Physics Department
Royal Holloway
University of London

PH2510 - Nuclear Physics Laboratory

High-Resolution Gamma spectroscopy (NP2)

1 Objectives

The aim of this experiment is to demonstrate how high resolution γ-ray energy spectra may be obtained using a High-Purity Germanium (HPGe) planar detector. The spectrometer will be used to investigate the energy spectrum of several radioactive gamma-ray sources. In the main part of the experiment, you will use the spectrometer to estimate the half-life of K-40.

2 Apparatus

The figure below shows the block diagram of a simple $\gamma-$spectrometer. The demonstrator will identify the components and explain the function of each of the electronic modules.

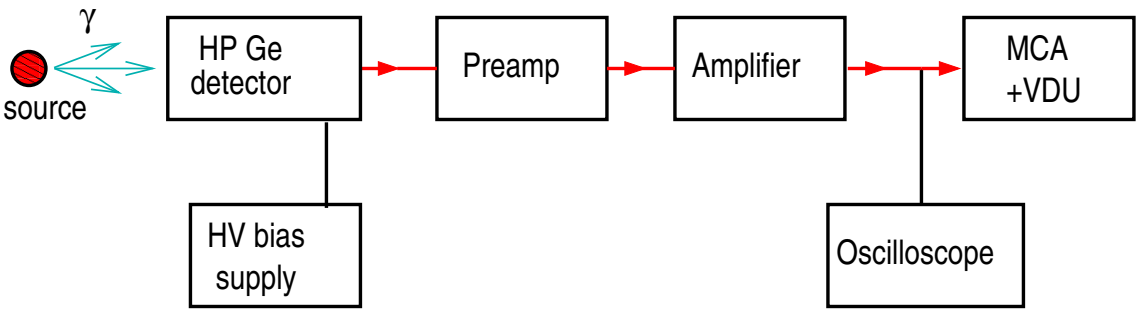

Figure 1: Schematic diagram of the High-Purity Ge detector system used in this experiment. MCA= Multi-Channel Analyser; VDU= Visual Display Unit.

3 Procedure

3.1 Calibration of the spectrometer

When a gamma ray enters the sensitive region of the detector it ionises atoms around its trajectory thus producing many electrons, which are collected, forming an electric pulse. The total charge of the electric pulse produced is proportional to the total energy deposited in the detector by the incident gamma ray. The Multi-Channel Analyser (MCA) is the part of the spectrometer that histograms ("analyses") the pulses according to their charge. In order to be able to produce readings of energy, the MCA must first be calibrated.

Record the spectra of the Na-22, Co-60[1] and Cs-137 sources. Calibrate the spectrometer using two suitable photopeaks of known energy, chosen from the various spectra you have recorded.

In your **report** explain succinctly what is the calibration supposed to achieve. Include the printout of the calibration spectra, clearly indicating the two peaks used for the calibration, and justifying your choice of calibration energies. Use two other peaks of known energy to quantify the uncertainty in your calibration:

$$\frac{\mathrm{E_{measured}} - \mathrm{E_{actual}}}{\mathrm{E_{actual}}}$$

3.2 Energy resolution

For each photopeak, determine ΔE the full-width at half-maximum (FWHM) as well as the peak position (its centroid) $\bar{E}$. The energy resolution of the spectrometer at a given energy can be estimated as $\Delta E/\bar{E}$.

In your **report**, include the printouts of all the spectra, with all the features clearly labelled (photopeaks, Compton continua, Compton edges, sum peaks). Explain the physical origin of these features succinctly. Include a table with the values of $\bar{E}$, ΔE and the resolution $\Delta E/\bar{E}$ at each of the photopeak energies. Plot the resolution as a function of energy. Does the resolution vary with the gamma ray energy? How does this compare with the expected trend?

Note: when you have finished using the spectrometer, ask the demonstrator for the K-40 sample (KBr salt) and start recording its spectrum at once.

3.3 Measuring the half-life of K-40

Potassium 40 is a naturally-occurring radioactive isotope which is very long lived; its lifetime is of the order of a billion years. For such long-lived radioactive substances, the probability of decay is so low that it is impossible to determine the half-life by detecting the actual exponential decay over time. (Why? How long would it take to detect a measurable decrease in activity?) However, we know that the activity (number of decays per unit time) of a radionuclide is given by

[1] Ask the demonstrator to give you the special *calibrated* Co-60 source and place it on the plastic stand, before starting to record this spectrum.

$$A(t) = (\frac{-dN}{dt}) = \lambda \times N$$

where the *decay constant* λ is the probability of decay per unit time and N is the number of radioactive nuclei in the sample at time t. By measuring the activity and determining N it is then possible to determine λ, which is trivially related to the half-life $t_{1/2}$.

