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Abstract

The first characterization of an artEmis gamma-ray sensor was performed at SURO (National Radiation Protection Institute in in Prague, Czech Republic) where the CsI detector was sealed inside a water tight housing and put inside a water filled container with an infused Rn activity. The measured γ-ray spectrum clearly showed the fingerprint of the Rn daughters. Based on the analysis of the results, it was concluded that the sensitivity of the sensor is very good being 1Bq/L and that the shielding effect of water contributes to an increased sensitivity. It was also concluded that the total number of events in the γ-ray spectra can be related to the radon concentration and the detailed knowledge of the spectral shape was not necessary for the analysis, as long as we can identify at least one known γ-ray peak in the spectra.

After the test at SURO, six prototype sensor units were installed in the selected measurement sites. Two of the sensors were energy calibrated during data taking in order to check the detector performance. This gave us convincing results regarding the energy range the sensors were covering. Apart from two sensors that had technical problems, four of the others showed clearly the 609 keV γ-ray transition which is a clear indication of the presence of the radon daughters. This peak can be used for monitoring possible changes in the calibration.

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1 Introduction

The artEmis prototype sensor units were designed and produced at GSI, Darmstadt. Their properties were discussed in detail in the Deliverables of WP1, D1.1 and 1.2. The most important part of a sensor unit is the CsI(Tl) scintillator detector which collects the γ-radiation coming from the Rn daughters. The crystal is small with a length of 20 mm – 60 mm and a diameter of 10 mm - 20 mm, and the signal amplification is done using a Silicon Photo-Multiplier(SiPM).

The measurements at SURO showed that the γ – ray spectrum is strongly dominated by γ rays that originate from the decay of radon daughters and have been Compton scattered in the water, while the usual radiation background from natural radioactivity in the environment is strongly suppressed by the shielding effect of the water. This shielding effect adds to the sensitivity of the method as essentially the full spectrum can be used for the analysis and not only the peaks. The latter, in particular the peak at 609 keV which originates from a radon progeny , serves mainly as control of the integrity and gain stability of a detector.

Following the tests at SURO, six prototypes were deployed in selected areas, three in the Abruzzi region, two on Lefkada Island and one in the underground laboratory of ETH inside the Bedretto tunnel. Detailed information regarding the selection of the sites is given in the reports prepared by WP2, D2.1 – D2.8 and the deployment information is given in D1.2. Apart from two sites where we experienced technical problems, the γ -ray spectra were observed just after the installations and gave a clear indication of the 609 keV line. In two locations in Lefkada, detailed energy calibrations were performed in order to check the quality of the data.

In summary, since we can use the whole γ - ray spectrum for our analysis, a detailed energy calibration is not needed for the analysis of the ArtEmis data. Furthermore, the peak at 609 keV which is also visible in the test data that was collected at the measurement sites, can serve as control of the gain stability of a detector. So far, we did not notice any serious shifts in the peak position of the 609 KeV peak.

2 Radon Decay and Simulations

In the uranium decay chain, 222Rn is generated by the alpha decay of 226Ra. The most prominent γ-rays are observed at energies 242 keV, 295 keV and 352 keV and occur after the β- decay of 214Po, while the 609 keV transition occurs after the β-decay of 214Bi. The decay of 222Rn is shown in Figure 1a.
Since γ -ray measurements in water are very scarce, simulations were performed in order to make an estimate on the effect of water and CERN-based simulation tool GEANT4 [1], which has proven to be a powerful instrument for simulating radiation measurement experiments. In the simulation shown in Fig 1b, the CsI detector is placed either in a tank filled with water (blue curve) or in air (red curve). The source, 222Rn was distributed evenly in the water or in air. In the case of the water tank, the interesting energy range of γ-rays (200 keV - 700 keV) is dominated by Compton scattering by the atoms in the medium. Since water has a higher density than air, far fewer events are visible in the peaks and more events are spread out on a continuum of lower energies.

