Neutron and photon spectroscopy with diamond detectors

Pavel Kavrigin

The objective of this PhD project is the research of the neutral particle spectroscopy using diamond detectors. The project covers such topics as neutron spectroscopy and neutron cross-section measurements, photon counting and photon spectroscopy, research and development of the hardware and software for neutral-particle detection with diamond. This research project in the framework of oPAC is supported by CIVIDEC Instrumentation GmbH and supervised by Prof. Erich Griesmayer. The project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement №289485.

Diamond detectors

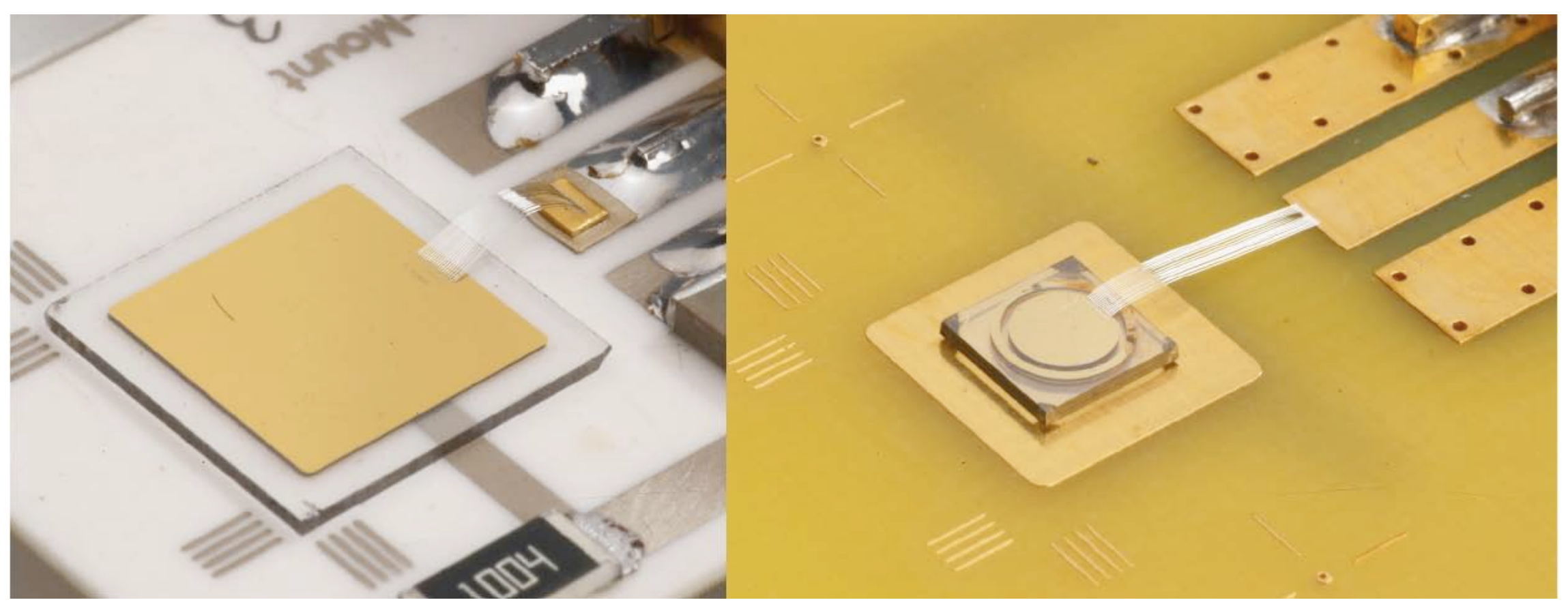

Figure 1. Diamond detectors designed by CIVIDEC Instrumentation: single crystal diamond detector (left) and polycrystalline diamond detector (right).

Diamond is highly versatile and efficient material for particle detectors due to its properties:

- Low leakage current;
- Low capacitance;
- High electron-hole mobility;
- High sensitivity;
- Excellent timing resolution;
- High radiation resistance;
- High thermal conductivity;
- Possibility of discrimination between different types of particles based on the shape of a pulse read out from diamond.

