Characteristics of natural neutron radiation background performed within the BSUIN project

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BSUIN

Underground physics (I)

The Baltic Sea Underground Innovation Network (BSUIN) project aims to make the underground laboratories (UL's) in the Baltic Sea region more accessible for innovation, business development and science by improving the information about the underground laboratories, the operation, user experiences and safety.

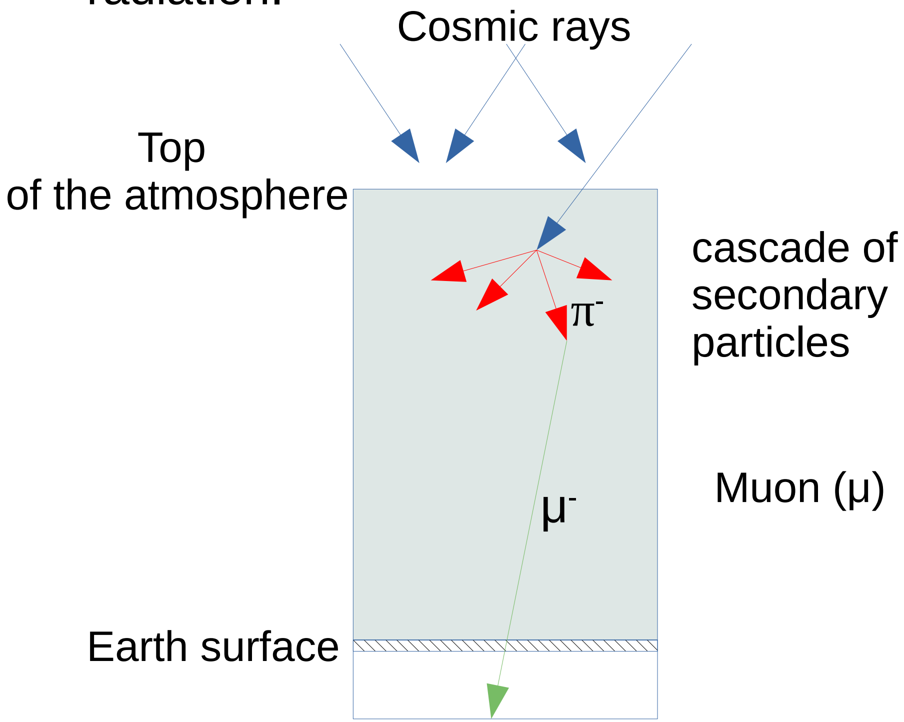
An important aspect of this activity is the development of UL's characterization methods due to various features and one of these features is the natural radioactive background (NRB).

Our team dealt with an important aspect of the NRB which is the neutron background. It is particularly important for deep underground detectors looking for rare phenomena like neutrino astronomy, dark matter search or neutrino-less double beta decay search.

These are the fundamental problems of modern physics and astrophysics, therefore the importance of measuring neutrons will be discussed here on their example. First, however, think about why physical experiments are placed underground.

Underground physics (II)

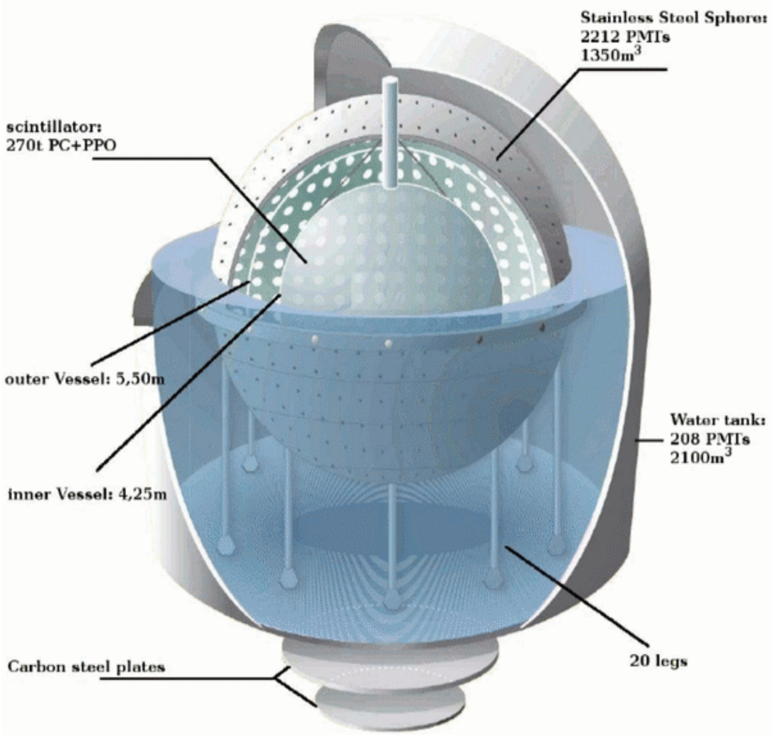
The Earth is constantly hit by flux of particles (mainly protons) from galactic origin. This phenomenon is known as ‘’cosmic ray’’. Particles comes from all directions on the sky with the same intensity. Detectors are hide deep underground against this radiation.



- Cosmic ray hits the top of the Earth's atmosphere and its flux is about 10^4 particles per m^2 per second. This are ‘’primary cosmic rays”
- As a result of the collision of cosmic rays with atoms in the atmosphere, cascades of secondary particles are formed. This are ‘’secondary cosmic rays”
- Most of the secondary particles are absorbed in the atmosphere, but sometimes very penetrating particles called muons (μ) are produced which can reach the Earth's surface and even penetrate deep into the ground

Underground physics (III)

The muons flux on the Earth's surface is about 200 per m^2 per second.
As detectors looking for rare phenomena usually are building size, the counting rate would be tens of thousands of Hz

