Characterization of a scintillator-based γ-ray detector

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Goals for this experience

- Understand the principle of operation of a **γ-ray detector** based on **scintillating crystals**.
- Understand the working principle of a **solid-state photodetector** and its front-end **electronic chain**.
- Hands-on experience in laboratory:
    - ➡ Acquire spectra of radioactive sources
    - ➡ Calibration and derivation of principal operating parameters of the detector
    - ➡ Have fun!

Scintillators

- In the γ-ray range from ~100 keV to ~20 MeV scintillator-based detectors are the **most common** ones
- A *scintillator* is a material that **converts an energy deposit** (from a photon or a charged particle) in **optical photons**
- The amount of light generated is **proportional** to the deposited energy

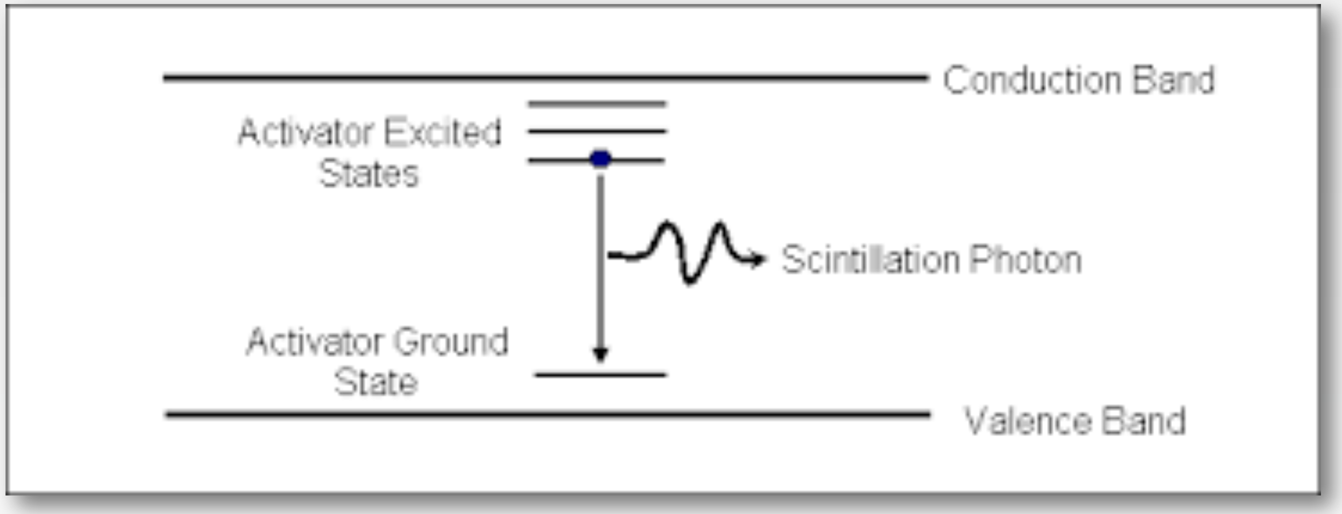
Scintillators

Scintillators

Two main families of scintillators

ORGANIC	**INORGANIC**
Liquids, plastics	*Crystals*
(e.g. LXe, anthracene)	(e.g. CsI, NaI, $LaBr_3$, ...)
• Low density and stopping power	• High density and stopping power
• Low mean atomic number	• High mean atomic number
• Fast light output (~ns)	• Slow(er) light output
• Easily customizable in shape and dimensions	• More photons per energy deposit w.r.t. organics (better energy resolution)
• Lightweight	• Heavy
• Inexpensive	• Better linearity
• Non linear	

Inorganic scintillators



Inorganic crystals are *doped*, e.g. with Tl or Ce: scintillation light is emitted thanks to the additional activator energy levels

Main characteristics

- ✓ Emission spectrum
- ✓ Light output (ph/MeV)
- ✓ Mass and density
- ✓ Energy resolution
- ✓ Hygroscopicity
- ✓ Internal background

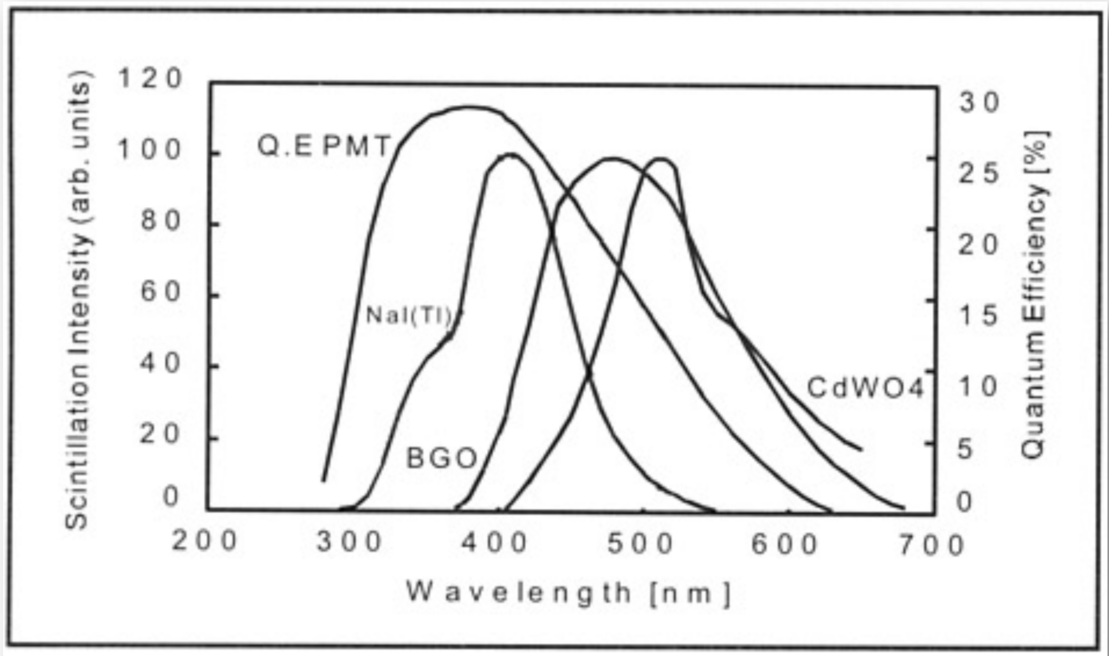


Fig. 3.1 ***Emission spectra of NaI(Tl), BGO and $CdWO_4$, scaled on maximum emission intensity.***

Inorganic scintillators

Material	Density (g/cm^3)	Radiation length, X_0 (cm)	PL output (Photons/MeV)	Decay (ns)	Application
NaI:Tl	3.67	2.59	38000	230	General purpose
CsF	4.11	2.23	2000	2.8	
CsI:Tl$^+$	4.53	1.86	59000	1050	X-CT
CsI	4.51	1.85	30*	6, 35	
$Bi_4Ge_3O_{12}$	7.13	1.12	8200	300	PCT, NP, HE
$CdWO_4$	7.68	1.06	15000	5000	X-CT
Gd_2SiO_5:Ce	6.71	1.38	10000	60	PET
Lu_2SiO_5:Ce	7.4	1.14	30000	40	PET
$PbWO_4$	8.2	0.92	490	10	HE

