4

Instrumentation for Gamma-Ray Spectroscopy

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4.1 INTRODUCTION

The subject of this chapter is the function and operation of the components of a gamma-ray spectroscopy system. In Chapter 3 it was shown that the output pulse amplitude from most gamma-ray detectors is proportional to the energy deposited by the gamma ray. The pulse-height spectrum from such a detector contains a series of full-energy peaks superimposed on a continuous Compton background. Although the spectrum can be quite complicated (for example, see Figure 1.10 of Chapter 1) and thereby difficult to analyze, it contains much useful information about the energies and relative intensities of the gamma rays emitted by the source. The information that is important for the quantitative nondestructive assay (NDA) of nuclear material is contained in the full-energy peaks. The purpose of the electronic equipment that follows the detector is to acquire an accurate representation of the pulse-height spectrum and to extract the desired energy and intensity information from that spectrum.

This chapter provides a relatively brief introduction to the wide variety of instrumentation used in the gamma-ray spectroscopy of nuclear materials. It emphasizes the function of each component and provides information about important aspects of instrument operation. For a detailed description of instrument operation, the reader should refer to the instruction manuals provided with each instrument. Because of the rapidly advancing state-of-the-art of gamma-ray spectroscopy equipment, the best sources of current information are often the manufacturers and users of the instruments. Although the manufacturers are clearly the best source of information about the electronic capabilities of their equipment, those active in the application of gamma-ray spectroscopy to NDA are usually the best source of information on effective assay procedures and the selection of equipment for a given application. Books and reports on gamma-ray spectroscopy equipment are often out of date soon after they are published.

Gamma-ray spectroscopy systems can be divided into two classes according to whether they use single-channel analyzers (SCAs) or multichannel analyzers (MCAs). Figures 4.1 and 4.2 show block diagrams of the two classes. Both systems begin with a detector, where the gamma-ray interaction produces a weak electrical signal that is proportional to the deposited energy. Section 4.2 discusses the process of selecting an appropriate detector for different NDA applications. Sections 4.3 through 4.8 discuss the basic components of gamma-ray spectroscopy systems; the discussion of each component is presented in the order in which the electrical signal flows through the system. Section 4.9 presents auxiliary electronic equipment. Usually, components other than those shown in Figures 4.1 or 4.2 must be added to form a useful NDA system. Shields, collimators, sample holders, sample changers, scanning mechanisms, and source shutters are discussed in later chapters that describe specific assay techniques and instruments.

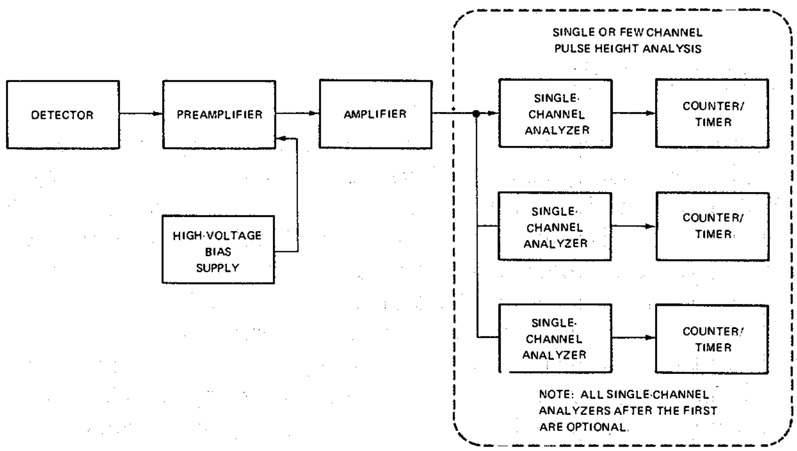

Fig. 4.1 *Block diagram of a single-channel-analyzer-based gamma-ray spectroscopy system for simple NDA applications.*

4.2 SELECTION OF DETECTOR

Some general guidance is given in this section to the often difficult matter of selecting an appropriate detector for a particular NDA application. There are not only several generic types of detectors but myriad variations of size, shape, packaging configuration, performance, and price. The detector choice must be evaluated in the light of the technical requirements of a proposed application and the nontechnical but often overriding matter of budgetary constraints.

The first and most important detector parameter to consider is resolution. A detector with high resolution usually gives more accurate assays than one with low resolution. The resolution of a germanium detector is typically 0.5 to 2.0 keV in the energy range of interest for NDA applications, whereas the resolution of a NaI detector is 20 to 60 keV. It is easier to determine accurately the area of full-energy peaks in a complex spectrum when the peaks do not overlap, and the probability of overlap is

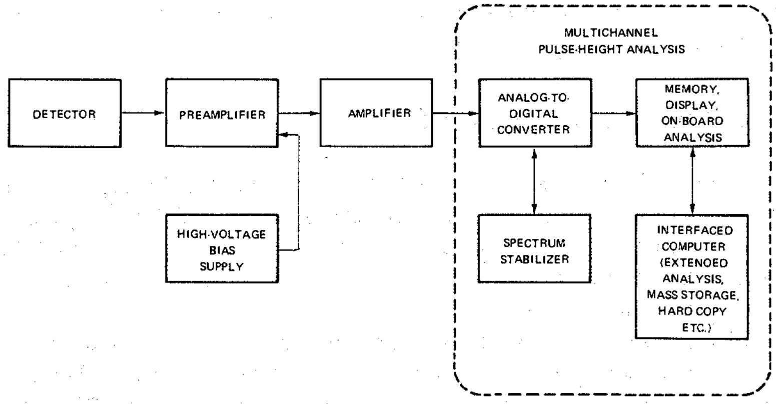

Fig. 4.2 *Block diagram of a multichannel-analyzer-based gamma-ray spectroscopy system for complex NDA applications.*

less with narrower peaks. The background continuum under the full-energy peaks is easier to subtract from a high-resolution spectrum because it is a smaller fraction of the total activity in the peak region. Full-energy-peak areas are easier to evaluate in high-resolution spectra because the interference from small-angle Compton scattering in the sample is reduced. Gamma rays that undergo small-angle scattering lose only a small amount of energy. If these scattered gamma rays still fall in the full-energy-peak region, the calculated full-energy-peak area is likely to be incorrect. This problem is minimized by using a high-resolution detector, which provides narrow, full-energy peaks.

The complexity of the spectrum should influence the detector choice; the more complex the spectrum becomes, the more desirable high resolution becomes. Plutonium has a much more complex gamma-ray spectrum than uranium does, and germanium or silicon detectors are used more often in plutonium assay applications than in uranium assay applications.

The second performance parameter to consider is efficiency, which determines the count rates that can be expected, the time that is required to achieve a given precision, and the sensitivity that can be achieved. Higher efficiency always costs more for a given detector type, but a given efficiency is less expensive to obtain in a low-resolution NaI detector than in a high-resolution germanium detector. There is considerable motivation to use a less-expensive, lower-resolution detector when it can give satisfactory assay results.

Other parameters such as space and cooling requirements and portability must be considered and are sometimes the dominant considerations. The selection of an appropriate detector is often difficult and may involve painful compromises among conflicting requirements. Once the selection is made, considerable care should be taken to specify all pertinent parameters to prospective vendors to ensure that the desired detector is obtained.

4.3 HIGH-VOLTAGE BIAS SUPPLY

All of the commonly used gamma-ray detectors require a high-voltage bias supply to provide the electric field that collects the charge generated by the gamma-ray interaction in the detector. The bias supply is not a part of the signal path but is required to operate the detector. It is usually the most reliable unit in a spectroscopy system and the easiest to operate.

Germanium and silicon diode detectors require very low currents, typically $<10^{-9}$A. The voltage requirements range from a few hundred volts for a small silicon detector to several thousand volts for a large coaxial germanium detector. Bias supplies for germanium and silicon detectors usually provide up to 5 kV and 100 μA. The voltage-resolution and low-frequency-filtering requirements are modest because there is no charge amplification in the detector. The voltage is usually continuously variable from 0 to 5 kV. In the past, it was necessary to vary the voltage very slowly ($<$100 V/s) when turning on or changing the detector bias because the field-effect transistor (FET) used in the first stage of the detector preamplifier is easily damaged by sudden voltage surges. However, the protection now provided by the filter included in all high-quality preamplifiers is so good that an FET is rarely destroyed for this reason. Battery packs are sometimes used as bias supplies for germanium and silicon detectors because they are portable and do not generate noise. A charged capacitor can be used as a "power supply" for many hours; in fact, the capacitor in the high-voltage filter located in the preamplifier can often operate a detector for an hour or two.

The bias supply requirements for photomultiplier tubes used with scintillation detectors are more stringent than for solid-state diode detectors. The required voltage is typically a few thousand volts, but the required current is usually 1 to 10 mA. Because the gain of a photomultiplier is a very strong function of the applied voltage, the stability and filtering must be excellent. The 100-μA supplies used with germanium detectors will usually not operate a photomultiplier tube.

Bias supplies come in a variety of packages. The most common is the nuclear instrumentation module (NIM), which plugs into a frame or bin (NIM bin) that supplies the necessary dc voltages to power the module. NIM modules meet internationally accepted standards for dimensions, voltages, wiring, and connectors and are widely used in NDA instrumentation. Other bias supplies fit in NIM bins but take power from the normal ac source. The high-current bias supplies used to power multiple photomultiplier-tube arrays are often mounted in standard 45.7-cm (18-in.)-wide instrumentation racks.

