³Information on references can be found in Clause 2.

3.1.14 bipolar pulse: A signal pulse having two lobes, one above and the other below the baseline (IEEE Std 194-1977). When produced by a linear filter network, the two lobes have the same area but not necessarily the same peak amplitude.

3.1.15 breakdown: A phenomenon occurring in a reverse-biased semiconductor diode that appears as an increase in noise, reverse current, or both when the bias is increased beyond a certain value.

3.1.16 breakdown voltage: The voltage measured at a specified current in the breakdown region.

3.1.17 capacitance, detector: The small-signal electrical capacitance measured between terminals of the detector under specified conditions of bias and frequency.

3.1.18 channeling, lattice: A phenomenon that results in a crystallographic directional dependence of the rate of energy loss of ionizing particles.

3.1.19 channel, surface: A thin region at a semiconductor surface of p- or n-type conductivity created by the action of an electric field (for example, that due to trapped surface charge).

3.1.20 charge carrier (abbreviation: carrier): A mobile electron or hole.

3.1.21 charge collection time: The time interval after the passage of an ionizing particle for the integrated current flowing between the terminals of the detector to increase from 10% to 90% of its final value.

3.1.22 charge-sensitive preamplifier: An amplifier preceding the main amplifier in which the output amplitude is proportional to the charge injected at the input. *See:* voltage-sensitive preamplifier.

3.1.23 constant-fraction discriminator: A discriminator in which the threshold is set at a fixed *fraction* of the input signal (instead of to a fixed *amplitude*). This is one of a class of timing discriminators.

3.1.24 contact, ion implanted: A detector contact consisting of a junction made by the process of ion implantation. *See:* ion implantation.

3.1.25 contact, ohmic: A purely resistive contact that has a linear voltage-current characteristic throughout its entire operating range.

3.1.26 contact, Schottky-barrier: A metal-semiconductor contact structure in which the rectification that occurs is heavily influenced by the difference in the work functions of the materials. The contacts frequently consist of an interfacial metal/semiconductor compound such as a silicide.

3.1.27 contact, surface-barrier: A metal-insulator-semiconductor contact structure in which the rectification properties are dominated or heavily influenced by charge trapped at the interfaces and in the insulator.

3.1.28 CR differentiator: A high-pass electrical filter section consisting of a capacitor in series with the signal path followed by a resistor across the path.

3.1.29 crest factor (of an rms voltmeter): The highest ratio of peak-to-rms voltage that can be applied to an ac voltmeter before overload sets in. The crest factor may depend on the full-scale setting of the voltmeter.

3.1.30 $(CR)^m - (RC)^n$ shaping: In an amplifier, the pulse shape produced by m CR high-pass filter sections (differentiators) in conjunction with n RC low-pass filter sections (integrators), all with the same time constant. If the input signal is a step function and no other high-pass sections are in the signal path, the pulse shape is unipolar if $m = 1$, bipolar if $m = 2$. For unipolar pulses, the waveform is described by $Kt^n e^{-t/\tau}$ where K is a constant, t is time, and τ is the time constant of the differentiator.

3.1.31 crossover time (of a bipolar pulse): The instant at which the transition between the two lobes passes through a designated level (usually the baseline). At this level, the timing with respect to the initiating events is nearly invariant with pulse amplitude.

3.1.32 dead layer: In a semiconductor detector, a layer (frequently associated with a contact region) in which no significant part of the energy lost by photons or particles can contribute to the resulting signal.

3.1.33 decay time constant: In the absence a low-pass network preceding the point of observation, the time for a single-exponential waveform to decay to the fraction $1/e$ of its original amplitude.

3.1.34 depletion region: A region in which the mobile charge-carrier density is insufficient to neutralize the net fixed charge density of donors and acceptors. In a diode-type semiconductor radiation detector, the depletion region is the active (sensitive) region.

3.1.35 depletion voltage: The voltage at which a junction detector becomes fully depleted.

3.1.36 detector, coaxial: A detector in which all or part of the two electrical contacts on the detector element are substantially coaxial. Typically one end of each contact configuration is closed (closed-ended coaxial detector), but both ends may be open (open-ended coaxial detector).

3.1.37 detector, coaxial, conventional-electrode geometry: A coaxial detector in which the outer contact is an n-type layer.

3.1.38 detector, coaxial, reverse-electrode geometry: A coaxial detector in which the outer contact is a p-type layer.

