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SUMMARY REPORT

Designing and Testing a Neutron Spectrometer

Neutronispektrometrin suunnittelu, rakentaminen ja testaus

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Abstract

A portable capture-gated fast neutron detector was developed. The sensitive part of the detector is a 3”x3” borated plastic scintillator. The detector has two complementary neutron detection signals: the capture-gated fast neutron signal and an indirect high-energy (>3.5 MeV) gamma signal. In addition, specific indicators for source identification were identified. The detector makes discrimination between fission and beryllium-based sources possible even with shielded sources. The detector is thus a versatile tool for in-field security applications.

1. Introduction

Radioactive sources, such as neutron sources, can be used maliciously against society or individuals. Neutrons are emitted by nuclear material (such as plutonium and uranium) and neutron generators. Nuclear material is used in nuclear weapons and in nuclear reactors. Neutron generators consist of two isotopes: a radioactive isotope that decays by emitting alpha radiation and another isotope that absorbs the alpha radiation and then emits neutrons. This type of source constitutes a special danger, since the source can be transported without emitting significant amount of radiation. Traditionally, the helium isotope He-3 has been used for neutron detection. However, there is a world wide lack of this helium isotope and new detection methods are needed.

The importance of radiation detection is emphasized both in the EU (CBRN Action Plan 2009) and Finland (Yhteiskunnan turvallisuusstrategia 2010). The detection of neutron sources relies on direct or indirect methods. Direct methods include thermal neutron counters and fast neutron spectrometers. Indirect methods utilize gamma radiation or activation products caused by neutron reactions. In the MATINE project MAT 798, indirect neutron detection ability was added to gamma portal monitors in operational use in Finland. The portal monitors detect neutron sources indirectly by high-energy gamma radiation emitted in neutron reactions and by the neutron source itself.

In the present project a portable fast neutron spectrometer was developed. The spectrometer uses a direct detection method: capture-gated recoil proton detection. The sensitive part of the detector is a 3″x3″ borated plastic scintillator. The detection principle is as follows: An incident fast neutron loses its energy in scattering reactions (i. e. collisions) with the hydrogen in the plastic. This is registered as a pulse that is related to the energy of the neutron. Within 0 - 3 μs, a second pulse is produced as the thermalized neutron is captured by the boron in the scintillator. The boron emits an alpha particle in the capture reaction, causing a second pulse with a fixed energy. By recording each pulse separately, these coincidental pulse pairs can be found and discriminated from pulses caused by gamma radiation.

The Q value of the neutron capture reaction of the boron isotope ^{10}B is 2.8 MeV. With a 94 % branching ratio, there is a 477.6 keV photon emitted in the reaction. The total energy of the alpha and lithium particles is then 2.34 MeV, out of which the ^{7}Li isotope gets

0.84 MeV. The energy released in the reaction causes a pulse equivalent to that of a 76 keV electron (76 keVee). Heavy, charged particles cause smaller light pulses than lighter, charged particles with equal energy. For the same reason, the height of the scattering pulses caused by the scattered protons is also smaller than what electrons of equivalent energy would produce. The neutron energy response of the detector is, however, complicated by the non-linear light output of the scattering reactions. The energy of the pulse depends on the random scattering history of the neutron.

2. Research objectives and accomplishment plan

A portable, in-field fast neutron spectrometer was developed and its response with different sources was studied. The research objectives were:

1. Develop a portable, in-field fast neutron spectrometer.
2. Identify sources and source shields by the measured neutron spectrum.
3. Study simultaneous neutron and gamma spectrometry (including neutron detection by high-energy gamma radiation).

3. Materials and methods

The capture-gated neutron spectrometer consists of a cylindrical plastic scintillator coupled to a photomultiplier and 2048 channel digital multichannel analyzer (Canberra Osprey). The Canberra Osprey MCA is very suitable for in-field measurements and can be used in list mode (storing the energy and a time stamp for each pulse). The scintillator material was 3″x3″ EJ-254 (Eljen Technologies) containing 5 % natural boron. The isotope ^{10}B, which constitutes about 20 % of natural boron, has a large neutron capture cross section.

