Gamma Ray Spectrometers

John 1.. Callas
Jet Propulsion Laboratory
4800 oak Grove Drive
Pasadena, California 91109

Gamma rays arc high energy electromagnetic radiation with energies typically starting from a fcw tens of keV and extending to beyond TeV energies. Although gamma rays, like other electromagnetic radiation, can be characterized by frequency and wavelength, they arc more particle-like in nature and carry energy ($E = h\nu$), and momentum ($p = h/\lambda$). The par[iclc-like quality allows gamma rays to be observed and counted as individual photons. Gamma-ray spectrometers employing ioniz,ation-sensitive devices, detect individual gamma rays and measure their energy. From the analysis of the energy spectrum of detected gamma rays, the source identity, its elemental composition, the processes involved, the environment of the source, and the intervening material between the source and the observer may, under various circumstances, be inferred. Applications of gamma-ray spectroscopy range from measurements of the spin and parity of nuclei and particles involved in nuclear reactions, to inference of quantitative information about the extent and hazard of a nuclear accident, to medical imaging of human tissue, to measurements of material abundances in planetary objects, to observation of gamma-ray lines and features from the Sun and distant astrophysical sources.

Production of Gamma Rays

A variety of phenomena can produce gamma rays. Some of the most prevalent sources of gamma rays arc nuclear reactions. These reactions usually involve discrete transitions that arc often accompanied by the emission of onc or more gamma rays of unique energy. The details of these transitions arc governed by quantum theory much in analogy to atomic transitions. The energies associated with these transitions arc typical] y in the rangebetween 10 keV to 10 McV. Reactions

include radioactive decay where unstable elements decay into more stable daughter nuclei with the emission of one or more gamma rays. Reactions where a particle, such as a neutron, can be captured by the nucleus of an atom constitute another major nuclear source of emitted gamma rays. This reaction often leaves the resulting nucleus in an excited state emitting additional gamma rays upon de-excitation. Inelastic scattering of particles, such as a neutron or proton, off atomic nuclei can excite discrete transitions within the nucleus producing gamma rays upon de-excitation. Other gamma-ray producing nuclear reactions include induced radioactivity, spallation and nuclear fission.

Many sources of gamma ray radiation are purely electromagnetic. The electromagnetic acceleration of energetic charges results in the emission of a continuum of photons. When energetic electrons interact in matter, part of their energy is converted into gamma rays in the form of bremsstrahlung radiation ("braking" radiation). The gamma rays are emitted over a broad continuum of energies with the maximum energy being of order of the kinetic energy of the initial electron energy. Energetic electrons accelerated by strong magnetic fields emit part of their energy as synchrotrons radiation (so called because observed at synchrotrons accelerators). Like bremsstrahlung radiation, synchrotrons radiation is emitted over a broad energy continuum with the maximum energy comparable to the initial electron energy. Low energy photons can Compton scatter off energetic charged particles to much higher (gamma-ray) energies. This phenomenon is exploited at accelerator facilities to produce intense beams of gamma rays. 'J'his phenomenon is also observed in solar flare events and in hot plasmas associated with astrophysical objects. The scattered gamma rays will have energy comparable to the energy of the charged particles. The resulting gamma-ray spectrum can be either sharp or broad in energy depending on the spectrum of charged particles.

Subatomic particles can be another source of gamma rays. Very energetic events such as large solar flares, energetic cosmic-ray interaction in the atmosphere, or accelerator induced events,

can produce shell-lived subatomic mesons. Many of these mesons produce one or more energetic gamma rays upon decay. The neutral pion (π^0) decays with a very short mean life of 8.4×10^{-17} seconds into two photons each with energy equal to half of the rest mass of the π^0 (67.5 McV per photon). The energy of the gamma rays may shift if the decay takes place in flight. Several other more massive mesons (η, p, ω, etc.) also have decay modes that produce energetic photons. Positrons (the antimatter counter part of the electron), produced in energetic reaction such as a solar flare or as a result of some radioactive decays, produce gamma-ray radiation by annihilation. The positron annihilates with an electron to produce two photons each of energy equal to the electron rest mass (511 keV). The annihilations usually occur at or near rest. However, the annihilation may take place in flight resulting in shifted photon energies. An unstable bound state of the positron and electron, called positronium, can form before the subsequent annihilation. This results in the production of two or three photons of varying energy.