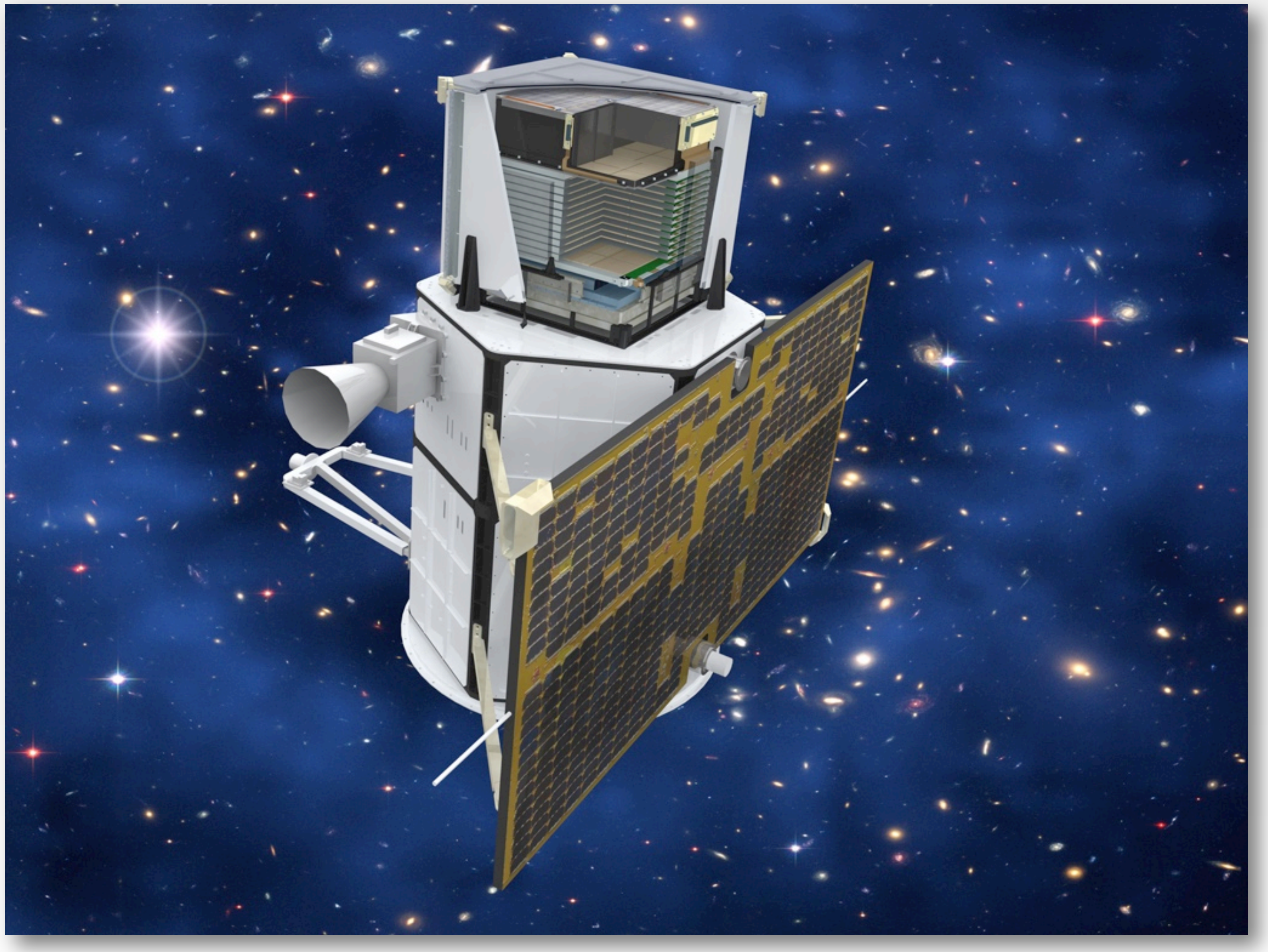
NP: Nuclear physics experiment

HE: High energy physics experiment

* Faster decay component

+ Slight hygroscopicity

Example of scintillators in high-energy astrophysics

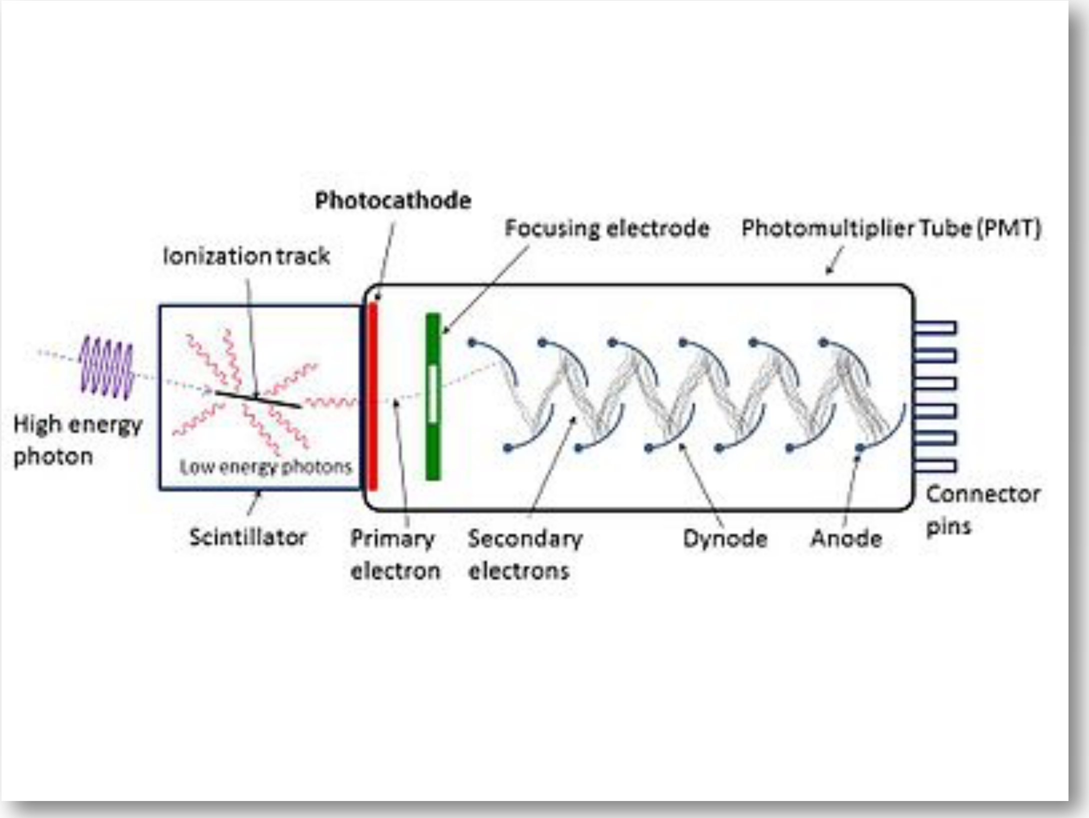


The AGILE anticoincidence and minicalorimeter are made of scintillators (plastic and CsI)

FERMI Gamma Burst Monitor has 12 NaI and 2 BGO crystals coupled with PMTs, while LAT has a CsI calorimeter

Photodetectors

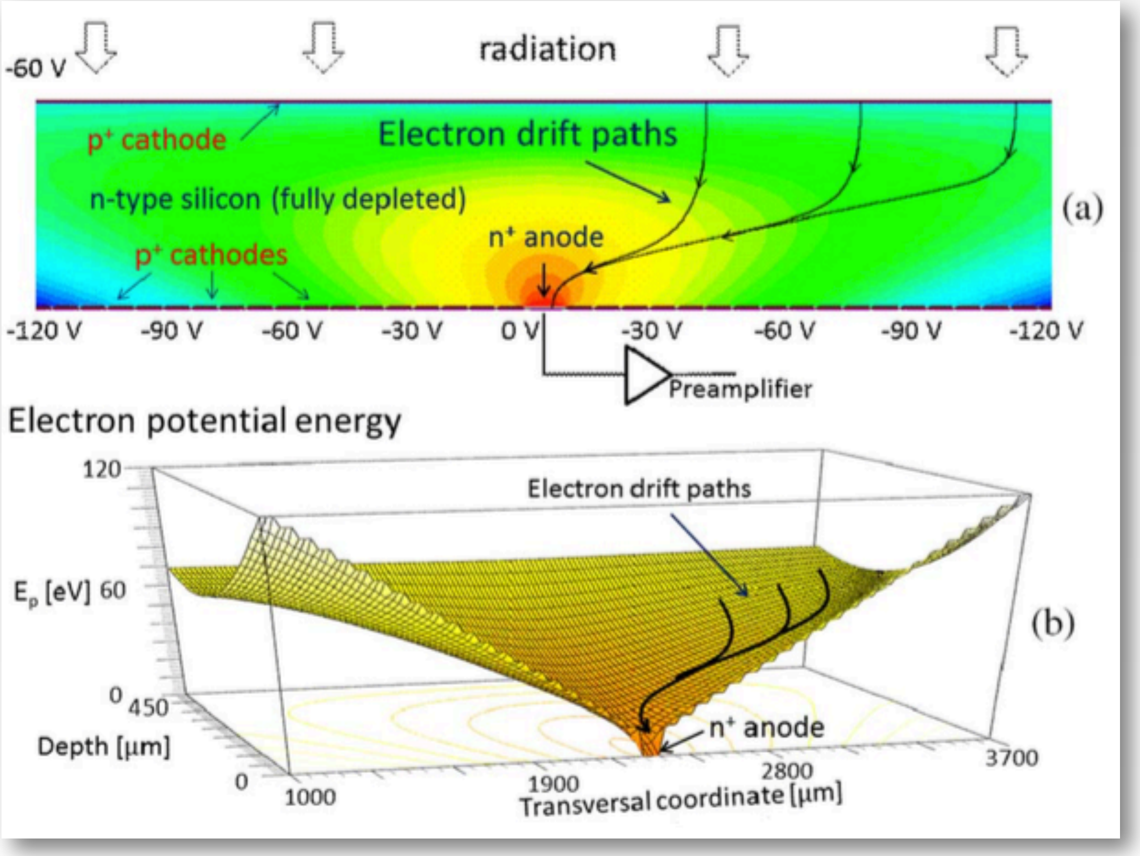
- The scintillation light has to be **collected** and **read out**!
- The most common photodetector is the **Photomultiplier Tube** (PMT)
- Also: **solid state** detectors (SiPM, APD, Silicon Drift Detectors...)



Silicon Drift Detectors

In this experience, we will use a **Silicon Drift Detector**, a very promising solid-state detector invented by Emilio Gatti and Pavel Rehak in 1984.

