Chalmers, Department of Physics
Division of Subatomic and Plasma Physics
Original Idea: Thomas Nilsson, 1994
Revised in 2017 by Håkan Johansson and Andreas Heinz

K8

Coincidence Measurements

The purpose of this laboratory is to get familiar with a number of key concepts in subatomic physics:

- The detection of *neutral* particles, in this case photons, is difficult. Therefore, the detection is typically based on energy transfer to *charged* particles, here electrons, which are much easier to detect.
- The three different ways gamma radiation can interact with matter: photo absorption, Compton scattering and pair production. All of these processes result in charged particles, which carry a part or all of the energy of the initial photon.
- The use of coincidence techniques, demonstrated by using γ-γ coincidence measurements. Coincidence techniques are highly useful to reduce unwanted background or electronic noise, while they also allow to extract information on quantum-mechanical systems that is otherwise not accessible. For example, angular correlations of two subsequently emitted cascade gamma rays provide information that can be used to determine the total angular momentum of excited nuclear states.

Prior Knowledge You should have basic knowledge about β- and γ-decays, the interaction of gamma photons with matter and electrical measurement techniques. Answer the Questions at the end of these instructions **before the laboratory**.

Name: ..... Course: .....

Date: ..... Supervisor: .....

Approved: .....

1 Introduction

The vast majority of modern experiments in subatomic physics, but also in other fields, is based on coincidence methods, i.e. measuring several quantities for the same event. This experimental approach is one of the most important ones in experimental physics. Successes, like the discovery of the Higgs Boson in 2012, would not have been possible without this technique, which is unique in its ability to reduce unwanted background and electronic noise[1].

In this laboratory, coincidence methods are illustrated by the simultaneous detection of gamma radiation in two detectors. For the investigation of nuclear structure this approach is very important. As an additional benefit, the interaction of γ radiation with matter, modern γ-ray detectors, and their associated electronics are discussed, while a careful calibration of the two detectors is the basis for subsequent measurements performed in this laboratory.

A coincidence measurement means that several quantities that relate to the same physical process are measured simultaneously. This has several advantages, but complicates the measurement considerably. A few examples of benefits with coincident data:

- Better signal-to-background ratios, because only data that fulfil already at least one condition are recorded. Radiation from sources that are not of interest as well as electronic noise can be suppressed.
- Consecutive γ-transitions can be measured. This allows to build level schemes of excited states in nuclei. Moreover, the multi-polarity of the radiation can be determined by measuring angular correlations. This, in turn, can be used to assign total angular momenta (often called *spin* by nuclear physicists) to ground and excited states in nuclei (see, e.g., Krane, Ch. **10.5**, or Martin, Ch. **7.8**).
- To study multi-step processes, e.g. a β-decay followed by γ emission, or β-delayed particle emission. Such processes often compete with and therefore often are accompanied by single-step processes, which might not be of interest and therefore form unwanted background events.
- Timing information is necessary to extract information at large experimental setups for measurement of complex reactions, where many detector systems are involved.

The advantages are such that basically all experiments in subatomic physics today are coincidence experiments. Note that this laboratory realizes coincidence measurements in *hardware*, that means we realize the coincidence condition by electronics. It is sometimes also possible to require coincident detection by two or more detectors after

[1] *Background* and *noise* are two different things. The former originates from sources of radiation other than the one we are interested in, hence the term background radiation. The latter is more appropriately called electronic noise, as it is caused by e.g. thermal noise in electronic components or the pick-up of electromagnetic signals by the circuits used in our setup.