Gamma-Ray Interaction

Gamma rays, because they are not charged, do not directly produce ionization in detector materials. Therefore, detection must be performed by indirect processes. There are three principal gamma-ray interaction mechanisms that indirectly produce ionization in detector material, the photoelectric effect, Compton scat tering, and pair production.

With the photoelectric effect, a gamma ray will strike a bound electron transferring its energy to the electron. The gamma ray is totally absorbed. The electron is liberated with energy equal to the gamma ray energy minus the binding energy of the electron. The binding energy is recovered in the signal pulse as the empty electron level is filled in. The recoiling electron deposits its energy by ionization in the local media. For detection, the local media is chosen to be ionization sensitive (i.e., a charge particle detector). The photoelectric effect is typically the dominant absorption mechanism for low energy gamma rays. The cross section for this effect is roughly

proportional to Z^4 of the detector material. The importance of high atomic number (Z) material is obvious.

With the Compton effect, an incident photon scatters off an electron, transferring some of its energy to the electron. The remaining energy persists as a scattered photon of lower energy. The electron recoils from the interaction depositing its energy through ionization in a sensitive detector. The photon may be completely absorbed after several Compton scatters with multiple electrons with its final energy being absorbed by a photoelectric interaction or it may scatter out of the detector. The sum of all energy deposited by the interacting electrons equals the incident photon energy, if fully absorbed. Since the interaction between the incident photon and the electron is governed by simple two-body kinematics, the relation between the incident energy, the recoil energy and the recoil angle is known. This relationship can be exploited to determine the directionality of the incident photon.

With pair production, a photon with energy above the threshold of $2m_ec^2$ (1022 kcV) can interact with the electric field of a nucleus, to be converted into a positron-electron pair (e^+e^-). The kinetic energy of the resulting pair will be equal to the residual photon energy above the two-electron mass threshold. The positron (e^+) from the production will eventually annihilate, producing two 511 keV photons. These photons may be fully absorbed in the detector or one or both may escape. The cross section for pair production is proportional Z? of the detector material, again favoring high-Z materials.

Gamma-Ray Detectors

There are two detection technologies that are principally used for gamma-ray spectroscopy, scintillator detectors and semiconductor detectors. These two technologies are well suited (and somewhat complementary) for gamma-ray spectroscopy because of their performance in two important detector characteristics, detection efficiency (stopping power) and energy resolution.

Simply put, detection efficiency is the ability of the detector to absorb all of the gamma-ray energy in the sensitive portion of the detector. This is complicated because a gamma ray may deposit only part of its energy duc to the escape of Compton scattered or pair produced photons. A partial deposition contributes to the continuum appearing in an energy spectrum. Since the detection efficiency is, of course, less than unity, the detected signal must bc corrected for this effect to determine the actual gamma-ray signal incident on the detector.

The other important detector characteristic, energy resolution, is most apparent with gamma-ray lines from sources with discrete transitions. These lines, observed in the spectrum, arc broadened to a greater or lesser extent by the detecting device. The amount of this broadening is the energy resolution, Energy resolution is often specified as the full-width of the peak at half its maximum value above the local continuum background (abbreviated FWHM). The resolution performance of a gamma-ray spectrometer system is dominated by two effects, the intrinsic resolution of the detector and the effect associated with electronic noise. Electronic noise is mostly indcpcndcnt of energy and can dominate at low energies. Intrinsic detector resolution is governed by the statistics of the number of charge carriers produced by the interaction in the detector. The number of charge carriers is proportional to the absorbed energy in the detector. Therefore the resolution, expressed in energy units as FWHM, is roughly proportional to the square-root of the energy.