Charged particles are registered by a diamond detector directly due to the ionization charge created via electromagnetic interaction when they traverse through the diamond volume. Neutrons and photons do not ionize the diamond directly. They can undergo an absorption or scattering in diamond with a production of secondary charged particles (electrons, protons, alpha-particles, tritons). The charge created by these secondary particles can be read out in an electrical field and used for neutral-particle counting and spectroscopy.

Neutron spectroscopy

There are two ways of neutron detection and spectroscopy with a diamond detector. Neutrons can be detected via registration of the charged particles which are produced as a result of neutron interaction with diamond itself, or use a converter with a sufficiently high neutron absorption cross-section and detect the charged products of the neutron absorption in the converter.

Fast neutrons

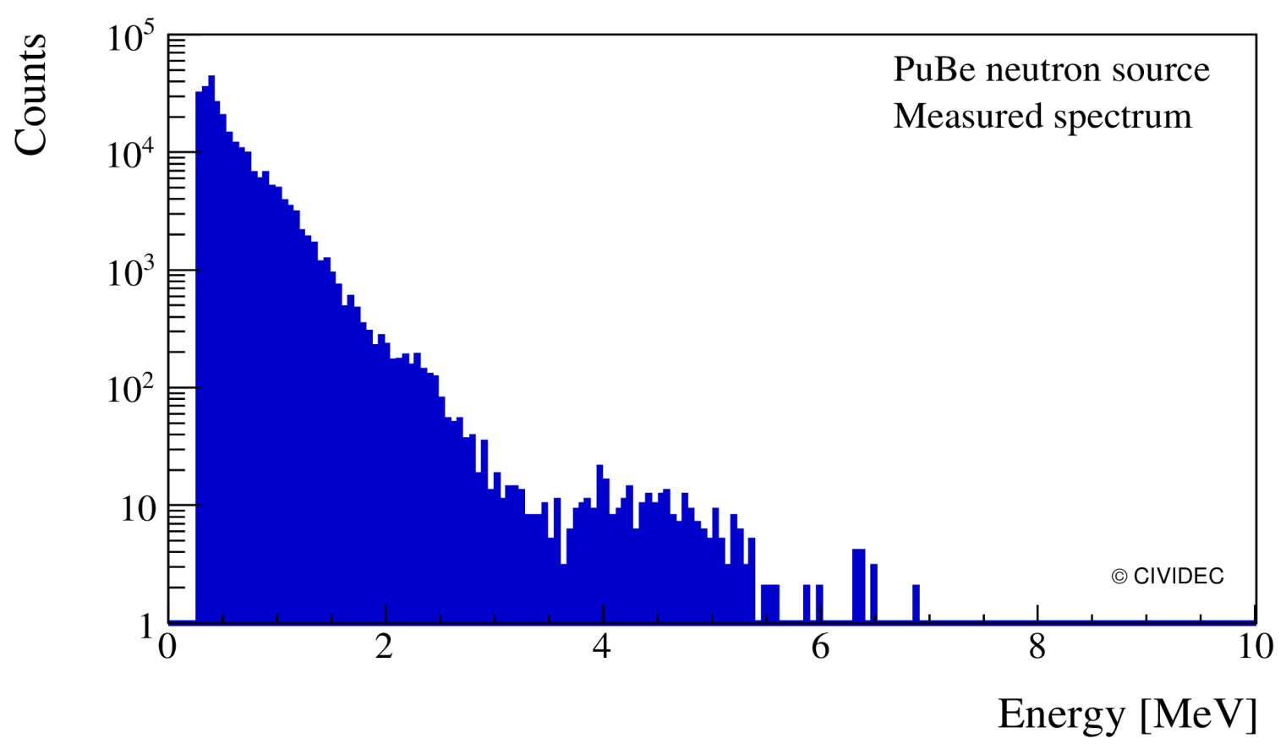

Figure 2. The spectrum of the PuBe neutron source as measured by a diamond detector with a Cx spectroscopic amplifier.

Fast neutrons undergo elastic and inelastic scattering in diamond. They can be detected through registration of the alpha-particles produced in the inelastic neutron reactions, such as ^{12}C(n, α)^{9}Be and ^{12}C(n, n + 3α). These reactions have energy thresholds for the incident neutrons of 6.2 and 7.9 MeV respectively.

A spectroscopic measurement with a NUMEC plutonium-beryllium neutron source was carried out at the Atominstitut (TU Wien). Maximum source neutron energy is 11 MeV. In Figure 2 the spectrum that was measured with a CIVIDEC B1 Diamond Detector and a Cx Spectroscopic Shaping Amplifier is shown.