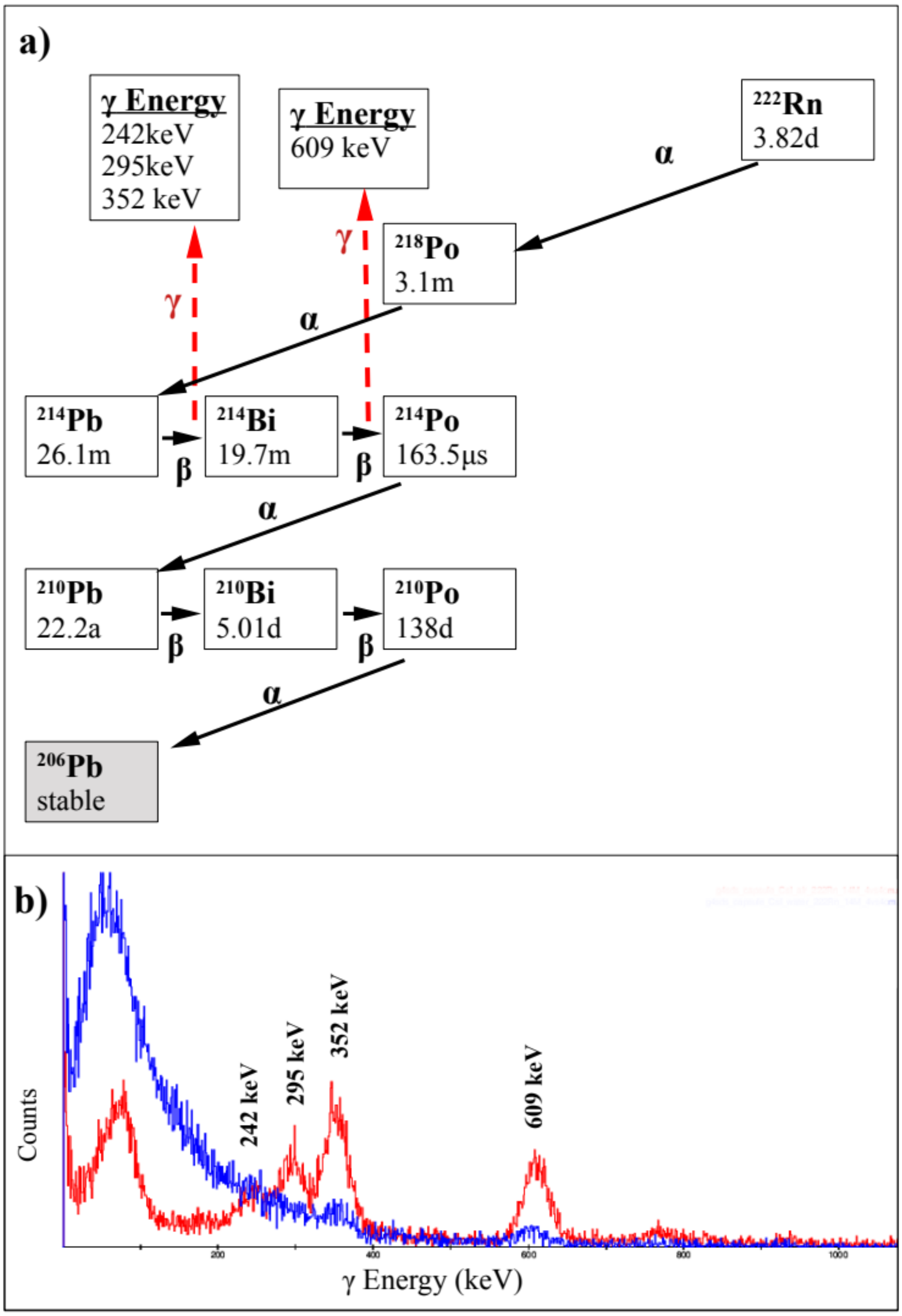


Figure 1. Decay of 222Rn and its daughters. In the uranium decay chain, 222Rn is generated by the alpha decay of 226Ra. a) The most prominent γ-rays occur at 242 keV, 295 keV, 352 keV and at 609 keV. b) Simulated γ-spectra for 222Rn. Here, the CsI detector is placed either in a tank filled with water (blue curve) or in air (red curve).

3 Sensor characterization and calibration at SURO

The sensor was first tested at SURO, where the prototype was put inside a container, with a well-defined infused Rn activity, see Figure 2. The size of the sensor, the water container and the Rn activity level had similar values as the GEANT4 simulations mentioned in Sect.2. The measurements were taken overnight for two days to determine the detector sensitivity and the Spectrum formed by Rn daughters. Based on a careful analysis, the sensitivity of the γ - detector was calculated to be 1Bq/L.