As cited, scintillators arc commonly used as detectors for gamma-ray spectroscopy. Scintillators arc materials that emit flashes of light when ionizing radiation (e.g., energetic electrons) passes through them. Phototubes or photodiodcs must bc used to convert the scintillation light from these detectors into an electrical signal for analysis. These photo-sensitive devices employ an optically sensitive, low work-function cathode. Scintillation light stimulates the emission of electrons from the cathode that arc then accelerated by the voltage difference within the device to produce an electronic signal. Low quantum efficiency (typically than 25% for phototubes and

70% for photodiodes) and low light collection (typically 0% to 50%) degrade the energy resolution performance of scintillators.

The most common type of scintillator used for gamma-ray spectroscopy arc inorganic scintillators. Inorganic scintillators are typically alkali-halide crystals and include sodium iodide (NaI), cesium iodide (CsI), bismuth germanate (BGO), and barium fluoride (BaF_2). The effective atomic number (Z) is typically much higher than organic scintillators making thcm attractive for gamma-ray detection. Scintillators like sodium iodide and cesium iodide can bc doped with thallium (T]) to enhance the probability of visible photon emission during the deexcitation process within the scintillator. Sodium iodide exhibits the highest light output among scintillators, resulting in the best resolution performance, about 50 keV FWHM at an energy of 1.3 McV. Sodium iodide dots need special handling and encapsulation because it is highly hydroscopic and mechanically fragile. Bismuth germanate, on the other hand, owing to its high effective atomic number and density exhibits the best detection efficiency (stopping power) among commonly used scintillators. BGO is also structurally rugged and chemically stable making it attractive for gamma-ray shielding.

The best energy resolution performance for gamma-ray spectroscopy is achieved with semiconductor detectors. Semiconductor detectors arc electrically rcvcrsc-biased diode junctions made of materials which include silicon (Si), germanium (Gc), cadmium telluride (CdTc) and others. Mercuric iodide (HgI_2) is also used but is technically not operated as a diode. The reverse biasing forms a depletion region within the semiconductor that is sensitive to ionization. Within this region recoiling electrons from gamma-ray interactions will produce hole-clcctrcm pairs in the semiconductor. Thc hole-electron pairs will move under the influence of the applied bias voltage (electric field) producing current pulses directly detectable as electronic signals. Because of the low hole-electron pair energy of formation (typically a fcw cV), many charge carriers arc produced from an incident gamma ray, resulting in very fine energy resolution performance. The

resolution is in reality superior to that expected from the Poisson statistics associated with the number of charge carriers. The ratio of observed statistical variance to the expected variance (based on the number of charge carriers) is called the Fano factor. This factor is much less than unity (approximately 0.14 for silicon and 0.1 for germanium). This factor also applies to scintillators, but is much closer to unity.

Germanium coaxial detectors, including high-purity and lithium doped (Ge(Li)) crystals, often provide the best choice for gamma-ray spectroscopy owing to their large size, high atomic number (Z = 32) and excellent energy resolution. Resolution performance of about 1.8 keV near 1.3 McV is common. Germanium detectors require both high voltage for full depletion and cooling to around 85 to 100 K to reduce noise induced by leakage current. The first stage of the sensing electronics is cooled as well to improve the resolution performance. Liquid nitrogen is often used to achieve the necessary cooling. Germanium detectors can be produced in either of two polarities, n-type and p-type depending on the doping and impurity levels in the crystal and on the desired electrode configuration. The n-type detectors are often preferred because of the thinner outside dead layer and greater resistance to radiation damage. Figure 1 is a diagram of a commercially available coaxial germanium detector illustrating various design details.

Semiconductor detectors made from silicon are either thin pure crystals or thicker lithium-drifted crystals. They are typically employed for energies up to 30 kcV. Because of their relatively modest atomic number, they are less effective for higher energy gamma-ray detection. Mercuric iodide, cadmium telluride, cadmium zinc telluride semiconductors are of interest because of their high effective atomic number and ability to operate at room temperature. They are currently limited to small crystal sizes and low energies with moderate energy resolution (about 2 keV at 100 keV).

Other gamma-ray detectors include ionization chambers, proportional chambers and Geiger-Mueller counters. These devices use various gas mixtures under high voltage as the ionizing medium. They typically have low sensitivity to gamma rays due to the low density gas used in the device and have slow timing response since charges must drift through the gas before detection. The spectroscopic performance is generally poor, although proportional chambers do exhibit better energy resolution than scintillators in the hard X-ray region between 20 and 80 keV. Liquid argon or xenon detectors have promise as gamma ray detectors. The liquid density of the ionization medium makes them more sensitive than the gas chambers. However, they require very pure, cryogenic noble elements and their recombination properties are not well known.

