Studies of excited nuclear states by using the $\gamma\gamma$-coincidence technique

Lab Exercise in Nuclear Physics

In this lab exercise we will study the excited states of a nucleus by the so-called *coincidence technique* using two germanium detectors. The exercise aims to teach you to:

- Connect and tune the experimental equipment by yourself.

- Understand and be able to use some common signal processing devices.

- Understand the idea behind coincidence measurements.

- Build up a level scheme based on the measured coincidence data.

- Interpret the different structures of the level scheme.

Before the lab exercise you should read the following chapters in the Krane textbook (K.S. Krane, *Introductory Nuclear Physics*).

- Energy Measurements, (Krane, chapter 7.6)

- Coincidence Measurement, (Krane, chapter 7.7)

- Collective Structure, esp. Rotational Bands, (Krane, chapter 5.2)

1 Introduction

Every quantum mechanical system can be described theoretically by its Hamilton operator. From this operator, the eigenfunctions and eigenvalues of the system can, at least in theory, be deduced. This means that the nucleus is described by a model that can be checked e.g. by experimentally measuring energy levels. In the course in nuclear physics both the shell model and models for collective motion are described. The validity of the models can of course also be tested by measurement of other observables, for example the total moment of inertia, the magnetic dipole moment, the electrical quadrupole moment and the transition probabilities. These are related to the wave functions of the nucleus through the matrix element for a given operator. In order to further develop
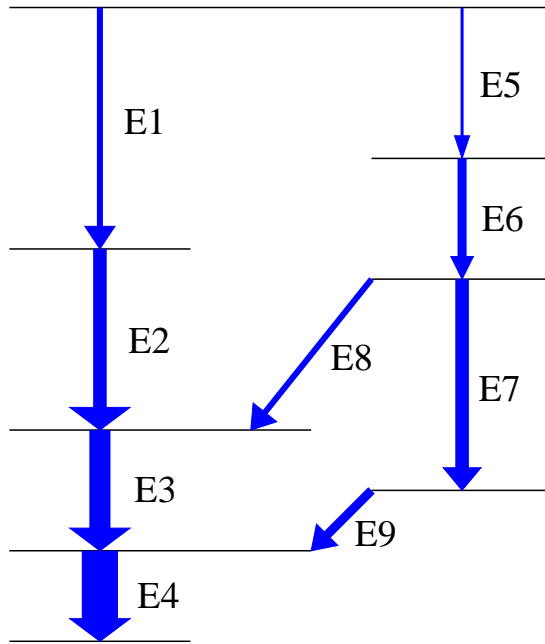
Figure 1: Part of a level scheme. If we use only one detector to count the decays from several nuclei in the source we obtain a so-called *singles spectrum* where all the energies E1-E9 can be seen. But if we can count which γ-photons that were emitted in a cascade from *one single nucleus* we can obtain information about the position of the levels in the level scheme.

the theories of the nucleus and to be able to understand new phenomena, it is thus important to measure how the excited states of the nucleus are distributed.

If we can create the nucleus in an excited state, for example using a nuclear reaction or through alpha or beta decay, the nucleus is often deexcited by the emission of a cascade of gamma radiation. This cascade connects different states with each other. If we use only one detector to detect the gamma decay we get a so-called singles spectrum, from which it is not possible to deduce anything about the relative positions of the energy levels. We only get a number of peaks in the spectrum which correspond to the energy differences between different states in the nucleus. In order to build up the level scheme, the deexcitations of the nucleus must in some way be related to each other. This can be done by using at least two gamma ray detectors in the experimental setup, and demanding that these detect one gamma quantum each during a time gate with a length that is comparable to a typical life time of a nuclear state.

