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► **To cite this version:**

M. Bacak, M. Aïche, G. Bélier, E. Berthoumieux, M. Diakaki, et al.. A compact fission detector for fission-tagging neutron capture experiments with radioactive fissile isotopes. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 2020, 969, pp.163981. 10.1016/j.nima.2020.163981 . hal-02557731

HAL Id: hal-02557731

<https://hal.science/hal-02557731>

Submitted on 20 May 2022

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A compact fission detector for fission-tagging neutron capture experiments with radioactive fissile isotopes

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Abstract

In the measurement of neutron capture cross-sections of fissile isotopes, the fission channel is a source of background which can be removed efficiently using the so-called *fission-tagging* or *fission-veto technique*. For this purpose a new compact and fast fission chamber has been developed. The design criteria and technical description of the chamber are given within the context of a measurement of the $^{233}\text{U}(n,\gamma)$ cross-section at the n_TOF facility at CERN, where it was coupled to the n_TOF Total Absorption Calorimeter. For this measurement the fission detector was optimized for time resolution, minimization of material in the neutron beam and for alpha-fission discrimination. The performance of the fission chamber and its application as a fission tagging detector are discussed.

Keywords: Fission detector, ^{233}U , n_TOF, time-of-flight

1. Introduction

The neutron capture cross-sections of fissile isotopes are of interest in nuclear reactor as they influence the neutron economy of the reactor. However, the knowledge of those cross-sections is limited due to difficulties associated to the background from the fission reaction channel. For the fissile isotopes ^{233}U , ^{235}U and ^{239}Pu the fission cross-section is on average a factor 2 to 10 larger than their respective capture cross-section, depending on the isotope and energy range, which is shown in Figure 1. This implies that in a measurement of the capture cross-section the γ -rays coming from the fission channel are a major source of background, which has to be taken care of in the analysis. In the past [1] a method of efficiently dealing with this source of background has been developed, the so-called fission-tagging or fission-veto technique. In addition to the γ -detector this technique employs a fission detector to measure the fission fragments. The γ -rays from the

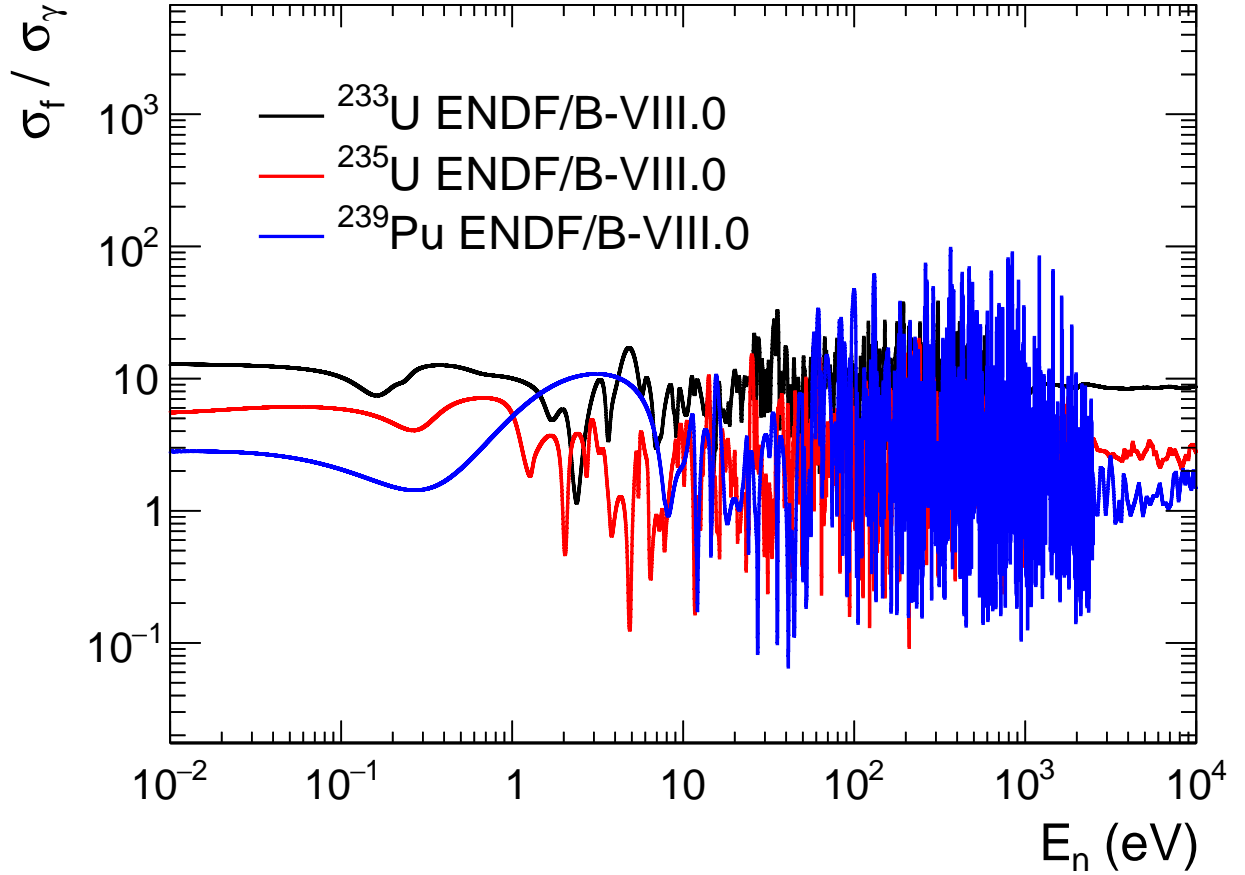


Figure 1: Cross-section ratios of the fission σ_f and capture σ_γ channels for the fissile isotopes ^{233}U , ^{235}U and ^{239}Pu .

11 fission reaction can then be identified or tagged by operating the two detectors in coincidence. In recent years
 12 new efforts have been made to measure the capture cross-sections of the fissile isotopes using the fission-
 13 tagging technique at different facilities [2–5]. Despite fission-tagging technique’s effectiveness in dealing with
 14 the fission background, it has the drawback of introducing another component to the background, namely
 15 the sample substrates and the detector itself. In the recent measurements performed at n_TOF a Micromegas
 16 based detector was used as a fission detector [2, 4]. The so-called *micro-mesh* of such a detector is made
 17 out of copper, which is a significant source of background due to its large scattering and capture cross-
 18 sections. With the goal of measuring the $^{233}\text{U}(n,\gamma)$ cross-section a new fission detector was designed aiming
 19 at reducing the background from the detector and providing the necessary performance to reliably identify
 20 the fission γ -rays. The design of the described fission chamber (FICH) is adapted to the measurement of
 21 the $^{233}\text{U}(n,\gamma)$ utilizing the fission chamber coupled to the n_TOF Total Absorption Calorimeter (TAC) [6]
 22 in experimental area 1 (EAR1) of the n_TOF facility [7].

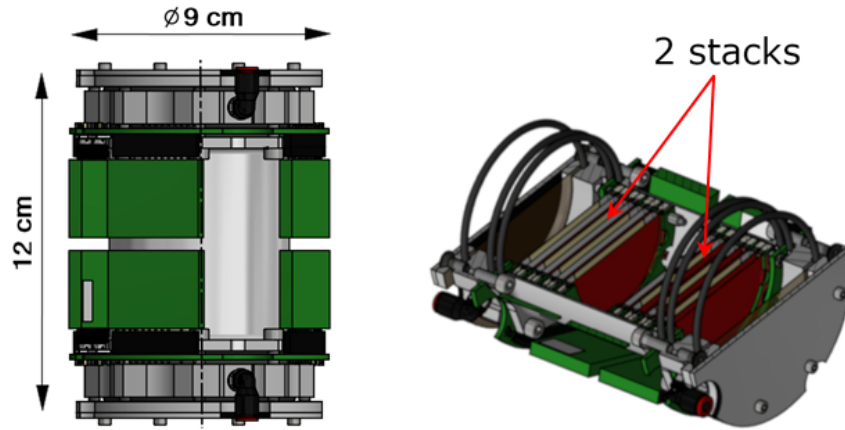


Figure 2: CAD drawings of the fission chamber and a sectional view. The green blocks around the chamber represent the preamplifiers.