In the measured spectrum we can see a peak (in the interval between 4 and 5 MeV) which corresponds to the energy deposition of the secondary alpha-particles of the neutron inelastic reactions.

Thermal neutrons

Thermal neutrons can be detected by using a neutron absorbing converter material. Neutrons undergo inelastic interactions in the converter and the secondary charged particles are created. ^{6}Li is one of the commonly used converters. ^{6}Li(n, α) reaction produces alpha-particles (2.05 MeV) and tritons (2.73 MeV) in the converter which can be registered by a diamond detector.

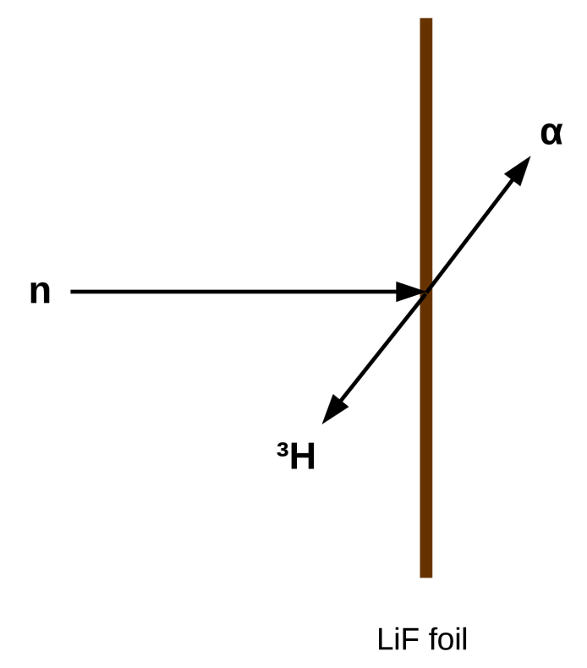

Figure 2. Thermal neutron inelastic scattering in a converter foil.

In Figure 2 the inelastic scattering of a thermal neutron in lithium converter foil is illustrated. The charged products of the reaction are created with the oppositely directed initial momenta.

In the experiment carried out at the Atominstitut (TU Wien) the converter foil was mounted on the top of a CIVIDEC B1 Diamond Detector. In this setup only a fraction of alpha-particles and tritons created in the converter foil were registered by the detector. Two types of amplifiers were used with the detector: a CIVIDEC Cx Spectroscopic Shaping Amplifier and a CIVIDEC C2 Broadband Amplifier.

CIVIDEC ROSY® readout system was used for data acquisition and analysis. The goal of the experiment was to measure the energy spectra of the alpha-particles and tritons of ^{6}Li(n, α) reaction.

The measurements were performed at the monochromatic thermal neutron beam line (wavelength 2.6 Å) of the TRIGA reactor at the Atominstitut. In Figures 4 and 5 the spectrum measured using a lithium foil converter is shown. In the measurement presented in Figure 4 a CIVIDEC Cx Spectroscopic Shaping Amplifier was used. The Cx amplifier produces Gaussian-shaped pulses with FWHM of 180 ns. The energy spectrum is derived from a measured pulse height distribution. In the measurement presented in Figure 5 a CIVIDEC C2 Broadband Amplifier was used, with the energy calculated from an area of the measured pulse. We can see a significant contribution from a background in the low energy part of the spectra due to the interaction of reactor beam line gamma-rays with the detector and the neutron absorption in the detector. A peak on the right side (2.6 MeV) corresponds to the energy deposition of the tritons of ^{6}Li(n, α) reaction in diamond.

In this measurement the triton peak can be separated from the background spectrum by introduction of a pulse height threshold in the signal readout electronics. However, the spectrum of the secondary alpha-particles cannot be distinguished from the background.

