Neutron speed measurement

Study of the $D - T$ fusion reaction realised by using a *Van de Graaff* accelerator

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Abstract

The goal of the experiment is to measure the speed of neutrons produced by the $D - T$ fusion reaction. The reaction is realised using a *Van de Graaff* accelerator and the measurement is achieved by building a trigger circuit based on coincidence modules.

1 Introduction

The aim of this experiment is to provide evidence that a fusion reaction between tritium and accelerated deuterium ions is happening. Deuterium ions are accelerated using a *Van de Graaff* accelerator up to 300keV, and collide into a tritium fixed target. The two particles can undergo a nuclear fusion reaction producing a helium nucleus and a neutron. Detecting those particles, and making sure their characteristics correspond to the ones predicted proves that this reaction is indeed taking place. In this specific case, the alpha particle and the neutron have to be detected in coincidence, and the speed of the neutrons is measured and compared to the theoretical calculation.

Although consisting of a fusion reaction, the study does not focus on producing energy, since the deuterium needs to be accelerated for the reaction to happen admittedly far below critical regime. The present experiment is at a more fundamental level, like the ones carried out at CERN. Although much smaller in size and targeting at the scale of nuclei, the fundamental principles and techniques remain the same: colliding particles, detecting the products of the reaction and see whether it is consistent with theory.

And most important of all you will a trigger circuit, an essential component of every modern particle physics experiment. Nowadays accelerator can produce billions of collisions per second and the limit of modern analyses is the ability of store and analyse all those events. A trigger identifies so called “interesting events” and records them on the computer only if they have interesting characteristics. This makes a first selection and prevents from recording huge amounts of useless data.

This laboratory work will allow you to perform a “pocket LHC experiment” and to become familiar with particle physics experiments. The trigger circuit, based on coincidence, will be built, calibrated and timed properly. Then, several well chosen measurements within the available time can be taken to study the response of the detector. Finally the obtained data will be analysed using *ROOT*, the data analysis framework most used in particle physics.

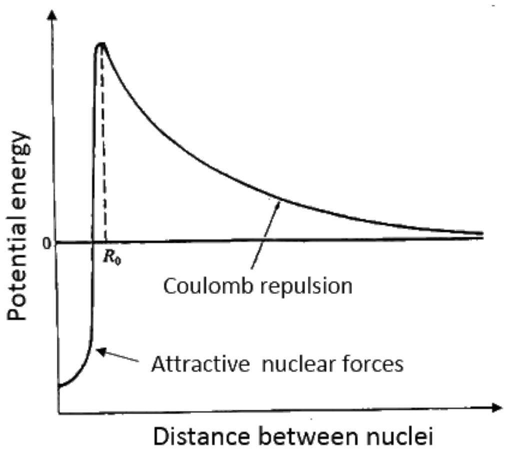
2 Theoretical principles

Before getting deeper in the description of this experiment, it is worth reminding the general concepts being at the core of the latter. In this section, the principles of fusion reactions are recalled and the functioning of a *Van de Graaff* accelerator is explained.

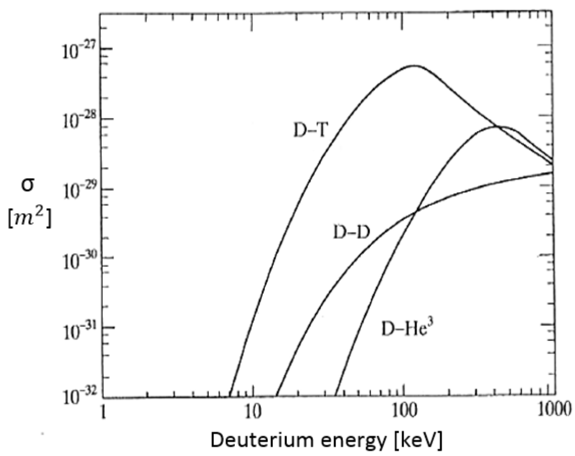
2.1 Features of the $D-T$ fusion reaction

A fusion reaction consists of the process in which two light nuclei come sufficiently close to each other, overpassing the Coulomb repulsion, and enter the strong interaction regime that leads to the formation of a new heavier nucleus (see Fig. 1a).

As it can be seen on Fig. 1b, two good candidates to operate a fusion reaction are the nucleus of Deuterium[1] D and of Tritium[2] T, as the cross section of the reaction happens to be greater for smaller energies.