All these different detection technologies produce charge pulses proportional to the incident gamma-ray energy. The electronics must integrate the charge pulse and translate it into a voltage pulse, and then amplify and shape the voltage pulse for analysis. The integration is performed by a preamplifier, generally located near the detector to reduce noise pickup. The pulse shaping and amplification is accomplished with a shaping amplifier with a variety of gain settings and shaping time constants from less than 1 μs to over 20 μs. The shorter shaping times are used for timing applications, while the longer shaping times are used to achieve the best spectroscopic performance (energy resolution).

Pulse height analysis is performed on each count (photon) received by the detector and electronics. The pulse height is analyzed with one of two techniques. The first technique is to use an array of discriminators each with different level settings that are arranged to produce a set of energy windows or energy channels, sometimes called a "Flash ADC." This technique is typically very fast with conversion times in the nanosecond range, but is limited in the number of energy channels. The second technique to analyze the pulse height is to use an analog-to-digital converter (ADC). These devices produce a digital number proportional to the voltage (height) of

the analyzed pulse. Two ADC designs are typically used in gamma-ray spectroscopy, the Wilkinson ADC and the successive approximation ADC. The Wilkinson ADC stores the peak voltage of the pulse height on a capacitor that is then discharged at a constant current. The time it takes the capacitor to discharge, measured by a digital clock, is proportional to the pulse height. These ADCs are precise and typically can digitize to a precision of 14 bits, corresponding to 16,384 energy channels. The digitization time can be many tens of μs. The successive approximation ADC, on the other hand, compares the pulse height to a series of successive reference levels that decrease by a factor of two until the desired precision is reached. Precision as high as 14 bits of digitization is possible. This type of ADC tends to be faster than the Wilkinson ADC. Typical digitization times are around 5 or 6 μs. Once digitized, the signal value is then accumulated in a histogramming memory or read out by a computer for analysis.

Digitizing speed is important when measuring gamma rays at high count rates. When the ADC is analyzing a signal pulse from the detector, the detector is effectively unavailable to process any additional signals until the analyzer completes the digitization. This results in a dead time for the detection system. The dead time is dominated by the shaping time of the shaping amplifier and the conversion time of the ADC (a few μs to several tens of μs per count). When count rates and signal strengths are to be measured the dead time must be accurately accounted. Many analyzers contain precise internal timers that accurately measure the dead time associated with the pulse analysis.

Gamma-Ray Spectroscopy

A gamma-ray energy spectrum is simply a plot of observed gamma-ray radiation as a function of energy. More practically, a spectrum is represented as an accumulation of gamma-ray counts in each of several energy channels. To extract information about a signal in a spectrum, the signal must be isolated from various sources of interference present in the spectrum. These are mainly composed of the natural background (present if the source is removed) and the continuum

associated with the Compton scattering and pair-produced escapes from the signal. Gamma-ray lines arc easier to isolate since they arc usually characterized by a narrow gaussian peak superimposed on the continuum. Once isolated, the gamma-ray signal must be corrected for detector efficiency to determine the actual number of photons incident of the detector.

Both gamma-ray lines and continuum contain information about the source of gamma rays and the environments where the gamma rays arc produced. For example, spectral differences between thermal and non-thermal distributions from an astrophysical source (e.g., neutron star) can be distinguished with the analysis of the continuum. When gamma-ray lines are present in a spectrum and their energies precisely dctcrmincd, the isotopic identity of the source can be inferred. The intensity of the lines can bc used to infer the chemical abundance of source material. As an application of this, a gamma-ray spectrometer in orbit about an airless planet or an asteroid can remotely map the elemental and isotopic composition of the body's surface. The gamma rays arc produced by cosmic-ray activation and natural radioactivity of the surface material. When several lines of different energy arc present from the same isotope, the relative attenuation of the different line energies can bc studied to determine the amount of intervening material between the source and detector. A study of gamma-ray lines from reactor experiments can provide insight into the structure, states and transitions of the nucleus, and into nuclear processes in general.