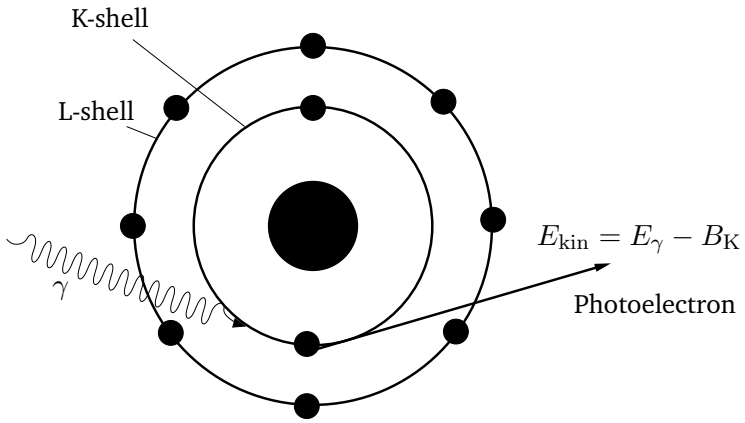

Figure 1: Schematic illustration of photo absorption.

data were recorded using appropriate *software*. Most experiments in subatomic physics use a combination of those approaches. The laboratory uses a setup where two germanium detectors are used to study coincident γ-rays. Krane, Ch. **7.6-7.7**, discusses γ and coincidence measurements in depth, see also Martin, Ch. **4.5**.

Interactions of Gamma Radiation with Matter

In order to detect γ-photons, they must somehow interact with the detector material. The behaviour of a gamma detector is therefore directly linked to how gamma radiation interacts with matter, which occurs in three ways:

1. Photo absorption (or photoelectric effect), where the incoming photon transfers all its energy to one atomic electron. The kinetic energy of the electron, E_{kin}, is equal to the energy of the incoming photon, E_γ, minus the binding energy of the electron, B_{K}:

$$E_{\text{kin}} = E_\gamma - B_{\text{K}}. \tag{1}$$

   Photo absorption is illustrated in Fig. 1.

2. Compton scattering, where the photon is scattered against an atomic electron, thereby transferring a fraction of its energy to the latter, see Fig. 2. The energy of the electron after the scattering process is a function of the initial photon energy, $E_\gamma = h\nu$ and the scattering angle θ:

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

   with m_e denoting the electron mass. This relationship is a consequence of energy and momentum conservation.

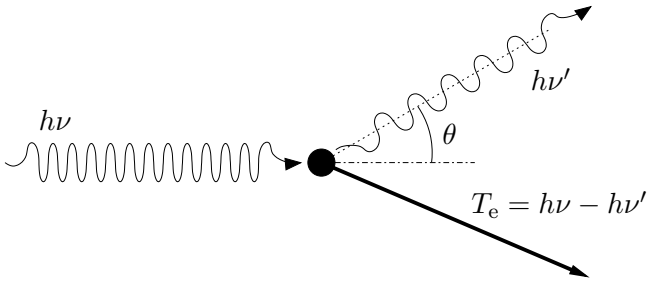

Figure 2: Schematic illustration of Compton scattering.

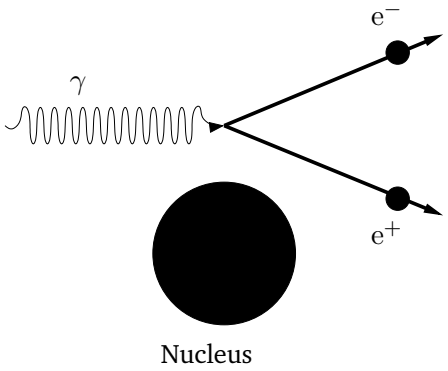

Figure 3: Schematic illustration of pair production.

3. Pair production, where one photon is converted to an electron-positron pair, can only occur for gamma energies above 1.022 MeV, because the photon has no rest mass and the two created particles each have a mass of 511 keV. This process cannot occur in vacuum due to momentum conservation, however it is possible in the vicinity of a nucleus, which can absorb the recoil momentum (in return for a small energy fee). The energy left after the creation of the electron and position is shared by both particles, not equally, as their kinetic energy. This process is presented schematically in Fig. 3.

Reality is often a combination of these effects, as shown in Fig. 4. A photon can be Compton-scattered several times, successively loosing energy, before it finally is photo-absorbed (case 2 in Fig. 4). In such a process, the photon will deposit all its energy in the detector material. However, if the photon leaves the detector after one or several Compton scatterings, only a fraction of the energy will be detected. This is illustrated in case 1 of Fig 4.