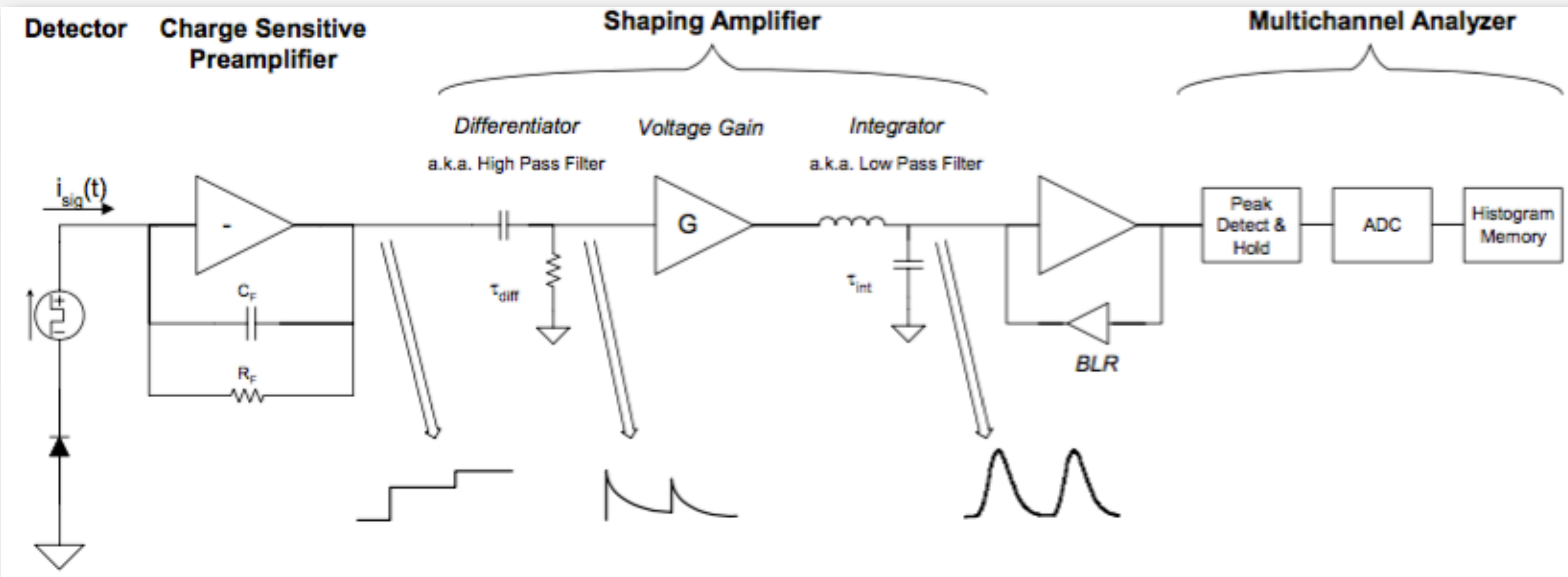
With respect to PMTs, they have a **much lower noise** (thus better energy resolution), **mass** and **power consumption** (crucial for **space** applications), but require a much more sophisticated readout electronics (no **intrinsic gain**)
While being mostly X-ray (and particle) detectors, they are **sensitive also to optical light.**



http://redsox.iasfbo.inaf.it

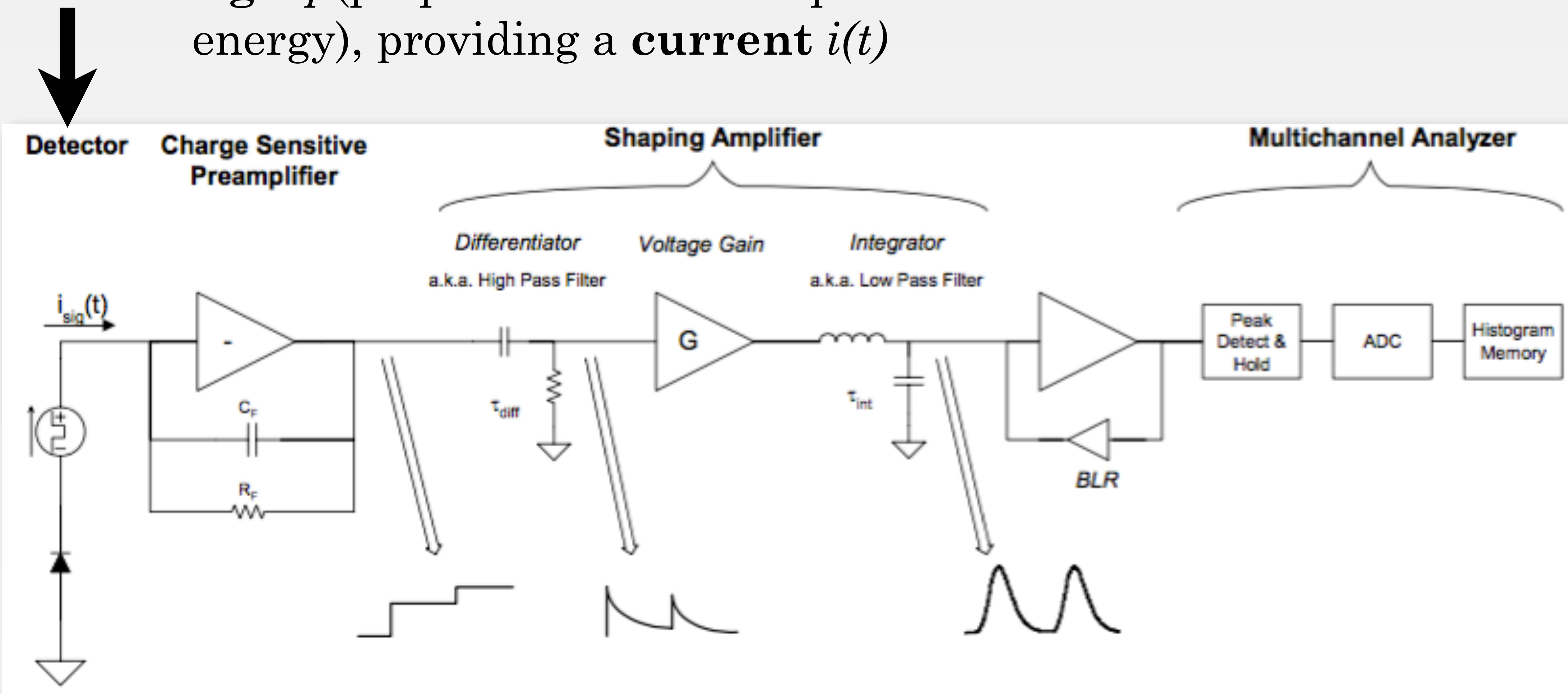
Acquisition chain

In the lab, we will see each step of a classical **analog acquisition chain**



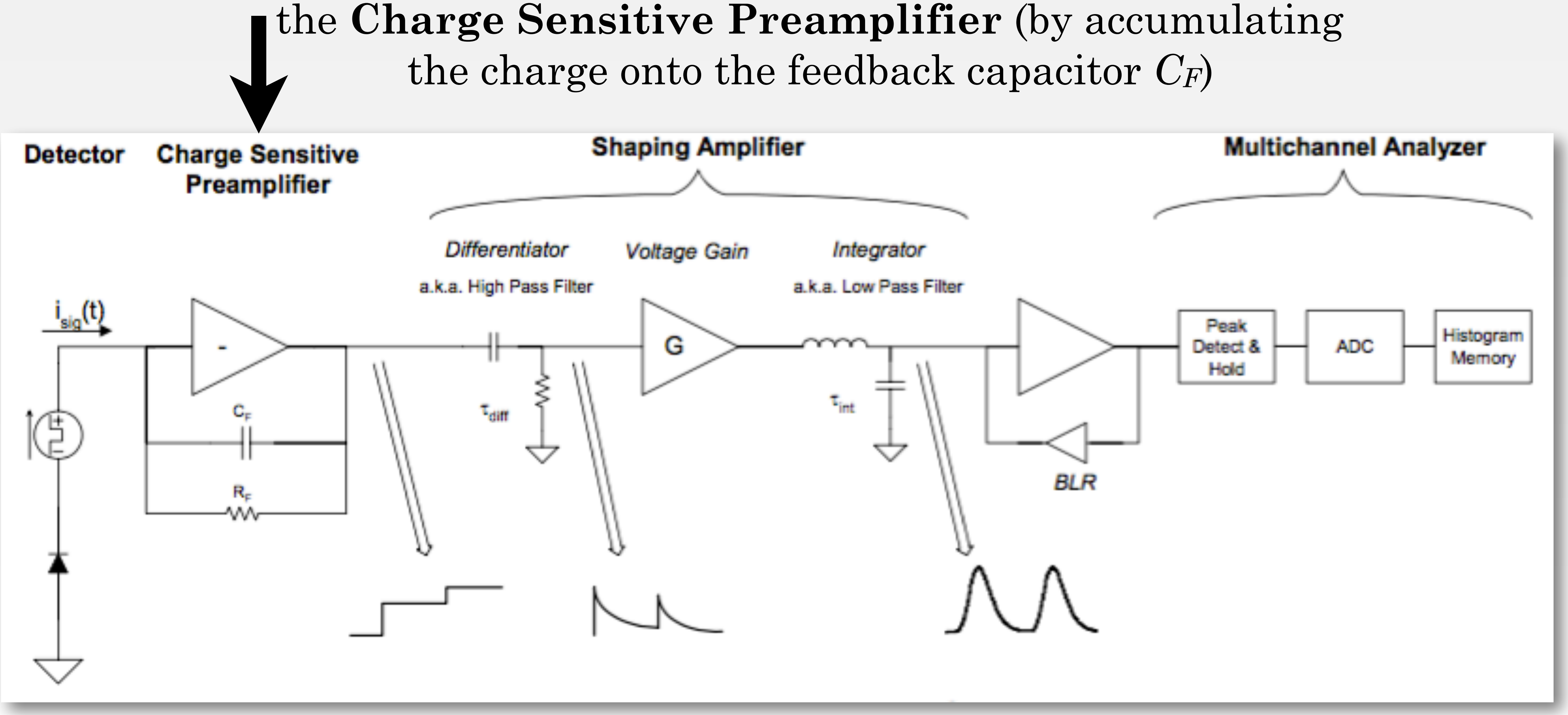
Acquisition chain

I. At the detector anode arrives a quantity of **charge** *q* (proportional to the deposited energy), providing a **current** *i(t)*



