Study of a NaIL-detector as a neutron detector

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1 ABSTRACT

Within the past decade a significant shortage of ^{3}He has occurred. Since this material is widely used in neutron detection applications, e.g. by first responders, during on-site inspections, and in safeguard applications where nuclear and radioactive material has to be localized and possibly identified, alternative materials need to be considered, selected, implemented in a corresponding detector, and thoroughly tested.

One of these promising replacement materials is ^{6}Li, which, e.g., is utilized in a sodium iodide detector (NaIL). There are also other detector applications with Li such as ^{6}LiF/ZnS, CLYC (Cs_2LiYCl_6:Ce), and CLLB ($Cs_2LiLaBr_6$:Ce) which were investigated elsewhere. NaIL offers the possibility of measuring gamma and neutron radiation simultaneously with good discrimination capability.

Within the detection material neutrons are captured by ^{6}Li, triggering the nuclear reaction ^{6}Li(n,t)α. The secondary particles then create light pulses in the scintillation crystal which ultimately serve as detection signals. Due to the large Q-value of the reaction of 4.78 MeV, the signals are of the same order of magnitude as those of high energetic gamma photons. The discrimination of neutron and gamma radiation is realized by pulse shape analysis.

Measurements with a NaIL-detector have been performed and the detectors' capabilities verified with measurements of several neutron sources. The possibility of detecting such sources, which create a radiation field only slightly above the background radiation level, is of particular interest. In addition to results gained with different neutron sources, the influence of moderator material (HDPE) was also investigated. Other figures of interest were the FWHM (full width at half maximum) resolution of the gamma spectrum and the detectors' efficiency, also with regard to detectors equipped with ^{3}He. The results of these verification tests will serve as supportive information regarding suitable neutron detection materials free of ^{3}He for first responders and other experts who work in the field of nuclear safety and security.

Key words: Neutron measurements, Neutron detection materials, ^{3}He replacement.

2 INTRODUCTION

NaIL is a scintillation material for simultaneous gamma-ray and neutron detection. In addition to the usual Tl dopant, 95 % enriched ^{6}Li is used as co-dopant. It enables thermal neutron detection to the established gamma-ray scintillator while retaining the scintillation properties of NaI(Tl). The detection capability for thermal neutrons A*ε is given as 13 cm^2, with A the detector area and ε the probability of detecting an impinging thermal neutron for the scintillator size used [1]. This is slightly below the values given for CLYC and CLLB with 20 cm^2 respectively 22 cm^2 for the same crystal size. In comparison to the standard NaI(Tl) the light yield is slightly lower and the scintillation properties of NaIL shall degrade less at high temperature than standard NaI(Tl).

In the present paper the main focus is on neutron detection and the results obtained for different neutron sources and their distinguishability. Gamma rays and neutrons are distinguished through pulse shape discrimination (PSD). The different absorption processes of high energetic photons on the one hand and the charged reaction products of the ^{6}Li(n,t)α reaction on the other hand in the NaI matrix leads to scintillation pulses of different length. The gamma ray pulses are longer than the neutron reaction pulses and they can be separated through PSD. In addition, the obtained energy spectra lead to further information for identification of the radiation source.

3 SETUP AND PERFORMANCE

For the presented studies a NaIL scintillator 2M2NaIL/2-X from Saint-Gobain was used. The crystal has a diameter of 50 mm and a length of 50 mm. It is combined with a Hamamatsu Photomultiplier R6231. The supply voltage is + 900 V. For the data readout and analysis, a CAEN Digitizer DT5730S was used together with the CoMPASS [2] software, a multiparametric data acquisition software for physics applications.

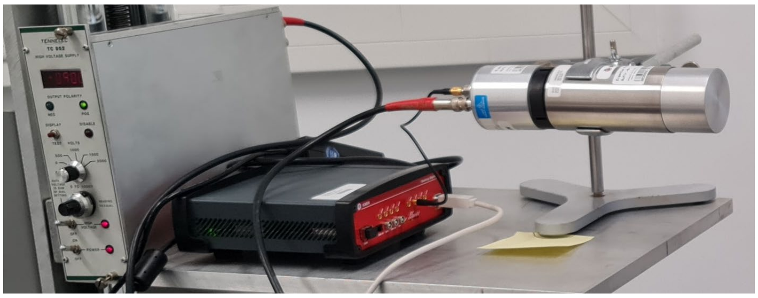

Figure 1: Setup with high voltage power supply (left), digitizer (middle) and the NaIL detector consisting of the crystal, the photomultiplier tube and the base (right).