(a) Potential energy [8]



(b) Cross section of some fusion reactions [2]

The $D - T$ fusion reaction is written as the following [9]:

$$D \ + \ T \quad \longrightarrow \quad \alpha \ + \ n \tag{1}$$

where α is the nucleus of helium and n a neutron.

Knowing the mass of the involved nuclei it is possible to compute the kinetic energy, and thus the velocity, of the neutron in the laboratory frame. Masses:

- $m_D = (1875.612914786176 \pm 0.000000425091)$ MeV
- $m_T = (2808.921022289743 \pm 0.000002390543)$ MeV
- $m_\alpha = (3727.380000 \pm 0.000002)$ MeV
- $m_n = (939.5654000 \pm 0.0000005)$ MeV

2.2 A linear accelerator: the *Van de Graaff* accelerator

As it is revealed on Fig. 1b, the deuterium has to reach a certain energy so that the fusion reaction can happen. In this experiment, this energy will be conferred by the acceleration of the deuterium thanks to a linear accelerator. It is thus worth characterizing the main principles of functioning of the latter.

A linear accelerator is a device that is used to confer kinetic energy to particles thanks to electrostatic interaction. A particle of charge q placed in an electric field $\vec{E}$, generated

[1] Natural isotope of the hydrogen whose nucleus is made of one proton and one neutron: $T \equiv {}^2H$. It exists profusely.

[2] Isotope of the hydrogen whose nucleus is made of one proton and one neutron: $T \equiv {}^3H$. It is unstable and must be produced by fission reaction as it is very rare [1].

by a difference of potential ΔV, feels a force $\vec{F} = q\vec{E}$. This means that a charge can be accelerated by a difference of potential. Its kinetic energy is then $T = \int \vec{F} \cdot \vec{dl} = q\Delta V$. A *Van de Graaff* accelerator is the most elementary linear accelerator one can think of, as it uses a constant electric field[3].

This kind of accelerator does not allow to reach very high energies, as it is hard to get important differences of potential or to construct very long devices.

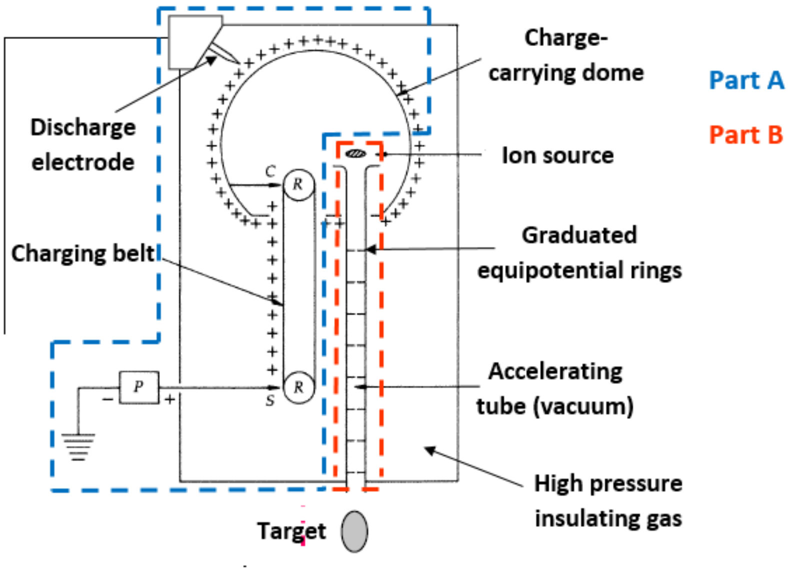


Figure 2: Layout of a typical *Van de Graaff* accelerator [3]

A scheme of a *Van de Graaff* accelerator is given by Fig. 2. The outline of its functioning is the following [5] [6]:

- Part A: the high voltage is generated thanks to a play between different components: a power generator creates positive charges, that are carried out on a moving charging belt up to a charge-carrying dome, embedded in a compressed gas to avoid electric arcs.

- Part B: the source is then ionised thanks to a radiofrequency oscillator, and the positive charges are thrown in the accelerating tube. They are accelerated due to the decrease of potential, ensured by equipotential rings set at lower and lower potential. Note that vacuum has to reign inside the accelerating tube, so that the ions do not encounter any parasite particles. This highly reduces the variation of the energy and focuses the beam.