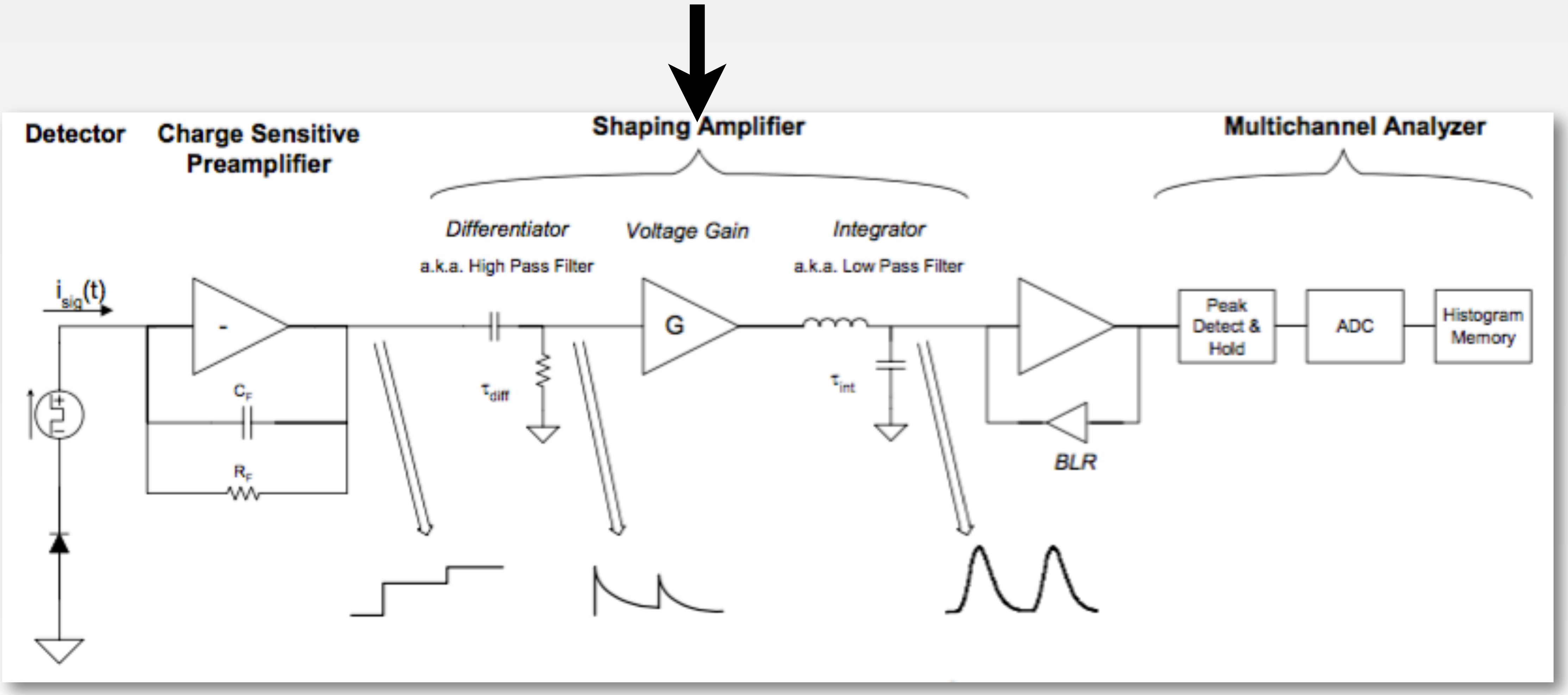
Acquisition chain

II. The current *i(t)* is converted in a **voltage step** by the **Charge Sensitive Preamplifier** (by accumulating the charge onto the feedback capacitor C_F)



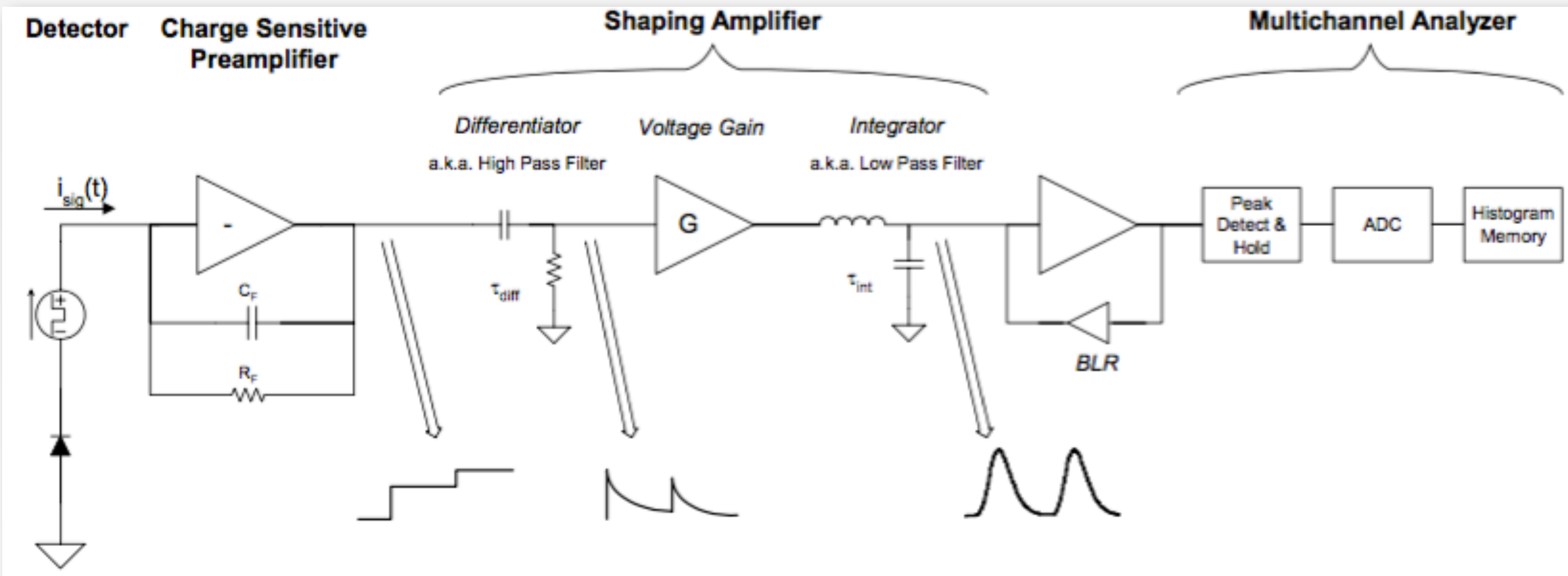
Acquisition chain

III. The **shaper** amplifies the signal, changing its shape to maximize the signal-to-noise ratio and minimize pile-up



Acquisition chain

IV. The peak voltage value is proportional to the deposited energy. Its value is detected, digitized and stored e.g. by means of a **multichannel analyzer**