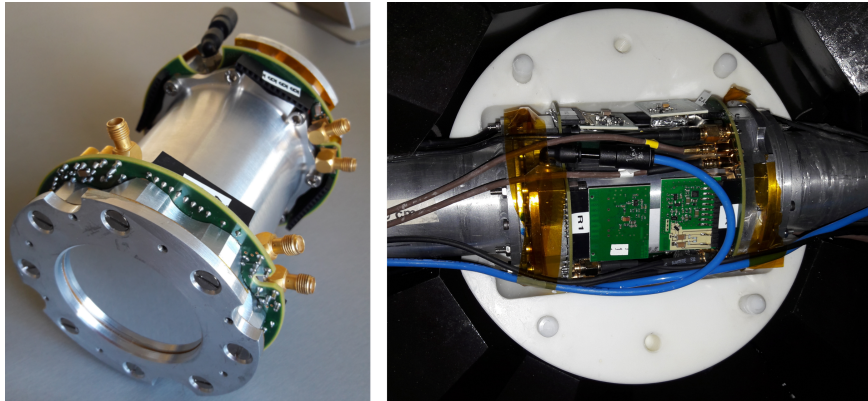


Figure 3: Pictures of the fission chamber in the lab (left) and embedded in one half of the TAC absorber (white) with electronics and gas supply connected (right).

2. The multi-plate fission chamber

Due to the experience obtained from the measurement with the fission-tagging micromegas detectors [2, 4], a simple ionization cell geometry is chosen as the basic detector design to minimize the material in beam. The development of the fission chamber is focused on different, partially contradictory, criteria: excellent time resolution for the coincidence and time-of-flight measurement; low quantities of structural material to avoid additional background for the capture measurement; reasonable amount of ^{233}U to obtain a sufficient count rate for high statistics measurements; compact design as the fission chamber (FICH) must fit inside the TAC of n_TOF. All these requirements are detailed in the following sections.

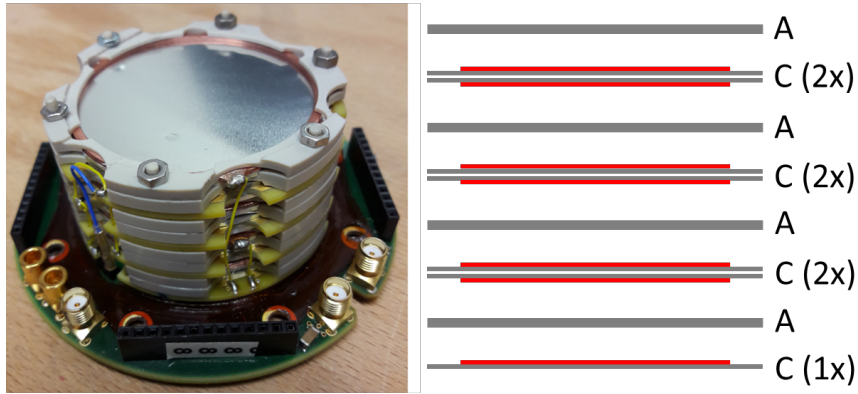


Figure 4: Picture of one of the two stacks of ionization cells mounted on the motherboard (left). Arrangement of the cathodes (C) and anodes (A) of one stack (right), ^{233}U deposits are indicated in red. There is one anode that reads only from 1 deposit while the others read signals from two deposits.

2.1. Technical description

As a result the fission chamber (FICH) is designed as a multi-plate ionization chamber containing two stacks of axial ionization cells. Figures 2 and 3 show CAD drawings and pictures of the chamber. The housing is made of a 1.5 mm thick aluminum tube with an outer diameter of 66 mm and a length of 78 mm. With a maximum outer diameter of 90 mm and a total length of 120 mm including the flanges with the gas connections and windows, it fits nicely in the γ -calorimeter leaving sufficient space for its absorber (explained in section 3.1.2) and the connecting beam pipes. Two stacks of seven ionization cells each are mounted directly on their respective motherboards and are inserted from each end of the chamber. The stacks have a minimum inner diameter of 50 mm leaving enough space for the n_TOF neutron beam with a FWHM of roughly 16 mm and a total width of less than 40 mm. In total 8 anodes are collecting signals from 14 ^{233}U targets deposited on the cathodes. The arrangement of the cathodes, anodes and deposits is illustrated in Figure 4. To avoid cross-talk from alpha-particles, the ionization cells are separated by 20 μm aluminum, either one 20 μm anode foil or two 10 μm cathode foils, resulting in a total of 300 μm aluminum in the neutron beam which is a negligible neutron beam perturbation. The chamber is closed with aluminized 25 μm thick Kapton windows to provide a Faraday cage.

2.2. Choice of gas and gas system

The gas is of high importance and has to exhibit a high drift velocity and provide the best possible alpha-fission separation. High purity tetrafluoromethane CF_4 is a fast gas and is often used where high count rates are expected [8] but has the drawback of being electro-negative, worsening the energy resolution and hence the alpha-fission discrimination. Nevertheless, the advantage it offers due to its higher drift velocity compared to other gases outweighs the disadvantages. Fission fragments (FF) and α -particles deposit their

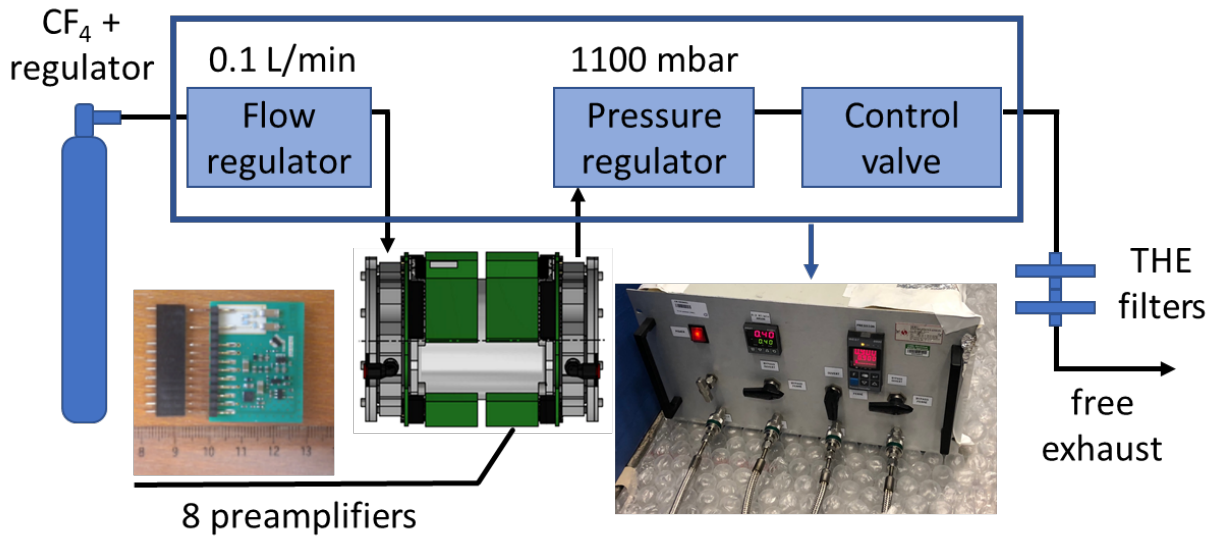


Figure 5: Schematic illustration of the full FICH set-up including the chamber, a schematic drawing of the gas system, and pictures of one preamplifier-filter printed circuit board (PCB) and of the gas regulation system with the gas filters (THE).

energy in the gap between the electrodes filled with the gas. Simulations [8] have shown that a gap distance of about 1.5 mm is sufficient to achieve a reasonable alpha-fission separation for ^{252}Cf . Due to mechanical considerations the gap is chosen to be 3 mm. To achieve a drift velocity of about 11 cm/ μs an electric field of 1400 V/cm is applied at atmospheric pressure. This drift velocity corresponds to a total electron drift time of 27 ns in the 3 mm gap, leading to a suitable intrinsic time resolution. In order to guarantee stable conditions throughout the measurement period of four weeks a gas pressure and flow regulation system was employed and is schematically shown in Figure 5. The fission chamber was operated with a constant gas flow of 0.11/min and at an absolute pressure of 1100 mbar to allow for the use of thin windows of the fission chamber, hence to reduce the background in the γ -calorimeter.