3.1.39 detector, differential (dE/dx): *See:* detector, transmission.

3.1.40 detector, diffused-junction: A semiconductor detector in which the rectifying junction is produced by diffusion of acceptor (p) or donor (n) defects.

3.1.41 detector element: The semiconductor crystal including its contacts.

3.1.42 detector, germanium gamma-ray: A complete assembly, including the detector element, cryostat, integral preamplifier, and high-voltage filter. *See:* detector element.

3.1.43 detector, p-i-n: A detector consisting of an intrinsic or nearly intrinsic region between a p- and an n-region.

3.1.44 detector, position-sensitive: A detector in which the centroid of the area of impact of ionizing radiation can be determined from the signals issuing from its terminals. Depending on the design, position sensing can be in one or more dimensions.

3.1.45 detector, semiconductor radiation: A semiconductor device in which the production and motion of excess free carriers is used for the detection and measurement of incident particles or photons.

3.1.46 detector, Schottky-barrier: A semiconductor radiation detector in which the blocking contact is of the Schottky-barrier type.

3.1.47 detector, surface barrier: A radiation detector in which the principal rectifying junction is a surface-barrier contact.

3.1.48 detector, totally depleted: A detector in which the thickness of the depletion region is essentially equal to the thickness of the semiconductor material.

3.1.49 detector, transmission: A detector that is thin compared with the range of the incident particle and in which the entrance and exit dead layers are thin compared with the thickness of the detector.

3.1.50 detector, well-type coaxial: A coaxial detector that is mounted and encapsulated in such a way that a radioactive sample can be placed within the inner cylindrical electrode such that the sample is essentially surrounded by active detector material.

3.1.51 differentiator: A high-pass filter network in which the waveform of the output signal approximates the mathematical derivative of the input waveform.

3.1.52 discriminator: A circuit having a threshold below which signals applied to the input will not cause an output signal and above which the input signal will trigger an output having an amplitude independent of the input signal height.

3.1.53 energy count-rate product: Obsolete. *See:* energy rate limit.

3.1.54 energy rate: The average energy per event times the number of events per second.

3.1.55 energy rate limit: In a preamplifier dc-coupled to a detector, the highest energy rate in units of MeV per second that causes no more than a specified fraction of the pulses (usually 1%) to overload the preamplifier.

3.1.56 energy resolution: The full width at half maximum of a peak in a spectrum, after subtracting the background under the peak; expressed in units of energy, usually keV; or as a percentage of the energy corresponding to that peak.

3.1.57 equivalent noise resistance referred to the input of an amplifier: This is an ambiguous term; the qualifiers “series” or “parallel” must be specified. *See:* equivalent series (parallel) noise resistance referred to the input of an amplifier.

3.1.58 equivalent series (parallel) noise resistance referred to the input of an amplifier: In a hypothetically noise-free amplifier, the value of resistor that, when connected in series with (shunted across) its input, will produce the same output noise spectrum as is observed in the real amplifier. The gain and bandwidth of the real and hypothetical amplifiers must be the same for this definition to be valid.

3.1.59 fall time t_f (of a pulse): The interval on the last transition between the 90% and 10% points (unless other levels are specified) with respect to peak height. *See:* transition.

3.1.60 full width at half maximum (FWHM): The full width of a distribution measured at half the maximum ordinate. For a normal distribution, $\text{FWHM} = 2 \cdot (2 \ln 2)^{1/2} = 2.355$ times the standard deviation, σ .

3.1.61 gated integrator: A circuit for obtaining an output pulse with an amplitude proportional to the integral of the input signal over a definite time interval.

3.1.62 geometry, detector element: The physical configuration of a detector element. *See:* detector element.

3.1.63 high-purity germanium (HPGe): Germanium with a low, net electrically active, uncompensated defect concentration usually less than $\approx 10^{10} \text{ cm}^{-3}$.

3.1.64 inactive region (of a semiconductor radiation detector): A region of a detector in which charge created by ionizing radiation does not contribute significantly to the output signal.

3.1.65 integrated pulse: In the absence of qualifiers (such as “true integration”), a pulse that has passed through one or more low-pass networks (“integrators”).

3.1.66 intrinsic semiconductor: A semiconductor containing an equal number of free holes and electrons throughout its volume. The term *intrinsic germanium* often is used incorrectly to describe high-purity germanium.

3.1.67 ion implantation: A process in which a beam of energetic ions incident upon a solid results in the imbedding of those ions into the material.