The decay scheme of K-40 is shown in Figure 2. Most of the K-40 decays proceed via

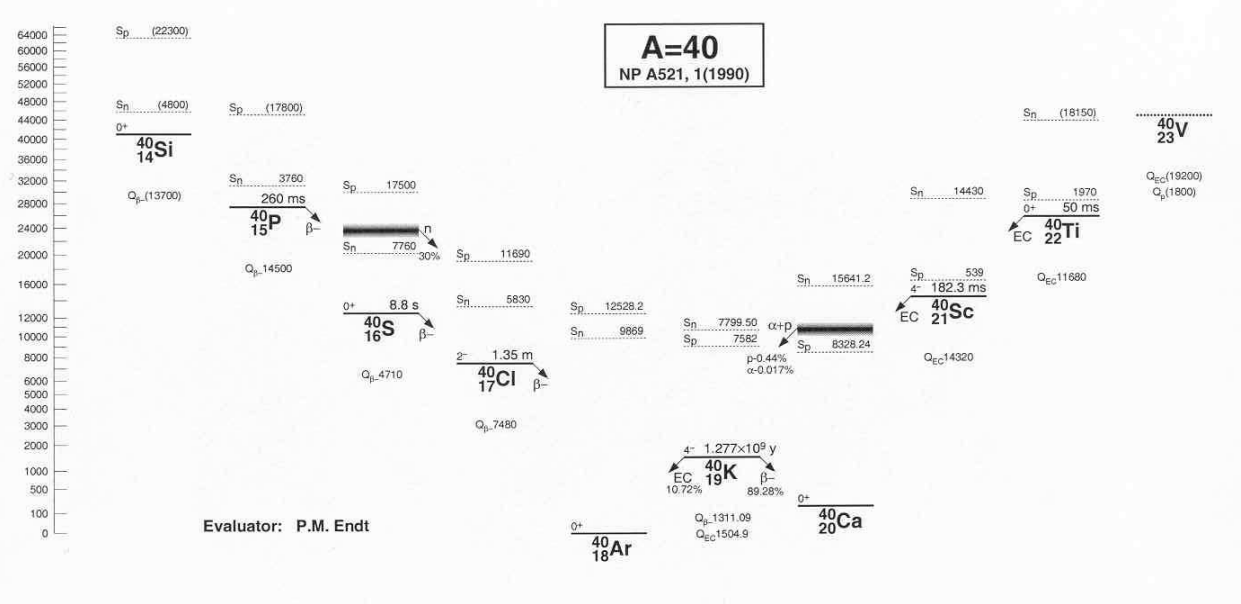

Figure 2: Decay scheme for isotopes with $A = 40$ [1]. For K-40 two decay modes are allowed: via electron capture (E.C.) and β^- decay. The percentage for each mode is indicated.

β^- emission. The decay via electron capture results in the emission of a 1460 keV gamma ray, which can be detected with the gamma spectrometer.

3.3.1 Detector efficiency

The HPGe spectrometer which is used in this experiment has a very good energy resolution. However, it has very low gamma-ray detection efficiency (see Figure 3) for energies above ∼1000 keV. In order to determine the *actual* (as opposed to *measured*) activity of the K-40 sample you will have to estimate the spectrometer's gamma-ray detection efficiency, at the relevant energy. In order to do this you will rely on the data you collected earlier, using the calibrated Co-60 source. The activity of this particular source was determined accurately at a well-defined date in the past (see Table 1).

Determine what is the expected activity of this source *today* and include all the calculations in your **report**. Using the data in the Co-60 spectrum and the expected activity, estimate the efficiency, ϵ, of the HPGe detector for 1460 keV gamma rays. In your **report**, explain clearly how you have done this, including all calculations.

