e^+e^- ANNIHILATION

EXPERIMENT

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Abstract: The annihilation is a very well known physical process, in which an electron (e^-) and its antiparticle, a positron (e^+), annihilate. The most probable result of this process is the appearance of two equally energetic photons: $e^+e^- \rightarrow \gamma\gamma$. Due to energy and momentum conservation, the two photons are emitted with equal energy $E_\gamma = m_e c^2 = 511$ keV, and opposite identical momenta. The goal of the present experiment is to detect these annihilation photons, using NaI(Tl) scintillators coupled to photomultipliers. Their energy spectrum will also be measured. This will imply the direct observation and understanding of a few basics of the interaction of photons with matter (i.e. photoelectric effect and Compton scattering) and the familiarization with some basic logics in nuclear and particle electronics (e.g. concept of discrimination, coincidence, gates etc). The positrons are emitted by a low activity ^{22}Na radioactive source.

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1 Safety instructions: radio-protections definitions

Extracted from Annex 1 of the Radiological Protection Ordinance (SR 814.501) [11].

Activity Number of disintegrations per unit time. The unit of activity is the becquerel (Bq); 1 Bq = 1 s^{-1}.

Activity concentration Activity per unit volume. The activity concentration is expressed in becquerels per cubic meter (Bq/m^3).

Activity, specific Activity per unit mass. Specific activity is expressed in becquerels per kilogram (Bq/kg).

Controlled areas

1. working areas for the handling of unsealed radioactive sources, as specified in Art. 69;
2. areas in which air concentrations may exceed 1/20 of the guidance values specified in Annex 3 Column 11;
3. areas in which surface contamination may exceed the guidance values specified in Annex 3 Column 12;
4. areas in which people may accumulate an effective dose of more than 1 mSv per year as a result of external exposure;
5. areas in which equipment is operated without a full protection system;
6. areas designated as such by the supervisory authority.

Becquerel (Bq) Unit of activity of a radionuclide. 1 Bq = 1 disintegration per second. The Becquerel supersedes the Curie (1 Ci = $3.7 \cdot 10^{10}$ Bq).

Dose Quantity used to assess the health risks of ionizing radiation. Unless indicated to the contrary, the term is used in this Ordinance to mean effective dose.

Dose, absorbed The amount of energy deposited per unit mass of material as a result of interaction with ionizing radiation. The unit of absorbed dose is given the special name gray (Gy); 1 Gy = 1 J/kg.

Dose, ambient The ambient dose is taken to be

1. the quantity H*(10) (ambient dose equivalent) for strongly penetrating radiation;
2. the quantity H'(0.07) (directional dose equivalent) for weakly penetrating radiation.

Dose, ambient equivalent, H*(10) The ambient dose equivalent H*(10) at the point of interest in the real radiation field is the dose equivalent that would be produced by the corresponding expanded and aligned field in the ICRU sphere at a depth of 10 mm on the radius opposing the direction of the aligned field.

Dose, committed effective (E50) The effective dose that accumulates in the body over a period of 50 years as a result of the intake of a nuclide.

Dose, directional equivalent H'(0.07) The directional dose equivalent H'(0.07) at the point of interest in the real radiation field is the dose equivalent that would be produced by the corresponding expanded field in the ICRU sphere at a depth of 0.07 mm on a radius in a specified direction.

Dose, effective (E) The sum of the equivalent doses in all organs and tissues weighted with the factor w_T.
$E = S_T \cdot w_T \cdot H_T = S_T \cdot w_T \cdot S_R \cdot w_R \cdot DT_{T,R}$
$D_{T,R}$ = absorbed dose in tissue T due to radiation R
w_R = radiation weighting factor
w_T = tissue weighting factor (contribution of tissue/organ T to the overall risk)
H_T = equivalent dose for tissue/organ T
The special name for the unit of effective dose is the sievert (Sv); 1 Sv = 1 J/kg.

Table 1: Radiation weighting factors

Radiation type and energy range	Energy	Radiation weighting factor, w_R
Protons, all energies Electrons and muons, all energies Neutrons	< 10 keV	1
	10 keV to 100 keV	1 - 5
	100 keV to 2 MeV	5 - 20
	2 MeV to 20 MeV	20 - 10
	> 20 MeV	10 - 5
Protons, other than recoil protons	> 20 MeV	5
Alpha particles, fission fragments, heavy nuclei		20

Dose, equivalent (H) The product of the absorbed dose DT,R due to radiation R in tissue T and the radiation weighting factor w_R (cf. Dose, effective). The special name for the unit of equivalent dose is the sievert (Sv); 1 Sv = 1 J/kg.
$H_{T,R} = w_R \cdot D_{T,R}$; for a mixture of radiation types: $H_T = S_R \cdot w_R \cdot D_{T,R}$

Table 2: Tissue weighting factors

Tissue or organ	Tissue weighting factors, w_T
Gonads	0.20
Bone marrow (red)	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Bladder	0.05
Breast	0.05
Liver	0.05
Oesophagus	0.05
Thyroid	0.05
Skin	0.01
Bone surface	0.01
Remainder	0.05

Dose, personal deep, $H_p(10)$ [short form: Hp] Equivalent dose in soft tissue at a depth of 10 mm in the thoracic region.

Dose, personal surface, $H_p(0.07)$ [short form: Hs] Equivalent dose in soft tissue at a depth of 0.07 mm in the thoracic region.

Dosimeter Instrument used to measure ambient or personal doses.

Gray (Gy) The special name for the unit of absorbed dose. 1 Gy = 1 J/kg.

Half-life The time taken for the activity of a radionuclide to lose half its value by decay.

Ionizing radiation Radiation that has sufficient energy to eject electrons from an atomic shell (ionization).

Ionizing radiation generators Equipment and devices used to generate photon or particle radiation with an energy greater than 5 keV.

Irradiator A device used for irradiation purposes, containing a sealed radioactive source. The radiation source is enclosed within shielding, to which it remains mechanically connected irrespective of the operating state.

Non-occupationally exposed persons People who could be exposed to higher-than-background levels of controllable radiation as a result of circumstances not related to work or training.

Occupationally exposed persons:

- could accumulate an effective dose of more than 1 mSv per year in the course of their work or training through controllable radiation exposure; or
- regularly work or undergo training in controlled areas.

Radioactivity Spontaneous disintegration of nuclides, accompanied by the emission of ionizing radiation.

Radiation sources Equipment and articles containing radioactive substances (sealed and unsealed radioactive sources) and installations capable of emitting ionizing radiation.

Radionuclide Nuclide that disintegrates spontaneously, emitting radiation.

Radionuclide generator Radioactive source with a fixed parent radionuclide producing a daughter radionuclide which can be removed by elution or by any other method.

Sievert (Sv) The special name for the unit of equivalent dose or effective dose. 1 Sv = 1 J/kg.

Sources, radioactive Sealed and unsealed sources.

Sources, sealed radioactive Radiation sources which contain radioactive substances and whose structure is such as to prevent, under normal conditions of use, any release of the radioactive substances and thus preclude any risk of contamination. The source encapsulation must satisfy the requirements of the ISO standards for the intended use and be classified as such.

Sources, unsealed radioactive Radiation sources containing radioactive substances that are capable of spreading and causing contamination.

2 Introduction

Note: The present chapter will provide only a quick overview of the main theoretical and detector concepts useful for the present experiment. By no mean this represents a complete description of all the addressed topics. Further reading (for example [1]-[4] and references therein) is recommended.

2.1 Electron - positron annihilation process

The positron (e^+) - firstly discovered by Anderson in 1932 in cosmic rays [5] - is the antiparticle of the electron (identical properties, but opposite charges). It is spontaneously emitted in the β^+ decays of radioactive nuclei, such as ^{22}Na:

$$^{22}\mathrm{Na} \rightarrow {}^{22}\mathrm{Ne} + e^+ + \nu_e \tag{1}$$

Once emitted, the positron quickly loses energy via scattering in the medium and annihilation between a positron and an electron takes place at rest (i.e. zero, or nearly zero momentum of the positron and electron). Actually, before annihilation, the positron combines with an electron to form a short lived bound state, called *Positronium* decaying into 2γ or 3γ where γ is a photon.

Positronium decay When the electron-positron pair forms Positronium, a spin triplet or a spin singlet state can be formed, depending on whether the spins of the electron and positron are parallel or anti-parallel. These states are called respectively *ortho-Positronium* (*o-Ps*, triplet S_1 state, parallel spins) and *para-Positronium* (*p-Ps*, singlet S_0 state, anti-parallel spins).
The singlet state (*para, p-Ps*) is annihilated with the emission of two photons, while the triplet state (*ortho, o-Ps*) has to emit three photons in order to conserve the total spin:

$$p\text{-}Ps \rightarrow \gamma\gamma \tag{2}$$

$$o\text{-}Ps \rightarrow \gamma\gamma\gamma. \tag{3}$$

By momentum conservation, the two photons from the *p-Ps* decay must be emitted with the same but opposite momenta (i.e. along the same line, in the two opposite directions). By energy conservation, each photon has an energy equal to the electron rest mass: $E_\gamma = m_e c^2 = 511$ keV. Because of the multi-pole nature of the *o-Ps* decay, it has a lifetime (1.42×10^{-7} s in vacuum) significantly longer than that of *p-Ps* (1.25×10^{-10} s in vacuum).
Transitions between the two states are strictly forbidden in vacuum, due to total angular momentum conservation. In materials, however, different processes related with the structure of the material itself and the atomic kinetics may result in a conversion of *o-Ps* into *p-Ps* states. As a consequence, the branching ratios of annihilation in three or two photons and the relative lifetimes of the two Positronium components are strongly material dependent.

