European Commission

Gamma-ray Spectrometry

Basic Concepts I –
Interactions of gamma-ray with matter

Mikael Hult (Docent, PhD, Lic Eng, MSc)

European Commission – Joint Research Centre – Institute for Reference Materials and Measurements

Mikael.hult@ec.europa.eu

European Commission

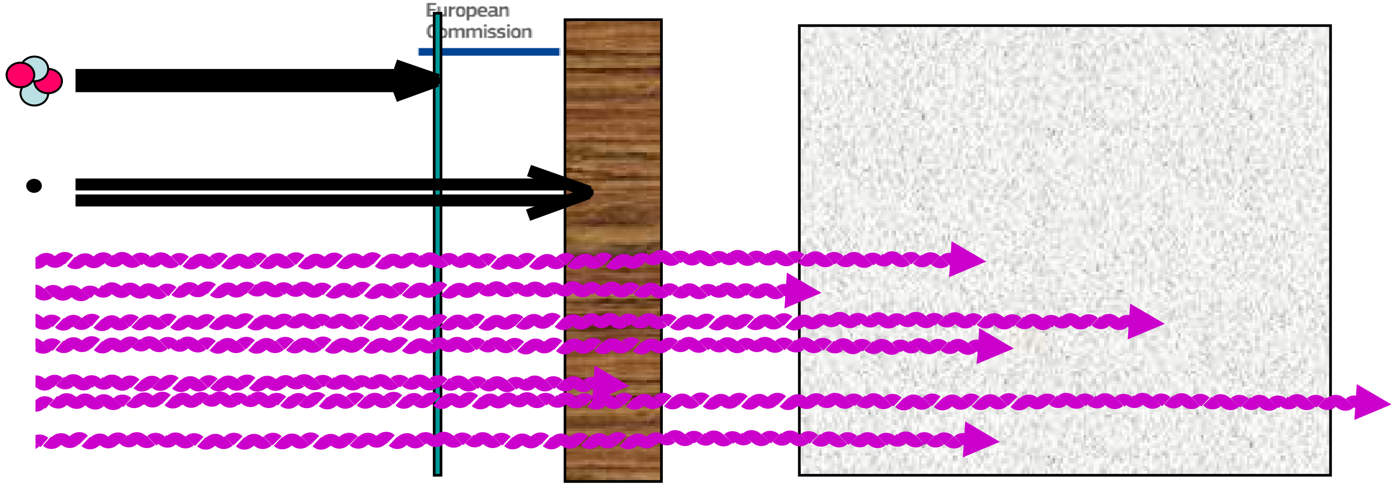
Obligatory slide

Slides 3 to end are the intellectual property of Dr. Mikael Hult, EC-JRC-IRMM, Retieseweg 111, 2440 Geel, Belgium.

Alpha-particle

Beta-particle

Gamma-rays

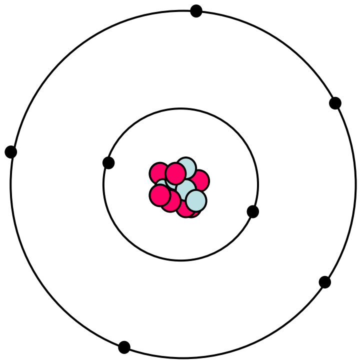


Radiowaves **Microwaves** **Light** **X-rays** **Gamma-rays**

micro-eV **meV** **eV (electron-Volt)** **keV** **MeV**

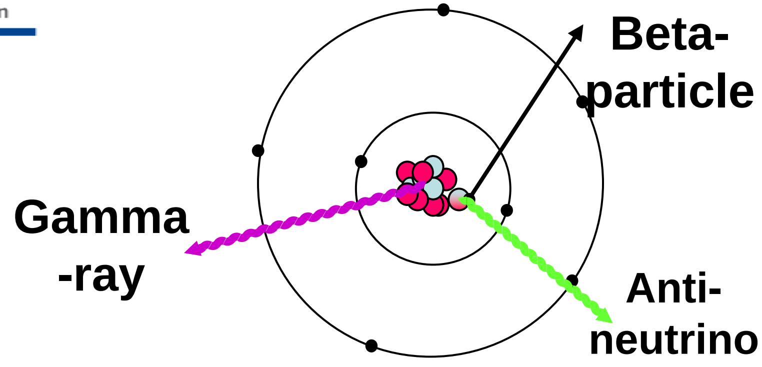
Photon Energy

European Commission



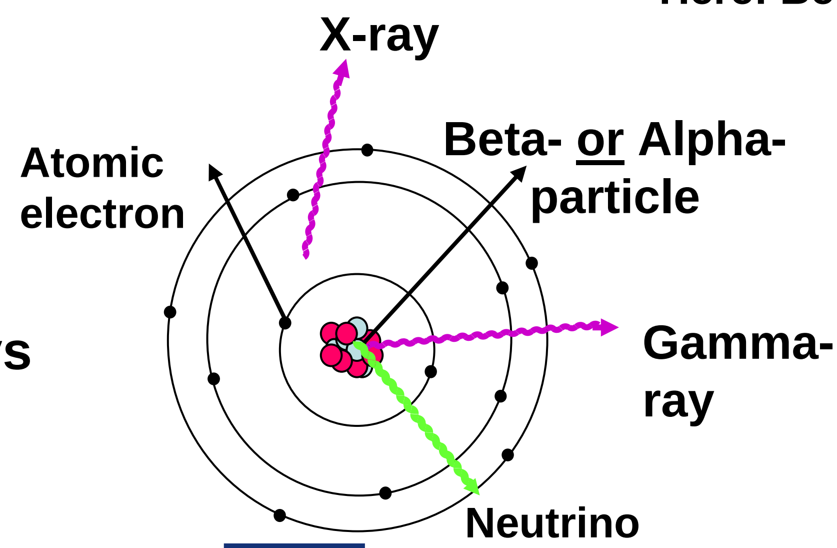
A stable atom

The electrons circulate around the nucleus in certain shells



An unstable atom = a radionuclide

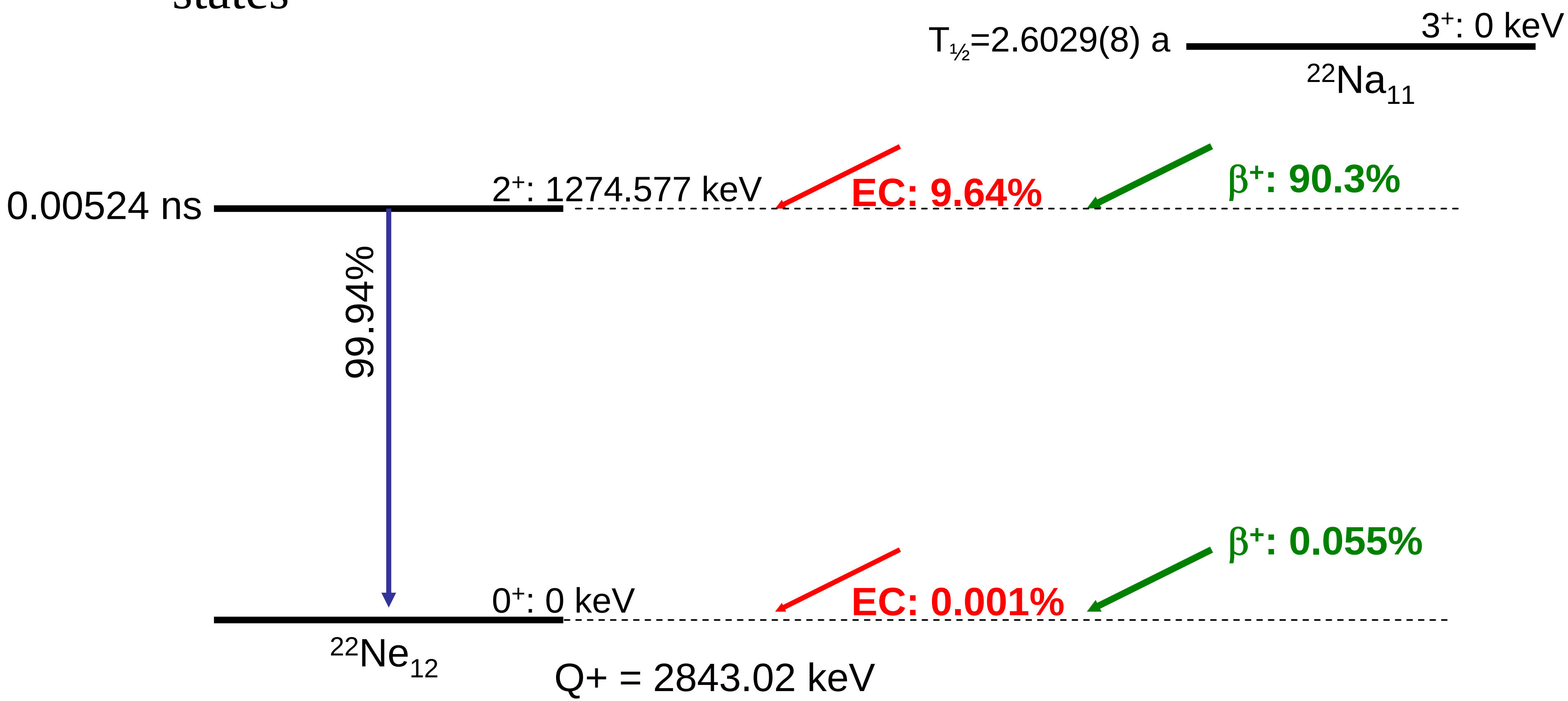
Here: Beta-decay



When a radionuclide decays many different types of radiation can be emitted

Gamma-rays

- Emitted in the de-excitation of nuclear states populated in either alpha or beta decay.
- Their energies are defined by the energies of the nuclear states



European Commission

Gamma Rays

- Typically 0.1-10 MeV

$$E_i = E_f + E_\gamma + T_R$$

Recoil kinetic energy of the nucleus

$$0 = p_R + p_\gamma$$

Conservation of momentum:

$$E_\gamma = Mc^2 \left[-1 \pm \left(1 + 2 \frac{\Delta E}{Mc^2} \right)^{1/2} \right]$$

European Commission

Gamma Rays

Since: ΔE are typically of the order of MeV, while the rest energies *Mc*^{2} are order of A x 10^3 MeV, A is mass number.

$$\Delta E << Mc^2$$

$$E_\gamma \cong \Delta E - \frac{(\Delta E)^2}{2Mc^2} \Rightarrow E_\gamma \cong \Delta E$$

European Commission

Gamma Rays

Selection rules for gamma-ray transitions

Type	Symbol	Angular momentum change, *l*	Party change
Electric dipole	*E1*	1	yes
Magnetic dipole	*M1*	1	no
Electric quadrupole	*E2*	2	no
Magnetic quadrupole	*M2*	2	yes
Electric octupole	*E3*	3	yes
Magnetic octupole	*M3*	3	no
Electric 16-pole	*E4*	4	no
Magnetic 16-pole	*M4*	4	yes