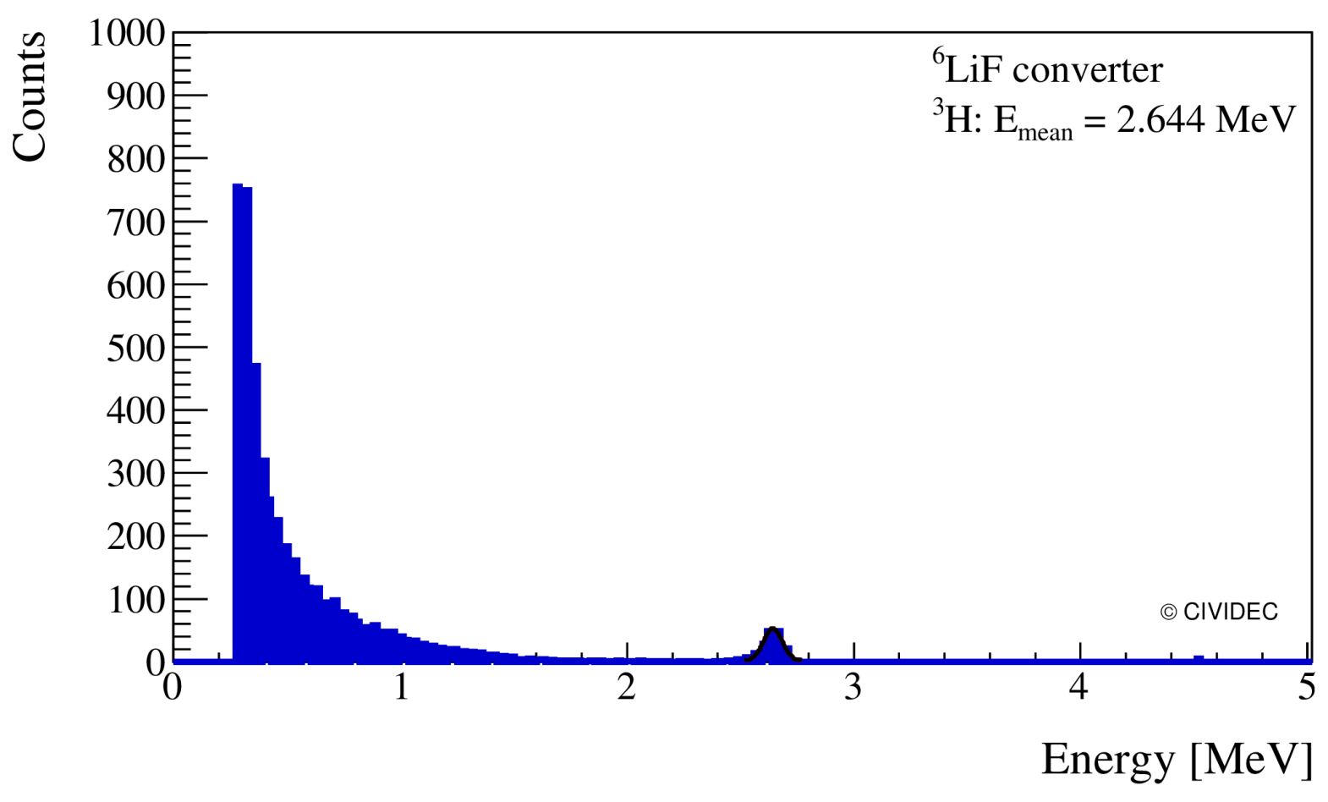

Figure 4. The spectrum measured with lithium converter using the Cx Spectroscopic Shaping Amplifier.