In most measurements, the sensitive part of the detector was surrounded with a 1 mm thick layer of lead. This reduces the gamma background significantly. Figure 1 presents the detector connected to a laptop.

Figure 1. Capture-gated neutron spectrometer with laptop.

The gain and the signal processing filter values of the Osprey were set to minimal values. This ensured a maximum energy range of 0 – 5 MeV and a short dead time (ca 500 ns) after a detected pulse. This way, the neutron detection method studied in MAT 798 can be applied. Neutron sources emit and induce high-energy photons. For instance, beryllium based neutron sources, such as AmBe, emit 4.4 MeV photons. The energy range of 0 – 5 MeV is enough to identify these sources.

List mode data acquisition and analysis software, known as Liisteri, was created for the interactive coincidence analysis of the measurements. Liisteri reads measured pulse lists and generates triggered spectra. The spectra can be saved as lml-files compatible with the Linssi database.

Californium and AmBe sources were used in the measurements. Californium (^{252}Cf) decays by emitting alpha radiation (97 %) or by fission (3 %). The fission neutron yield is about 0.11 neutrons per decay with an energy spectrum very close to that of plutonium. An AmBe source is a neutron generator containing a mixture of americium (^{241}Am) and beryllium. The mixture produces about 70 neutrons per million americium decay. In addition, a characteristic 4.4 MeV photon is emitted. Neutron and gamma shields were used together with the sources.

Monte Carlo Simulations of the scintillator were performed using both MCNPX and Geant4. The neutron absorption efficiency and the time difference distribution of the scattering and capture pulse were simulated. The simulations were compared to measurement results.

4. Results and discussion

Source detection and identification

The capture-gated neutron spectrometer provides two signals for neutron detection:

1. Fast neutron signal
2. High-energy (>3.5 MeV) signal

The fast neutron signal is a direct method that measures only fast neutrons and has a very low background count rate. The high-energy signal is an indirect method measuring both thermal and fast neutrons as well as gamma radiation emitted by the source or source shield. The signals are complementary: the capture-gated signal has a lower and better defined background count rate, but the high-energy signal can detect neutron sources even if they are shielded with neutron shields. For optimal performance, the signals should be monitored separately and together as a sum.

With a source-detector distance of 2 m, the absolute efficiencies were $8 \cdot 10^{-7}$ – $7 \cdot 10^{-6}$ for bare sources (the efficiency depends on the source and signal type). This can be compared to the absolute efficiency of a 3″x2″ NaI gamma spectrometer using the high-energy signal (3.5 – 8 MeV): $5 \cdot 10^{-6}$ – $1 \cdot 10^{-5}$. The advantages of the capture-gated spectrometer are the lower background count rate and the neutron energy information.

The spectrometer provides four indicators for source identification:

1. High-energy spectrum
2. High-energy to fast neutron signal ratio $R_{high/fast}$

3. Capture peak to fast neutron signal ratio $R_{peak/fast}$
4. Capture-gated spectrum

As described above, the high-energy spectrum can be used to identify beryllium-based neutron sources. A very heavy gamma shield around the source is needed to make this impossible. The ratios $R_{high/fast}$ and $R_{peak/fast}$ indicate if the source surrounded by a neutron shield. A neutron shield lowers the fast neutron signal, while the other signals (high-energy and capture peak area) are less affected or even higher. The $R_{peak/fast}$ ratio can be seen as an indicator on how soft the neutron energy spectrum is.

No attempt on unfolding the capture-gated spectrum was made. Instead, the exponential slopes of the spectra were compared. It was found that the AmBe and californium sources produced differently sloped triggered spectra. The slope can be used for source discrimination both with bare sources and gamma-shielded sources.

Lead shield

The background count rate can be reduced significantly by surrounding the sensitive part of the detector with a lead shield. This is because the lead absorbs gamma radiation that would otherwise cause random coincidence pulses in the neutron signal. The lead shield also increases the efficiency (an increase of 30-40 % at source-detector distance 1 m was measured with a 2.5 cm lead on the side and 1 cm in front of the detector). This was attributed to the larger cross section of the shielded detector and neutron reflection properties of lead.