Gamma Rays

Selection rules for gamma-ray transitions

Useful for a lot of calculations. E.g. conversion coefficients:

See e.g. http://www.nndc.bnl.gov/

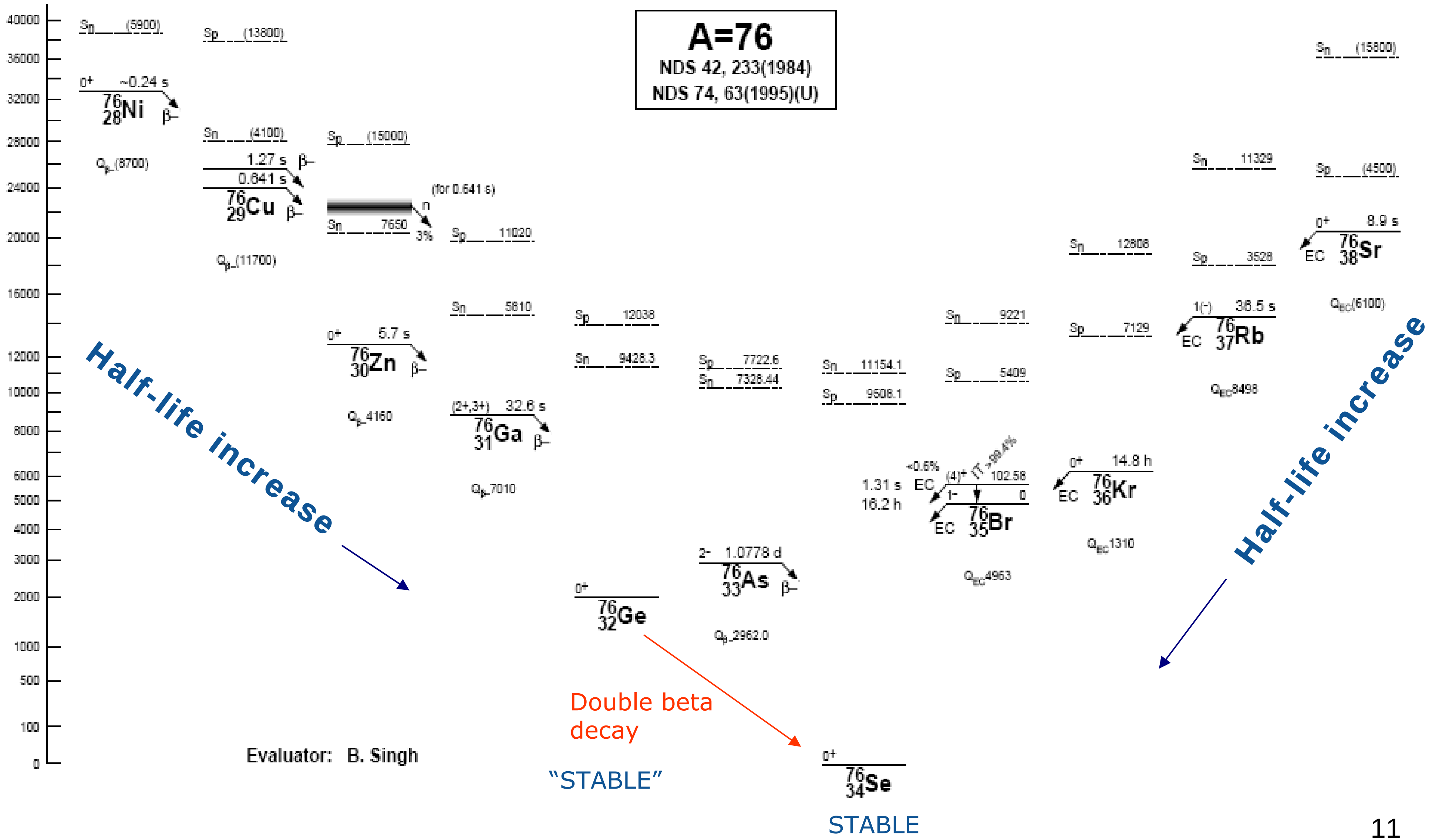
European Commission

Gamma Rays

Depending on the initial and final state each gamma-ray has a description:

E1, M1, E2, M2, E3, M3 etc.

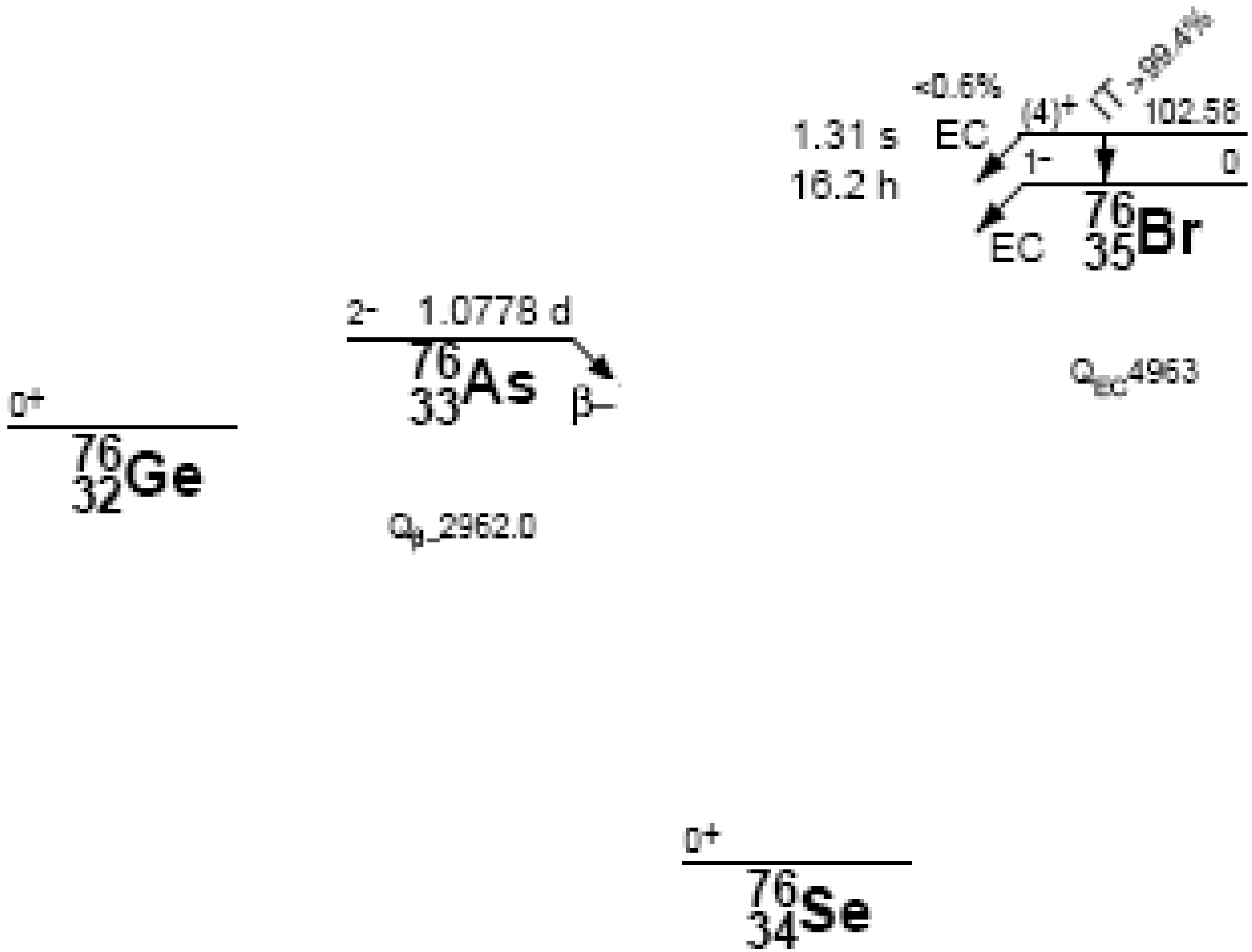
E.g. a 2+ to 0+ transition: No parity change, Angular momentum changes by 2 $\Rightarrow$ E2 transition



A=76
NDS 42, 233(1984)
NDS 74, 63(1995)(U)
Evaluator: B. Singh
Half-life increase
Half-life increase
Double beta decay
"STABLE"
STABLE
0+ ~0.24 s
76 28 Ni β−
Qβ−(8700)
1.27 s β−
0.641 s
76 29 Cu β−
Qβ−(11700)
(for 0.641 s)
0+ 5.7 s
76 30 Zn β−
Qβ−4160
(2+,3+) 32.6 s
76 31 Ga β−
Qβ−7010
0+
76 32 Ge
2- 1.0778 d
76 33 As β−
Qβ−2962.0
0+
76 34 Se
1.31 s
16.2 h
76 35 Br
QEC4963
0+ 14.8 h
76 36 Kr
QEC1310
1(-) 36.5 s
76 37 Rb
QEC8498
0+ 8.9 s
76 38 Sr
QEC(6100)

Internal transition

Isomeric state



European Commission

Beta decay

"beta-minus": β^- $n \longrightarrow p + e + \bar{\nu}$

"electron capture" *EC* $e + p \longrightarrow n + \nu$

$\in$ in ToRI

"beta-plus": β^+ $p \longrightarrow n + \beta^+ + \nu$

(If Q > 1022 keV)