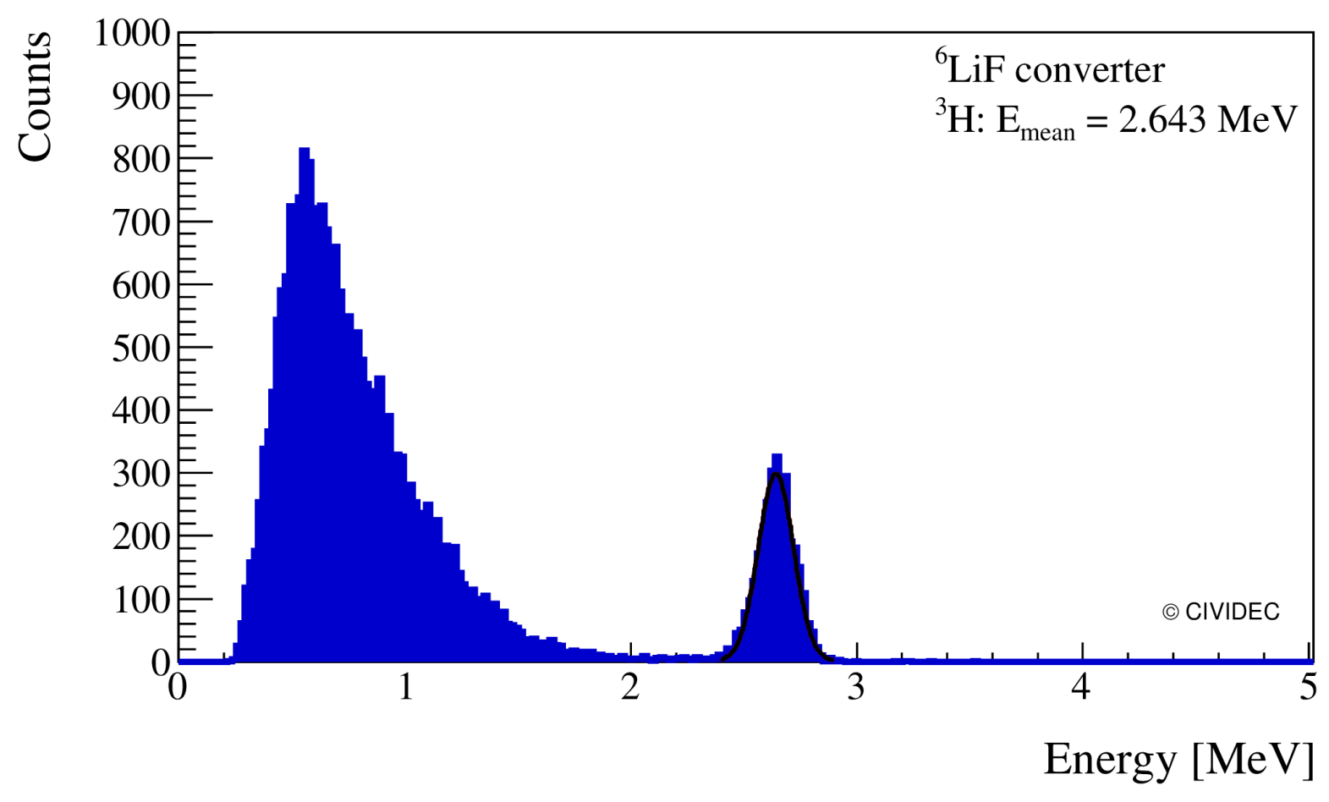

Figure 5. The spectrum measured with lithium converter using the C2 Broadband Amplifier.

Pulse shape analysis

In order to separate signals from the alpha-particles of ^{6}Li(n, α) reaction from the background, one of the crucial advantages of a diamond as a spectroscopic detector material can be employed. Two different types of pulses can be produced by a diamond when an incident particle interacts with the material. If a particle traverses the diamond, the pulse shape of a signal will be triangular. If a particle stops in the diamond, close to the electrode, the pulse shape will be rectangular. This property allows to perform a pulse shape analysis for the discrimination between different particles. In Figure 6 the triangular pulse shape produced by a Compton electron is shown. In Figure 7 the rectangular pulse shape produced by an alpha particle in diamond is shown. The theoretical pulse shapes are plotted in blue colour, the measured pulses are plotted in red colour.