The cost of this modification is the larger weight and loss of the gamma spectrometry possibility. However, the detector is still portable and its gamma spectrometric performance is in any case bad (low energy resolution and peak efficiency). Because of the significantly smaller minimum detectable activity, the detector will be packed in a lead shield.

Spectra

Figure 2 shows the raw gamma spectra (background and sources). The spectra reveal two important features: 1. The 76 keV neutron capture peak (visible in the zoomed plot). 2. The high-energy (> 3.5 MeV) gamma signal with different shapes for californium and AmBe source.

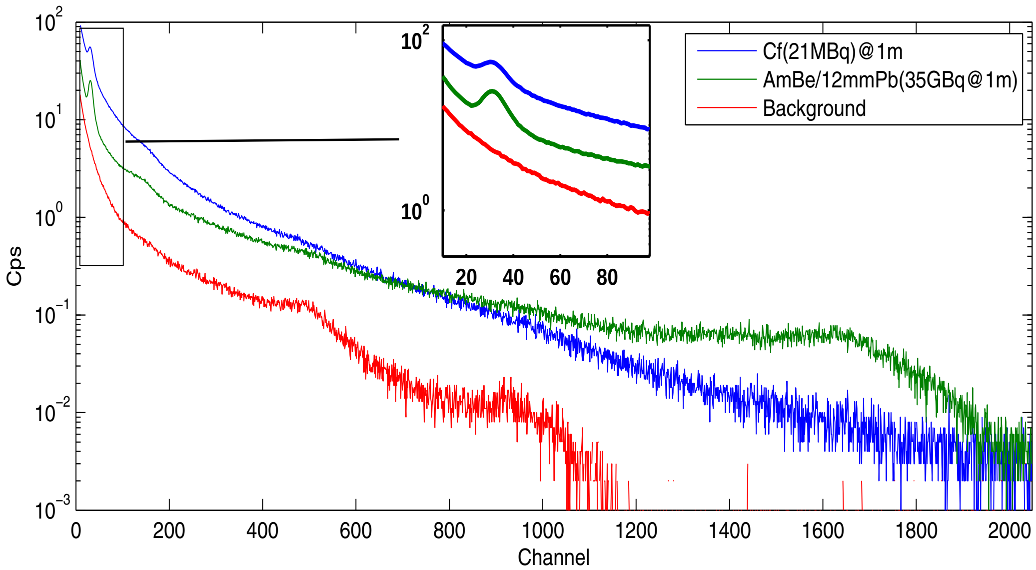

Figure 2. Raw gamma spectra measured with californium and AmBe sources at source-detector distance 1 m. The energy of the capture peak is 76 keV, while the high-energy Compton edge of the AmBe spectrum is 4.2 MeV.

Figure 3 presents the capture-gated spectra. The AmBe source produces a harder spectrum compared to the californium source. This is expected, since AmBe sources emit neutrons of higher energy compared to californium sources.