NIM bias supplies frequently use an electronic switching device to generate the required voltage. The switching device generates a high-frequency noise that can find its way into the preamplifier and cause significant degradation of spectral quality. This problem can be minimized by careful grounding and cable positioning. The noise generated by the power supply can also introduce false signals into any pileup rejection circuitry being used. Photomultiplier-tube bias supplies, even those that are not the NIM type, can also be sources of high-frequency noise. As usual, an oscilloscope is a most useful aid in detecting the presence of interfering electrical noise from any source.

Note that detector bias supplies can be lethal. Caution is always required, particularly when working with the high-current supplies that power photomultiplier tubes. Persons who are accustomed to working with low-voltage, low-power, transistorized circuits must be made aware of the danger associated with the use of detector power supplies.

4.4 PREAMPLIFIER

Preamplifiers are required for germanium and silicon detectors and improve the performance of NaI scintillation detectors. The detector output signal is usually a low-amplitude, short-duration current pulse; a typical pulse might be 10 mV high and 200 ns long. The preamplifier converts this current pulse to a voltage pulse whose amplitude is proportional to the energy deposited in the detector during the gamma-ray interaction. To maximize the signal-to-noise ratio of the output pulse and preserve the gamma-ray energy information, the preamplifier must be placed as close to the detector as possible. The closeness of the preamplifier minimizes the capacitance at the preamplifier input, thereby reducing the output noise level. The preamplifier also serves as an impedance-matching device between the high-impedance detector and the low-impedance coaxial cable that transmits the amplified detector signal to the main amplifier. The amplifier and preamplifier may be separated by as much as several hundred meters.

Because the detector and preamplifier must be close, the preamplifier is often in an inconvenient location, surrounded by shielding, and inaccessible during use. Most preamplifiers have no external controls; the gain and pulse-shape adjustments are included in the main amplifier, which is usually in a more convenient location close to the other system electronics. Because it lacks external controls, the preamplifier occupies only a few hundred cubic centimeters. Its small volume is advantageous when the preamplifier must be located inside the detector shielding. The preamplifier is usually housed in a small rectangular box. For single NaI detectors, the preamplifier is often built into the cylindrical housing that holds the photomultiplier-tube socket. In recent years, preamplifiers for germanium and silicon detectors have been packaged in an annular configuration behind the end cap of the detector cryostat. This configuration

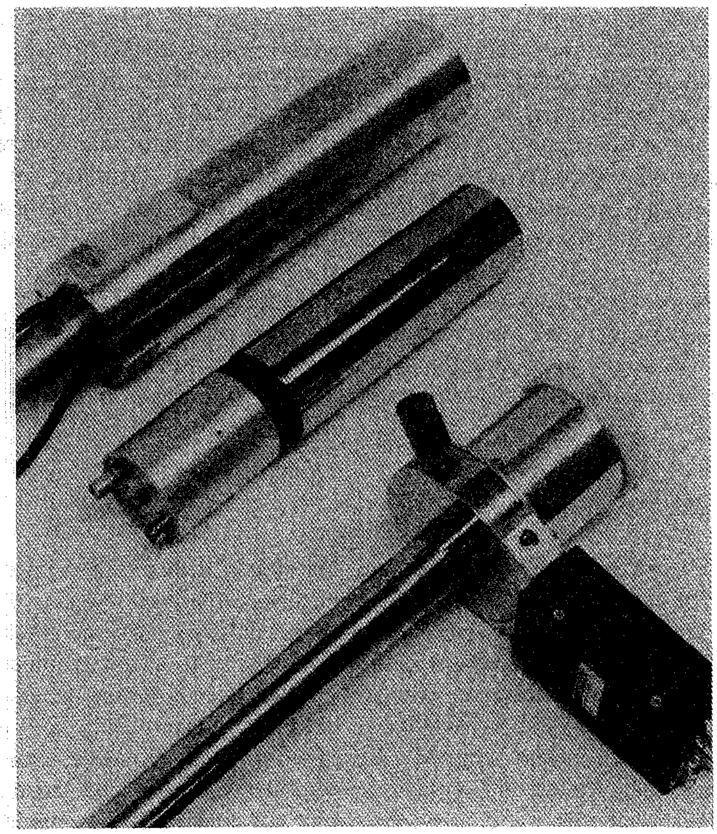

Fig. 4.3 Detectors having annular, cylindrical, and rectangular preamplifiers.

eliminates awkward boxes that stick out at right angles from cryostats and makes the detectors easier to shield. Figure 4.3 shows the basic preamplifier configurations just described.

Although preamplifiers have few controls, they have several connectors. Usually included are one or two output connectors and a test input through which pulses can be routed from an electronic pulser to simulate gamma-ray events for testing the performance of the preamplifier and the other signal-processing instruments in the system. (The simulated gamma-ray peak produced in the acquired spectrum can also give a good estimate of the electronic losses suffered by the system; see Chapter 5.) The detector bias is often applied through a connector mounted on the preamplifier. A multipin connector is usually included to provide the power needed for operating the preamplifier; the power is often supplied by the main amplifier. Certain NaI preamplifiers generate the required low voltage from the detector bias voltage.

The preamplifier output pulse is a fast positive or negative step followed by a very slow decay. The risetime is a few tenths of a microsecond and the decay time is 50 to 100 μs. The amplitude of the fast step is proportional to the charge delivered to the preamplifier input and therefore proportional to the energy deposited in the detector by the gamma ray. The long decay time means that a second pulse often occurs before the tail of the preceding pulse has decayed. This effect is seen in Figure 4.4, which shows the preamplifier output from a large, coaxial germanium detector. The amplitude of the fast-rising step, which contains the important energy information from the gamma-ray interaction, is distorted only if the energy deposition rate becomes so high that the average dc level of the preamplifier rises to where some of the fast-rising steps are beyond the linear range of the amplifier.

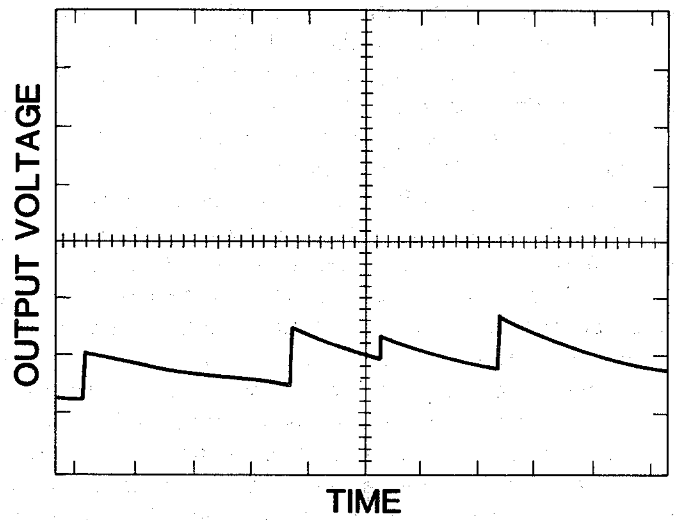

Fig. 4.4 *Output pulses from a typical germanium-detector preamplifier. The important energy information is contained in the amplitude of the fast-rising voltage step (~0.5 μs). The pileup of pulses on the long tails (~50 μs) does not affect the validity of the energy information.*

Most manufacturers offer several preamplifier models that are optimized for different detector types. Parameters such as noise level, sensitivity, risetime, and count-rate capability may be different for different models. The count-rate capability is usually specified as the maximum charge per unit time (C/s) delivered from the detector to the preamplifier input. For germanium and silicon detectors the equivalent energy per unit time (MeV/s) is often specified; when this number is divided by the average gamma-ray energy, the result is the maximum count rate that the preamplifier can handle.

Usually, few choices can be made when selecting a preamplifier for a NaI detector. However, several significantly different options are available for germanium detectors; the selection depends upon the detector and the measurement application. Because germanium detectors are always sold with an integral preamplifier, the selection must be made when the detector is purchased.

Because of its low noise, an FET is always the first amplifying stage in a germanium-detector preamplifier. When germanium detectors were first produced, the FET was always operated at room temperature in the main preamplifier enclosure. However, better resolution can be achieved when the FET is cooled along with the detector crystal. The improvement in resolution is especially significant at gamma-ray energies below 200 keV. Preamplifiers are now available with either room-temperature or cooled FETs. The preamplifier feedback resistor and other associated circuit components may be located inside the cryostat with the FET and the detector crystal. The penalty for the improved performance is that if the FET fails and must be replaced, the cryostat must be opened, usually by the manufacturer at considerable expense to the user. However, preamplifiers that use cooled FETs are now so reliable and so well protected from high-voltage surges that the transistors rarely fail. As a result, this type of preamplifier is now the most commonly used.

Most manufacturers also offer a high- or low-count-rate option. This option is needed because detector resolution cannot be optimized simultaneously for high and low count rates. Most detector-preamplifier units are optimized to operate at low count rates (<10 000 count/s) because this provides the best resolution possible. If the primary application will involve count rates greater than 50 000 count/s, the manufacturer should be asked to optimize the detector for high-count-rate performance.

