Neutron detection with the MX-10

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Abstract

The MX-10 particle camera is already in use at a number of schools and institutions, including the Elixir for Schools. This version, as you know it, is used mainly to detect charged particles and photons. When used with a convertor, it is also able to detect neutrons. This article describes experiments with neutrons, which are connected, for example, to the control of nuclear reactors.

Detection of charged and uncharged particles

The MX-10 pixel detector is used in schools, Elixir for Schools centers and other institutions primarily to demonstrate the radioactivity of weak sources included in the MX-10 Edukit set – uranium glass, tungsten-thorium electrode and americium. Large round traces caused by the impact of alpha particles, curved traces of beta and gamma particle impact and small traces caused by photons (both gamma and X-ray) are usually shown. Direct traces of muons caused by cosmic rays can also be picked up. Alpha, beta and muon particles have a charge and directly ionize the silicon atoms contained in the 300 μm thick detector. Photons do not have a charge and after interacting with an electron (Compton effect and photoeffect) in the detector, energy is transmitted, and the electron ionizes the silicon. This is called indirect ionization. Let's ask ourselves whether it would also be possible to detect neutrons with the MX-10. Neutrons don't have any direct ionization effects and don't interact with electrons.

How neutrons interact

In 1931, it was known that there were positively charged protons in the nucleus, but neutrons were not yet discovered. The same year, Bothe and Becker bombarded beryllium with alpha particles and detected a radiation, which they thought were photons. They called it beryllium radiation. This radiation then began to be studied in several other laboratories. The essence of this radiation was explained in 1932 by Chadwick, who, in his experiment, put paraffin in the path of beryllium radiation and recorded charged protons in the detector placed behind the paraffin. He concluded that beryllium radiation is made up of neutral particles (neutrons) that have about the same mass as protons (hydrogen nuclei contained in paraffin). Fast neutrons were hitting protons, pushing them out of the paraffin. Chadwick was awarded the Nobel Prize in 1935 for his discovery of the neutron.

In schools, this process can be demonstrated as an elastic collision of spheres using Newton's cradle, see Fig. 1. With equally heavy spheres, the incoming one will stop, and the motionless sphere at the end will move at the same speed. The last sphere represents an accelerated proton capable of ionization. If a lighter sphere hits a much heavier sphere (a heavy atomic nucleus), it would gain little speed. Such a slow moving nucleus is not capable of ionization.

Fig. 1. A model of neutron-proton collision demonstrated on a Newton's cradle. The incoming ball stops and the other one flies away at almost the same speed.

How to get free neutrons

The most used neutron sources nowadays are nuclear reactors. However, we can also acquire neutrons by a less demanding way also used in the 30s. By interaction of alpha particles with beryllium. Next, I will be describing a source called AmBe. In a metal cylinder several centimeters long, americium oxide $^{241}_{95}\mathrm{Am}$ is compressed with metal beryllium. Americium decays by alpha decay

$$^{241}_{95}\mathrm{Am} \to {}^{237}_{93}\mathrm{Np} + {}^{4}_{2}\alpha.$$

The emitted alpha particles have an energy of 5.5 MeV and are accompanied by photons of 60 keV (from the nucleus) and photons of the characteristic X-ray radiation with an energy of about 15 keV (from the electron shell) [1]. If an alpha particle enters the beryllium nucleus, nuclear reactions can occur in which a fast neutron is released

$$^{4}_{2}\alpha + {}^{9}_{4}\mathrm{Be} \to {}^{12}_{6}\mathrm{C} + {}^{1}_{0}\mathrm{n} \quad (1) \qquad \text{or} \qquad ^{4}_{2}\alpha + {}^{9}_{4}\mathrm{Be} \to {}^{12}_{6}\mathrm{C} + {}^{1}_{0}\mathrm{n} + \gamma \quad (2)$$

According to equation (1), a ground state carbon nucleus is formed, and the released neutron can have an energy of up to 11.1 MeV. According to equation (2), an excited state carbon nucleus is formed and after emitting a photon with an energy of 4.4 MeV it transitions back to the ground state. The emitted neutron can have a maximum energy of 6.4 MeV. In both cases, neutrons, which can be categorized as fast, are produced.

Since the nuclei of atoms are very small relative to their distances from each other, the nuclei interacting with an alpha particle is a rare occurrence. It takes about 10,000 alpha decays to hit a nucleus in the AmBe source and generate one neutron. To obtain an activity of 10^6 neutrons per second, the american source must have an activity of 10^{10} Bq. In addition to strong neutron radiation, such a source also emits strong gamma radiation, which is dangerous.

The measurements described in this article were made using an AmBe source with an activity of 1 Ci (curie), which is $3.7 \cdot 10^{10}\ \mathrm{Bq}$. We can see the energy spectrum of emitted neutrons in Fig. 2.