3.1.68 junction: The transition boundary between semiconductor regions of different electrical properties (for example, $n - n^+$, $p - n$, $p - p^+$ semiconductors, or between a metal and a semiconductor).

3.1.69 junction, rectifying: A region between two materials, typically n-type or p-type semiconductors, or between a metal and a semiconductor, arranged to provide a very low resistance to current flow in one direction and a very high resistance to current flow in the opposite direction.

3.1.70 leakage current: In the absence of external ionizing radiation and at the operating bias, the total current flowing through or across the surface of the detector element.

3.1.71 line (in a spectrum): A sharply peaked portion of a spectrum that represents a specific feature of the incident radiation, usually the full energy of a monoenergetic X ray, gamma ray, or charged particle.

3.1.72 linear filtering: Pulse shaping in which the filter response does not change with time. $[CR - (RC)^n]$ shaping is an example of linear filtering.]

3.1.73 main amplifier (shaping amplifier): The section of amplifier following the preamplifier that contains the pulse-shaping networks (filter networks). These networks optimize the signal-to-noise ratio in the amplifying chain.

3.1.74 Marinelli beaker: A reentrant (inverted well) beaker that can be fitted over a detector endcap for the purpose of holding a radioactive sample in a configuration that surrounds a major portion of the detector.

3.1.75 microphonics, microphonic noise: Electrical noise caused by mechanical or audio-induced vibration of the detector assembly.

3.1.76 NIM: A standardized modular instrumentation system consisting of NIM Modules and NIM Bins as defined in DOE Report DOE/ER-0457T.

3.1.77 NIM Bin: A mounting unit or housing for NIM Modules that conforms to the requirements of DOE Report DOE/ER-0457T. It includes bussed connectors at the rear that mate with connectors on the modules to provide the modules with power.

3.1.78 NIM Module, NIM Instrument: A modular functional unit or instrument that mounts in a NIM Bin and conforms to the requirements of DOE Report DOE/ER-0457T.

3.1.79 noise linewidth: The contribution of electrical noise to the width of a spectral peak. (Electrical noise adds to the peak width in quadrature.)

3.1.80 noise referred to the input (of an amplifier): The electronic noise level at the input of a hypothetically noise-free amplifier that would produce the same noise as measured at the point of observation in the actual amplifier. This definition is implied when the term “amplifier noise” is used without qualifications.

3.1.81 parallel noise (of a device): Electrical noise that can be attributed to a hypothetical white noise generator connected in parallel with the input of the device.

3.1.82 peak (in a spectrum): See: line (in a spectrum).

3.1.83 peaking time t_p (of a pulse): The interval between the 1% point on the first transition, with respect to the peak height, and the top center line (see transition and top centerline).

3.1.84 preamplifier: The input section of an amplifier chain, usually located as close to the detector element as possible.

3.1.85 preamplifier, pulsed optical feedback: An integrating preamplifier in which the charge that accumulates on the feedback capacitor is periodically reset by a pulse of light incident on a photosensitive element, such as the gate of the n-p junction of the input FET.

3.1.86 pulse duration (at the baseline): The width of a pulse measured close to the baseline, typically at 1% of the peak height (t_{01}).

3.1.87 quasi-Gaussian pulse shape: A pulse shape approximated by the curve of a normal or Poisson distribution. In this standard, four or more integrators shall be used in producing the pulse. *See:* integrated pulse.

3.1.88 quasi-triangular pulse shape: A pulse shape approximated by a triangle with a truncated top. Such a shape can be obtained from a $CR - (RC)^n$ or sine^n network by summing appropriate signal fractions from the n integrating sections. *See:* $CR - (RC)^n$ shaping and sine^n shaping.

3.1.89 RC integrator: A low-pass electrical filter section consisting of a resistor in series with the signal path followed by a capacitor across it.

3.1.90 resolution: *See:* energy resolution.

3.1.91 rise time t_r (of a pulse): The interval on the first transition between the 10% and 90% points, with respect to peak height, unless other levels are specified. *See:* transition.

3.1.92 semiconductor: Material in which the conductivity is due to charge carriers of both signs (electrons and holes), is normally in the range between metals and insulators, and in which the charge-carrier density can be changed by external means.

3.1.93 semiconductor, compensated: A semiconductor in which one type of impurity or imperfection (for example, donor) partially cancels the electric effects of the other type of impurity or imperfection (for example, acceptor).