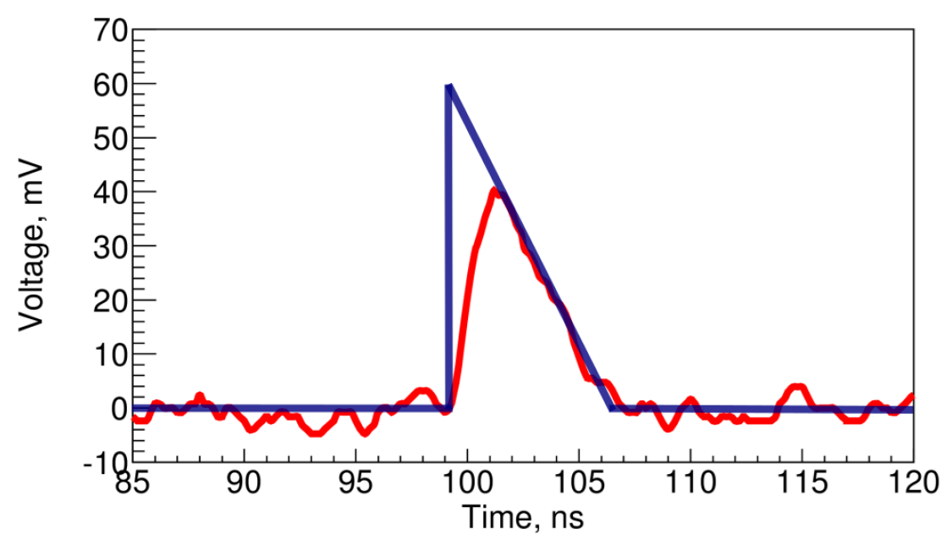

Figure 6. A pulse produced by a Compton electron in diamond.

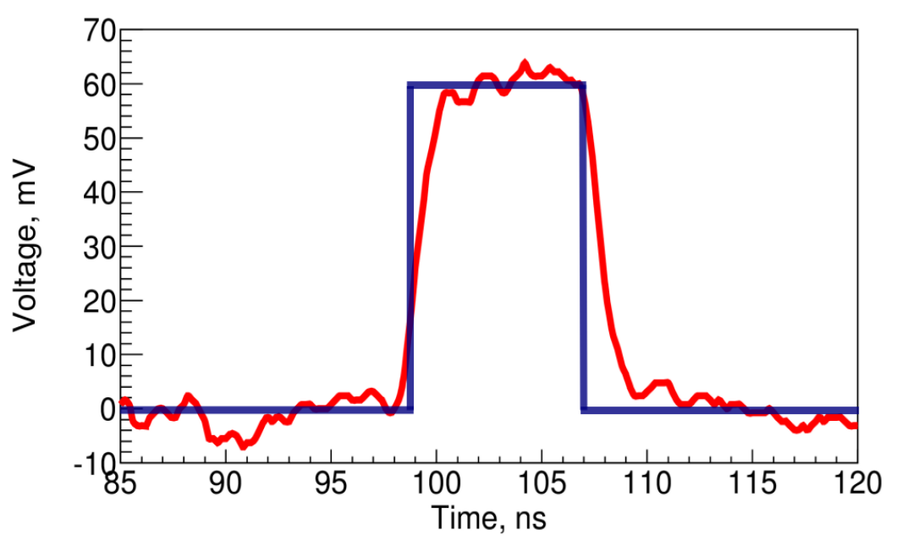

Figure 7. A pulse produced by an alpha-particle in diamond.