The measured signal is analyzed and two windows are set, a long one and a short one. From the associated summed charge of the corresponding windows the PSD factor is calculated as the ratio between the integral of the tail ($Q_{long} – Q_{short}$) and the total charge (Q_{long}). The PSD spectra plots the counts versus the PSD factor, the principle is demonstrated in Figure 2.

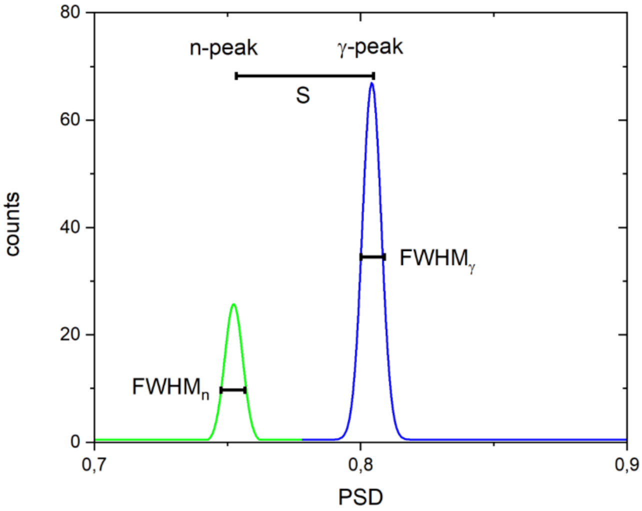

Figure 2: Principle of PSD spectra. The PSD value is determined as the integral of the tail ($Q_{long} – Q_{short}$) and the total charge (Q_{long}). The figure of merit FoM is determined as FoM = S / ($FWHM_\gamma + FWHM_n$).

The PSD value is bound in the range from 0 to 1 and if the parameters are well set, two clear peaks can be observed: one represents events emerging from neutron captures while the other is produced from gamma events. To assess the detector, the figure of merit (FoM) is defined as the ratio of the distance of the neutron and gamma peak to the sum of the peaks' full width at half maximum (FWHM) as shown in Figure 2. A large FoM is produced by a large separation of the two peaks together with a narrow width, which allows a good discrimination between neutrons and photons. Thus, a large FoM is a desired feature of the detection system.

4 NEUTRON SOURCES

Four different neutron sources are investigated in the framework of the paper: Depleted uranium (DU), ^{252}Cf, an Am/Be source and an Am/Li source. An overview of the source characteristics is given in Table 1. The neutrons generated by the different sources are of different energy. Am/Li generates neutrons of somewhat above 1 MeV, Am/Be neutrons with a mean energy of about 4-5 MeV and the energy of neutrons generated by ^{252}Cf and DU is in between at about 2-3 MeV [3]. Thus, the neutron energy of the used sources is above the energy of thermal neutrons in all cases. Therefore, the use of polyethylene (PE) as moderator is of special interest.

source	**label**	**source strength [n/s]**	**activity [Bq]**	**neutron energy [MeV]**
DU	No. 6	250	2.3e8	2-3
^{252}Cf	MM141	9000	5.5e4	2-3
Am/Be	AMN17/AMN2387	200000	3.4e9	4-5
Am/Li	N409	53000	4.3e10	1

Table 1: Summary of the neutron sources. The first column states the kind of neutron source followed with the internal label, the source strength and activity at the date of the measurement.

5 MEASUREMENTS AND TEST RESULTS

Distance-dependent measurements have been carried out with ^{252}Cf, Am/Be and Am/Li without additional PE and with 5 cm PE between source and detector. At a fixed distance of 35 cm also the amount of PE was varied from 0 – 25 cm. With the depleted uranium a few measurements without PE have been performed.

5.1 Dependence of the distance - FoM

Figure 3 gives the FoM for the distance-dependent measurements with Am/Be with and without 5 cm PE according to Figure 2.

