GAMMA SPECTROSCOPY - OVERVIEW

The Identification of Gamma Emitting Radionuclides

6/1/2011

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General

Direct Gamma Spec Analysis of Radionuclides

- Radionuclides must emit gamma rays to be analyzed directly by gamma spectroscopy

- Gamma rays are like fingerprints: they have specific energies that can be used to identify the radioactive material.

- The next two slides show a somewhat random selection of common gamma emitting radionuclides.

- Many of these nuclides emit gamma rays at many different energies. Only the most important gamma rays are shown.

General

Direct Gamma Spec Analysis of Radionuclides

Radionuclide	Gamma Ray Energy (keV)	Gamma Intensity
Na-22	1274.5	1.0
	511.0 (annihilation)	1.8
K-40	1460.8	0.11
Cr-51	320.1	0.098
Co-57	122.1	0.855
Fe-59	1099.2	0.565
	1291.6	0.432
Co-60	1173.2	1.0
	1332.5	1.0
Zn-65	1115.5	0.507
Ga-67	93.3	0.357
	300.2	0.16
Mo-99	739.6	0.128

General

Direct Gamma Spec Analysis of Radionuclides

Radionuclide	Gamma Ray Energy (keV)	Gamma Intensity
Tc-99m	140.5	0.89
Cd-109 (Ag-109m)	88.0	0.037
I-131	364.5	0.81
Ba-133	356.0	0.60
Cs-134	604.7	0.976
	795.8	0.854
Cs-137 (Ba-137m)	661.6	0.85
Ir-192	316.5	0.829
Tl-201	167.4	0.10
Ra-226	186.2	0.036
U-235	143.8	0.1
	185.7	0.54
Am-241	59.5	0.36

General

Non-Gamma Emitting Radionuclides

- Radionuclides that do not emit gamma rays, or do so in a very small percentage of their decays (e.g., H-3, C-14, P-32, Sr-90, Pu-239) cannot be identified or quantified directly by gamma spectroscopy.

  In most cases, they must be analyzed by some other means, e.g., radiochemistry.

- However, if a ratio can be established between a gamma emitting nuclide and a non-gamma emitter, the latter can be analyzed indirectly by gamma spec.

General

Non-Gamma Emitting Radionuclides – Secular Equilibrium

- If a non-gamma emitter and a gamma emitting radionuclide are in secular equilibrium, their activities are equal (1:1 ratio).

- Secular equilibrium involves a long-lived parent (usually the non-gamma emitter) and a short-lived decay product (usually the gamma emitter).

- There can be several reasons why secular equilibrium might not exist, hence everyone involved in the analysis must agree with the assumption that the gamma emitter and non-gamma emitter are in equilibrium.

General

Non-Gamma Emitting Radionuclides – Secular Equilibrium

Example 1.

U-238, which does not emit gamma rays, can be quantified by measuring the activity of one of its short-lived gamma emitting decay products: Th-234 or Pa-234m.

U-238 (4.5 x 10^9 a) → Th-234 (24 d) → Pa-234m (1 min)

Th-234 emits 63 keV gammas in 3.7% of its decays.

Pa-234m emits 1001 keV gammas in 0.84% of its decays.

General

Non-Gamma Emitting Radionuclides – Secular Equilibrium

Example 2.

Th-232, which does not emit gamma rays, can be quantified by measuring the activity of its short-lived gamma emitting decay product Ac-228.

Th-232 (1.4 x 10^{10} a) → Ra-228 (5.75 a) → Ac-228 (6.1 h)

Ac-228 emits a 911 keV gamma in 28% of its decays.

The long time required for Ac-228 to grow into secular equilibrium from purified thorium-232 makes the assumption of equilibrium a little problematic.

General

Non-Gamma Emitting Radionuclides – Secular Equilibrium

Example 3.

Ra-226, which emits a 186 keV gamma that is impossible to distinguish from the 186 keV gamma ray of U-235, can be quantified by measuring the activity of its short-lived gamma emitting decay product Pb-214.

Ra-226 (1600 a) → Rn-222 (3.8 d) → Po-218 (3 min) → Pb-214 (27 min)

Pb-214 emits a 352 keV gamma in 37% of its decays.

Equilibrium is reached very quickly (ca. 1 month). A potential concern is the possible escape of the Rn-222 from the sample matrix.

General

Non-Gamma Emitting Radionuclides – Scaling Factor

- There are times when it is acceptable to make a less accurate determination of the non-gamma emitter activity, e.g., assaying low level waste.

  In this case, considerable uncertainty might be tolerated in the ratio (aka scaling factor) between the non-gamma emitter and the gamma emitter.

  The ratio just has to be "good enough."

- For example, the ratio might be derived from the known activities of the two nuclides that were used in a given process or facility.

General

Non-Gamma Emitting Radionuclides – Scaling Factor

- If the gamma emitter and non-gamma emitter are produced by the same process, it might be reasonable to assume ratio between them.

  For example:

  Radionuclides produced by fission such as the gamma emitter Cs-137 and Sr-90.

  Radionuclides produced by neutron activation such as the gamma emitter Co-60 and Fe-55.

- A somewhat different example: There is often a usable ratio between the gamma emitter Am-241 and Pu-239. Am-241 is a decay product of Pu-241 which is often present along with Pu-239.

General

Spectroscopy vs. Spectrometry

- A distinction is not always made between these two terms.

- Often the term gamma spec is used to cover both.

- When a distinction is made:

  Gamma spectroscopy refers to the process of using the energies of gamma rays to identify radionuclides

  Gamma Spectrometry refers to the process of using the number of emitted gamma rays to quantify the activity of the radionuclides.

General

Advantages of Gamma Spec (vs. radiochemistry)

- Less expensive when compared to radiochemistry

- Fast

- Multinuclide analysis. All the gamma emitters can be analyzed at once.

  A radiochemical analysis will be for one element only (e.g., U-234, U-235 and U-238)

- Non-destructive

- In some cases can be performed at a distance (remotely) in the field without the need for a sample.

General
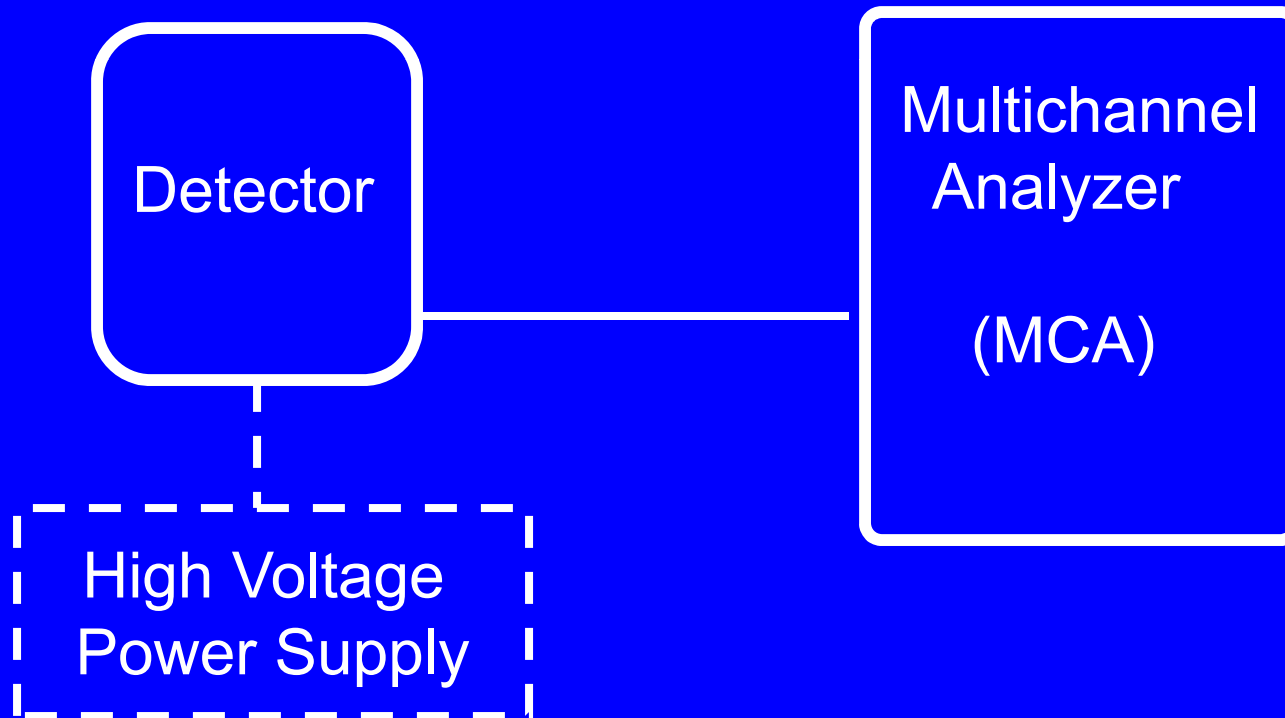
Disadvantages of Gamma Spec (vs. radiochemistry)

- Often less sensitive than radiochemistry, i.e., the MDCs for radiochemical analyses are usually lower than for gamma spectroscopy

- Usually requires larger sample masses than radiochemistry

Components of a
Gamma Spectroscopy System

Components of a Gamma Spectroscopy System

The Most Basic Components

1. Detector (and high voltage power supply)

2. Multichannel analyzer (MCA)

Detector

Multichannel Analyzer

(MCA)

High Voltage Power Supply

Components of a Gamma Spectroscopy System

Detector Types

- The most common (not the only) detectors in gamma spectroscopy systems:

    - Sodium Iodide (NaI)

    - Lanthanum Bromide (LaBr)

    - High Purity Germanium (HPGe)

- Of these, the HPGe is easily the best.