By systematically choosing each of the peaks that are in the singles spectrum, and for each such peak look at what other transitions appear in the same cascade
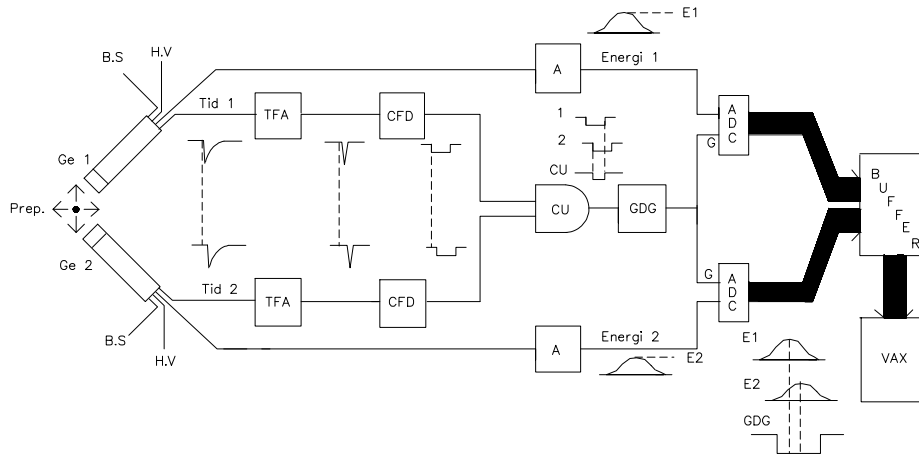
Figure 2: A sketch of the experimental setup of the lab exercise. The abbreviations and the functionality of the units are explained below.

as this peak, a number of conditions that will have to be fulfilled in the final level scheme can be deduced. If another nucleus happens to decay during the same time gate, transitions may appear to be in coincidence although they are really not. These events are called random coincidences and give an unwanted background. The number of detected events that are of this kind depends on the number of gamma rays that hit each detector per unit of time. If the number of events in detectors 1 and 2 are R_1 and R_2 per second and the time gate is Δt seconds wide, in average $R_1 R_2 \Delta t$ random coincidences are detected each second. By minimizing the time gate, this number can be kept at an acceptable level. In some cases a level is metastable, or isomeric, which has as a consequence that all transitions that are below (or after) this level will end up outside this time gate if the gate is started by a transition above this level. In such a case, the levels below and above the isomeric state can be tied together by increasing the length of the time gate.

2 Equipment

For the measurements, two Ge detectors made from highly enriched germanium (Krane, ch 7.4) will be used. The detectors are kept in contact with a container of liquid nitrogen through a cooling rod made from copper. This reduces the thermal noise in the detectors, caused by thermal excitations of electrons across the band gap, that will otherwise disturb the measurements. The detectors also have a temperature sensor. Through feedback of this signal to the voltage supply, the detector will automatically shut down if the temperature of the crystal becomes to high. This function is called Bias Shutdown.

2.1 Signal Processing

Two identical output signals are taken from each detector. After the pre-amplifier, they have the shape of a negative pulse with a short rise time ($\approx$ 20 ns), but a relatively long fall time. One of these signals will give information about the amount of energy that was deposited by the incoming gamma quantum, and the other will be used for determining when the energy was deposited.

2.2 Energy Amplifier

The charge of the pulse, i.e. the area under the current curve, is proportional to the deposited energy. Therefore, one of the signals is processed by a slow linear amplifier (A in Fig 2). This amplifier gives an output signal of gaussian shape, for which the amplitude is proportional to the area of the input signal, so that the energy information that is contained in the input signal is conserved. There are two other reasons for changing the shape of the signal. One is improvement of the signal-to-noise ratio, which in principle means filtering out the the frequencies that are dominated by noise. By reducing the band width, i.e. removing these Fourier components from the signal, the shape of the pulse will be changed. Also, superposition of succeeding signals on the tail of the first pulse (so-called pile-up) should be avoided, since the pile-up would distort the energy signal. This can be avoided by reducing the length of the tail. A linear amplifier consists in principle of a number of integrating and differentiating steps. Usually, the time constant of these steps can be varied. Since as much as possible of the charge of the input signal should be retained, a long integration time is favorable.

2.3 Timing Filter Amplifier (TFA)

The other output signal from the detector is passed to a fast amplifier. This device should amplify the signal, optimize the pulse shape in order to improve the time definition, and reduce the noise. This is achieved by processing the signal in a number of filters with a small time constant. The result is a pulse with a very short rise and fall time. The output signal has a typical half width of some ten nanoseconds. From the TFA the signal is passed on to a discriminator.