2.3. Dedicated electronics

To ensure a good time resolution and reduce potential α -particle pile-up, fast electronics adapted to the geometry of the ionization cells and the electron drift velocity have been developed. Charge preamplifiers with a short RC decay time constant have been developed to ensure good amplitude discrimination, avoid saturation due to very high alpha activity and to preserve the good timing response of the chamber. A dedicated card combining the preamplifier and a fast timing filter amplifier was directly mounted on the fission chamber. This reduces the input capacitance and improves the signal-to-noise ratio. A picture of those cards can be seen in the lower left part of Figure 5. The signals recorded by the data acquisition system were digitized, stored and processed offline using the pulse shape analysis routine developed by the

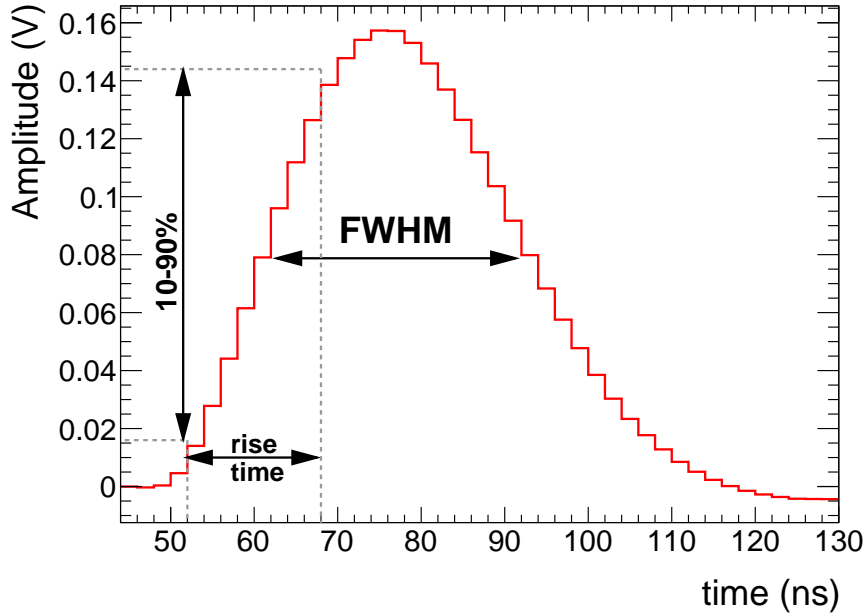


Figure 6: Average shape of a fission fragment signal from the FICH.

70 n_TOF collaboration [9]. An example of a typical signal of a fission fragment is shown in Figure 6 with a
 71 full width at half maximum (FWHM) of 34 ns and a rise time (10-90 %) of 16 ns.

72 2.4. Fissile deposits

73 Thin uranium oxide layers, with 99.9361 % enrichment in ^{233}U , had a diameter of 40.00 ± 0.02 mm and
 74 were molecular plated on $10\ \mu\text{m}$ thick aluminum foils at JRC-Geel. The impurities in the sample have a
 75 negligible effect on fission. Nevertheless, a small effect on the ^{233}U α -ratio is expected due to the first
 76 capture resonance of ^{234}U at 5.15 eV. This contribution can be taken into account during the resonance
 77 analysis. The activity of each of the 14 samples hosted in the chamber has been determined by well-defined
 78 solid angle α -particle counting and amounts to an average α -activity of about 1.16 MBq or an average areal
 79 density of $264.5\ \mu\text{g}/\text{cm}^2$ per sample (with a standard deviation of $30.9\ \mu\text{g}/\text{cm}^2$ among the 14 samples), which
 80 permits fission fragments to escape the deposits, resulting in a total mass of 46.5(3) mg of ^{233}U .

81 3. Fission-tagging experiment at n_TOF

82 ^{233}U is a prime example for the application of fission tagging as it exhibits a fission cross-section which
 83 is on average a factor 10 larger than the corresponding capture cross-section. Thus, the fission reaction will
 84 introduce a background into the measurement that comprises of two components: the prompt component
 85 caused by the de-excitation of the highly excited fission products and the delayed component caused by
 86 either fission neutrons being captured in the experimental set-up or decays of unstable fission fragments

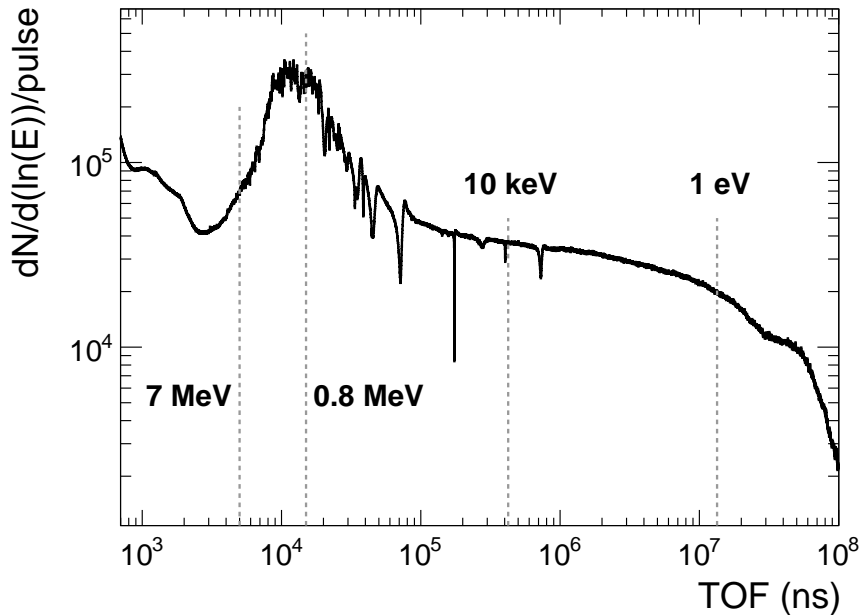


Figure 7: Neutron fluence at n_TOF EAR1 185 m from the source.

87 with half-lives larger than a few nanoseconds up to microseconds. The prompt component causes a much
 88 larger background and appears quasi-instantaneous with the fission reaction and can be easily quantified
 89 and removed using fission-tagging. The delayed component can also be studied with fission-tagging but
 90 depends on the experimental set-up's sensitivity to neutrons and shall not be the focus of this work.

91 3.1. Experimental set-up

92 3.1.1. The n_TOF facility at CERN

93 The n_TOF experimental area 1 (EAR1) facility [7] is devoted for the measurement of energy dependent
 94 neutron cross-sections in an energy range from thermal up to GeV. Neutrons are produced by a high-
 95 intensity 20 GeV/c proton beam impinging on a lead target and moderated in a borated water-layer down
 96 to thermal energies. The proton beam is delivered by CERN's Proton Synchrotron with an average proton
 97 beam intensity of $7 \cdot 10^{12}$ or $4 \cdot 10^{12}$ protons per bunch for dedicated or parasitic bunches respectively. The
 98 neutron fluence as a function of the arrival time in EAR1 located approximately 185 m from the lead target
 99 is shown in Figure 7.

100 The n_TOF facility provides a fully digital Data Acquisition system (DAQ) [10] and a large storage space,
 101 namely the *CERN Advanced STORAGE manager* (CASTOR) [11]. The waveforms of all signals are digitized
 102 with high performance digitizers, ADQ412 or ADQ414 [12], with 12 or 14 bit resolution respectively which
 103 are operated at 500 MSamples/s. This allows an offline analysis to be performed with dedicated pulse shape
 104 analysis routines [9]. The digitizers are triggered with a common external clock to avoid time drifts between

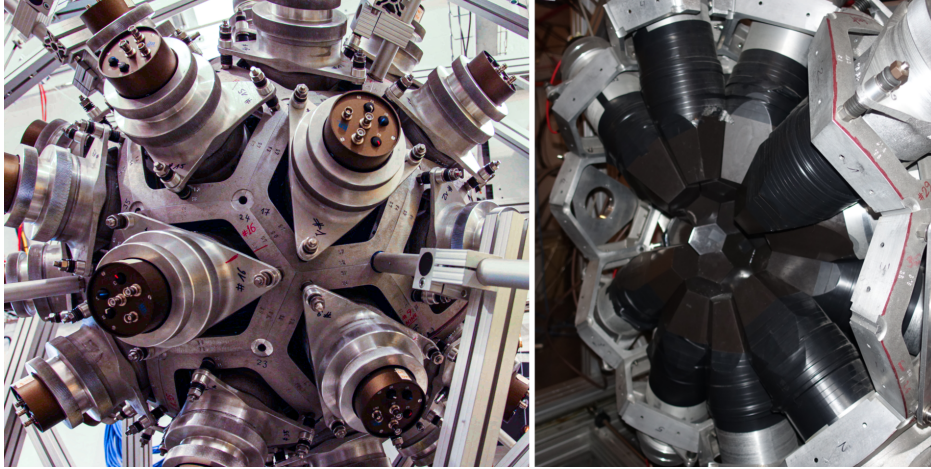


Figure 8: Picture of the fully assembled (left) and open (right) TAC.