European Commission

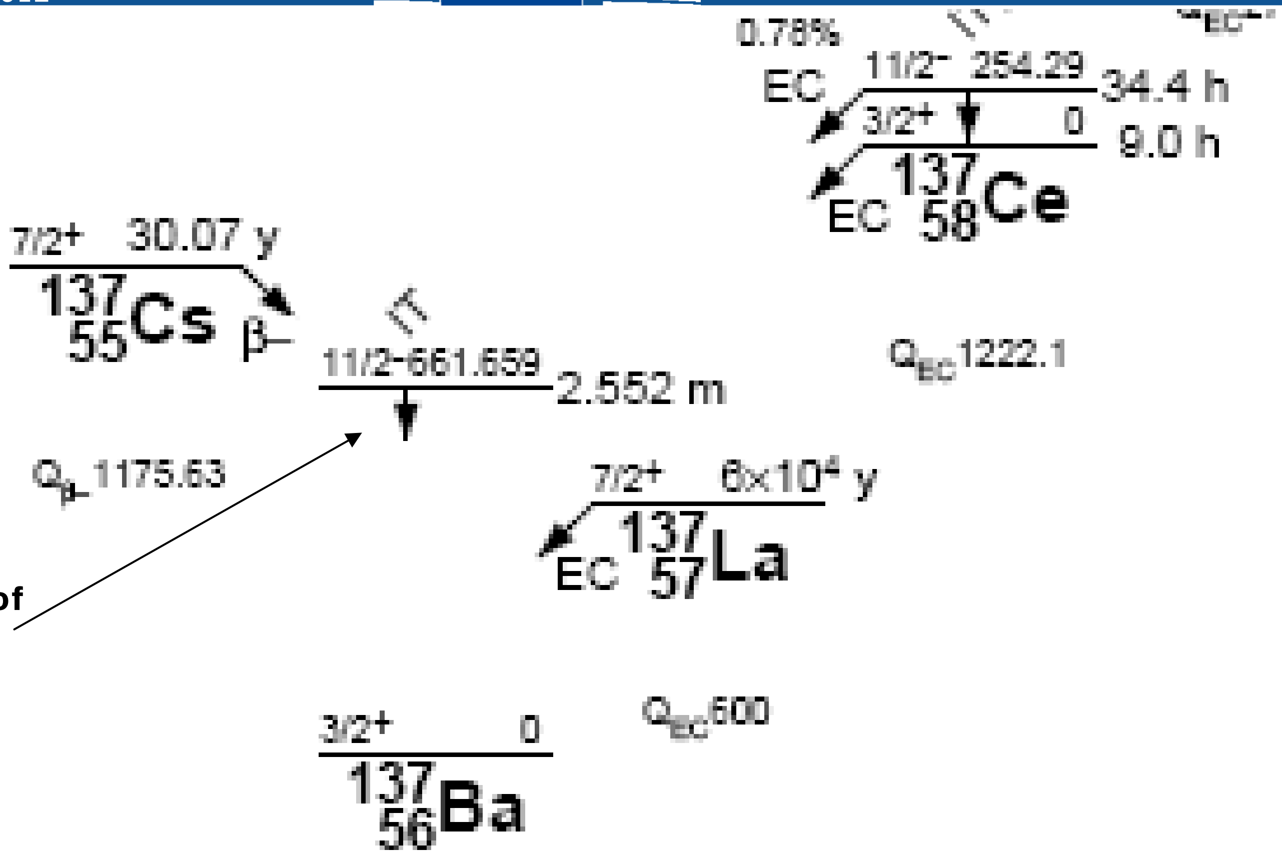
Beta decay

"beta-minus": β^{-} $^{137}Cs \longrightarrow {}^{137}Ba + e + \bar{\nu}$

"electron capture" *EC* $^{109}Cd \longrightarrow {}^{109}Ag + \nu$

"beta-plus": β^{+} $^{22}Na \longrightarrow {}^{22}Ne + \beta^{+} + \nu$

Some radionuclides can decay with several different beta decays



What type of transition?

Conversion coefficient?

http://ie.lbl.gov/toi/nuclide.asp?iZA=560437

One cannot measure ^{137}Cs using (normal) $4\pi\beta-\gamma$ coincidence technique

European Commission

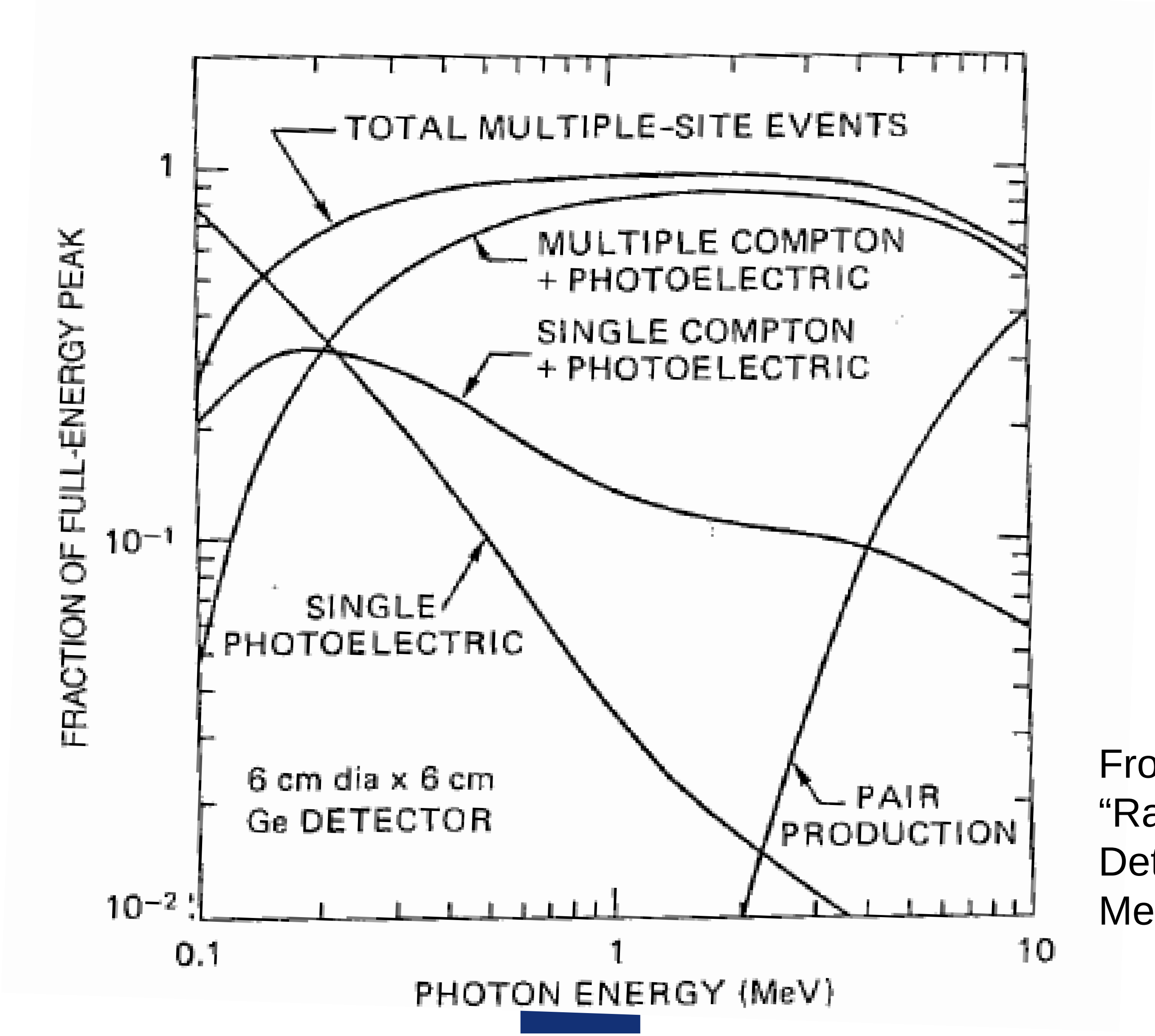
Interactions of Gamma Rays with Matter

- The interactions of gamma rays with matter all produce **high energy electrons** which cause measurable ionisation in the material through which they pass.

Interactions of Gamma Rays with Matter

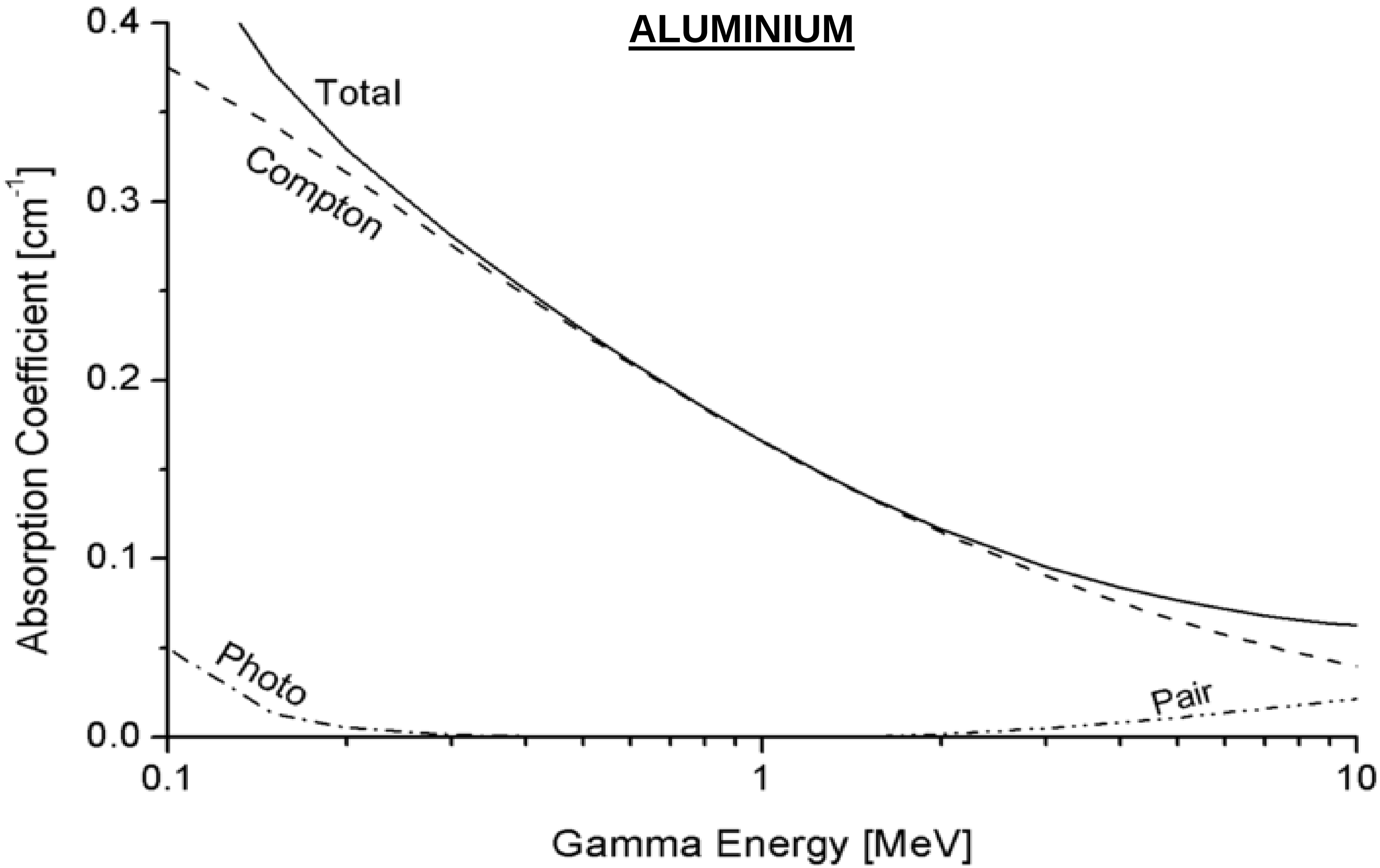
- Photoelectric effect
- Compton effect
- Pair production