All the described processes finally give energetic electrons (positrons). These in turn interact with the atomic electrons, are decelerated and transfer their energy to the detector material which becomes excited. When a semiconductor like germanium or silicon is used, the interaction process creates electron-hole pairs in the material. When pair-production is involved, further processes come into play; the positron is essentially de-

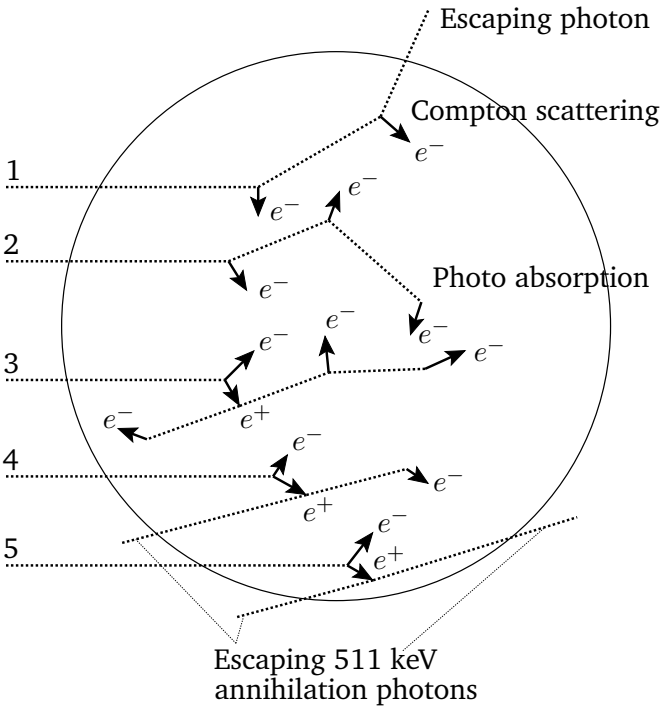

Figure 4: Some of the incoming photons can interact with the detector material via a single process or a combination of photo absorption, Compton scattering or pair production. See text for details.

celerated in the same way as the electron, thereby exciting the detector material. When it has reached a sufficiently low energy, it can form positronium with an atomic electron. The electron and positron are the anti-particle of each other. They will annihilate under emission of two gamma photons, each with an energy of 511 keV and propagating in opposite directions (momentum conservation). These two photons can also be detected and completely absorbed, and in this case the total initial photon energy has been transferred to the detector material. This process is shown as case 3 in Fig. 4. If one or both of the annihilation photons escape from the detector without interacting (case 4 and 5, respectively) only an energy corresponding to the initial energy minus 511 keV or 1022 keV is registered. The peaks that thus appear in the energy spectrum are denoted as **single** and **double escape** peaks.

A characteristic energy spectrum from a germanium detector is shown in Fig. 5, with one sharp total absorption peak and a broad distribution from Compton-scattered photons. As can be seen, the events where only a part of the photon energy is registered are dominating, but the very good energy resolution makes the total-energy events anyhow clearly visible.

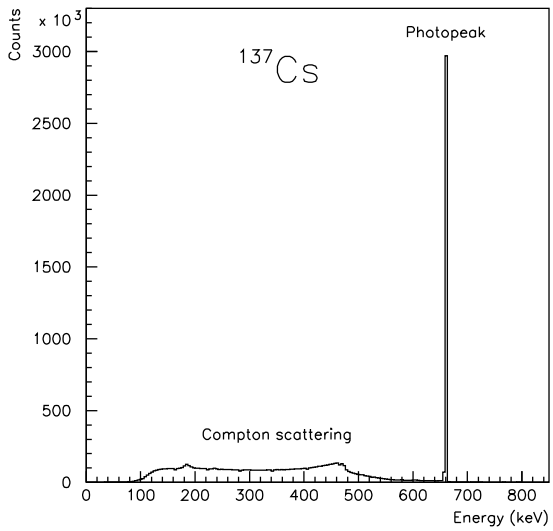

Figure 5: Energy spectrum acquired with a Germanium detector and a ^{137}Cs γ-ray source, following the β-decay to ^{137}Ba. The sharp peak corresponds to total absorption by photoelectric effect and the distribution at lower energies is related to photons escaping the detector after Compton scattering.