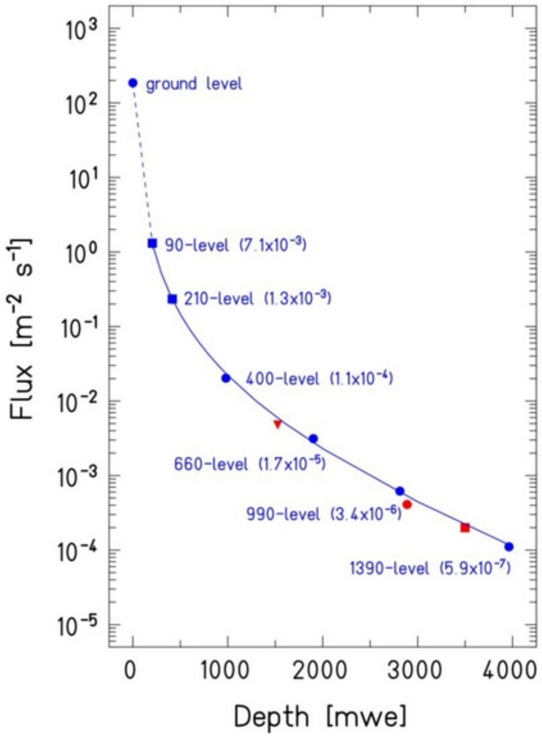


An example: schematics of the Borexino detector. **Note** that the diameter of the outer sphere is 11 m

(D'Angelo, Davide & Bellini, G.B. & Benziger, Jay & Bick, D. & Bonfini, G. & Avanzini, M. & Caccianiga, B. & Cadonati, Laura & Calaprice, Frank & Cavalcante, P. & Chavarria, A. & Chepurnov, A. & Davini, S. & Derbin, A. & Empl, Anton & Etenko, Alexander & Feilitzsch, F. & Fomenko, Kirill & Franco, Davide & Zuzel, G.. (2014). Recent Borexino results and prospects for the near future. EPJ Web of Conferences. 126. 10.1051/epjconf/201612602008)

Underground physics (IV)

The muons flux decreases quickly if the detector is placed underground. Although muons are registered even a few kilometers below the ground surface, they are very few. **This is the reason the detectors are placed underground.**



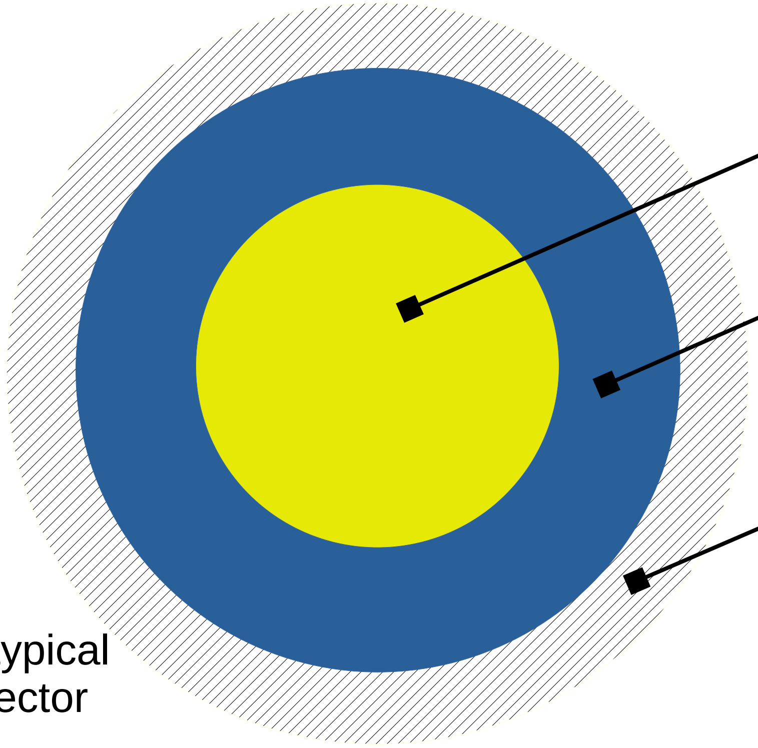
Muon flux measured at various depths at the Pyhasalmi mine (Finland). In parentheses the corresponding reduction of the flux compared with the flux at the surface is given.

Note that at a depth of 1 km undergound (2.7 km of water equivalent or mwe) the muon flux decreases a million times compared to the surface flux

(Enqvist, Timo & Mattila, A & Föhr, V & Jämsén, T & Lehtola, M & Narkilahti, Janne & Joutsenvaara, J. & Nurmenniemi, S & Peltoniemi, J & Remes, H & Sarkamo, J & Shen, C & Usoskin, I.. (2005). Measurements of muon flux in the Pyhäsalmi underground laboratory. Nuclear Instruments and Methods in Physics Research Section A Accelerators Spectrometers Detectors and Associated Equipment. 40. 10.1016/j.nima.2005.08.065.)

The neutron problem (1)

In underground locations (UL), rocks emit different types of ionizing radiation. The detectors are protected against this radiation by passive and active shields.