3.1.94 series noise (of a device): The fraction of electrical noise that can be attributed to a hypothetical white noise generator connected in series with the input of the device.

3.1.95 shaped pulse: In this standard, the pulse shape produced by passing the output signal from the preamplifier (approximately a step function) through the pulse-shaping network in the main amplifier (shaping amplifier).

3.1.96 shaping amplifier: *See:* main amplifier.

3.1.97 shaping index: In a main amplifier, the width of the shaped unipolar pulse measured at 50% of its peak height, designated as $t_{0.5}$.

3.1.98 shaping time (in an amplifier): *See:* amplifier shaping time.

3.1.99 signal-to-noise ratio: In this standard, “signal” refers to peak signal, and “noise” refers to rms noise.

3.1.100 sine^n shaping: In an amplifier, the pulse shape produced by one CR high-pass filter section (differentiator) followed by n RC low-pass filter sections (integrators), all with different time constants, but follow-

ing a particular pattern related to the differentiating time constant τ . If the input signal is a step function and no other high-pass sections are in the signal path, the pulse shape is unipolar and is described by $Ke^{-3t/\tau} \sin^n(t/\tau)$, where K is a constant, t is time, and τ is the time constant of the differentiator.

3.1.101 skewing factor $S_{0.1}$ or $S_{0.2}$ (of a peak): The ratio (FW.1M)/(1.823 FWHM) or (FW.02M)/(2.376 FWHM). For an ideal Gaussian shape, the factors are 1.000. If the peak is wider at FW.1M or FW.02M than it should be relative to FWHM, the factors are >1.000 . (For a perfect Gaussian peak, FW.1M/FWHM = $[(\ln 0.1)/(\ln 0.5)]^{1/2} = 1.823$ and FW.02M/FWHM = $[(\ln 0.02)/(\ln 0.5)]^{1/2} = 2.376$).

3.1.102 source, radioactive: A radionuclide prepared in a form convenient for use in testing a detector or spectrometer.

3.1.103 space-charge generation (in a semiconductor radiation detector): The thermal generation of free charge carriers in the depletion region.

3.1.104 space-charge region: See: depletion region.

3.1.105 spectrum, energy: A differential distribution of the intensity of radiation as a function of energy.

3.1.106 straggling, energy: The random fluctuations in energy loss whereby those particles having the same initial energy lose different amounts of energy when traversing a given thickness of matter. (This process may lead to the broadening of spectral lines.)

3.1.107 timing discriminator: A class of discriminators in which the initiation of the output signal is keyed to the instant when the input signal crosses the discriminator threshold. See: discriminator, constant-fraction discriminator.

3.1.108 time-variant filtering: Pulse shaping in which the filter response varies with time.

3.1.109 top center line (of a pulse): In a peaked pulse, the ordinate that passes through the peak; in a flat-topped pulse, the ordinate that bisects the nominally flat-topped region (IEEE Std 194-1977).

3.1.110 transistor reset preamplifier: An integrating preamplifier in which the charge that accumulates on the feedback capacitor is drained off through a transistor when the charge exceeds a predetermined value.

3.1.111 transition (of a pulse): The region of a pulse in which a major change in amplitude occurs, such as at the leading edge (first transition) or final trailing edge (last transition) (IEEE Std 194-1977).

3.1.112 unipolar pulse: A signal pulse having a single lobe above (or below) the baseline.

3.1.113 voltage-sensitive preamplifier: An amplifier, preceding the main amplifier, in which the amplitude of the output signal is proportional to the signal voltage appearing across the capacitance that exists at the input of the preamplifier. See: charge-sensitive preamplifier.

3.1.114 walk (in a pulse): The change in the timing (with respect to the initiating event) of a reference point on a pulse caused by a change in pulse amplitude.