For the annihilation in vacuum, the ratio between the occurrences of three to two photons decay has been computed to be equal to 1:370 [6]. Direct experimental measurements confirmed this expectation [7]. Similar measurements also showed how the decay probability for three photons is higher in materials (e.g. Al, Teflon) and depends on the material itself [7].

Applications of annihilation The material dependence of Positronium lifetime finds an important application in positron annihilation spectroscopy (PAS), which is nowadays a powerful technique adopted for the detailed study of the material properties and defects. This is done by measuring the lifetime of the two components of Positronium. In a similar way, also the deviation from the co-linearity of the two emitted photons (due to a residual Positronium momentum) is used to characterize materials (Fermi radius, for example).

Another very important application of the positron annihilation process is the Positron Emission Tomography (PET). PET is a nuclear medicine imaging technique, widely used for example in oncology for tumors diagnosis, but also in clinical researches (e.g. neuroscience) and drugs development. A biologically active compound, mixed together with a short-lived positron emitter, is injected into the body of a living organism. The most common radiotracer emitting positrons - mainly used in tumor diagnosis - is FDG, a glucose-like molecule containing β^+-decaying ^{18}F ($\tau_{1/2} \sim 2$ hours). In a short period after the injection, these molecules concentrate in the tissues of interest (e.g. tumoral cells, characterized by a faster metabolism), resulting in a localized concentration of "back-to-back" photons emitting points. If those photons are detected, the contour of the emitting region can be reconstructed, with the help of sophisticated reconstruction algorithms (tomography). This results is a 3-D image of functional processes in the body, with the valuable information about their localization, shape and size.

3 Theoretical background

3.1 Interaction of photons with matter

Photons interact with matter in a very different way from the charged particles, which slow down gradually through continuous interactions with the atoms (inelastic collisions). There are three types of interactions between γ rays and matter: the *photoelectric absorption*, the *Compton scattering* and the *pair production*. All these processes lead to a partial or complete prompt transfer of the initial photon energy to electron energy.

In the **photoelectric absorption**, the photon interacts with an atomic electron (almost always an electron in the K-shell). The result is that the photon is absorbed and the electron (also called *photo-electron*) is ejected from the atom. If is the energy of the incoming photon, the electron is emitted with a kinetic energy:

$$E_e = E_\gamma - E_b \tag{4}$$

where E_b is the binding energy of the photo-electron in its original shell.
It is important to notice that a free electron cannot absorb a photon and conserve the momentum. Then the photoelectric absorption can occur only on bound electrons, with the nucleus absorbing the recoil momentum. This implies that the photoelectric absorption - together with a photo-electron - creates an ionized atom with a vacancy in one of its bound shells. This vacancy is quickly filled (free electron of the medium and/or rearrangement of electrons from other shells). The re-filling of the vacancy leads to emissions of X-rays, which are characteristic of the material. In most of the cases these X-rays are immediately reabsorbed by the material, but they could also escape.

The **Compton scattering interaction** is the scattering of photons on electrons. In such a scattering, the photon transfers a portion of its energy to the electron and it is deflected from its original direction by an angle θ. The electron itself (assumed to be initially at rest) gains a kinetic energy equal to:

$$E_e = E_\gamma - E'_\gamma \tag{5}$$

where and E'_γ are respectively the initial and final photon energy (before and after the interaction). From energy and momentum conservation it can be derived that:

$$E'_\gamma = \frac{E_\gamma}{1 + \frac{E_\gamma}{m_e c^2}(1 - cos\theta)} \tag{6}$$

where $m_e c^2$ is the electron rest mass energy (511 keV). All scattering angles are possible, so the energy transferred to the electron can vary from zero ($\theta = 0$, i.e. no scattering) to a maximum, corresponding to the photon scattered in the back direction ($\theta = \pi$). This maximum recoil energy of the electron is known as *Compton edge* and can correspond to a large fraction of the incoming photon energy. Some of the original energy however

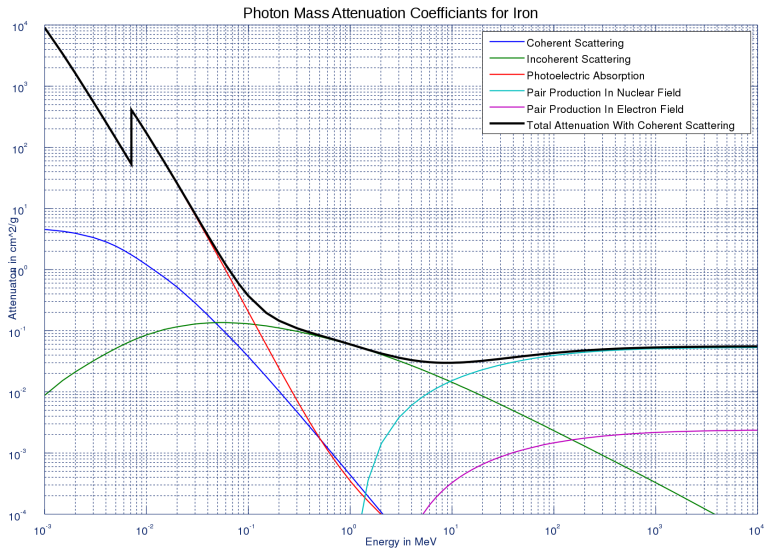

Figure 1: Attenuation coefficient of iron, where the various contributing processes are shown separately [10]. The attenuation coefficient scales linearly with the cross section. Additional description is provided in Appendix A.1.

is always retained by the photon, even in this latter extreme case (i.e. Compton edge <). In the peculiar case of our experiment (= $m_e c^2$), the minimum energy retained by the photon in the *back-scattering* (i.e. $\theta = \pi$) corresponds to $E'_\gamma = \frac{E_\gamma}{3} = 170$ keV. In the same way, the maximum energy acquired by the electron (Compton edge) is $E_e = \frac{2}{3}E_\gamma = 340$ keV.

The **pair production mechanism** is the transformation of a photon into an electron-positron pair. For this process to occur, the photon must have at least an energy of 1.022 MeV (i.e. $2 \times m_e c^2$). However, the probability of this interaction remains practically negligible until the photon energy approaches several MeV. The pair production effect is then completely irrelevant for our experiment.

The relative importance of the three processes described above depends not only on the energy of the photon, but also on the absorbing material. Figure 1 shows the dependence of the cross section (proportional to the attenuation coefficient) as a function of the photon energy. For photon energies larger than the binding energy ($E_\gamma > E_b$) the photo-effect cross section has approximately the following dependence [8]

$$\sigma_{ph} \sim \frac{Z^5}{E_\gamma}. \tag{7}$$

For heavy elements it is therefore the most important process for energies $E_\gamma < m_e c^2$.

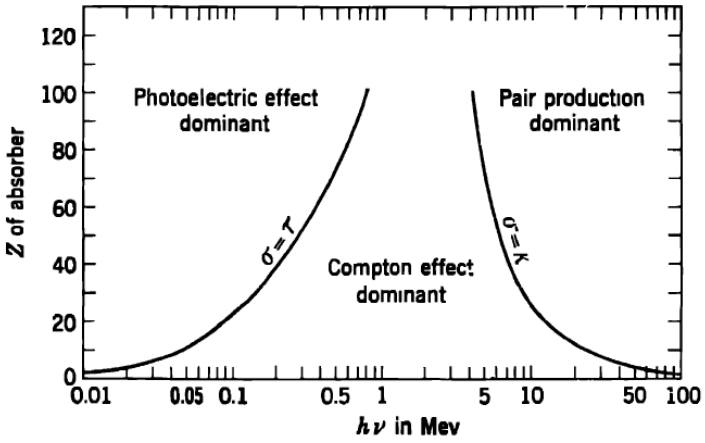

Figure 2: Relative importance of the three types of photon-matter interaction in the $Z-E_\gamma$ space. The line $\sigma = \tau$ represents the border where the photo-electric cross section equals the Compton cross section, whereas at $\sigma = \kappa$ the Compton cross section is as large as the pair production cross section [9].

The cross section for pair production scales like [8]

$$\sigma_{ph} \sim Z^2 \ln E_\gamma \tag{8}$$

before saturating to a plateau value at high energy. The Compton process only varies linearly with Z and has a complex energy dependence [8]. In the energy region of interest for the present experiment, both the photoelectric and the Compton effects will play an important role. Figure 2 shows which process in the $E_\gamma - Z$ region dominates the photon-matter interaction.