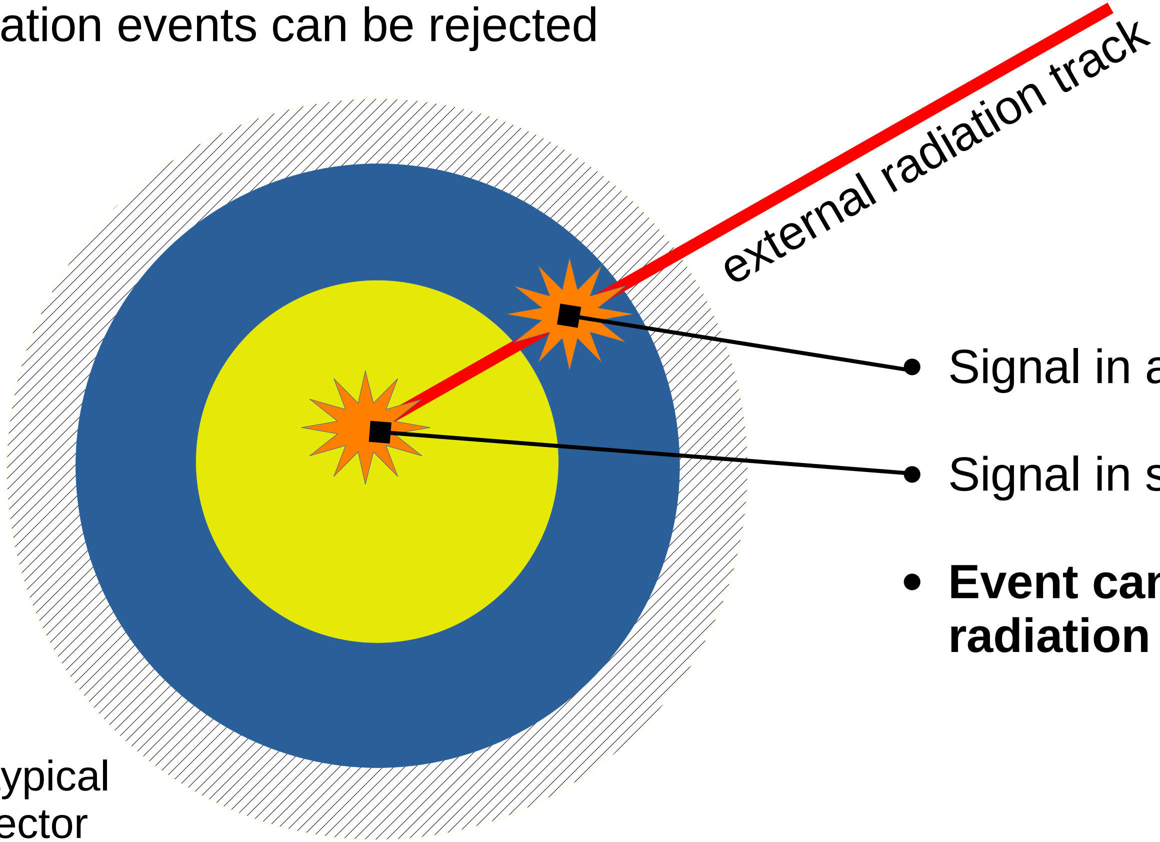


- Sensitive volume – this part measures neutrinos
- Active shield (anti-coincidence detector) – the secondary detector surrounds the sensitive volume and detects external radiation
- Passive shield – a wall of dense materials absorbs external radiation

scheme of typical neutrino detector

The neutron problem (2)

If the external radiation penetrates the detector, a signal will appear both in sensitive volume and in an anti-coincidence detector. Thanks to this, external radiation events can be rejected

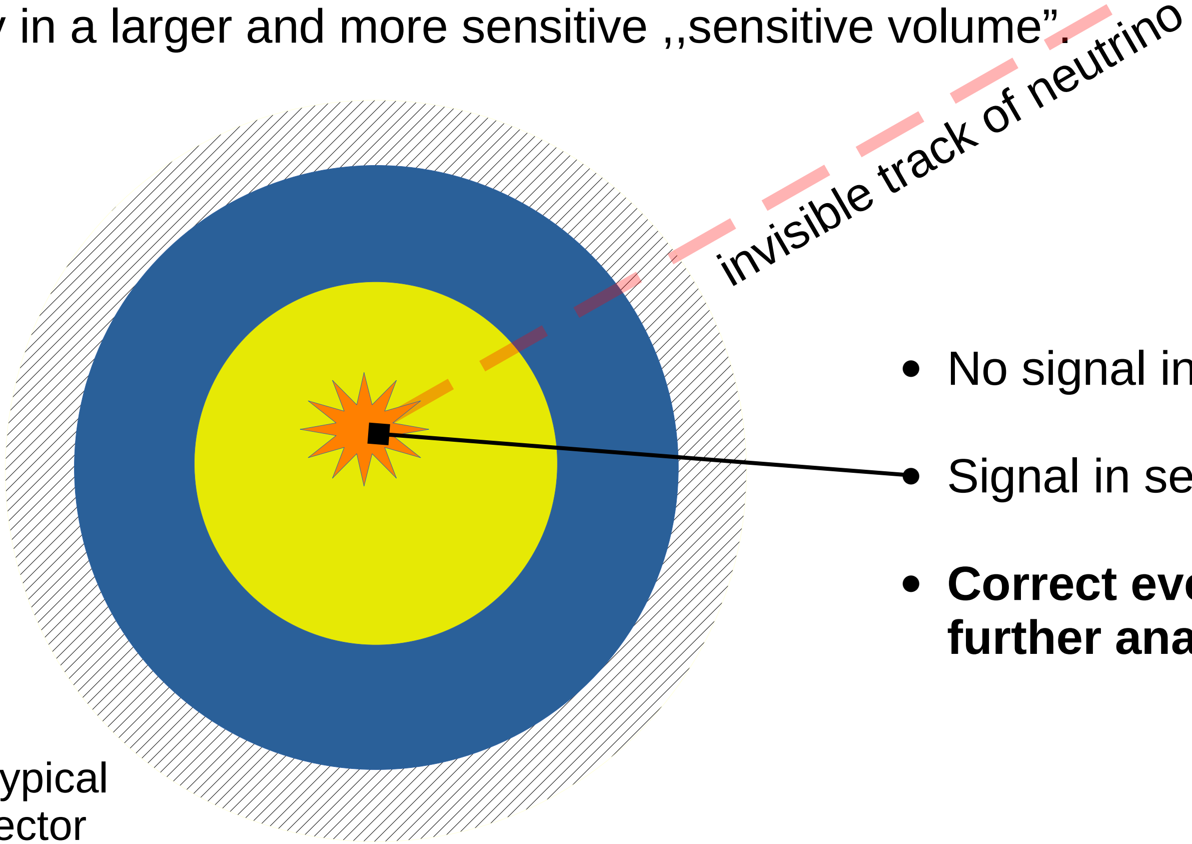


- Signal in anti-coincidence detector
- Signal in sensitive volume
- **Event can be recognized as external radiation and rejected**

scheme of typical neutrino detector

The neutron problem (3)

Neutrinos or dark mater particles interacts very weakly with matter. That is why they penetrate the anti-coincidence detector without a signal and generate the signal only in a larger and more sensitive ,,sensitive volume”.