105 the different channels.

106 3.1.2. The *n*-TOF Total Absorption Calorimeter

107 The *n*-TOF Total Absorption Calorimeter *TAC* [6] is designed to detect in coincidence the γ -rays of the
 108 electro-magnetic cascade following a neutron capture event. The TAC is a segmented 4π scintillator array
 109 consisting of 40 BaF₂ crystals mounted in a honeycomb structure which holds the full spherical detector shell
 110 as shown in Figure 8. The spherical BaF₂ shell has a 20 cm and 50 cm inner and outer diameter respectively,
 111 covering 95 % solid angle resulting in an efficiency of detecting at least one γ -ray from a cascade close
 112 to 100 %. To reduce the neutron sensitivity, namely the probability of detecting neutrons of the beam
 113 scattered from the in-beam materials, a so-called *absorber* is placed between the crystals and the sample
 114 to be measured. The absorber is made out of polyethylene loaded with 7.56 w% natural lithium to absorb
 115 scattered neutrons and consists of two spherical shell halves in which the fission chamber was embedded as
 116 shown in the right panel of Figure 3. TAC events are characterized by three parameters: the time-of-flight,
 117 the number of hit crystals referred to as crystal multiplicity m_{cr} and the sum of the deposited energy in all
 118 40 crystals E_{Sum} within a time coincidence window of $T_{coinc}^{TAC} = 12$ ns.

119 3.2. FICH performance

120 3.2.1. Pulse height spectrum and alpha-fission discrimination

121 Figure 9 shows the pulse height spectrum of the fission chamber for neutrons of less than 10 keV energy
 122 and without neutron beam (beam off). Small pulse heights are dominated by the α -particle background and
 123 are several orders of magnitude larger than the contribution of the fission events. The blue line in Figure 9
 124 is a scaled version (for visualization purposes) of the pulse height spectrum of the fission chamber without

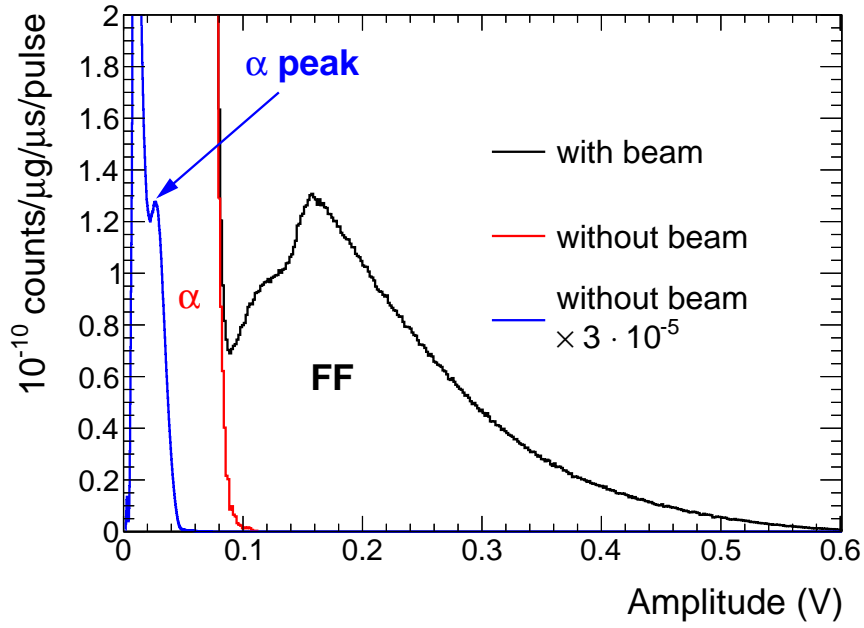


Figure 9: Pulse height spectra of ^{233}U with and without neutron beam for events with $E_n < 10\text{ keV}$ from a single FICH channel.

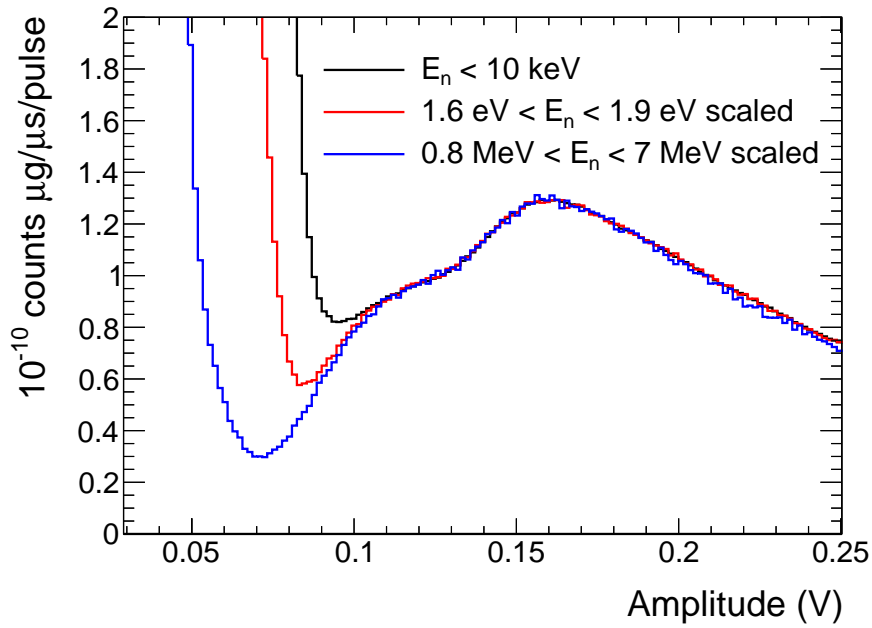


Figure 10: Pulse height spectra for different E_n regions corresponding to different fission fragment to α -particle ratios from all FICH channels.

125 neutron beam and shows the α -peak which corresponds to α -particles that deposit their full energy in the
 126 gas.

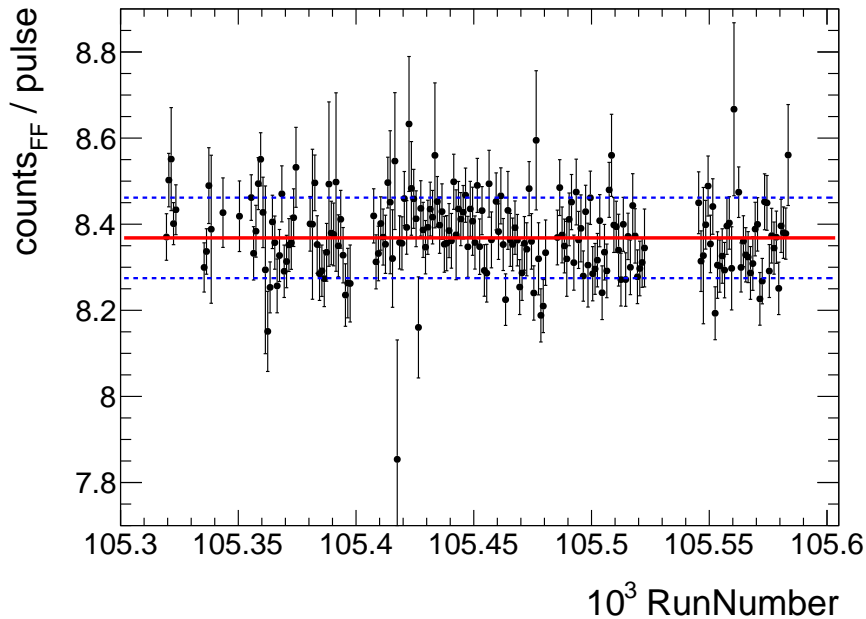


Figure 11: Variation of the gain over time: number of events with $amp > 0.1$ V and $E_n < 0.8$ MeV per protons per run - typically 4 hours per run. The red line corresponds to the weighted average of 8.36 FF counts per pulse with an uncertainty of the fit of 0.1%. The blue dashed lines indicate the standard deviation of the data points which is 1%.