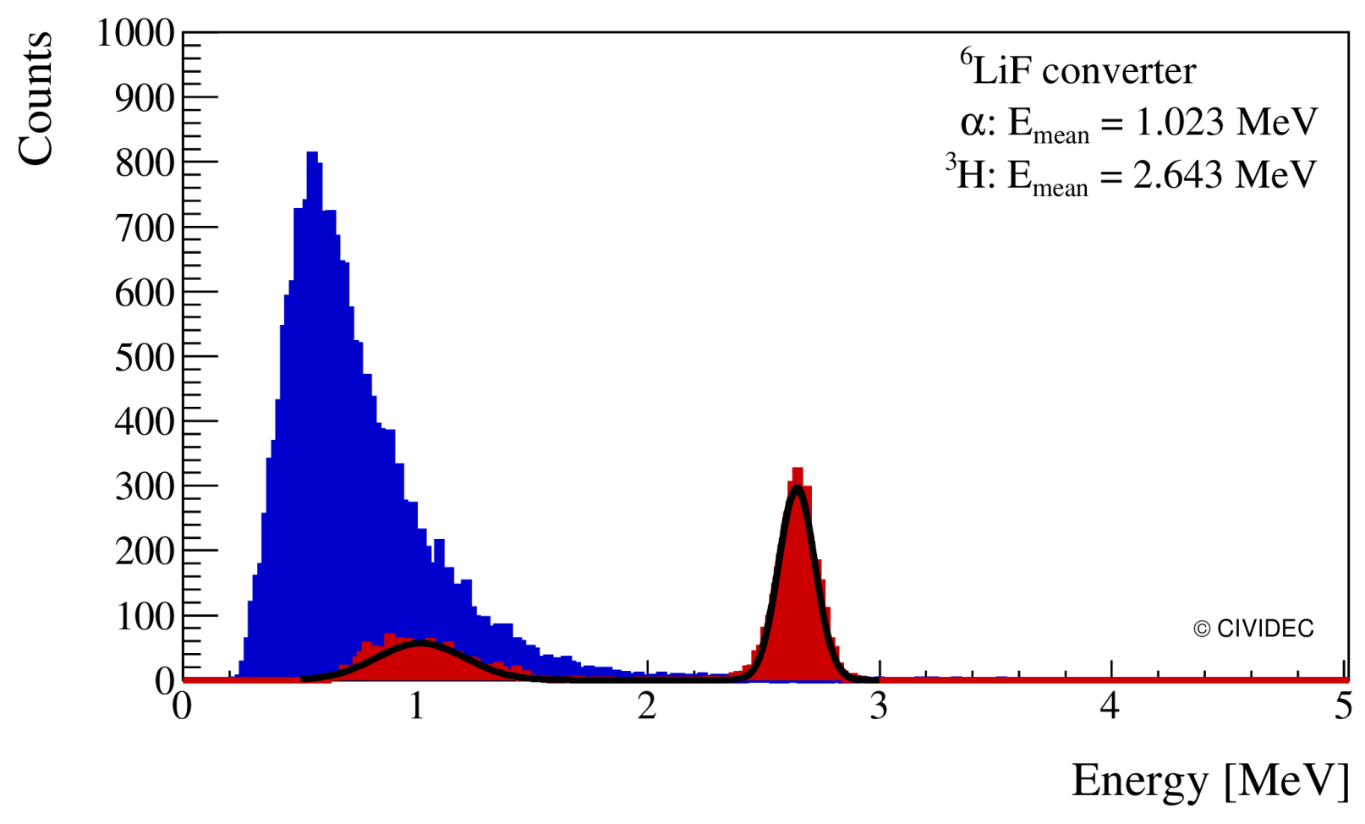

Figure 8. The spectrum measured with lithium converter using the C2 Broadband Amplifier, with the background (blue) and the alpha and triton peaks (red) separated.

The pulses that were recorded at the experiment at the monochromatic thermal neutron beam line using a CIVIDEC C2 Broadband Amplifier were analyzed. Rectangular pulses which corresponded to the alpha-particles and tritons of the ^{6}Li(n, α) reaction were separated from the triangular pulses that had been produced by gamma background. In Figure 8 the measured spectrum of the background is shown (blue) with the spectra of the alpha-particles and tritons (shown in red colour). The measurement was performed in air, so the products of the ^{6}Li(n, α) reaction underwent an energy loss in the air gap between the lithium converter foil and the detector. Another fraction of their initial energy was deposited in the detector electrode. Since the alpha-particles deposited larger fraction of their energy than tritons, and the energy straggling is stronger, the spectrum of the alpha-particles is wider that the triton peak.

Photon spectroscopy

X-rays and gamma rays can interact with diamond via three processes: photoelectric absorption, Compton scattering and e^-e^+ pair production. They can be detected by registering the secondary electrons which are produced during the photon interactions in diamond.