The underlying characteristic of the photon detection mechanism is that the detector must first act as a conversion medium, in which incident γ rays have reasonably high probability to interact, and then it has to serve as a detector for those electrons. In gamma ray spectroscopy, i.e. photon energy measurement, the direct measured quantity is the energy of the electron to which the photon has transferred its initial energy (all, or part of it). In an unrealistic case in which only photoelectric absorption can occur (e.g. very high Z material and low energy γ) the typical detected energy spectrum would look like the one in Figure 3(a): one single peak at a total electron energy corresponding to the energy of the incident photon. In case of the Compton interaction instead, the recoil electron will have a continuous energy distribution, from zero ($\theta = 0$) to the Compton edge ($\theta = \pi$), and the detected energy spectra would be as shown in Figure 3(b). In a realistic case, when both the photoelectric and the Compton effects occur together in the same detector, the measured energy spectrum would be a superpositions of the two, Figure 3(c). It should be noticed that this energy distribution is qualitatively true only for low energy photons (i.e. no pair production, which otherwise would contribute to different structures in the spectrum) and in the hypothesis of a small detector, in which the Compton scattered photon escapes undetected. In the sketch also an idealized infinite energy resolution is assumed (i.e. sharp edges); in real-

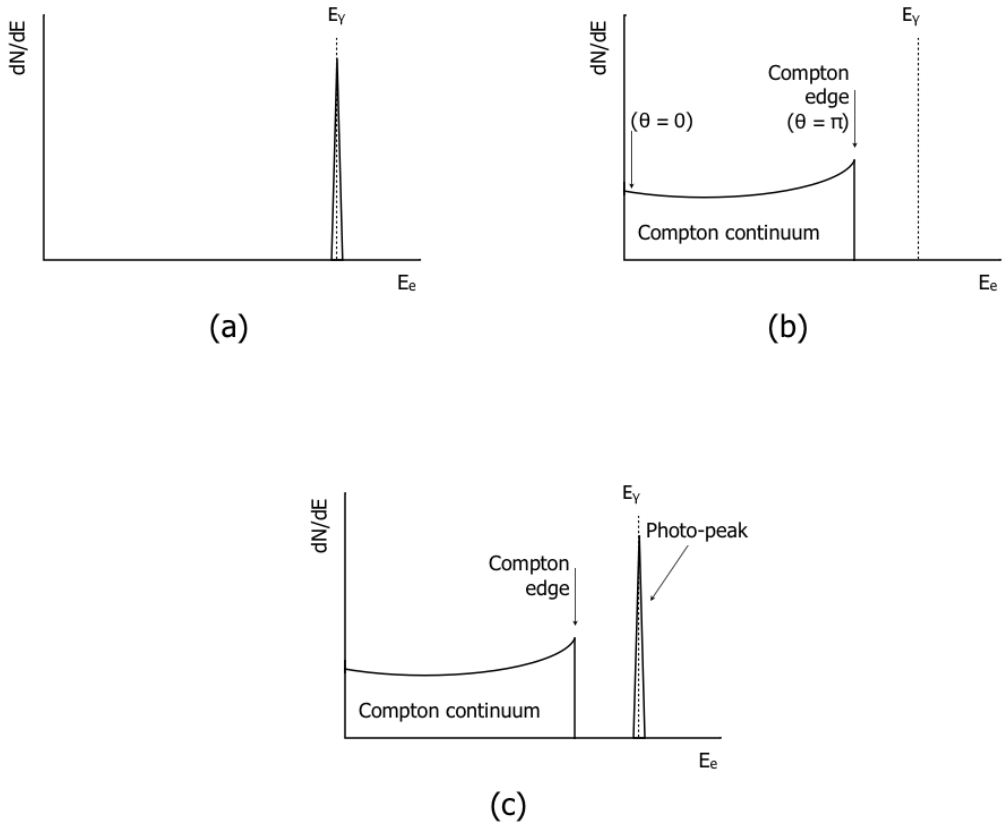

Figure 3: Sketches of the detected energy spectra for photoelectric absorption (a), Compton scattering (b), and both interactions (c), in the approximation of small detectors, infinite energy resolution and low energy incident photon (i.e. no pair production occurring).

ity, the detector energy resolution smooths the shape of the spectrum. The photo-peak is typically a Gaussian. From its width, the energy resolution R_{FWHM} (Full Width Half Maximum) is usually derived:

$$R_{FWHM} = \frac{\Delta E}{E} = 2.35 \times \frac{\sigma}{E}. \tag{9}$$

Question: In the hypothesis of an infinitely extended detector, how would the final detected energy spectrum look like?

3.2 Scintillators and photomultipliers

Scintillators are one of the most popular detectors for gamma-ray spectroscopy and particle detection, and probably also one of the simplest. Their functioning is based on the *fluorescence* process, i.e. the prompt emission of visible (or near-visible) photons, when an incoming radiation deposits some energy in the scintillator. The incoming radiation

can be both photons or particles. In case of photons, they first interact yielding several electrons; then these electrons ionize and excite the atoms and molecules, which in turn de-excite producing fluorescence light (i.e. scintillating photons). These scintillating photons are collected by the photo-cathode of a photomultiplier, where they are converted into photo-electrons. The photo-electrons are subsequently multiplied and accelerated inside the photomultiplier (several dynodes stages). Finally the output collected charge is converted to a voltage pulse. Its pulse height is proportional to the initial radiation deposited energy.

Scintillator materials are generally classified into two big categories: organic scintillators (e.g. anthracene, plastic scintillators) and inorganic scintillators (e.g. NaI(Tl), CsI(Tl), BGO, LYSO...). The scintillation mechanism is significantly different in the two: it has a molecular nature in organic materials, it is related with the crystals electronic band structure in inorganic scintillators. Each specific material has its own characteristics. It is generally valid, however, that organic scintillators have a much faster signal than inorganic ones. The decay times for organic materials are typically of the order of a few ns, while they are 2-3 orders of magnitude slower in inorganic crystals. The advantage of inorganic scintillators on the other hand is their higher stopping power (due to higher density and higher atomic number) and a much more competitive light output when compared with organic materials, which results in a better energy resolution.

The detector chosen for this experiment (i.e. detection of 511 keV photons) is crystalline sodium iodide with thallium doping: NaI(Tl). This is a very classical choice, being the crystal characterized by a very high light yield of the scintillation process (38000 γ/MeV), high density and high stopping power (i.e. high probability of photons to interact). One major disadvantage of NaI - together with its relatively slow decay time - is its hygroscopicity: that's why NaI crystals are usually housed in an air tight enclosure.
In appendix A.1 a plot with the comparison of the linear attenuation coefficients (i.e. interaction probability) of NaI and NE102A is given. NE102A is a typical plastic scintillator.

Question: From the comparison between NaI and NE102A, it appears that the Compton contribution is quite similar for the two scintillators, while the photoelectric and pair production are significantly greater in NaI. Why does this make the NaI scintillator the preferential detector for detection and energy measurements of gamma-rays?

4 Experimental setup

As described in the previous chapter, the typical "signature" of the annihilation photons is extremely clear: they are two photons of known energy (511 keV, equal to the electron rest mass), emitted at the same time, collinearly, in opposite directions[1]. Their detection is then straightforward: it is sufficient to place two photon detectors (in our case, scintillators coupled to photomultipliers) on the two opposite sides of the e^+ source, and select only those events in which the two detectors respond at the same time (i.e. they are *in coincidence*).
In this experiment we want to be able to properly detect those photons; we also want to acquire their energy distribution, both individually (i.e. when they are not used in coincidence) and when they are in coincidence.
The mechanical setup is provided already assembled (see section 4.2); the electronics readout chain has to be built, step by step, using the instructions and the hardware components provided.

4.1 Goals of the experiment

The goals of the present experiment of detection of photons from the annihilation can be summarized in the following items:

1. Get familiar with basic detector concepts mainly concerning photons interaction with matter, providing also the answers to the few questions and exercises proposed in the text.

2. Build your own readout electronics setup. This implies getting familiar with the oscilloscope, NIM logic basic units, concept of discrimination and coincidence...

3. Measure the typical energy spectra of photons emitted by the annihilation process, understand them and be able to discuss their characteristics.

4.2 Setup Description

Figure 4 shows a sketch of the setup adopted for the experiment: two NaI(Tl) scintillators, each one coupled to its photomultiplier, are placed one in front of the other at a distance of 10 cm. In between, a ^{22}Na source (positron source) is placed. All the setup is surrounded by a thick lead (Pb) shield.
The photomultipliers are optically coupled directly to the scintillators in hermetically sealed packages (i.e. the scintillators are not visible). The NaI(Tl) scintillators are cylindrical crystals (L = 25.4 mm; diameter = 25.4 mm).
As also shown in the picture, there is the possibility to add a third scintillator in the setup, either for the detection of the positron decay in three photons, or for Positronium lifetime determination. For the moment, this only represents a possible extension of the present experiment, and it is not currently used.