Germanium detector crystals are fabricated in planar or coaxial geometries; the designation refers to the shape of the crystal and the location of the charge-collecting contacts. Because of their very low electrical capacitance, small planar detectors (<10 cm^3) have lower noise and better resolution than large detectors. To obtain the best possible resolution from small planar detectors, the feedback resistor is sometimes removed from the preamplifier. However, without the feedback resistor, the decay time of the output pulse is very long and the output level increases with each successive pulse. Figure 4.5 shows the output of a preamplifier that does not have a feedback resistor. When the maximum allowable dc level is reached, the preamplifier must be reset using a pulsed-optical or transistorized method. However, the reset pulse can saturate the main amplifier for up to several hundred microseconds, and the data acquisition equipment must be disabled to avoid the analysis of invalid, distorted pulses. Because of this complication, pulsed-optical preamplifiers are chosen only when the small improvement in resolution is absolutely required. Pulsed-optical preamplifiers have a low-count-rate capability, often only 5000 MeV/s rather than the more than 50 000 MeV/s usually available with other types of preamplifiers. For low gamma-ray energies (<100 to 200 keV), the count-rate limitation may not be a problem.

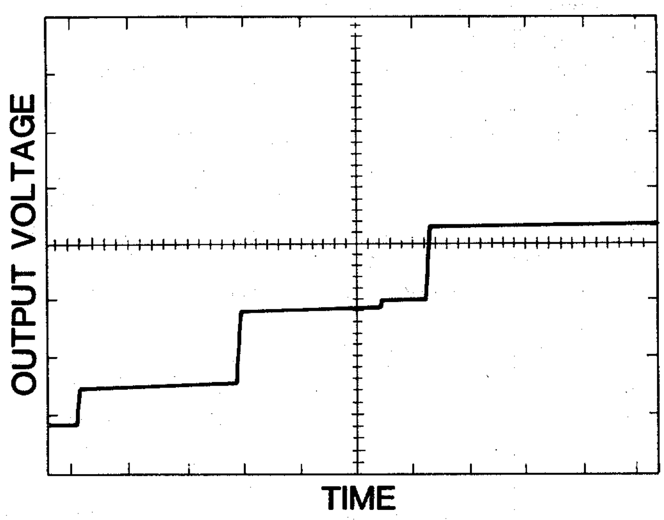

Fig. 4.5 *Output pulses from a pulsed-optical preamplifier on a germanium detector. Because there is no feedback resistor, the noise level is lower than in resistively coupled preamplifiers and the dc output level rises in a stair-step fashion and must be reset when the maximum allowable voltage is reached.*

In recent years, preamplifiers that use variations of the pulsed-optical method have been developed for high-count-rate applications. In one case, the optically coupled reset device is replaced by a transistor network. In another case, the reset is accomplished by optical means but the preamplifier is reset after nearly every event, thereby reducing the amplifier saturation time.

4.5 AMPLIFIER

After leaving the preamplifier, the gamma-ray pulses are amplified and shaped to meet the requirements of the pulse-height-analysis instrumentation that follows the main amplifier. Most spectroscopy-grade amplifiers are single- or double-width NIM modules. Portable multichannel analyzers often have a built-in amplifier, which may be adequate for the intended application.

The main amplifier accepts the low-voltage pulse from the preamplifier and amplifies it into a linear voltage range that is 0 to 10 V for most high-quality amplifiers. Within the linear range all input pulses are accurately amplified by the same factor. The amplification is nonlinear for output pulses that exceed 10 V. The maximum output voltage or saturation voltage of most amplifiers is approximately 12 V. The amplifier gain can be adjusted over a wide range, typically from

10 to 5000. Amplifiers usually have two gain controls (coarse and fine) to allow continuous gain adjustment.

The shaping function of the main amplifier is vital to the production of high-quality spectra. The amplified pulses are shaped to optimize the signal-to-noise ratio and to meet the pulse-shape requirements of the pulse-height-analysis electronics. Because single-channel and multichannel analyzers measure the input pulse amplitude with respect to an internal reference voltage, the amplifier output must return quickly to a stable voltage level, usually zero, between gamma-ray pulses. The stability of the baseline voltage level is extremely important because any baseline fluctuation perturbs the measurement of the gamma-ray pulse amplitude and contributes to the broadening of the full-energy peak.

A narrow pulse shape permits a quick return to baseline. However, the pulse must be wide enough to allow sufficient time to collect all of the charge liberated by the interaction of the gamma ray in the detector. Figure 4.4 shows that 0.25 to 0.5 μs could be sufficient to allow complete charge collection. The pulse shape should also provide a signal-to-noise ratio that minimizes the variation in output pulse amplitude for a given quantity of charge deposited at the preamplifier input. Unfortunately, the pulse width that provides the optimum signal-to-noise ratio is usually wider than that required for a quick return to baseline. At low count rates, the pulse can be wide because the probability is small that a second pulse will arrive before the amplifier output has returned to the baseline level. As the count rate increases, however, the probability that pulses occur on a perturbed baseline also increases, and the spectrum is distorted in spite of the optimum signal-to-noise ratio. A narrower pulse width than required for the optimum signal-to-noise ratio usually gives the best resolution at high count rates; the resolution, however, is not as good as can be obtained at low count rates.

The amplifiers used with high-resolution germanium and silicon detectors employ a combination of electronic differentiation, integration, and active filtering to provide the desired pulse shape. Qualitatively, differentiation removes low frequencies from a signal and integration removes high frequencies. Differentiation and integration are characterized by a time constant, usually having units of microseconds, that defines the degree of attenuation as a function of frequency. The greater the time constant, the greater is the attenuation of low frequencies by differentiation and the attenuation of high frequencies by integration. When both differentiation and integration are used, the low- and high-frequency components are strongly suppressed and a relatively narrow band of middle frequencies is passed and amplified. Because most spectroscopy amplifiers function best when the differentiation and integration time constants are equal, there is usually a single control that selects time constants in the range 0.25 to 12 μs. When the two time constants are equal, the amplifier output pulse is nearly symmetrical (see Figure 4.6). The total pulse width is approximately six times the time constant. At low count rates, large coaxial germanium detectors usually have optimum resolution with time constants of 3 to 4 μs. Small planar germanium detectors resolve best with time constants of 6 to 8 μs, and small planar silicon detectors usually operate best with values of 8 to 12 μs. The problem of pulse pileup is more severe when long time constants are used to exploit the intrinsically better resolution of the smaller detectors. The time constant used in a given situation depends on the detector, the expected count rate, and whether resolution or data throughput is of greater importance.

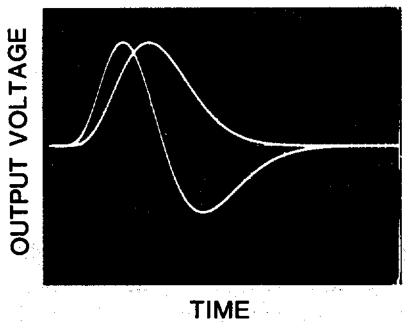

Fig. 4.6 *Unipolar and bipolar output signals from a typical spectroscopy amplifier with differentiation/integration pulse shaping.*

High-resolution germanium and silicon detectors are relatively slow and require time constants longer than those needed for other types of detectors. NaI scintillation detectors, which have resolutions that are 10 to 20 times worse than those of germanium detectors, operate well with time constants of 0.25 to 1.0 μs. Organic scintillation detectors, which have almost no energy resolution, can operate with time constants of only 0.01 μs; when energy resolution is not required but high-count-rate capability is, they are very useful. Unfortunately, no detector now available combines very high resolution with very high count rate capability.

Spectroscopy amplifiers usually provide two different output pulse shapes: unipolar and bipolar. The bipolar pulse is usually obtained by differentiating the unipolar pulse. Figure 4.6 shows both unipolar and bipolar output signals from a typical spectroscopy amplifier. The unipolar output has a better signal-to-noise ratio and is usually used for energy analysis, whereas the bipolar output has superior timing information and overload recovery. The bipolar pulse shape is usually better for timing applications because the zero crossover point (the point where the bipolar pulse changes sign) is easily detected and is very stable. The crossover point corresponds to the peak of the unipolar output and is nearly independent of output pulse amplitude.

Delay lines can be used in pulse-shaping circuits. Delay-line shaping can provide unipolar or bipolar pulses, depending on whether one or two delay lines are employed. Delay-line amplifiers are economical and provide adequate performance when used with low-resolution detectors; they are rarely used with germanium or silicon detectors because their noise level is higher than that found in amplifiers that use differentiation and integration. The output pulse shape of a delay-line amplifier is distinctly different from that of an amplifier that uses differentiation and integration. Figure 4.7 shows the unipolar and bipolar output signals from a typical delay-line amplifier.

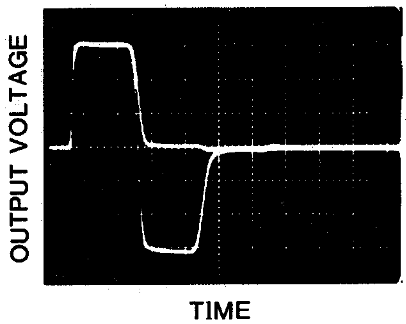

Fig. 4.7 Unipolar and bipolar output signals from an amplifier with delay-line pulse shaping.

