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subtask 1.2.3 - D1.6 deliverable report: development of Germanium detectors for (n,xn) measurements at n-TOF

Measuring (n,n'g) and (n,xn) cross-sections has been a long standing idea at n_TOF. The facility offers a high instantaneous flux in the neutron energy region of interest from 100s of keV to 100 MeV and even beyond. Detector tests performed from various institutes with different Germanium detectors during the 2010s, see Figure 1 and 2, revealed the challenge of using High Purity Germanium (HPGe) detectors at n_TOF [1].

Figure 1: Several HPGe detectors tested a n_TOF with different commercial electronics [1].

Together with the high instantaneous flux an intense gamma-flash from the spallation process arrives in the experimental bunker at a flight path of approx. 185 m. The gamma-flash caused a detector response which corresponds to some 100 MeV energy deposition in the Ge crystal completely saturating the electronics up to several milliseconds corresponding to neutron energies (eV) far below from the region of interest (100s keV-MeV, TOF~0-20 microseconds), see Fig. 2.

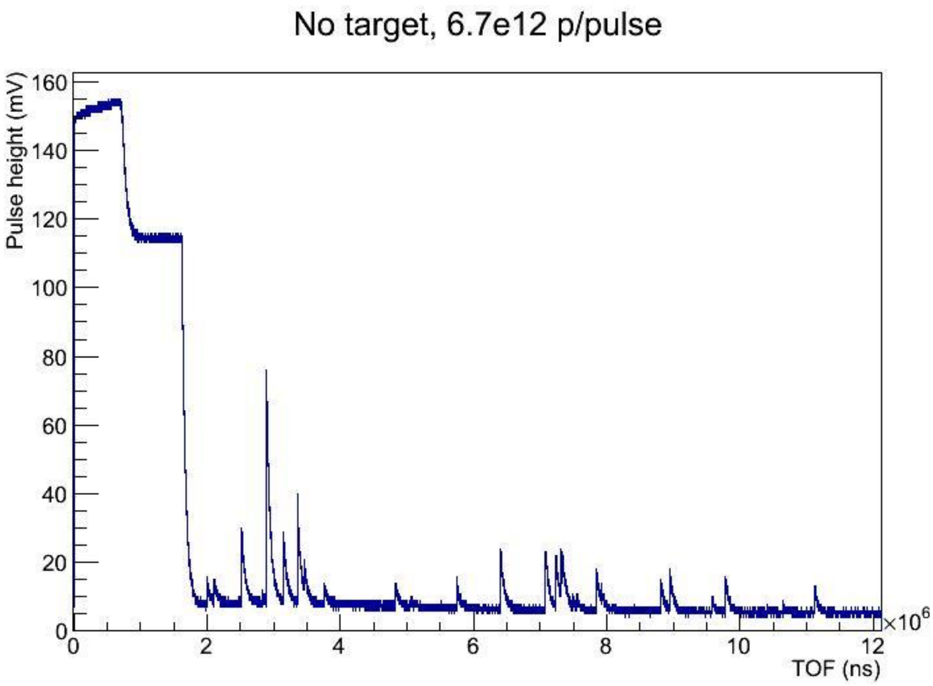

Figure 2: Data buffer from test measurements with HPGe detectors at n_TOF. The saturation of the detector is obvious up to 2 ms corresponding to a neutron energy of 45 eV [1].

The solution was developed within the n_TOF collaboration and applied to various detectors. The switch or gate circuit [2] essentially diverts (switch) the output of the crystal to ground for a certain time period (gate) that can be adjusted via a logic signal. For the HPGe the circuit was implemented together with Mirion Technologies the manufacturer of the detector – Mirion developed two implementations, one where this circuit is mounted in the cold and sealed part of the detector and one where it is implemented in the room temperature amplifier. For practical reasons the latter version was chosen for the detector. A p-type coaxial HPGe detector EGPC 25S/N 54035 with 26% relative efficiency and the integrated switch circuit on the only warm amplifier (10 mV / MeV) was delivered to n_TOF in October 2018 by CANBERRA/Mirion Technologies, see Figure 3.