2.4 Time Resolution

The discriminator converts the analogous input signal to a digital pulse which can then be used for making a digital AND of the two detector branches. Various types of discriminators exist, and they can be distinguished by the way the trigger condition is defined. The most simple form of trigger conditions is the so-called "leading edge" (LE) trigger. When the input signal passes a certain level, a digital pulse is given on the output. The problem with this kind of amplifier is that signals with the same rise times but different amplitudes will reach the trigger level at different times, which gives a time displacement between the two
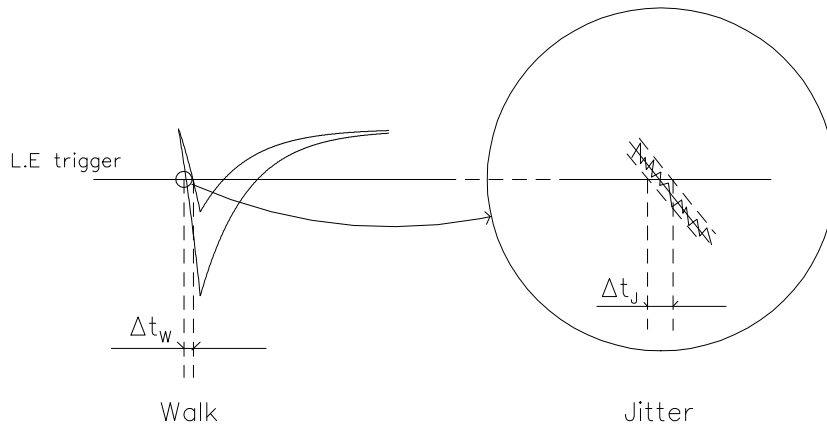
Figure 3: "Walk": Two input signals with the same rise time pass a given level at different time. The trigger point is walking and a shift is introduced.
"Jitter": Overloaded noise also causes a time displacement, but not as large as the displacement caused by walk.

digital pulses that these signals give on the output. This effect, known as "walk" (see Fig. 3), must be eliminated if the coincidence within a few nanoseconds between two signals is to be determined. Another cause for the deterioration of the time characteristics of the signal is the so-called time jitter which is caused by high frequency noise on top of the signal. Two identical signals will never trig at exactly the same time, since the noise causes the trigger level to be reached at different times. This effect is much smaller than the former one, since the noise normally has very low amplitude, and very high frequency as compared to the signal. If a source that emits two gamma quanta at exactly the same time is used (for example annihilation radiation from β^+ decay) and these two quanta hit one detector each, measurement of the time between these events will give information about the size of the time jitter. This can most easily be done by using one of the signals as a start signal, and the other one as a stop signals for a time to amplitude converter (TAC, see Krane ch. 7.7). The output signal from the TAC is proportional to the time between the start and the stop signal, and can be passed to a MCA. The half width of the measured curve defines the time resolution of the system, which also means the times that are shorter than this can not be distinguished by the system. Another source of time jitter is the collection of charges in the detector crystal. Depending on where an interaction has taken place in the germanium crystal, the distance that the charge carriers will have to travel to the electric contact before total charge collection has been achieved will vary. This gives a time difference between two simultaneous events.
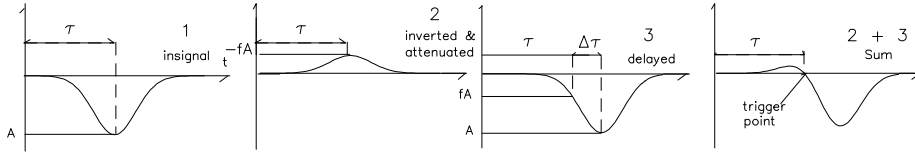
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Figure 4: The principle of CFD triggering: Signals with the same rise time can be triggered at the same time if the input signal is divided into two parts which are treated differently and then added back together.

2.5 Constant Fraction Discrimination (CFD)

A way of avoiding "walk" is to have a different trigger level for signals of different amplitudes. The output signal of the TFA has, with a good accuracy, a constant rise time and also such a pulse shape that it takes two signals of different amplitudes the same time to rise to a given fraction of the maximum amplitude. The CFD uses this in the following manner (see also Fig. 4):

The input signal is divided into two parts. One of them is damped to a fraction f of the total amplitude A, and inverted. The other signal is delayed a time $\Delta\tau$, which is the time it takes for the signal to rise from the amplitude fA to A. This delay can be adjusted with an external delay cable, so that an optimal trigger level is created. If these two signals are added, all signals with the same rise time, τ, will pass the zero at the same time, and the time walk of the LE triggering is avoided. However, the time shift between time signals of different rise times is still present. Since the difference in rise time usually is small, the shift can be reduced by making the delay a little bit shorter than $\Delta\tau$. Then the zero cross over will happen before the maximum amplitude is achieved, which means that the difference in rise time matters less. The width of the digital pulse from the output of the CFD can be varied. In our case, it should be around 50 ns. There is also a possibility to set a lower threshold level. This is done by using the output signal of the CFD as a trigger pulse on the oscilloscope, and at the same time looking at energy signal that corresponds to the trigger point. If pulses are coming from the CFD without any energy signal, the unit is triggering on electronic noise and the threshold level must be increased. Otherwise, the ADCs will be continuously open and the count rate will be so high that their inputs are blocked. The threshold should be set so that low energy signals are detected, but high enough to reduce the noise.