[1] We completely discard the 3-γ's decay, because of its too low rate of occurrence.

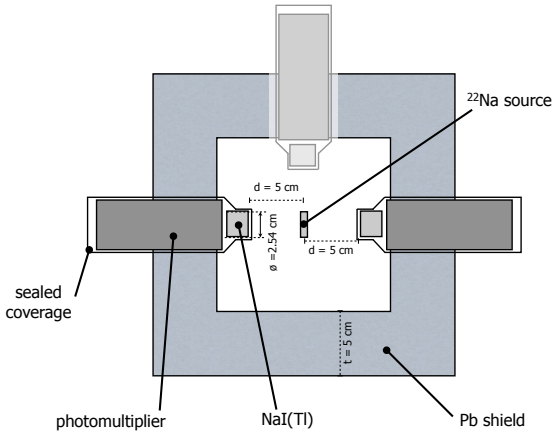

Figure 4: Sketch of the experimental setup (top view) for the detection of annihilation photons, with two (eventually three) NaI(Tl) scintillator crystals and a ^{22}Na radioactive source in between.

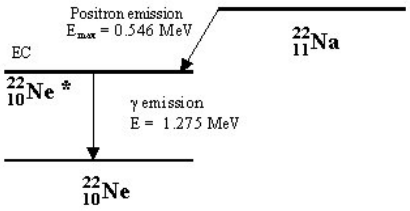

Figure 5: Decay scheme of the ^{22}Na radioactive isotope.

4.3 The ^{22}Na source

The ^{22}Na isotope is decaying to an excited state of the ^{22}Ne isotope by emitting a positron as shown in Figure 5. The latter then decays to its ground state, with the emission of a photon of energy 1.275 MeV. The emission of the positron and the 1.275 MeV photon is simultaneous (within 10^{-12} sec).
A process competitive to the β^+ decay, but with much lower probability, is the electron capture (EC, branching ratio ~ 10%) of ^{22}Na into ^{22}Ne* (without positron emission), still followed by the 1.275 MeV disintegration photon.
The source is contained in a high strength plastic disk (~ 25 mm diameter) in a small volume of active deposition. The active diameter is 5 mm. The initial activity of the source - when purchased, April 2009 - is 370 kBq. Its half life is 2.6 years.

Question: Which is the present activity of the source now?

Question: To convince yourself about the role of Pb as a shielding material, do the following exercise: Knowing the activity of the source and the energy of the emitted

photons, which is the rate of photons that will still survive after the 5 cm Pb thickness? In appendix A.1 you will find the information required for this exercise.

Question: According to the Swiss regulation, the maximum dose limit for non exposed persons corresponds to 1 mSv/year. The same regulation provides a table which defines the dose induced by every different isotope [11]. In case of ^{22}Na, a quantity h_{10} = 0.33 (mSv/h)/GBq is assigned. This h_{10} quantity represents the dose[2] acquired at a distance of 1 m from a radioactive source with an activity of 1 GBq. Knowing that the dose scales linearly with the source activity, and scales with 1/distance^2, you can calculate the total dose that you will accumulate during the experiment. You need to give a reasonable estimation of the time exposure and working distance. Notice that what you compute here refers to the non shielded source: the actual dose after the shielding will be totally negligible.

Question: The distances and dimensions of the scintillators are given. Assuming a full detection efficiency in the scintillators, can you estimate the expected rate of events detected by each one of the scintillators? (You might use the information contained in Appendix A.1 for a more realistic estimation, which also takes into account the real detection efficiency).

4.4 Provided equipment

Check out the following list of material/equipment provided for the experiment :

- Mechanical setup, which includes:
  - two photomultipliers (PMT)
  - two NaI(Tl) scintillators
  - a Pb shield
  - a ^{22}Na source.

  The photomultipliers are already coupled to their scintillator in the sealed coverage (i.e. not directly visible) and they are arranged one in front of the other; the source is placed in between.
- Oscilloscope.
- Multimeter.
- Low voltage power supply (PS 2403 Pro).
- High voltage cables (×2).
- Several coaxial cables (LEMO and BNC types) for the signals, see Fig. 6.

[2] at 10 mm depth in tissue (which is the same criteria to define the environmental radioactivity).

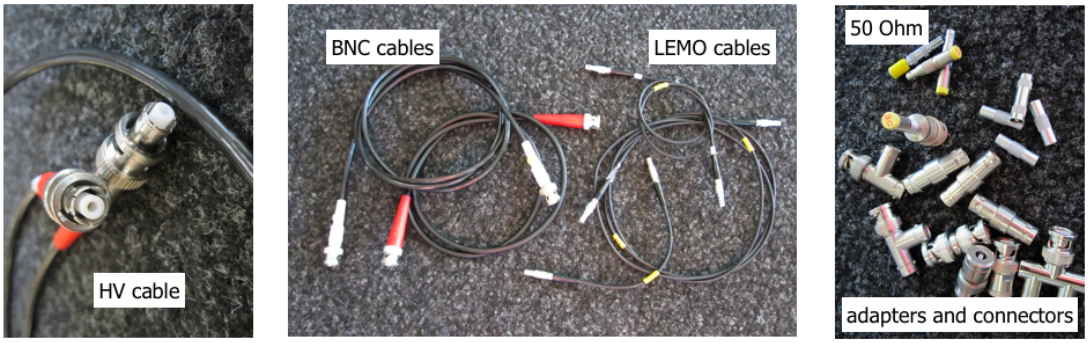

Figure 6: Cables, adapters and terminators.

- resistor terminations.
- BNC and LEMO cables adapters.
- NIM crate.
- NIM electronics units. In particular:
  - one discriminator unit (Lecroy Mod 623)
  - one coincidence unit (SIN FC103)
  - one counter/scalar (Tennelec TC532)
  - one fan-in/fan-out unit (Lecroy Mod 428F)
  - two high voltage units (Tennelec TC948)
  - one amplifier (Tennelec TC241)
  - one delay trigger unit
- Data sheets of the adopted NIM units.
- Screwdriver 00.
- Labels.
- PC with MultiChannel Analyser card (MCA) integrated.

Useful information about the usage of the provided photomultipliers and a description of the NIM dedicated electronics units are given in the next sections.

4.5 Photomultipliers

Every photomultiplier (also called PMT) must be equipped with a dedicated PMT base, in charge of the distribution of the high voltage to the dynodes and the collection of the output signals.
The two available PMT's (Hamamatsu, R980 model) are equipped with a custom made base (Figure 7), which has been designed according to the following requirements:

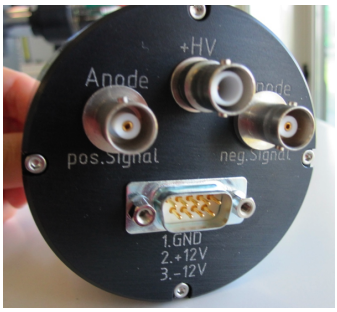

Figure 7: Photograph of the custom made PMT base.

- A positive high voltage (HV) must be applied at the PMT
- Two output analogue signals are available: the anode (i.e. full collected charge, after all amplification stages) and the last dynode signal (i.e. all amplification stages, but the last one).
- The **anode** signal is a direct output, with negative polarity, fast risetime and no shaping.
- The **dynode** signal output has an integrated inverting preamplifier, which has multiple functions: it acts mainly as a shaper for the signal but it also inverts the anode signal. As a result the dynode is positive polarity and slower signal.
- The output impedance on both anode and dynode signals is .
- **Important: the maximum allowed high voltage for the PMT's is 1250 V.**

4.6 NIM units

NIM (Nuclear Instruments Module) is the first - and simplest - electronics standard established for nuclear and particle physics. It is a modular system, comprising basic electronics units (e.g. discriminators, coincidence units) which fulfill standard mechanics and electrical specifications. Any NIM module will fit into any NIM crate.
NIM modules include both analog and digital instruments. In analogue signals, information is carried in the amplitude or shape of the signal. Digital (or logic) signals are of fixed shape and have only two possible states: yes or no. Conventionally a NIM logic signal is such that 0 mV corresponds to the logical 0, -700 mV corresponds to the logical 1. Unless differently specified, standard NIM units have input and output impedance.

Important: When - on the oscilloscope - you look at a signal from a standard NIM unit, **always remember to terminate the scope with to avoid signal reflections.** Figure 8 shows how this could be done.

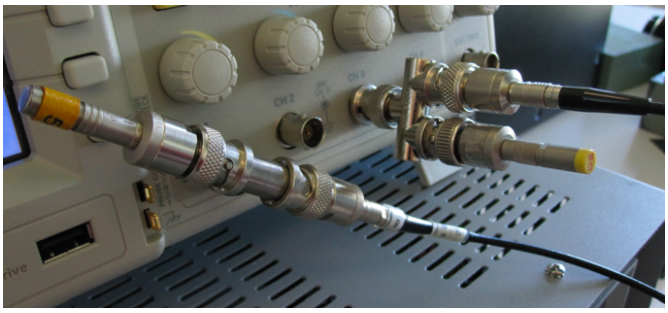

Figure 8: Two possible examples of termination of the input signal on the scope.