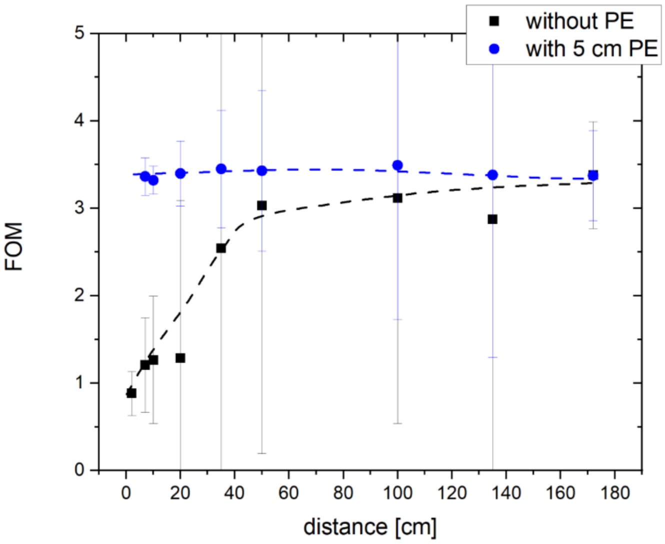

Figure 3: Figure of Merit (FoM) of pulse shape measurement on Am/Be with and without PE. The dashed lines are not fitted to the data and demonstrate the trend.

For short distances, the advantage of using additional PE can be clearly seen. The FoM is significantly higher than without PE.

5.2 Energy spectra

In addition to the obtained PSD spectra also the energy spectra are obtained. Figure 4 shows the results for spectra obtained in 10 cm distance with and without additional 5 cm PE in measurements of 5 min for the three different sources ^{252}Cf, Am/Li and Am/Be. In the measurements without PE the count rate is lower and the neutron peak is not visible, only in the case of the Am/Li measurement a slight indication might be present. The situation changes completely when using PE. One can clearly see the difference in the energy spectra between the three sources which enables an identification concerning the kind of source. A spectrum obtained with depleted uranium is shown in Figure 5.

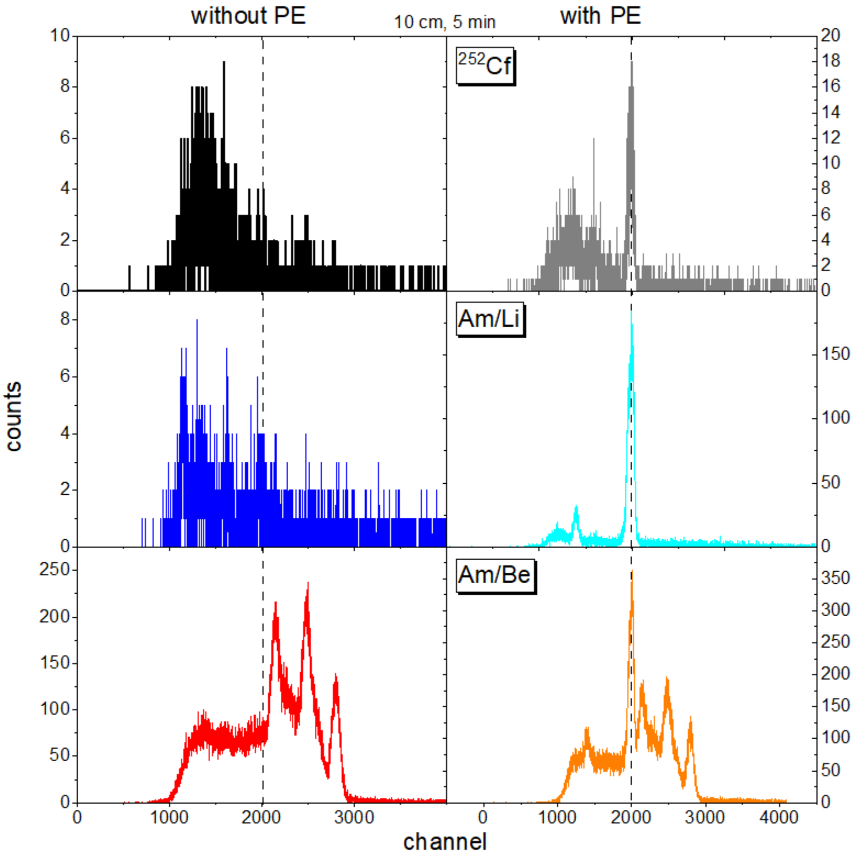

Figure 4: Energy spectra obtained in 10 cm distance for 5 min with and without 5 cm PE between the source and the NaIL detector with counts versus channel. Three different neutron sources ^{252}Cf, Am/Li and Am/Be were used according to the description in the diagram. The spectra differ according to the characteristic radiation of the different sources and enable the identification of the neutron sources. The dashed lines mark the position of the expected neutron peak.