Note that the steps described above must take place in vacuum, in order to control as much as possible the trajectory of the beam and its energy. See [6] if interested.

[3] More evolved linear accelerators use oscillating electric field, in order to reach higher energies [3] [11].

2.3 Detectors

2.3.1 Overview of main features of detectors

Detectors are the devices allowing experiment to detect particles and therfore collect data. Detectors used for this experiment are a set composed by two elements: a scintillator and a photomultiplier.

- Scintillator: it is a transparent medium whose atoms get excited as a particle comes through it. As the atoms go back to their initial energy state, they emit photons. Since the medium is translarent these can travel trhough it and be collected. Organic crystals, such as plastics, are often used: their molecular energy level spectrum is made of vibrational bands, which leads to the existence of intermediate electronic bands. Those intermediate energy states imply that the emitted photon will not have the same energy as the one needed to excite the atom, and will thus not be re-absorbed by the scintillator [3] Usually, the energy particles loose energy in a material due to their electromagnetic interaction as the collide or their trajectory it bent by the charge of the nucleai in the material.

- Photomultiplier: it is the device that converts photons into electrical signal. On the side connected to the scintillator, there is a photocathode, so that a photon which hits it produces a single or few electrons by photoelectric effect. Because those are too few to generate an electric signal, they are multiplied thanks to a set of dynodes placed in an increasing potential. Each electron colliding with a dynode will extract of the latter some other electrons, that will be accelerated thanks to the increasing potential, and are going to collide with the next dynode, and so on. At the end, the electric signal gains orders of magnitude. A sketch of a photomultiplier is given by Fig. 3.

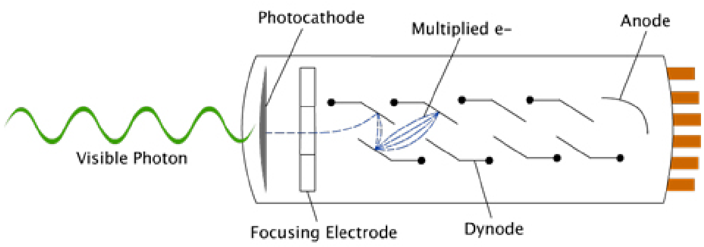


Figure 3: Layout of a photomultiplier [10]

The above gives the general principles of functioning of detectors, but all of them are still not identical, as they aim to target different kinds of particles. Let us focus on the ones relevant for this experiment.

2.3.2 Alpha detector

The alpha detector is made of a thin layer of scintillating material, as this particle is very ionizing, and is thus easily detected. The thinness of the detector ensures a very low probability to detect other particles, such as cosmic rays. Moreover, it is very unlikely for neutrons to interact on such a small distance. Of course, it cannot be taken for granted that no other particle than alpha is detected, but the probability is reasonably small.

2.3.3 Neutron detector

Because neutrons do not have any charge, they interact very few with matter, and their ability to ionize it is very small. The greater their energy is, the smaller the cross section gets (see [7]). The process of scattering is the one that allows neutrons to be detected: as a high energic neutron collides with a particle, called a moderator as it makes the energy of the neutron decrease, it transfers to it a part of its kinetic energy, and the recoil particle can then be detected [4]. The most efficient moderator is hydrogen, because the neutron can lose all its energy in a single collision [7]. Furthermore, the scintillator has to be large to enhance the probability of detection.

This kind of detector enables also to detect photons, even if not in an optimal way. This will be useful to calibrate the trigger circuit.
The neutron detector could detect alpha particles as well. However, as it is further away from the reaction chamber, almost no alpha particles manage to reach the detector.

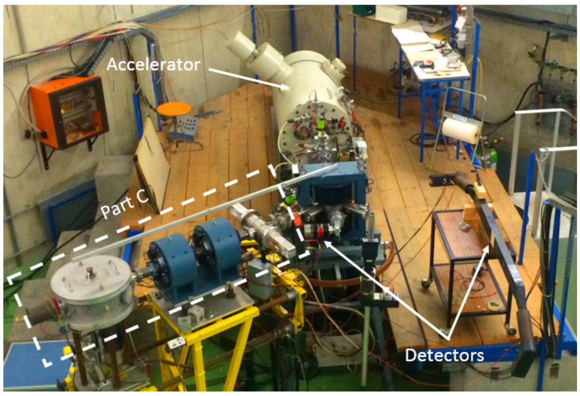
3 Experimental approach

Figure 4a is a picture of the experimental setup used to perform the experiment. The ions accelerated are nuclei of deuterium, and the source is made of tritium, in order to realize the reaction 1.