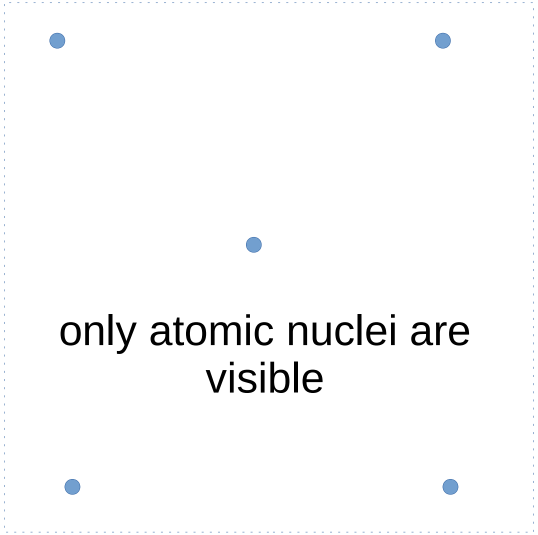


- No signal in anti-coincidence detector
- Signal in sensitive volume only
- **Correct event: will be saved for further analysis**

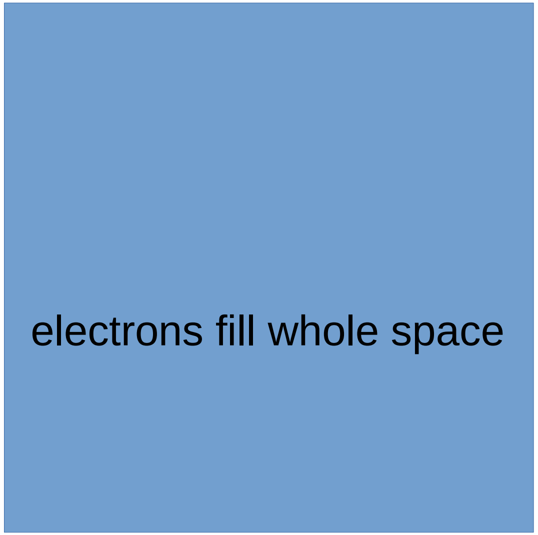
scheme of typical neutrino detector

The neutron problem (4)

Neutrons are particles that together with protons build atomic nuclei. They are very similar to protons, but they are not charged. This property means that they can easily penetrate matter



Matter, as the **uncharged** particle sees it

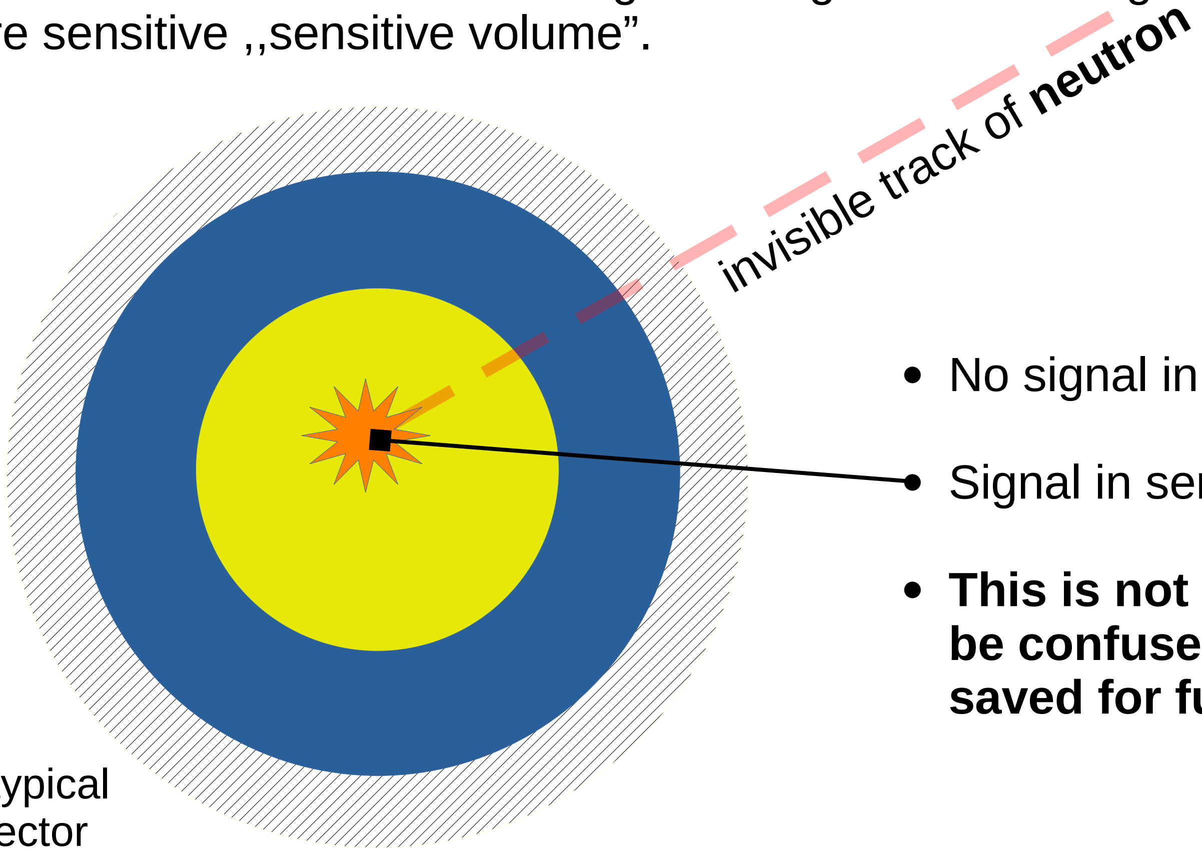


Matter, as the **charged** particle sees it

- Matter consists of atoms that can be imagined as small nuclei surrounded by electron clouds. An atomic nucleus is 100,000 times smaller than whole atom.
- Charged particles interact with electrons so they quickly lose energy
- Uncharged particles lose energy only if they collide with the nucleus
- neutrons are not as penetrating as neutrinos (because neutrinos interact with nuclei even less than they do) but it is enough to be mistaken for them in the detector

The neutron problem (5)

Neutrons can mimic neutrinos or dark mater particles and penetrate the anti-coincidence detector without a signal and generate the signal only in a larger and more sensitive ,,sensitive volume”.