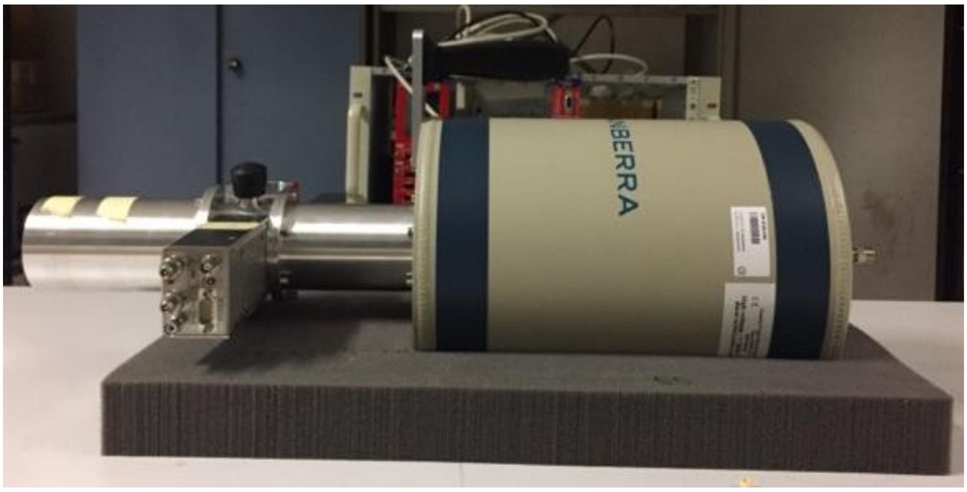

Figure 3: p-type coaxial HPGe detector EGPC 25S/N 54035 as delivered in 2018 [1].

The detector was immediately tested with beam as CERN went into a long shutdown in November 2018 until July 2021. This first test is considered a huge success, as the switch circuit worked as intended and the saturation effect observed in the previous detector tests was solved – see Figure 4.

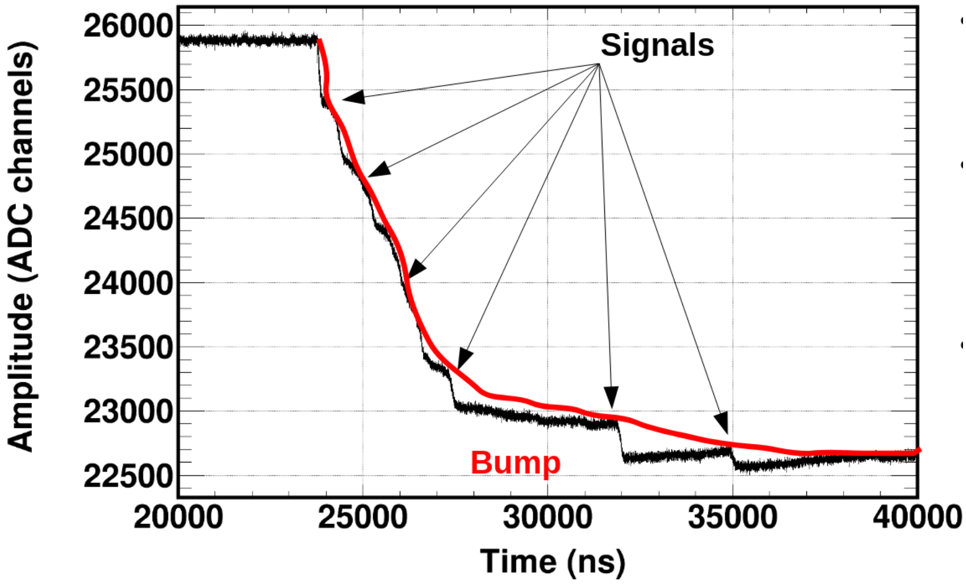

Figure 4: Data buffer with the new detector from Oct. 2018. The switch circuit works as intended and no saturation of the detector is seen. Signals can be clearly observed sitting on top of an underlying bump (red) in the detector response which is not saturating the detector though [3].

Furthermore the detector was characterized at the n_TOF electronics lab with sources and the energy resolution (2.85 keV @ 1408 keV) as given by the manufacturer was confirmed [4,5]. The detector was implemented in GEANT4 according to manufacturer's specifications and its geometry was tuned to match the measured efficiency with a well-known calibration source. A high precision agreement was achieved as shown in Figure 5.