- A LaBr detector is generally preferable to a NaI detector.

Components of a Gamma Spectroscopy System
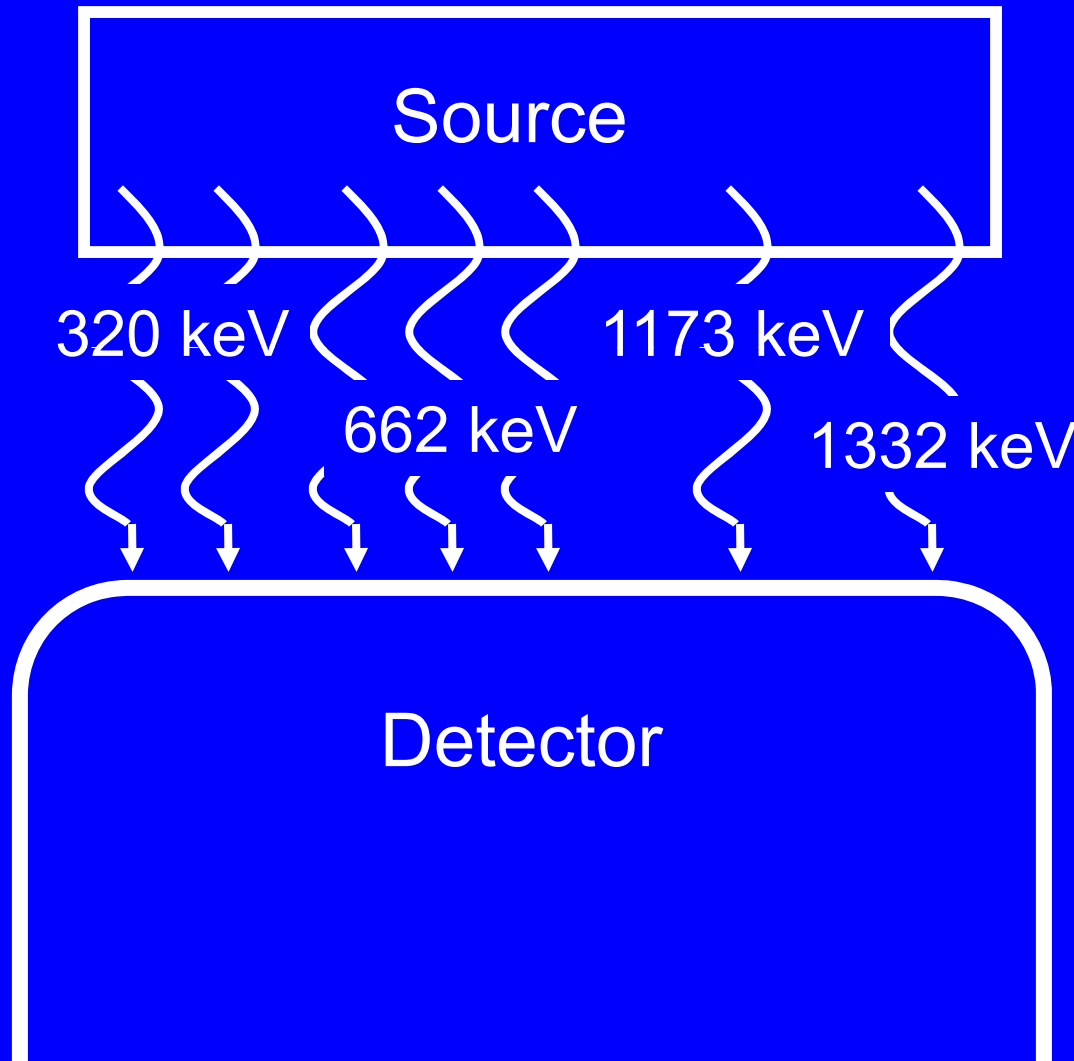
Two "Functions" of the Detector

1. A pulse is produced for each gamma ray interacting in the detector.

    A pulse is a short-term change in the voltage.

2. The greater the energy deposited in the detector, the larger the pulse.

Components of a Gamma Spectroscopy System

Two "Functions" of the Detector

Source

320 keV
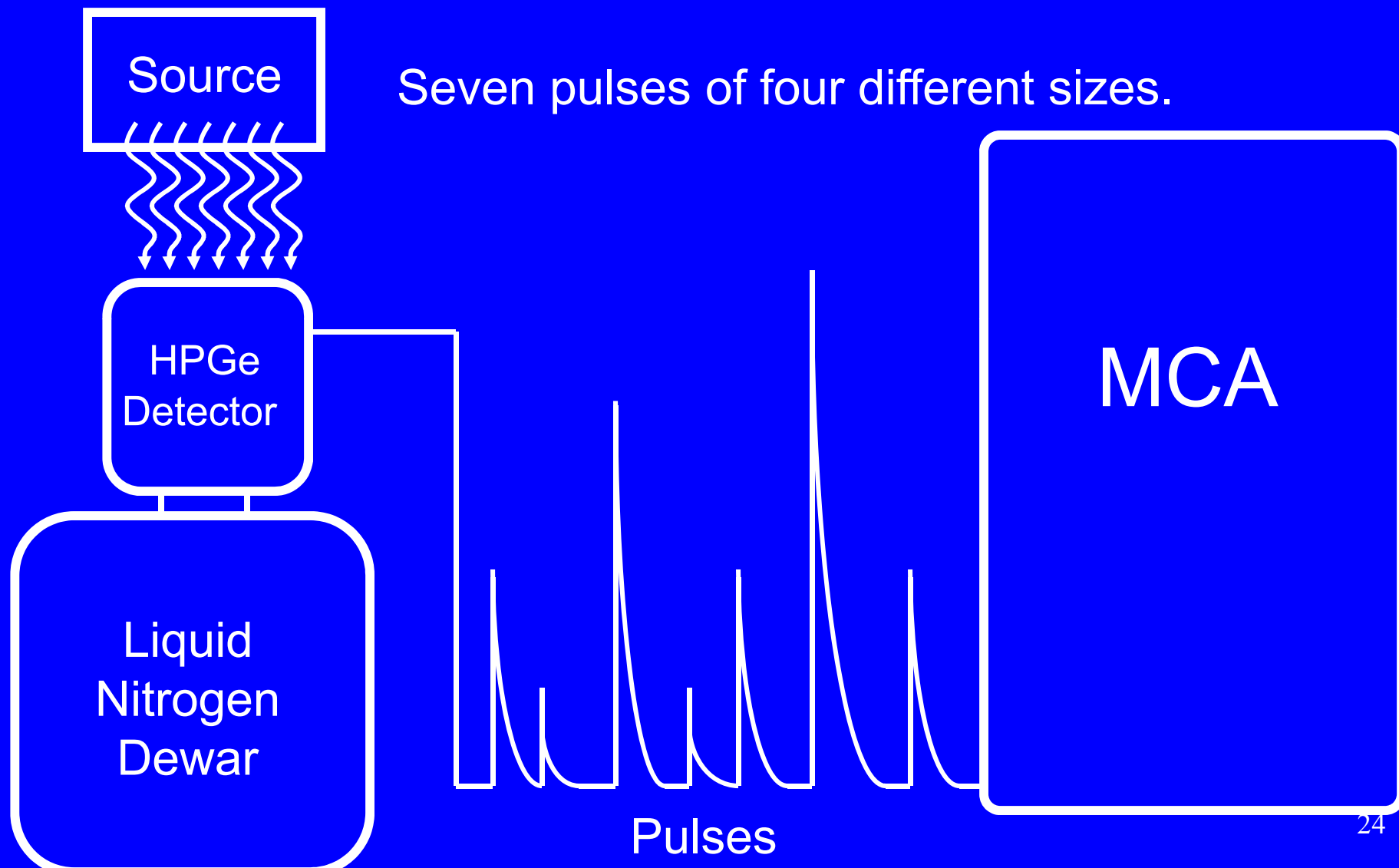
1173 keV

662 keV

1332 keV

Detector

How many pulses would the detector produce?

How many different pulse sizes would the detector produce (assume each gamma ray energy deposits all its energy in the detector) ?

Components of a Gamma Spectroscopy System

Two "Functions" of the Detector

Source

Seven pulses of four different sizes.

HPGe Detector

Liquid Nitrogen Dewar

MCA

Pulses

Components of a Gamma Spectroscopy System

Multichannel Analyzer

- The MCA contains most of the system's electronics.

- All of the MCA components (and possibly the detector as well) might be housed in a single stand-alone unit. In some cases, this might be a portable hand-held device.

- In the laboratory, the memory, display and analysis functions of the MCA are usually handled by a computer.

  The rest of the MCA's electronic components might be housed in a single "box" connected to the computer.

  In other cases, the MCA electronics might consist of several modules arranged in a NIM bin.