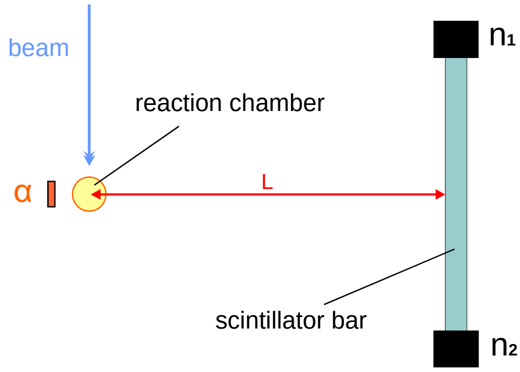
Figure 4b is a scheme of the detecting part. As sketched in it, an α detector is placed next to the reaction chamber, and a neutron detector on the other side, further away from the chamber. The neutron detector itself actually consists of two photomultipliers fixed at each end of a scintillating bar. This is mainly to prevent noise on one of the detectors to trigger a signal. Note that alpha and neutron detectors are placed on both sides of the place of the reaction, as particles are ejected in opposite directions[4].

Beside the experimental setup presented on Fig. 4, the setup is also made of a trigger circuit, described in section 3.1, and of a rack allowing to control the accelerator, situated in the control room.

[4]This is due to the fact that the laboratory frame is approximately the the center of mass frame, where the total momentum is equal to zero.



(a) Picture of the setup



(b) Scheme of the detecting part

Figure 4: Accelerating and detecting setups

3.1 Description of the trigger circuit

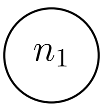
As the main goal of this experiment is to measure the speed of the neutrons produced by the fusion reaction, we need to ensure that the data acquired with the detectors is indeed the result of these very neutrons. Since the scintillators provide an electrical signal as soon as they are crossed by a high energy particle (such as α particles, β particles or γ photons), a significant amount of other sources can trigger a signal on the detectors and thus give rise to odd events. There could also be noise on a detector for some internal reason, or electrical interference between different components of the logical circuit. So you need to design the experimental setup to record only events due to neutrons released by the fusion reaction.

This is done using coincidences. Furthermore the logical circuit has to handle the readout. In other words it has to ensure that the energy and time spectra are recorded only when an alpha particle is detected on the alpha detector and little later a neutron by both of the photomultipliers on the scintillator bar and when the computer is ready to receive data.

Of course, a large number of "good" events are ignored by this experimental setup, because of its geometry. Ideally one would built this experiment all around the interaction point but this can present both technical problems and budget ones.

Figure 5 shows a schema of the trigger circuit as built in previous years. In order to build the trigger circuit you will be using the following components used on the schema:

Source signals



The source signals are outputs of detectors. There are three of them : the α signal comes from the alpha particle detector and the n_1 and n_2 signals come from the two photomultipliers at both ends of the scintillator block.