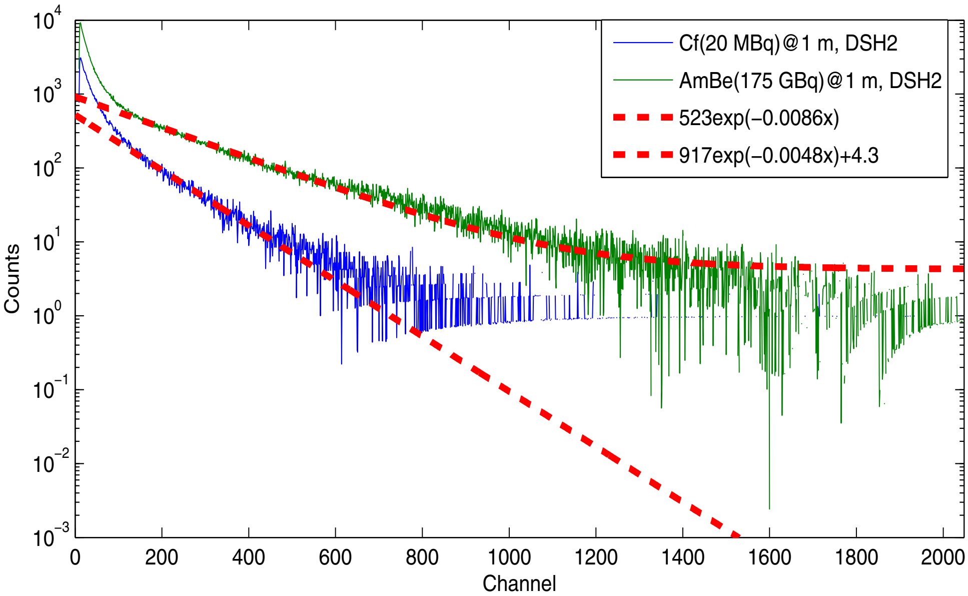

Figure 3. Capture-gated spectra measured with californium and AmBe sources at source-detector distance 1 m. The dashed red lines are fitted exponential functions.

Simulations

Simulations of the detector were performed with MCNPX and Geant4. Figure 4 shows both the simulated and measured distribution of the time difference between the capture and scattering pulse. The results are essentially the same, since the slope of the simulated and measured distributions are equal. The figure also demonstrates the limit of the Osprey Canberra: there is no measurement data for time differences smaller than 500 ns.

The neutron absorption efficiency in the scintillator was simulated for different neutron energies. The simulated geometry was a plane source at the front side of the scintillator. The results are presented in Figure 5. The absorption efficiency decreases with higher neutron energies. Above 8 MeV, neutron capture by carbon becomes a dominating process, producing ^{9}Be isotopes in the detector. The absolute detection efficiency for a californium source at source-detector distance 1 m was also simulated. The simulated efficiency was 15 % higher than the measured efficiency.

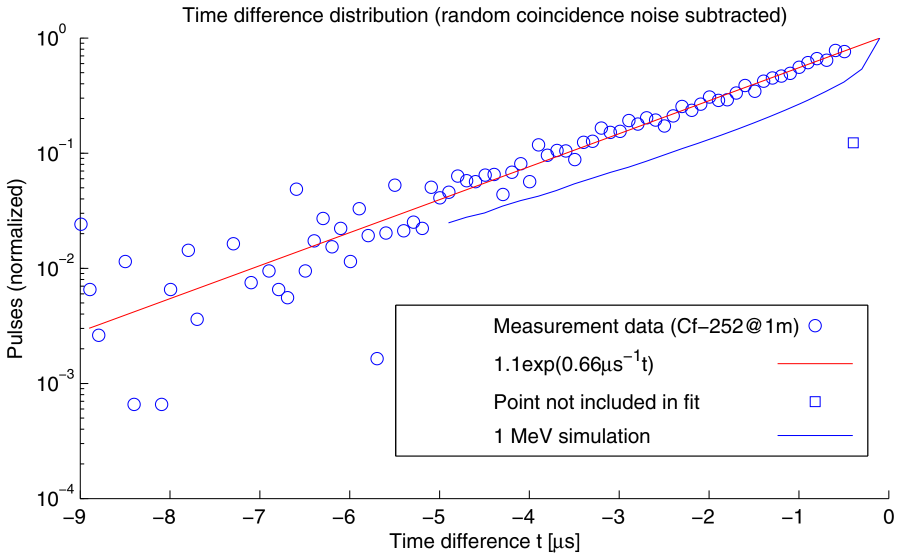

Figure 4. Time difference distribution of capture and scattering pulses. The simulations were performed with MCNPX. The simulation is normalized with the data at 0.1 µs.