Components of a Gamma Spectroscopy System

Multichannel Analyzer

Stand-alone MCA
(old system)

MCA's hardware on
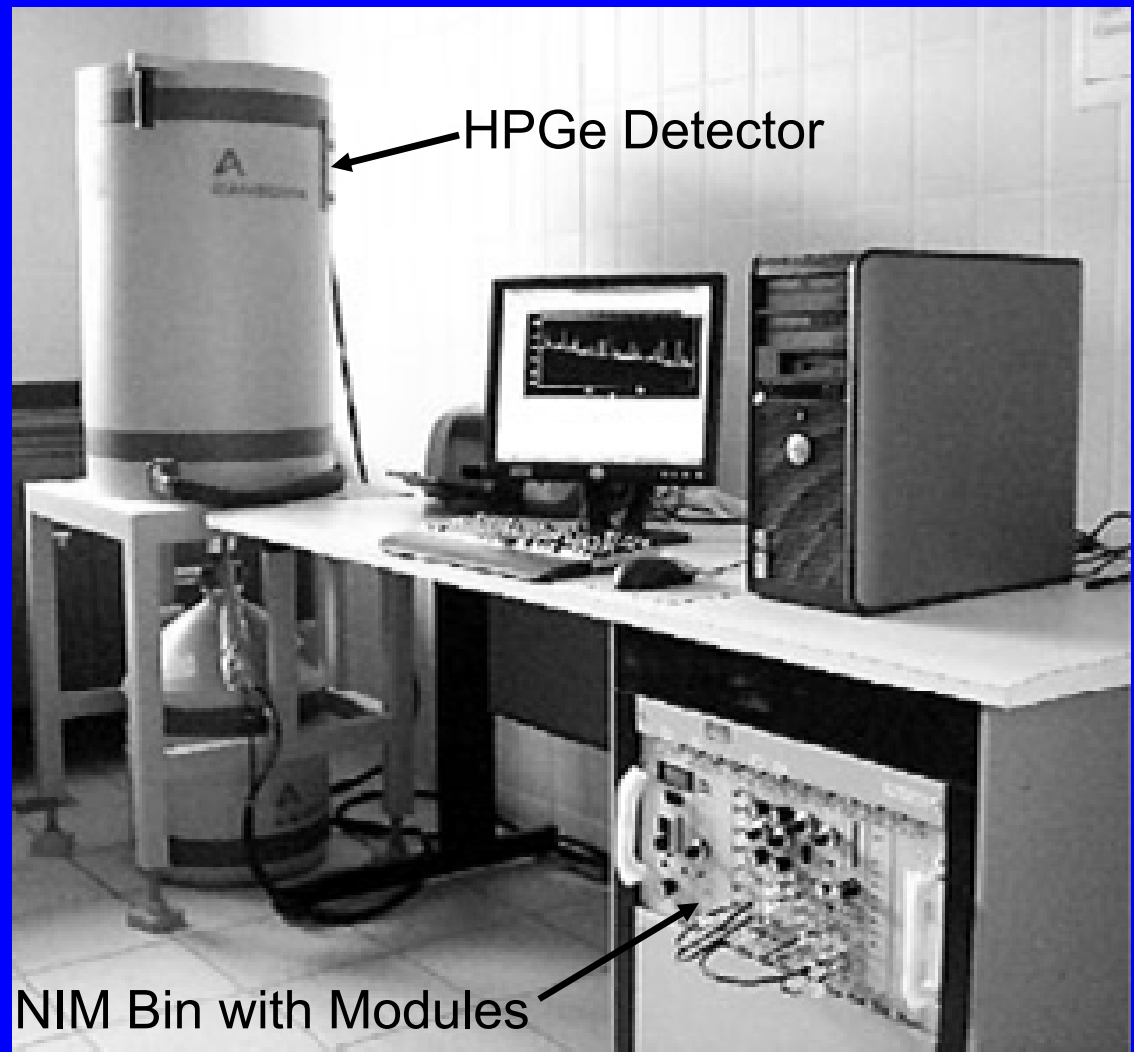computer circuit board
(old system design)

Components of a Gamma Spectroscopy System
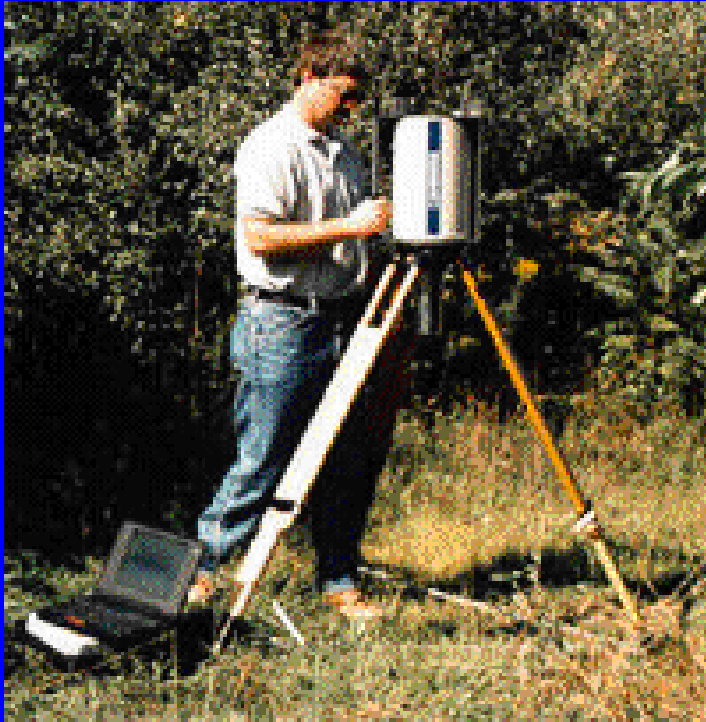
Multichannel Analyzer

Common laboratory setup.

MCA electronics consists of modules in external NIM Bin.

Computer stores, displays and analyzes the spectra.

HPGe Detector

NIM Bin with Modules

Components of a Gamma Spectroscopy System

Multichannel Analyzer

In-situ gamma spec. Identifying and quantifying gamma emitters in soil.

Portable hand-held gamma spectroscopy system with internal NaI detector.

Components of a Gamma Spectroscopy System

Two "Functions" of the MCA

1. Count the pulses from the detector.

   The number of pulses can be related to the activity of the radionuclides in the sample (gamma spectrometry).

2. Measure the size of the pulses (pulse height analysis).

   The height of the pulses can be related to the energy of the gamma rays. This is used to identify the radionuclides in the sample.

Components of a Gamma Spectroscopy System

Major Components of the MCA

- Amplifier

- ADC

- Memory

- Display

Components of a Gamma Spectroscopy System

Amplifier

- The amplifier increases the size of the pulses by a factor called the "gain."

- The gain determines the range of gamma ray energies that are seen on the spectrum.

  For example, a particular gain might result in a spectrum viewing gamma rays of 20 to 2000 keV.

  If higher energy gamma rays must be seen, the gain is lowered.

  The gain might be increased if only low energies are of interest.

Components of a Gamma Spectroscopy System

Amplifier

- The amplifier also changes the pulse shape. It shortens the long tails on the pulses coming from the preamplifier and rounds off their leading edge.

  In most cases the resulting amplifier output pulse is semi-Gaussian.

- This makes it easier to measure the height of the pulses.

- The amplifier also filters out electronic noise (random fluctuations in the baseline voltage.

Components of a Gamma Spectroscopy System

Analog to Digital Convertor

Information is of two types:

- Analog - Analog information has an infinite and continuous variety of values.

  Output pulses from the amplifier are analog.

- Digital - Digital information has discrete values (e.g., binary data). It is easier to store and manipulate digital data.

  Output pulses from the ADC are digital.

Components of a Gamma Spectroscopy System

Analog to Digital Convertor

- Pulse conversion is the process of turning the analog pulses into digital pulses.

- As it converts the pulses, the ADC sorts them into discrete size ranges called channels.

- The total number of channels (size categories) is known as the "conversion gain."