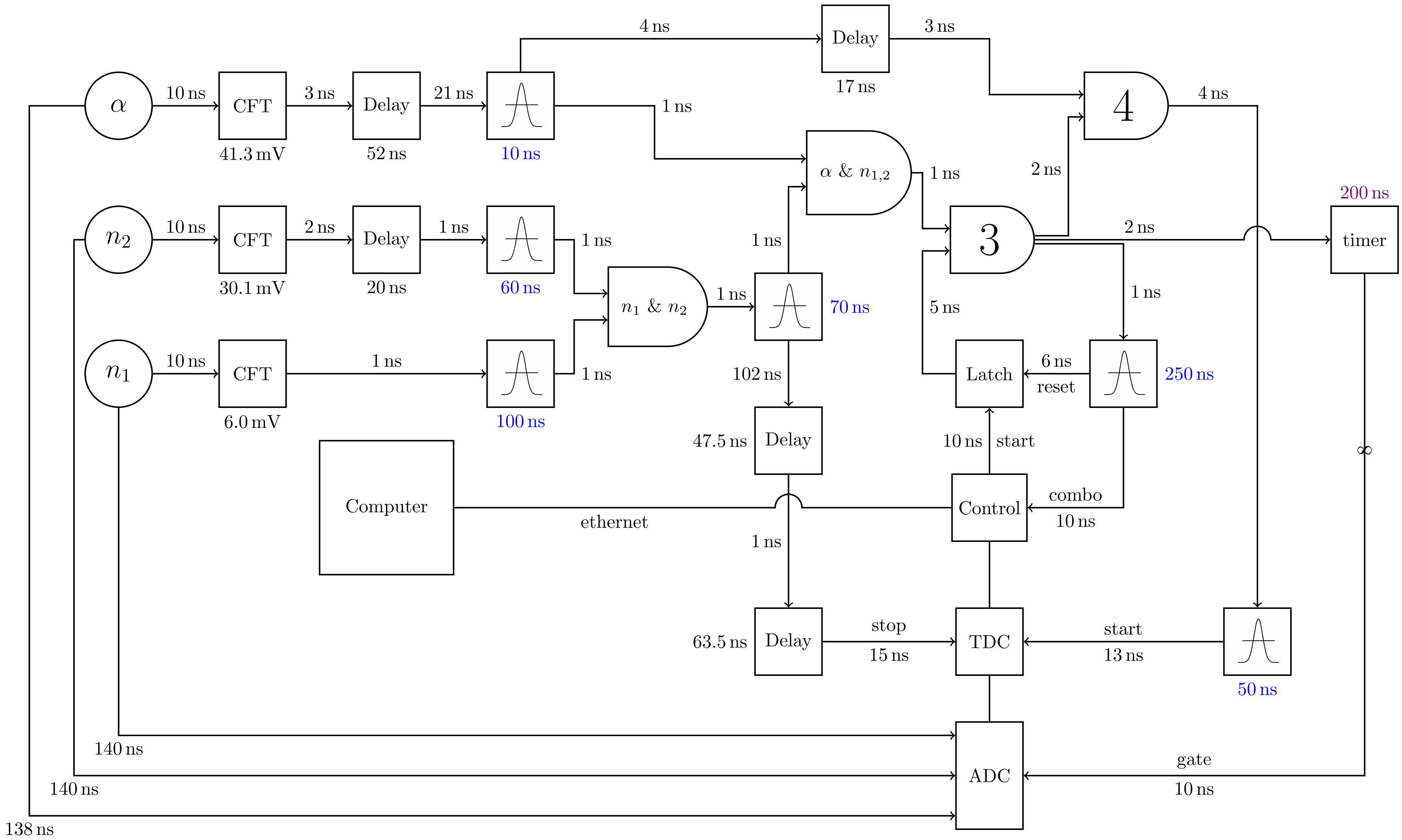


Figure 5: Schema of the trigger circuit.

Constant fraction trigger (CFT)

30.1 mV

A constant fraction trigger gives an output when the input pulse reaches a given fraction of its maximum amplitude. It is obtained by splitting the input pulse into two signals, inverting and delaying one of them and finally summing them together [7] : see Fig. 6. In this way, the output is independent of the input amplitude and is constant for constant shape inputs : see Fig 7. If only a simple threshold trigger were used after the scintillator, there would be a delay between the input and the output which would depend on the energy deposited in the scintillator [15]. The number below the symbol of the CFT indicates the threshold used.

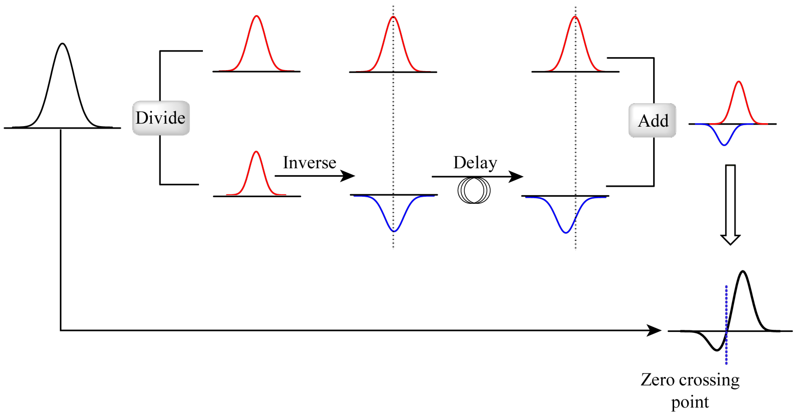


Figure 6: Simplified schema of operation of a CFT [15]