During the measurement at SURO, the electronic instrumentation was selected to give a linear correlation between the energy deposition in the detector and the sensor signal. This enabled an energy calibration based on the identification of the known gamma transitions. The γ -ray spectrum shown in Figure 3, is dominated by gamma radiation from the radon daughters and the corresponding Compton scattering in the water. In addition to the lines marked in Fig. 1, there is also an indication that the 1120 keV transition appears after the β-decay of 214Bi. The peaks visible in this spectrum well exceed our expectations.

In a standard background measurement in air, one would expect a sharp peak around 1460 keV, which originates from the radioactive isotope 40K that is ubiquitous in nature. Due to the shielding effect of water, such a peak is not visible at 1460 keV, but the related Compton background may make a only a small contribution at lower energies. GEANT4 simulations also verify this result. In any case, there is no evidence that the 40K concentration in nature is affected by earthquakes. We can thus conclude that an increase in the total number of events in this spectrum can be related only to an increased radon concentration and take this as a basis in our analysis.

Figure 2: Detector dipped in 1m^3 water tank with 297 kBq Rn.

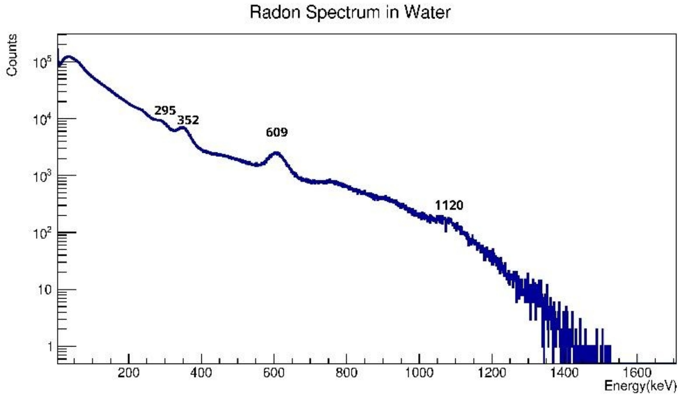


Figure 3. Rn Spectrum taken after the initial measurements, where the identified peaks are fingerprints of Rn222 daughters.

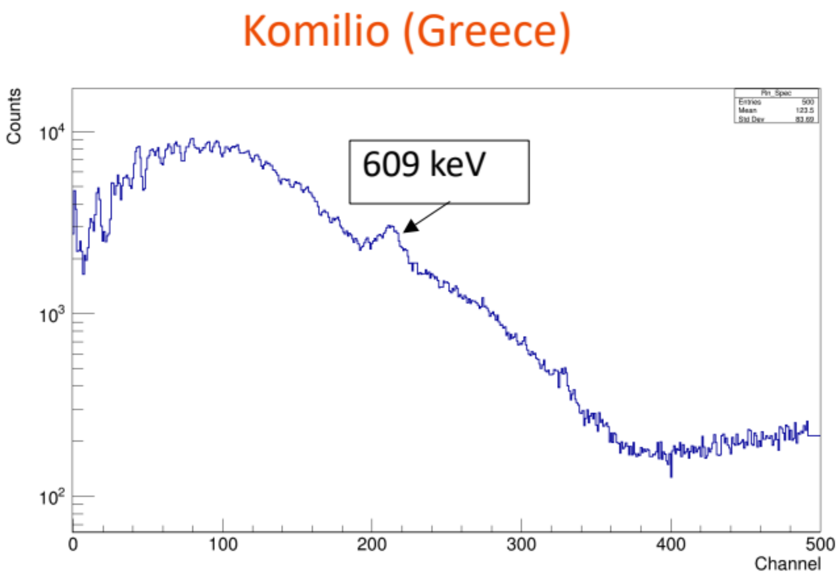
4 Deployment of prototype sensors

Following the tests at SURO, six prototypes were built, that besides gamma detector also contain a PTH sensor (pressure, temperature, humidity), microphone (fast pressure changes) and accelerometer. The selection of the measurement sites was done by a team of seismologists and hydrologists with deep knowledge of the area. Eventually, three sites were selected in the Abruzzi region in Italy, two on the Lefkada Island in Greece and one in the underground laboratory of ETH inside the Bedretto tunnel in Switzerland. Two of the sites in the Abruzzi are placed within the Gran Sasso tunnel, home to the largest underground laboratory for nuclear and particle physics. This site offers excellent infrastructure and access to the large Gran Sasso aquifer below the tunnel. The third site was a spring with flowing water. On Lefkada island, the sensor were installed in two wells, with a depth of a couple of meters. In such cases the sensor is kept floating with the help of a buoy and an anchor that provides a constant depth of the device. At the Bedretto laboratory, the sensor is placed into a container with a constant inflow of water from the tunnel. Also at Gran Sasso, one sensor is placed under similar conditions, whereas the other has been fixed by a construction to the wall. Each time, it is assured that the water volume is sufficient to warrant the quality of measurements. More details are given in D1.2.