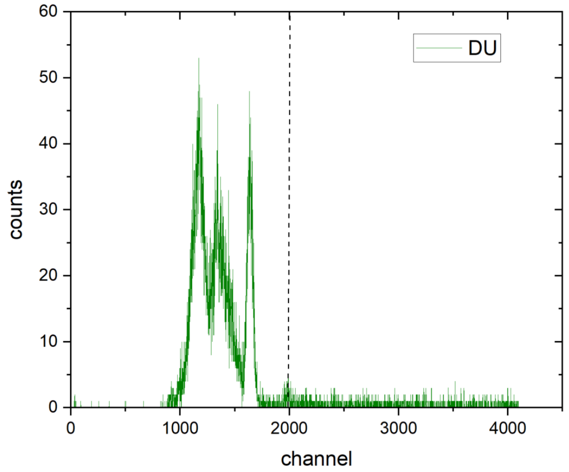

Figure 5: Energy spectra obtained for the DU source in 100 cm distance with 3 h measurement time without PE between the source and the NaIL detector. The dashed line marks the position of the expected neutron peak.

5.3 PSD spectra

In this section PSD spectra obtained with all neutron sources as well as a background measurement are shown. Figure 6 shows the result for 5 min measurements in 10 cm distance for Am/Be and Am/Li. Both results are shown without (dashed lines) and with 5 cm PE (solid lines). As illustrated in Figure 2 the peak at about 0.74 is due to the neutrons and the one at about 0.79 due to the gamma rays. The influence of PE is also clearly visible here. Without PE the PSD peaks caused by the neutrons are rather weak and not visible, therefore the region is shown enlarged.

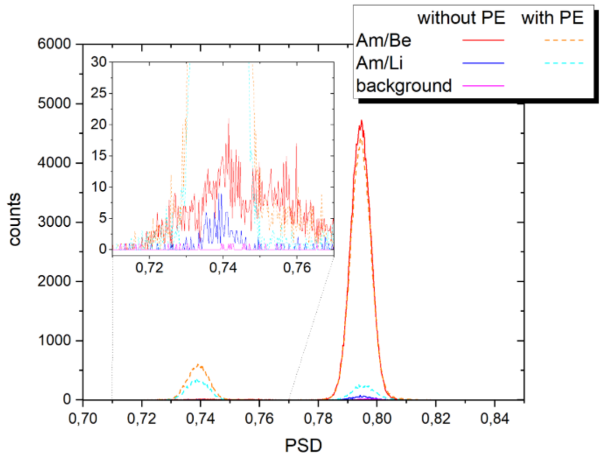

Figure 6: PSD spectra of Am/Be and Am/Li sources. For measurements with and without 5 cm PE in a distance of 10 cm with a measurement time of 5 min. The region of the neutron PSD peak is shown enlarged.

Due to the larger source strength of the Am/Be source and the resulting higher count rate, the results for Am/Be are separated from the others. Figure 7 shows the results for three different distances 10 cm, 35 cm, and 50 cm on the left without and on the right with PE. The comparison with the result obtained from a background measurement indicates that even for the measurement without PE an increase of the count rate is observed. The measurement in the shortest distance also shows an effect of the high count rate which leads to a worse peak form. With 5 cm PE the counts at the peak maximum increase by a factor of 40, 7, and 4 for distances of 10 cm, 35 cm, and 50 cm, respectively. This is the same effect like observed during the distance-dependent measurements with ^{252}Cf. For shorter distances the use of PE is extremely helpful and becomes less important for larger distances.

