Neutron energy measurement

& n/γ discrimination

using a liquid scintillator

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Introduction

Neutron energy measurement is a difficult task in nuclear physics experiments. Being neutral particles, it is impossible to relate the energy they deposit in materials to their kinetic energy. The “simplest” way to perform energy measurements on neutrons is to measure their time of flight. In order to maximize the probability of detecting fast neutrons at their first interaction (to measure their time of flight), we must use hydrogenated materials. This implies the use of organic scintillators.

A major difficulty in neutron studies lies in the fact that neutron fields are generally mixed with gamma (γ) fields (coming from targets, wall activation, radioactivity…). Measuring the interaction of a particle in a detector doesn’t necessary mean you detected a neutron.

Fortunately, liquid scintillators exhibit interesting properties. First they are hydrogenated ($(C\text{-}H)_n$). Second, their light pulse shape depends slightly on the nature of the charged particle that created this pulse. When a gamma interacts in a detector, it is a recoil electron that produces the signal. But when a neutron interacts on a hydrogenated material, the recoil particle is generally a proton. We have here the premises of neutron versus gamma identification by the mean of pulse shape analysis techniques.

What will you find in this educational document?

- An example of neutron energy measurement using the time of flight between an accelerator driven neutron source and a liquid scintillator.
- The principles of neutron vs γ pulse shape discrimination.
- How the dynamic baseline restorer and the clocking of FASTER simplify data analysis and timing calibrations.
- How to integrate scintillator pulse shape discrimination and accelerator radio-frequency demodulation in the FASTER data acquisition and processing system.

1. The device and its electronic

The experiment described below consists on sending an intense pulsed proton beam on a tritium target producing 2.4MeV neutrons.

The "start" signal is produced by a capacitive pickup placed in the beam line (Fig. 1). This capacitive pickup produces a fast bipolar signal each time the beam packet passes thru it.

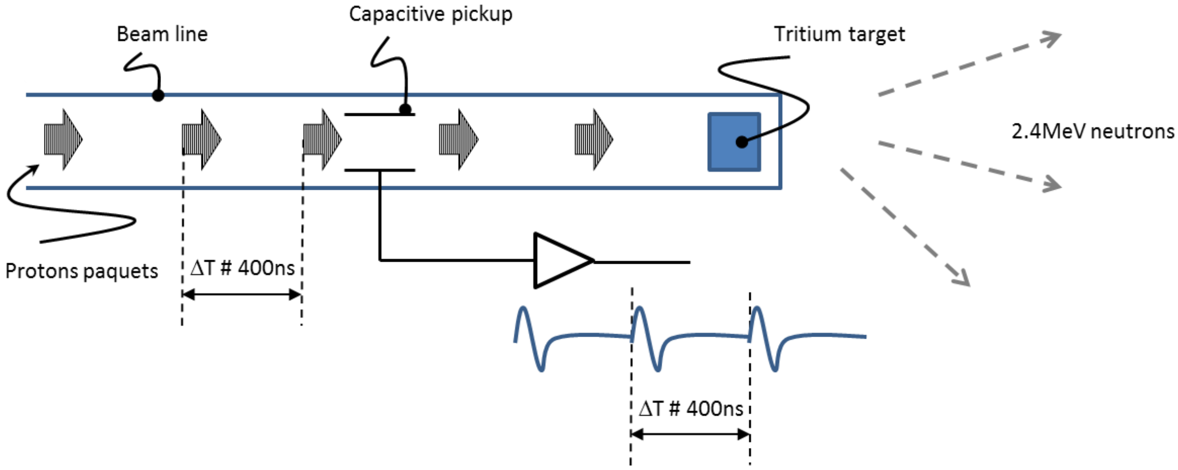

Fig. 1: beam line experimental setup

The neutron detector (see Fig. 2) is a liquid scintillator (BC501A) tank coupled to a photomultiplier tube (PM). This detector gives the "stop" signal for the time of flight measurement between the target and the scintillator tank.