Gamma-ray spectroscopy

Level schemes show the energies of excited states in a given isotope as well as their quantum numbers such as total angular momentum and parity (as far as they are known). In general such level schemes can be quite complex, as demonstrated by the example given in Fig. 6. The complexity should not discourage you. There are many regular features in level schemes, typically called *bands*, that allow to draw conclusions on the structure of the nucleus in question. Note that not all levels are connected to the ground state via arrows that indicate γ-transitions (because γ-transitions with higher multipolarities are unlikely). Hence, a given level decays usually via a cascade of γ-rays to the ground state. Using appropriate coincidence measurements, it is possible to infer the individual levels and to build up such level schemes. In modern experiments some 100 detectors might be used and γ-γ-γ coincidences and in some cases even γ-γ-γ-γ coincidences are used in experiments and analysis.

The preferred interaction of γ-rays with matter is photo absorption, as here the kinetic energy of the electron provides direct access to the energy difference between two levels in a nucleus. The missing binding energy of the photoelectron that is not detected is typically small and taken into account by a proper calibration.

Compton scattering, on the other hand, is a problem, because a detector cannot distinguish between photo absorption, when a γ photon deposits *all* of its energy and Compton scattering, where only a *part* of the γ-ray energy is detected. When many different γ-rays are emitted this can create very severe problems in the analysis. There

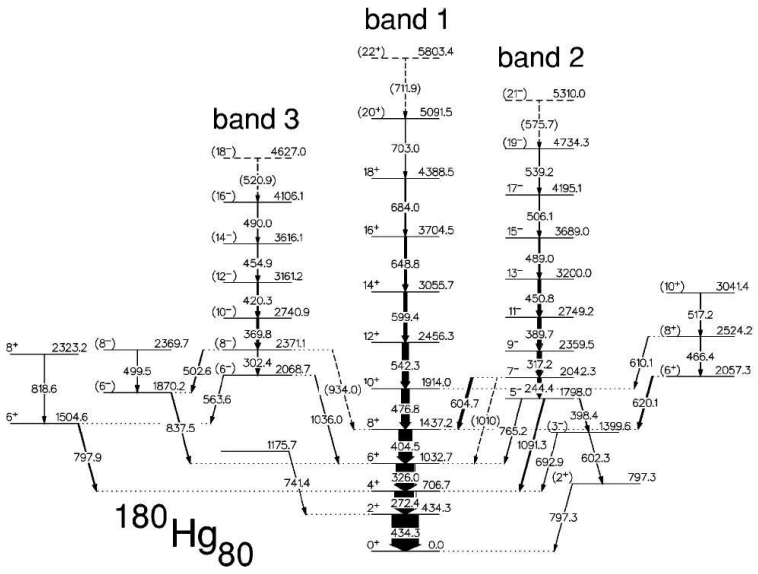

Figure 6: Level scheme of ^{180}Hg as an example. The thickness of each arrow is proportional to the intensity of a given γ transition. Note that not all excited states in ^{180}Hg decay by emission of a single γ-ray to the ground state. See text for further discussion. Reprinted figure with permission from from F.G. Kondev *et al.*, Phys. Rev. **C 62**, 044305 (2000). Copyright (2000) by the American Physical Society.

are two ways around this problem:

- Anti-Compton shielding: each germanium detector is surrounded by a scintillation detector (typically made of a material called BGO or bismuth germanate). These detectors are comparably cheap, have a much higher detection efficiency for γ-rays than germanium detectors but also a much lower energy resolution. As soon as a germanium detector detects a γ-photon in coincidence with the surrounding BGO detector, it is assumed that Compton scattering took place and the signal of the germanium detector is not recorded. This results in spectra with very much reduced Compton-scattered events. Note that the BGO detector does not detect γ-rays directly from the source because of a heavy metal absorber that blocks its line-of-view towards the source. This is illustrated in the left part of Fig. 7.