Interactions of Gamma Rays with Matter

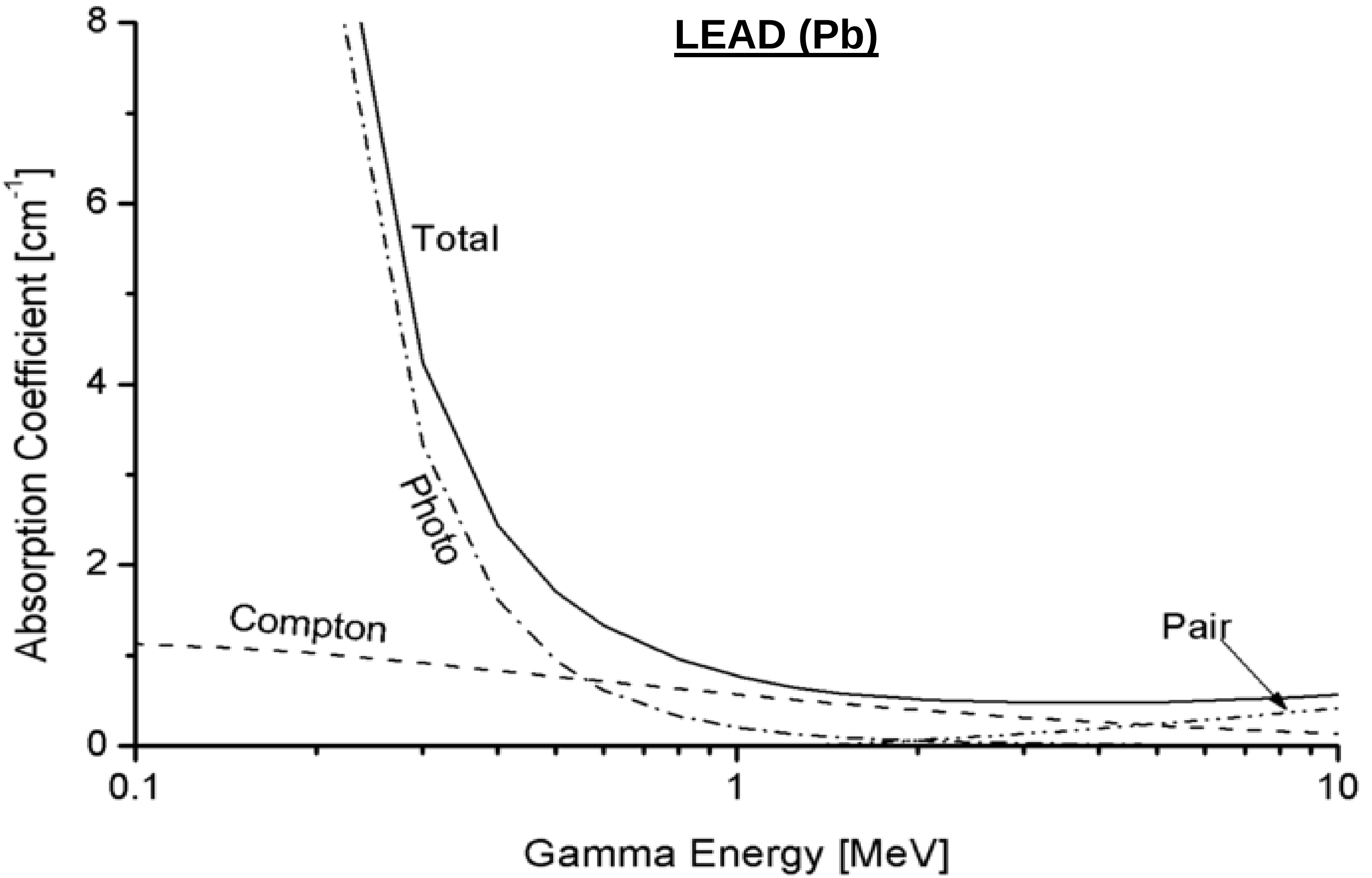


From Knoll, "Radiation Detection and Measurements"

Interactions of Gamma Rays with Matter



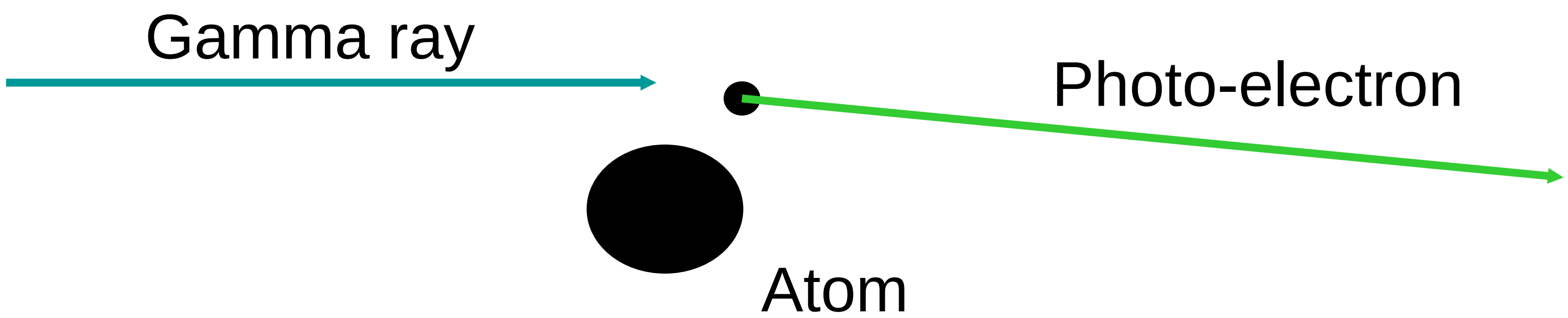
Interactions of Gamma Rays with Matter



European Commission

Interactions of Gamma Rays with Matter

- **Photoelectric Effect**
- The gamma-ray gives up all its energy to a bound electron;
- energy and momentum cannot be simultaneously conserved in such a reaction with a free electron.



Photoelectric Effect

- Conservation of energy:

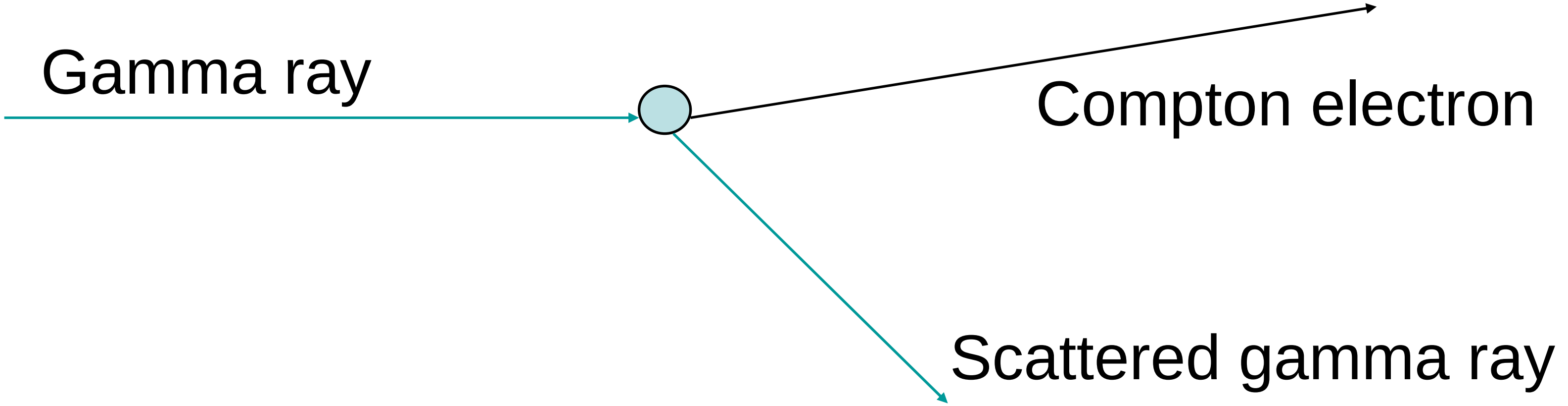
$$E_e = E_\gamma - E_b$$

$$\text{where } E_b \text{ is the electron binding energy.}$$

- The photoelectric effect is most important at low gamma ray energies and for high atomic number materials.

Interactions of gamma rays with matter

- **Compton Scattering** is an interaction between a gamma ray and an electron where the gamma ray gives up part of its energy to the electron.
- This interaction may occur with free electrons.



European Commission

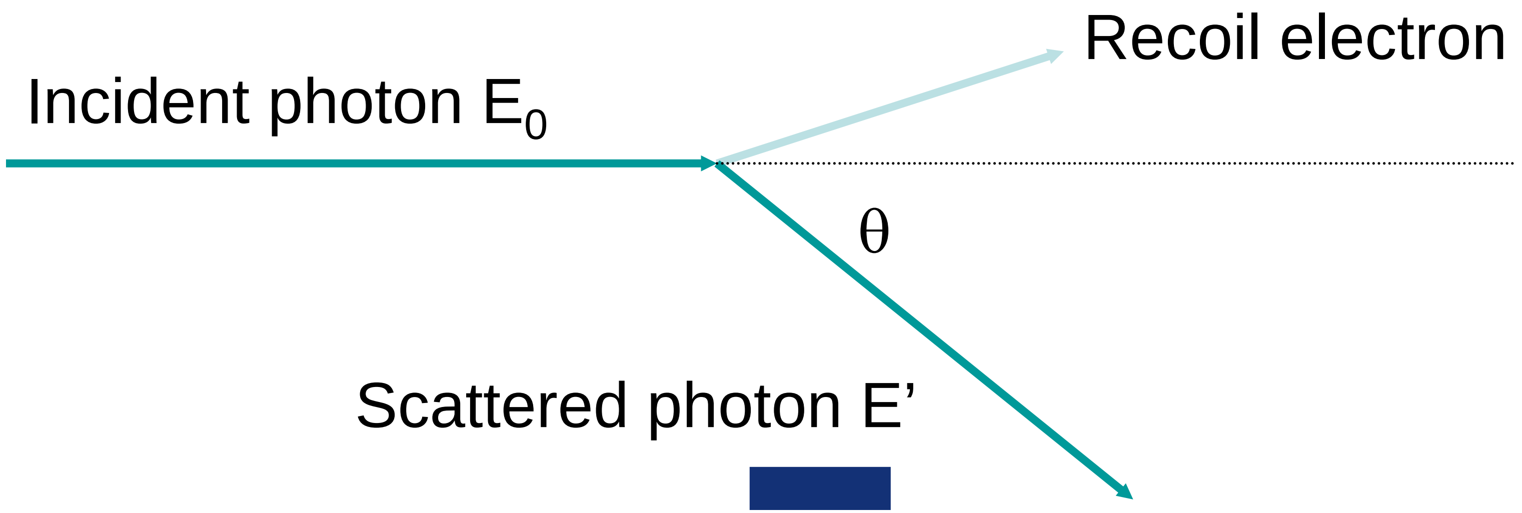
Compton Scattering

- In this reaction, the outgoing electron can have an energy between zero (gamma ray continues with the same energy and direction) and a maximum value when the gamma ray is scattered through 180^0.
- Compton scattering dominates for intermediate gamma ray energies (100 keV – 10 MeV) and for low to medium atomic number materials.