4.5.1 Pole-Zero Compensation Circuit

Most amplifiers include a pole-zero compensation circuit to help maintain a stable baseline. The pole-zero circuit was introduced in about 1967 and was the first major improvement in amplifier design after the introduction of transistors. It significantly improves amplifier performance at high count rates. The term "pole zero" arises from the terminology of the Laplace transform methods used to solve the simple differential equation that governs the circuit behavior. The circuit is very simple; it consists of an adjustable resistor in parallel with the amplifier input capacitor. In spite of the simplicity of the circuit, the proper adjustment of the pole-zero control is crucial for correct operation of most modern amplifiers. When the pole-zero control is properly adjusted, the amplifier output returns smoothly to the baseline level in the minimum possible time. When the control is incorrectly adjusted, the following conditions result: the output pulses are followed by a long undershoot or overshoot that perturbs the output baseline and seriously degrades the amplifier performance at high count rates; the full-energy peaks are broader and often have low- or high-energy tails depending on whether an undershoot or overshoot condition exists; accurate determination of the full-energy peak areas is difficult. Figure 4.8 shows the amplifier pulse shapes and full-energy peak shapes that result from correct and incorrect pole-zero adjustment.

Adjustment of the pole-zero circuit is simple and is best accomplished using an oscilloscope to monitor the amplifier output pulse shape and following procedures found in the amplifier manual. The adjustment should be checked whenever the amplifier time constant is changed.

4.5.2 Baseline Restoration Circuit

Baseline restoration (BLR) circuits were added to spectroscopy amplifiers soon after the advent of pole-zero circuits. Like the pole-zero circuit, the BLR helps maintain a stable baseline. The pole-zero circuit is located at the amplifier input and is a very simple circuit; the BLR is located at the amplifier output and is often remarkably complex. The pole-zero circuit prevents undershoot caused by the finite

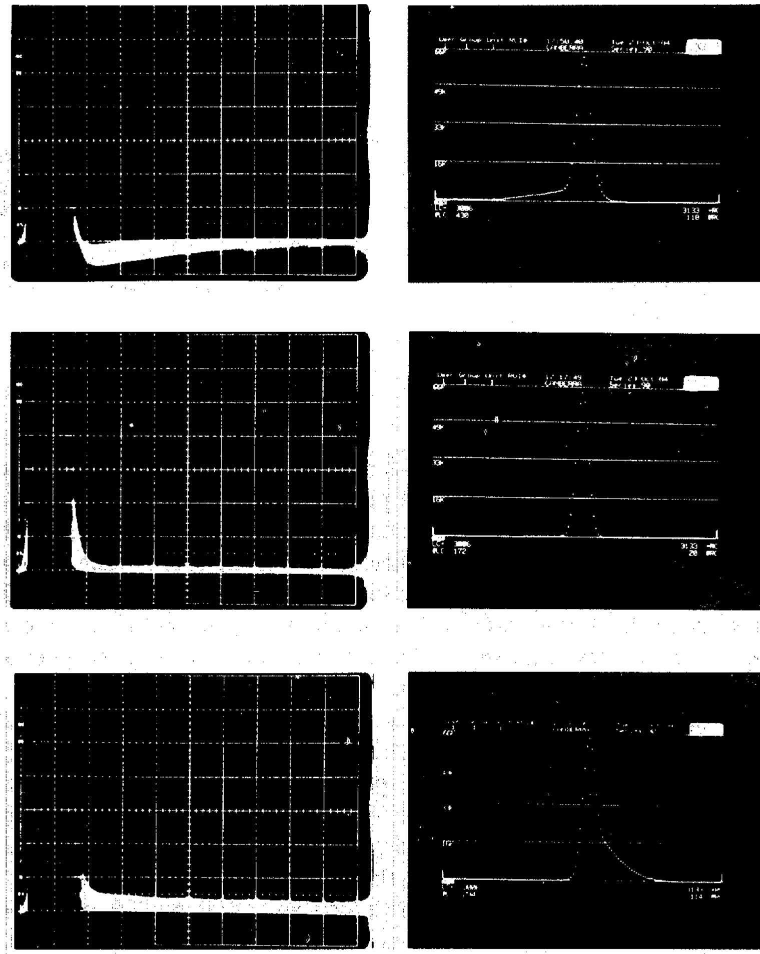

Fig. 4.8 *The effect of pole-zero adjustment on the amplifier output (left) and the full-energy-peak shape (right). The upper frames show pole-zero undercompensation, which causes amplifier undershooting and low-energy tailing on the MCA peak. The middle frames show correct pole-zero compensation. The lower frames show pole-zero overcompensation, which causes amplifier overshooting and high-energy tailing on the MCA peak.*

decay time of the preamplifier output pulse; the BLR suppresses the baseline shifts caused by the ac coupling of the unipolar output pulses. Although operation of the BLR is totally automatic in some amplifiers, other amplifiers have several controls to optimize amplifier performance for different count rates and preamplifier types. The optimum BLR setting is often determined by trial and error.

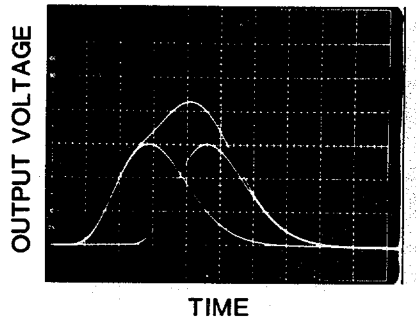

Fig. 4.9 The origin and effect of pulse pileup on the output of a spectroscopy amplifier. When two pulses are separated by less than the amplifier risetime, the amplitude of the resulting sum pulse is not representative of either input pulse.

4.5.3 Pileup Rejection Circuit

Pileup rejection circuits have been added to many top-of-the-line amplifiers to improve performance at high count rates. A pileup rejector uses timing circuitry to detect and reject events where two or more gamma-ray pulses overlap. Such events have a combined pulse amplitude that is not characteristic of any single gamma ray and only increases the height of the background continuum in the acquired spectrum. Figure 4.9 shows how two gamma-ray pulses overlap to produce a pileup pulse. For germanium detectors, the minimum pulse separation that can be resolved by the pileup rejector is approximately 0.5 μs. The pileup rejector usually provides a logic pulse that can be used to prevent analysis of the pileup pulses. In high-count-rate situations, the pileup rejector can provide better resolution and a lower background continuum; as a result, determination of the full-energy-peak areas is simplified. Figure 4.10 shows the improvement in spectral quality that can result from using a pileup rejector. The figure also shows that the pileup rejector can sharpen the appearance of sum peaks such that they may be mistaken for real full-energy peaks.

The considerable benefits of pileup rejection are offset by increased complexity of operation and more stringent requirements for the preamplifier output pulse. The preamplifier output pulse must be free of high-frequency ringing that can cause false pileup signatures in the timing circuits. It must also be free of high-frequency interference from power supplies, scalers, computers, and video display terminals. Such high-frequency pickup is usually filtered out in the main amplifier but can cause false pileup signatures in the pileup rejection circuit and lead to excessive rejection of good gamma-ray pulses and spectral distortions. Considerable care must be used when adjusting pileup rejection circuits.

The proper use of pole-zero, baseline restoration, and pileup rejection circuits can greatly improve the quality of the measured gamma-ray spectrum. Because an oscilloscope is virtually indispensable for adjusting these circuits for optimum performance, a good quality oscilloscope should be readily available to every user of a gamma-ray spectroscopy system. Users should understand the operation of the oscilloscope as well as they understand the operation of the spectroscopy system. They can detect and/or prevent more difficulty through proper use of the oscilloscope than through the use of any other piece of equipment.

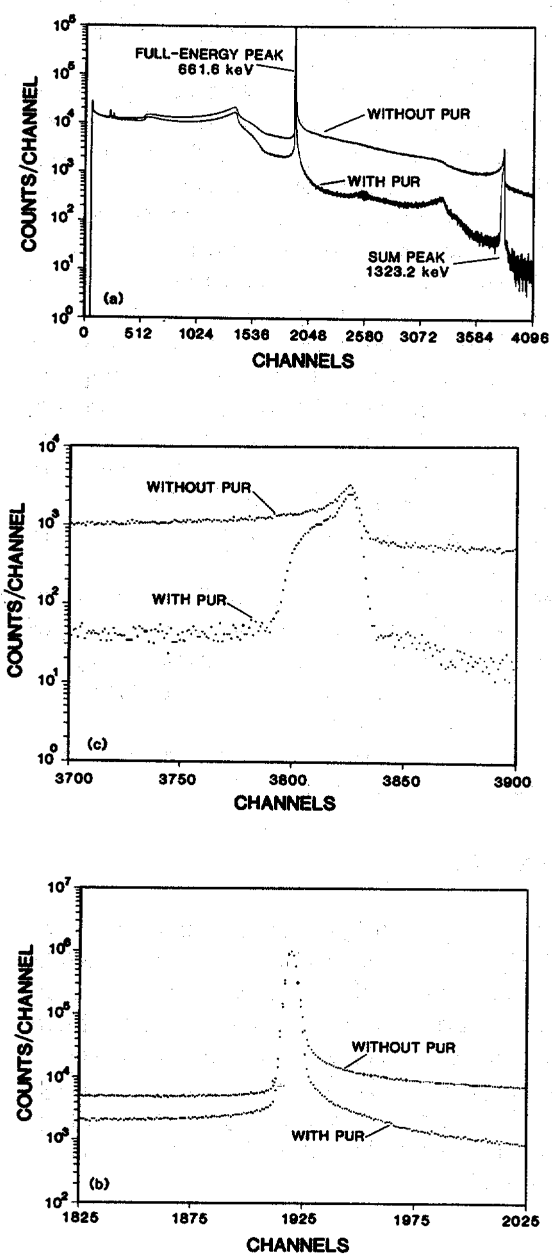

Fig. 4.10 *A high-rate (50 000 count/s) spectrum of ^{137}Cs showing the improved spectral quality obtained with pileup rejection (PUR). Top: the entire spectrum. Middle: the full-energy peak at 661.6 keV. Bottom: the sum peak at 1323.2 keV; pileup rejection reduces the pileup continuum near the sum peak by a factor of 25 but does not significantly reduce the sum-peak amplitude.*

4.5.4 Advanced Concepts in Amplifier Design

Two recent advances in amplifier design improve the ability of gamma-ray spectroscopy systems to operate at high count rates without excessive spectral degradation. Both concepts use a narrow pulse shape to reduce pileup losses while preserving good peak shape, signal-to-noise ratio, and resolution.