- γ-ray tracking: is a more modern approach. Here the source is surrounded by germanium detectors, which are *segmented*, that means they are split due to a special way of manufacturing the germanium crystals into independent electric segments. Those are essentially independent detectors. Now, coincident hits in different segments can be identified as events with Compton scattered photons when fulfilling (2). Remaining hits are assumed to be due to photo absorption, where a photon deposited all its energy. The advantage of this approach is that the energy of all segments involved in Compton scattering can be added so that it is

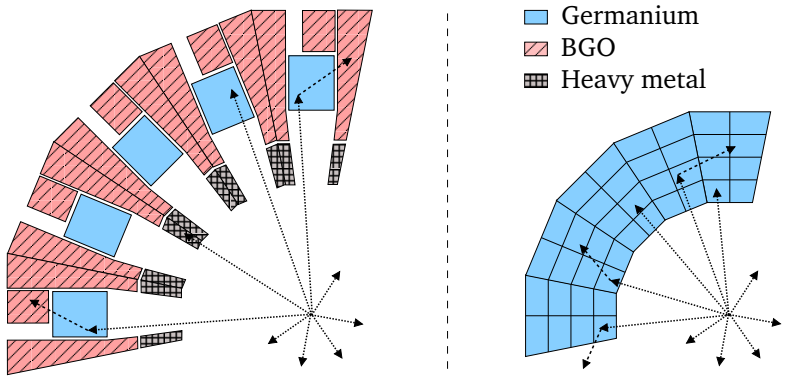

Figure 7: Gamma-ray detection with arrays of germanium detectors. **Left:** An array of germanium detectors, each of which is surrounded by BGO scintillating detectors. Each time a BGO and a germanium detect a γ-ray in coincidence, the event is considered to be caused by Compton scattering and therefore discarded. Note that the line-of-sight between the γ-ray source and the BGO detectors is blocked by heavy metal that has a high probability for absorbing γ-photons. **Right:** A γ-ray tracking array, where Compton-scattered photons are detected in other segments of the same or another detector. The energy deposited in different segments can be added up to recover the full-energy information. For details see text. Figure inspired by I.Y. Lee, M.A. Deleplanque, K. Vetter, Rep. Prog. Phys. **66**, 1095 (2003).

possible to reconstruct the original energy of the photon. A schematic illustration of this approach is presented in the right part of Fig. 7.

Experimental Setup

Germanium detectors are used at the boiling point of nitrogen (77 K) to reduce the intrinsic conductivity and the thermal noise. A voltage is applied to the detector, which behaves as a diode, and depletes it of charge carriers. The voltage (a few kV) is determined by the size of the crystal. The detector, being a high-purity single-crystal, normally only conducts a very small current. As previously mentioned, electron-hole pairs are produced when incoming quanta of radiation interacts with the crystal. This makes it electrically conductive for a short moment, and the applied high voltage drives the liberated charges towards the electrodes. The charge is proportional to the number of created electron-hole pairs, which in turn is proportional to the energy deposited in the material.

The charge pulses are converted to voltage pulses by a pre-amplifier, which is built into the detector encapsulation. The pulses are then led to spectroscopic amplifiers which transforms them to Gaussian shaped pulses, where the amplitude carries the information about the energy. To study an energy spectrum, the height of these pulses are