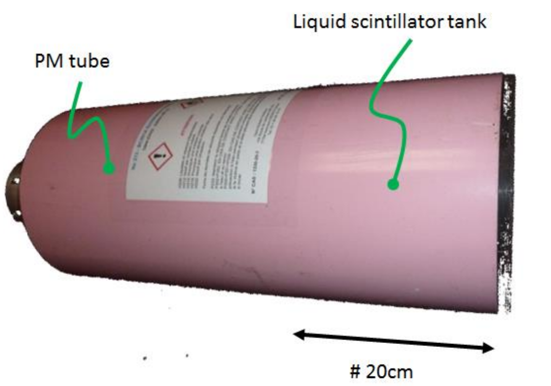

Fig. 2: a liquid scintillator for neutron TOF measurements

Optimal discrimination of neutron vs γ is generally obtained by the mean of two integration gates (Fig. 3). *Qtot* being the total charge gate (starting before the pulse and ending after the pulse) and *Qanalysis* being the analysis gate (fast part of the pulse or delayed part, we will see later how to adjust this gate. In this example, we used a "delayed" gate, as drawn on Fig. 3).

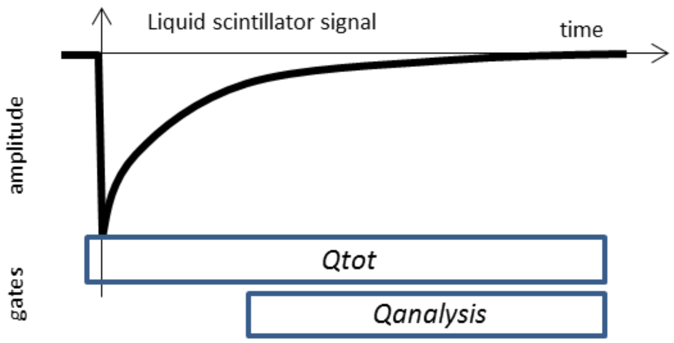

Fig. 3: pulse shape analysis of liquid scintillator signal by the mean of two gates

2. Data acquisition:

This experiment uses two kinds of signal processing techniques both based on CARAS daughter boards (12bits, 500MHz) (see Fig. 4).

The radiofrequency signal coming from the accelerator enters directly in the FASTER data acquisition and processing system. After filtering, this signal feeds a digital Phase Locked Loop (PLL) that creates, on board, two high level data, first, the current estimator of zero crossing time of the input signal, and second, an estimator of the period of the input signal. Once started, the PLL locks and produces one output every 100 (for instance) signal zero crossing times in order to lower bandwidth requirements.

The signal emanating from PM tube coupled to the liquid scintillator enters directly into the FASTER data acquisition and processing system. You can either select Level Discrimination or better, Constant Fraction Discrimination, depending on your signal quality and physics requirements. In this example, the capacitive pickup had too much jitter to obtain good time measurements.