The examination of Doppler effects on the gamma-ray energies is another powerful tool in deducing more information from a spectrum. The determination of the apparent shift of the ccntroid of a gamma-ray line determines the relative velocity of the source and detector. This is seen in accelerator experiments where excited or short-lived nuclei decay in flight, and with astrophysical red or blue shifts due to relative motion, strong gravity, or cosmological effects. Doppler broadening of a gamma-ray line can indicate the temperature or dynamics of the environment in which the source exists, such as a solar flare event.

A spectrum of ^{228}Th, ^{60}Co and ^{241}Am gamma-ray sources collected with a large coaxial, intrinsic germanium detector in the laboratory is shown in Figure 2. This spectrum has not been corrected for detector efficiency effects, The spectrum is plotted with a semi-logarithrnic ordinate to bring out the detailed line features. The highest energy line is the 2614.5 keV line from the thorium decay chain. Several effects arc apparent. A broad continuum composed of background gamma rays and gamma rays from incompletely absorbed Compton scattered photons is apparent. An edge feature due to Compton scattering from the 2614.5 keV line is seen near 2300 kcV. Single and double escape peaks caused by escaping 511 keV photons from pair production induced by the 2614.5 keV line arc seen at 2103.5 keV and 1592.5 kcV, respectively. The background line from naturally occurring ^{40}K is seen at 1460 kcV. Many of the other visible lines are from the thorium decay sequence. The energy resolution (FWHM) is approximately 1.5 keV at the 59.5 keV line of ^{241}Am and 2.4 keV at the 1332.5 keV line of ^{60}Co. A simulated NaI scintillator response to the same gamma-ray signal with an exaggerated vertical scale is shown for energy resolution comparison.

Spectrometers employing a single detector arc the most common type found in the laboratory. More advanced spectrometers employ an anticoincidence shield around the spectrometer to suppress the Compton induced continuum and the natural background. The anticoincidence shield is usually several centimeters of scintillator such as BGO. An entrance window for the gamma rays is provided at the front of the detector. The shield provides two functions. First, it attenuates unwanted gamma rays entering from the side or back of the detector. Second the shield actively vetoes any signal that appears in both the enclosed detector and the surrounding shield. This helps suppress events with escaping radiation, especially Compton scattered photons, that contribute to the continuum in the spectrum.

Many applications require directional information as well as spectroscopic data about a gamma-ray source. Compton telescopes can be constructed from several detectors that are positioned such that the individual energy depositions from the Compton scattering can be measured and the scattering angle calculated. The information from many gamma rays canbe used to point back to the gamma-ray source. Other imaging systems usc many detectors, closely arrayed to form a position sensitive system of spectrometers, along with modulating apertures to create an imaging system, much in analogy to the pin-hole camera concept. A spectrum is collected for each pixel in the image allowing each pixel to be separately analyzed. These imaging techniques have strong applications in astrophysical, industrial and medical uses.

Gamma-ray spectrometer technology continues to improve. Continuing progress is being made in producing large intrinsic germanium crystals resulting in detectors with increasing sensitivity while offering excellent spectral resolution. Small, low-power, highly reliable mechanical coolers to provide cooling for germanium detectors arc available and arc particularly well suited for space-based applications of gamma-ray spectrometers, reducing the launch mass and extending the mission life. Position-sensitive germanium detectors arc currently in development and show promising results in imaging applications. Large volume coaxial germanium detectors have been segmented in onc dimension into several distinct charge collection regions. Energy depositions inside the detector can be localized to individual segments without loss in overall sensitivity or energy resolution. Thick, planar germanium detectors arc being developed which will have the face electrodes segmented into many two dimensional pixels. Energy depositions can be localized to a single pixel. These segmented germanium detectors offer greatly improved imaging capabilities with excellent sensitivity and spectral resolution. Room temperature semiconductor crystals including CdZnTe continue to improve in size and resolution performance. Quantum efficiencies of photomultiplier tubes and photodiodes continue to increase, improving the resolution performance of scintillators. Gamma-ray spectrometers continue to be an ever more powerful tool in the investigation of a variety of physical processes.