In one design, a gated integrator is added to the output of a standard high-quality amplifier. The amplitude of the integrator output pulse is proportional to the integral of the amplifier output pulse. The integrator output is digitized in the normal way by the analog-to-digital converter. For a given gamma-ray interaction, the charge collection time depends on the electric field strength in the detector and the location of the interaction. Charge carriers that are produced far from the collection electrodes or in regions where the electric field is weaker arrive later at the electrodes. Charge that is collected very late may not contribute to the information-carrying part of the preamplifier pulse; such charge is said to cause a ballistic deficit. If the amplifier time constants are comparable to the charge collection time, the integral of the amplifier output pulse is more nearly proportional to the collected charge than is the pulse amplitude. Qualitatively, the integration allows a longer period for charge collection and decreases the ballistic deficit. Shorter time constants can be used with the amplifier-integrator combination than can be used with the amplifier alone. The short time constants reduce pileup losses and increase data throughput. Figure 4.11 shows the amplifier and corresponding integrator output pulse.

The second design uses time-variant filters in place of the normal differentiation-integration filters. The technique requires special preamplifiers and analog-to-digital converters, but it can operate at count rates as high as 10^6 count/s with data throughput rates of 80 000 count/s. Figure 4.12 shows that the output pulse shape from this system is much different from the familiar Gaussian pulse shape.

It should be emphasized that the selection of a detector with excellent charge collection is essential to high-resolution, high-rate spectroscopy.

4.6 SINGLE-CHANNEL ANALYZER

The single-channel analyzer (SCA) is the pulse-height-analysis instrument shown in the simple spectroscopy system of Figure 4.1. Historically, the first pulse-height-analysis instrument was a simple discriminator with a single, adjustable voltage threshold. If the voltage of the amplifier output pulse exceeds the discriminator threshold, the discriminator emits a logic pulse. Logic pulses are used for counting and control functions and have a fixed amplitude and width, usually 5 V and 1 μs in spectroscopy equipment. The threshold voltage is calibrated for its equivalent gamma-ray energy. When the discriminator output is connected to a scaler, the scaler counts all gamma rays that exceed the desired energy threshold.

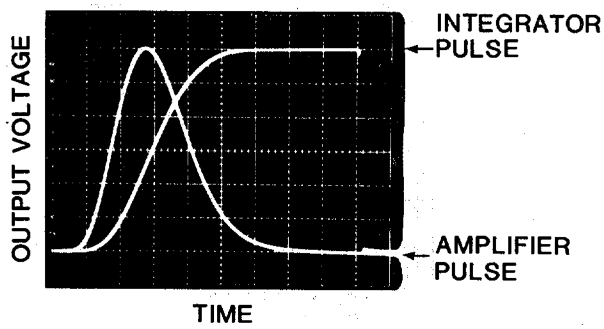

Fig. 4.11 *The regular output and gated-integrator output from an amplifier using gated integration to reduce the ballistic deficit at short time constants. The gated integrator permits good resolution and lower pileup and deadtime losses at high input rates.*

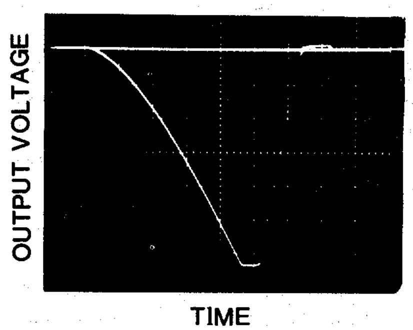

Fig. 4.12 *The output from a pulse processor using time-variant filters to shape preamplifier output pulses.*

An SCA is essentially two discriminators with independent thresholds. If the amplifier pulse amplitude exceeds the lower threshold and is less than the upper threshold, the SCA emits a logic pulse. If the SCA output is connected to a scaler, the scaler will count all gamma rays in a selected energy interval or channel. Figure 4.13 illustrates the function of the SCA.

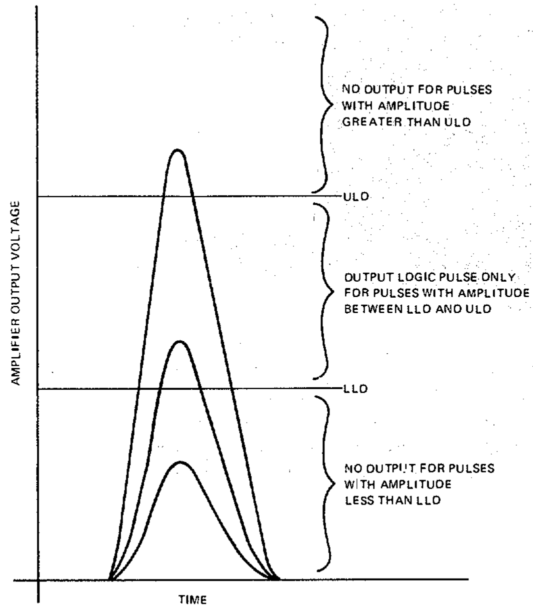

Fig. 4.13 *The function of a single-channel analyzer. (LLD is lower-level discriminator, ULD is upper-level discriminator.)*

The gamma-ray energy spectrum can be measured by setting a narrow window and taking a series of counts as the window is moved across the energy region of interest as a series of contiguous but nonoverlapping channels. The method is very tedious when the window is narrow and many counts must be taken. Before the advent of multichannel analyzers (MCAs), SCAs were used to measure gamma-ray spectra (see Figure 4.14). The technique was sometimes automated by adding a mechanical drive to the lower threshold control and a recording ratemeter to the SCA output.

The two SCA thresholds may be referenced to the same voltage, usually 0 V. If the upper threshold is referenced to the lower threshold voltage, the count window can be advanced through the spectrum by adjusting only the lower threshold control. Some SCAs can function as two independent discriminators, as an SCA with independent thresholds or as the window SCA just described. Some extract pulse-height information only, and others provide both pulse-height and timing information. Several procedures can be used to set the SCA window to the desired energy interval by gating an oscilloscope or MCA from the SCA output.

4.7 COUNTERS, SCALERS, TIMERS, AND RATEMETERS

The counter/timer shown in Figure 4.1 is the simplest part of the spectroscopy system; its function is to count the SCA output logic pulses.

The terms *counter* and *scaler* are usually used interchangeably. Before the advent of digital electronic displays such as light-emitting diodes and liquid crystal displays, electromechanical registers were used to indicate the number of pulses counted. The electromechanical registers were very slow and were often preceded by an electronic circuit that emitted a single logic pulse for a fixed number of input logic pulses; the "scaling" factor was often a power of 10. Historically, the term *scaler* was correctly applied to the electronic circuit that preceded an electromechanical register. Although mechanical registers are no longer used, the term scaler is often applied to counting instruments that have no timing or control capability. *Counter* is the preferred and more descriptive term. The term *timer* is usually applied to a separate instrument that measures time and can turn on one or more counters for a selected time interval. In the past, counters and timers were usually separate instruments; now the two functions are often combined in a single instrument, which may be called a *counter/timer* or, simply, a *counter*. A *ratemeter* measures the average pulse rate of the signal applied to its input and may be used in place of, or in conjunction with, a counter.

Modern counters operate at maximum count rates of approximately 2×10^7 count/s and can count two pulses separated by as little as 50 ns. Most counters have a capacity of six decimal digits; however, seven- and eight-digit counters are available. Although counters and timers usually have a visual display of the number of counts or seconds, counters without visual displays are available for applications that only require automatic readout to a computer or printer. Many counters provide an overflow logic pulse to indicate when the count capacity is exceeded. Some counters can be gated (turned on or off) by logic pulses from other control electronics. Other counter options include internal discriminators, printer and computer interfaces, and the ability to count positive or negative input pulses.