Easy electronic chains for various applications can be created using different NIM units. In the following sections, an introduction of the aim of each of the needed elements is given. The detailed specifications and the usage description for most of the adopted modules have to be found in the data sheets.

Amplifier The amplifier is a device that can accept positive and negative pre-shaped input signals. The output would be a shaped unipolar or bipolar analog signal, whose amplitude is G times the original one. The linear amplification factor G between the input and the output signal is known as gain, and it can be set through a potentiometer on the NIM module.
The amplifier functionality is to shape and increase the amplitude of signals that may be too small to be processed by the electronics readout.

Discriminator unit The discriminator (Figure 9) is a device which responds only to input signals with a pulse height greater than a certain threshold value. The input is an analogue signal (negative polarity); the output is a logical signal. The threshold to be applied and the duration of the output pulse (width) are generally adjustable parameters. In the provided unit (Lecroy NIM Model 623), 8 independent channels can be used. Threshold and width of the output pulse are adjusted - independently for each channel - by potentiometers on the front panel of the module ("hidden" inside two small holes). The set threshold could always be measured with a multimeter (DC voltage measurement, using the test pin on the front panel). Read carefully the data sheet: there is a factor 10 between the threshold that you really set and the threshold that you read back with the multimeter (e.g. THR_read = 300 mV ⇒ THR_real = 30 mV).

Coincidence unit The coincidence unit (Figure 10) determines if two or more logic signals are coincident in time. It generates a logic output signal when this is true, and no signal when it's false. Being *coincident in time* here exactly means that the pulse widths of the two (or more) input signals overlap in time. If this condition is met, a pulse of fixed width (adjustable from the potentiometer in the front panel) is produced as output. Several coincidence units produce also the so called linear (or direct) output, whose width is not fixed but corresponds to the overlapping in time of the two (or more)

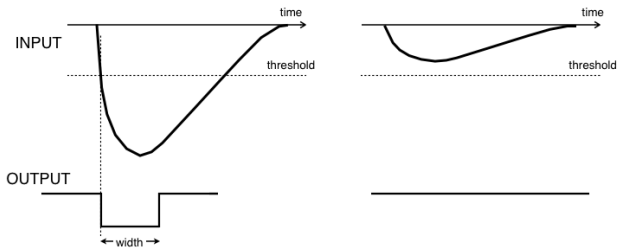

Figure 9: Discriminator operation principle.

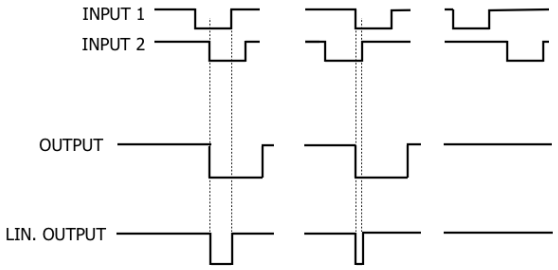

Figure 10: Coincidence principle.

input signals. Although in most of the applications the two are equivalent (because their leading edges are at the same time), the usage of the output is generally preferable to the linear output.
The provided unit (SIN FC 103) has 2 independent channels (A and B), each one can accept up to 6 input signals. In the coincidence unit, you have to enable the input channels that you want to use (see data sheets). This same unit could be used as logical OR, so make sure that to enable correctly the channels to be used.

Fan Out A fan out unit is a unit which copies the input pulse into several identical signals, of same shape and pulse height.
The provided module (Lecroy 428F) is a linear fan out (i.e. it accepts as inputs both analogue and digital signals). It has 4 independent channels, each one providing 4 outputs. Although the shape of the signal is preserved, a DC offset could be introduced in 3 of the 4 available outputs (adjustable with the ZERO potentiometer from the front panel). The output marked with a capacitance is the only AC-coupled output, i.e. with no offset. The module has the additional feature that could reverse the polarity, if the proper switch is set to inverting (INV) mode.
The same unit could be used as a fan in module, accepting several inputs (up to 4) and performing their analogue sum (if analogue inputs), or their OR (i.e. logical sum, if logical inputs).

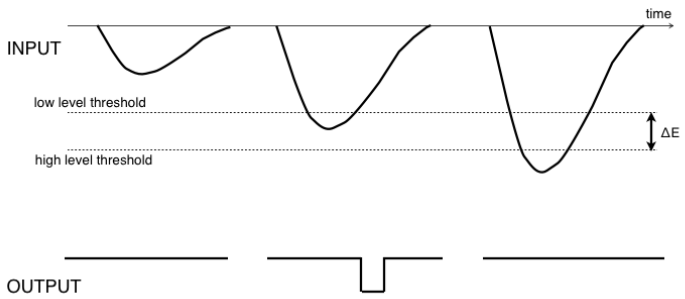

Figure 11: Operation principle of a single channel analyzer.

Single Channel Analyser (SCA) The single channel analyzer (SCA) is a differential discriminator, in which the signal amplitude is compared not only with a low level threshold, but also with a high level one. Only (analogue) input signals which fall within the window defined by the lower and upper level will produce a (digital) output pulse. If this condition is not met, there is no output. See Figure 11.
The provided unit (ELSCINT Mod SCA-N-2A) can be used either with the two threshold independently set, or (recommended) in ΔE mode, in which the parameters to adjust are the window width (ΔE) and the low level discriminator (LLD). Typically the width is adjusted at the beginning and kept fixed, and only the LLD is regulated. Important: the provided SCA unit, differently from the other NIM modules described so far, works with positive polarity signals (both for the input and the output), and produces TTL output signals[3].

Delay Trigger Unit (D.TRIGGER) The delay trigger module (D.TRIGGER) is a unit designed to work with digital signals, both in input and output. Two independently adjustable time parameters - delay and width - can be applied, in a very large dynamic range (from ns to ms). The output signal will have the required width and will be delayed with respect to the input by the required delay time. NIM standard signals are accepted as inputs, both NIM and TTL standards are produced as output.

Pulse counter The counter, also known as a scalar, is a device that counts the number of TTL pulses (positive digital signals) at the input for a pre-set time duration. The counter in this lab has one signal input and a gate input. The gate input accepts an external gate signal that tells the counter to only count the input signals when the gate signal is high. In the experiment it is more convenient to use the counter with an internal gate, which can be toggled by pressing the "Int/Ext" button on the front panel (the corresponding LED will light up). The internal gate signal will be high while the timer counts down. For high count rates one can select a short (~10 s) count time. For low

[3] TTL is another standard for logic signals, different from NIM. TTL standard is such that the digital "1" corresponds to a signal voltage between 1.5 V and 5 V; the digital "0" is a signal voltage is between 0 V and 0.7 V.

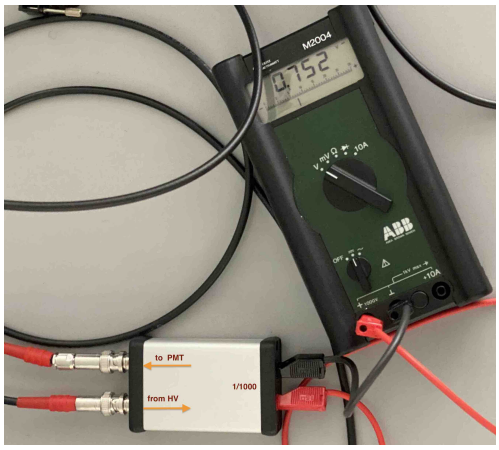

Figure 12: High voltage measurements. From the divider (silver box) one SHV cable is connected to the power supply, the other to the PMT. The set high voltage is 752 V. The voltage shown on the volt meter is $1/1000^{th}$ of the set high voltage.

count rates, it is better to set the timer to 100 s or longer.

5 Experimental Protocol

The following steps (in the proposed order) are suggested for the experiment:

1. Preliminary observation of signals with the oscilloscope.
2. PMT working point characterization (optimal high voltage).
3. Photon energy spectrum acquisition for one detector (i.e. no coincidence requirement).
4. Photon spectrum acquisition with coincidence.
5. Discussion of the results.

5.1 Preliminary observation of PMT signals with the oscilloscope

- Be sure that the NIM crate is off and the HV is not enabled (HV off).
- Fully cable the base of one PMT (high voltage, anode, dynode).
  - To measure the high voltage and simultaneously ensure that you always obtain the same HV value, connect the high voltage through a 1000:1 divider and a voltmeter as shown on the Figure 12. **(CAUTION: Do not disassemble the voltage divider box!)**
- Connect the anode signal output of the photomultiplier to the scope.

- Switch on the crate. Set the HV value to ~ 800 V. Check on the data sheets how to use the HV units. Enable the HV from the module (HV on ⇒ green light LED). **The maximum voltage is 1250 V, corresponding approximately to 410 a.u. on the HV knob.**

- Tips for the correct usage of the scope: You are going to observe the analogue anode signal, which has negative polarity (see Section 4.5). Trigger the scope on the same channel in which you are sending the anode signal, and use a low (negative) threshold.