127 The relatively poor separation of fission fragments and α -particle background at around 0.09 V is not
 128 surprising considering the high α -particle count rate. Choosing appropriate conditions allows to study the
 129 response of the FICH to fission fragments with a much better separation as shown in Figure 10 where the
 130 pulse-height spectra for different alpha to fission ratios are displayed. For example, gating on the first and
 131 largest resonance at $1.6 \text{ eV} < E_n < 1.9 \text{ eV}$, corresponding to the TOF region of 10.6-9.7 ms, improves the
 132 separation of α -particles and fission fragments. Furthermore, the characteristics of the neutron fluence at
 133 n_TOF EAR1 can also be exploited by choosing the neutron energy region around of corresponding to a TOF
 134 range of 5-15 μs (0.8-7 MeV), see Figure 7. Due to the higher fluence in this TOF region the alpha-fission
 135 separation is further improved.

136 3.2.2. Gain monitoring

137 The gain of the FICH has been monitored throughout the measurement by counting the number of fission
 138 fragment (FF) events (> 0.1 V) per nominal ($7 \cdot 10^{12}$ protons) pulse. Figure 11 shows the gain fluctuation of
 139 one of the ionization cells over time, indicated in *RunNumber*. No drift of the gain can be observed, proving
 140 a good detector stability throughout the whole measurement time of about four weeks.

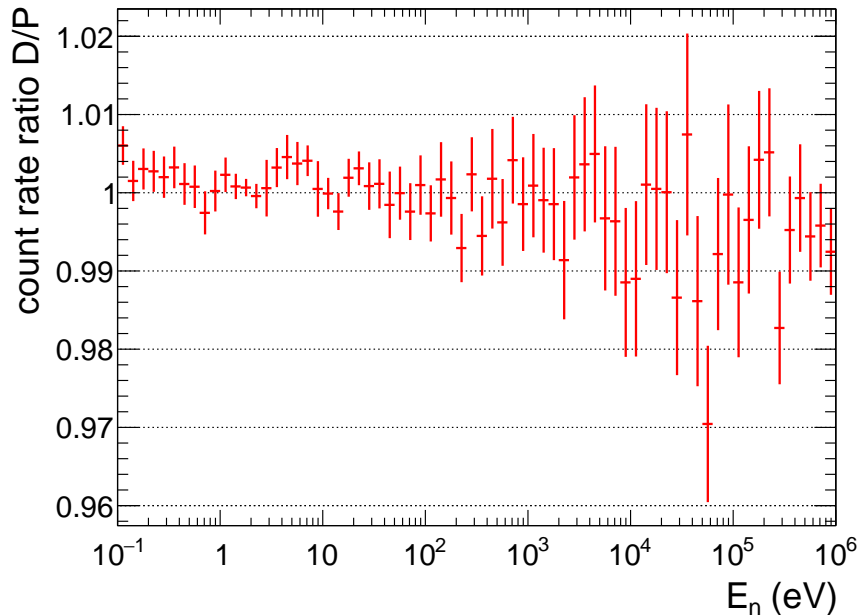


Figure 12: Ratio of the fission count rates for dedicated (D) and parasitic (P) beam pulse types.

141 *3.2.3. Dead time and validation*

142 With high count rates dead time and pile-up can become severe. Due to its design as a fast fission
 143 chamber, count rates of several MBq should be sustainable without the need to correct for pile-up effects
 144 in fission fragment detection. Figure 12 shows the ratio of the count rates for dedicated (D) and parasitic
 145 (P) beam pulse types of fission events ($amp > 0.1$ V). A good agreement with 1% is reached up to 1 MeV,
 146 indicating that there are no pile-up or dead time issues. The outlier around 55 keV most likely corresponds
 147 to dips in the neutron flux due to aluminum resonances, hence very low statistics.

148 To verify the satisfactory behaviour of the fission detector the shape of the $^{233}\text{U}(n,f)$ cross-section has
 149 been calculated from the FICH events and the shape of the neutron flux. The resulting shape of the $^{233}\text{U}(n,f)$
 150 cross-section has then been normalized to evaluated libraries in the neutron energy range from 8.1 eV to
 151 17.6 eV because this region is well separated avoiding interference from neighbouring resonances, as has been
 152 suggested in [13]. Figure 13 shows the ratio of the scaled $^{233}\text{U}(n,f)$ cross-section obtained from this work
 153 and the evaluated libraries, ENDF/B-VII.1 [14], ENDF/B-VIII.0 [15], JEFF-3.3 [16] and JENDL-4.0u2 [17],
 154 from 0.1 eV up to 10 keV. The deviations are within the evaluations' uncertainties in the resolved resonance
 155 region (< 600 eV) while the evaluations are discrepant in the unresolved region (> 600 eV). Thus, taking
 156 only the resolved resonance region into account it can be concluded that the fission chamber is working
 157 satisfactorily in the neutron energy range of this measurement (< 10 keV). An accurate prompt fission
 158 background subtraction for the measurement of the $^{233}\text{U}(n,\gamma)$ can thus be assured.

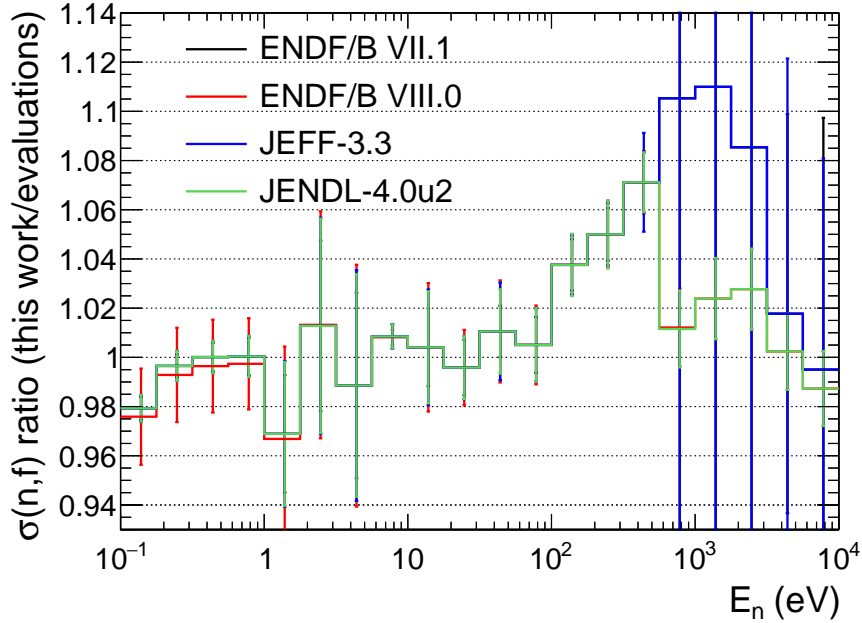


Figure 13: Ratio between the experimentally determined cross-section, scaled to the evaluated libraries in the neutron energy range from 8.1 eV to 17.6 eV, and the corresponding evaluated library.

159 3.3. Fission tagging

160 Events that produce signals in both detectors (FICH & TAC) in coincidence are related to fission events.
 161 The time correlation is given by the time difference between the detection of the event in the two detectors.
 162 Prompt fission events (small time difference) are characterized by high γ -multiplicity [18], as was observed
 163 and suggested in previous works [2, 3].

164 3.3.1. Event reconstruction

165 The coincidence algorithm is based on the use of a coincidence window $T_{coinc}^{TAC-FICH}$ between TAC and
 166 FICH and allows positive and negative time differences. Figure 14 shows the distribution of time differences
 167 $\delta T = TOF_{TAC} - TOF_{FICH}$ for all found coincidences and can be explained as follows:

- 168 • Events with $\delta T < -200$ ns show a flat distribution and correspond to random coincidences.
- 169 • The shape for -200 ns $< \delta T < -20$ ns can be described by an exponential sitting on top of the
 170 constant background. The exponential increase corresponds to events where a γ -ray is emitted before
 171 the nucleus fissions. These events can be explained by the existence of the (n, γ f) process (fission
 172 isomers) [19–22].
- 173 • A main peak for -10 ns $< \delta T < 10$ ns corresponding to the prompt fission events as suggested by the
 174 characteristics of those events with high E_{sum} and m_{cr} , indicated by the blue line.