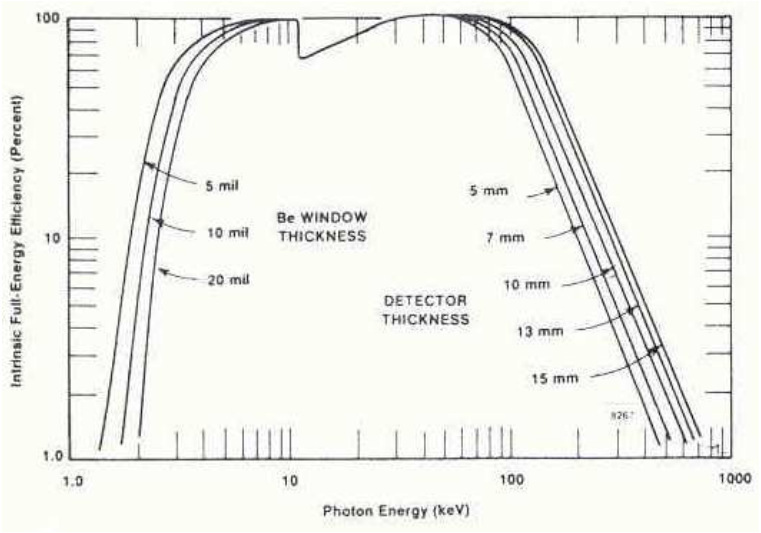

Figure 3: Typical intrinsic detection efficiency curve for an HPGe detector, as a function of the photon energy. (EG&G ORTEC manual.)

Activity of Co-60 source calibrated on April 1^{st}, 1975	$11.95\,\mu$Ci
Co-60 half-life, $t_{1/2}$	5.271 y

Table 1: Activity of Co-60 source, in Curies, and half-life of Co-60.

3.3.2 Determining the half-life

In this experiment you will be using a sample of 40.0 g of a potassium bromide (KBr) salt. K-40 is a relatively rare potassium isotope (see Table 2). In your **report** calculate

Atomic weights:	
K	$39.1\,\mathrm{g.mol^{-1}}$
Br	$79.9\,\mathrm{g.mol^{-1}}$
K-40 abundance	0.0117%

Table 2: Atomic weights of K and Br, and relative abundance of the potassium isotope K-40.

the number, N, of K-40 nuclei present in your sample.

Given the very long half-life of K-40 and the low detector efficiency, you should accumulate the spectrum of K-40 for a relatively long period (*i.e.*, up to $\sim$ 24 hours). Using the measured peak at 1460 keV, you should now be able to determine the K-40 half-life, $t_{1/2}$.

Include all necessary explanations and calculations in your **report**. Compare the value you obtained with the tabulated value (*e.g.*, see Appendix C of Reference [2]).

3.3.3 Discussion

In your **report** identify any assumptions and/or approximations that were required in your calculations, and which may have an impact on the final result. Indicate the expected

impact on the final result, at least qualitatively (*i.e.*, does the assumption result in an increased or a decreased measured value of the K-40 half-life?)

In addition, some of the quantities used in your calculation are only known with finite precision: they have an associated measurement uncertainty. Identify any such quantities and their uncertainties, and propagate the effect of these uncertainties to the uncertainty on the final $t_{1/2}$ result.

3.4 Radioactive rock sample (optional)

This part of the experiment is **optional**. Please ask the demonstrator whether you should carry out this part of the experiment or not.

Record the spectrum of the radioactive rock sample and list the energy and total count for all the peaks. Match the observed photopeaks to those in the MCA's photopeak database (library function).

In your **report**, include a printout of the rock's spectrum, as well as a list with the counts, energy and identification of the most prominent peaks. Comment on the origin of the radioactivity of the rock.

Radiation safety

In this experiment you will need to use radioactive sources. These are to be dealt with with care. You must follow these rules:

- Keep the source in its container when not in use;
- Do not point the open end at yourself or anyone else;
- Do not tamper with the source;
- Handle using tongs or wearing disposable gloves;
- No eating or drinking in the lab;
- Wash your hands thouroughly before touching food;
- Do not handle the source if you are pregnant;
- When you have finished using the source, advise the demonstrator so that it can be returned to the store.

References

[1] L.P. Ekström and R.B. Firestone, WWW Table of Radioactive Isotopes, database version 2/28/99; URL `http://ie.lbl.gov/toi/`

[2] Introductory Nuclear Physics, KS Krane, Chapter 7.

PTD, February 2007.

30. COMMONLY USED RADIOACTIVE SOURCES

Table 30.1. Revised November 1993 by E. Browne (LBNL).