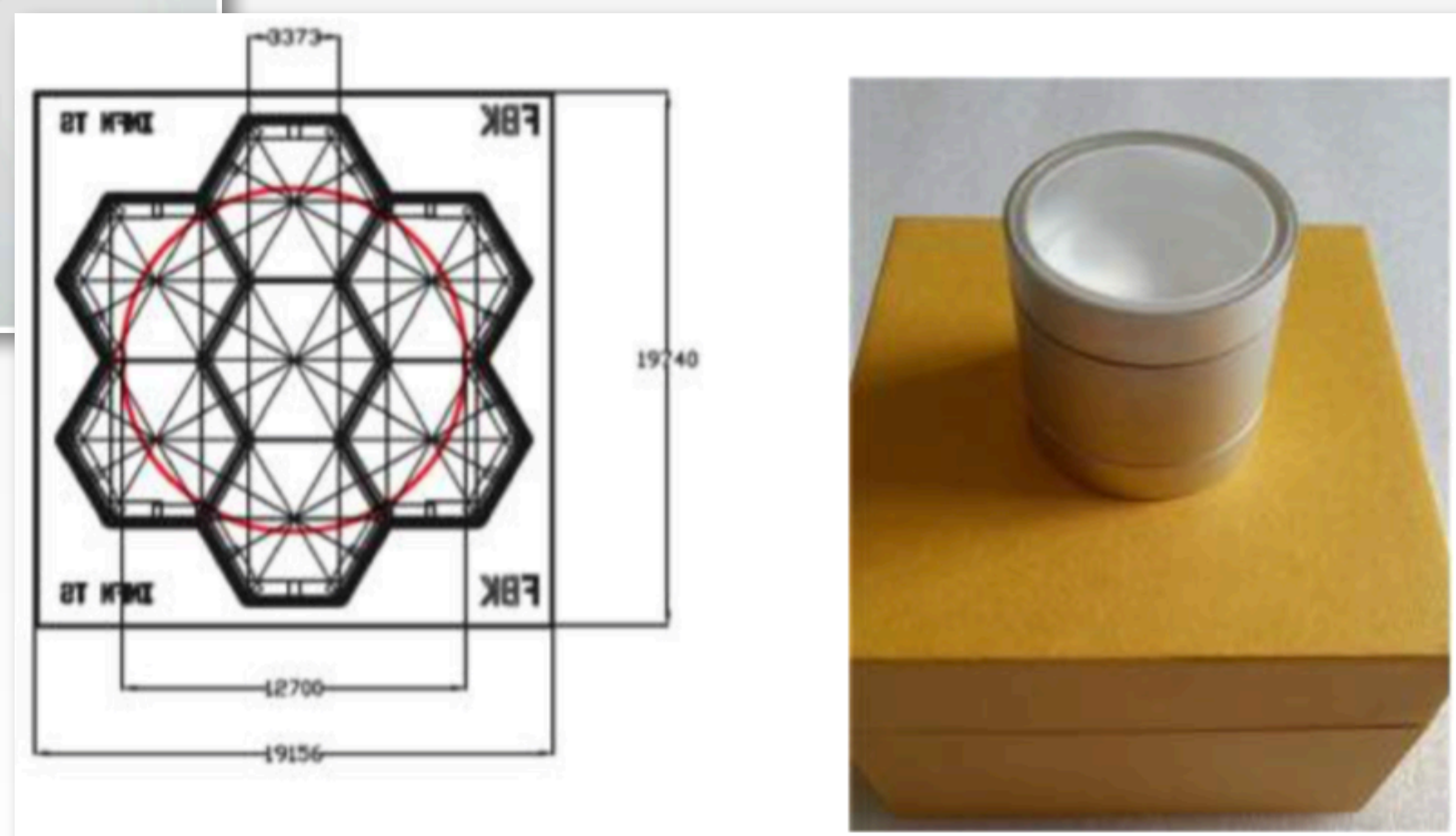


Laboratory experience

- We will use a multi-anode Silicon Drift Detector: a matrix of **7 independent hexagonal SDD cells**
- We will use a cerium-activated lanthanum bromide scintillator: **$LaBr_3$(Ce)**, one of the most recent and promising crystals: fast, high light output, excellent energy resolution, but hygroscopic and intrisically radioactive

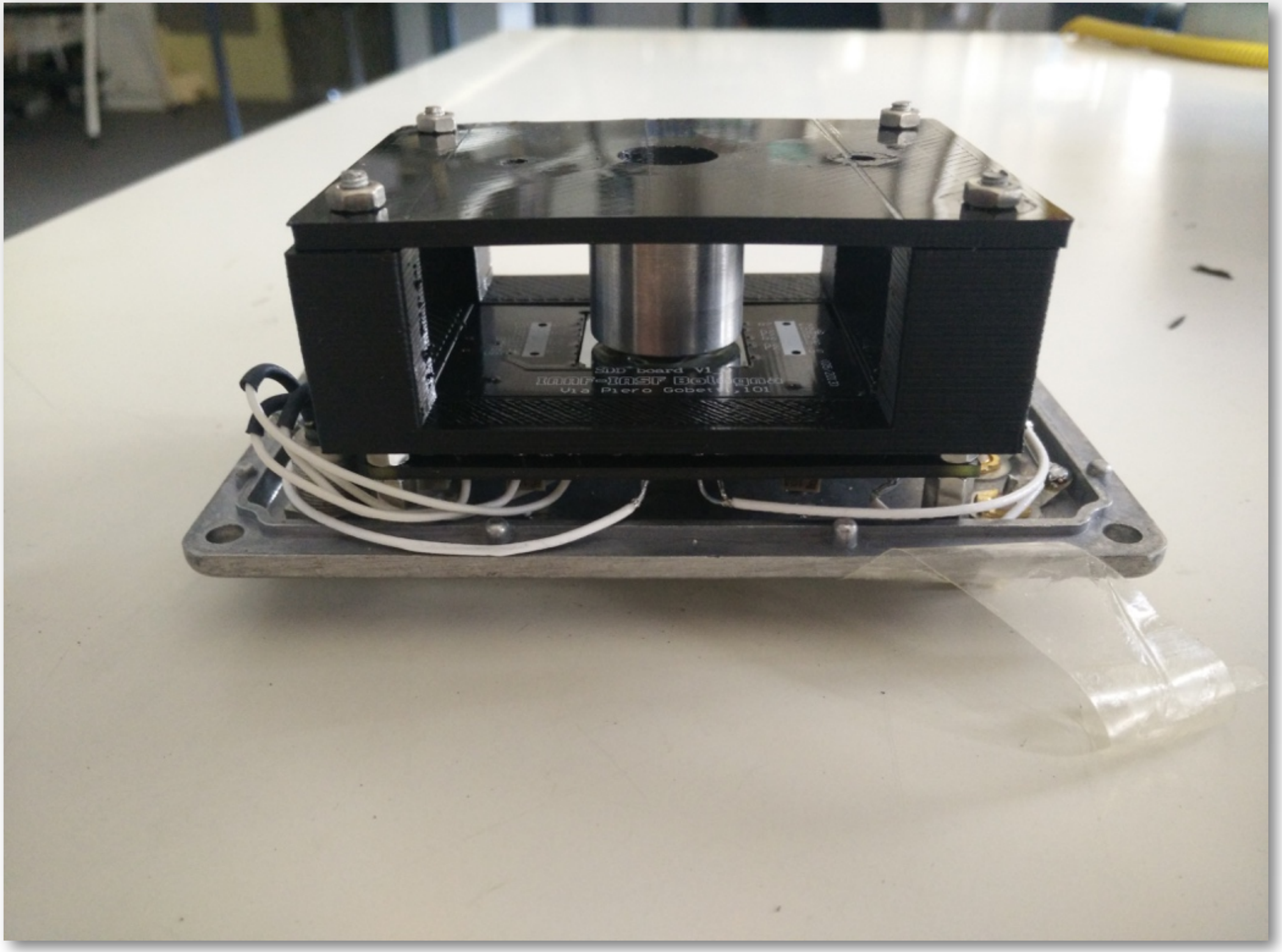
Laboratory experience

The 7-cell SDD matrix mounted in its printed circuit boards that hosts also the preamplifiers



The 1/2 inch diameter, 1/2 inch height $LaBr_3$ crystal covers fully the central SDD, but only ~55% of the peripheral cells

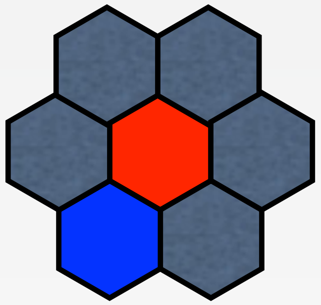
Laboratory experience



Laboratory experience

We will measure a gamma-ray spectrum of a radioactive source (^{137}Cs) with:

a. only the **central** cell (**CH1**)
b. with one **peripheral** cell (**CH6**)
c. **summing** the signal of the two cells