3.2 Symbols

B_{Δ}	The background counts-per-channel difference between the low- and high-energy sides of a peak
B_H	The average background counts per channel on the high-energy side of a peak
B_L	The average background counts per channel on the low-energy side of a peak
C	The electrical capacitance

C_c	The calibrated capacitor that couples a pulse generator to a circuit under test
C_f	The feedback capacitance in the charge-sensitive loop of a preamplifier
C_t	The total capacitance at the input of a preamplifier
Δ	The full width at half maximum (FWHM) of a spectral peak
ΔE_O	FWHM, expressed in units of energy, due to all factors other than electronic noise
ΔE_S	FWHM, expressed in units of energy, derived in spectral energy resolution measurement
ΔE_T	FWHM, expressed in units of energy, due to the combined effects of detector and amplifier noise
ΔN_O	FWHM, expressed in channels, due to all factors other than electronic noise
ΔN_S	FWHM, expressed in channels, of a spectral peak used for energy resolution determination
ΔN_T	FWHM, expressed in channels, due to the combined effect of detector and amplifier noise
E, E_i	The energy of a particle or radiation (or energy of a specific value, E_i , where i is an integer, 1, 2,...)
e	The charge of the electron
ε	The average energy required to form one hole-electron pair in a semiconductor detector
I	The electric current
N_c	The number of counts in channel c of a spectrum where channel c lies within a specified energy range within the Compton continuum
N_X	The number of counts in channel X of a spectrum
$\hat{N}$	The number of counts in the peak channel $\hat{X}$ of a spectrum
Q	The electric charge
R_f	The feedback resistor in the charge-sensitive loop of a preamplifier
$S_{0.1}$	The skewing factor at FW.1M = (FW.1M)/(1.823 FWHM)
$S_{0.2}$	The skewing factor at FW.02M = (FW.02M)/(2.376 FWHM)
$t_{.01}$	The pulse width at 1% of the peak pulse height
$t_{0.5}$	The pulse width at half maximum
t_r	The pulse rise time (10–90% of its peak value)
τ	The time constant
τ_d	The time constant for the decay of a pulse
X, X_i	The channel number, and that number corresponding to energy E_i
$\hat{X}$	The interpolated channel number corresponding to the maximum of a monoenergetic spectral peak

3.3 Abbreviations and acronyms

ADC	analog-to-digital converter
BLR	baseline restorer
c/s	counts per second
CSP	charge-sensitive preamplifier
ERL	energy rate limit in units of megaelectronvolts per second
FET	field-effect transistor
FoM	figure of merit
FWHM	full width of a peak at half its maximum height
FW.1M	full width of a peak at one-tenth its maximum height
FW.02M	full width of a peak at one-fiftieth of its maximum height
Ge(Li)	lithium-drifted germanium
HPGe	high-purity germanium
LN	liquid nitrogen
MCA	multichannel pulse-height analyzer
MDA	minimum detectable activity
NaI(Tl)	thallium-activated sodium iodide
NIM	nuclear instrument module

P/C	peak-to-Compton ratio
rms	root-mean-square
SNR	ratio of the peak signal to the rms noise

4. General

4.1 The interaction of gamma rays with matter

Gamma rays interact with matter through three principal processes: the photoelectric effect, the Compton effect, and pair production.

4.1.1 Photoelectric effect

The photoelectric effect takes place when an incident photon transfers its entire energy to a bound electron in an atom, resulting in the ejection of that electron. Its kinetic energy equals the photon energy less the electron binding energy. The cross section for the photoelectric effect increases approximately as $Z^{4.5}$ where Z is the atomic number of the absorber, and decreases approximately as E^{-3} where E is the photon energy.

4.1.2 Compton effect

The Compton effect may be considered as an elastic collision of a photon with an atomic electron. The electron is ejected from the atom, and the photon is scattered with reduced energy. The scattered photon may then repeat the scattering process, be fully absorbed, or escape from the absorber. The cross section for the Compton effect decreases with increasing energy, but much less rapidly than for the photoelectric effect.

Compton-scattered photons that escape the detector element are lost to the detection process. Those remaining behind produce counts in the energy region below the photopeak, contributing to a continuous background (not to be confused with the natural background; see 4.1.6). The problem is particularly serious in environmental studies of low-level radiation consisting of spectra with many peaks, because each of the higher energy lines adds to the background distribution in the energy region below it, making the measurements increasingly difficult as the search moves toward lower energies. The Compton background is the limiting factor in establishing the minimum detectable activity (MDA) in a given measuring time, or in determining the number of samples that can be processed to a specified MDA.

Generally, large detector elements exhibit lower Compton background than small ones (see 4.6).

4.1.3 Pair production

Pair production takes place when the energy of a photon is converted into an electron and a positron in the presence of a nearby nucleus. This process requires a minimum energy of 1.02 MeV, which is the sum of the rest mass energies of the electron and the positron. Above this energy the cross section for pair production increases to a maximum, then decreases due to screening effects.