- No signal in anti-coincidence detector
- Signal in sensitive volume only
- **This is not a correct event, but will be confused with the correct one and saved for further analysis**

scheme of typical neutrino detector

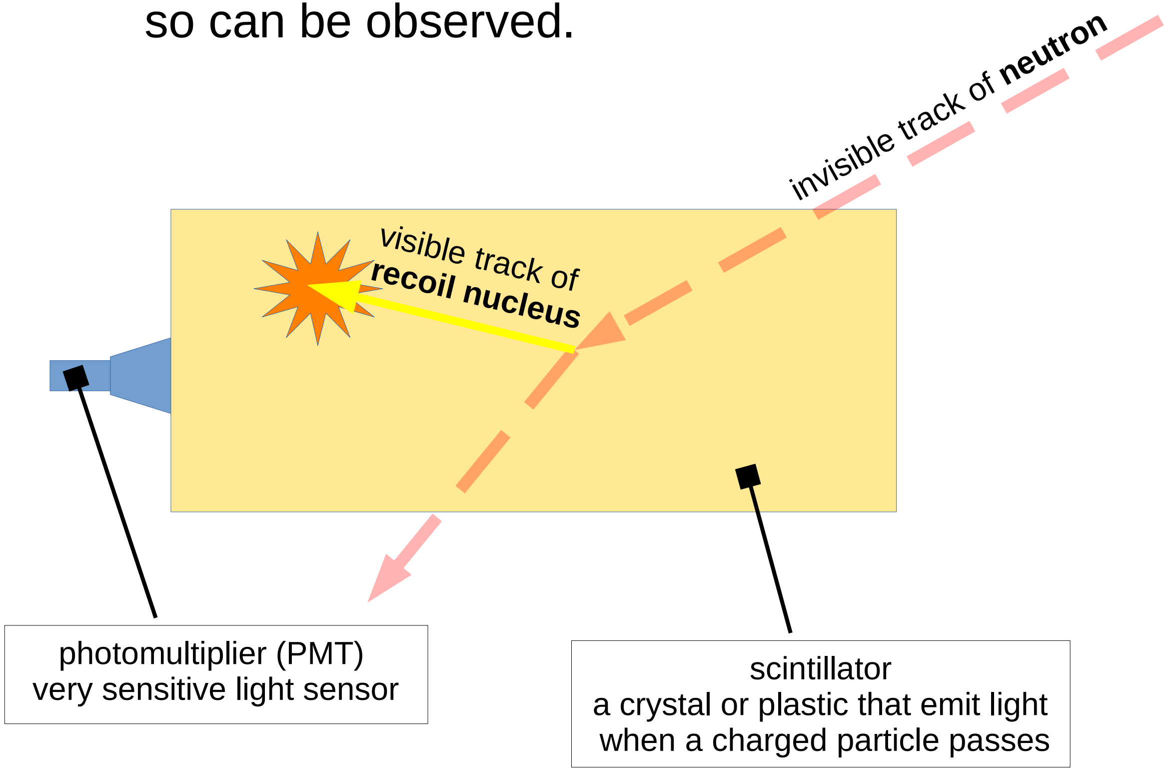
Methods of neutron measurements (I)

The neutron measurements are not so easy.

- The principle of particle detectors is to detect ionization, i.e. the effect of the passing of a charged particle through the detector's matter.Neutrons are not charged, so they must produce charged particles before detection. This complicates the measurement very much.
- Neutrons can collide elastic with the nuclei of matter and change direction in these collisions - it is difficult to determine where their source is.
- Neutrons lose some energy in each collision - it is difficult to determine what the primary energy was, i.e. it is difficult to determine what process is their source.
- There are usually much less neutrons than other types of radiation (thousands of times smaller flux)

Methods of neutron measurements (II)

Recoil nucleus method: if neutrons have sufficient energy, the atomic nuclei with which they collide will start to move. The moving atomic nucleus is a charged particle so can be observed.

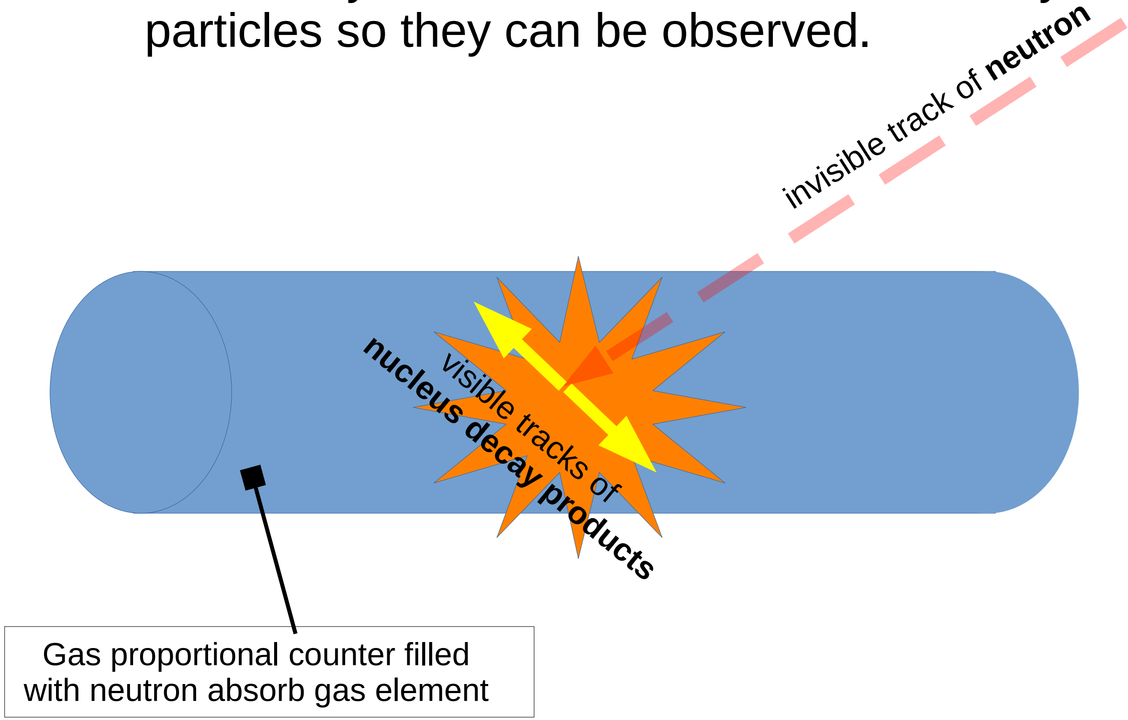


Sheme of recoil nucleus neutron detector

- Neutrons must have at least ~ 1 MeV energy (so-called fast neutrons) for the recoil nucleus to be registered.
  - This is an advantage: in natural processes neutrons are born with such energies.
  - This is a disadvantage: after traveling to the detector, the neutron often collides with the matrix, so it loses some energy and may be undetected
- This method allows you to measure the energy spectrum of neutrons which is desired but very difficult. In single collision neutron transfers to recoil nucleus only a random portion of its energy. Only after registering many such cases the primary spectrum can be calculated by statistical methods
- Because the detector needs to measure signals of very different energy, it is difficult to reject signals from other types of radiation, which can distort the measurement very much.