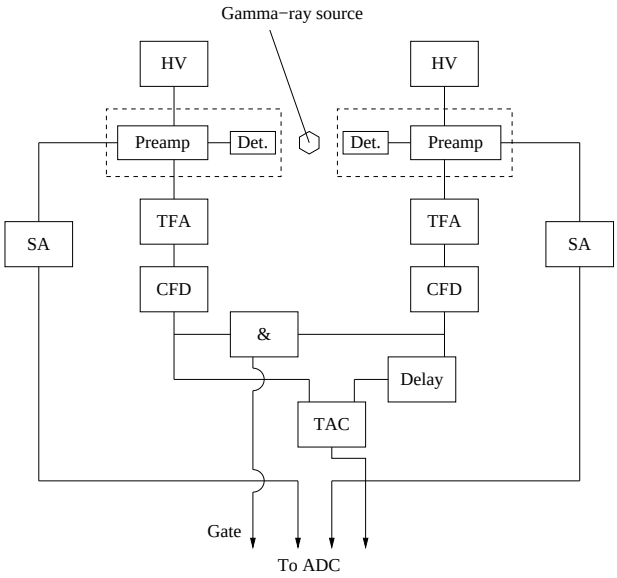

Figure 8: Principle operation of the electronics used in the laboratory. Gamma source, HV (High Voltage power supply), detector, preamplifier (inside the detector housing), SA (Spectroscopy Amplifier), TFA (Timing Filter Amplifier), CFD (Constant Fraction Discriminator), coincidence logic unit (&), delay, TAC (Time-to-Analog Converter), gate for, and signals to, the ADC (Analog-to-Digital Converter).

digitised in an **ADC** (analog-to-digital converter) and presented on a standard PC (c.f. Laboratory K5).

We do however want to study *coincident* γ-photons, which requires a slightly more complicated setup than for K5. In addition to the energy information, also the timing information must be used, to only register those events where both detectors detected a photon within a short period of time. A setup for this purpose is shown in Fig. 8. The previously-mentioned spectroscopy amplifiers are marked **SA**. Each detector signal is also connected from the pre-amplifier to a timing filter amplifier (**TFA**). The output signal of each TFA is fed into a constant fraction discriminator (**CFD**). This module generates a logic signal with a well-defined timing (0 or 1, corresponding to 0 V or -0.8 V) when the pulse height exceeds a pre-set value (to ignore noise signals). The time is determined e.g. by the incoming pulse reaching 30 % of its total amplitude, independent of the amplitude. Thus the name constant fraction. This signal is used to tell when a detector has registered a radiation quantum.

The logic signals from the two CFDs are connected to an AND-gate (see timing scheme in Fig. 9) in a module that produces a logic signal when the AND-condition is fulfilled, i.e. both detectors registered something simultaneously. What is meant by simultaneously is determined by the length of the signals that are sent to the AND-gate — they must overlap in time. The output of the AND-gate is used as a **trigger** to the data acquisition system, i.e. to signal that an event, a collection of data values, shall be con-

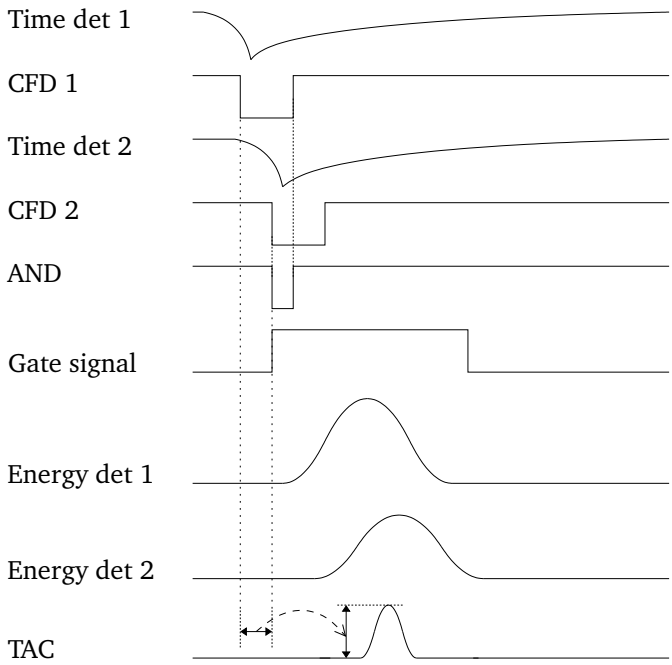

Figure 9: Timing scheme for the pulses (analog and logical) used in the experimental setup.

verted in an ADC. The ADC converts the amplitude of the pulses from the spectroscopy amplifiers that carry the energy information, and the pulse that comes from the time-to-amplitude converter (**TAC**) to digital values when a gate-signal is active (logic 1). This gate-signal is also delivered by the AND-module, but positive and stretched to be long enough to cover the shaped energy signals, which is required for the ADC to convert the pulses.