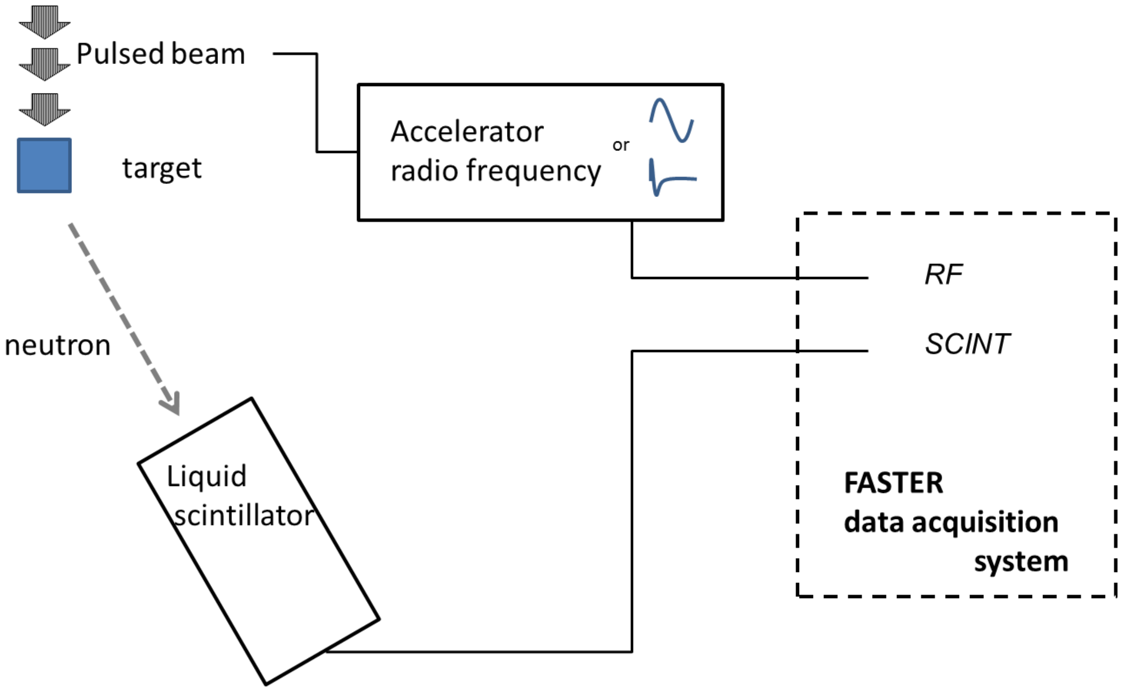

Fig. 4: the complete system for identification and energy measurement of incident ions

3. Data analysis

3.1. Gates adjustment

The quality of n/γ discrimination relies on two distinct things:

(1) You absolutely need perfect EMC shielding as it affects the low energy discrimination aptitude of your device. FASTER contains a Dynamic Base Line Restorer (BLR) that helps dealing with baselines variations.

(2) The analysis gate must be perfectly adjusted.

We will now have a look on how to adjust this gate. This kind of adjustment can be performed with a neutron source, like AmBe for instance. As previously mentioned, the *Qtot* gate should integrate the signal before it arrives and stop after its completion (in the example below [-6ns → 300ns]). The analysis gate can be a "fast" gate (starting at -6ns and ending a few nanoseconds after the pulse start) or a "delayed" gate (starting a few ns after the pulse start and ending at 300ns). The real difficulty consists on defining what a few ns after pulse start means? This study is time consuming and we will discuss a more sophisticated method.

- *Raw data plotting in oscilloscope mode*

This method is performed in five steps sketched on Fig. 5:

(1) you acquire many signals in oscilloscope mode and store these signals.

(2) you numerically integrate each signal with the two previously mentioned gates, the *Qdelayed* being roughly adjusted (select start at 10ns for instance).

(3) you display, in a bidim plot, *Qdaleyed* vs *Qtot*. The bidim should display two arms, the lower one corresponding to γ and the upper one containing neutrons.

(4) you graphically select areas mainly containing γ and mainly containing neutrons and you average oscilloscope signals in order to produce γ_{mean} and n_{mean} signals.

(5) you plot the two signals normalized to their respective surface (=charge).