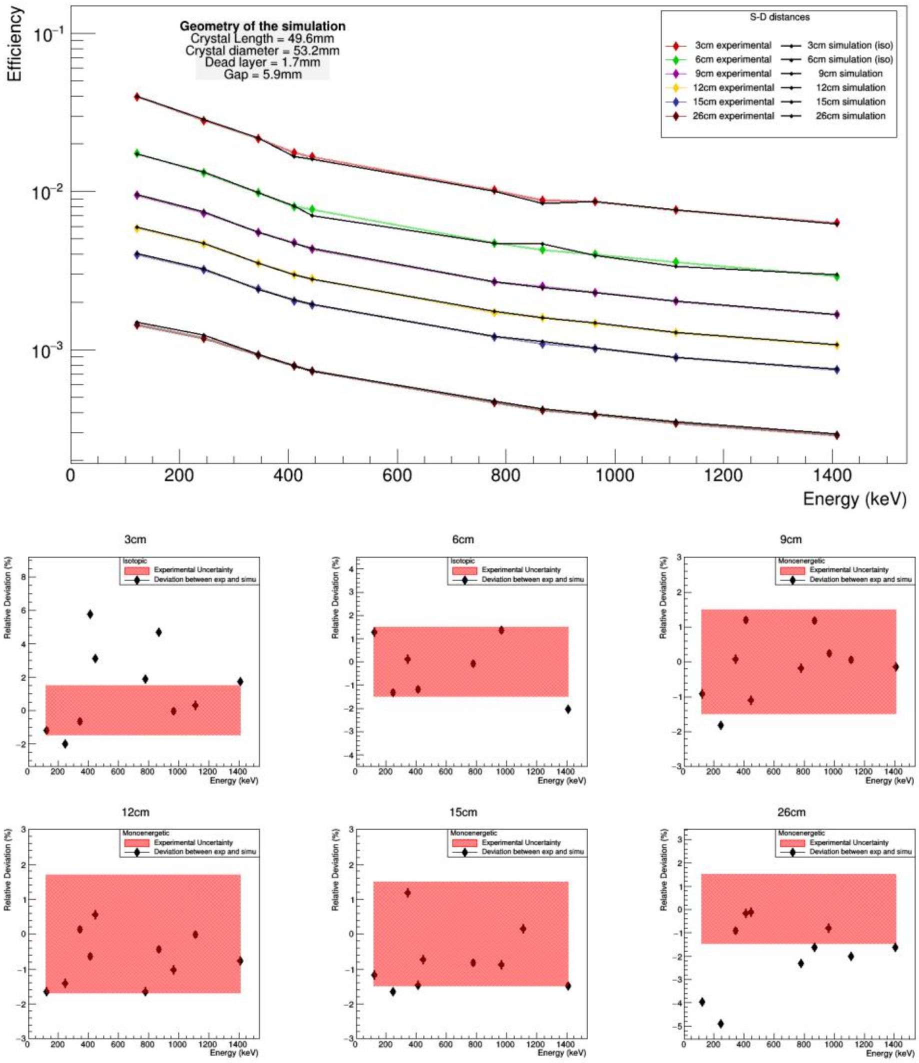

Figure 5: Comparison of simulated and measured efficiency as a function of the distance between detector and source. An excellent agreement is reached after tuning the geometry of the detector slightly deviated from the manufacturer's specifications [4, 5].

In Figure 4 the signals seem to sit on an underlying structure/response of the detector, the so-called bump. Previously this was masked by the saturation of the electronics. The nature of this bump was investigated via simulations scoring energy deposition and time stamps of interactions of scattered neutrons from the sample in the Germanium crystal [6]. The simulations could reproduce the size and time structure of the underlying bump well, see Figure 6, which indicates the bump originates most likely from scattered neutrons into the Germanium crystals and depositing energy via elastic and inelastic reactions leading to an accumulation of many small indistinguishable signals leading to the shape of the bump [6].