In order to determine to what degree the detected gamma photons are coincident, a TAC is used. It acts as a stop-watch, converting the time between a start and a stop signal to the amplitude of a pulse. It is used to measure the time between the signals from two detectors, and is started with one CFD pulse and stopped with the other. To prevent the stop pulse from arriving before the start pulse of the same event, the former is delayed with a fixed delay.

Typical subatomic physics experiments involve a large number of detectors, which puts stringent requirements on the reliability and standardisation of the electronics in use. The electronics shown in Fig. 8 is realised by **NIM** (Nuclear Instrument Module), with standardised sizes, supply voltages, etc... The modular equipment makes it easy to build and change experimental setups, without adaption problems, soldering, and so on. The modules are mounted in and draw power from a NIM crate.

Data Acquisition and Analysis

The conversion of data occurs in an ADC that operates according to **CAMAC**-standard. This describes electronic modules that can be controlled and read out with a computer. Also here, dimensions and voltages are standardised, such that modules from different suppliers can be used together. The modules are mounted in a CAMAC crate, which has connectors both for supply voltages and data transmission. The crate also houses a crate controller module, which is connected to the computer controlling the data acquisition (DAQ). The computers used to process and present the data are connected to the DAQ computer via normal network.

With this setup, three quantities from one and the same gamma-gamma coincidence can be measured; the energy deposited in each detector, and the time between the detection of the two photons. These coincident data-points are our events.

In large experiments, the physical interpretation of the data is often less clear during the data collection, as calibrations etc. have not yet been finally evaluated. The efforts of the experimentalists are concentrated on ensuring that the measured signals show reasonable values, so called on-line analysis. The acquired data is stored in files as lists of events, such that later off-line analysis can replay the measurement and see what happened. More complicated conditions and cuts can be made, and physical quantities can be calculated from the measured values. Completing this analysis can take several years. A simple example, applicable to the present setup, is the use of the TAC signal. The information about simultaneity it provides us with allows us to use a fairly generous (hardware) coincidence requirement, to be tightened later during off-line analysis through software.

Questions

1. Why can the momentum not be conserved at pair-production in vacuum?
2. What materials are suitable for radiation protection against γ radiation on the basis of its interaction with matter?
3. Why can a single-escape peak be seen clearly in an energy spectrum, despite the fact that the probability for total absorption of one annihilation photon and the complete escape of the other must be small?
4. Assume an initial photon energy of $E_\gamma = 3$ MeV. Draw a schematic measured energy spectrum, including the single and double escape peaks.
5. How many electron-hole pairs can theoretically be produced when one 1332 keV photon is photo-absorbed in a germanium crystal?
6. How many bits of resolution are needed in our ADC to fully use a Ge detector with a resolution of 2 keV, with a dynamic interval of 2 MeV?

Tasks

1. Acquaint yourself with the setup and try to understand the components.
2. Measure the gamma radiation from ^{60}Co without coincidence requirements, a so called singles measurement. Study the spectrum and calibrate the system.

   Investigate prominent background sources.
3. Redo the measurement, but now with a condition on coincident photons. Analyse the result, and draw conclusions about the decay scheme of ^{60}Co.

   Why do the singles spectra change appearance?
4. Repeat the measurements in 2. and 3. for ^{22}Na.
5. Measure the coincident γ-spectrum for ^{22}Na with the two germanium detectors at an angle of 90°. Interpret the coincidence spectrum.
6. Measure the γ-singles spectrum of an unknown sample and determine the origin of the radiation with the help of the chart of the nuclides.