- If everything is correctly done, you should be able now to see the analogue signal on the scope. Adjust the time and amplitude scale on the scope to best observe the signal. Use the scope in persistence mode (DISPLAY button → PERSIST on the scope).

Question: Record now one scope screenshot (in persistence mode) on the USB stick (use the PRINT button).

- Repeat all the above steps - including the record of the typical screenshot - for the dynode signal (i.e. positive polarity) (you must now obviously trigger the scope on positive threshold).

Question: For the anode signal, together with the screenshot, record also one waveform (SAVE/RECALL button). From the analysis of this curve (possibly a fit), could you estimate the typical fluorescence decay time of NaI(Tl)? Compare your result with the one you find in literature. Why would it be wrong to extract the fluorescence decay time from the dynode pulse? Briefly describe what the dynode signal decay time corresponds to.

Question: Look at the analogue signals acquired in persistence mode. On top of an almost continuous distribution of signals of varying amplitude in the full range, a more pronounced line is evident (i.e. higher frequency of events with this exact amplitude), both for anode and dynode. What does this line represent?

As an example, Figure 13 shows a typical screenshot saved for both the anode and the dynode signal of one photomultiplier.

While looking at the anode signal on the scope, change the HV on the PMT (**max allowed voltage = 1250 V**), moving the knob on the front panel of the HV module. You should be able to observe that the amplitude of the signals changes rapidly with the change in the HV. You will also observe that - for high HV values - the PMT output is distorted, because of saturation effects on the PMT base. For the following, always try to work with non saturated signals.

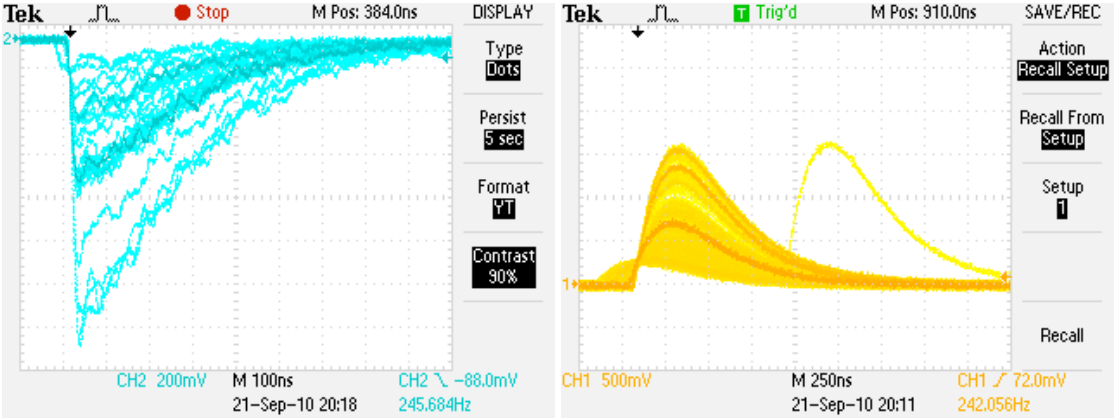

Figure 13: Example of the anode (left) and dynode (right) output signals of one photomultiplier, observed with the scope used in persistence mode.

Question: Write down in your logbook the HV value for which PMT saturation starts to occur, and draw a sketch of the shape of the saturated signal.
PMT working point characterization As observed before, the high voltage applied to the photomultiplier determines its overall gain and thus the pulse height of the output signals. A simple way to characterize the optimum HV working point of the photomultiplier is to measure its count rate as a function of the applied HV ("counting curve" or "plateau measurement"). The scheme of the setup to be used to derive such a curve is shown in Figure 14, together with a theoretical counting curve. At low HV, signals are too small to pass the discriminator. With increasing HV, the curve rises sharply and then remains flat (plateau region). Above the plateau, the curve rises sharply again, due to non-desirable regeneration effects in the PMT like after-pulses, discharges, etc. The correct voltage for the PMT is normally fixed in the plateau region (usually in the middle), where a minimum variation of counting rate is observed, even with drifts in the gain or voltage supply.

5.2 PMT working point characterization

You should now derive your PMT counting curves. Do it only for PMT1:

- Build the setup shown in Figure 14.
- Note: it is important to connect the anode (negative polarity) and not the dynode (positive polarity) to the discriminator, because the standard discriminator NIM unit works on negative polarity signals only. It is important to use the AC coupled output of the Fan-In/Fan-Out as input to the discriminator, to avoid any threshold effect related with a possible DC offset. Remember to terminate the scope with .
- Check the threshold value on the chosen discriminator channel and set it to a reasonably low value (e.g. 50 mV).
- Apply ~ 800V on the PMT. Look at the signals on the scope (anode and discriminator output) triggering this time on the anode. You will see that one single anode

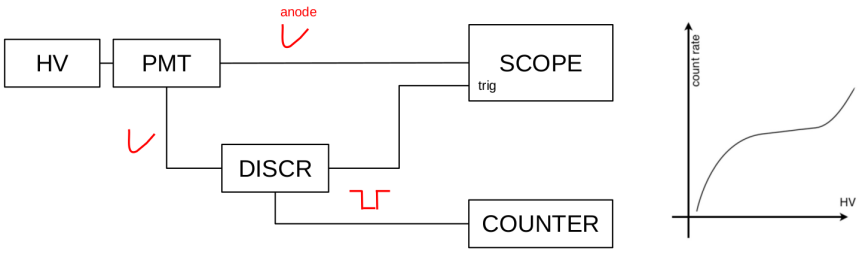

Figure 14: Left: Setup used to determine the PMT counting curve. Right: Sketch of the PMT counting curve.

signal may produce multiple discriminator outputs.

- Check the counting. On both the scope and the pulse counter, you should be able to see your signals (respectively the analogue shape and the counting rate).

You are now ready to acquire the counting curve for the PMT1:

- Record scalar rates as a function of the HV in the range between [0-1200] V and plot the data.
- A curve like the one in Figure 14 should be obtained. Define the working point of the photomultiplier, finding the best compromise between the HV defined from the counting curve and the maximum HV allowed before saturation starts to occur.

Question: Insert the PMT counting curve in the report and define the HV working point. Set this HV values on both PMT's (we assume PMT1 and PMT2 behave similarly). Check on the scope the anode and dynode signals of both PMT's and record some screenshots. Write down in your logbook also the signal characteristics (pulse height range, pulse height at the photo-peak, peaking time) for anode and dynode of PMT1 and PMT2. Compare the measured counting rates with the expected ones you computed in Section 4.2.

5.3 Single counter integrated spectra

Next, measure the energy spectrum of the γ's, i.e., the integrated spectrum of the observed signals from the scintillators. First measure the single photon energy spectrum of a NaI scintillator for one of the two detectors without any additional condition (Section 5.3). As a second step, you will acquire the photon energy spectrum of a NaI scintillator when both detectors are used in coincidence (Section 5.7).
For the single photon energy spectrum measurement (without coincidence) two different methods are used:

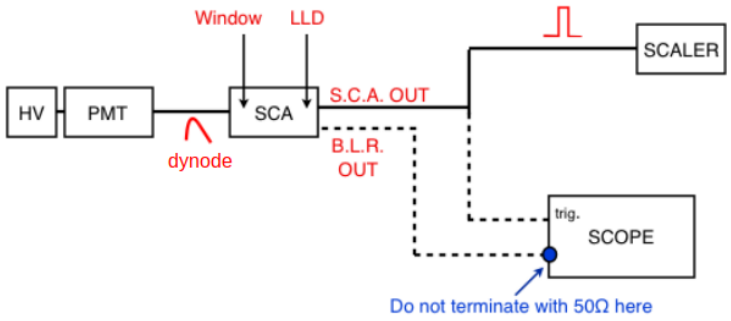

Figure 15: Setup for the acquisition of the photon energy spectrum with the SCA sweeping the full signal amplitude range.

- Measure the energy spectrum by hand with the single channel analyzer (SCA) and the scalar (see Sec. 5.4).
- To have higher statistics, use the automated acquisition program installed in the provided PC which is equipped with a multi-channel analyzer (MCA) (see Sec. 5.5).

5.4 "Hand-made" integrated spectrum: SCA and scalar

Figure 15 shows the simple setup that is needed for the spectrum acquisition. The idea is to use the SCA in *Window mode* (ΔE) i.e., fixed amplitude window width, and to sweep the Lower Level Discriminator (LLD). In other words sweep the ΔE-window through the full signal amplitude range and measure the event rate at each ΔE-window position. This yields directly the photon energy spectrum.