- Typical conversion gains:

       NaI detectors: 256, 512, 1024

       HPGe Detectors: 4096, 8K, 16K
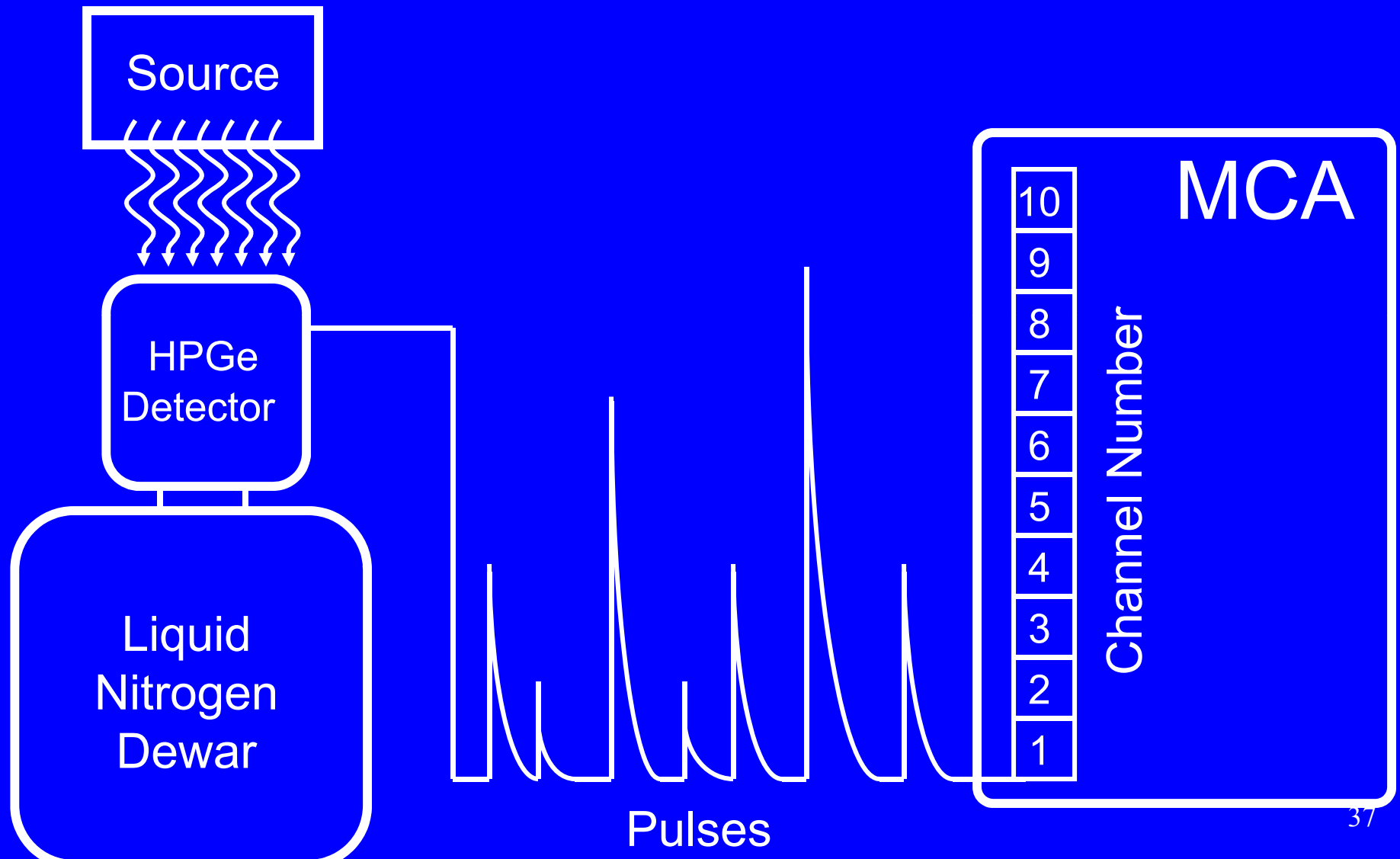
Pulse Height Analysis

Pulse Height Analysis

General

- The different types of ADCs measure the pulse heights in different ways.

- We will imagine that the ADC measures the size of the pulses with a ruler.

- The conversion gain is 10.

- Looking at the following figure, how many pulses will be sorted into each of the ten channels?

Pulse Height Analysis

General

Source

HPGe
Detector

Liquid
Nitrogen
Dewar

Pulses

MCA

Channel Number

10
9
8
7
6
5
4
3
2
1

Pulse Height Analysis

General

Channel Number	Number of Pulses
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	

Pulse Height Analysis

General

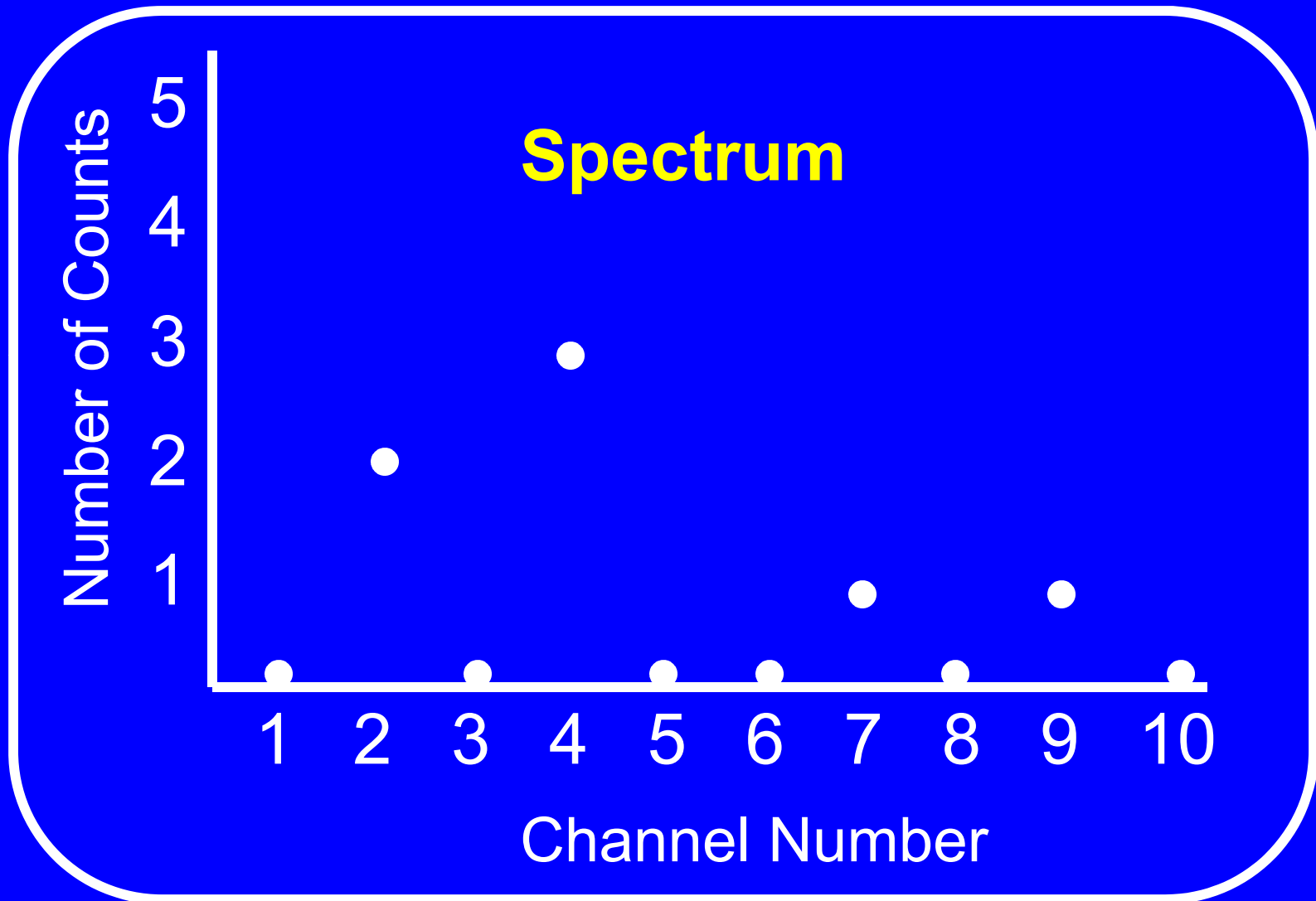| Channel Number	Number of Pulses
1	0
2	2
3	0
4	3
5	0
6	0
7	1
8	0
9	1
10	0

The Spectrum

The Spectrum

General

- The results of the ADC's analysis of the pulse sizes is stored in a memory.

- The contents of the memory are displayed on a LCD monitor or CRT.