European
Commission

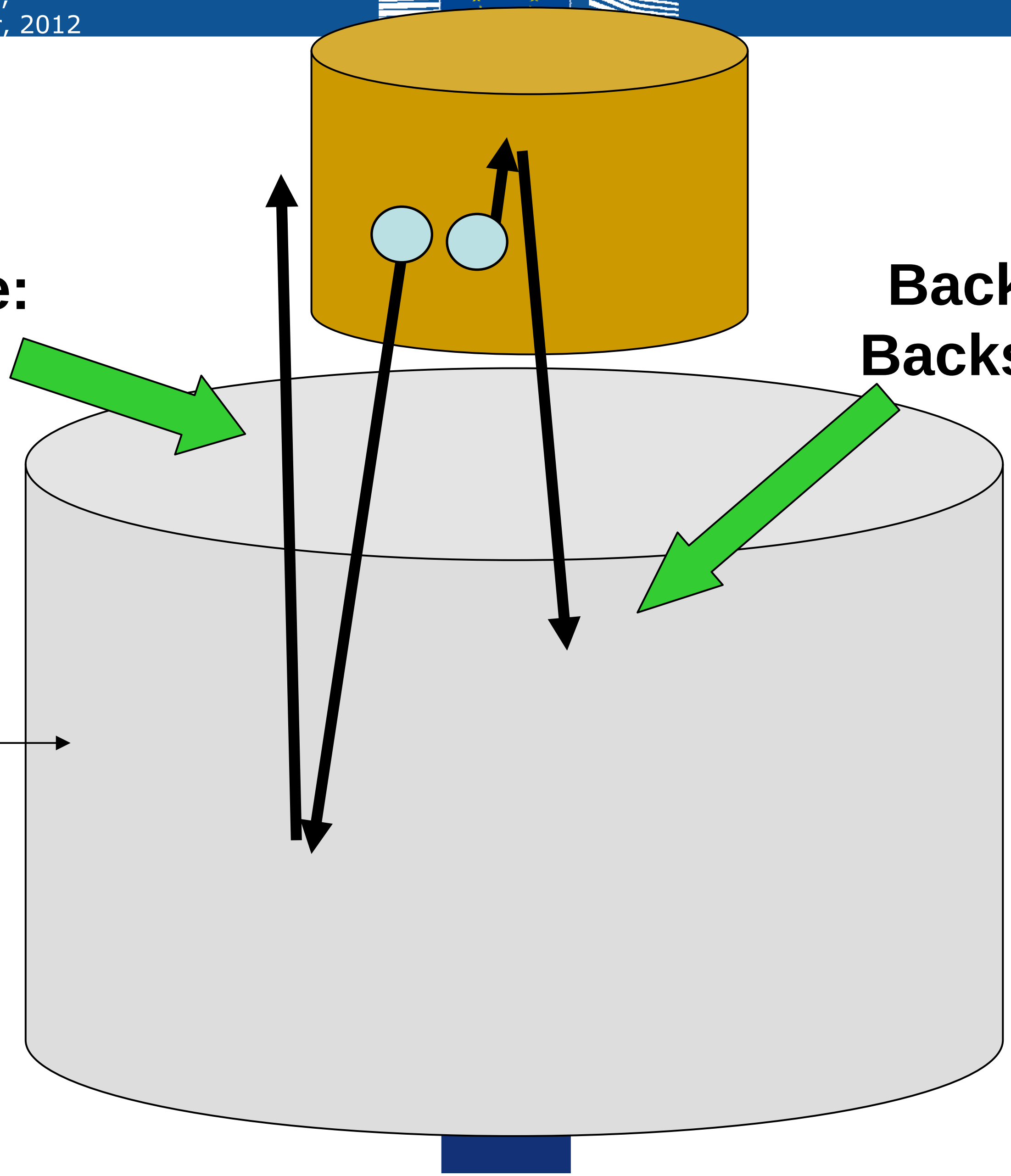
Compton Scattering

$$E' = \frac{E_0}{1 + \frac{E_0}{m_0 c^2}(1 - \cos\theta)}$$



Compton edge:
Backscatter inside crystal

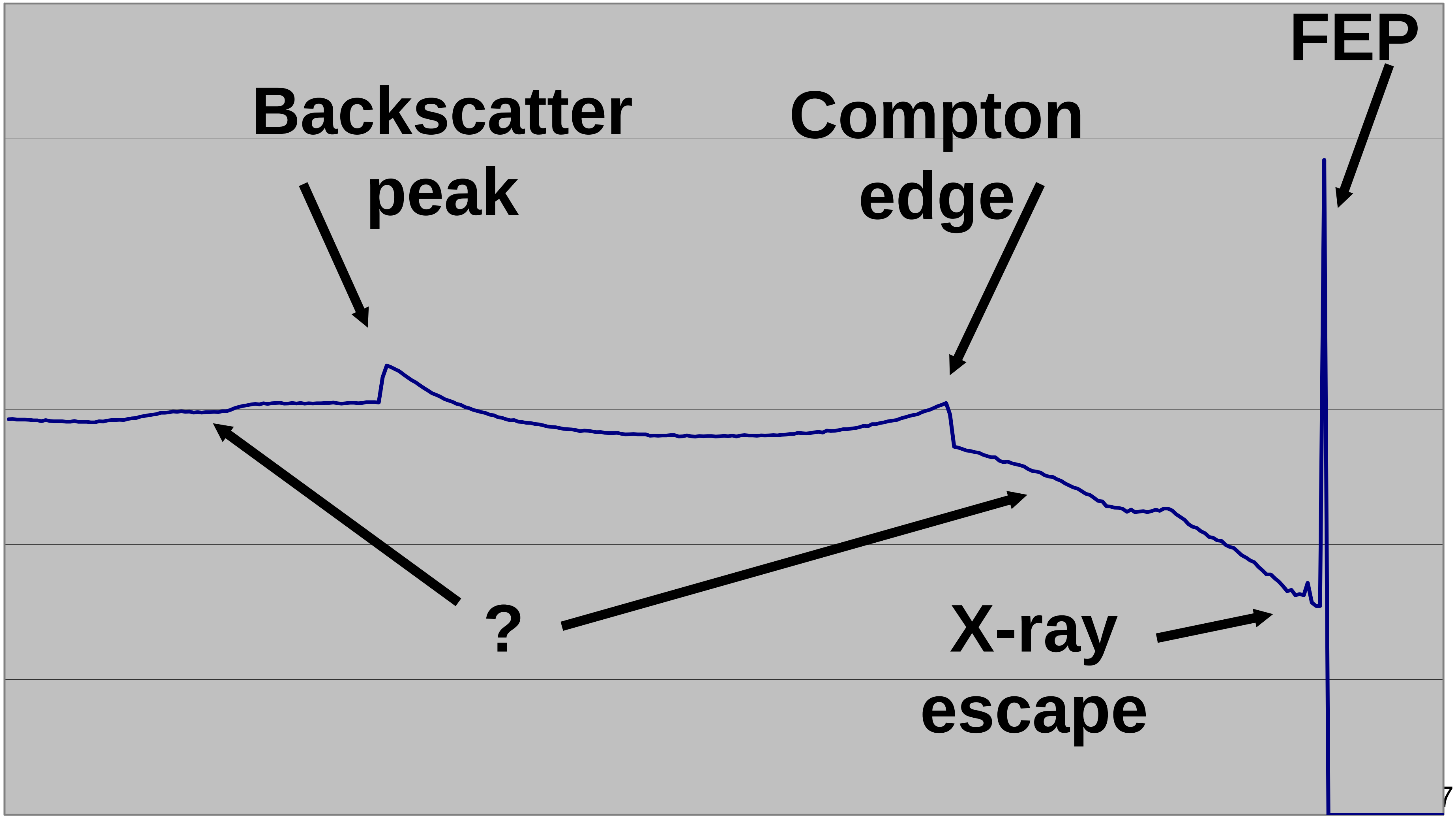
Backscatter peak:
Backscatter outside crystal