Timers are counters that count a fixed frequency oscillator to determine the desired time interval. The reference time signal comes either from the ac line (60 Hz in the United States) or from an internal crystal-controlled oscillator. The line-frequency oscillator is less expensive and is adequate for all but the most demanding applications. If the frequency of the ac power line is averaged over a day, the accuracy of the line-frequency oscillator is very good. If intervals shorter than a day must be measured to better than 0.1%, a crystal-controlled oscillator should be used. Many counter/timer combinations can either count for a preset time or measure the time required to count a preset number of counts; the latter mode allows all measurements to have the same statistical precision.

In the past, all ratemeters were analog instruments that provided a current signal proportional to the average count rate. The rate-related signal was displayed on a meter and was available at an output connector to drive an optional chart recorder. All ratemeters offered a choice of time constants to select how rapidly the instrument responded to count-rate changes. Linear and logarithmic scales were available, and some units gave an audible alarm if the count rate exceeded a preset limit. Modern ratemeters may be either analog or digital instruments. A digital ratemeter is a counter/timer that automatically resets and repeats a count; the count time is often set to 1 s so that the digital display shows the number of counts per second. The visual

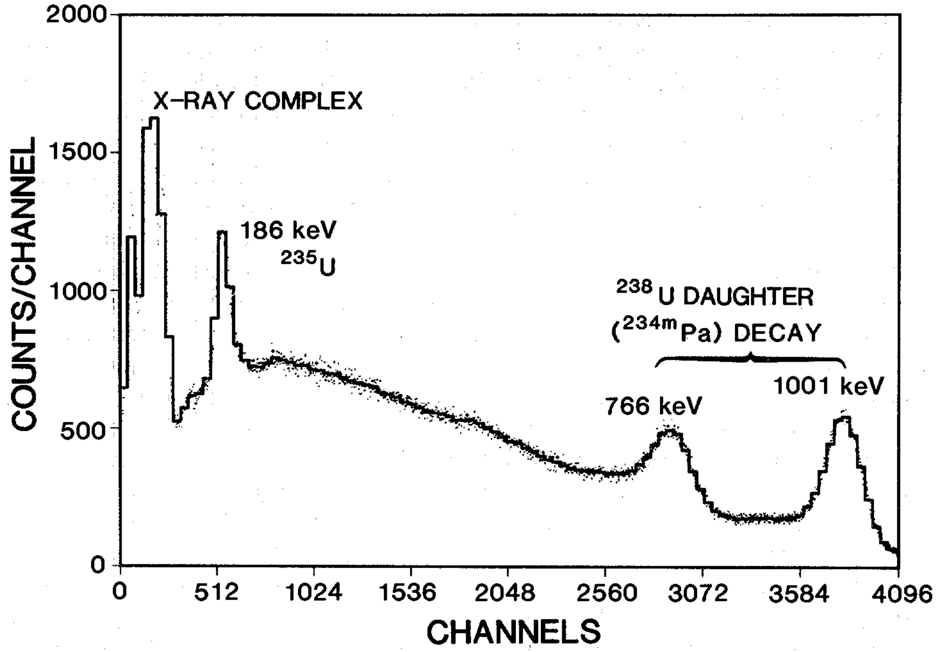

Fig. 4.14 *The gamma-ray spectrum of highly enriched uranium measured with a high-quality NaI detector. The points show a 4096-channel MCA spectrum and the histogram shows a 100-channel SCA spectrum. The total number of counts in both spectra is the same; therefore, the precision of an individual point in the 4096-channel spectrum is only about one-sixth that of a corresponding bar in the 100-channel spectrum. The vertical scales of the two spectra have been normalized.*

display of a digital ratemeter is far more readable than the meter display of an analog ratemeter. A digital ratemeter is often used to measure the total rate of gamma-ray pulses coming from the system amplifier. Because the total count rate has an important effect on system performance, the count rate is often monitored continuously.

4.8 MULTICHANNEL ANALYZER

The functions listed inside the dashed line in Figure 4.2 are usually performed by a multichannel analyzer (MCA) operating in the pulse-height-analysis mode. The terms multichannel analyzer and pulse-height analyzer (PHA) are often used interchangeably. The MCA can operate in several modes, including pulse-height analysis, voltage sampling, and multichannel scaling. It sorts and collects the gamma-ray pulses coming from the main amplifier to build a digital and visual representation of the pulse-height spectrum produced by the detector.

4.8.1 Analog-to-Digital Converter

The analog-to-digital converter (ADC) performs the fundamental pulse-height analysis and is located at the MCA input. The ADC input is the analog voltage pulse from the main amplifier; its output is a binary number that is proportional to the amplitude of the input pulse. The binary output number is often called an address. Other MCA circuits increment a storage register in the MCA memory that corresponds to the ADC address. The ADC performs a function that is analogous to that of the oscilloscope user saying "five volts" when a 5-V pulse is applied to the oscilloscope input terminals. The ADC accepts pulses in a given voltage range, usually 0 to 8 or 10 V, and sorts them into a large number of contiguous, equal-width voltage bins, or channels. Because of the sorting function, the early MCAs were often called kicksorters, with the amplifier pulse being compared to an electrical kick.

The number of channels into which the voltage range is divided is usually a power of 2 and is called the ADC conversion gain. In the mid 1950s a high-quality ADC could divide 100 V into 256 channels. Now, ADCs routinely divide 10 V into as many as 16 384 channels. This capability is impressive; an individual channel is only 0.6 mV wide. The required conversion gain varies with detector type and with the energy range being examined. Figure 4.15 shows part of an 8192-channel plutonium spectrum measured with a high-resolution germanium detector. The full-energy peaks should contain enough channels to clearly define the structure of the spectrum. As few as five channels may suffice for some situations. When peak fitting is required, 10 or more channels are needed to clearly define peak shape.

The ADC sorts the amplifier output pulses according to voltage; the voltage is proportional to the energy deposited in the detector during the gamma-ray interaction. Like the relationship between voltage and energy, the relationship between channel number and energy is nearly linear. The relationship can be represented by Equation 4-1:

$$E = mX + b \tag{4-1}$$

where E = energy in keV
X = channel number
m = slope in keV/channel
b = zero intercept in keV.

The slope m depends on the conversion gain and the amplifier gain; common values are 0.05 to 1.0 keV/channel. Although it may seem logical to assume that zero energy corresponds to channel zero (b = 0), this is often not the case. The slope and zero intercept can be adjusted to fit the energy range of interest into the desired channel range. For example, plutonium measurements often use gamma rays in the 60- to

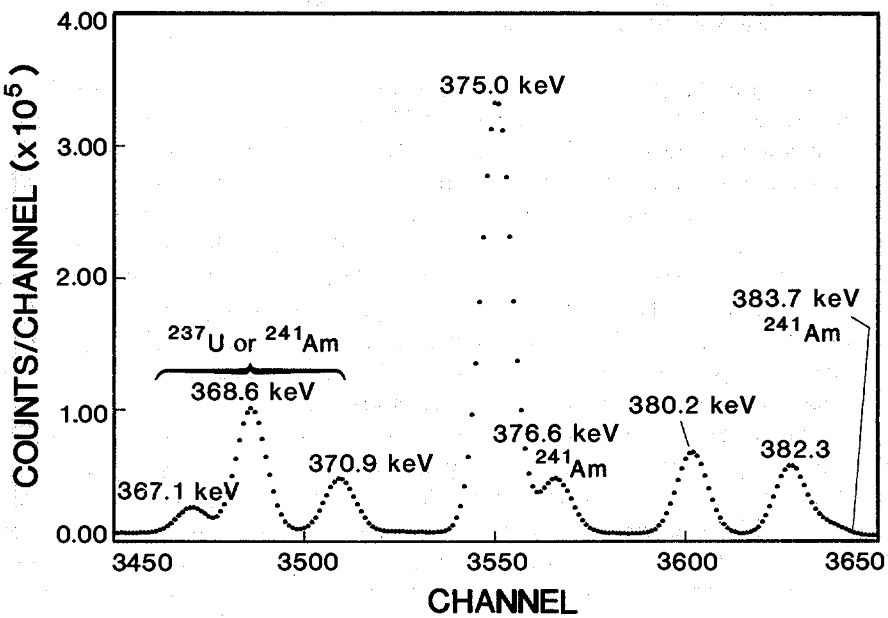

Fig. 4.15 A small portion of an 8192-channel plutonium spectrum taken with a high-quality coaxial germanium detector. The major peak is the 375.0-keV peak from ^{239}Pu decay.

420-keV range. If the gains are adjusted to 0.1 keV/channel and the zero intercept to 20 keV, a 4096-channel spectrum covers the 20- to 429.6-keV energy range and includes the important gamma ray at 413.7 keV. In the example, the channel number can be converted easily to energy. Most ADCs have both analog and digital controls to adjust the zero intercept. The analog control is labeled baseline or zero adjustment, and the digital control is labeled digital offset.

Because preamplifiers, amplifiers, and ADCs are not exactly linear, the relationship shown in Equation 4-1 between energy and channel number is not exact. However, with good equipment, gamma-ray energies can be readily measured to a tenth of a keV by assuming a linear calibration. ADC linearity is usually specified with two numbers: integral and differential linearity. Integral nonlinearity is a slight curvature in the relationship between energy and channel number; differential nonlinearity is a variation in channel width. It is difficult to design an ADC that does not have differential nonlinearity. Often, adjacent channels have measurably different widths, as can be seen when all even-numbered channels have more counts than all odd-numbered channels in a flat region of the spectrum. Such odd-even effects are common and may affect alternate groups of two, four, or even eight channels. A common ADC problem that can influence assay results is a slow increase of the differential nonlinearity over time. The 1% differential nonlinearity of most ADCs is totally acceptable for most applications.