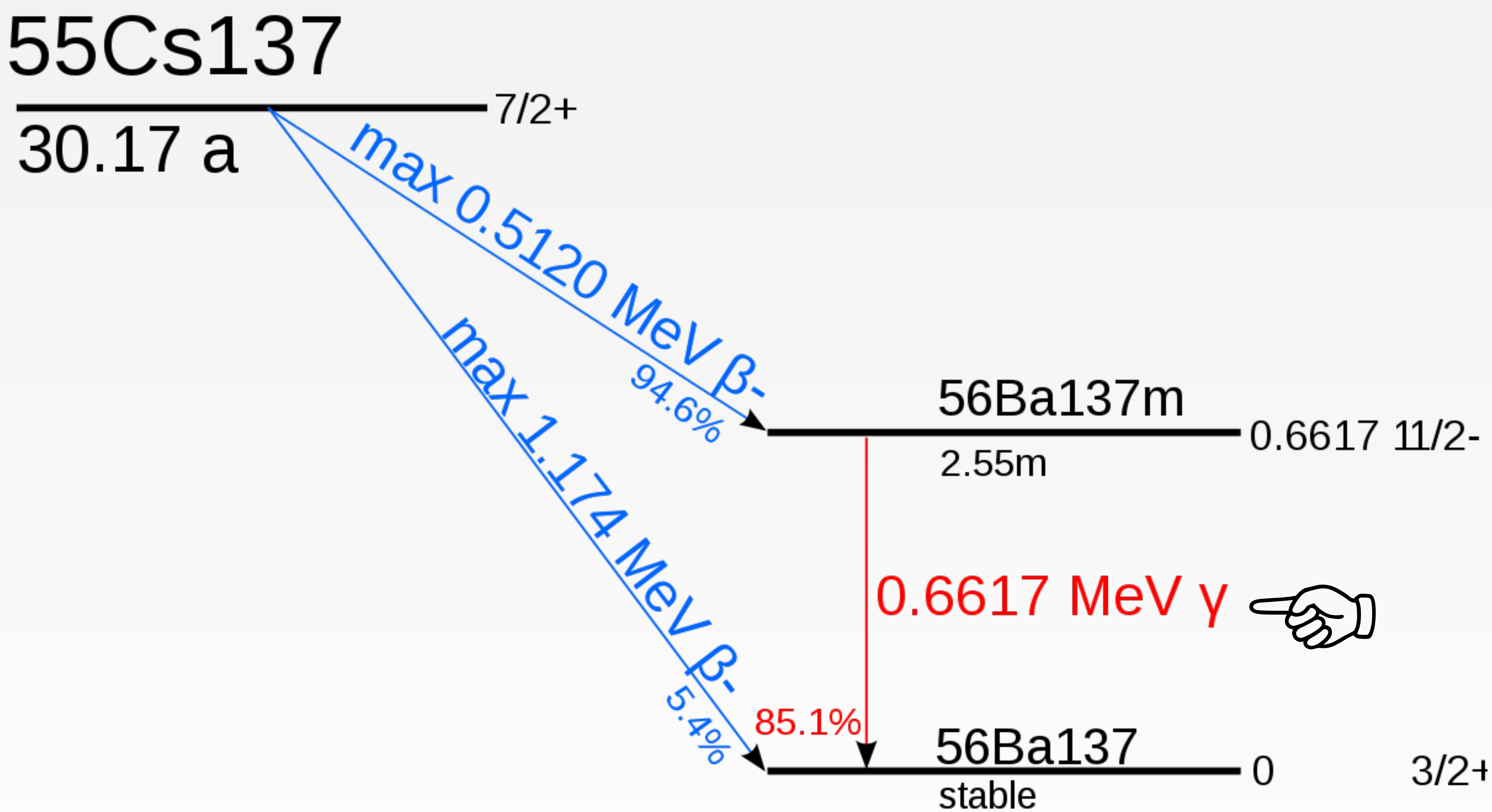


aiming to:

1. understand what we will see
2. derive some interesting parameters:
   i. the *effective light output*
   ii. the *energy resolution*