Methods of neutron measurements (III)

Nuclear reaction method: some atomic nuclei can absorb a neutron as a result of which they will become unstable and decay. The products of this decay are charged particles so they can be observed.

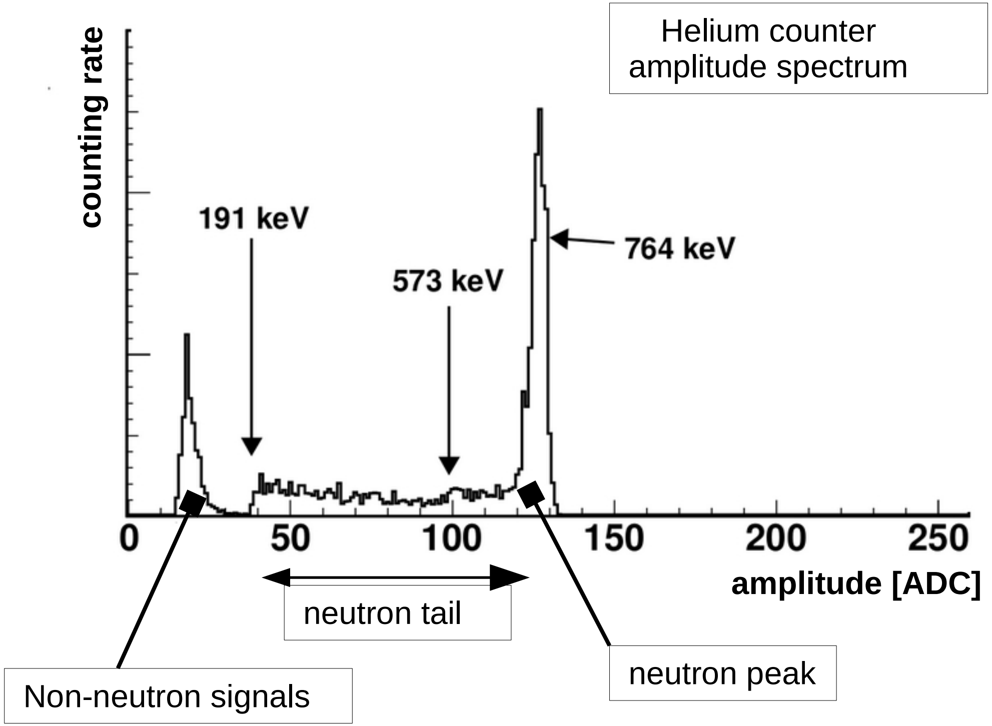


Sheme of nuclear capture neutron detector

- Neutrons must have very low energies (so-called thermal neutrons E ~ 0.02 eV). For higher neutron energies, the cross section for nuclear uptake is very small and the method works very inefficiently.
  - This is an advantage: the recorded energy is always the same (decay energy) so it is easy to distinguish neutrons from other particles.
  - This is a disadvantage: measuring the energy spectrum of neutrons is impossible.
- But neutrons in the underground laboratory lose energy as a result of collisions with matter and eventually become thermal (the so-called thermalization process). Therefore, measuring the thermal neutron flux allows you to evaluate the overall neutron flux

Our method: helium counter

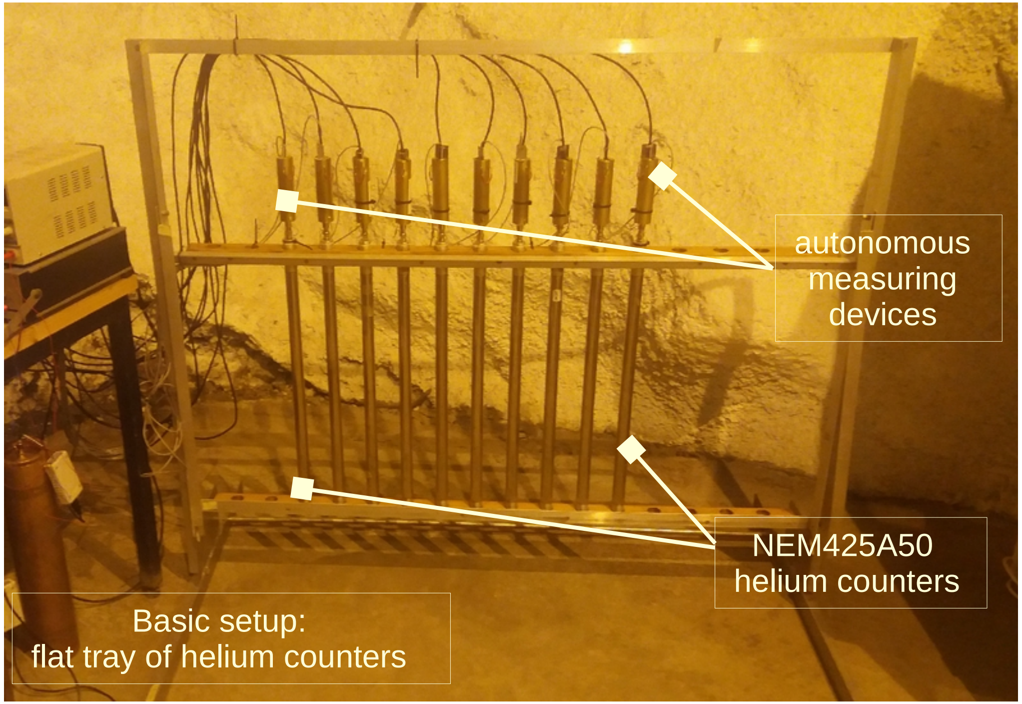
Our team uses nuclear reaction method. We uses gas proportional counters filled with helium-3 (^3He) aka helium counters. A gas proportional counter is a detector that measures the deposited energy of charged particles passing through it. Helium counters are filled with ^3He -- helium isotope which has a large cross section for neutron capture. After capture, charged products appear: proton and tritium nucleus, which carry 764 keV energy. This energy is measured by the counter and this is proof that the neutron was measured.