			Particle		Photon	
Nuclide	Half-life	Type of decay	Energy (MeV)	Emission prob.	Energy (MeV)	Emission prob.
$^{22}_{11}$Na	2.603 y	β^+, EC	0.545	90%	0.511	Annih.
					1.275	100%
$^{54}_{25}$Mn	0.855 y	EC			0.835	100%
					Cr K x rays	26%
$^{55}_{26}$Fe	2.73 y	EC			Mn K x rays:	
					0.00590	24.4%
					0.00649	2.86%
$^{57}_{27}$Co	0.744 y	EC			0.014	9%
					0.122	86%
					0.136	11%
					Fe K x rays	58%
$^{60}_{27}$Co	5.271 y	β^-	0.316	100%	1.173	100%
					1.333	100%
$^{68}_{32}$Ge	0.742 y	EC			Ga K x rays	44%
$\rightarrow {}^{68}_{31}$Ga		β^+, EC	1.899	90%	0.511	Annih.
					1.077	3%
$^{90}_{38}$Sr	28.5 y	β^-	0.546	100%		
$\rightarrow {}^{90}_{39}$Y		β^-	2.283	100%		
$^{106}_{44}$Ru	1.020 y	β^-	0.039	100%		
$\rightarrow {}^{106}_{45}$Rh		β^-	3.541	79%	0.512	21%
					0.622	10%
$^{109}_{48}$Cd	1.267 y	EC	0.063 e^-	41%	0.088	3.6%
			0.084 e^-	45%	Ag K x rays	100%
			0.087 e^-	9%		
$^{113}_{50}$Sn	0.315 y	EC	0.364 e^-	29%	0.392	65%
			0.388 e^-	6%	In K x rays	97%
$^{137}_{55}$Cs	30.2 y	β^-	0.514 e^-	94%	0.662	85%
			1.176 e^-	6%		
$^{133}_{56}$Ba	10.54 y	EC	0.045 e^-	50%	0.081	34%
			0.075 e^-	6%	0.356	62%
					Cs K x rays	121%
$^{207}_{83}$Bi	31.8 y	EC	0.481 e^-	2%	0.569	98%
			0.975 e^-	7%	1.063	75%
			1.047 e^-	2%	1.770	7%
					Pb K x rays	78%
$^{228}_{90}$Th	1.912 y	6α:	5.341 to 8.785		0.239	44%
		$3\beta^-$:	0.334 to 2.246		0.583	31%
					2.614	36%
($\rightarrow {}^{224}_{88}$Ra	$\rightarrow {}^{220}_{86}$Rn	$\rightarrow {}^{216}_{84}$Po	$\rightarrow {}^{212}_{82}$Pb	$\rightarrow {}^{212}_{83}$Bi	$\rightarrow {}^{212}_{84}$Po)	
$^{241}_{95}$Am	432.7 y	α	5.443	13%	0.060	36%
			5.486	85%	Np L x rays	38%
$^{241}_{95}$Am/Be	432.2 y	6×10^{-5} neutrons (4–8 MeV) and				
		$4 \times 10^{-5}\gamma$'s (4.43 MeV) per Am decay				
$^{244}_{96}$Cm	18.11 y	α	5.763	24%	Pu L x rays	$\sim 9\%$
			5.805	76%		
$^{252}_{98}$Cf	2.645 y	α (97%)	6.076	15%		
			6.118	82%		
		Fission (3.1%)				
		$\approx 20\ \gamma$'s/fission; 80% < 1 MeV				
		≈ 4 neutrons/fission; $\langle E_n \rangle = 2.14$ MeV				

"Emission probability" is the probability per decay of a given emission; because of cascades these may total more than 100%. Only principal emissions are listed. EC means electron capture, and e^- means monoenergetic internal conversion (Auger) electron. The intensity of 0.511 MeV e^+e^- annihilation photons depends upon the number of stopped positrons. Endpoint $\beta^\pm$ energies are listed. In some cases when energies are closely spaced, the γ-ray values are approximate weighted averages. Radiation from short-lived daughter isotopes is included where relevant.

Half-lives, energies, and intensities are from E. Browne and R.B. Firestone, *Table of Radioactive Isotopes* (John Wiley & Sons, New York, 1986), recent *Nuclear Data Sheets*, and *X-ray and Gamma-ray Standards for Detector Calibration*, IAEA-TECDOC-619 (1991).

Neutron data are from *Neutron Sources for Basic Physics and Applications* (Pergamon Press, 1983).