- The display, known as the spectrum, shows the number of pulses (counts) as a function of pulse size (channel number).
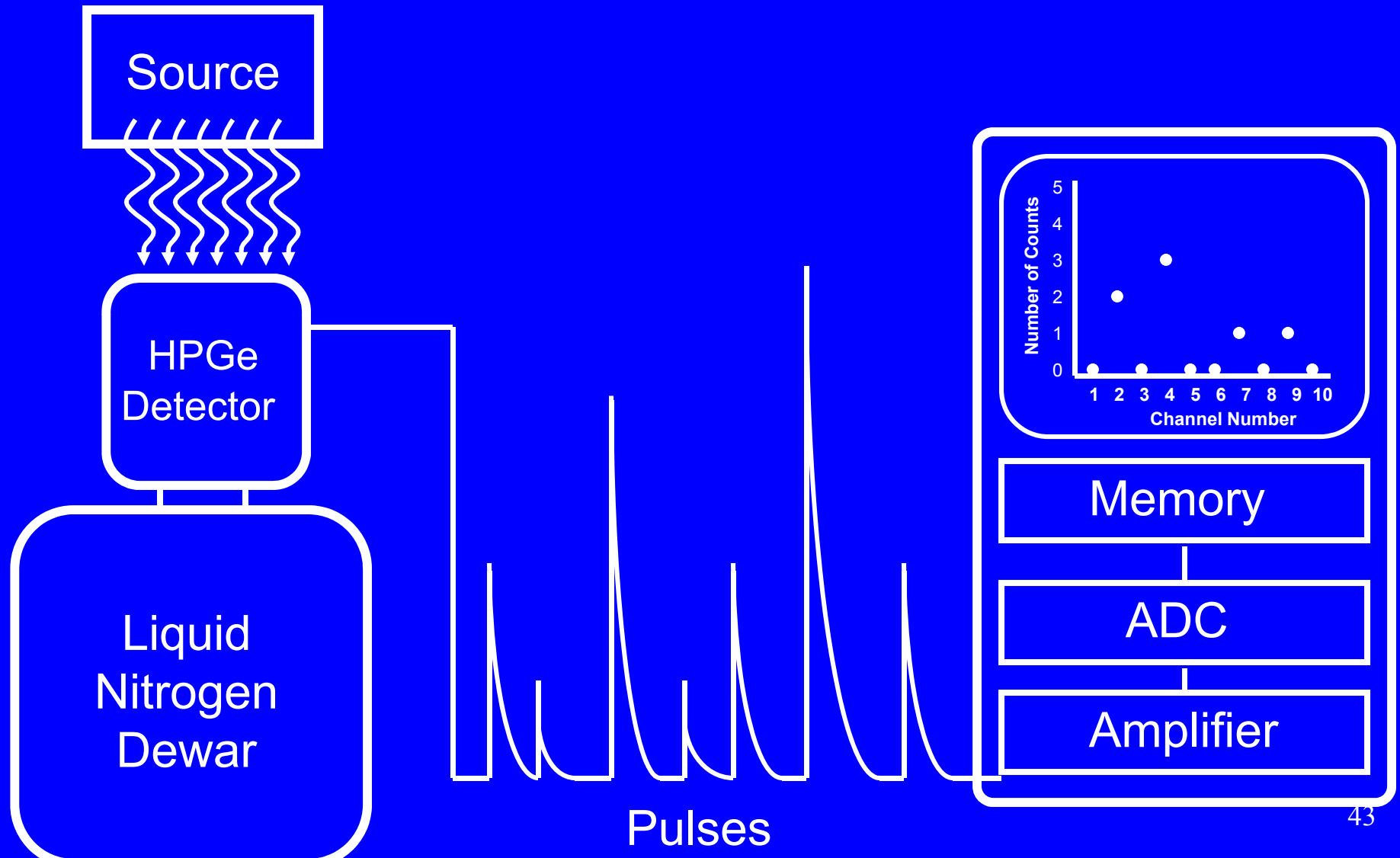
The Spectrum

General

The Spectrum

The Big Picture

Source

HPGe Detector

Liquid Nitrogen Dewar

Pulses

Memory

ADC

Amplifier

Number of Counts

Channel Number
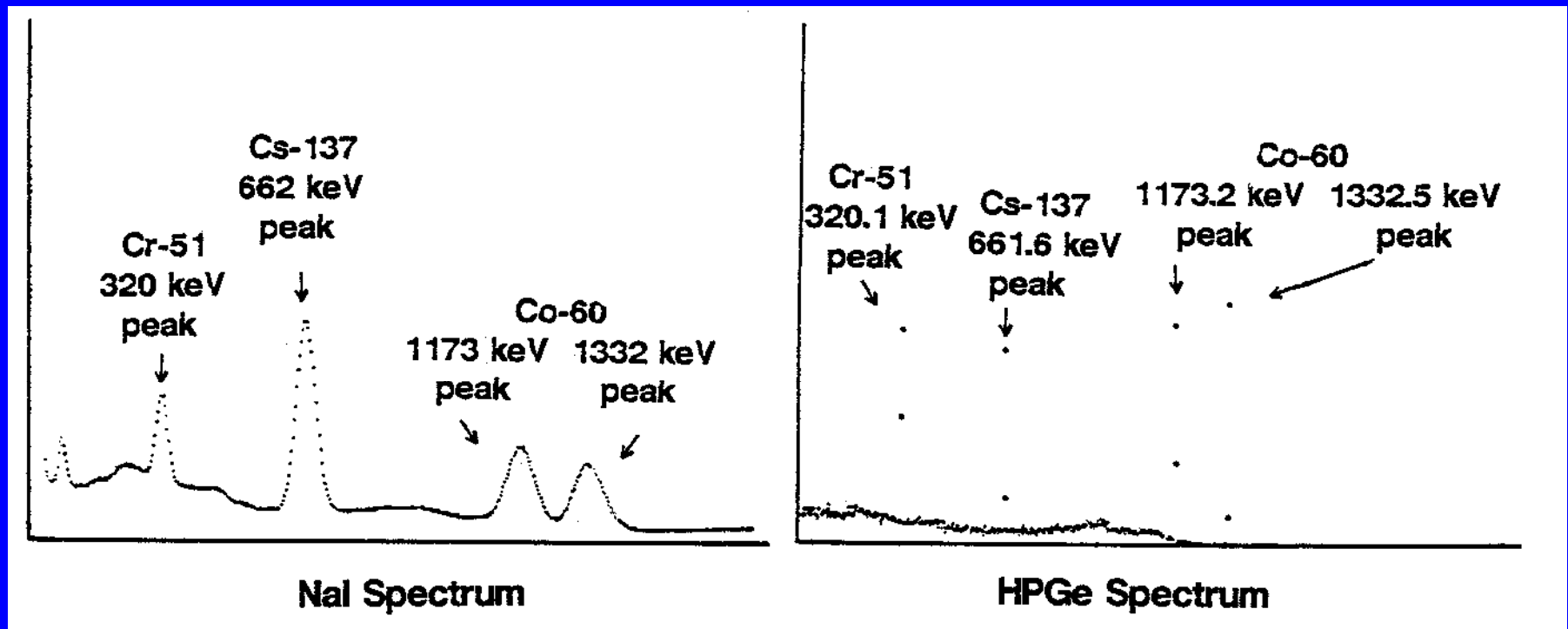
43

The Spectrum

Real Spectra

- In reality, a spectrum will have hundreds to thousands of channels rather than ten.

- In reality, there will usually be much more than one, two or three counts in a given channel.

- The next slide shows two side-by-side real spectra.

  That on the left was produced by a NaI detector while that on the right was generated using a high purity germanium detector.

The Spectrum

Real Spectra

Cs-137
662 keV
peak

Cr-51
320 keV
peak

Co-60
1173 keV   1332 keV
peak   peak

Nal Spectrum

Cr-51
320.1 keV
peak

Cs-137
661.6 keV
peak

Co-60
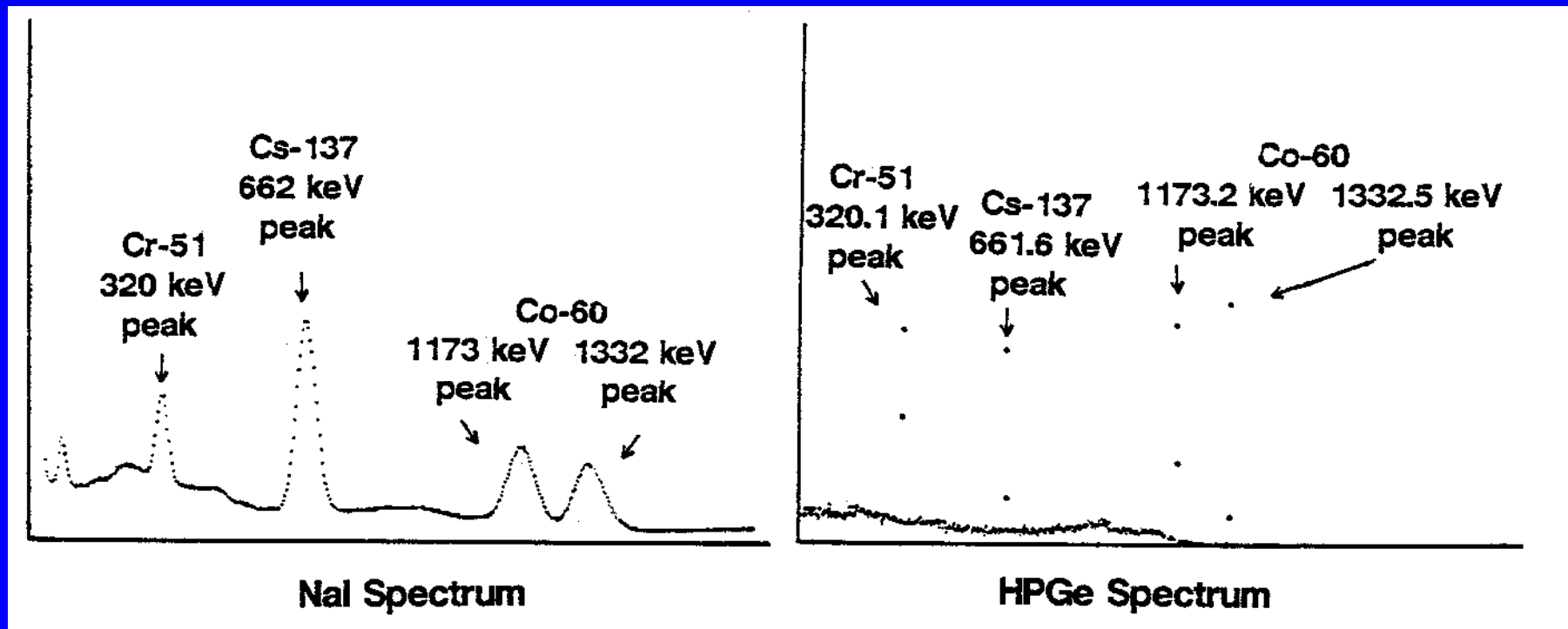1173.2 keV   1332.5 keV
peak   peak

HPGe Spectrum

The most important features on a spectrum are the peaks.