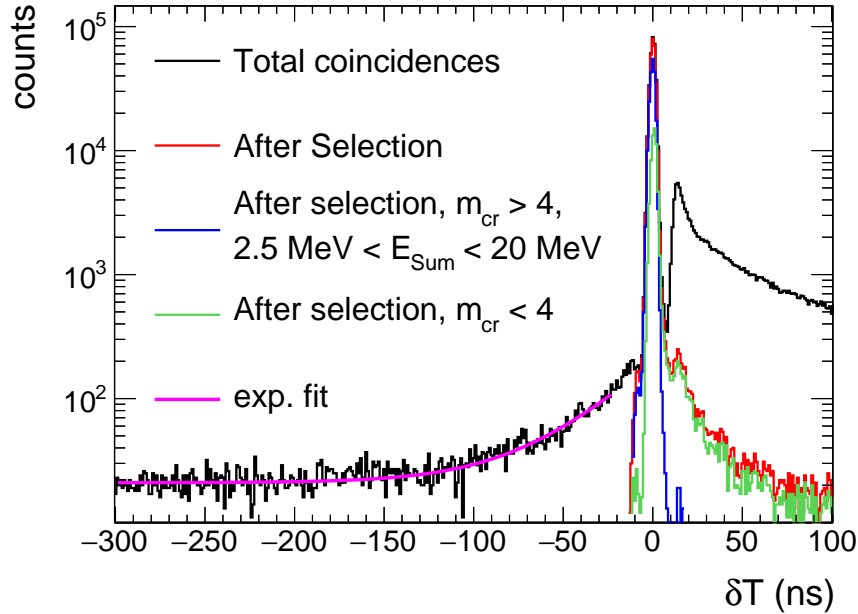


Figure 14: Time difference distribution between TAC and FICH events. The selection refers to the algorithm that selects the corresponding prompt event, as described in the text. The features of the distribution are explained in the text.

- Another sharp structure or side peak for $10 \text{ ns} < \delta T < 20 \text{ ns}$ is an artifact of the event reconstruction process. The time difference between the main peak and this side peak corresponds exactly to the TAC coincidence window of 12 ns which is the minimum time difference between two TAC events due to how the TAC coincidence reconstruction algorithm works. The position of the side peak will shift with the TAC coincidence window.
- Events with $\delta T > 20 \text{ ns}$ form an exponential tail and correspond to delayed events. Such events can be induced by fission neutrons which are subsequently captured in the experimental set-up thus emitting γ -ray cascades or isomeric states of the fission products that de-excite via γ -ray cascades with a delay corresponding to the half-life of the isomeric state. These events are related to fission but are not prompt fission γ -rays.

For reasons of causality the TAC-FICH coincidence window may not be smaller than the TAC coincidence window, otherwise there is the possibility of losing coincidences artificially. The optimal time window is a compromise between pile-up and efficient tagging. $T_{coinc}^{TAC-FICH} > T_{coinc}^{TAC}$ can lead to multiple coincidences found for a single FICH event. The different coincidences will be characterized by different TAC events, hence different E_{sum} , m_{cr} and δT . If two or more TAC events are assigned to the same FICH event, the TAC event with the highest crystal multiplicity m_{cr} is selected as the corresponding prompt fission event. If the TAC events happen to have the same crystal multiplicity then the event with higher E_{sum} is selected

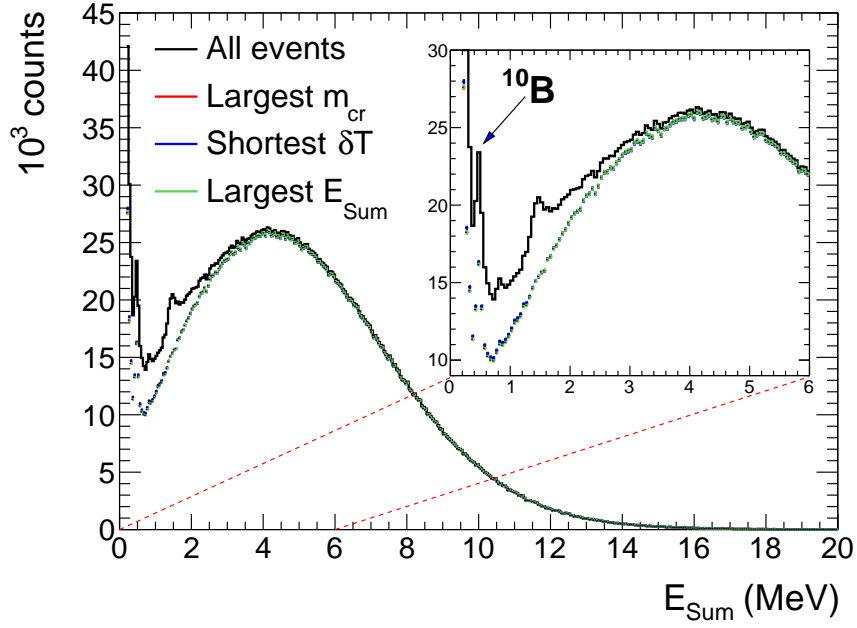


Figure 15: Comparison of the different event selection algorithms using either largest E_{sum} , largest m_{cr} or smallest δT as primary criteria. In the zoom in the region for $E_{sum} < 6$ MeV the suppression of the 480 keV γ -ray emitted in the $^{10}\text{B}(n,\alpha)$ reaction and the 1435 keV γ -ray from inelastic scattering of fission neutrons on ^{138}Ba can be observed.

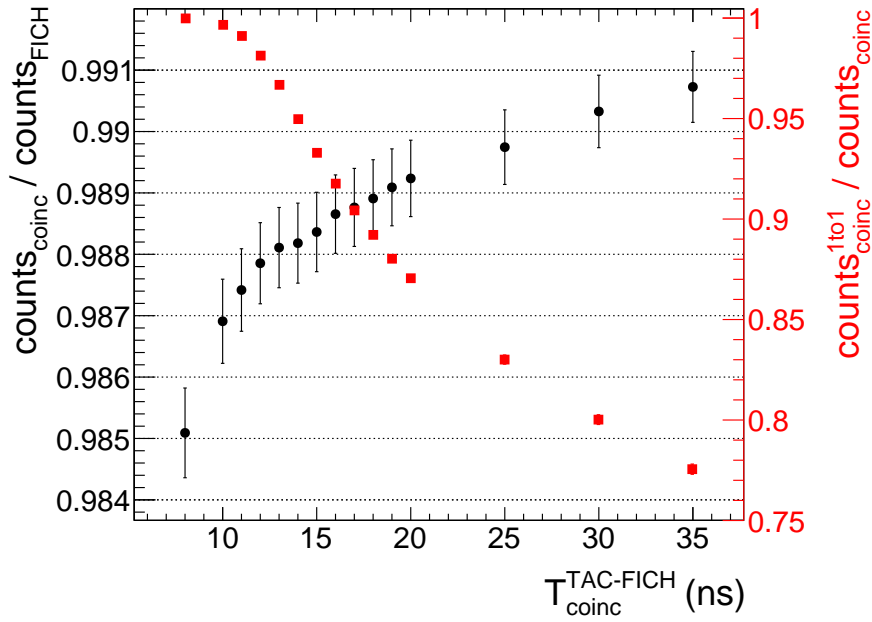


Figure 16: Fraction of found coincidences with respect to the total number of fission events in the FICH (black dots; left axis). Fraction of events where exactly one TAC event is found for one FICH event with respect to all found coincidences (red squares; right axis). Both for events with $amp > 0.09$ V and $1.6 \text{ eV} < E_n < 1.9 \text{ eV}$. Notice the different scales on the two y-axes.

192 as the corresponding prompt fission event. In principle these criteria are arbitrary and the performance
 193 of the different event selection algorithms is illustrated in Figure 15. It shows the E_{sum} spectra of the
 194 corresponding prompt fission events selected with different algorithms. It is evident that no matter which
 195 algorithm is chosen the difference is negligible.

