Basics of γ-rays interaction with semiconductor detector

1) **Photo-electric effect**: in the photo-electric absorption process, a photon undergoes an interaction with an absorber **atom** in which the photon completely disappears. In its place, a *photo-electron* is ejected by the atom from one of its bound shells (typically the K shell). The photoelectron appears with an energy

$$E = h\nu - E_b$$

where E_b is the binding energy of the electron in its original cell (often negligible).
If the photo-electron energy is completely adsorbed by the surrounding medium (the detector sensitive part), it results in a *full-energy peak* (or *photo-peak*) in the recorded spectrum.
This effect is dominant for low-energy photons and/or large detectors and/or detectors with high atomic number: in fact the probability τ of photo-electric absorption is roughly

$$\tau \div \frac{Z^n}{(h\upsilon)^{3.5}}$$

with n between 4 and 5 depending on the energy region of interest.

2) **Compton effect**: Compton scattering takes place between the incident photon and an **electron** of the absorbing material: the photon is deflected of an angle θ with respect to its original direction, and it transfers **a portion** of its energy to such a *recoiling electron*. Because **all angle of scattering are possible**, the energy transferred can vary from zero to a large fraction of the photon energy. Because the energy of the scattered photon is

$$h\upsilon' = \frac{h\upsilon}{1 + \frac{h\upsilon}{m_0 c^2}(1 - cos\theta)}$$

all energies detected result in a continuum (*Compton continuum*) spread between zero and the maximum transferred energy (corresponding to a 180° scattering):

$$E_{max} = h\upsilon \frac{2h\upsilon/m_0c^2}{1 + 2h\upsilon/m_0c^2}$$

This energy level is known as the *Compton edge*. The **gap** between the maximum transferred energy and the photo-peak energy is

$$E_C = \frac{h\upsilon/m_0c^2}{1 + 2h\upsilon/m_0c^2}$$

For photons of high energies ($h\nu >> m_0c^2/2$), thus $E_c \approx 0.256$ MeV.

Multiple Compton scattering processes are also possible, with a much more complicated behavior.

3) **Pair production**: if the photon energy exceeds twice the **rest-mass energy of an electron** (1.022 MeV), the photon completely disappears and is replaced by an *electron-positron pair*[1]. All the energy in excess of 1.022 MeV carried in by the photon goes into kinetic energy shared by the recoiling electron and positron. Because the positron will subsequently annihilate after slowing down to almost zero kinetic energy in the absorbing medium, two *annihilation photons* (with energy 0.511 MeV) are normally produced as secondary products of the interaction. If such annihilation photons are fully adsorbed by the medium, all the energy of the initial photon is recorded (thus superimposing to the full-energy peak); however, if one or both annihilation photons are lost, the result is a *single escape* or *double escape* peak, respectively, with energies

$$E_{se} = h\nu - 0.511 \text{ MeV}$$
$$E^{de} = h\nu - 1.022 \text{ MeV}$$

As a result, the spectrum recorded by a semi-conductor detector (like a HPGe) has the general shape shown in Figure 1. This must be regarded as *a very general indication* for the shape of the spectrum recorded by your detector; in fact, the spectrum depends also on the detector dimensions, the initial photon energy etc.

[1] The interaction of the electron-positron pair production actually takes place through the Coulomb field of the nucleus.

As a matter of fact, all the three processes give origin to a count into the full-energy peak if the secondary products of the reaction are eventually absorbed by the medium.

Some "practical hints"

a)	Your detector is large	→	The full-energy peak is dominant
b)	Your detector is "heavy" (high Z)	→	The full-energy peak is dominant
c)	Your photon energy is large	→	The Compton continuum is dominant
d)	Your photon energy is large	→	The Compton edge is at $h\nu$ – 256 keV
e)	Your photon energy is > 1022 keV	→	You may see escape peaks
f)	Your photon energy is < 1022 keV	→	No escape peaks at all