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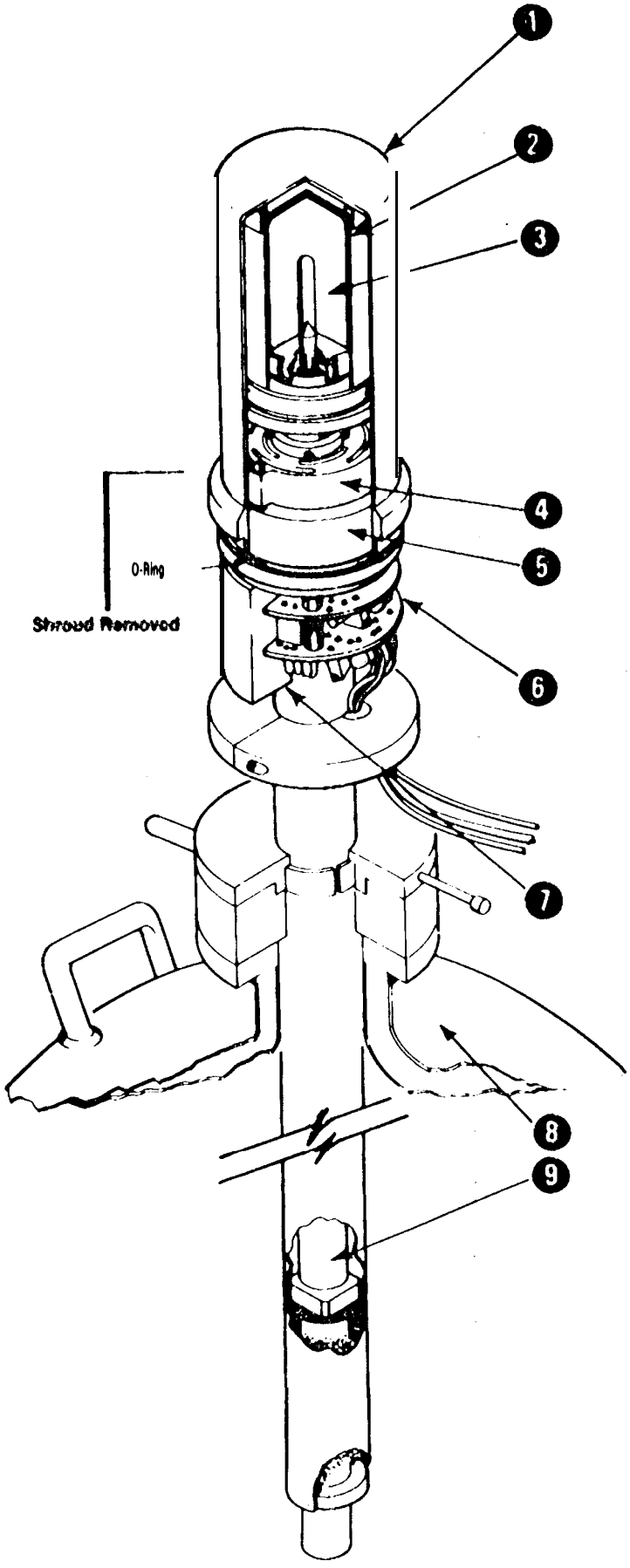
Figure 1. Diagram of a commercial coaxial germanium detector. Details of the detector mounting and cryostat assembly arc illustrated. Legend: (1) End-cap, (2) detector mount cup, (3) germanium detector element, (4) thermal insulator, (5) lead shield, (6) preamplifier, (7) HV filter, (8) LN_2 dcwar, and (9) cooling rod. (Reproduced with permission from reference 2.)