Two types of ADC are in common use: the Wilkinson and the successive-approximation ADC. A Wilkinson ADC counts pulses from a fast oscillator for a time interval that is proportional to the amplitude of the amplifier pulse. The digitization time determines the channel number assigned to each pulse. A successive-approximation ADC examines the amplifier pulse with a series of analog comparators. The first comparator determines whether the pulse amplitude is in the upper or lower half of the ADC range. Each successive comparator determines whether the pulse amplitude is in the upper or lower half of the voltage interval determined by the previous comparator. Twelve comparators determine the pulse amplitude to one part in 2^{12} (or 4096) channels. The digitization time of a successive-approximation ADC is constant and independent of pulse height. Until recently, Wilkinson ADCs dominated the gamma-ray spectroscopy field because they had superior differential linearity. Now, successive-approximation ADCs have comparable differential linearity and are becoming more popular because they are often faster than Wilkinson ADCs.

ADC speed is an important consideration for high-count-rate spectroscopy. While the ADC is processing one pulse, all other pulses are ignored. The pulse processing time, or deadtime, can be a substantial fraction of the total acquisition time. A deadtime of 25% means that 25% of the information in the amplifier pulse stream is lost. For both ADC types, the deadtime per event is the sum of the digitization time and a fixed processing time (usually 2 to 3 μs). The 450- to 100-MHz oscillators used in Wilkinson ADCs require 12 to 43 μs to digitize and store a gamma-ray event in channel 4000. Successive-approximation ADCs (4096 channels) require 4 to 12 μs to analyze a gamma-ray event. A detailed comparison of ADC speed requires specification of the gamma-ray energy spectrum, the overall system gain, and the ADC range. In general, successive-approximation ADCs are faster than Wilkinson ADCs for spectra with 4096 channels or more. For spectra with few channels, the Wilkinson ADC may be faster. In a spectrum with an average channel number of 512, a 400-MHz Wilkinson ADC has a average deadtime per event of 3 μs.

Several common features appear on most ADCs independent of type or manufacturer. Lower-level discriminators (LLD) and upper-level discriminators (ULD) determine the smallest and largest pulses accepted for digitization. The discriminators can be adjusted to reject uninteresting low- and high-energy events and reduce ADC deadtime. The discriminator adjustment does not affect the overall gamma-ray count rate and cannot be used to reduce pulse pileup losses that occur in the detector, preamplifier, and amplifier. The discriminators form an SCA at the input to the ADC; most ADCs provide an SCA output connector. Most ADCs have coincidence and anticoincidence gates that allow external logic circuits to control the ADC. Pileup rejection circuits frequently provide an inhibit pulse that is fed to the anticoincidence gate to prohibit processing or storage of pileup pulses. The coincidence gate is also used to analyze gamma-ray events that are detected in two separate detectors. Most

ADCs have an adjustable conversion gain and range; the range control determines the maximum channel number to be digitized. There is usually a deadtime indicator that displays fractional deadtime. In computer-based MCAs, the ADC parameters often can be set under program control. Most small MCAs have a built-in ADC; large MCA systems use separate NIM or rack-mounted ADCs.

4.8.2 Spectrum Stabilizers

For germanium and silicon detectors, the relationship of energy and channel number changes with time even though the energy-to-charge-collection factor is constant. The preamplifier, amplifier, and ADC are all subject to small but finite changes in gain and zero level caused by variation in temperature and count rate. Under laboratory conditions, the position of a full-energy peak at channel 4000 may shift only a few channels over a period of many weeks; however, even this small drift may be undesirable. Larger drifts may be encountered in the uncontrolled environment of production facilities. Spectrum stabilizers are electronic modules that fix the position of one or more full-energy peaks by adjusting a gain or dc level in the spectroscopy system to compensate for drift; they are especially recommended for gamma-ray spectroscopy systems that must be operated in uncontrolled environments by unskilled operators (as often required by routine production-plant assay systems). Stabilizers are also recommended whenever channel-summation procedures are used to determine full-energy peak areas.

The spectrum stabilizers used with germanium and silicon detectors are usually digital circuits connected directly to the ADC. The stabilizer examines each gamma-ray-event address generated by the ADC and keeps track of the number of counts in two narrow windows on either side of a selected full-energy-peak channel. The stabilizer generates a feedback signal for the ADC that is proportional to the difference in the number of counts in the two windows. The feedback signal adjusts the ADC gain or zero level so that the average number of counts in each window is the same; the adjustment fixes the position of the selected stabilization peak. Often two peaks are stabilized independently: a peak at the high-energy end of the spectrum is used to adjust ADC gain and another peak at the low-energy end is used to adjust the ADC zero level. With two-point stabilization, the spectroscopy system stability is often so good that no spectral peak shifts position by more than a tenth of a channel over a period of many months. Digital stabilizers can be used to easily establish simple and convenient energy calibrations (for example, $E = 0.1X$).

Stabilization peaks should be free from interference, adequately intense, and present at all times. Often one of the stabilization peaks comes from a gamma-ray source that is attached to the detector to provide a constant signal in the detected spectrum. Usually, such a stabilization source is monoenergetic and provides the low-energy stabilization peak so that its Compton continuum does not interfere with other gamma-ray peaks of interest. In some cases, a very stable pulser may be connected to the test input of the preamplifier to provide an artificial stabilization peak. Peaks from pulsers or special stabilization sources may also be used to provide corrections for pulse-pileup and deadtime losses (see Chapter 5).

Digital stabilization is not available for all ADCs and it is frequently unavailable for portable MCAs and successive-approximation ADCs. Digital stabilizers are normally single- or double-width NIM modules. All stabilizers have controls to set the desired peak-centroid channel number and the width of the stabilization peak windows; there is often a control to set the stabilizer sensitivity. Digital stabilizers that can be controlled by an external computer are now available; this feature is useful when stabilization peaks must be changed during automatic assay procedures.

Digital stabilizers that have a small correction range are inadequate for use with NaI detectors. In addition, digital stabilizers operate with an ADC and many NaI detector systems use SCAs to acquire the desired spectral information. Because of the relatively greater instability of scintillator/photomultiplier detectors (as large as 1 to 2%/°C), spectrum stabilization is often more necessary for NaI detectors than it is for germanium or silicon detectors.

Scintillation detector stabilizers are similar to digital stabilizers but operate with the amplifier rather than the ADC. The stabilizer compares the count rate on either side of the selected stabilization peak and generates a feedback signal that adjusts the amplifier gain to keep the two count rates equal. NaI stabilizers are packaged as NIM modules and may consist of amplifier/stabilizer combinations or separate stabilizers. When a suitable stabilization peak is not available in the NaI spectrum, a pulser peak cannot be substituted because it can only correct for preamplifier and amplifier instability; the major drift in a NaI system occurs in the photomultiplier tube. Although an external gamma-ray source can provide a stabilization peak, the Compton background from the source can interfere excessively with the gamma rays of interest. An alternative solution is to use a detector with a built-in light pulser. NaI crystals can be grown with a small doping of an alpha-particle-emitting nuclide like ^{241}Am. The alpha-particle interactions in the crystal provide a clean spectral peak with a fixed rate and gamma-ray-equivalent energy. Because the temperature dependences of alpha-particle-induced and gamma-ray-induced scintillation light are not identical, accurate stabilization over a large temperature range may require special temperature compensation circuitry.

4.8.3 Multichannel Analyzer Memory, Display, and Data Analysis

After the ADC converts the amplifier voltage pulse to a binary address, the address must be stored for later observation and analysis. All MCA systems have memory reserved for spectrum storage, and most have a spectral display and some built-in data analysis capability.

Although the most common memory size is 4096 channels, MCAs are available that have other memory sizes such as 1024, 8192, or 16 384 channels. The smaller memory size is adequate for NaI detector applications and for germanium or silicon detector applications that involve a small energy region. To have sufficient channels in a full-energy peak, an overall system gain of 0.1 keV/channel is often required; however, with this gain, a 1024-channel MCA can only collect data in a 100-keV-wide region. Large MCA systems usually can accept data from several ADCs simultaneously. A 16 384-channel MCA can collect four 4096-channel spectra simultaneously. For multiple ADC applications, MCAs are available with as many as 65 536 channels.

The maximum number of counts that can be stored per channel is often an important consideration because it sets a limit on the precision that can be obtained from a single measurement. Early transistorized MCAs often had a maximum capacity of 65 536 counts per channel. The present standard is typically 10^6 counts per channel, however large MCAs are available with capacities of 1.6×10^7, 2.56×10^8, and even 4×10^9 counts per channel. (The last number quoted is probably more than will ever be required in any anticipated application.) Although the present standard of 10^6 counts per channel is adequate for many low-rate applications, it is a definite limitation for applications involving high-precision measurement of high-activity samples. The limitation is especially apparent when both strong and weak peaks must be measured in a single spectrum, as is the case for many plutonium measurements. The count time must be chosen so that the strongest peak of interest does not overflow the channel capacity; unfortunately this count time may provide unacceptably low precisions for the weaker peak areas, with the result that multiple measurements are required. The intended application must be considered carefully when deciding the MCA memory-size and count-capacity requirements.