A single peak is produced by many pulses of similar size.

Ideally, each gamma ray energy produces a peak.

The Spectrum

Real Spectra

NaI Spectrum — Cr-51 320 keV peak, Cs-137 662 keV peak, Co-60 1173 keV peak, 1332 keV peak

HPGe Spectrum — Cr-51 320.1 keV peak, Cs-137 661.6 keV peak, Co-60 1173.2 keV peak, 1332.5 keV peak

The higher the energy of the gamma ray, the farther to the right the peak appears on the spectrum.

A peak should be perfectly symmetrical unless it overlaps with another peak (a doublet).
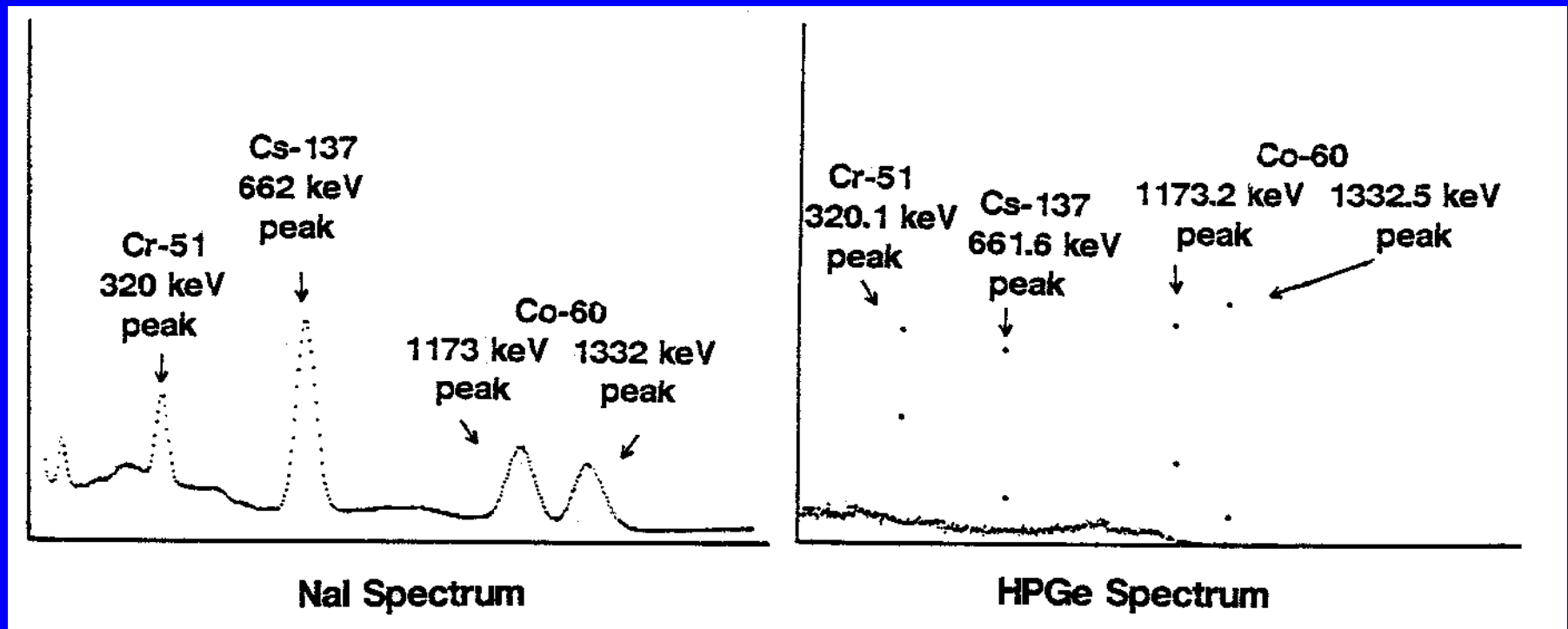
The Spectrum

Resolution

- The narrower the peaks, the better the resolution.

- Narrower peaks (better resolution) means a greater ability to distinguish gamma rays of similar energies.

- HPGe detectors have much better resolution than NaI detectors.

- The resolution of LaBr detectors is better than that of NaI detectors, but poorer than that of HPGe detectors.

- On a given spectrum, the peaks get broader as the energies get higher. In other words, peaks get broader as we move to the right.

The Spectrum

Resolution

The peaks on the NaI spectrum are approximately 20 times wider than those on the HPGe spectrum.

The Spectrum

Resolution

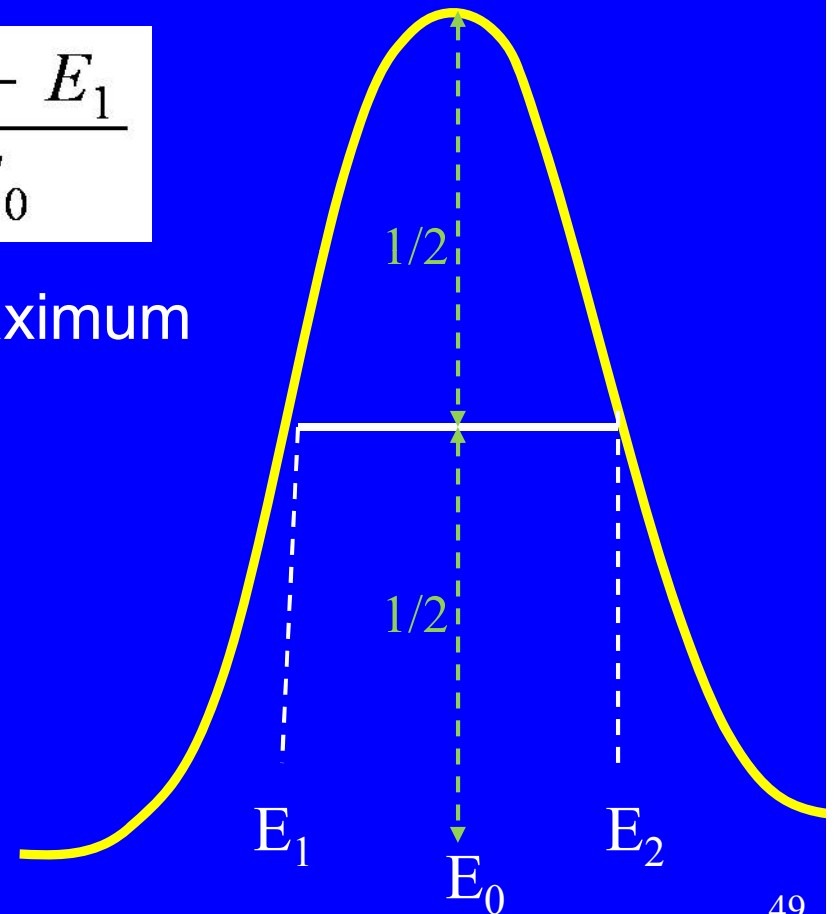- The resolution of a scintillator (e.g., NaI or LaBr) is specified for the 662 keV gamma ray of Cs-137

$$\% \; resolution \;\; = 100 \; x \; \frac{E_2 - E_1}{E_0}$$

E_2 - E_1 is the full width half maximum (FWHM)

E_0 is 662 keV

Typical NaI resolution: 7-8%
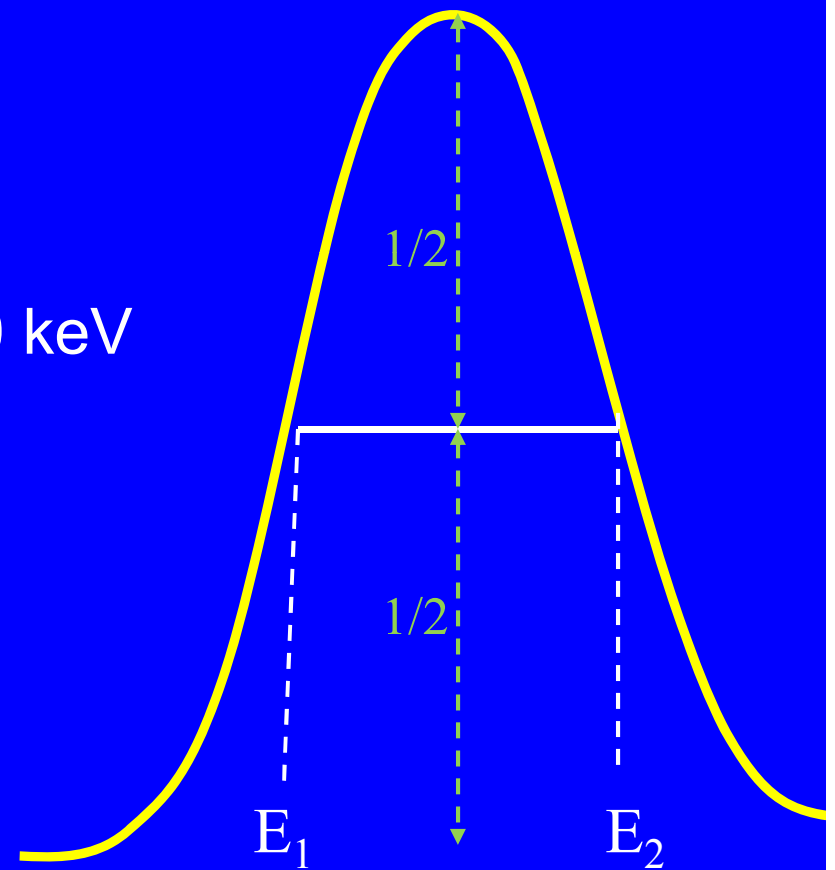
Typical LaBr resolution: 2.7-3%

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The Spectrum

Resolution

- The resolution of a HPGe detector is usually specified as the FWHM (in keV) for the 1332.5 keV peak of Co-60.

$$FWHM = E_2 - E_1$$

- Typical resolutions are 1.7 – 2.0 keV

1/2

1/2

E_1

E_2

The Spectrum

Resolution

- In a gamma spectroscopy laboratory, it is common to measure the detector resolution each morning.