The linear attenuation coefficients for silicon and germanium are shown in Figure 4-1. In all of these absorption processes the energy of incident photons is transferred to one or more electrons. These rapidly lose their energy in the absorber material, largely through Coulomb interactions that produce a cascade of free electrons and holes. Energy from these processes also produces phonons, the production of which is a competing form of energy loss that adds to the statistical fluctuation in the amplitudes of recorded events but not to their average magnitude. In this standard, the interest is in the events arising from those interactions of gamma rays with matter that produce ionization in the form of electron-hole pairs, the average quantity being directly proportional to the absorbed energy of the incident photon.

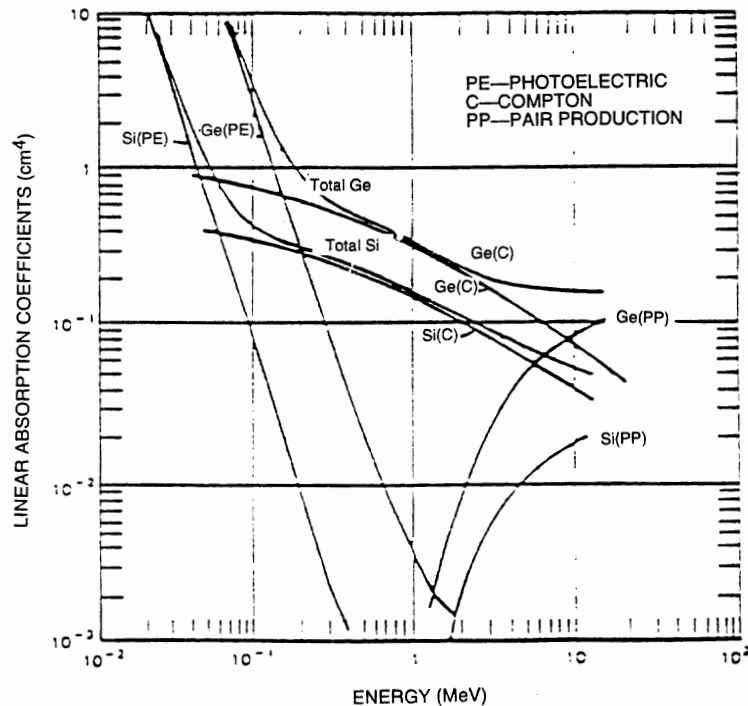


Figure 4-1—Linear absorption coefficients vs. gamma-ray energy for Si and Ge

4.1.4 Average energy ϵ required for production of electron-hole pairs

In three published studies ([B4], [B12], and [B17]⁴), the average energy ϵ required to produce an electron-hole pair at 77.3 K (the temperature of LN at 760 mmHg) falls into the narrow range of 2.96 to 2.98 eV. However, in each of the studies, the slope of the ϵ versus temperature curve (at 90 K) is substantially different: -120 ppm/K [B15], -370 ppm/K [B4], and -450 ppm/K [B17]. In the absence of a compelling reason to choose one value over another, the approximate average of the three is used in this standard: 300 ppm/K.

4.1.5 Range-energy relationships in germanium

The thickness of germanium for which there is a 50% probability that a normally incident photon will be absorbed before traversing that thickness is shown in column 2 of Table 4-1. If the photon transfers all of its energy to an electron, the maximum range of that electron is that shown in column 3. There is a wide disparity between the two figures. In practice, the distance of HPGe traversed before all of the photon energy is absorbed, by whatever process, is intermediate between the two extremes. The range-energy relationships are pertinent to the selection of detector geometry for a particular application (see 4.5.1–4.5.3).

Table 4-1—Range-Energy relationships of photons and electrons in HPGe

Energy (keV)	Photon half thickness ^a (mm)	Electron full range (mm)
10	0.05	—
100	8	0.03
1000	21	0.7