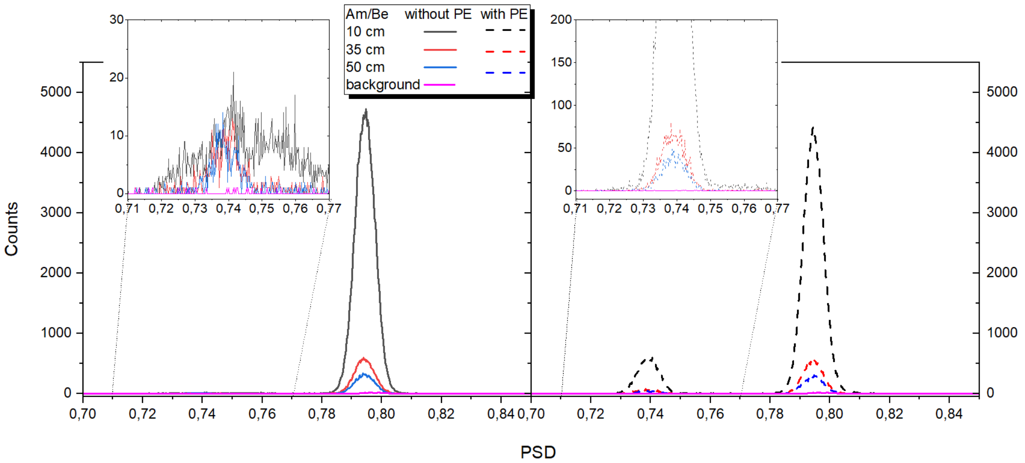

Figure 7: PSD spectra of Am/Be for three different distances 10 cm, 35 cm and 50 cm. On the left - in solid lines - without and on the right - in dashed lines - with 5 cm PE between source and detector. Measurement time in all cases 5 min. In addition, the result of a 10 min background measurement is given in magenta. The region of the neutron PSD peak is shown enlarged.

Figure 8 shows the results for Am/Li, ^{252}Cf and DU as well as the comparison with the background measurement. Except for the DU measurements the distance between the source and the detector is 10 cm and the measurement time 5 min. The data for DU without PE was obtained in a measurement time of 3 h in a distance of 100 cm. In addition, the data for a background measurement is given for comparison.

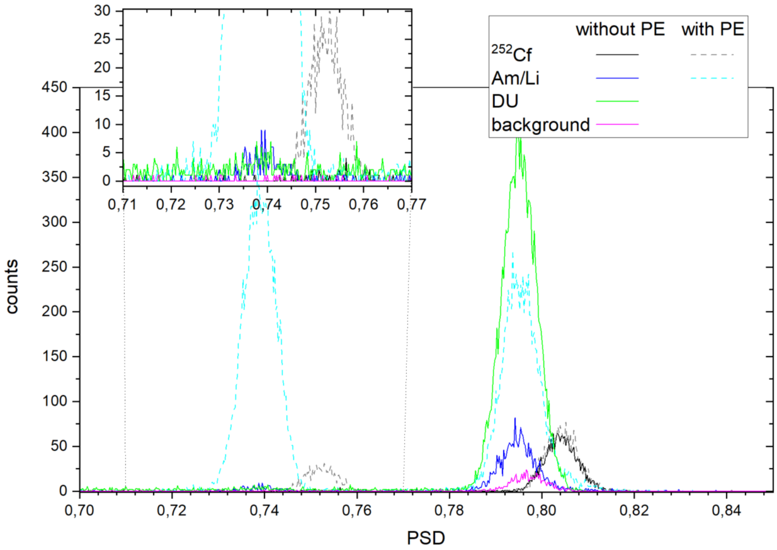

Figure 8: PSD spectra of ^{252}Cf and Am/Li sources. For measurements with and without 5 cm PE in a distance of 10 cm with a measurement time of 5 min. And the data for DU without PE obtained in a measurement time of 3 h in a distance of 100 cm. In addition, the data for a background measurement is given for comparison. The area of the neutron peak is additionally shown enlarged.

While the position of the gamma and neutron PSD peaks is the same for the measurements with Am/Li, Am/Be and DU, a shift of the PSD peaks can be observed between the measurements with the ^{252}Cf source and the others (see Figure 8). A possible explanation for this shift is the fact, that the measurements with the ^{252}Cf source were performed at a different time, a different laboratory and a different input channel of the digitizer had to be used. All other parameters of the digitizer were identical for all measurements presented in this paper.

5.4 PE variation

The sensitivity of the NaIL material for thermal neutrons is proved by the influence of the PE material. For further measurements PE shall always be used. In this section results for measurements with different amounts of PE are shown. Figure 9 shows the PSD spectra obtained with the Am/Be source in 35 cm distance during a measurement time of 10 min. The PE between the source and the detector varies from 0 to 25 cm. The neutron peak is largest with 5 cm and 10 cm. Figure 10 gives an overview of the corresponding energy spectra for Am/Be as well as for Am/Li. For a further and more detailed investigation a calibration of the x-axis using known gamma sources have to be done. This will be done in a further step.