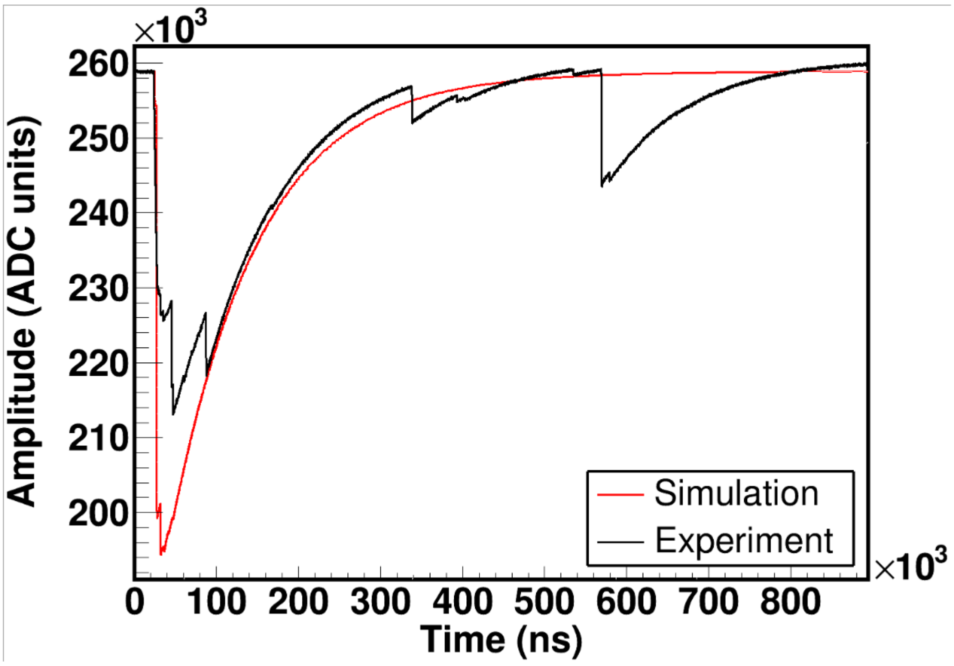

Figure 6: Comparison of simulated and experimental shape of the bump [6].

The bump scales in theory with the primary proton pulse intensity, though as an off-beam detector the size and time structure of the bump depend on the time dependent energy distribution of scattered neutrons in the Germanium crystal and hence is more a stochastic process. Therefore the bump shape is not constant on a pulse-by-pulse basis and cannot simply be subtracted [7]. The signal reconstruction proved to be very challenging leading to the development of two independent pulse shape analysis (PSA) codes which both yielded similar results for the energy resolution of about 3.9 keV @ 1.4 MeV [3, 6, 7] and are still under further development.

For practical reasons of detector handling in an underground work sector type A room at n_TOF EAR1, the detector was sent back to MIRION in 2019 for replacement of the LN2 cooling with CP5 electrical cooling [5]. At the same time MIRION offered to add another high-gain amplifier free of charge which was happily accepted. The detector was delivered back to CERN in 2020 and efficiency, energy resolution and gate behaviour were checked again in laboratory conditions. No difference to the previous behaviour was observed, and the electro cooling made life easier. The resolution of the 2^{nd} high gain amplifier agreed with the specifications of the manufacturer. It was not possible to test with beam conditions due the shutdown at CERN. Due to the confidence from the laboratory results and progress in the signal reconstruction a letter of intent (LoI) to do a first test measurement on 7Li(n,n’g) and 56Fe(n,n’g) [8] was submitted to and approved by CERN.

After COVID19 related delays, the CERN accelerator complex restarted in 2021 and the first beam for n_TOF’s new spallation target was received in mid July 2021. The detector was used for activation measurements during the commissioning phase [9]. At the end of 2021 the HPGe detector was measuring with the last few shots of beam of the year. The data showed that there was a new issue with the detector, an undershoot of the baseline as well as high frequency parts in the signal. It is clear that in this state the detector could not be used for a physics experiment though as sometimes the detector response would also again saturate in the energy region of interest. It was not clear if the additional amplifier or electro cooling were responsible and no further interventions could be done as the CERN complex went into winter shutdown soon after.