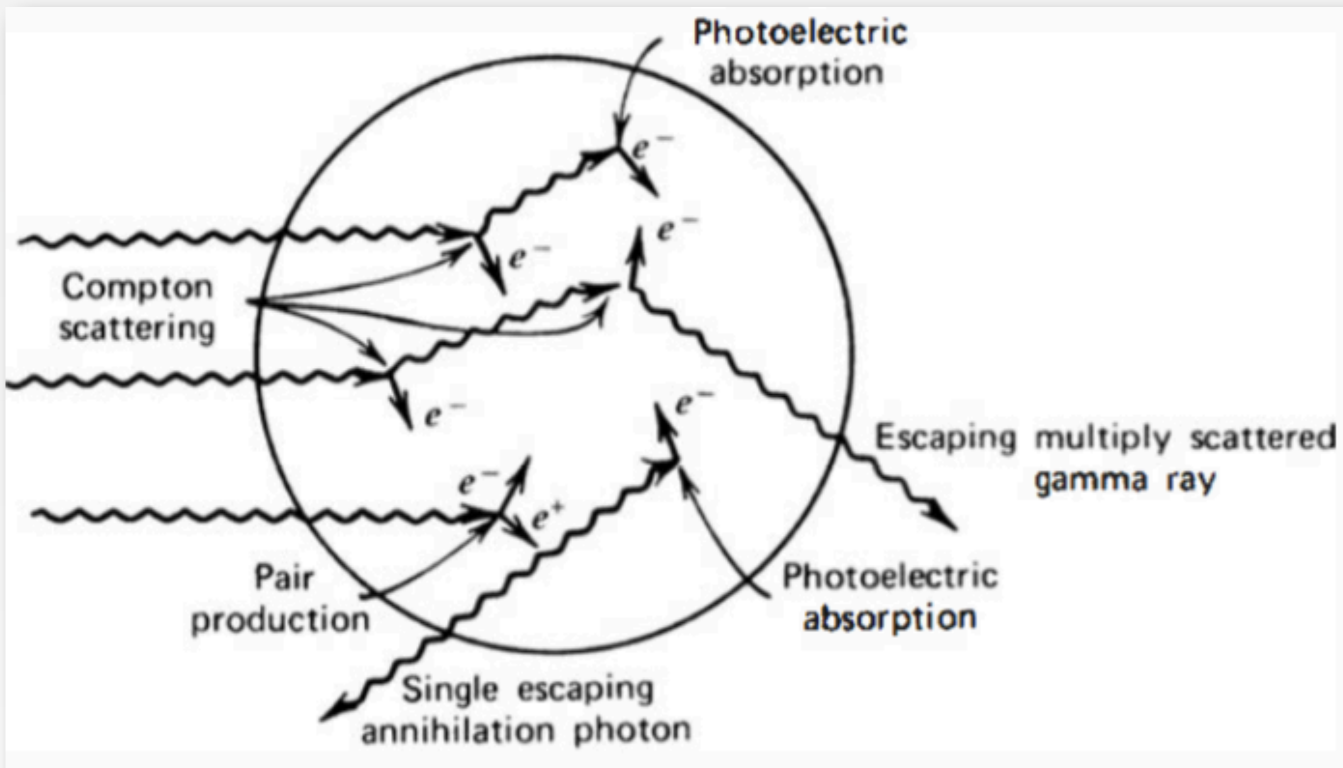
Laboratory experience

^{137}Cs emits mainly a 662 keV gamma-ray

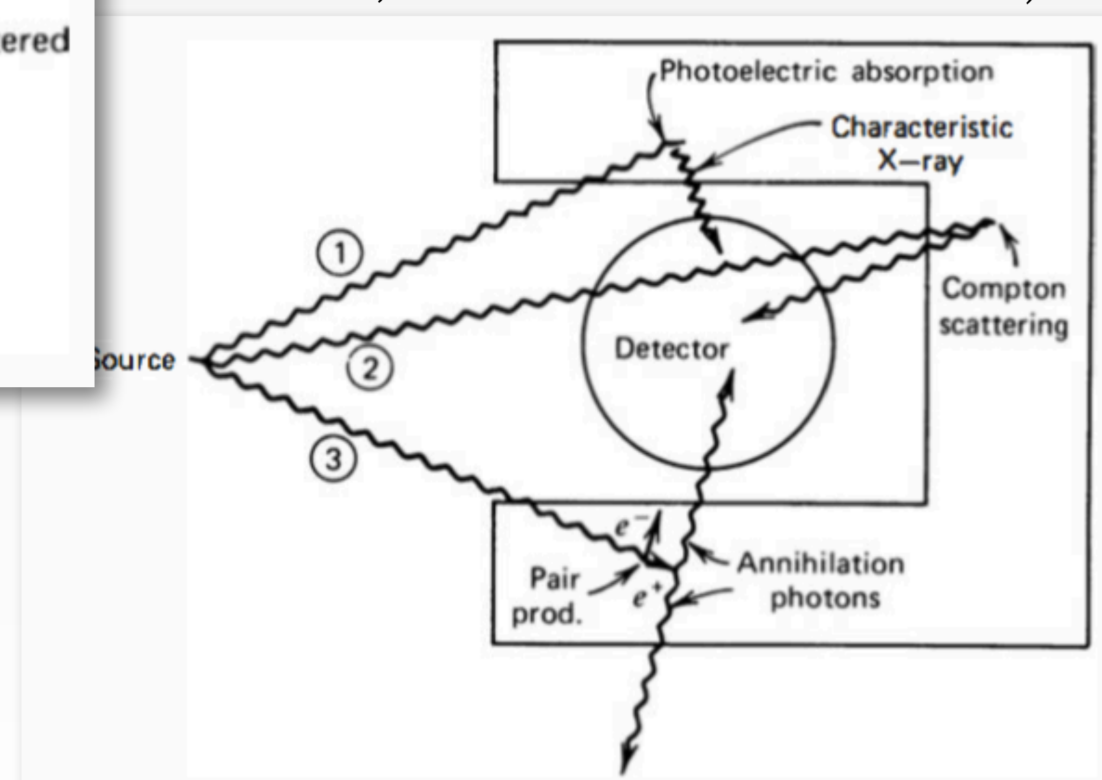


Laboratory experience

^{137}Cs emits mainly a 662 keV gamma-ray



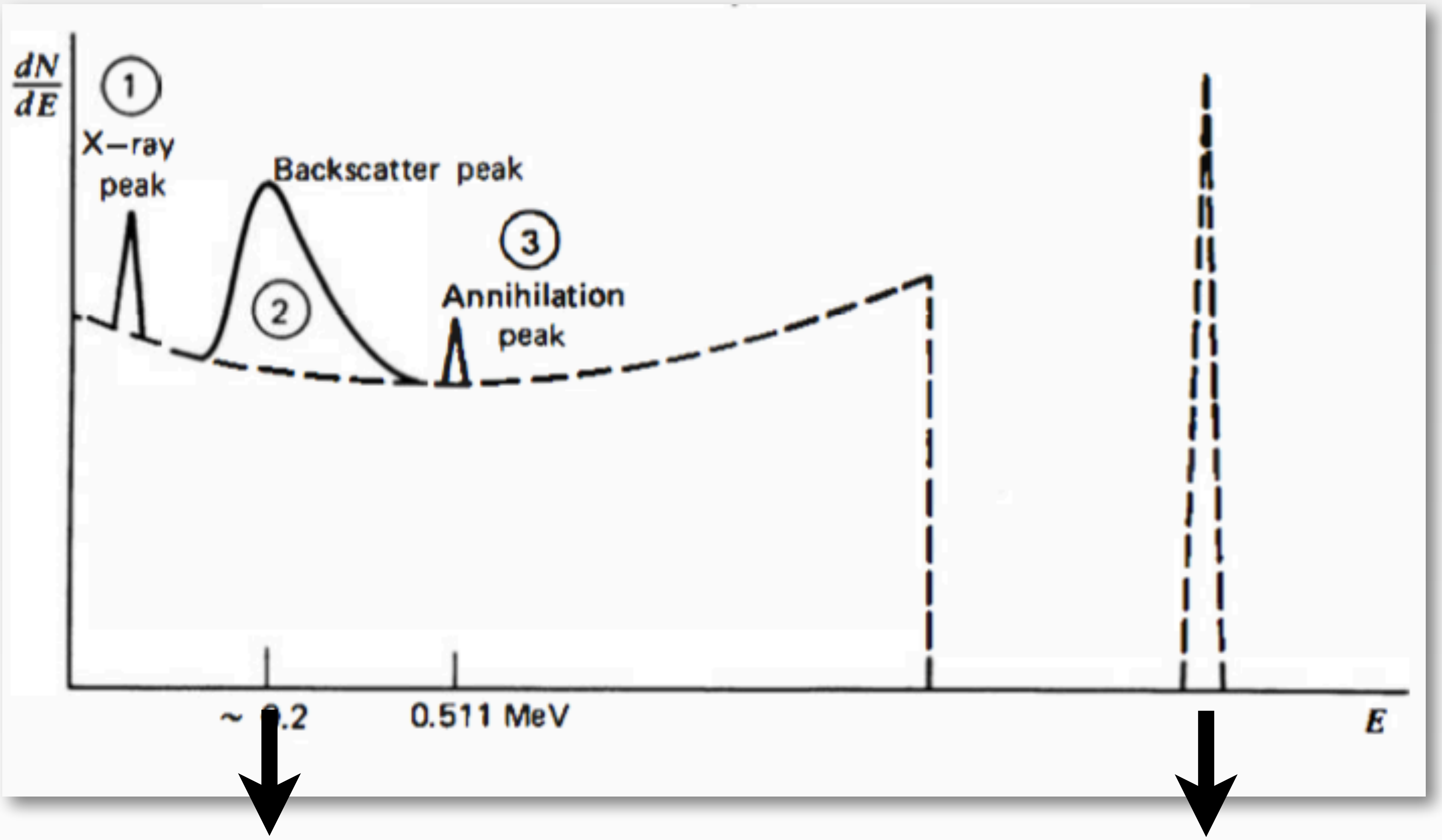
Two possible interactions:
a. Photoelectric effect
b. Compton effect
(pair production is not energetically allowed, threshold 1.022 MeV)



Surrounding structures can also leave their effects on the resulting spectrum

Laboratory experience

^{137}Cs emits mainly a 662 keV gamma-ray

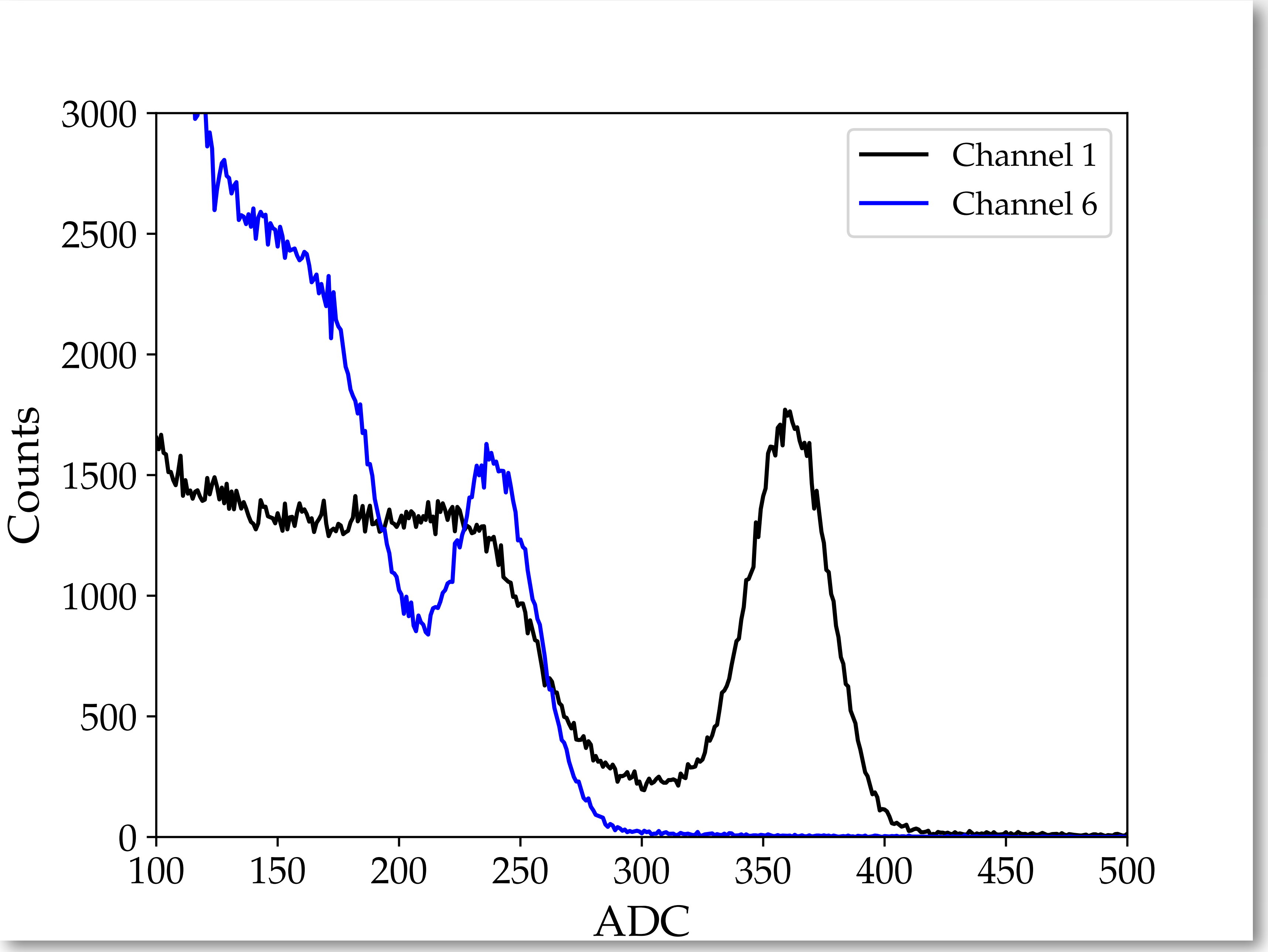


Compton continuum
(we see the energy transferred to the electron, the scattered photon escapes)

Photopeak at the same energy of the incident photon
(photoelectric absorption or full-containment)

Laboratory experience

SPOILER ALERT: This is what we will see!



Laboratory experience

The **position** of the peak (in mV or ADC units) is proportional to the **amount of light collected** by the channel under study.

This depends on:

1. the **intrinsic light output** (photons per unit of absorbed energy, for $LaBr_3$(Ce) the typical value is 63 photons/keV)
2. the quality of the **optical coupling** and the **absorptions along the optical path** (typically we can collect roughly only half of the scintillation photons emitted in the crystal)
3. the **quantum efficiency** of the detector (low for PMTs, high for SDDs)

One *optical* photon detected by the SDD produces **one electron** at the anode: the **effective light output** is measured in **e-/keV**

Laboratory experience

Therefore...