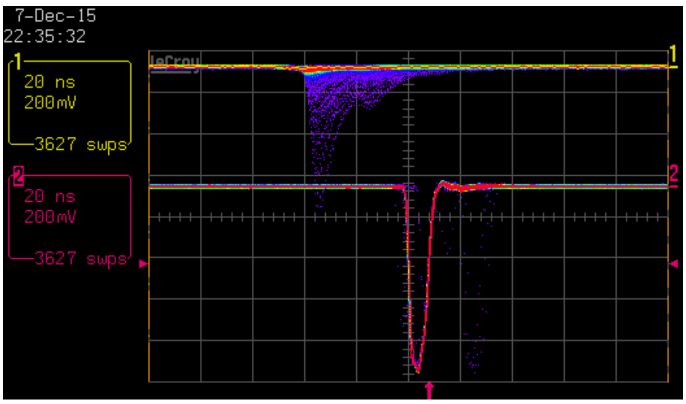
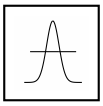


Figure 7: Signals obtained on an oscilloscope before (1) and after (2) a CFT module.

Discriminator



100 ns

Each time the amplitude of its input signal exceeds a threshold value, a discriminator gives a logical signal with a width and amplicude which can be adjusted. The blue number below the symbol of the discriminator indicates the output width.

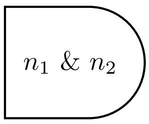
Delay

20 ns

Adjustable delays are obtained by adding cable length between two modules. These delays occupy an important place of the circuit; they are used for several reasons :

- Before entering a coincidence module to align rectangular pulses which come from discriminators
- Before the stop of the TDC to give enough time to the trigger circuit to start it
- To calibrate the TDC by adding known delay before its stop and therefore obtain the time-channel conversion relation

Coincidence module

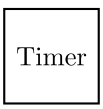


A coincidence module is an electronic realisation of the logic AND gate: it gives a logic pulse only if it receives a signal from its two inputs at the same time.

Timer

A timer is a module which, once started by a pulse, gives a continuous positive output. It stops if it reaches a certain time T (the violet number) that can be set on the module or if it receives an input on its stop port. It can also be reset by a signal on another port. In the circuit described above, a timer is used as a gate : the ADC only records data when a signal is given by the timer.

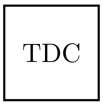
200 ns



Latch

An electronic latch is needed to stop the triggering system in the time used to record data. The latch is here realised by a timer which the end time T is set to be ∞. When the system is ready to make a measurement, the control starts the latch which gives a continuous signal to the AND 3 module and the latter resets the latch each time the trigger circuit detects a relevant event.

Time to digital converter (TDC)



This device converts a time interval into digital output, that is, a number of bits, understandable by the computer. The interval of time that is measured is bounded with two signals, a start and a stop, that occur as the rising, falling edge, respectively of a pulse crosses a determined threshold.

Analogic to digital converter (ADC)

This device converts a continuous signal to a discrete one, that is, to a sequence of digital values that represent the amplitude of the input. The most general way to do it is by measuring the time a charged capacitor takes to discharge across a resistor. Of course, the quantization of the signal unavoidably introduces some errors, as the resolution cannot be infinite. Moreover, it converts only signal whose amplitude belongs to a certain bandwidth.

4 Work plan

You will work on this experiment 1 day per week for 12-13 weeks

- Days 1: Introduction. Explanation of the experiment and the setup. Explanation of the components that you will use. Get a ^{60}Co source and have a look at some signals. Calculate the theoretical value for the neutron speed and start buiding the circuit.
- Day 2-4: Build the circuit. Try to understand step by step the response of the detector. Take some data and start having a look. Install ROOT and learn how to fo fits with RooFit. Calibrate the time measurement.
- Day 5-6: Switch on the accelerator, move from the calibration detector for photons to the alpha detector. Optimise the setup. Take data and have a look at the energy spectra.
- Day 7-8: Accelerator on. Take measurements at different positions to measure neutron speed. Analyse data. Take background runs. Eventually try to do some small simulation.
- Day 9-13: Analyse data, take extra data runs if needed. Write the report.

5 Acknowledgement

Thanks, to Marc Huwileu, Anne-Mazarine Lyon and Cyrille Praz on whose work this document is based.

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[15] https://upload.wikimedia.org/wikipedia/commons/5/52/Operation_of_a_CFD.png consulted in September 2015