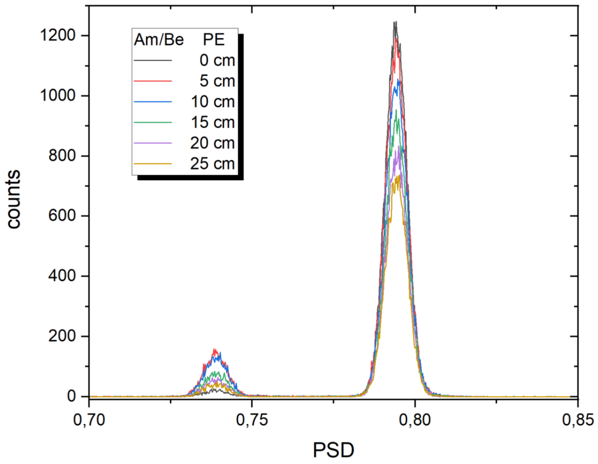

Figure 9: PSD spectra obtained with Am/Be source in 35 cm distance with a measurement time of 10 min and PE between source and detector between 0 and 25 cm. The left neutron peak is largest with 5 cm and 10 cm.

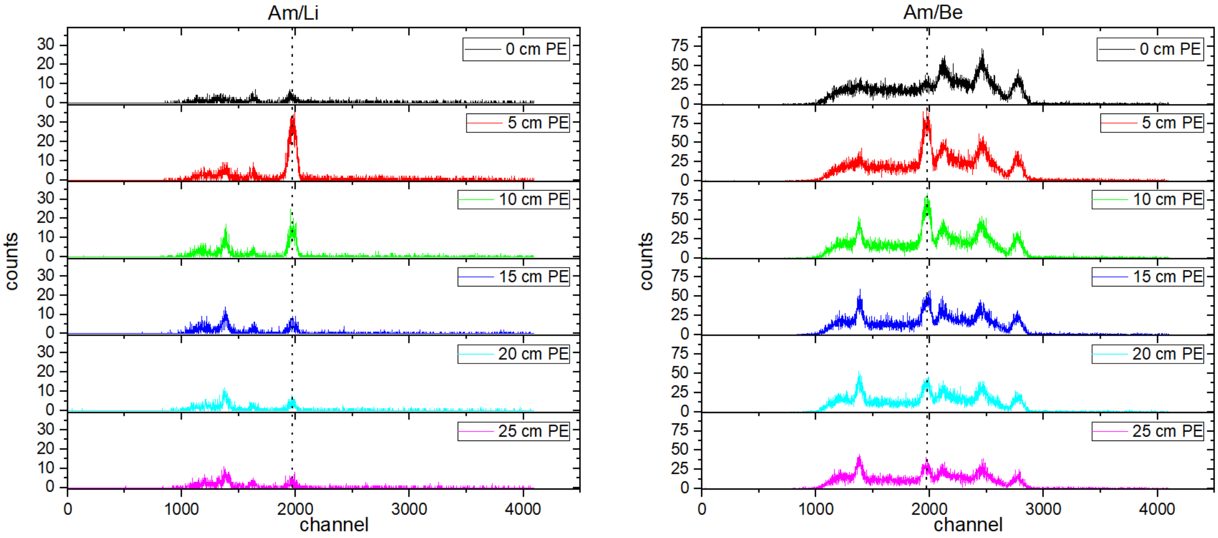

Figure 10: Energy spectra obtained with the Am/Li source and the Am/Be source in 35 cm distance und with 10 min measurement time with PE from 0 – 25 cm in front of the detector as given in the diagram. The dashed line marks the expected neutron peak.

6 CONCLUSIONS AND FURTHER RECOMMENDATIONS

For further measurements additional PE of 5 cm to 10 cm thickness is recommended. The moderator is necessary because NaIL is only sensitive for thermal neutrons. The optimal setting depends on the thickness of the PE used, the distance between detector and source, and the source strength.

The NaIL detector enables the user to detect neutron sources using pulse shape discrimination. Further evaluation of the spectra allows the identification of the neutron source and enables to distinguish between DU, ^{252}Cf, Am/Li and Am/Be. This has to be investigated in further experiments in detail.

7 REFERENCES

[1] Saint-Gobain Ceramics & Plastics (2019): NaI(Tl+Li) Neutron-Gamma Scintillator [2 pages]. https://www.crystals.saint-gobain.com/sites/hps-mac3-cma-crystals/files/2021-08/nail-material-data-sheet.pdf [Acessed 2023-04-19]

[2] CAEN S.p.A. (2022): UM5960 CoMPASS User Manual – Revision 20 [126 pages]. https://www.caen.it/?downloadfile=7961 [Accessed 2023-04-19]

[3] Köble, T., W. Rosenstock, M. Risse, H. Friedrich, W. Berky, and S. Chmel. "Neutron Measurement Techniques for Hand-Held Devices", 2009. https://publica.fraunhofer.de/handle/publica/363511.