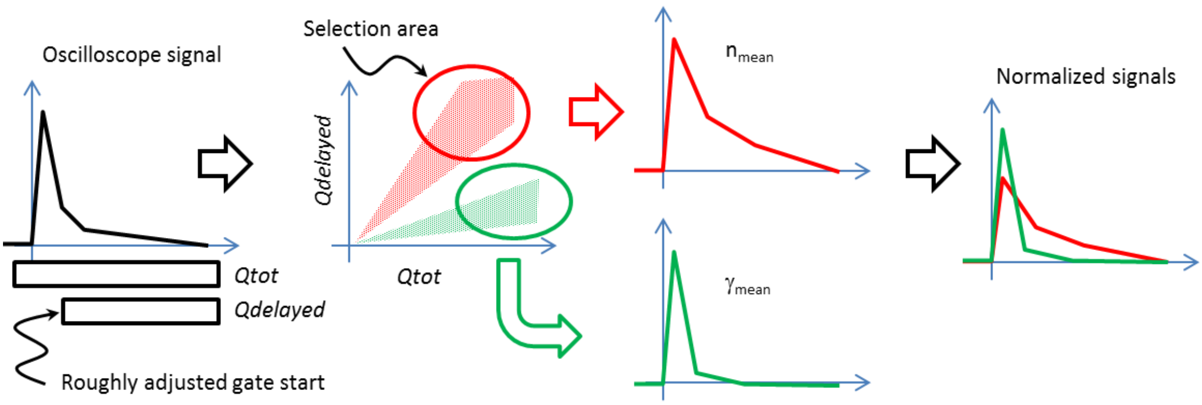

Fig. 5: data processing for optimal gate tuning

- *Practical gates adjustment*

Under the assumption that signal measurement obeys a Poissonian distribution (ie. photons counting fluctuations), good analysis gate settings are easy to find. The end of a fast gate (resp. the start of a delayed gate) is the point where the normalized n_{mean} signal crosses the normalized γ_{mean} signal, as drown on Fig. 6. At least, it's a good start for optimal performances.

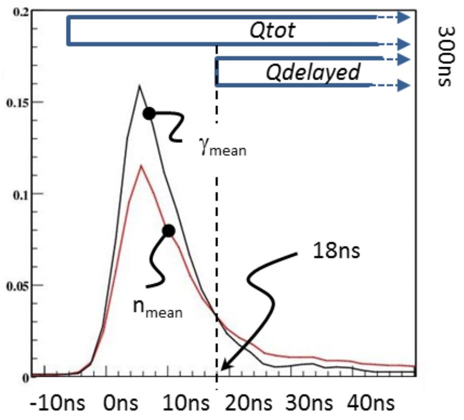

Fig. 6: optimal analysis gate should start or end at 18ns is our case

- *n/γ discimination*

A practical way to display discrimination maps, making identification easy, is to plot a *Qanalysis*/*Qtot* vs *Qtot* bibim as drawn below.

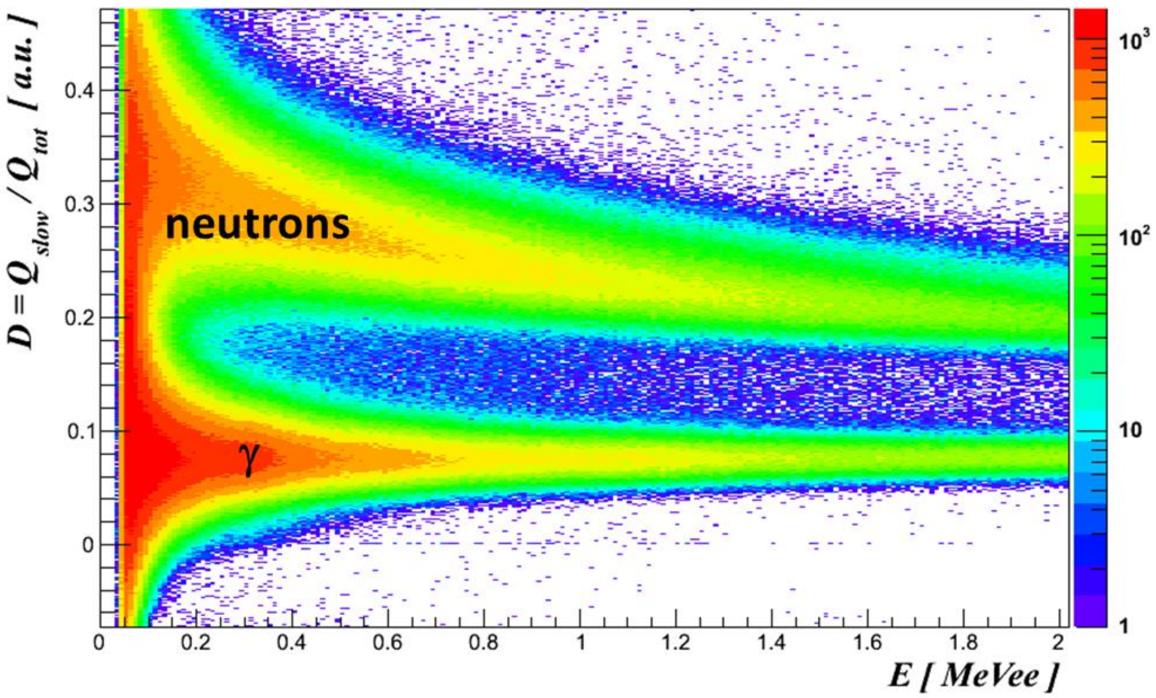

Fig. 7: identification plot

When gates are properly set, γ should lie on a straight horizontal line (there is no quenching for electrons in this kind of scintillators). Neutrons are above y=0.18 (in this case). As can be seen, the neutron/proton identification line is lightly curved, meaning that the scintillator is quenched for these particles (in fact, it's a chance, because it's the way the identification runs!).