196 Figure 16 shows the effect of different coincidence windows $T_{coinc}^{TAC-FICH}$ on the total number of found
 197 coincidences normalized to the total number of fission events detected by the FICH (black dots; left axis)).
 198 A steady increase can be seen with increasing $T_{coinc}^{TAC-FICH}$ which is understandable, although those addi-
 199 tionally found TAC events in coincidence are not necessarily related to the prompt fission event but might
 200 correspond to random or delayed events. On the other hand Figure 16 shows the number of coincidences
 201 where exactly one TAC event is found for one FICH event (red squares; right axis). With increasing coinci-
 202 dence window $T_{coinc}^{TAC-FICH}$ the number of one to one coincidences drastically decreases, as the probability
 203 of multiple tagging starts to increase. A coincidence window $T_{coinc}^{TAC-FICH}$ slightly larger than the T_{coinc}^{TAC}
 204 is already sufficient to tag close to 99% of the FICH events while a window too large might result in an
 205 uncertain assignment of multiple TAC events to a FICH event. To reduce this uncertainty the $T_{coinc}^{TAC-FICH}$
 206 coincidence window is set to 14 ns.

207 FICH-TAC coincidence tagging also allows for a better alpha-fission separation as the probability of
 208 tagging an α -particle is negligible compared to a fission fragment. In Figure 17 the tagged fission amplitude
 209 spectra for different E_n regions are compared to the amplitude spectra of the best achievable separation
 210 solely using the FICH. The improvement is obvious and allows the investigation of the shape of the fission
 211 fragment energy deposition in the fission chamber below what was possible with the FICH alone. It shall
 212 be noted that the TAC data for $0.8 \text{ MeV} < E_n < 7 \text{ MeV}$ is usually not used in the analysis of cross-sections
 213 due to the so-called γ -flasheffect [6, 7, 23] which blinds the detector.

214 3.3.2. Tagging and FICH efficiency

215 In analogy to previous works [2, 4], the tagging efficiency $\varepsilon_{Tagg}(A_{th}; E_{Sum}, m_{cr})$ describes the probability
 216 of detecting a fission event identified as such by the FICH in the TAC and depends on the applied amplitude
 217 threshold A_{th} . It is defined as the ratio between the tagged fission events $c_{Tagg}(A_{th}; E_{Sum}, m_{cr})$ and the
 218 total fission counts detected by the TAC $c_{Fiss-TAC}(E_{Sum}, m_{cr})$ (dependencies on E_{Sum} and m_{cr} are implicit
 219 for readability):

$$\varepsilon_{Tagg}(A_{th}) = \frac{c_{Tagg}(A_{th})}{c_{Fiss-TAC}}. \quad (1)$$

220 The fission detection efficiency $\varepsilon_{FICH}(A_{th})$ is the probability of detecting a fission reaction by the FICH
 221 detector and depends only on the amplitude threshold A_{th} applied to the FICH events.

222 Under the assumption that the probability of detecting a fission event in one of the detectors does not
 223 depend on whether it was detected in the other one, the tagging efficiency ε_{Tagg} and the fission detection

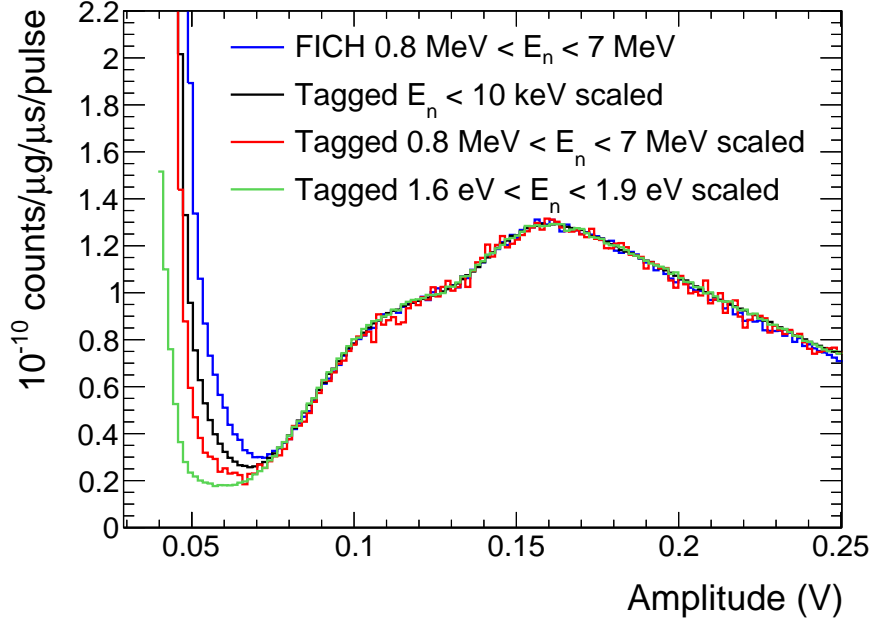


Figure 17: Pulse height spectra of the events in the fission chamber for $0.8 \text{ MeV} < E_n < 7 \text{ MeV}$ compared to tagged events for different E_n regions from all FICH channels. The neutron flux of n_TOF can be seen in Figure 7.

224 efficiency ε_{FICH} are the same quantity and the tagging efficiency depends only on the applied amplitude
 225 threshold A_{th} .

226 Following equation (1) c_{Tagg} and $c_{Fiss-TAC}$ have to be determined to calculate the tagging efficiency.
 227 While the tagged counts c_{Tagg} can be taken directly from the coincidence algorithm, the TAC events
 228 corresponding to fission reactions $c_{Fiss-TAC}$ have to be cleaned from the background first. The background
 229 consists of the ambient, the neutron beam induced and the sample induced background. The $^{233}\text{U}(n,\gamma)$
 230 reaction sets the lower threshold for the sum energy as the calculation will be biased if sum energies below
 231 the neutron separation energy of ^{234}U $S_n(^{233}\text{U} + n) = 6.85 \text{ MeV}$ are considered. Thus as a general rule the
 232 efficiency will only be calculated for $E_{Sum} > 8 \text{ MeV}$ to avoid this component of the background completely.
 233 Dedicated measurements of the ambient and neutron beam induced background have been performed to
 234 estimate their contribution to the overall background. Furthermore, the background subtraction is less prone
 235 to uncertainties and statistical fluctuations for high crystal multiplicity and large sum energies because there
 236 is little background for such conditions but a compromise between systematic and statistical uncertainties
 237 has to be made. Nevertheless, the sensitivity with respect to the applied conditions in crystal multiplicity
 238 and sum energy has to be investigated and is shown for two different amplitude thresholds A_{th} in Figure 18.
 239 Even though the residual background is subtracted a variation for lower multiplicities can be observed that
 240 decreases with increasing multiplicities. For $m_{cr} > 6$ the variation of the calculated efficiency becomes
 241 smaller than the statistical uncertainty, indicating that only fission events are left in the calculation. One

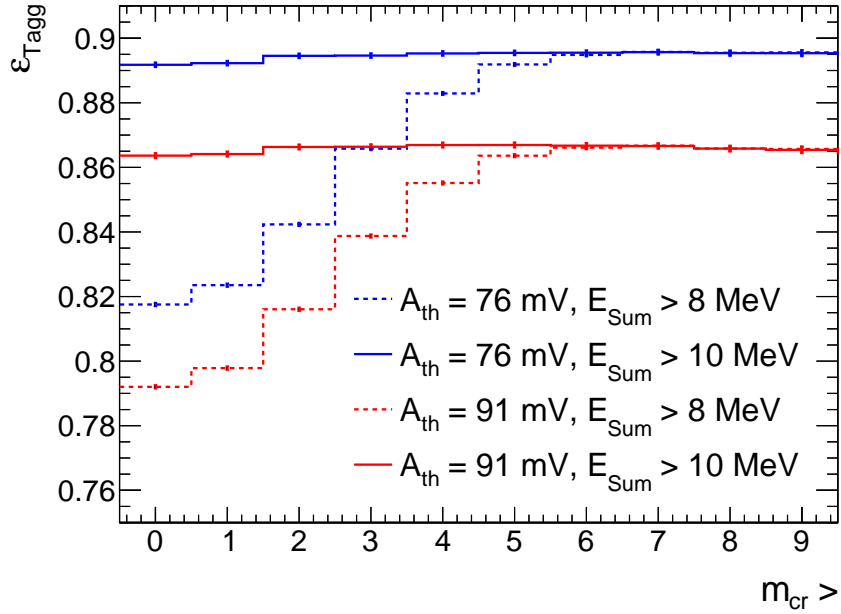


Figure 18: Fission tagging efficiency ε_{Tagg} as a function of the crystal multiplicity and sum energy for two different amplitude thresholds A_{th} in the neutron energy interval from 1.6 eV to 1.9 eV.