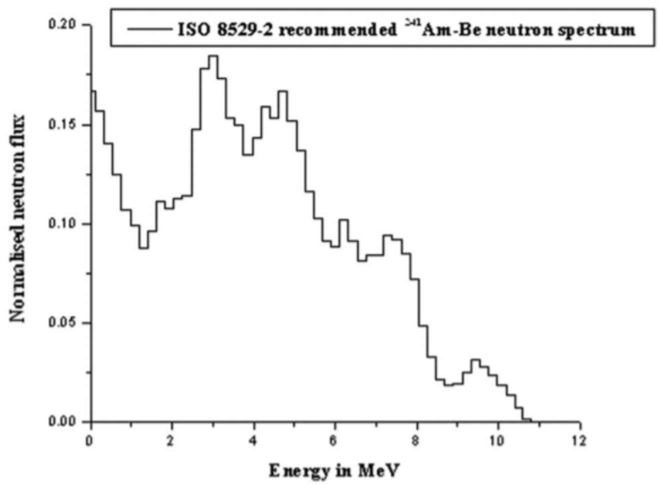

Fig. 2. Energy spectrum of neutrons generated in the AmBe source [2].

Experiment 1: Detection of fast neutrons by the MX-10 silicon detector

The neutrons generated by the AmBe source fall on the MX-10 silicon window. Can we detect them? As mentioned above, neutrons alone cannot be detected. But when they enter the silicon nucleus, they can trigger nuclear reactions that produce charged, that is, directly ionizing particles. There are two possible reactions:

$${}^{1}_{0}\mathrm{n} + {}^{28}_{14}\mathrm{Si} \rightarrow {}^{25}_{12}\mathrm{Mg} + {}^{4}_{2}\alpha \quad (3) \qquad \text{and} \qquad {}^{1}_{0}\mathrm{n} + {}^{28}_{14}\mathrm{Si} \rightarrow {}^{28}_{13}\mathrm{Al} + {}^{1}_{1}\mathrm{p} \quad (4)$$

Mg and Al nuclei, alpha particles and protons can all have ionizing effects. The kinetic energy of the products is indicated by the physical quantity Q – the energy of the reaction. This is defined as the sum of the resting energies (E_{0i}) of colliding particles (nuclei) before the reaction minus the sum of the resting energies (E_{0f}) of the particles (nuclei) after the reaction. Since the total energy is preserved in each reaction, i.e. the sum of the kinetic E_k and the resting energy E_0, therefore

$$E_{\mathrm{ki}} + E_{0\mathrm{i}} = E_{\mathrm{kf}} + E_{0\mathrm{f}}$$

and we can express the energy of the reaction as

$$Q = E_{0\mathrm{i}} - E_{0\mathrm{f}} = E_{\mathrm{kf}} - E_{\mathrm{ki}}.$$

We see that Q also expresses a change in kinetic energy. For reaction (3), $Q = -2.65$ MeV, and for reaction (4), $Q = -3.86$ MeV. Both values are negative, which means that reactions can only occur when the particles (nuclei) entering the reaction have more energy than the so-called threshold energy. Silicon nuclei can be considered stationary, so neutrons must have at least the threshold energy. For reaction (3) the threshold energy is $E_{thr} = 2.75$ MeV and for reaction (4) $E_{thr} = 4.00$ MeV. Therefore, fast neutrons are needed, which AmBe provides, since the maximum neutron energy is 11.1 MeV (Fig. 2). At such neutron energies, alpha particles with an energy of up to 8.21 MeV and protons with a maximum energy of 7.22 MeV should be formed. These energies and lower should be recorded by our detector.

We've conducted an experiment in which the AmBe source was at a distance of 12 cm from the MX-10 detector and 2400 images with an exposure time of 0.1 s were taken. A total of 191,836 particle traces were recorded within 4 minutes, but most of them correspond to the impacts of photons emitted from the americium and beryllium. The alpha particles from the americium could not pass through the AmBe metal shell and reach the detector, so the 70 traces that the pixelman software evaluated as "heavy blobs" came from nuclear reactions (3) and (4) taking place directly in the silicon detector.

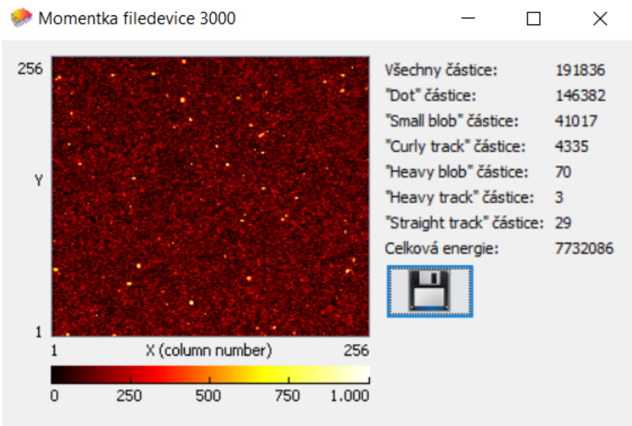

Fig. 3. Visualization of traces caused by the nuclear reaction of fast neutrons with silicon. Within 4 minutes, 70 "heavy blob" traces were detected.

So, the MX-10 can detect fast neutrons, but with very little efficiency. In 4 minutes of measurement AmBe generated approximately $5.38 \cdot 10^8$ neutrons of which about 600,000 passed through the MX-10 detector and of these only 70 produced nuclear reactions (3) and (4). The detector registered approximately only one of every 8500 passings of fast neutrons. The statistics are reminiscent of Rutherford's experiment, in which he discovered the atomic nucleus and found out that its size was very small relative to the distances between the nuclei.