Detector

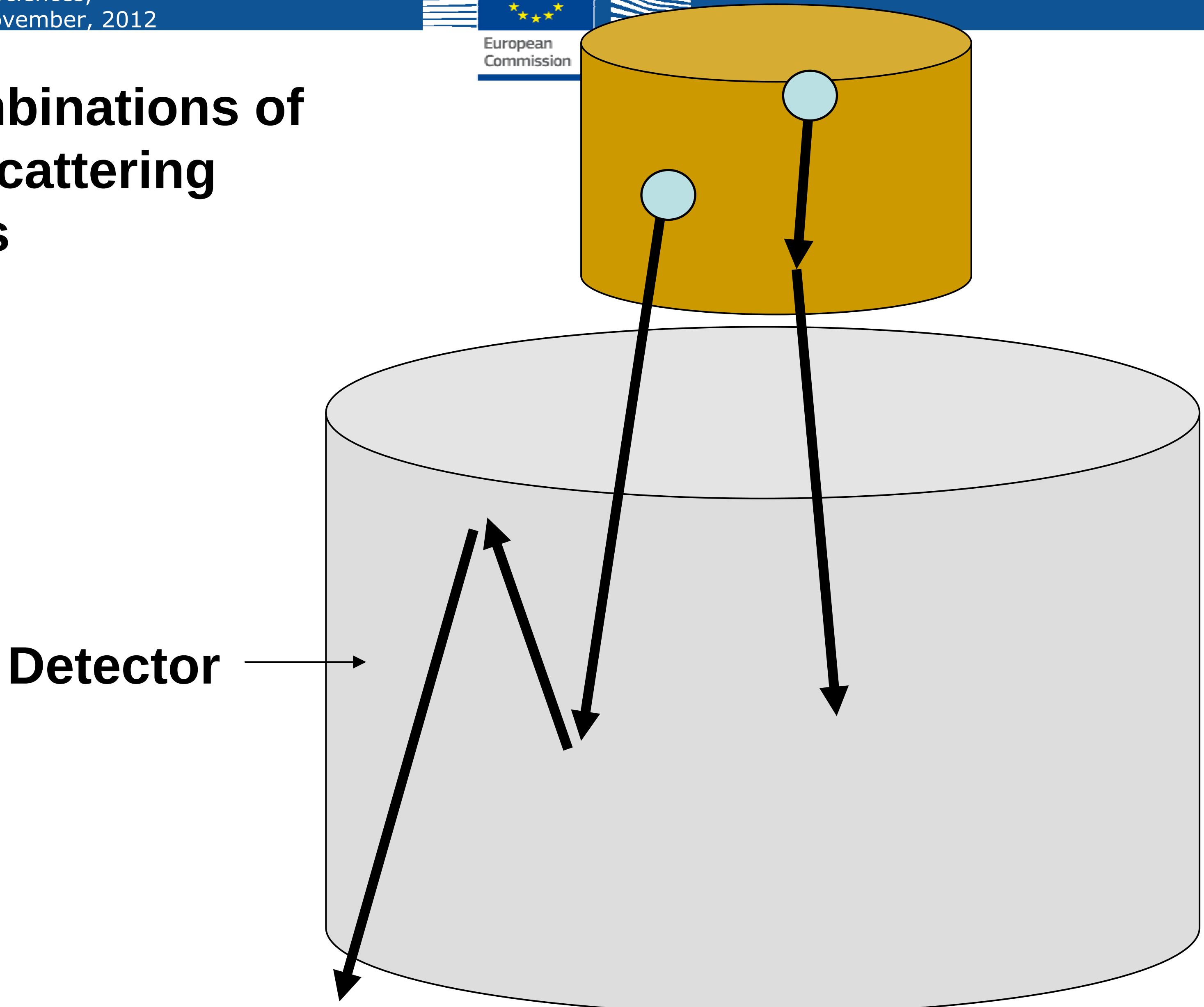
European Commission

HPGe-response function

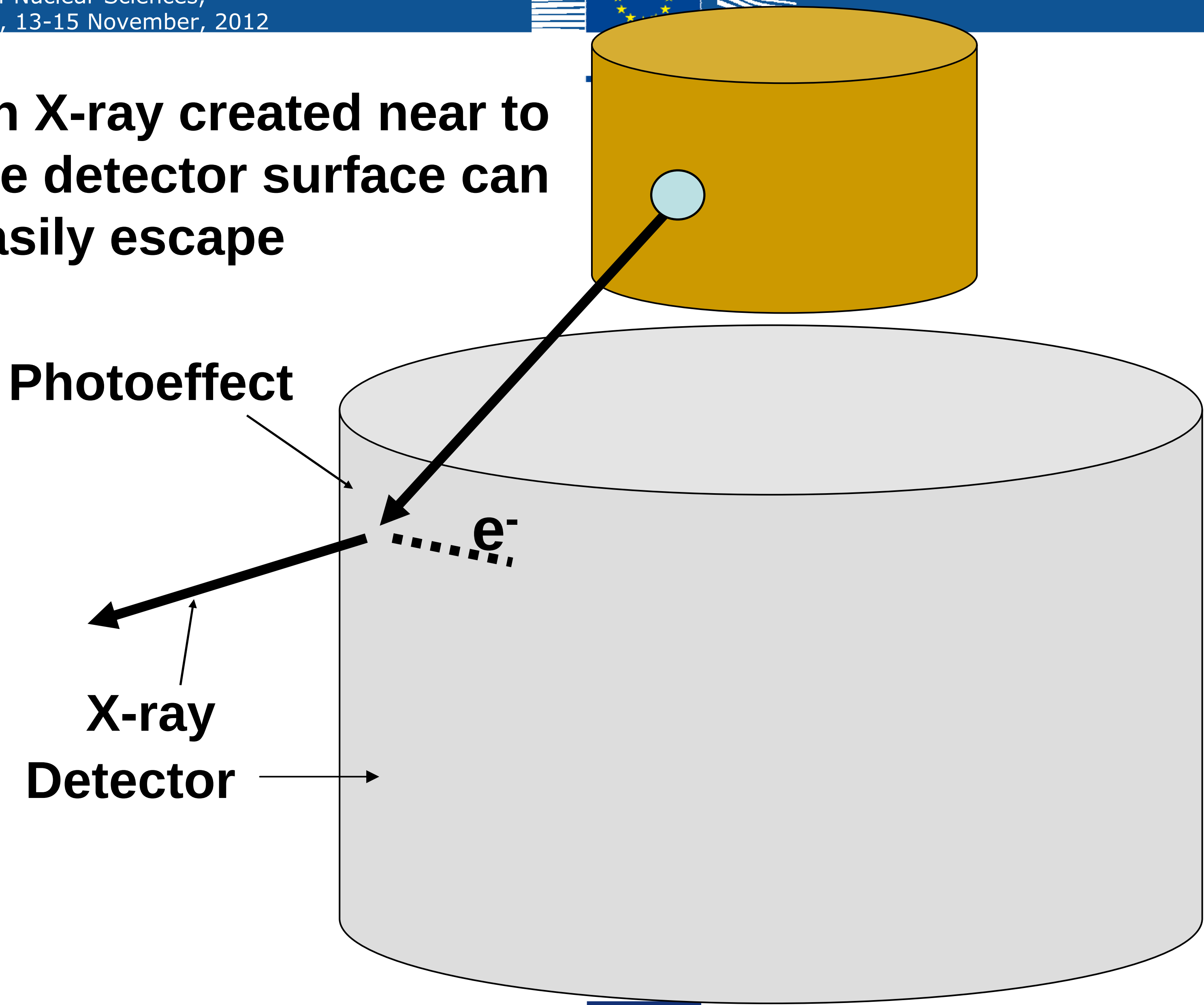


European Commission

Many combinations of multiple scattering processes



An X-ray created near to the detector surface can easily escape



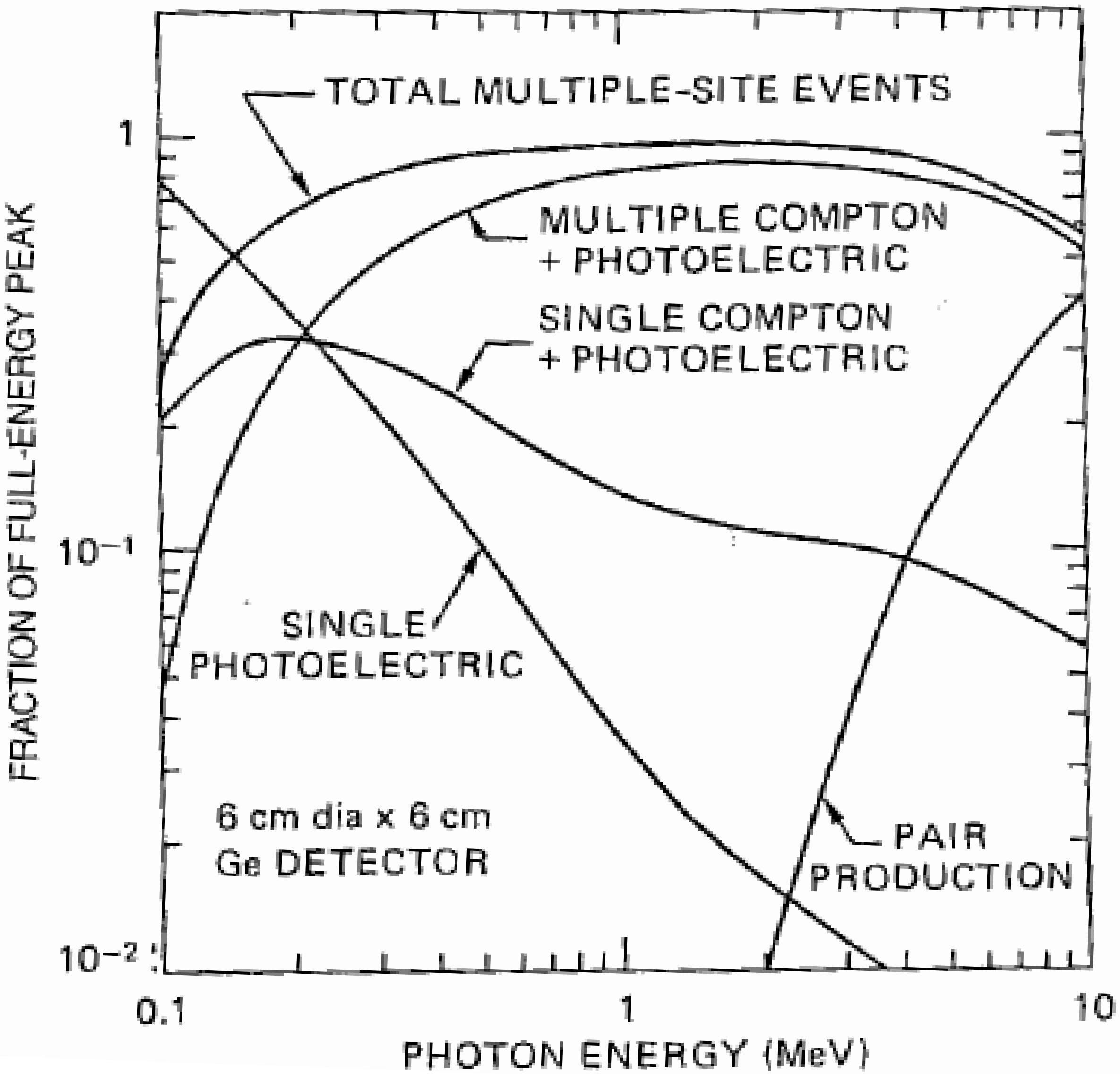
Pair Production

- In this reaction the gamma ray interacts with the Coulomb field of a nucleus to produce an electron-positron pair.

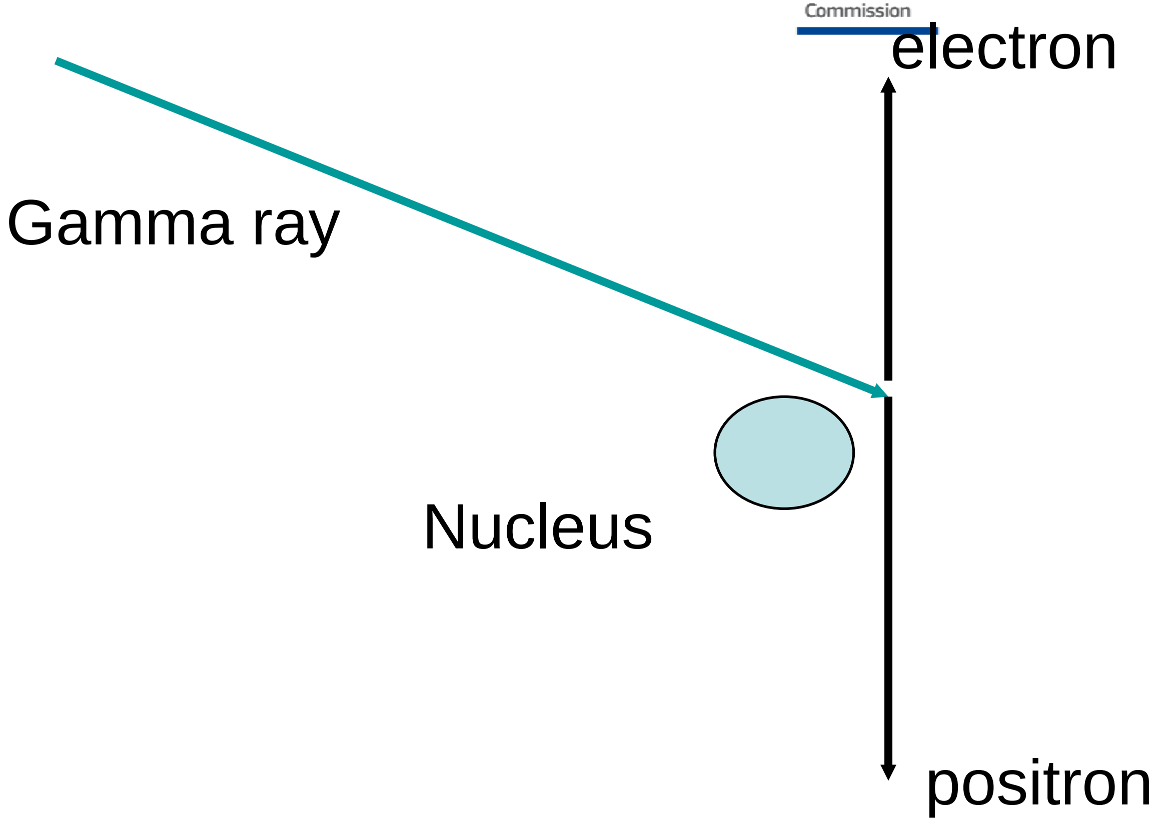
- The gamma ray energy must be greater than the the energy corresponding to the rest mass of two electrons, i.e. 2 x 511 keV = 1022 keV.