Figure 2. Spectrum of a mixture of ^{228}Th, ^{60}Co and ^{241}Am gamma-ray sources collected with a large coaxial, intrinsic germanium detector in the laboratory. Several gamma-ray lines from americium, cobalt and thorium arc apparent. Continuum effects and escape peaks (described in the text) arc obvious. A simulation of a NaI scintillator response for the same signal with an exaggerated vertical scale (x20) is shown illustrating the resolution performance differences between germanium and NaI detectors.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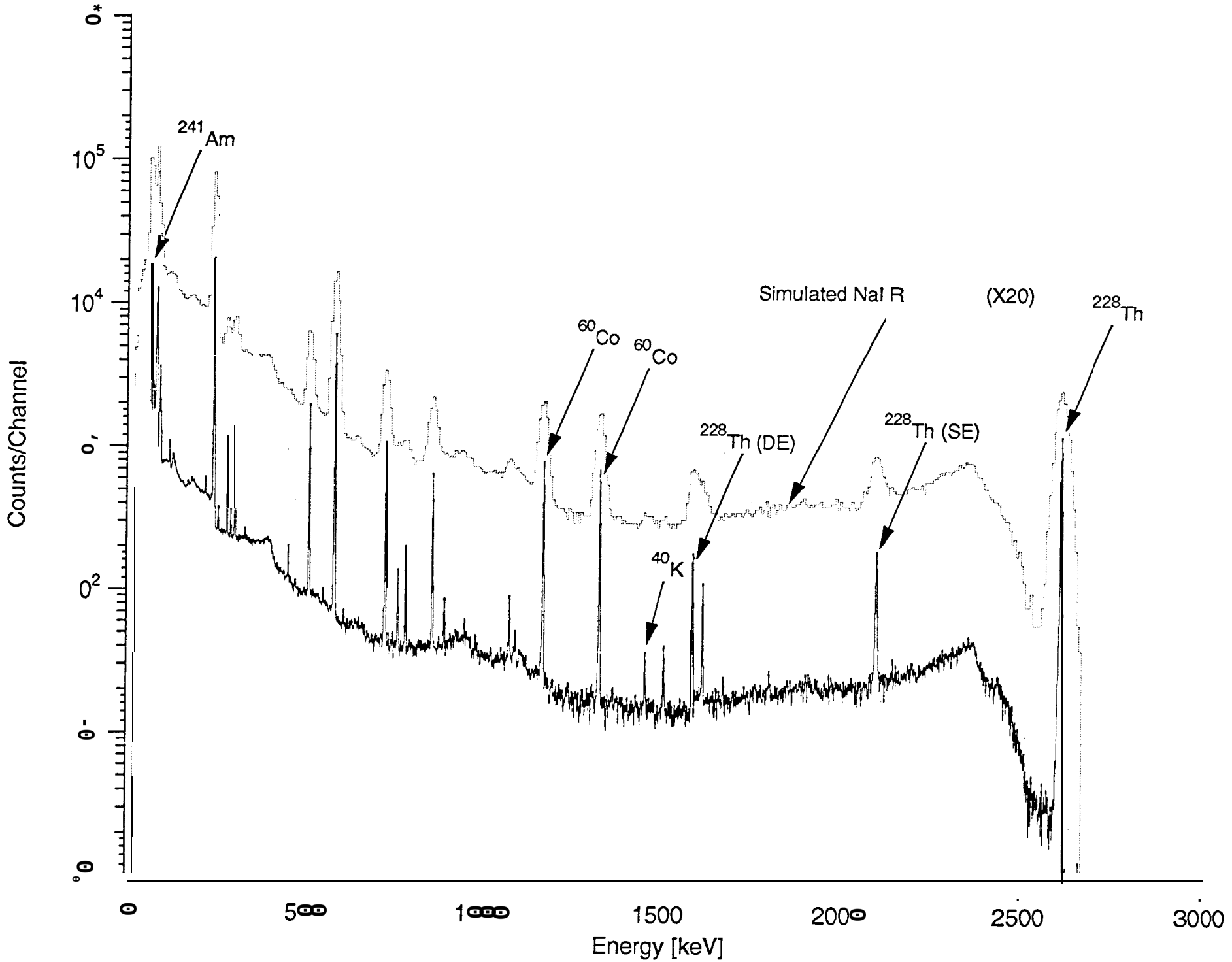
Counts/Channel
Energy [keV]
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60Co
60Co
228Th (DE)
40K
Simulated NaI R
(X20)
228Th (SE)
228Th
0
500
1000
1500
2000
2500
3000