The probability of a nuclear reaction between a neutron and silicon is described by a physical quantity called microscopic effective cross-section σ, which is measured in barny – b units (1 b = 10^{-28} m^2). The value of the effective cross-section depends on the target nucleus and the energy of the neutron. For the target nucleus ^{28}Si and neutron energy 11 MeV it's $\sigma \approx 0{,}02$ b for reaction (3) and $\sigma \approx 0{,}06$ b for reaction (4), as shown in Fig. 4. For energies less than 11 MeV the effective cross-section reaches a maximum value of 0.3 b.

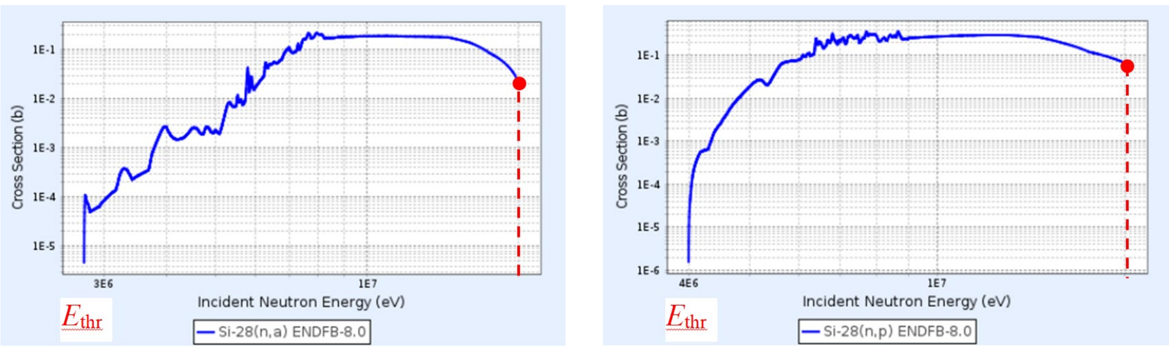

Fig. 4. Microscopic effective cross-section of the neutron reaction with ^{28}Si . On the left, according to equation (3), an alpha particle is emitted from the nucleus, and on the right, according to equation (4), a proton is emitted. The graphs show that the neutrons must have a minimal threshold energy of E_{thr}. Note: The graphs use a logarithmic scale for their axes. Source [3].

Experiment 2: Paraffin as a convertor of fast neutrons

In experiment 1, we demonstrated that the silicon detector itself has low efficiency in detecting fast neutrons. Let us now try to imitate Chadwick's experiment based on the ejection of hydrogen nuclei (protons) by fast neutrons from paraffin. Paraffin is a mixture of solid hydrocarbons of the C_nH_{2n+2} series. In our experiment, we used a regular candle. The hot wax was first poured into a square form the size of the silicon sensor (14 mm × 14 mm) and then placed on the sensor and secured using tape. The thickness of the paraffin was approximately 1 mm – Fig. 5.

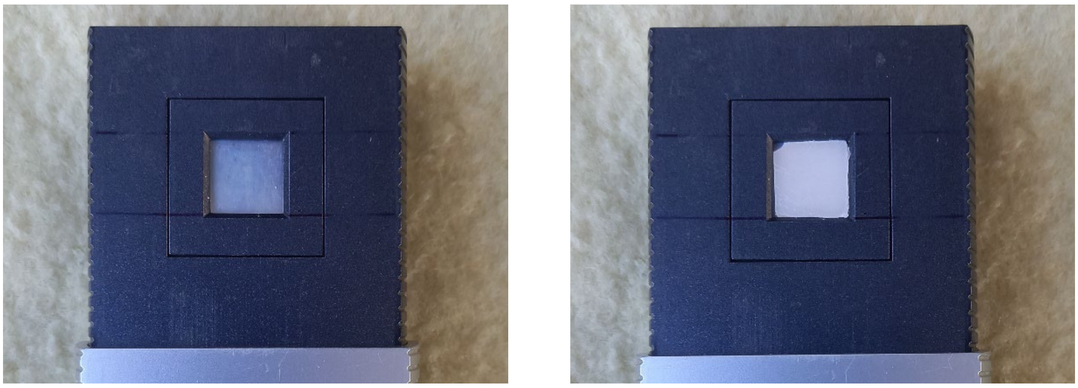

Fig. 5. On the left, the MX-10 silicon sensor without the convertor, on the right a paraffin convertor placed on the sensor.

We placed the MX-10 at the same distance from the AmBe source as in experiment 1 and left all the measurement parameters the same (2400 shots per 0.1 s). We can see the visualization in Fig. 6.