2.6 Coincidence Unit (CU)

As is mentioned above, the width of the coincidence window is set by using the CFD. This width determines within which time interval a pulse in the other branch of the system much appear for both of the pulses that are input to the CU to be active at the same time. The life time for a nuclear level is typically $\leq$ 1ns, while the time resolution is around 20 ns. Two gamma quanta that are not separated by a meta stable level can therefore not be separated in time by
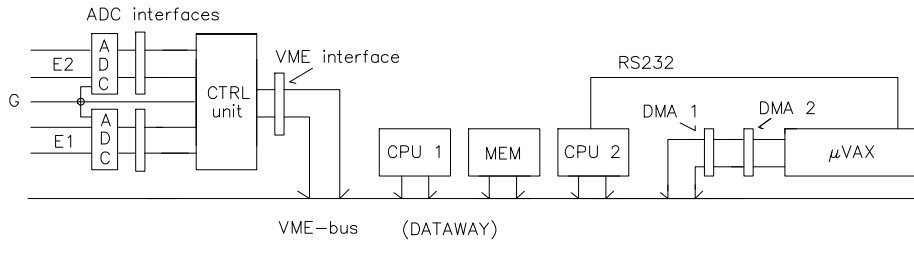
Figure 5: Data transfer scheme for the acquisition system

the acquisition system. Because of this, the emission of the two gamma quanta is said to happen promptly. Ideally, a prompt emission of two gamma quanta should give two time signals that are sinultaneous, but because of jitter, this will not happen. This is the reason for the introduction of a 50 ns gate. If this time is reduced, some coincident gamma pairs will be lost, and if it is too long, the number of random coincidences will increase. The random coincidences can never be completely avoided, since two nuclei may decay at the same time. When both of the input signals to the CU are active, the CU will give a digital pulse, just like a normal AND gate. However, this can not be used directly to open the ADCs.

2.7 Gate and Delay Generator

The total signal processing time from when two gamma quanta hits the detectors until a pulse is available on the output of the CU is some hundred nanoseconds. The processing of the energy signal, however, is not finished until after several microseconds. In order to put energy and gate signals in phase, the gate signal must be delayed, and this is done in the gate and delay generator (GDG). Also, the pulse length must be adjusted so that both ADCs are opened when the energy signals reach their maximum.

2.8 Acquisition (ACQ) System

When the ADC is opened by the gate pulse, the analogous input signal is digitized, provided that the acquisition system is ready to do this. The ADCs can
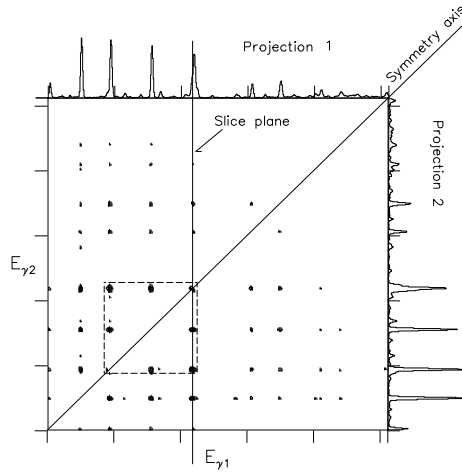
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Figure 6: 1/64 of a 4k×4k matrix seen "from above". The dashed part is seen magnified and from the side in Fig. 7.

both give 8k, i.e. 8192, output channels. They are supervised by a control unit via an interface. The control unit is connected to a VME interface, and is thereby in contact with other units via a 20 MHz bus (i.e. a fast parallel data cable). When an event is finished for retrieval from the ADCs, the control unit reads both energies, and data is transferred via the VME interface by a processor (CPU 1) to the local memory of the computer (MEM). Thereafter, the same processor restores the same processor the interface and the ADCs using the CU and data from a new event can be collected. In total, the ADCs process the signal during about 20 μs, while the transferring and restoring takes 40 μs for the processor to perform. When the local memory is full, the data is transferred by a so-called Direct Memory Access unit. It is controlled by yet another processor (CPU 2). Data can thereafter, independently of the rest of the system, be transferred to a similar DMA unit which is placed in the micro Vax which is the host computer for the acquisition system. The other processor is also in contact with the host via a serial RS232 cable, over which commands are given to the acquisition system. In the host, the events are stored both as integers in a matrix where the row an column indices, respectively, are the energies and also in one dimensional spectra, which are the total projections for the two axes of the matrix.