- Build the setup shown in Figure 15. The input signal for the SCA must have positive polarity (i.e. dynode signal); the output signal (OUT SCA) is a TTL signal and must be connected to the scalar (in TTL input).
- Tips for the SCA use: it has to be in ΔE mode and use the SCA output (no LLD).
- Check that the analogue signal fulfills the *window* and *threshold* conditions on the scope. Use the BRL output (without termination), and trigger the scope with the SCA output.
  - *window* setting.
  - *LLD threshold* setting.
  - *Note:* The settings made the knobs may not correspond to exactly to the desired voltage settings. There might be a slight systematic shift. Always, double check the settings with oscilloscope. Measure the lowest and the highest passing pulses in the BLR output. *Hint: Set oscilloscope display to infinite persistence.*

- For a fixed *window* width sweep the *window* position through the full range of amplitudes (0-5 V) by changing the *LLD threshold*. At each LLD position measure the counting rate with the scalar and plot it.
- A small window width, a high number of LLD steps and a long integration time in the scalar will of course provide a more accurate measurement. We advice do the measurement in 2 (or more) iterations: first obtain a rough (faster) curve, then take the time to repeat it with more accuracy (i.e.: finer steps, longer times).

Question: The obtained plot(s) must be included and discussed in the report. What does it represent? Compare it with the ones sketched in Figure 3 and recognize its main features: photo-peak, Compton-edge. Do you understand what is the tail at energies larger than the photo-peak?

5.5 Automated integrated spectrum: using a MCA

The same photon energy spectrum is measured with a multi-channel analyzer card (MCA) installed on the PC. The amplitude of the analog signal is converted into the digital number by the MCA and the ADC[4] information is stored in the PC. An histogram is automatically updated with such an information.

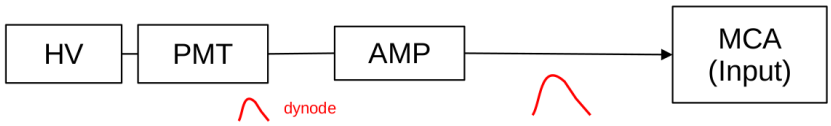

Figure 16: Setup for the acquisition of the photon energy spectrum with the MCA.

- The MCA card on the rear side of the PC has three inputs: (right) is the analogue signal you want to measure (positive polarity), (middle) is the gate (TTL signal, positive polarity), (left) unused. For this acquisition of single counter spectra the gate is not yet needed.
- Start the MCA-3 program (icon on the desktop). A graphical windows will pop-up as shown in Figure 17.
- Collect a first energy spectrum with the "play" button in the MCA-3 program. The continuously updating spectrum will start.
- Select an appropriate ADC resolution (number of channels) by selecting "Option"→ "Range preset" → Select "Range"→ "OK".

[4] Analogue to Digital Conversion

- Set a low threshold level, to see structures at low energy (low ADC channel). Select "Option"→ "Range preset" → "ADC"→ Set "LowerLevel"→ "OK".

- When the resolution and thresholds are set, stop the above measurement and start a new one.

- When you are satisfied with the statistics, stop the measurement and save it in a *.txt file in your newly created folder. Note that 2 files are produced: a *.txt file where the measured histogram is saved (number of events versus ADC channel) and a second file *.mcd where all the settings are recorded (useful for the offline analysis).

Question: In the logbook sketch the measured energy spectrum and understand it. Mark and identify its various structures (photo-peaks, Compton-edges…). Then try to fit the two gamma peaks that are visible in the spectrum (what is the best function to use in this case?). Remember to constrain the fit range around each peak and to check if the chi square is good. At the end the chi square indication should be also printed in the report to state the goodness of fit.

Question: Compare and study the two spectra obtained with SCA+scalar and with MCA. Compared with the theoretical spectrum of Figure 3, the measured spectra contain several additional structures and details beside the photo-peak and the Compton continuum. Also with the help of the literature, try to understand all the details of the measured spectrum. **The understanding of this spectrum is a key point of the experiment. Discuss it with the assistant.**

Question: Keeping in mind the first method you used for the spectra acquisition (with SCA), do you understand now the role of a device like the MCA? Which is the meaning of "channels" in the MCA for this particular application?

5.6 Energy calibration

The aim of the energy calibration is to define the conversion from MCA channel to energy. The measured spectrum i.e. the number of events versus the photon energy, has to be expressed in keV, instead of ADC channels. Since the actual energies of the photo-peaks (511 keV and 1275 keV) and of their Compton-edges are known, it is possible to perform an energy calibration using those 4 points. To extract the peaks and edges positions from the MCA spectrum do the following:

- On the MCA spectrum that you just acquired, determine the channel positions of the two photo-peaks with a Gaussian fit of the peaks. Use the MCA program to perform the fit and precisely determine the peak centroid position and its width (FWHM).

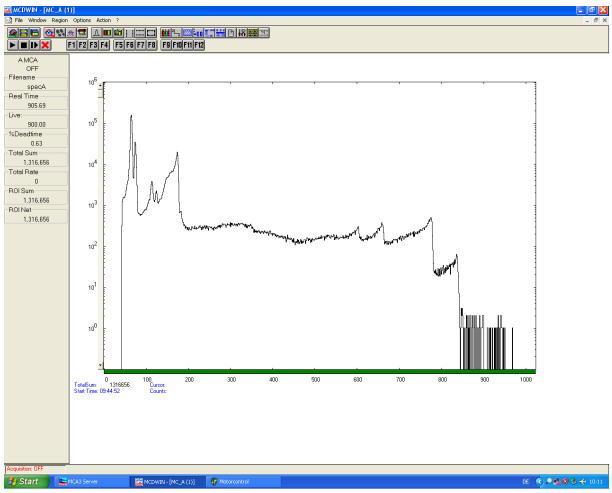

Figure 17: The MCA-3 graphical interface. The shown distribution corresponds to the energy spectrum of a multi-gamma source, in a totally different application.

Question: Write down in your logbook these values, together with their uncertainties. Determine the detector energy resolution (equation 9) at 511 keV and 1.275 MeV.

Question: Write down the Compton edge positions (ADC counts) in your logbook. Give also an estimate of their corresponding uncertainties. Compute the energy corresponding to those points (equation 6).

Question: Extract the calibration curve (Energy vs. ADC channel) using the 4 determined points, including the error bars and perform a linear fit. Is the detector linear?

Question: From the MCA spectrum, read out the position (in ADC channel) of the low energy peak and write it in your logbook. Using the energy calibration derived before, calculate its energy in keV. What can this peak be?

5.7 Energy spectrum with coincidence condition

Measure the energy spectrum of a NaI scintillator for events in coincidence: the signal from one detector is analyzed only if it is coincident in time with a signal in the opposite placed detector. At first build the coincidence (Section 5.7), then use this coincidence signal as a gate for the MCA to acquire the spectrum (Section 5.7).

Coincidence Setup The final setup to be used is the one shown in Figure 18. The dynode outputs of the two PMT's are sent into two different discriminators, the outputs of the discriminators are sent into a coincidence unit. Finally, the width of the coincidence output is stretched with the D.TRIGGER module to provide a gate for the MCA to cover the full length of the NaI anode signal.
Build the setup in different steps. Check each step on the scope:

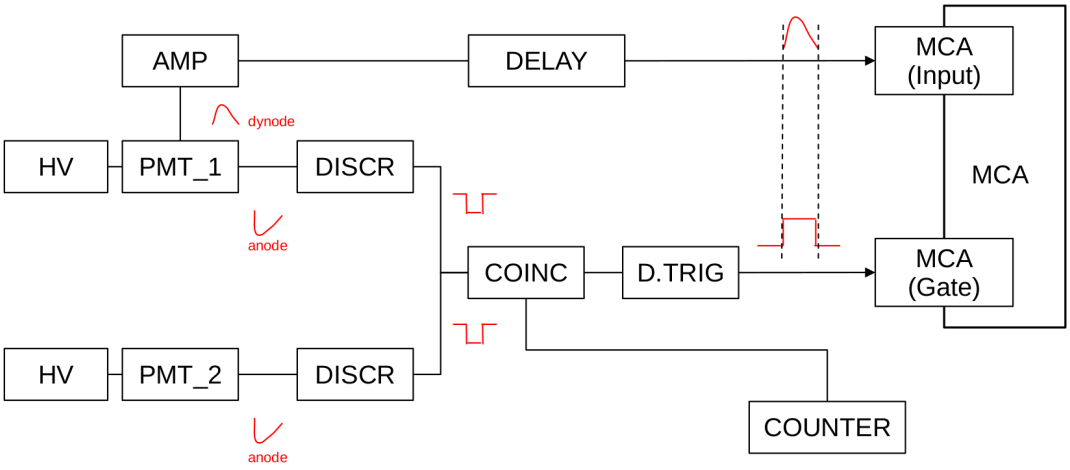

Figure 18: Setup for the coincidence of the two PMT's and the acquisition of one of them (PMT1) in the MCA.

- Check the discriminators thresholds and look simultaneously on the scope at both discriminator outputs. Check especially their relative timing and widths. These signals should generate a coincidence, therefore they should overlap in time (see Figure 10). If they are not properly set, change their widths and/or apply suitable delays. To change the relative delays you can use either the LEMO cables (different lengths), or the switch DELAY unit.
- Send the two discriminator outputs into the coincidence unit. On the scope look simultaneously at the coincidence output and at one discriminator signal. Repeat it for both discriminator outputs.
- The output of the D.TRIGGER module will provide the gate for the MCA. Its width must be sufficiently long so that the anode signal to be acquired by the MCA fully overlaps in time with the gate (as sketched in Figure 18). Using the small screws on the D.TRIGGER module and the scope, adjust the length and delay of the D.TRIGGER output gate.
- Delay the anode signal until it is well inside the D.TRIGGER gate using cables and/or the DELAY unit.
- The large width of the D.TRIGGER output also eliminates the multiple ringing in the discriminators already observed in Section **??**.