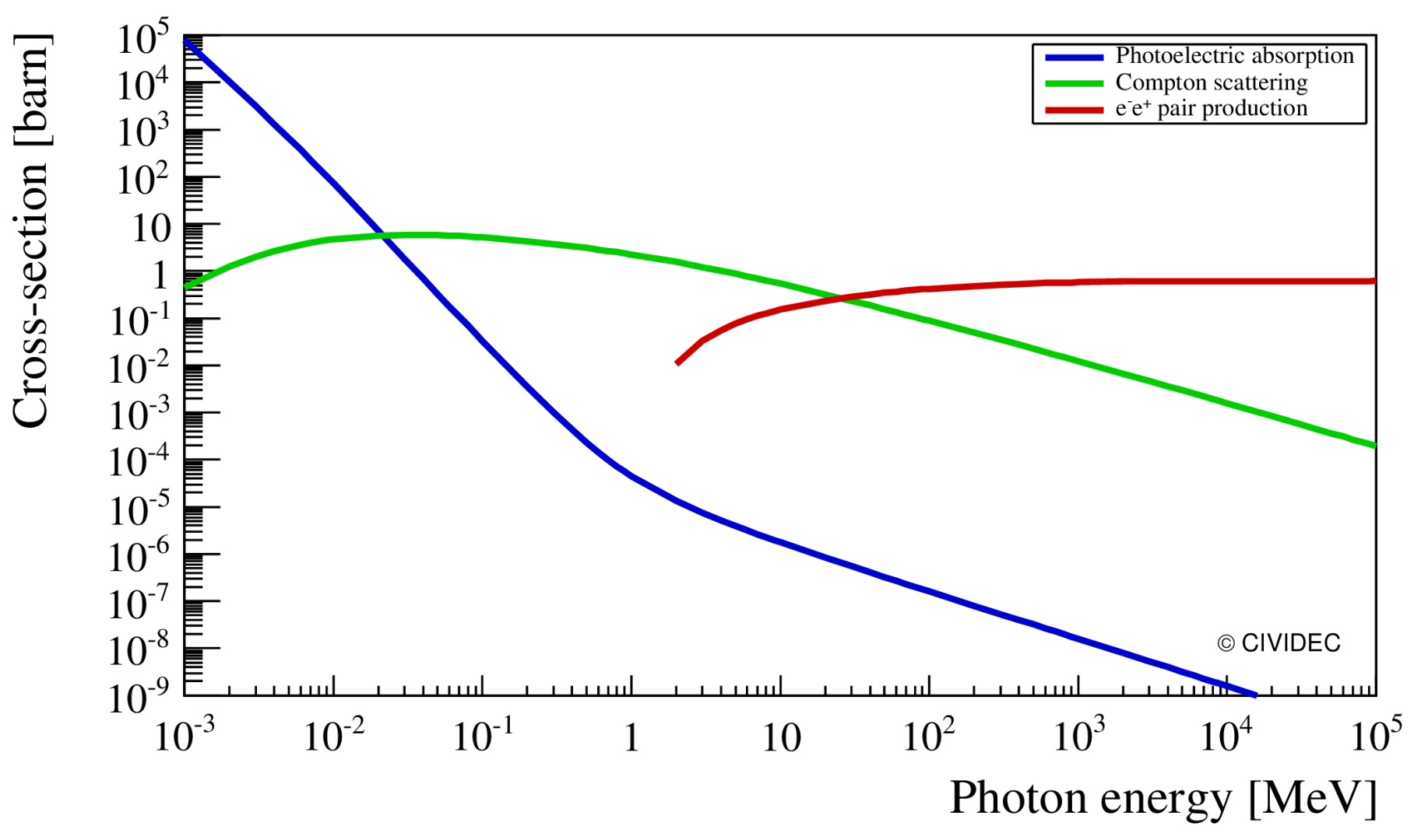

Figure 9. Cross-sections of photoelectric absorption, Compton scattering and e^-e^+ pair production in diamond.

In Figure 9 the cross-sections of the three photon interaction processes are shown.

Photoelectric absorption has the highest cross-section in the energy range up to 30 keV. Compton scattering is the dominating interaction in the interval from 30 keV to 30 MeV. Pair production becomes the most prominent process after 30 MeV.

In Compton interaction only a fraction of the incident photon energy is transferred to an electron which is ejected from a shell. In photoelectric effect and electron-positron pair production the photon is absorbed.

$$\boxed{E_{\mathrm{photo}} = \mathrm{h}\nu - W}$$

Energy of a photoelectron depends on the energy of an incident photon and the electron binding energy *W* of the material. If the incident photon beam interacting with diamond is monochromatic, the measured spectrum of the photoelectrons will have a narrow peak.

$$\boxed{E^{\max}_{\mathrm{compt}} = \mathrm{h}\nu \frac{2\varepsilon}{1+2\varepsilon}} \quad \boxed{\varepsilon = \frac{\mathrm{h}\nu}{m_e \mathrm{c}^2}}$$

Energy spectrum of Compton electrons is distributed from zero to a maximum electron energy $E^{\max}$. The corresponding spectrum measured by a diamond detector will have a smooth distribution up to a maximum electron energy deposition in diamond which depends on $E^{\max}$.

$$\boxed{E_{\mathrm{pair}} = \frac{1}{2}\mathrm{h}\nu - m_e \mathrm{c}^2}$$

A photon can undergo an electron-positron pair production process in diamond if its energy is greater than 1.022 MeV (sum of the rest masses of an electron and a positron). The energy of the electron depends on the incident photon energy.