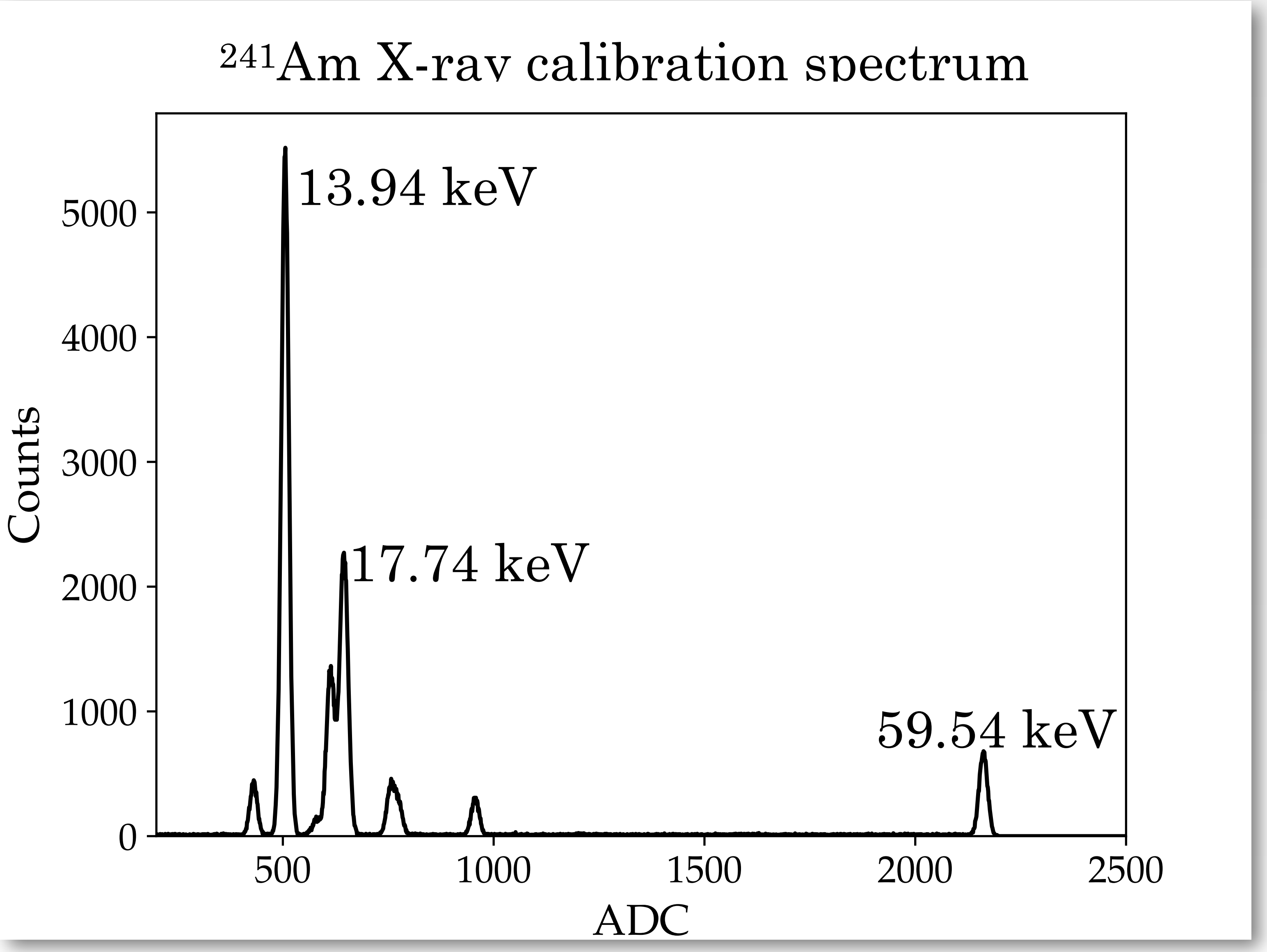
How many electrons are we seeing corresponding to the peak?

To answer this question (and thus to calculate the ***effective*** light output) we have to **calibrate** the detector!

We will use **direct** X-ray absorptions in the SDD: for each 3.6 eV of deposited energy, one electron/hole pair is produced in the silicon bulk.

Unfortunately, the crystal blocks X-rays, and removing and replacing it repeatedly is risky and cumbersome. Fortunately, X-ray spectra (^{241}Am) for the calibrations are already available!

Laboratory experience



The conversion factor ADC → electrons
(or ADC → keV for X-rays alone)
can be determined using the ^{241}Am X-ray peaks

Laboratory experience

The **width** of the peak is proportional to the **energy resolution**.

Energy resolution is expressed as a fraction or percentual:

$$R = \frac{\Delta E}{E}$$

For a Gaussian peak, $\Delta E = FWHM = 2.35\sigma$.

The total energy resolution has three contributions, **statistical**, **electronic** and **intrinsic:**

$$R = \sqrt{R_{\mathrm{stat}}^2 + R_{\mathrm{el}}^2 + R_{\mathrm{intr}}^2}$$

Laboratory experience

The **statistical** contribution depends on the **amount of electrons collected**.
This is a Poisson-distributed random variable, and therefore:

$$R_{\mathrm{stat}} = \frac{2.35\sqrt{N_e}}{N_e} = \frac{2.35}{\sqrt{N_e}}$$

But the number of electrons collected by the anode N_e is given by:

$$N_e = L_\gamma \cdot E_\gamma$$

where L_γ is the effective light output [e$^-$/keV] and E_γ is the deposited energy [keV]
Therefore:

$$R_{\mathrm{stat}} = \frac{2.35}{\sqrt{L_\gamma E_\gamma}}$$

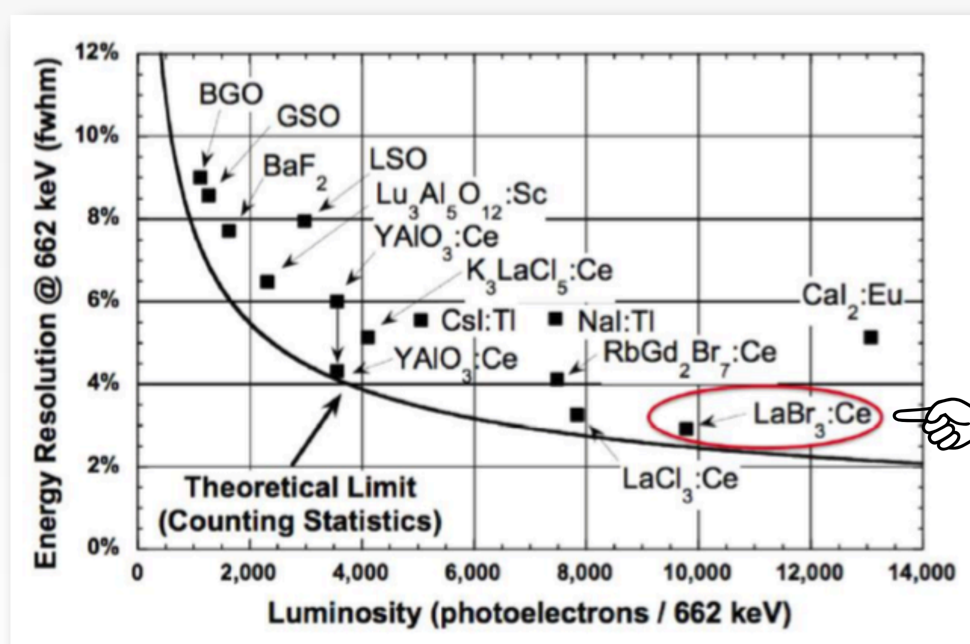
Laboratory experience

The **electronic** contribution depends on the intrinsic electronic noise of the detector, preamplifier, shaper, etc. It is also strongly temperature-dependent.

If the scintillation light is collected by several channels, the overall electronic noise is the quadrature sum of the noise of each channel.

$$R_{\mathrm{el}}^{\mathrm{tot}} = \sqrt{R_{\mathrm{el,ch0}}^2 + R_{\mathrm{el,ch1}}^2 + R_{\mathrm{el,ch2}}^2 + \cdots}$$

The **intrinsic** contribution depends on the intrinsic non-linearities in the response of the crystal. $LaBr_3$ is one of the best scintillators in this regard.



$R_{\mathrm{intr}} \sim 2\%$
for $LaBr_3(Ce)$

Outline

Procedure:

1. Acquire a ^{137}Cs spectrum for CH1 (a few minutes will suffice)

2. Acquire a ^{137}Cs spectrum also for CH6

3. Calibrate separately both ^{137}Cs scintillation spectra with the provided ^{241}Am direct absorption X-ray spectra:
    a. identify X-ray peaks in the ^{241}Am spectrum
    b. determine their ADC value
    c. fit linearly your (energy, ADC) data points
    d. convert the x-axis of your ^{137}Cs spectrum using the relation you found at the previous step

4. Derive the effective light output of both channels

5. Calculate the energy resolution for both channels, by measuring the width of the 662 keV peak

Bonus track

Sum the signal of the two channels:

1. Acquire a ^{137}Cs spectrum for CH1+CH6, feed through an analog electronic adder

2. Understand what you are seeing! What is the position of the peak? And what is the energy resolution? How it compares with the spectra of the two channels alone?

3. Food for thought: what would happen if we were to add more channels? (Remember the energy resolution formula and its contributions!)

Contatti

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