- A decrease in resolution (broadening of the peaks) is usually the first indication that a detector's performance is deteriorating.

Energy Calibration

Energy Calibration

General

- The first step in gamma spectroscopy is to perform an energy calibration.

  This involves determining the relationship between the energy of a gamma ray and the centroid channel number of the peak produced by that gamma ray.

- To perform an energy calibration, we count sources that emit gamma rays of known energy, e.g., Cr-51 (320 keV), Cs-137 (662 keV) and Co-60 (1173 and 1333 keV).

- We then determine the centroid channel numbers for the resulting peaks. The energy calibration curve is the plot of gamma ray energy as a function of channel number.
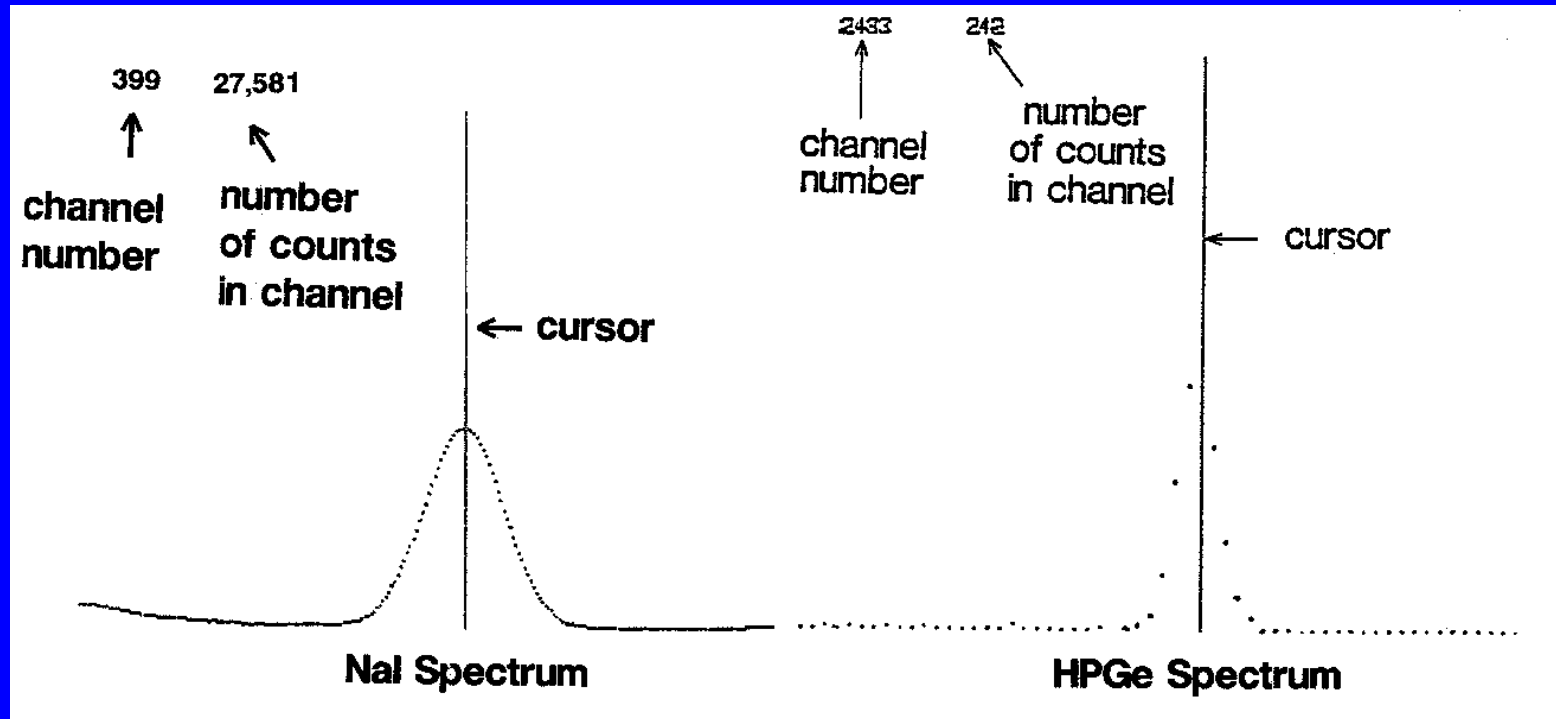
Energy Calibration

Peak Centroid

- Each peak on the spectrum spans many channels.

- Nevertheless we must select one channel to represent the peak location: the channel of the peak centroid.

- The centroid is the imaginary vertical line that divides the peak down the middle.

- Doing this by eye can be tricky because the peaks might be ragged. It is especially difficult when the peaks are very narrow.
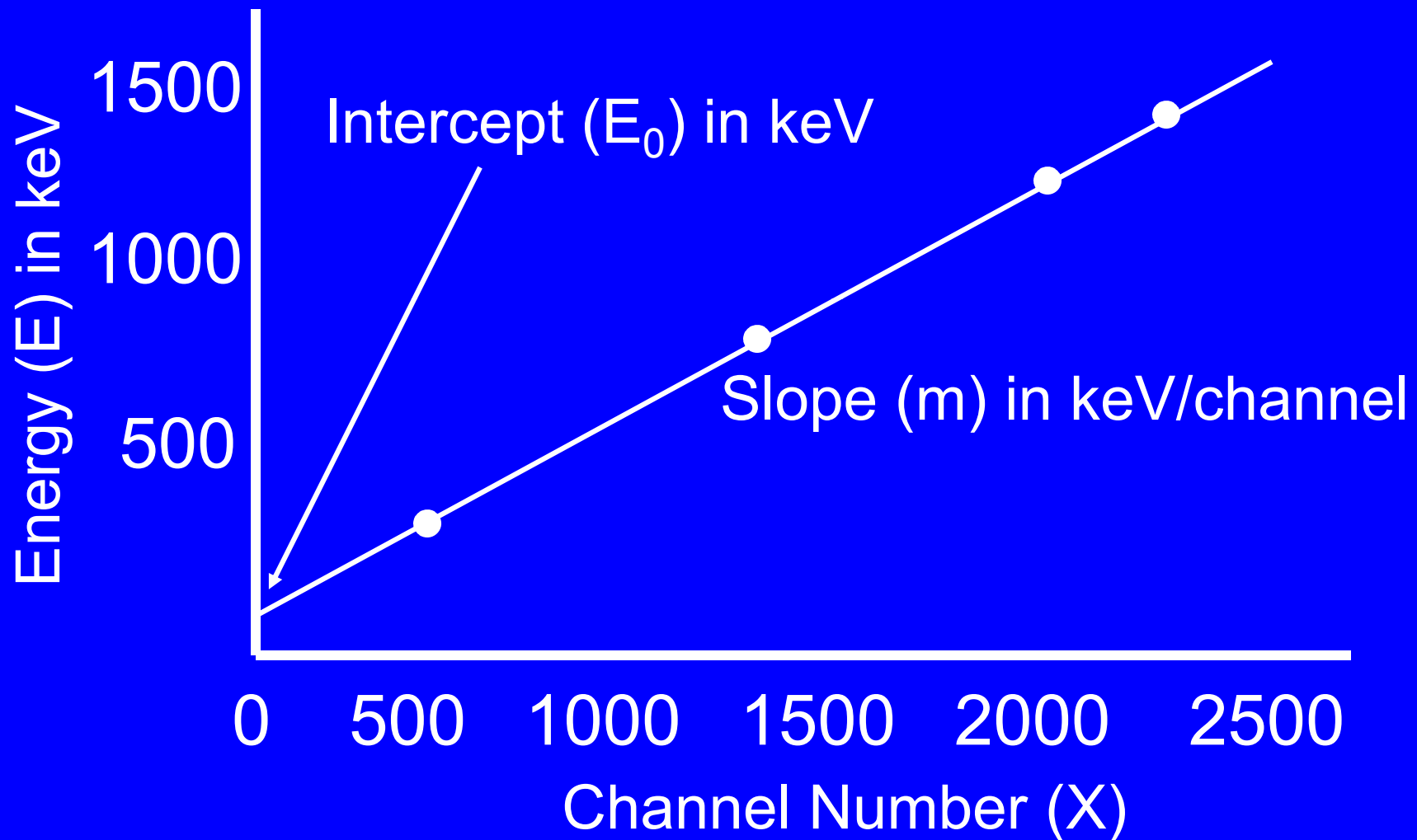
Energy Calibration

Peak Centroid

When the cursor is positioned in the peak centroid channel, the peak area to the left of the cursor is the same as the peak area to the right of the cursor.