- Pair production becomes the most important interaction for gamma rays above a few MeV.

Interactions of Gamma Rays with Matter



From Knoll, “Radiation Detection and Measurements”

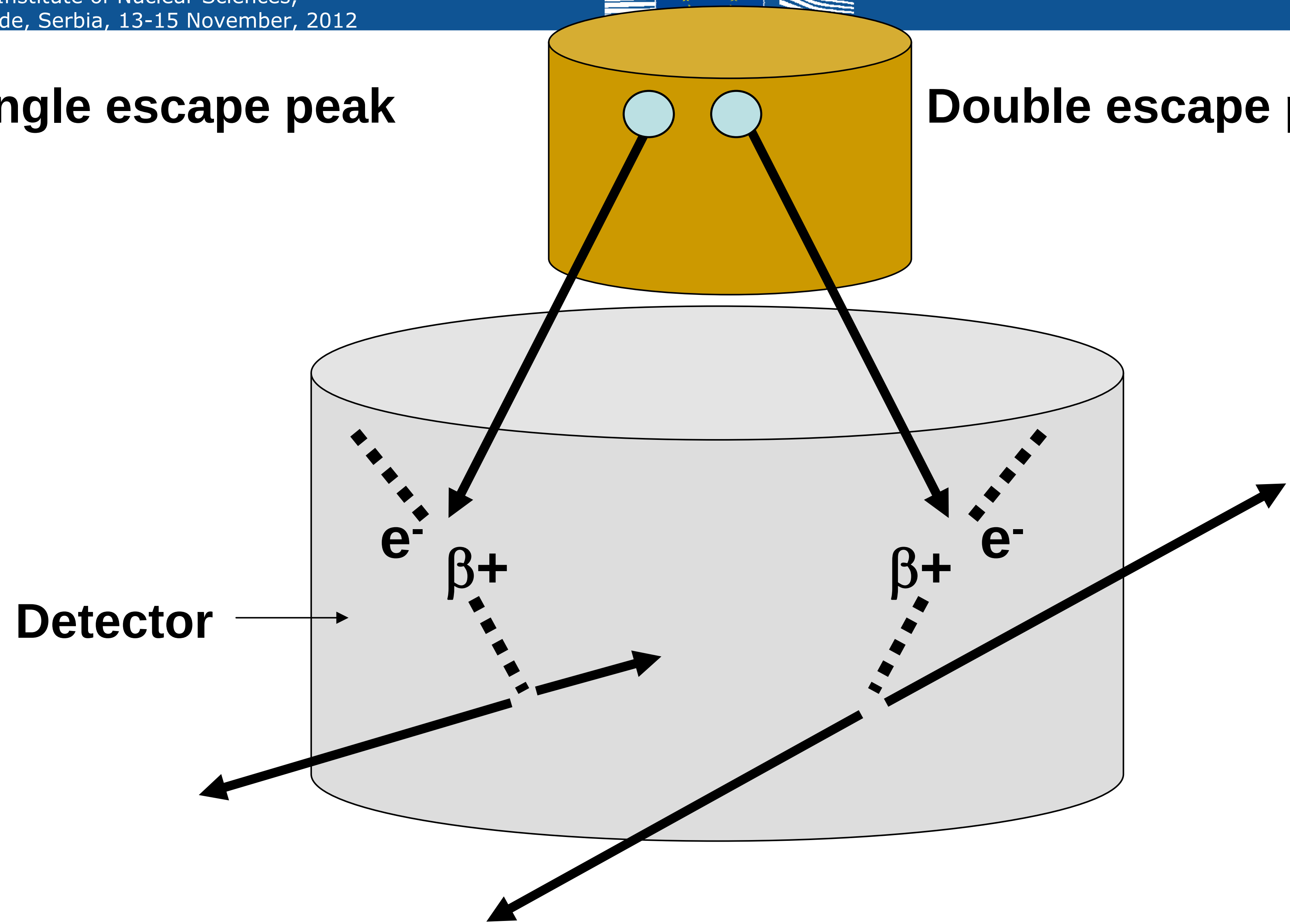


Pair Production

For E> 1022 keV

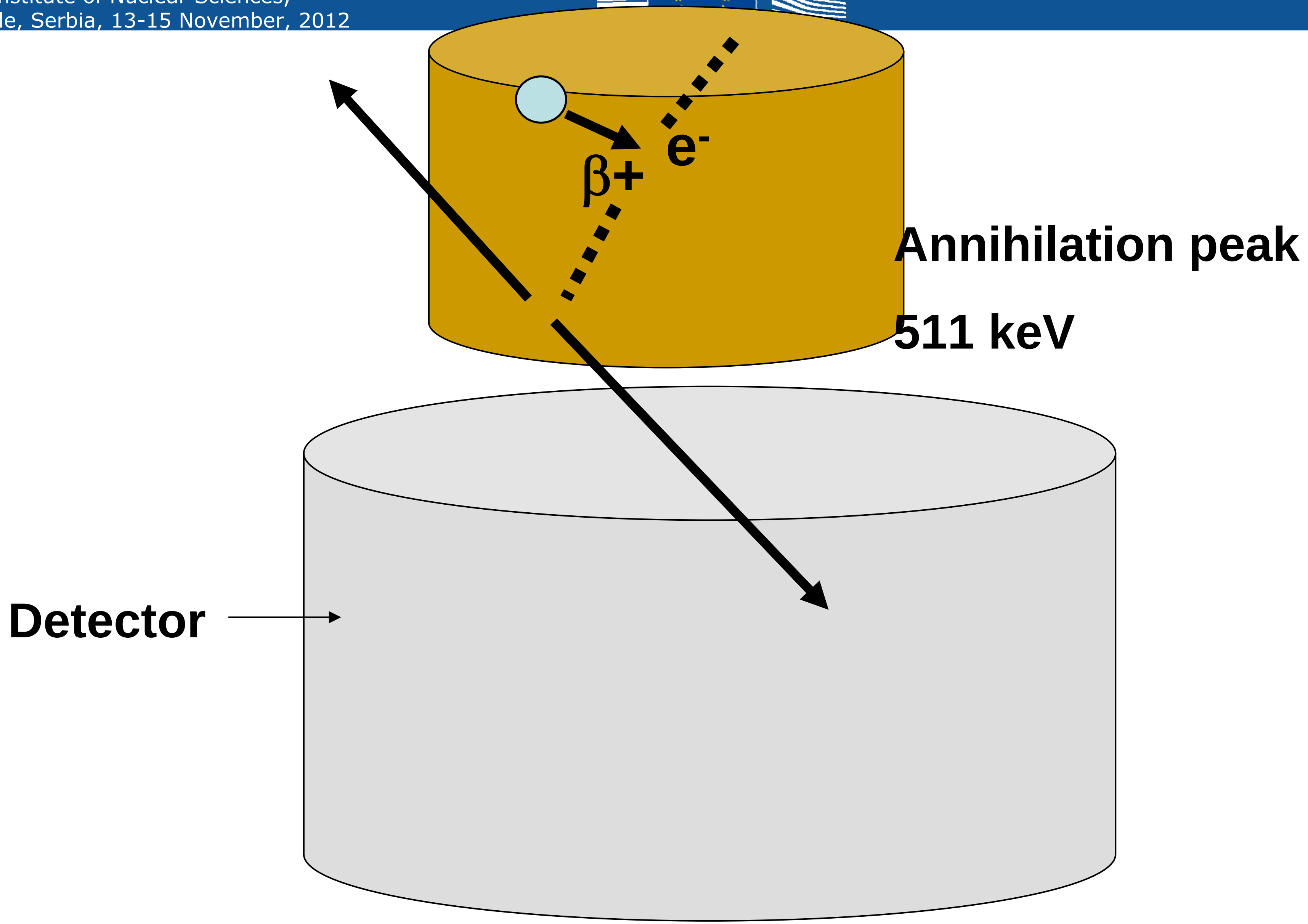
Single escape peak

Double escape peak



For E> 1022 keV

Vinča Institute of Nuclear Sciences,
Belgrade, Serbia, 13-15 November, 2012



European Commission

Spectrum from a gamma ray detector

- What you really measure in a gamma ray spectrometer is the energies of the electrons produced by the gamma ray interactions described above.

- **Photopeak:** produced by the total absorption of the gamma ray energy in the detector.
  Better word: **Full energy peak or FEP**

European Commission

Spectrum from a gamma ray detector

- **Compton continuum:** at energies lower than the FEP we see a continuum resulting from mainly Compton interactions where only part of the gamma ray energy has been deposited in the detector.