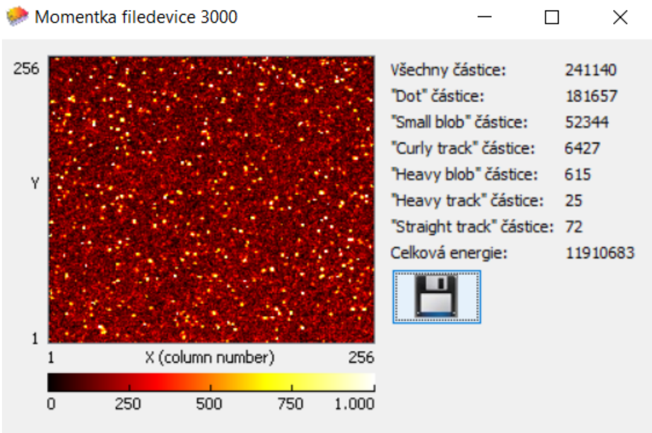

Fig. 6. Visualization of traces recorded by the detector with a paraffin convertor. Compared to Fig. 3, the number of "heavy blob" and curly tracks has increased. The increase of the "heavy blob" traces is due to the impact of protons ejected from paraffin by fast neutrons.

The number of heavy blob tracks increased from 70 to 615 compared to attempt 1. Paraffin thus proved to be a material suitable for converting hard-to-capture neutrons into more detectable protons. The reason for the increase is that the elastic scattering of neutrons (in which protons are ejected) generated by the AmBe source in hydrogen ^{1}H has an effective cross-section (for some of the represented energies) of up to $\sigma \approx 20$ b. This is two orders of magnitude greater than the effective cross-section of the nuclear reactions of these neutrons in silicon.

Similar results as with paraffin are achieved with a layer of polyethylene (PET), which is also rich in hydrogen and is therefore a suitable convertor.

It is also worth noting the increase in the number of curly tracks from 4335 without a paraffin convertor to 6427 with a paraffin convertor. These curly track are caused by high-energy gamma photons, the number of which has increased with the presence of paraffin. In addition to photons with an energy of 4.4 MeV produced in AmBe during the reaction (2), photons in paraffin began to be formed by radiation capture

$$^{1}_{0}\mathrm{n} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{2}_{1}\mathrm{H} + \gamma.$$

The energy of these photons is 2.22 MeV.

Nuclear reaction of neutrons with lithium

In experiment 2, we’ve shown that neutrons knock protons out of paraffin, and according to the Newton’s cradle model we know that the neutron can almost come to a stop (central collision). Paraffin and polyethylene are examples of materials that slow down fast neutrons, i.e. perform the function of a moderator. After a series of collisions, the neutrons in the moderator get to a state of thermal equilibrium with the moderator and have a Maxwell-Boltzmann energy distribution. For example, at a temperature of 20 °C, neutrons with an energy of only 0.025 eV are the most represented in the spectrum. These thermal neutrons can be detected using some light chemical elements with a high effective cross-section for these reactions (Table 1).

Table 1. Effective cross-sections for the nuclear reaction of neutrons with lithium and boron for thermal neutrons (middle column) and fast neutrons (right column) [4].

	0.025 eV	1 MeV
Target nucleus	σ [b]	σ [b]
$^{6}\mathrm{Li}$	938	1.28
$^{10}\mathrm{B}$	3845	2.68

^{6}Li is suitable for neutron detection due to its effective cross-section. The neutron reacts with lithium according to equation (5).

$$^{6}_{3}\mathrm{Li} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{4}_{2}\alpha + {}^{3}_{1}\mathrm{H} \qquad (5)$$

Graphically, we illustrate this nuclear reaction in Figure 7.

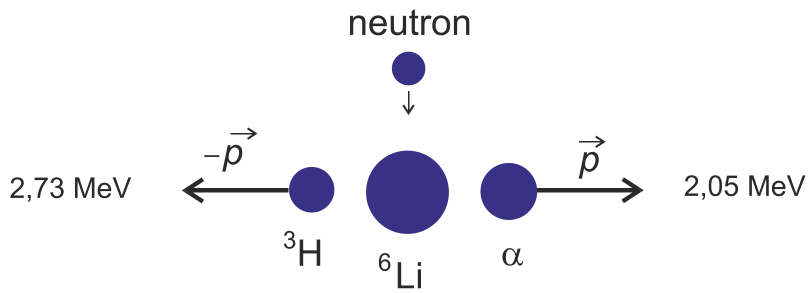

Fig. 7. Nuclear reaction between a neutron and a lithium nucleus and the formation of charged particles – triton and alpha particle. Triton and the alpha particle have the same momentum of opposite directions.

The energy of the reaction is positive Q = 4.78 MeV, so the reaction does not require the neutron to be of any threshold energy. The resulting tritons have an energy of 2.73 MeV and alpha particles 2.05 MeV. Since both the low-energy (thermal) neutron and the lithium nucleus are practically at rest, according to the law of conservation of momentum, both resulting particles have the same momentum and fly out practically in opposite directions. The MX-10 detector can register the one that flies into its sensor.