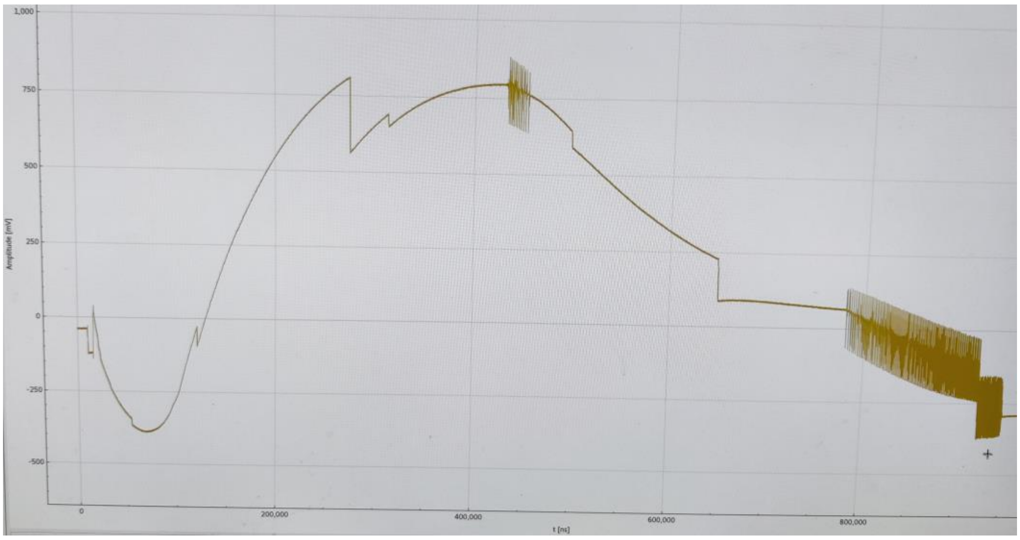

Figure 7: Example wave form from end of 2021 with modified detector (electro cooling and additional amplifier) [10].

During the winter shutdown of 2021/2022 amplifiers' response to the gate/switch circuit were studied and further optimized, but without a strong signal (gamma flash) it was not possible to reliably test the detector response until mid 2022.

In May 2022 the detector still showed the same behavior but together with MIRION we narrowed the issue down to the second amplifier that was added in 2020. With their instructions this amplifier was separated in July 2022 and the detector was immediately back in working conditions as in 2018. Another issue came up with respect to the 2018 conditions, a ~5 MHz radiofrequency ringing related to the proton beam that was suddenly visible in the HPGe output. This is a facility related problem which apparently is way worse in 2022 compared to 2018.

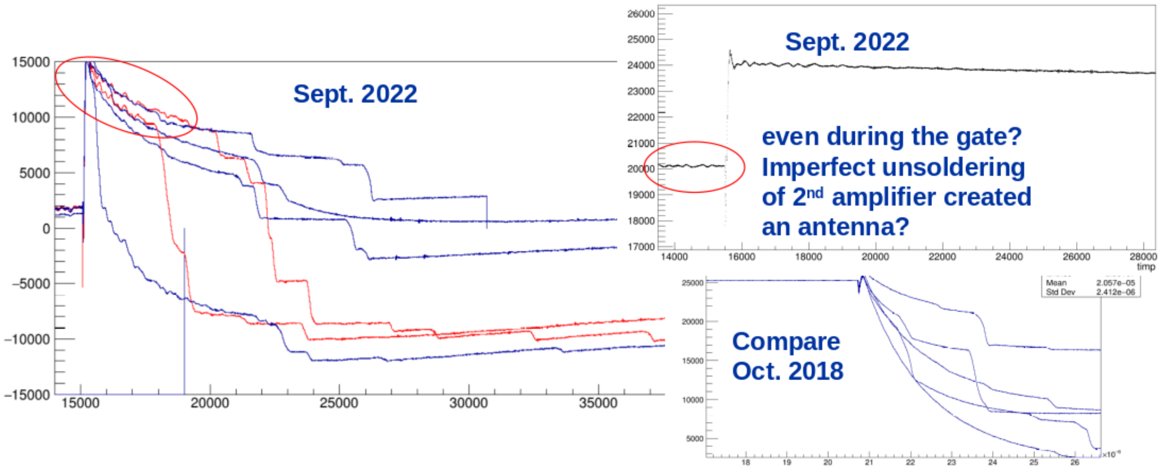

Figure 8: Example wave forms from July 2022 and October 2018 explicitly showing the ringing present in 2022 indicated with the red circles [10].

Despite these issues and as a preparatory beam test the detector was put in a dedicated configuration in September 2022 with a LiF sample intercepting the beam. With 0.25 days of beam the first beam data with the HPGe since 2018 was obtained [10] and showed a reasonable signal reconstruction as shown in the energy deposition plot in Figure 9.