European Commission

Spectrum from a gamma ray detector

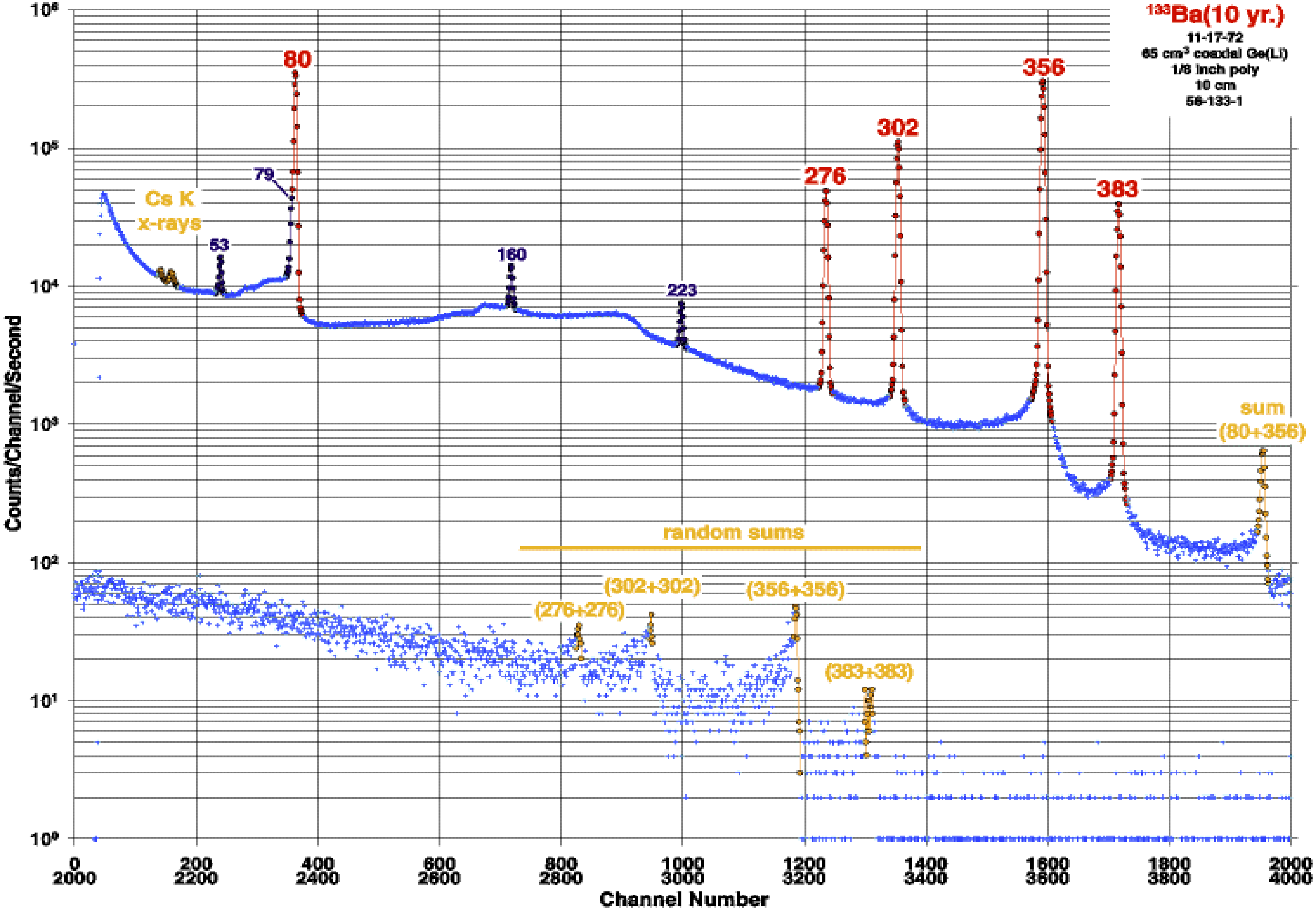
- **<u>Pair production:</u>** when this occurs the positron will annihilate with a another electron in the detector to produce two 511 keV photons.

- What you see in the spectrum depends on whether these two photons are absorbed in the detector or escape from it.

- If one photon escapes, you will find a peak at exactly 511 keV below the main photopeak, known as a single escape peak.

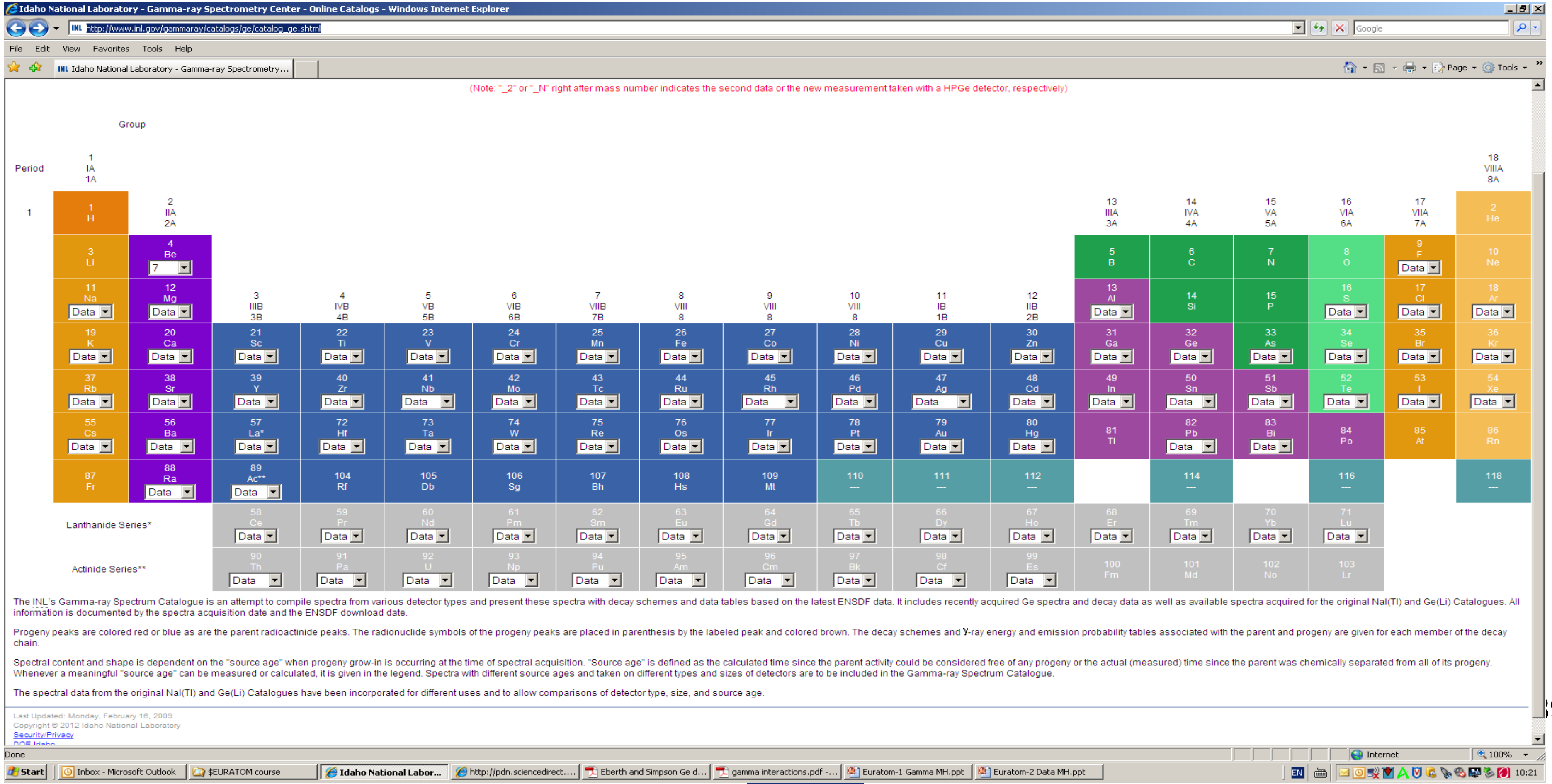
Germanium Spectrum of Barium-133

Vinča Institute of Nuclear Sciences,
Belgrade, Serbia, 13-15 November, 2012

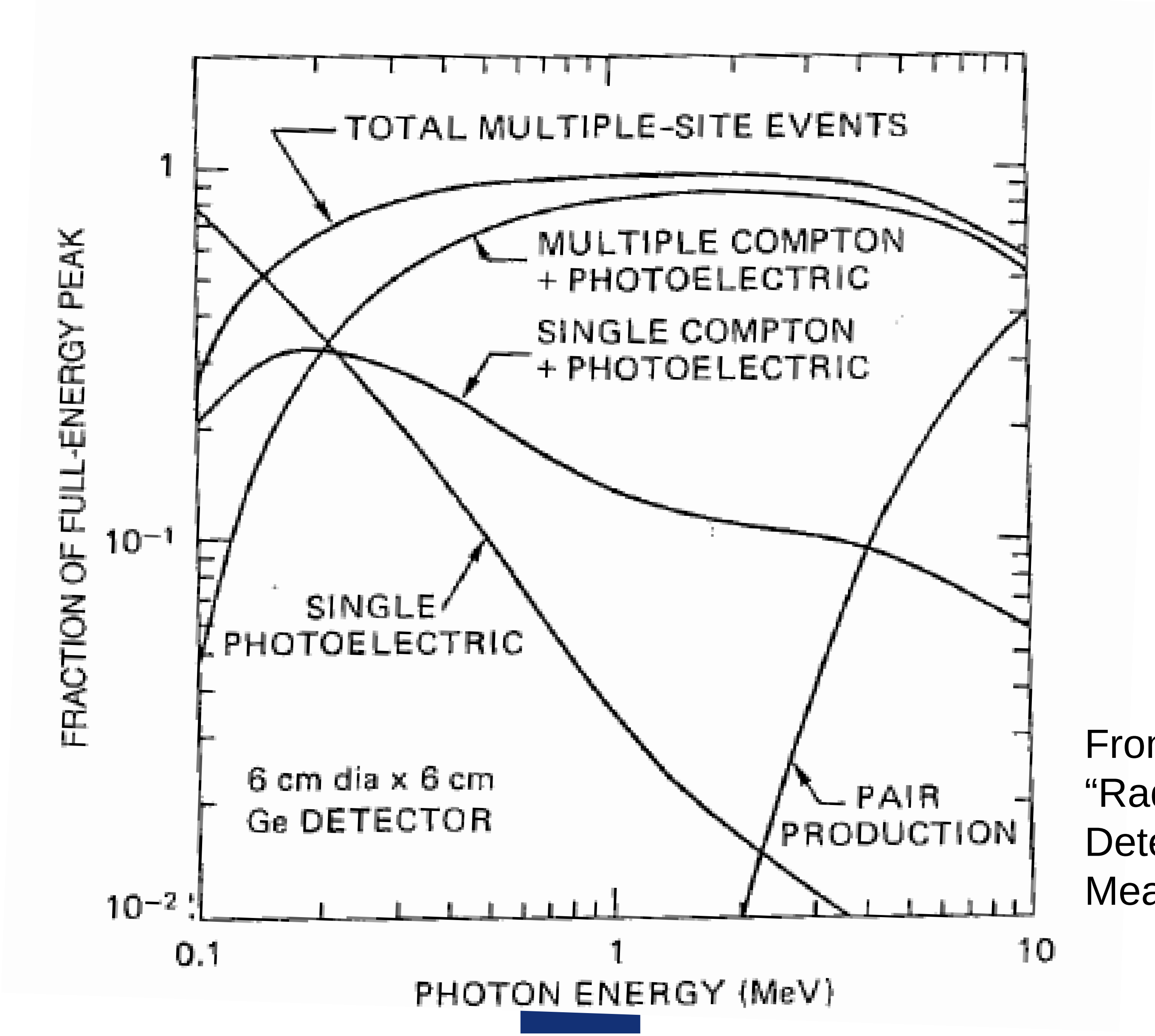


Examples of gamma-ray spectra – today easy to find on the web.

http://www.inl.gov/gammaray/catalogs/ge/catalog_ge.shtml



Interactions of Gamma Rays with Matter



From Knoll, "Radiation Detection and Measurements"