4.1 Gamma-ray spectra from selected sites

The prototype γ sensor consists of a CsI crystal coupled with Silicon Photo multipliers along with a pre-amplifier and a simple Time-over-Threshold (TOT) digitizer. The ToT technique has been used widely during the last years due to its lower power consumption than that of ordinary analog-to-digital converters (ADCs). In addition, the ToT method is easily implemented in application-specific integrated circuits. The drawback of this technique lies in the non-linear correlation between input energy loss and TOT of the signal. In order to make an energy calibration, one should establish the relationship between the energy deposition of an initial photon and the measured TOT values. This will be discussed in Section 4.2.

First γ-spectra from the four installed sites showed clearly the 609 keV line as a fingerprint of Rn222, see Figures 4 and 5. The water provides excellent shielding of the sensor and the background does not change drastically with time. Hence the total number of counts in the spectra are considered instead of just the peak counts. This simplifies the analysis of large data streams and enables pin down changes of Rn concentration with time. The 609 keV line can be used to monitor possible changes in the calibration or shifts in the peak positions which may occur as a result of e.g. temperature changes. Due to technical problems with sensor communication, no data was recorded from the last Italian site (spring with flowing water) and from the Bedretto Laboratory in Switzerland.



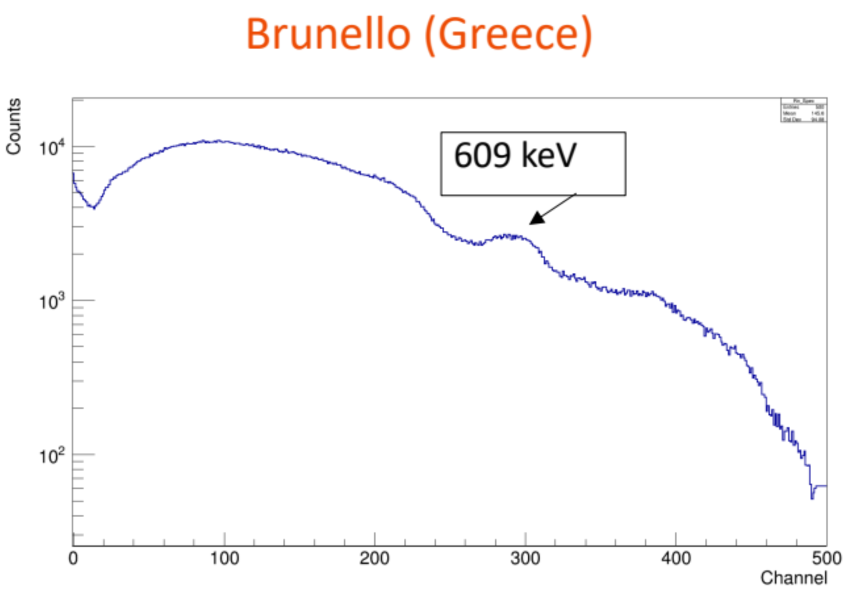


Figure 4. Examples of γ-spectra from the measurement sites on Lefkada island, Greece. The 609 keV line which is the fingerprint of Rn222 is clear visible in both cases.