The X axis has been calibrated by using a γ source (^{22}Na for instance) making the Compton edges clearly visible. Obviously, one can't measure γ or neutrons energy this way. It's just an absolute indicator of the discrimination ability of the system (here, the discrimination threshold is about 80keV electrons equivalent).

This kind of display is possible because FASTER data processing and acquisition system uses an internal baseline restorer which sticks the baseline at 0V. So, there is no pedestal contrary to other analog charge to voltage converters.

3.2. Neutron energy measurement

Usually, you don't know neutrons energy and that is what you want to measure. Neutron energy is calculated using the measurement of the TOF of these particles. As we know the distance L between the target and the scintillator (here, L = 3 meters), the velocity v_n of the neutrons is simply:

$$v_n = \frac{L}{TOF}$$

For the γ, obviously, the velocity is the speed of light c (ie. 30cm.ns^{-1}).

A little difficulty in TOF measurement comes from the fact that this variable is the difference between a start signal (here the RF) and a stop signal (produced by the PM tube) and this difference depends on cables lengths. So, the TOF always presents a constant offset that must be considered for proper measurements (see below).

Another point comes from the time measurement that generally needs careful timing calibration (by the mean of so called time calibrators, for instance). In fact, this step, at least, is simplified by the use of FASTER data processing and acquisition system, as the heart of the complete system is based on a 2ns clock whose period is perfectly defined by a quartz.

- *TOF Raw data plotting and calibration*

We saw above that γ travel at the speed of light. So every γ coming from the target takes the same time to travel to the scintillator, whatever its energy. The TOF spectrum (Fig.

8) shows a clearly visible γ peak (separated from neutrons) for which we know the arrival time provided t=0 corresponds to the start time. In our case, the travel distance being 300cm, γ flew for 10ns, so the γ peak centroid corresponds to a 10ns TOF! The constant offset in TOF is thus identified and calibrated.

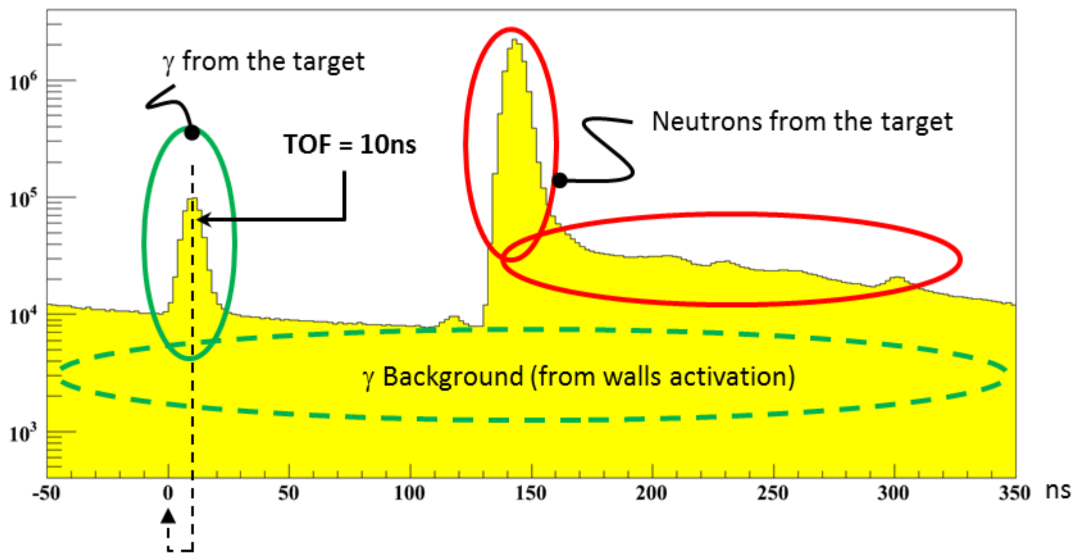

Fig. 8: TOF of γ is perfectly known (here 10ns), so we can measure 0ns TOF of this experiment. The rest of the scale comes from the 2ns clock of FASTER and doesn't need calibration.