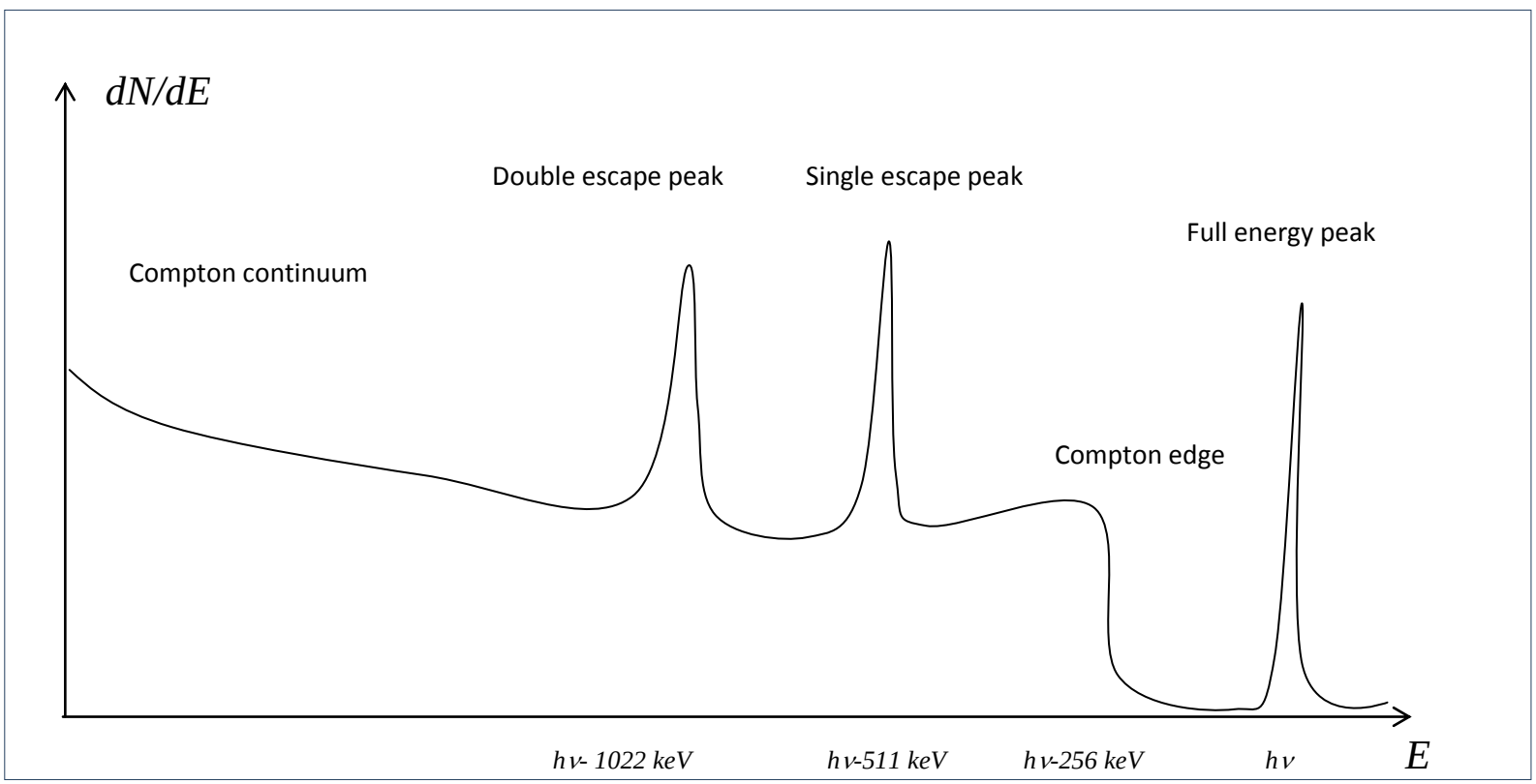

Figure 1: general *(and somehow simplistic….) shape of the spectrum recorded by a semiconductor detector from a monochromatic source with energy $h\nu$ > 1.022 MeV.*

What to do in practice

1) Before the experience, it is a good idea to check the cables, connections etc. The tutor will show the instrumentation and its use.
2) Switch on everything. The tutor will show how to switch on SLOWLY the HV of the HPGe.
3) While switching on the HV, it is interesting to connect the detector to an oscilloscope in order to “see” the signals.
4) Calibration of the instrument: start with a gain G=400 on the amplifier (for instance). Choose at least two sources from the set for the calibration. A good choice is to have at least a line at high energy and a line at low energy.
   a) Before recording a spectrum with MAESTRO, the tutor will show “on-line” the effect of changing the gain of the amplifier and the LLD, and the presence of low energy background. The students can suggest an appropriate level of gain and LLD.
   b) Record spectra with MAESTRO for the chosen set of G and LLD and for the chosen sources.
   c) The students can calculate by themselves the calibration parameters of the detector, then compare their calculation with the MAESTRO one.
   d) Check your calibration: choose another source with intermediate energy: the students can suggest where (which channel) the line will be located and verify the correctness of their calculated calibration.
5) Take the “mistery source” and take a spectrum with it. Basing on the table, try to identify the emitting isotope.

Some important practical constraints on the use of the HPGe detector

1) The HPGe detector must be refrigerated with liquid nitrogen before use. NEVER SWITCH ON THE DETECTOR WHEN IT IS NOT COOLED DOWN!
2) The working voltage of the HPGe is 3500 V. The bias has to be raised and lowered down SLOWLY!
3) The working voltage of the HPGe is POSITIVE. Always check the sign of HV before rising it up.
4) The detector head is covered with a VERY THIN beryllium cap, that is VERY FRAGILE. NEVER TOUCH, SCRATCH OR PUSH THE DETECTOR FRONT END! Whenever possible, keep the plastic cap in position.
5) Liquid nitrogen for cooling is at 77 K: not very good for your skin and fingers! Be careful when filling up the dewar and always use suitable gloves.

Some Gamma Rays sources.

The international standard primary X-ray source is K_{a1} from Tungsten: 59.31918 ± 0.00035 keV[2].

Nuclide	Energy (keV)	Compton edge	Single escape	Double escape
^{241}Am	59.54			
^{133}Ba (1)	302.82			
^{133}Ba (2)	356.06			
^{137}Cs	661.61			
^{57}Co (1)	122.05			
^{57}Co (2)	136.46			
^{131}I	364.49			
^{60}Co (1)	1173.23			
^{60}Co (2)	1332.51			
^{198}Au	411.79			
^{203}Hg	279.18			
^{54}Mn	834.84			
^{22}Na	1274.55			
^{88}Y	1836.13			
^{124}Sb	1691.02			

[2] Greenwood *et al.*, *Nucl. Instr. Meth.* **77** 141 (1970)