3   Analysis

In Fig 6, the total intensity of the matrix has been projected onto the two axes. The corresponding projections are used in the lab exercise for finding the energies for all gamma quanta that are emitted. In the analysis, a slice of the
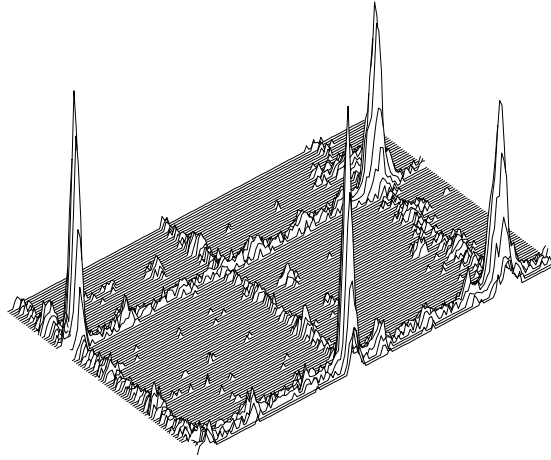
Figure 7: Parts of the matrix in Fig. 6 seen magnified and from above.

matrix is taken for each of the peaks in the projection. This slice corresponds to the slice plane in figure 7. For each slice, at least one background slice is also set.

The gamma rays that hit the detectors may also Compton scatter out of the detector. This will result in events where only part of the total energy has been registered for one or both of the gammas rays. Parallel to the axes, there is because of this a Compton distribution for each peak. These "strings" of events, which are called Compton ridges, are clearly visible in Figure 7. There is also a general background in all channels, which corresponds to events where both gamma quanta have scattered. Random coincidences are also part of this background. By assuming that the background of the peaks in the gate is very similar to the background next to the peak, the background of the gate peaks is approximated by the background of corresponding events in the background gate. By subtracting the background gate from the peak window, a coincidence spectrum almost without background is achieved. In the lab exercise, this is done automatically by the program. Before this, however, the peak and background gates must be set manually in the matrix.

Some useful information for analyzing coincidence spectra:

- Rotational spectra often contain both M1 transitions and E2 transitions. Two M1 transitions the connect the same states as one E2 transition.

- Mutually exclusive quanta must be placed in separate branches of the level scheme.

- All transitions in a cascade must "see" each other.

- The total sum of intensities of the transitions leading to a level is the same as the total intensity of the transitions from a level.

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- The intensities of the peaks are also dependent on the efficiency curve.

4   The Lab Exercise

- Set up the electronics according to the scheme in figure 2.

- Use the oscilloscope to check that the pulses have the expected shape after each unit. Set the CFD threshold levels. Assure that the gate pulse is active over both maxima of the pulses. Estimate the rise- and fall times for the pulses, and the time resolution.

- Start the acquisition and start by calibrating both detectors. Use for example ^{60}Co,^{22}Na, or ^{133}Ba as calibration sources.

- Put the source to be studied in front of the detectors and start the acquisition system.

- Stop the ACQ after about 2h 30 min.

- Start the analysis.

- Prepare the analysis of the level scheme by looking at the spectra before lab. 5. During lab. 5, the rest of the analysis is made in order to build the level scheme.

- The radioactive source to be measured has a long-lived isomeric state which β^--decays to the nucleus we are going to study. The mother nucleus has odd numbers of protons and neutrons. Both the mother and daughter nucleus are deformed. What is the spin and parity of the ground state for the daughter nucleus for which we are studying the excited states?

- You will find at least two rotational structures. One is built on the ground state, the other is built on a γ-vibrational state. What spin sequences are possible in these two case?

- Assume the nucleus to be of prolate shape, $\beta_2 = 0.3$. What value will we then get for the moment of inertia ($\mathcal{J}$) if we assume that the nucleus is a rigid body?

- What value will we get if we assume that the nucleus is a fluid?

- What can we assume about the excitation energy of the lowest excited state in the rotational band that is built on the ground state?

A report should be written, where all of the above points are discussed.