Question: Send the coincidence output (after the D.TRIGGER) into the counter and set a timer: Which rate of coincidence do you measure? Compare it with the rate of single detectors (i.e. no coincidence) acquired for the same amount of time. Can you justify the difference between the two count rates? (Tip: observe what happens on the counter when you remove one of the two PMT's from the coincidence, by switching off the coincidence button).

Acquisition of the energy spectra Now the coincidence is set up and you can measure the energy spectrum of one photon in coincidence condition. Use the MCA card, with the gate option enabled, which means that only signals falling inside the gate are analyzed.

- Use the TTL output signal of the D.TRIGGER as gate for the MCA card. Connect the anode signal (positive polarity) of the PMT you want to analyze to the right input of the MCA card. Make sure that the gate and the anode signal reach the MCA with the proper relative delay (anode signal fully contained inside the gate).
- Enable the gate option for the MCA: select the "Option" button → "Range Preset"→ "ADC" button → Select "Gate" and "coinc"
- Acquire a spectrum and save it.
- Look at the spectrum, also on a logarithmic scale (toggle lin/log button).

Question: Draw the spectrum in your logbook. In the report include the measured spectrum, both in linear and logarithmic scale.

Question: Compare the photon energy spectra measured with the gate (coincident with a photon in the opposite detector) and without the gate. Comment extensively about their similarities and differences. **This is the core of the experiment. Discuss it with the assistant.**

A Appendix

A.1 Linear and mass attenuation coefficient

The *linear attenuation coefficient* μ is a characteristic property of each material which describes the probability of interaction of photons with the material itself per unit path length. The number of transmitted photons I over a certain thickness d is then given by:

$$\frac{I}{I_0} = e^{-\mu d} \tag{10}$$

where I_0 is the number of photons without any absorber. μ is proportional to the material density and the total photon-matter interaction cross section. Thus it includes contributions from photoelectric, Compton and pair productions effects, and it is photon energy dependent. As an example, Figure 19 shows both the total and partial linear absorption coefficients for the NaI scintillator compared with a typical plastic scintillator (NE102A). Note the difference in the relative magnitudes of the photoelectric and Compton cross sections.

The practical use of the linear attenuation coefficient is limited by the fact that it varies with the density of the absorber, even though the absorber material remains the same. The *mass attenuation coefficient* $\frac{\mu}{\rho}$ (i.e. the linear coefficient normalized to the density material [g/cm^2]) is of more fundamental value, because it's independent of the actual density and physical state (gas, liquid or solid) of the absorber. Figure 20 shows the mass attenuation coefficient in lead (Pb, ρ = 11.34 g/cm^3), which is the most classical absorber material used for the shielding of radioactive sources. This same plot, together with the data table, is also found among the material data sheets.

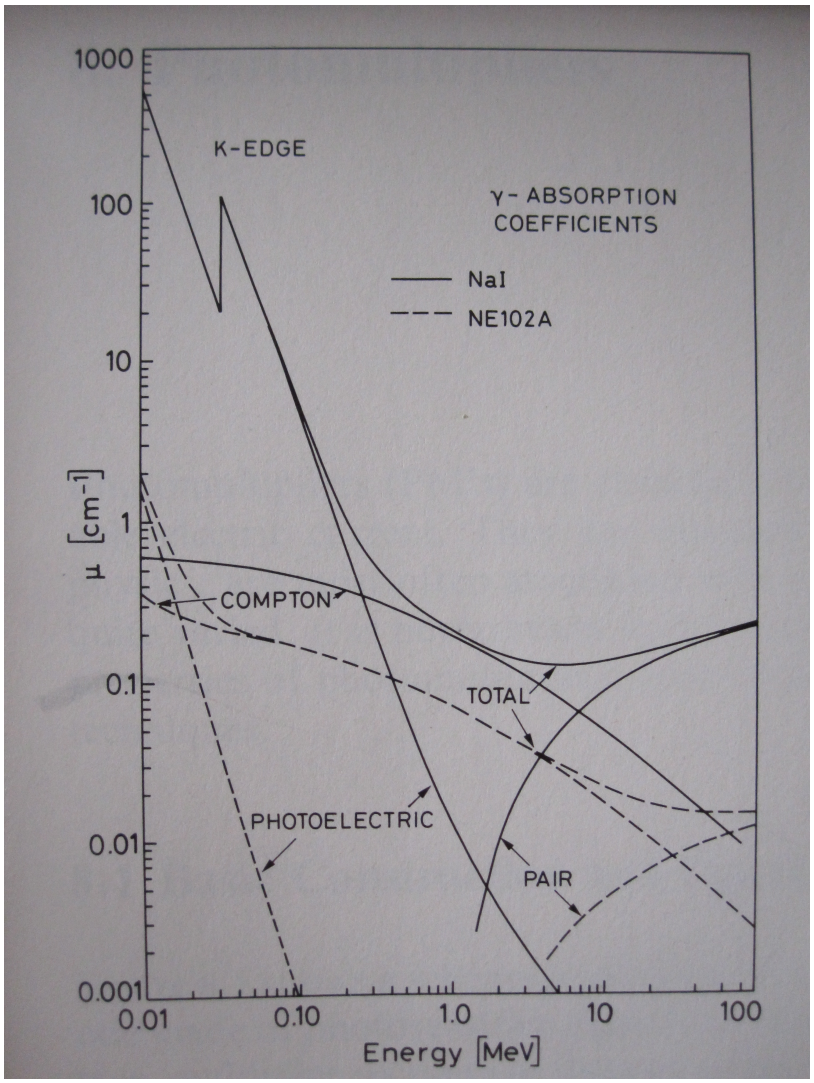

Figure 19: Linear attenuation coefficients as a function of the incoming photon energy for NaI (continuous lines) and NE102A plastic scintillator (dashed lines). Together with the total cross sections, also the partial photoelectric, Compton and pair productions contributions are drawn. [4]

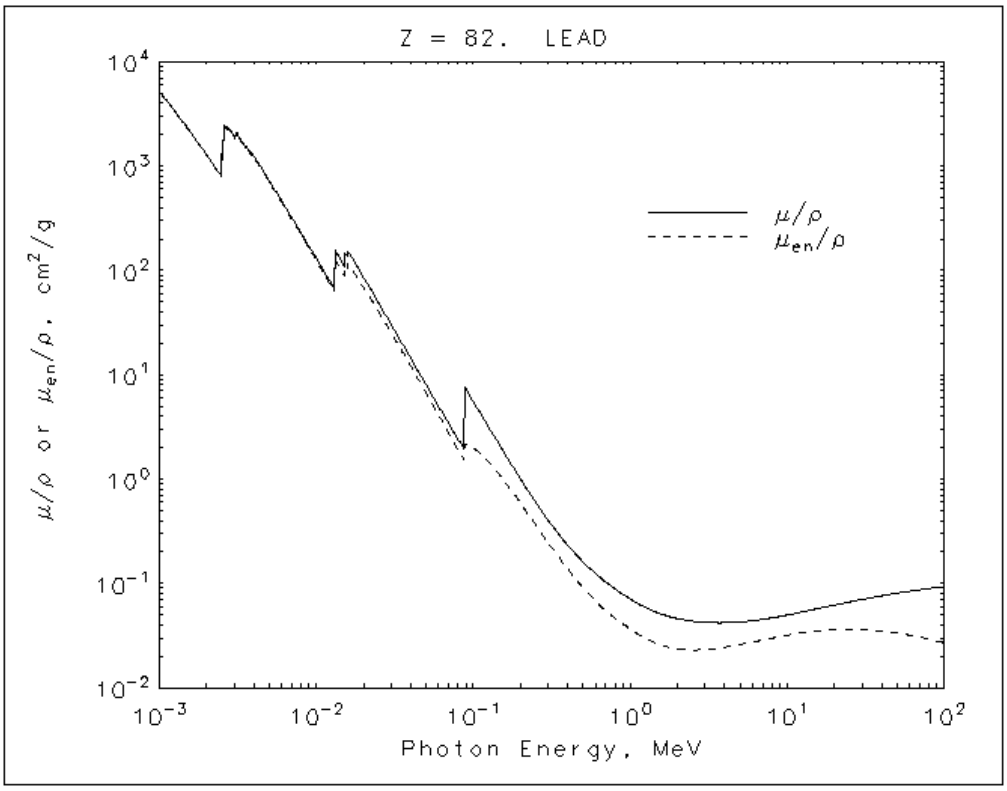

Figure 20: Mass attenuation coefficient for lead (Pb, ρ = 11.34 g/cm^3) as a function of the incoming photon energy. [13]

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