Note that the poor timing resolution (both visible on γ and neutrons peaks) is mainly due to the capacitive pickup of this experiment.

- *TOF spectra "cleaning" procedure*

The spectrum Fig. 8 contains lots of γ, some coming from the target (and that are synchronized with the proton beam) and some coming from walls activation. The formers are clearly separated from neutrons but the latter pollute neutron spectrum. By selecting events whose discriminating variable $y = Qdelayed/Qtot$ is above 0.18, one has essentially neutrons (at least neutron tagged events). The graph Fig. 9 presents the TOF spectrum for such selected events.

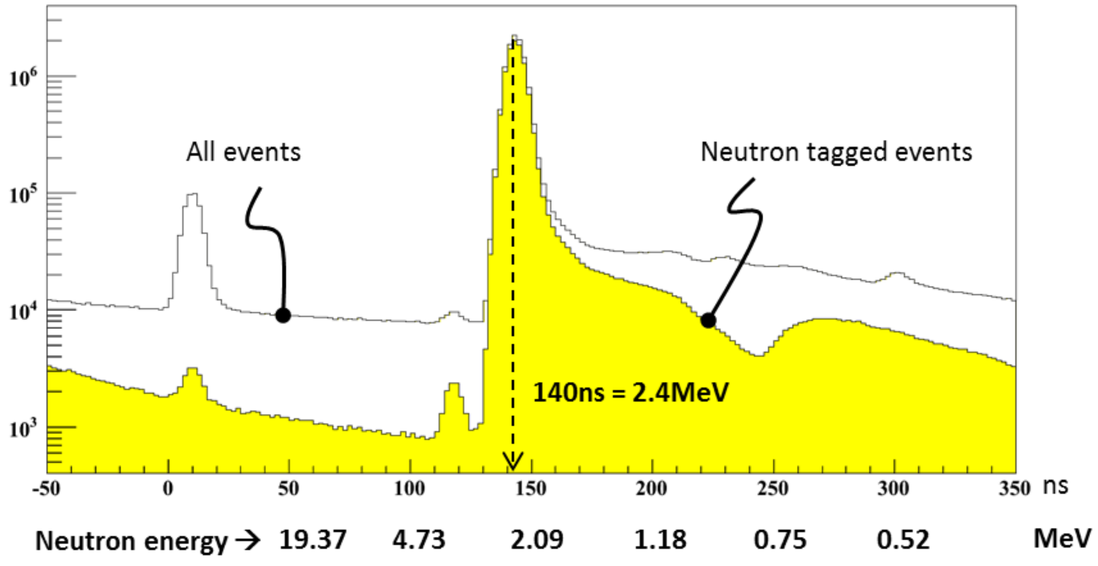

Fig. 9: neutron TOF and energy after complete calibration

Having the TOF spectra, one can calibrate the X axis in terms of neutrons kinetic energy T (MeV):

$$\gamma = \frac{1}{\sqrt{1-\left(\frac{TOF}{L\cdot c}\right)^2}} \quad \text{and} \quad T = (\gamma - 1)\cdot m_n c^2$$

m_n being the neutron rest mass, ie. 939.6MeV.c^{-2}.

As can be seen, this procedure clearly cleans the neutron TOF spectrum. One could have had better results by selecting events above 100keV electrons equivalent energy deposition in the scintillator, at the expense of "neutron" loss…

4. Conclusions

Liquid scintillators provide an interesting mean for neutron energy measurements. In spite of the apparent complexity of n/γ pulse shape discrimination, this technique remains far simpler than other methods.

Both dynamic BLR and efficient clocking of FASTER took part in largely simplifying all the calibration procedures explained above.

For more information on n/γ discrimination, have a look at Mathieu's PhD thesis.

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