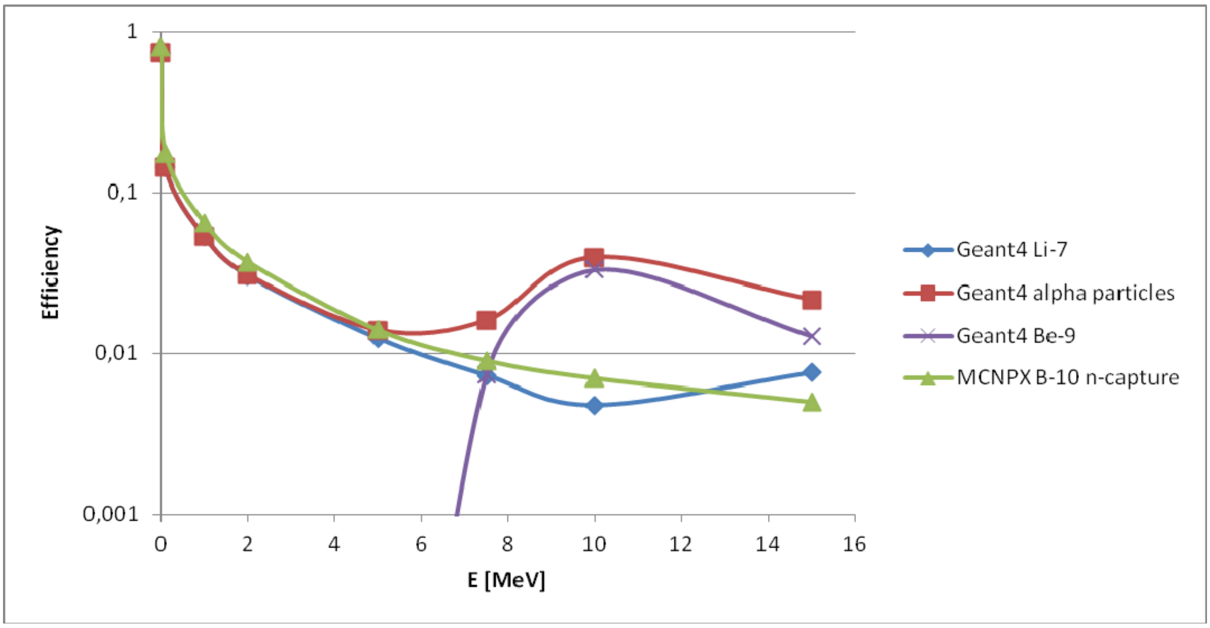

Figure 5. Simulated neutron absorption efficiency. In the Geant4 simulations, the Li-7, Be-9 and alpha particles were counted. Li-7 is produced in the boron neutron capture, while Be-9 is produced in neutron capture by carbon.

5. Conclusions

The developed neutron spectrometer is a versatile detector producing several useful signals for source detection and identification. One of the objectives was to identify sources using the capture-gated spectrum and the high-energy gamma spectrum. Two additional identification methods were invented. Together, these indicators make source and shield identification possible in many scenarios. Further measurements should be performed with different sources in different environments to improve the parameters of the source identification algorithm.

To our knowledge the field capability of our fast neutron detection system is unique. The expertise gained in the project opens up further possibilities for new type of applications using digital coincidence techniques.

5. Scientific publishing and other reports produced by the research project

Four technical reports (1-4) were written as part of the project. The principles of the spectrometer was planned already in 2011 as part of MATINE project 798 (5).

1. Holm P., Peräjärvi K., Siiskonen T., Toivonen H. Capture-gated neutron spectrometer: Assembly. TTL-TECDOC-2012-020, STUK 2012. (The spectrometer and signal processing is described).
2. Holm P., Peräjärvi K., Siiskonen T., Toivonen H. Capture-gated neutron spectrometer: Neutron and gamma shields. TTL-TECDOC-2012-022, STUK 2012. (Measurements were performed with neutron- and gamma-shielded sources as well as different detector shields).
3. Holm P., Peräjärvi K., Siiskonen T., Toivonen H. Capture-gated neutron spectrometer: Source identification flowchart. TTL-TECDOC-2012-023, STUK 2012. (Source identification was summarized in a flowchart).
4. Holm P., Peräjärvi K., Siiskonen T., Toivonen H. Capture-gated neutron spectrometer: Performance comparison with NaI detectors. TTL-TECDOC-2012-024, STUK 2012. (The detection efficiency and minimum detectable activity of the neutron spectrometer was compared with those of NaI detectors of different sizes. The NaI detectors utilize the indirect high-energy gamma radiation method studied in MAT 798).
5. Siiskonen T. Neutronispektrometrin vasteen simulointi. STUK 2012. (Monte Carlo simulations of a 3″x3″ and a 5″x4″ detector.).