A quick and useful way to obtain qualitative and semiquantitative information from a spectrum stored in memory is to look at a plot of channel content versus channel number. Most MCAs have a spectral display and many offer a wide range of display options. All displays offer several vertical and horizontal scale factors and many offer both linear and logarithmic scales. Most displays have one or two cursors (visual markers) that can be moved through the spectrum; the channel number and contents of the cursor locations are displayed numerically on the screen. Most MCAs can intensify selected regions of interest or change the color of the regions of interest to emphasize particular spectral features. A good MCA can display two or more spectra simultaneously and can overlap spectra for careful visual comparison.

Until recently, most MCA displays used cathode-ray tubes with electrostatic deflection. Electrostatic deflection is easily used only for small screen displays, up to approximately 15 by 15 cm. At present, most MCAs use magnetic deflection to allow larger screen size; the display is identical to a television display. Some displays are multicolored, but most are still monochromatic. In either type, each channel is represented by a dot or bar whose vertical height is proportional to the channel contents. Liquid crystal displays are just coming into use, mostly for low-power applications in portable MCAs.

Big-screen, magnetically deflected displays are economical and make an excellent picture but have one annoying drawback. The horizontal oscillator in the magnetic-deflection circuit generates bursts of electromagnetic interference at a frequency of approximately 16 kHz; the interference is easily picked up on preamplifier signal lines and can cause significant degradation of spectral quality. Great care must be taken in grounding, shielding, and routing signal cables to eliminate or minimize the problem. The video terminals usually used with large MCA/computer systems generate similar interference; all signal cables should be routed well away from the terminals.

Most large MCAs have some built-in data analysis functions. Common analysis functions determine the channel position and width of spectral peaks, the energy calibration, the number of counts in selected regions of interest, and the full-energy peak areas. Other available functions may include smoothing, normalizing, and subtracting (stripping) a background spectrum. The numerical results are usually displayed on the screen or printed on the system terminal. The functions are usually implemented by microprocessors that execute codes from read-only memory.

Large MCAs are frequently interfaced to external computers that can control complete assay systems and execute complex analysis codes. The computer system usually includes one or more mass storage devices such as hard or flexible disks that provide storage for spectral data and analysis programs. The last link in the spectroscopy chain is often a printer that provides hard-copy output of measurement results.

4.9 AUXILIARY ELECTRONIC EQUIPMENT

Figures 4.1 and 4.2 show only the basic components of gamma-ray spectroscopy systems. This section describes other instruments that may be used in addition to the basic components.

The oscilloscope is the most useful auxiliary instrument used with gamma-ray spectroscopy systems. It is virtually indispensable when setting up the spectroscopy system for optimum performance, monitoring system performance, detecting malfunctions or spurious signals, and correcting problems. An expensive oscilloscope is not required; a 50-MHz response, one or two vertical inputs, and an ordinary time base are usually quite adequate. Battery-powered portable oscilloscopes can easily be carried to systems in awkward locations.

Electronic pulsers are used to test system performance and correct for deadtime and pileup losses. Mercury-switch pulsers have excellent pulse amplitude stability but are quite slow and have limited pulse-shape variability. Other electronic pulsers often have high-repetition rate and very flexible pulse shaping but usually have neither great amplitude nor frequency stability. A few pulsers provide random intervals between pulses rather than the more common fixed intervals. Sliding pulsers are used to test ADC linearity; their pulse amplitude is modulated linearly with time.

Cameras are often used to take pictures of MCA and oscilloscope displays. Pictures of waveforms help to document and diagnose problems; pictures of spectra provide a quick and useful way to record information in a notebook. Cameras are available with the necessary adapters to couple them to most oscilloscopes and MCAs. A Polaroid-type film is usually used so that the pictures can be developed quickly.

Many different instruments are available to provide information on gamma-ray pulse timing, usually to establish temporal relationships between two or more detectors. Timing-filter amplifiers sacrifice signal-to-noise performance and overall resolution to preserve timing information. Other instruments examine the preamplifier output, the bipolar output of the main amplifier, or the output of a timing-filter amplifier and they generate a fast logic signal that has a fixed and precise temporal relationship to the gamma-ray events in the detector. The timing is determined using techniques such as fast leading-edge discrimination, constant-fraction discrimination, amplitude/risetime compensation, and zero-crossover pickoff. The timing outputs are either counted or presented to coincidence circuits that determine whether specified time relationships are met by the events in two or more detectors. Depending on the type of detector, the coincidence gates can be as narrow as a few nanoseconds. The logic output of a coincidence circuit is either counted or used as a control signal. When more detailed timing information is required, a time-to-amplitude converter can be used to generate an output pulse whose amplitude is proportional to the time interval between input pulses.

A linear gate can be used as a coincidence or control circuit at the input to an MCA. Linear gates pass analog signals with no change in amplitude or shape if they are gated by control signals that are derived from one of the timing circuits described above. A linear stretcher generates a pulse with the same amplitude as the input pulse but with an adjustable length. A stretcher is occasionally used to condition the amplifier signal before subsequent processing in the ADC. Summing amplifiers, or mixers, produce outputs that are the linear sum of two or more input signals. A mixer can be used in connection with routing signals for collecting spectra from several detectors with a single ADC.

Compton suppression, a common procedure that improves the quality of gamma-ray spectra, uses some of the timing circuits described above. A Compton-suppression spectrometer usually includes a high-resolution detector that is surrounded by a low-resolution, annular detector. The scattered gamma ray from a less-than-full-energy interaction in the high-resolution detector is often detected in the annular detector. A coincidence event between the two detectors inhibits the storage of the high-resolution event in the MCA and reduces the Compton continuum between the full-energy peaks.

4.10 CONCLUDING REMARKS

The instrumentation described in this chapter can be assembled to form different gamma-ray spectroscopy systems for different NDA applications. Many instrument manufacturers can provide integrated spectroscopy systems that include all components from the detector to the output printer. If the user has sufficient expertise, individual components can be procured from different manufacturers. In either case, careful consideration must be given to the requirements of the measurement application before selecting a spectroscopy system from the nearly endless array of options and configurations. References 1 through 4 provide detailed descriptions of the function and operation of gamma-ray spectroscopy instrumentation. For the user who is not active in gamma-ray spectroscopy, current information is best obtained from research reports, the commercial literature, and the developers and users of state-of-the-art instrumentation.

Gamma-ray assay systems that are dedicated to a particular operation can be very simple to operate. On the other hand, vast versatility and flexibility are provided by combining the appropriate detector, amplifier, MCA, and analysis capability to make a large, modern gamma-ray spectroscopy system. Unfortunately, a complex, versatile instrument can never be truly simple to operate; a labor of several weeks is usually required to master the operation of the typical large system. However, the effort required is usually readily exerted in order to use instruments of truly amazing power. The power of modern gamma-ray spectroscopy systems is perhaps best appreciated by those who remember from personal experience when all spectral measurements were done with a NaI detector, an SCA, and a counter.

Gamma-ray spectroscopy equipment has improved rapidly over the past 25 years as vacuum tubes were replaced by transistors and transistors were replaced by integrated circuits. The microprocessor chip has put greater capability into smaller and smaller volumes. The capability per dollar has increased in spite of inflation. The rate of improvement is still significant, particularly in the capability and flexibility of MCA memory, display, and data analysis. Spectral quality is not progressing as rapidly, although improvement is still occurring in pulse-processing electronics, especially in dealing with very high counts rates (up to 10^6 count/s) from high-resolution germanium detectors. The technology of NaI, germanium, and silicon detectors is quite mature and major improvements are not expected. Still, steady progress in all areas of gamma-ray spectroscopy technology will continue, and unexpected breakthroughs may indeed occur.

REFERENCES

1. G. F. Knoll, *Radiation Detection and Measurement,* second edition (John Wiley & Sons, Inc., New York, 1988).
   This book deals with all types of radiation detectors and associated electronics, including high-resolution gamma-ray spectroscopy systems. The treatment is very broad, with good qualitative explanations and many figures. There are many mathematical formulas and some derivations, but the book is very readable. This is probably the best single reference on gamma-ray spectroscopy equipment.

2. P. W. Nicholson, *Nuclear Electronics* (John Wiley & Sons, Inc., New York, 1974).
   This book is an extensive treatise on the electronics associated with high-resolution detectors. Detailed descriptions are given of detector preamplifiers, pulse shaping, rate-related losses, pulse-height analysis, and spectral resolution.

3. F. Adams and R. Dams, *Applied Gamma-Ray Spectroscopy* (Pergamon Press, Oxford, 1970).
Although older than Reference 1, this work provides a comprehensive coverage of gamma-ray spectroscopy. Information is available on NaI and germanium detectors and the accompanying instrumentation.

4. W. J. Price, *Nuclear Radiation Detection*, 2nd ed. (McGraw-Hill Book Co., New York, 1964).
Although older and of more limited scope than the three preceding references, this book gives useful alternative descriptions of the detection process and the functions of the electronic equipment. It also gives a glance at detectors and analysis methods that are now rarely used and provides an interesting view of spectroscopy equipment at the time when transistors were starting to replace vacuum tubes.