LiF convertor

A suitable material for thermal neutron to charged particle convertor is lithium fluoride LiF enriched with an isotope ^{6}Li. LiF is mixed with a liquid binder and applied to a thin film, in our case aluminum foil, where it solidifies and forms a thin layer. The LiF layer must not be too thick, because the tritons and alpha particles quickly lose energy in the LiF layer and may not reach the sensor. The mean linear range for an alpha particle with an energy of 2.05 MeV in LiF is R = 5.3 μm and for a triton with an energy of 2.73 MeV it's R = 30.7 μm [5]. If we wanted all the reaction products that fly perpendicular to the MX-10 silicon sensor to actually reach it, the LiF layer would have to be thinner than 5.3 μm. The silicon sensor has a thickness of 300 μm, which is significantly more than the mean linear range of tritons and alpha particles in silicon. So, if these charged particles reach the silicon, they will definitely stop in it and the detector will probably display them as a heavy blob and measure their energy.

In our measurement, a LiF with an areal density of 3.6 mg/cm^2 was used, which corresponds to a thickness of 18 μm. LiF was applied to the foil as a strip big enough to cover approximately the top third of the MX-10 sensor. As a second strip, PET with a thickness of approximately 1 mm was glued to the foil (middle third of the sensor) and the lower third of the sensor was covered with only the aluminum foil (fig. 8). The foil with convertors was then glued over the MX-10 window so that the convertors were as close as possible to the sensor surface (less than 1 mm).

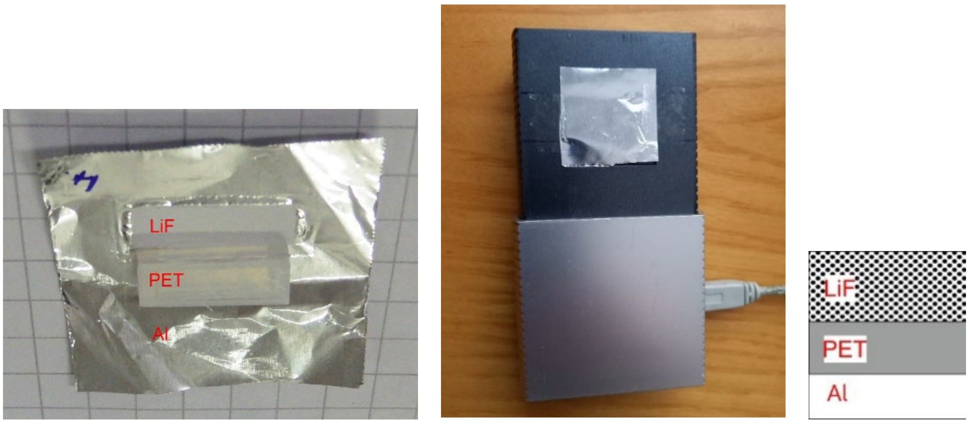

Fig. 8. LiF and PET convertors on aluminum foil and the location of the convertors on the MX-10 sensor.

Experiment 3: Detection of thermal neutrons using the LiF convertor

In order to obtain enough thermal neutrons, we created a moderator block measuring 12 cm × 12 cm × 24 cm from several polyethylene fittings with a cavity inside for the AmBe emitter – Fig. 9. Fast neutrons slow down in such a block and, like the thermal ones, exit its surface in all directions. We also attached an 8 cm thick PET cube to one of the walls and an MX-10 sensor to it, as shown in Fig. 9.

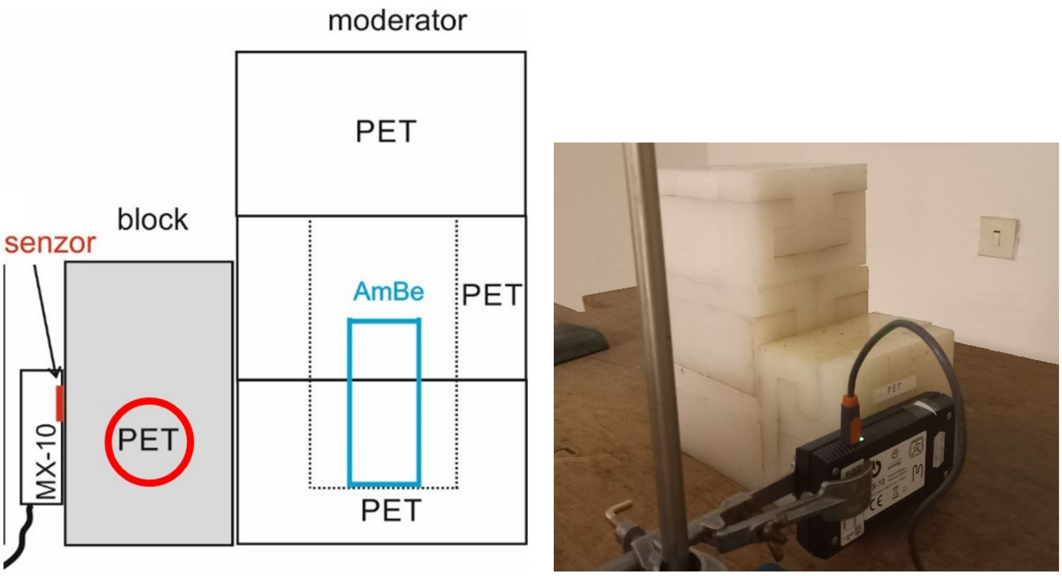

Fig. 9. Polyethylene moderator with the AmBe neutron source, PET shielding cube and the MX-10 detector.