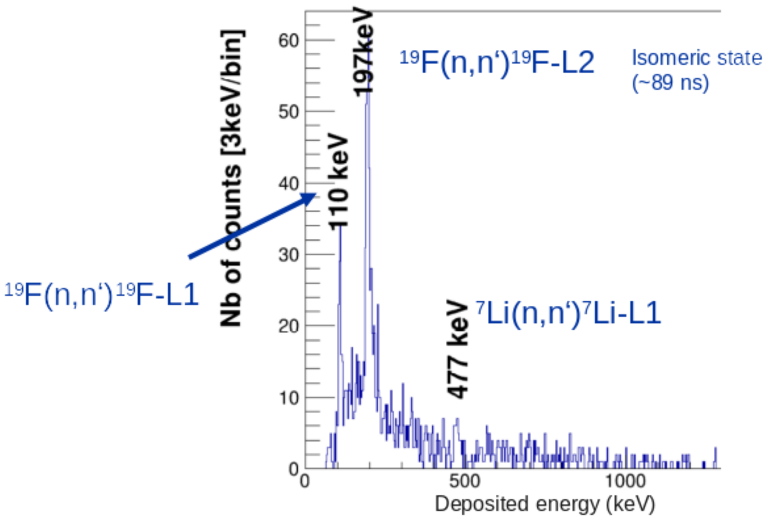

Figure 9: Deposited energy spectrum for neutron energies of 0.1 - 1 MeV from September 2022 [10].

Before performing the LoI measurements [8] the detector was sent back to MIRION early 2023 to professionally remove the 2nd amplifier and improve the RF tightness of the detector as much as possible. It returned in March 2023 and further improvements were made for the mechanical setup.

The LoI measurement was performed in May 2023 with a LiF and 56Fe sample. The deposited energy vs neutron energy spectrum is shown in Figure 10. Despite a significant amount of scattered neutron background indicated by the Ge(n,inel) peaks the 846 keV 56Fe line is clearly identifiable. This was the first time for this detector with a sizeable sample and in clean measurement conditions. The data analysis is pending but improvements have to be made in the signal reconstruction to achieve the resolution of laboratory conditions. Several more tests and measurements have been performed in this context and a publication with the results is in preparation.

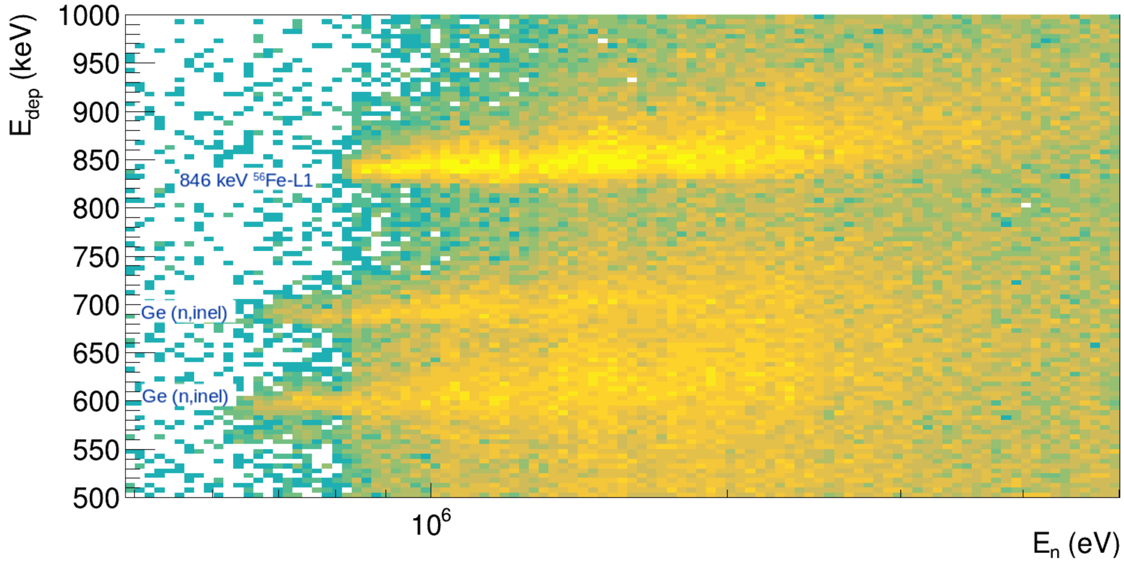

Figure 10: Deposited energy vs neutron energy spectrum of a 56Fe sample [11].

Conclusion

We believe to have an excellent understanding of the physics happening with the detector. Despite the challenging conditions at n_TOF due to the high instantaneous count rates as well as the neutron bump, the continuous progress in the analysis and data reconstruction allows to be optimistic and if the PSA can be improved further there is a clear justification for the use of a HPGe setup for (n,n'g) and potentially also (n, xn) cross-section measurements at n_TOF.

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