242 potential explanation for the systematic trend could be additional background components i.e. reactions
 243 induced by scattered (from the samples) or fission neutrons. Indeed, neutrons emitted in the fission process
 244 can be captured, preferably in the BaF₂ crystals themselves leading to TAC events with large deposited
 245 energies. This might also explain why the calculated efficiency in Figure 18 shows a stronger dependence
 246 on the multiplicity for $E_{Sum} > 8 \text{ MeV}$ compared to the more restrictive condition $E_{Sum} > 10 \text{ MeV}$, as
 247 the fission neutron induced background should not exceed 10 MeV sum energy according to the neutron
 248 separation energies of barium isotopes, i.e. $S_n(^{135}\text{Ba} + n) = 9.1 \text{ MeV}$.

249 Figure 18 shows that for $m_{cr} > 6$ the sensitivity to the background is reduced within error bars as both
 250 conditions in E_{Sum} coincide.

251 Using only events with $m_{cr} > 6$ and $E_{Sum} > 10 \text{ MeV}$ the efficiency was calculated in several neutron
 252 resonances in order to verify a possible variation. The values of the efficiency for the used amplitude
 253 threshold $A_{th} = 0.076 \text{ V}$ were all in agreement within their uncertainties, as shown in Figure 19. Thus the
 254 average tagging efficiency over all neutron energy intervals is calculated to $\varepsilon_{Tagg}(A_{th} = 0.076 \text{ V}) = 89.6(1) \%$
 255 and shown as a function of the fission amplitude threshold in Figure 20. The latter allows to calculate the
 256 tagging efficiency for any given amplitude cut and shows the stability of the value of $\varepsilon_{Tagg}(A_{th} = 0.076 \text{ V})$
 257 with respect to small gain fluctuations, which are equivalent to small variations in the amplitude threshold.
 258 This gives further confidence in the accuracy of the tagging efficiency, which is crucial to assess the capture
 259 cross section.

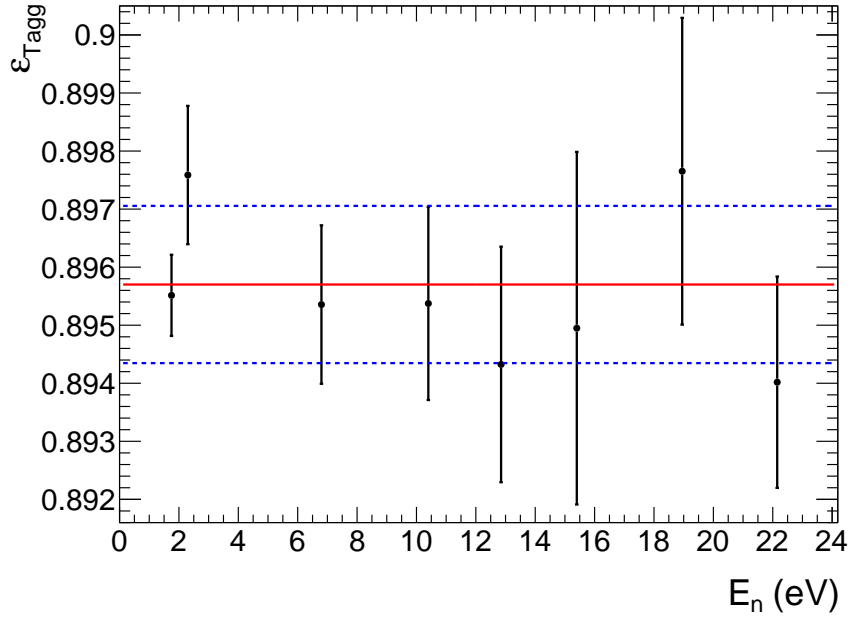


Figure 19: Fission tagging efficiency calculated in several neutron resonances for $A_{th} = 0.076$ V, $m_{cr} > 6$ and $E_{Sum} > 10$ MeV, their weighted average (red line) and the standard deviation of the data points (blue dashed lines). The uncertainties are calculated from the two highly correlated quantities in eq. 1.

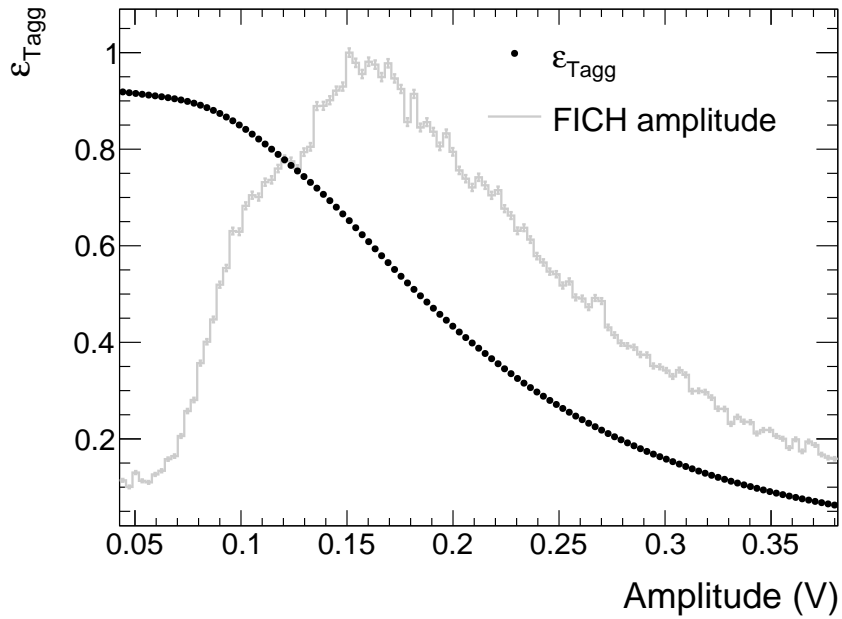


Figure 20: Tagging efficiency ϵ_{Tagg} as a function of the FICH amplitude threshold (black circles). A scaled FICH amplitude spectrum in coincidence with the TAC for events with $m_{cr} > 6$ and $E_{Sum} > 10$ MeV is shown too (gray line) as it is directly related to the efficiency.

260 In the measurement of the ^{233}U α -ratio the capture response is obtained by subtracting the efficiency
261 corrected tagged counts from the total counts in the calorimeter. Without giving a detailed calculation, from
262 the ^{233}U capture and fission cross-sections it can be expected that an uncertainty in the tagging efficiency of
263 0.1 % translates into a 1 % uncertainty in the ^{233}U α -ratio on average. The results show that this detector
264 is well suited to obtain an accurate alpha-ratio.

265 4. Conclusions

266 A new compact fission chamber was developed and optimized for the use in fission tagging experiments
267 to measure capture cross-sections of fissile isotopes. The development aimed at the use of the detection
268 system at the n-TOF facility (CERN), coupled to the Total Absorption Calorimeter of EAR1, but can be
269 generalized to other set-ups. The fission chamber was optimized for timing performance with an average
270 signal rise time of about 16 ns and a FWHM of 34 ns which is optimal for the high specific α -particle
271 count rates from ^{233}U as well as the alpha-fission discrimination and allows using a narrow coincidence
272 window between the calorimeter and the FICH facilitating low pile-up in the coincidence reconstruction. Its
273 compactness hosting a total of 14 samples as well as the minimal amount of structural material in beam
274 provide excellent conditions for low background and high statistics measurements. The whole experimental
275 set-up was further designed to achieve good performance, especially stability over time as well as effectively
276 tagging the fission events with an efficiency close to 90 %.

277 An experiment aiming at measuring the $^{233}\text{U}(n,\gamma)$ cross-section was performed and the results have
278 shown that the developed fission chamber is well suited to tag the prompt fission γ -rays, hence to have a
279 good control over the fission background in the capture measurement. Results of this measurement will be
280 presented in a separate publication.

281 Acknowledgements

282 This work was partially supported by the French NEEDS/NACRE Project and by the European Com-
283 mission within HORIZON2020 via the EURATOM Project EUFRAT.

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