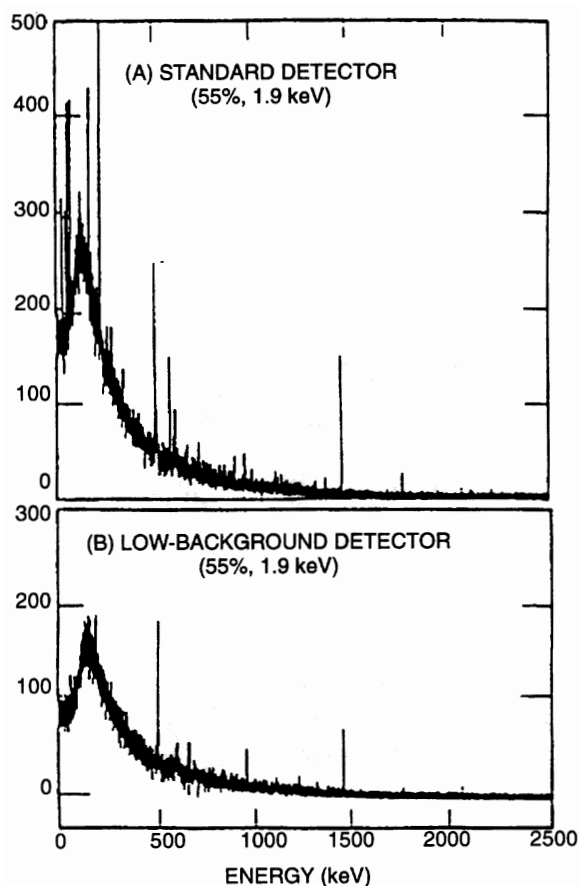
^a The photon half thickness is the range for which there is a 50% probability of photon absorption.

⁴The numbers in brackets correspond to those of the bibliography in Clause 16.

4.1.6 Natural background

Natural background is due to radioactivity in the environment. The background can arise from materials in the cryostat (including the detector element), from radionuclides external to the detector, or from the cosmic-ray continuum. Not much can be done to reduce the background from an existing cryostat, but that from the external environment can be reduced by surrounding the cryostat with a graded shield: a lead outer jacket with a series of liners made of metals with successively lower Z numbers (usually, a lead outer jacket with a single, oxygen-free copper liner is enough).

Typical background spectra obtained with two detectors [B12] are shown in Figure 4-2. The detectors were 55% relative-efficiency p-type HPGe detectors surrounded by a 20 cm low-background lead shield lined with 6 mm of copper;⁵ the upper spectrum (A) is from a standard type of cryostat while the lower spectrum (B) is from a detector in a cryostat made from materials selected to have a very low background.



NOTE—Each spectrum was acquired for 100 000 s.

Figure 4-2—Background spectra for two shielded, 55% relative-efficiency detectors
(A) Standard cryostat, (B) Low-Background cryostat

⁵This was an experimental shield. Standard practice is to use a copper liner 1.6 cm thick.

4.2 Germanium gamma-ray detector element⁶

A germanium detector element is a diode made by applying suitable electrical contacts to a single crystal of high-purity germanium (HPGe) (IEEE Std 1160-1993). The diode is reverse biased to establish an electric field, causing the detector element to become depleted of free charge carriers. In the depletion region, incoming photons produce a cascade of electron-hole pairs that are swept to the contacts under the influence of the field. The moving charges constitute a current that is proportional to the absorbed photon energy. The current is integrated by a preamplifier to produce an output voltage pulse.

In modern HPGe detectors, the net electrically active impurity concentration (IEEE Std 1160-1993) is typically less than the order of 10^{10} cm^{-3} . As detector elements have become progressively larger, a concomitant reduction in impurity concentration has been required. The high purity is necessary to allow full charge depletion at a reasonable voltage, usually less than 5 kV (see 4.4).

4.2.1 Contacts

The detector element has two electrical contacts (also called electrodes): n-type and p-type, with the n^+ contact biased positively with respect to the p^+ contact. N-type contacts are often made by a lithium diffusion, and p-type by boron ion-implantation, but several other contacting and metallization methods may be used. High-Z metals such as gold are usually avoided because they can produce high-energy fluorescent X rays.

In planar detectors, the contacts are applied to the parallel planes of the disc, one to each plane.

The so-called conventional-electrode coaxial detector is made of p-type germanium with an n^+ lithium contact diffused into the side and bottom of the detector element (outside surfaces) and with a thin, p^+ contact implanted into the sides and bottom of the hole (inside surfaces).

The so-called reverse-electrode coaxial detector is made with a thick n^+ lithium-diffused inner contact and a thin p^+ outer contact. This type of detector has at least two advantages over the conventional-contact one:

- a) The thin outer contact extends the detector usability into the X-ray region and makes the detector particularly appropriate for use with anti-Compton shields;
- b) Reverse-electrode detectors are more resistant to the effects of fast neutron damage and are also readily restored to their original resolution without a significant loss of efficiency, should such damage occur.