- Neutrons are captures in the reaction $^3He(n, p)\,^3H$ + 764 keV
- Neutron registrations form a characteristic peak in the amplitude spectrum.
- Sometimes one of the reaction products escapes from the counter so the measured energy is reduced. Such registrations form a characteristic tail on the amplitude spectrum, reaching up to 1/4 of the main peak position.
- The characteristic shape of the spectrum (peak + tail) allows to distinguish neutrons even with a large background of other types of radiation.
- Only thermal neutrons are registered.
- We use counters produced by ZDAJ (Poland) NEM425A50 type. They have the form of a steel pipe 50 cm long and 2.5 cm in diameter

Principles neutron measurements underground laboratories

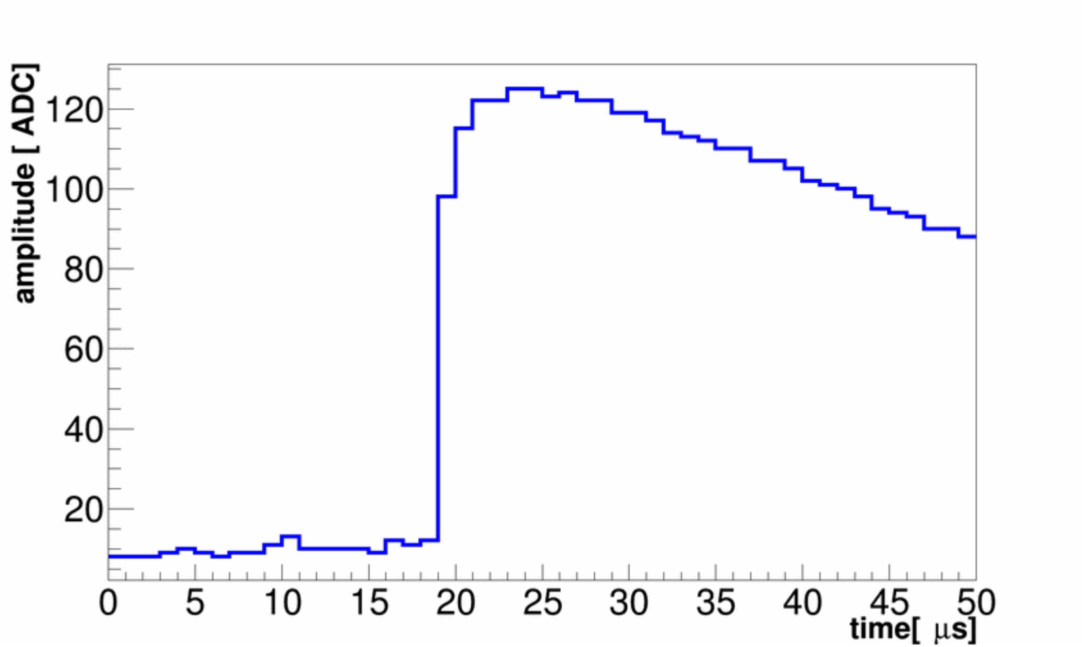
Our idea was to build a setup for measuring neutrons as simple as possible, but not simpler. The price and universality of the measurement setup are important parameters, but the reliability of the result is also very important.



- The measurement setup must consist of at least two helium counters. Then, by comparing the results, it is possible to evaluate the uncertainty of the methods of measure and analyze.
- The measuring system should record the shapes of the recorded signals (waveforms), not just their amplitudes. Then, by pulse-shape discrimination (PSD) it is possible to distinguish between correct signals and different types of noise.
- Interpretation of results should be based on reliable simulation of the measuring setup
- The system should be completely remote controlled, which will allow long-term measurements.

Our measuring setup

Our measurement setup was developed during subsequent pilot measurements. Various solutions were tested, but the main idea remained the same:Our measurement setup was developed during subsequent pilot measurements. Various solutions were tested, but the main idea remained the same:



example of neutron registration waveform

Helium counters (at least two) organized in a flat tray to limit the mututal shading of the counters.

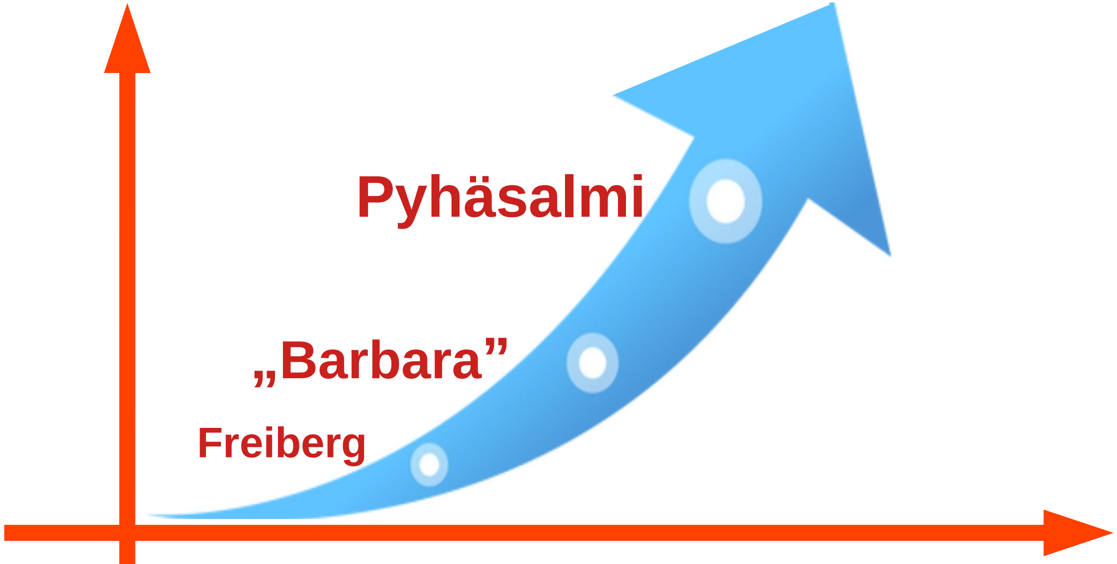
Main measurements are carried out with bare counters, sometimes different types of covers are used in additional measurements.