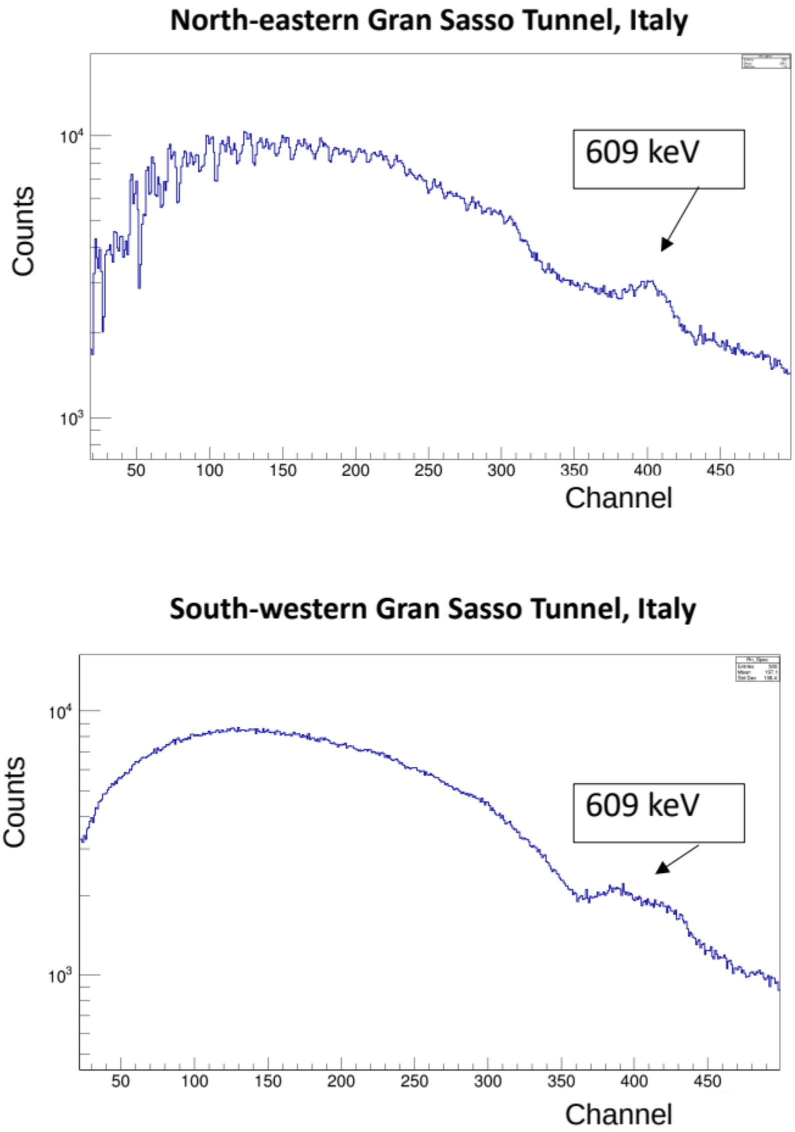


Figure 5. Examples of γ-spectra from the measurement sites at Gran Sasso Tunnel in Italy. The 609 keV line is clear visible in both cases.

4.2 Calibration of the sensor units in Greece

Two prototype sensors were placed in two wells on the Ionian island of Lefkada, on the northern (Brunello) and western (Komilio) side of the island respectively. The locations are marked on the map in Figure 6.
In both cases, a cage-like iron anchor was used with a rod to fix the sensor unit by means of a cable tie. Since the water level in a well can change, the cage is hung from a buoy which ensures that the sensor is always about 50 cm below the surface, (see Figure 7).

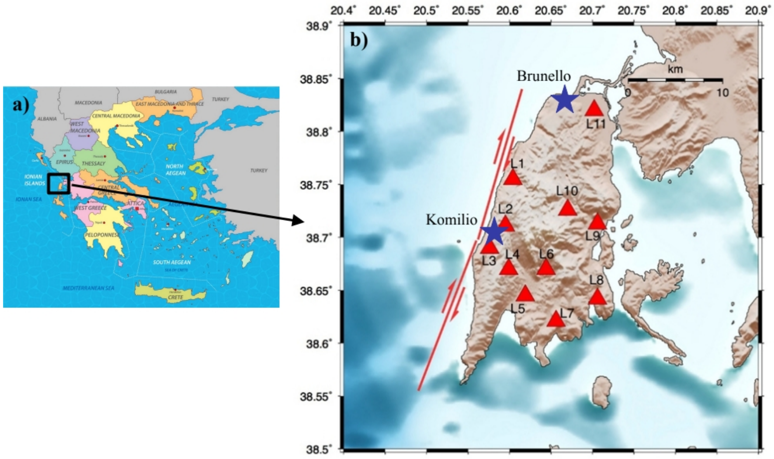


Figure 6. The Ionian Islands stretch offshore the north-west coast of the mainland of Greece. The figure shows the island of Lefkada where sensors have been placed at Brunello and Komilio. The red lines show the major fault lines running along western coastline of the island. The direction of the arrows indicates the movement along which the displacement occurs.