We've captured 2400 images with an exposure of 0.1 s. Visualization of the measurement can be seen in Fig. 10.

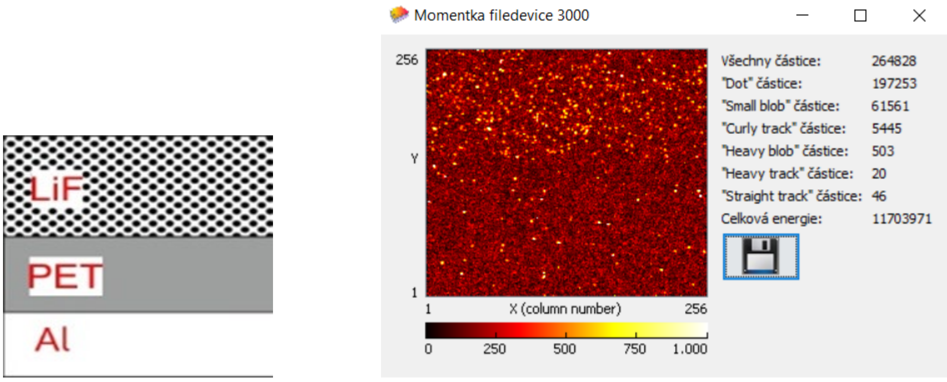

Fig. 10. Visualization of the measurements using the LiF and PET convertors via a PET cube. The LiF was located in the upper third of the sensor, where we see a high concentration of heavy blobs.

The detector recorded 503 traces of heavy blobs, the vast majority of which (416) were in the upper third of the detector where the LiF convertor was located. These traces can be explained by the impact of alpha and triton particles ejected from LiF according to equation (5) by thermal neutrons. In the middle third, where the PET convertor was, and in the lower third, covered only with aluminum, there are traces caused by the formation of fast neutrons. A similar thing can be seen in Fig. 3 and Fig. 6. We have proven that both thermal and fast neutrons can be detected using the PET cube.

The pixelman program which controls the pixel detector allows you to visualize a histogram of energy for traces in a selected area, in our case the upper third of the detector under the LiF layer. We can see the histogram in Fig. 11.

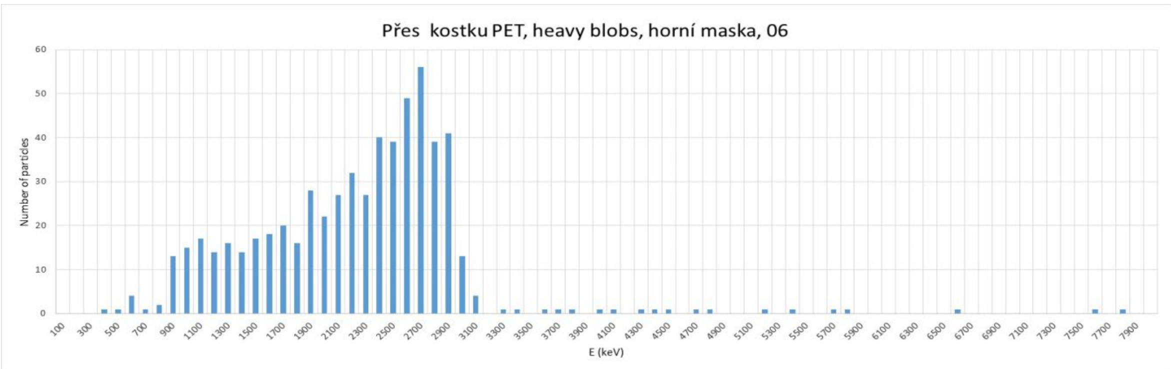

Fig. 11. Stop heavy blob energy histogram of the upper third of the sensor.

Most represented energy values are under 3000 keV, there's also a small number of energy signatures under 7900 keV. The lower energies correspond to the impacts of tritons, which at the time of formation had an energy of 2.73 MeV and alpha particles, which at the time of formation had an energy of 2.05 MeV. Why do we see a peak corresponding to an energy of 2.7 MeV and why is it "blurred"? It is because the flying tritons and alpha particles lose some energy by causing ionization in the material. The linear slowing capability of the LiF for the tritons is 26 keV/μm and for the alpha particles 320 keV/μm. The loss of energy for alpha particles is so great that most of them stop in LiF and do not reach the sensor at all. Only those that originate no further than 5.3 μm from the LiF surface closer to the sensor and fly to the sensor by the shortest trajectory are able to reach the sensor.

Traces with an energy of over 3,000 keV are certainly caused by fast neutrons that triggered nuclear reactions (3) and (4) in the silicon. However, these traces are few as we expected.

With Experiment 3, we have verified the ability of the MX-10 detector equipped with a LiF convertor to detect thermal neutrons.

Experiment 4: Shielding Thermal Neutrons using Lithium

The nuclear reaction (5), i.e. ^{6}Li(n, α)^{3}H, in combination with the moderation ability of PET, is used to shield neutrons. Polyethylene fittings with an addition of 10% ^{6}Li, whose function is to convert fast neutrons to thermal and then absorb them (in ^{6}Li) are usually used.