Each counter has its own independent measuring device based on a micro-controller. This device samples the signal from the counter at a frequency of 1 MHz and saves waveforms with a length of 50 samples. The waveform length can be extended to 4000 samples.

The counters and measuring devices are independent detectors that communicate with the main computer via USB. The main computer (PC type) stores the results and provides power and remote control via the Internet.

- The whole system can be remotely reset, settings can be changed, and remote firmware replacement is possible.ote firmware replacement is possible.

The pilot program: testing and development



Пусть от победы к победе ведёт!

To test our methods, we conducted pilot measurements in three underground locations cooperating with the BSUIN project:

- Reiche Zeche mine in Freiberg (Germany)
- Experimental mine ‘’Barbara’’ in Mikołów (Poland)
- Pyhasälmi mine im Pyhäsalmi (Finland)

Reiche Zeche

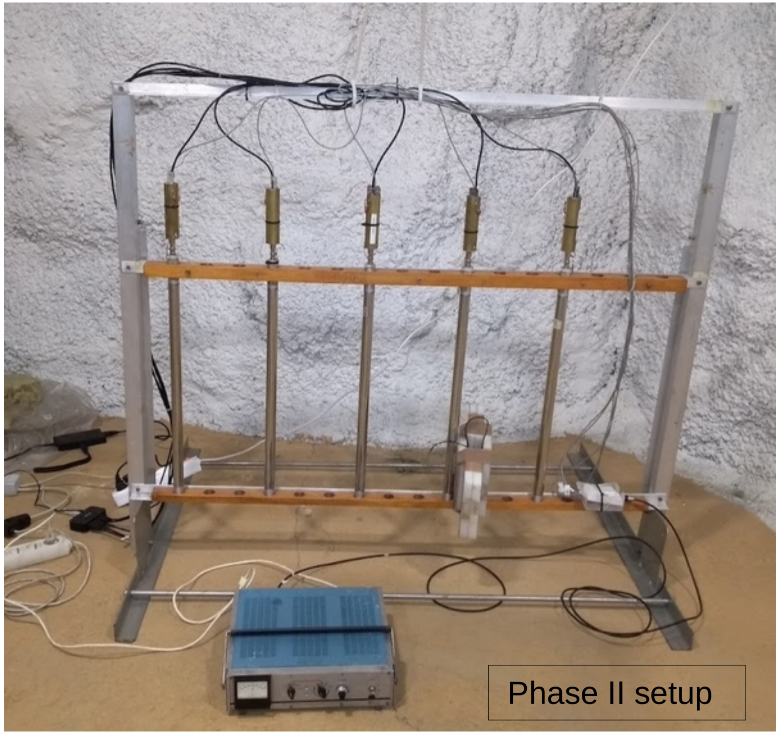
The underground is a former silver mine, located in the town of Freiberg in Saxony, Germany. The mine is used by the local mining school (TU Bergakademie) and as a tourist attraction.

Phase II setup

- The purpose of the measurements was the first test of the measuring setup in mine conditions, especially the test of high voltage supply in high humidity
- The measuring site was located at a depth of -250 m in the technical room.
- The measuring setup consisted of two helium counters.
- The measurements lasted from March to July 2018. The measurements had two phases:
- Phase I (45.5 days): measurement with bare counters, this was the main measurement to test the apparatus and determine the neutron flux
- Phase II (30.1 day): the Phase I setup was surrounded by a well made of plastic bottles filled with borax. It was a screen that reduced the neutron flux reaching the setup as the natural boron (borax component) contains a 10B isotope strongly absorbing neutrons. The decrease in the counting rate was evidence that the neutron signals were measured.
- The neutron flux was (3.12 +/- 0.10) 10^{-6} [cm^{-2} s^{-1}]

Pyhäsalmi

The underground is an active zinc and copper mine located in the city of Pyhasälmi in central Finland. Due to the great depth and easy access (apart from the elevator there is a road for cars), several laboratories (physical and biological) were organized there at various depths.


Phase II setup

- The purpose of the measurements was to test a larger measurement setup. Measuring devices have been significantly improved. The high voltage power supply method has also been changed.
- The measurements were carried out in two phases in 2018 and 2019. Between the phases the apparatus was improved. In both phases, the measuring system consisted of a meter tray but their number changed
- Phase I (7 days) setup consisted of 10 bare meters. Measurements were made at a depth of -1444 m, in the laboratory "Lab 2". Additional measurements using shields were also made
- Phase II (2 times 2 days) setup consisted of 5 bare meters. Measurements were made at a depth of -1444 m, in a new location, and in a biological laboratory at a depth of 600 m.
- The neutron flux was (1.73 +/- 0.10) × 10^{-5} $cm^{-2}s^{-1}$

Experimental mine “Barbara”

The underground is the underground laboratory of the Central Mining Institute (GIG) that investigates the effects of dust and methane explosions in mines. Located in the city of Mikołów in Poland

Bare part of the setup

- Measurements at "Barbara" were between measurements at Pyhasälmi
- The purpose of the measurements was test of remote control during a very long measurement. In addition, the stability of the setup during the carbon dust test explosions was tested
- The measurements were carried out in a technical room at a depth of -45 m.
- The measurements lasted 6 months from February to August 2019
- The measuring system consisted of two flat trays placed at a distance of about 5 m from each other. One tray consisted of bare counters, the other counters inside polyethylene blocks.
- The setup worked stably throughout the all measurement period. No significant impact of explosions was found.

Results

For a more detailed description of the results and method please see our articles:

- *Characterization of the radiation environment at TU Bergakademie inFreiberg, Saxony, Germany.* NIM A 946 (2019) 162652
- *Natural background radiation at Lab 2 of Callio Lab, Pyhäsalmi mine in Finland* NIM A 969 (2020) 164015

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