Diffused n^+ contacts are inherently thick: up to 1 mm. In contrast, boron-implanted or metallized (surface barrier) p^+ contacts are usually as thin as $0.3 \text{ }\mu\text{m}$ and, by special techniques, can be made as thin as $0.05 \text{ }\mu\text{m}$. Contacts are dead layers because charge carriers formed within them are not collected. The effect is to attenuate radiation passing through a contact, making it desirable to place the thin one at the surface of the crystal through which photons enter. However, it is not always possible to do so, with the result that the usable energy range is above $\approx 40 \text{ keV}$ in detectors with a diffused contact at the entrance. A detector with a $0.05 \text{ }\mu\text{m}$ layer can be used down to $\approx 300 \text{ eV}$.

Detectors damaged by neutron radiation can often be repaired by high-temperature annealing. That process thickens a diffused contact, but not an implanted or metallized one, giving further advantage to detectors with the thin contact at the entrance.

⁶The term *detector* used alone implies the combination of the detector element, cryostat, preamplifier, high-voltage filter, and, in some cases, means of cooling the detector element. The phrase *detector element* is used to denote the germanium crystal with its electrical contacts. In the interest of readability of this standard, the word “element” may be omitted at times when the term is called for, but when such an omission occurs, the intended meaning will be obvious.

4.3 Detector operating and storage temperatures

The germanium detector element is mounted in a cryostat. During operation, it is cooled to a low temperature, typically 80 K to 100 K, which is necessary to reduce leakage current and thermal noise. Cooling is usually by liquid nitrogen (LN), but LN-free, mechanical cooling is an alternative.

The cryostat serves a second purpose: to keep the crystal in an extremely clean environment, which is essential for long-term, trouble-free performance. To enhance the cleanliness, a sorption pump (usually, a molecular sieve) is included in the cryostat to scavenge impurities that may outgas from the internal surfaces.

Although HPGe detectors must be operated cold, they may be stored at room temperature,⁷ but there is some risk associated with this practice. When a detector is allowed to warm up, the sorption pump, instead of scavenging gas molecules, gives them off. The crystal is the last item to reach room temperature. During the time that a temperature differential exists between the crystal and its surroundings, gaseous impurities will condense on the surfaces of the crystal. Accordingly, warmup cycles should be completed once begun so that impurities that do condense have an opportunity to evaporate after the warmup is complete. Those impurities will be absorbed by the pump when the detector is next cooled down.

In general, it is desirable not to cycle the cryostat temperature more often than necessary. For example, if a detector is used daily, it should be kept cold continuously rather than be allowed to warm up during the period when it is not in use.

The longer that a cryostat has been kept cold, the greater the amount of gas that will be entrained by the sorption pump. After warmup, the longer the duration at room temperature, the greater the amount of outgassing by the pump and by the interior surfaces of the cryostat. Also, if the detector is kept warm for a period of months, lithium-diffused contacts will grow in thickness. If that type of contact is at the face of the detector, the increased thickness will cause a loss in efficiency when measuring low-energy gamma rays.

Detectors that fall into that category shall be recalibrated when returned to service.

It should be recognized that with the current state of the technology, problems such as those described above may take several years to appear.

4.4 Operating bias and variations in charge collection time

After establishing the bias necessary to fully deplete a detector element, it is usual to overbias it for the following reasons: Above an electric field strength of ≈ 100 V/mm, electron and hole mobilities ([B15], [B23]) approach a plateau (saturation mobility) of $\approx 10^7$ cm/s. Usually, the bias necessary for full depletion is adequate to establish saturation mobility throughout most of the crystal, but that may not be true in the lowest-field regions. (In a coaxial-geometry detector, the lowest field strength exists at the corner where the face meets the side of the cylinder. See 4.5.2.)

The signal risetime is inversely proportional to the ion mobility. In coincidence measurements, variations in signal risetime are undesirable because they increase the effective resolving time. In amplitude measurements, the CR section of the main amplifier's pulse-shaping network is a differentiator, causing the output signal of the shaping network to vary with input-signal risetime. If the risetime varies from pulse to pulse, the energy resolution can suffer because those pulses with longer risetimes produce less signal amplitude, a phenomenon known as ballistic deficit [B7].

⁷In the first germanium detectors (GeLi), electrically active impurity centers were neutralized by lithium atoms diffused into the crystal (lithium compensated), but this practice became obsolete when purer material became available.