In this experiment, we've created a cube of LiPET fittings of the same dimensions as the pure PET cube in Fig. 9 (thickness 8 cm) and captured 2400 images with an exposure of 0.1 s with the same geometry as in Fig. 9.

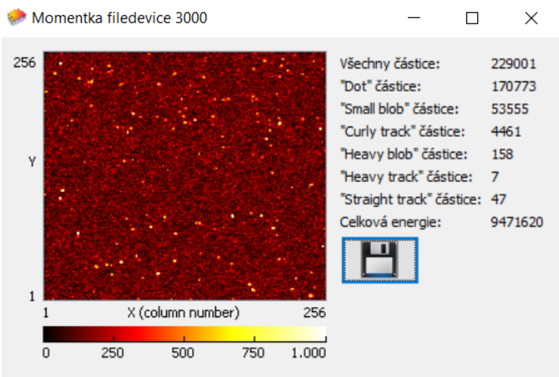

Fig. 12. Visualization of measurements made with LiF and PET convertors using the LiPET cube. In the upper third, we no longer observe a high concentration of stop heavy blobs.

Fig. 12 shows that there is no longer a high concentration of traces in the upper third of the sensor. Using the cube of pure PET in Experiment 3, we've recorded 416 traces out of a total of 503 traces in the top third and now in Experiment 4, using the LiPET Cube, we only see 89 traces out of a total of 158 traces in the top third. From this, we can assume that the ^{6}Li effectively absorbs thermal neutrons. Fast neutrons are still penetrating the sensor. They could be slowed down by a thicker PET wall and then let to be captured by lithium.

Nuclear reaction of neutrons with boron

Other nuclear reactions that can be used to detect and shield thermal neutrons are those with boron. This material has an even greater effective cross-section for the thermal neutron reaction than lithium (see Table 1).

$$^{10}_{5}\mathrm{B} + ^{1}_{0}\mathrm{n} \rightarrow ^{7}_{3}\mathrm{Li} + ^{4}_{2}\alpha \qquad (6)$$

$$^{10}_{5}\mathrm{B} + ^{1}_{0}\mathrm{n} \rightarrow ^{7}_{3}\mathrm{Li} + ^{4}_{2}\alpha + \gamma \qquad (7)$$

The detector is able to record alpha particles and lithium nuclei (our pixel detector is suitable for this) or the resulting gamma photons with an energy of 480 keV (our pixel detector is not very sensitive to them and therefore not suitable). Reaction (6) occurs in 6% of all cases and reaction (7) occurs in 94% of all cases.

Experiment 5: Shielding thermal neutrons using boron

For shielding thermal neutrons, fittings are made of polyethylene with an addition of 3.5% and 5% of ^{10}B, whose function is to moderate fast neutrons (in PET) and absorb the resulting thermal neutrons (in ^{10}B). We will refer to these fittings as BPET.

In our experiment, we've created a BPET (with 5% boron) cube with the same dimensions as in experiment 3, see Fig. 9 (thickness 8 cm) and captured 2400 images with an exposure of 0.1 s with the same geometry as in Fig. 9. Visualization of the measurement can be seen in Fig. 12. The number of heavy blobs detected is 117, which is lower than in the experiment using the LiPET cube (158), even though the concentration of boron in polyethylene was half that of lithium in the previous experiment. So, it seems that boron is more efficient in shielding, but there is a problem with 480 keV energy gamma photons. The thin pixel detector detects them with little probability, so we don't see them so often. But they exist, and to effectively shield from them a thick layer of lead must be used. In this respect, boron is disadvantageous compared to lithium, which does not emit any photons when absorbing a neutron.

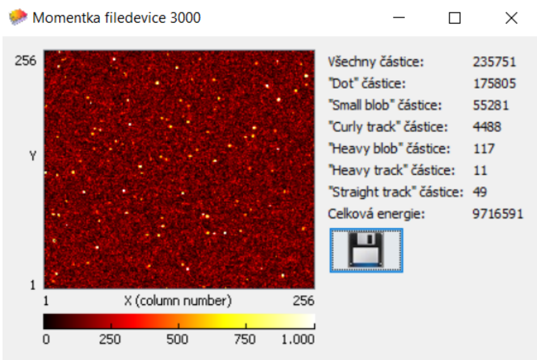

Fig. 13. Visualization of measurements using the LiF and PET convertors and the BPET cube. In the upper third, we do not observe a high concentration of stop heavy blobs.

Fig. 13 shows that there is no longer a high concentration of traces in the upper third of the sensor. Using the cube of pure PET, we've recorded 416 traces out of a total of 503 traces in in the top third and now in Experiment 5, using the BPET Cube, we see only 50 traces out of a total of 117 traces in the top third.

Experiment 6: Lead and cadmium shielding

Students know that lead is best for shielding radioactivity, because it has a large proton number of 82. Let's use a lead sheet with a thickness of 1 mm to try to shield neutrons passing through the PET cube according to Fig. 9. The lead sheet was glued as an additional layer over the Lif and PET convertors (this is the same convertor geometry as in experiment 3). Thus, the radiation first falls on the lead sheet, under which are the convertors, and under which is the silicon sensor. The exposition remained the same.