Energy Calibration

Energy Calibration Curve

Energy Calibration

Energy Calibration Curve

- While the curve is nice to look at, we really want an equation that relates the gamma ray energy (E) to the peak centroid channel number (X).

- This can be done with either a linear or quadratic expression:

$$E = mX + E_0$$

or

$$E = aX^2 + bX + E_0$$

Identifying Unknown Gamma Emitting Nuclides

Identifying Unknown Gamma Emitting Nuclides

General

- Unknown radionuclides are identified by comparing the energies attributed to the peaks on the spectrum with the energies of gamma rays known to be emitted by various radionuclides.

- The gamma ray energies emitted by different radionuclides are found in various gamma ray "catalogs," the "libraries" of gamma spectroscopy software, etc.

- If a radionuclide emits more than one gamma ray, the relative heights (or areas) of the different peaks can help in the identification.

Identifying Unknown Gamma Emitting Nuclides

General

The best gamma ray energy (often known as the key gamma) with which to identify and quantify a radionuclide should:

• Have a high intensity (abundance)

• Have a high energy to minimize attenuation.

  High energy peaks are on a cleaner portion of the spectrum. There is higher "background" on the low energy portion of the spectrum due to Compton continuum and x-rays.

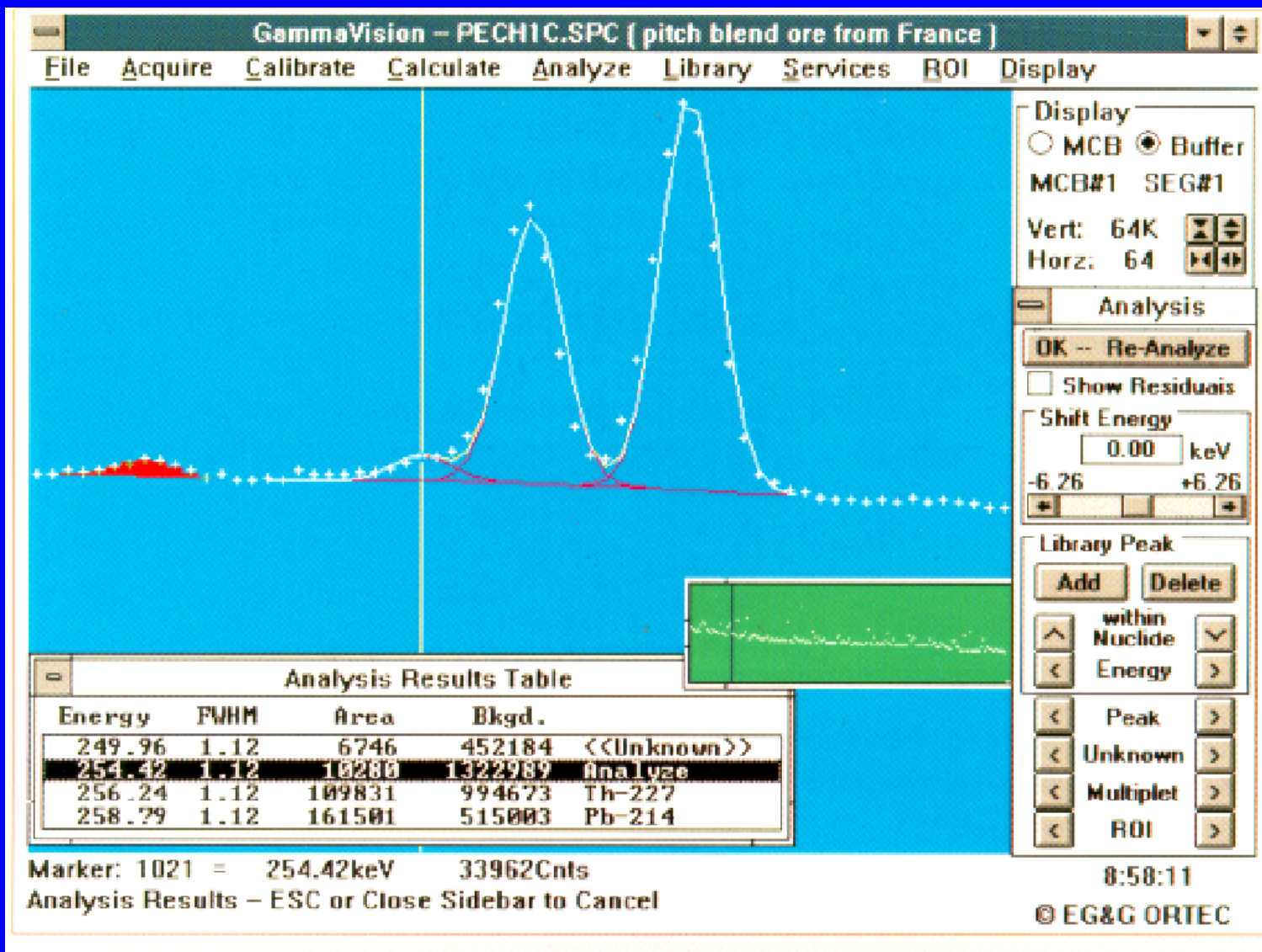• Be different from the gamma ray energies of common radionuclides.

Identifying Unknown Gamma Emitting Nuclides

Gamma Library

	SEARCH		NUCLIDE	HALF-LIFE		KEY GAMMA		ASSOCIATED GAMMAS		P OR D
	1157.0		Sc-44	3.93 h		1157.0 (1.00)		1499.4 (.009)	511.0 (1.89)	D. Ti-44 78.3
	1157.5		I-130	12.4 h		536.1 (0.99)		668.5 (0.96) 418.0 (.34)	739.5 (.82) 1157.5 (.11)	
	1173.2		Co-60	5.27 y		1332.5 (1.00)		1173.2 (1.00)		
	1175.1		Co-56	78.8 d		846.8 (1.00)		2034.8 (.78) 2598.4 (.169) 1037.9 (.14) 1360.2 (.043) 1175.1 (.023) 511.0 (.40)	1238.3 (.67) 1771.3 (.155) 3253.4 (.078) 2015.4 (.03) 977.4 (.014)	

Identifying Unknown Gamma Emitting Nuclides

Use of Computer

Identifying Unknown Gamma Emitting Nuclides

Common Problems

- If multiple gamma rays have similar energies, their peaks might overlap and not all of them might be recognized. This is very common with NaI detectors.

  The shape of the peak (peak width) might indicate that this is happening.

- Some peaks on the spectrum might not be directly attributable to gamma rays: x-ray peaks
  sum peaks
  single escape peaks
  double escape peaks
  backscatter peaks

Identifying Unknown Gamma Emitting Nuclides

Common Problems

- Not all the gamma ray energies of a radionuclide identified in the library might be seen.

- More gamma ray energies might be seen than are listed for a given radionuclide.

- More than one radionuclide emits a gamma ray at or very close to the energy attributed to the photopeak.

Appendix

Appendix

Dead Time

- The dead time is the difference between the "real time" and the "live time."

    Dead time = real time - live time

- The real time is the real-world count time, i.e., the time as measured by a clock.

- The live time is the time that the spectroscopy system is able to process incoming pulses. When we set a count time, we are specifying the live time.

- The larger the dead time, the greater the error associated with its estimated value.

- In general, it should be kept below 10% or so.

Appendix

Dead Time

Things that increase the dead time:

- Higher count rates

- Longer amplifier shaping times

- Higher conversion gains (Wilkinson ADCs)

- Larger pulse sizes (Wilkinson ADCs)

Appendix

Gain Shifts

- Gain shifts are undesirable

- They cause the pulse sizes to change (get larger or smaller) during the count.

- This causes the peaks to shift to the right or left on the spectrum.

  As such, the location (centroid channel number) attributed to these peaks will not reflect the true energy of the associated gamma rays.

- Gain shifts are larger on the high energy peaks than the lower energy peaks.

Appendix

Gain Shifts

Things that might cause a gain shift:

- Unstable high voltage

- Poor electrical connections, e.g., corrosion on the switches or in the socket of a PMT.

- Changes in count rates.

Appendix

Upper and Lower level Discriminators

- The LLD and ULD are used to set a window of pulse sizes that will be analyzed by the ADC.

- Pulses smaller than the LLD are not analyzed – it is often set around 0.2 volts.

- Pulses larger than the ULD are not analyzed - it is usually set at 10 volts.

- Narrowing the window established by the LLD and ULD can be a useful means to reduce excessive dead time.

Appendix

Single Channel Analyzer (SCA)

- An SCA uses the upper and lower level discriminators (other names are often used for these) to establish a window of pulse sizes that will be counted.

- The heights of the counted pulses are not analyzed so SCAs are not used for gamma spectroscopy (any more).

- As an example, they might be used with a FIDLER so that only Am-241 (59.5 keV) gamma rays are counted. This improves sensitivity by reducing background.