We then replaced the lead sheet with a 0.7 mm thick cadmium sheet and repeated the experiment with the same exposure.

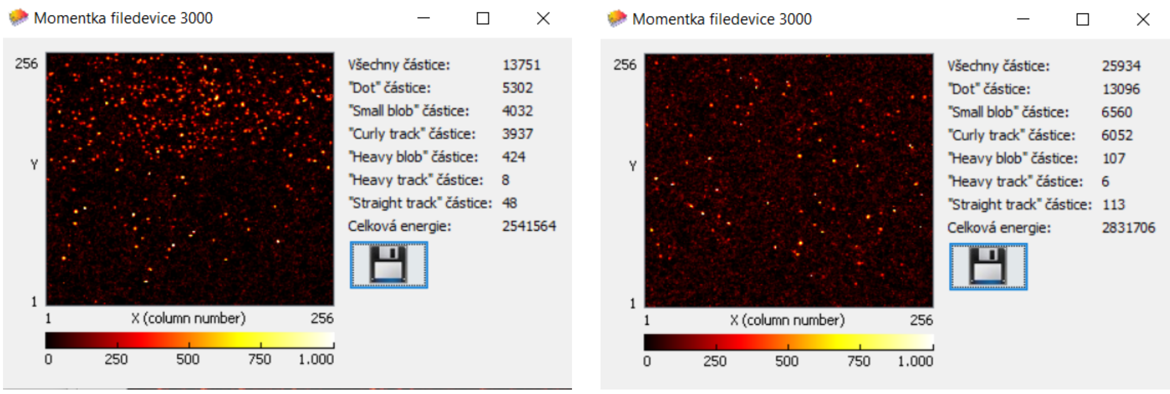

Fig. 14. Visualization of the measurements with LiF and PET convertors and lead sheet over the PET cube (left) and cadmium sheet over the PET cube (right). From the high concentration of traces in the upper third of the left picture it is clear, that the thermal neutrons passed through the lead sheet. In the right picture, we do not see a high concentration of traces in the upper third, which confirms the ability of the cadmium sheet to shield thermal neutrons.

There are fundamental differences between the measurements in Fig. 14. Through lead, which has a proton number of 82, thermal and fast neutrons pass through without any problems. A total of 424 traces were detected. Without lead it was 503 neutrons (Fig. 10). On the right, we see that only 107 neutrons were detected through cadmium, which has a proton number of 48, with thermal neutron traces (strip of traces in the upper third) disappearing. Lead is not suitable for shielding thermal neutrons, on the other hand cadmium shields thermal neutrons well.

Also, shielding sheets also have a significant effect on the absorption of photons. Photons can produce tracks that the MX-10 software categorizes as "dot" and "curly track." A clear comparison of the number of detected photons without the sheet metal shielding and with the shielding is shown in Table 2.

Table 2. Numbers of detected photons in experimental 3. Without sheets, with a Pb sheet and with a Cd sheet.

Type of tracks	Sheetless	Lead (1 mm)	Cadmium (0.7 mm)
Dot	197 253	5302	13 096
Curly track	5445	3937	6052
Sum	202 698	9239	19 148

The experiment shows that the lead sheet is not very effective for shielding thermal neutrons, but well effective for shielding photons, especially the photons of smaller energies (dot traces). Cadmium, with a very small thickness of 0.7 mm, perfectly shields thermal neutrons and also photons of smaller energies (dot traces), although not as well as lead. The total effective cross-section of the ^{113}Cd isotope for thermal neutrons is $\sigma \approx 2 \cdot 10^4$ b [3]. Because of this enormous value, Cd is used, for example, in control rods in nuclear reactors. Similarly to boron, it is a case of radiation neutron capture in which photons of a wide range of energies are emitted from the cadmium nucleus, increasing radiation. This corresponds to an increase in the number of curly track tracks (table 2) compared to the experiment without the presence of a cadmium sheet. Without sheets, 5445 curly tracks were detected and with the cadmium sheet, 6052 tracks were detected. The absorption of neutrons in the cadmium sheet comes at the cost of increasing photon radiation.

There are only two nuclei that absorb neutrons without emitting a gamma photon (not radiation capture, only absorption), and thus do not increase photon radiation. They are ^{6}Li and ^{3}He nuclei.

Conclusion

The experiments described in this article show further possible uses for the MX-10 detector - to detect both fast and thermal neutrons and are an introduction to the study of nuclear reactions caused by neutrons. Experiments show that to shield from fast neutrons, it is necessary to slow down these neutrons to the energy level of thermal neutrons with a moderator made of a material of light nuclei, capture these neutrons by suitable nuclei and shield the accompanying high-energy gamma radiation by heavy elements.

In the Czech Republic, NEUTROSTOP fittings for neutron shielding are produced in Kolín. Their designation is

H0, C0, E0 – pure polyethylene	in our text PET
H3, C3, E3 – with boron (3.5 %)	
H5, C5, E5 – with boron (5%)	in our text BPET
H10, C10, E10 – with lithium (10%)	in our text LiPET

Literature

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