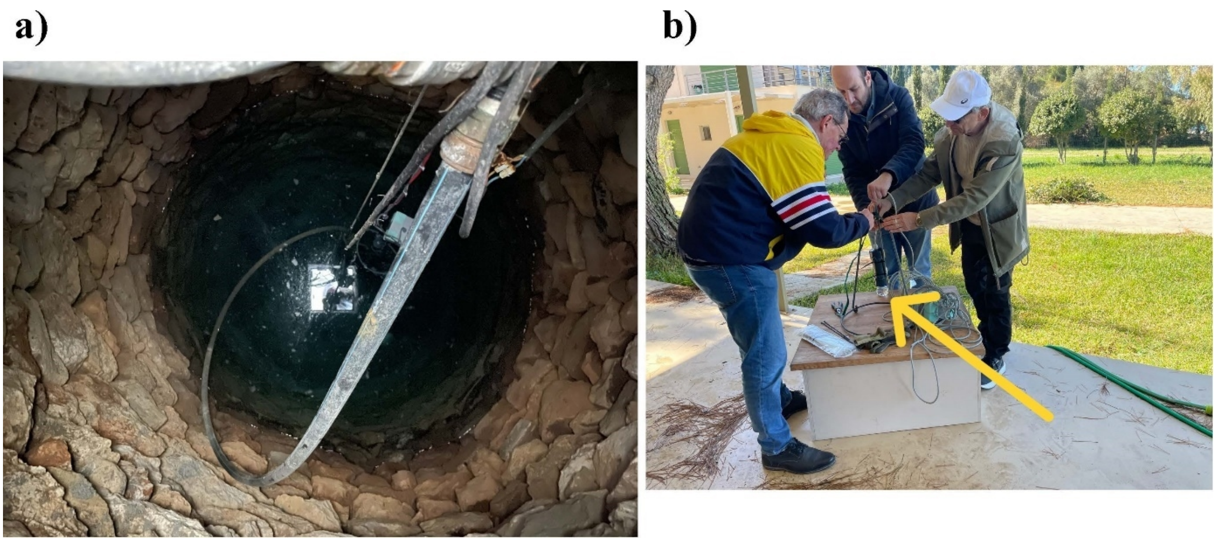


Figure 7 Pictures from the installation in Greece, Lefkada. The picture a) shows a typical well from the islands dug last or pre-last century. The sensor is attached to an anchor and placed hanging from a buoy in the well, about half a metre below the water surface. This device ensures that the sensor can follow variations in the water level. Figure b) shows the mounting of the sensor (marked with an arrow) in the 'anchor' before it is lowered into the well. The anchor also ensures that the sensor does not rest against a wall, where the effective volume of water would be smaller and thus reduce the sensitivity of the measurement.

4.2.1 Calibration Method

The prototype γ sensor consists of a CsI crystal coupled with Silicon Photo multipliers along with a pre-amplifier and a simple Time-over-Threshold (TOT) [2] digitizer. The ToT technique has been used widely during the last years due to its lower power consumption than that of ordinary analog-to-digital converters (ADCs). In addition, the ToT method is easily implemented in application-specific integrated circuits. The drawback of this technique lies in the non-linear correlation between input energy loss and TOT of the signal. The aim of this calibration is to develop the relationship between the energy deposition of an initial photon and the measured TOT values. Since the Rn related peaks can easily be observed in air compared to water, see Figure 1b, the sensors were lifted up from the wells and data was collected in air until several of the known peaks were identified.

4.2.2 Brunello

Figure 8 a) shows the raw spectrum measured in air by the γ-ray sensor at Brunello, which means the number of counts as a function of the TOT values (channels). Apart from the expected γ-rays at energies 242 keV, 295 keV, 352 keV and at 609 keV, indications of three higher energy γ-rays at 1120 keV, 1377 keV and 1764 keV are also visible. They are all emitted after the β-decay of 214Bi. Based on the identification of the peaks, the calibration curve which is shown in Figure 9 was obtained and the relationship between the energy deposition and the measured TOT values were established. Figure 8 b) shows the calibrated γ-ray spectrum. The non-linear relationship between the energy deposition and TOT can be described by the function:

$E_{dep} = A*[e^{(ToT/B)} + C - 1]$, where A,B and C are constants.

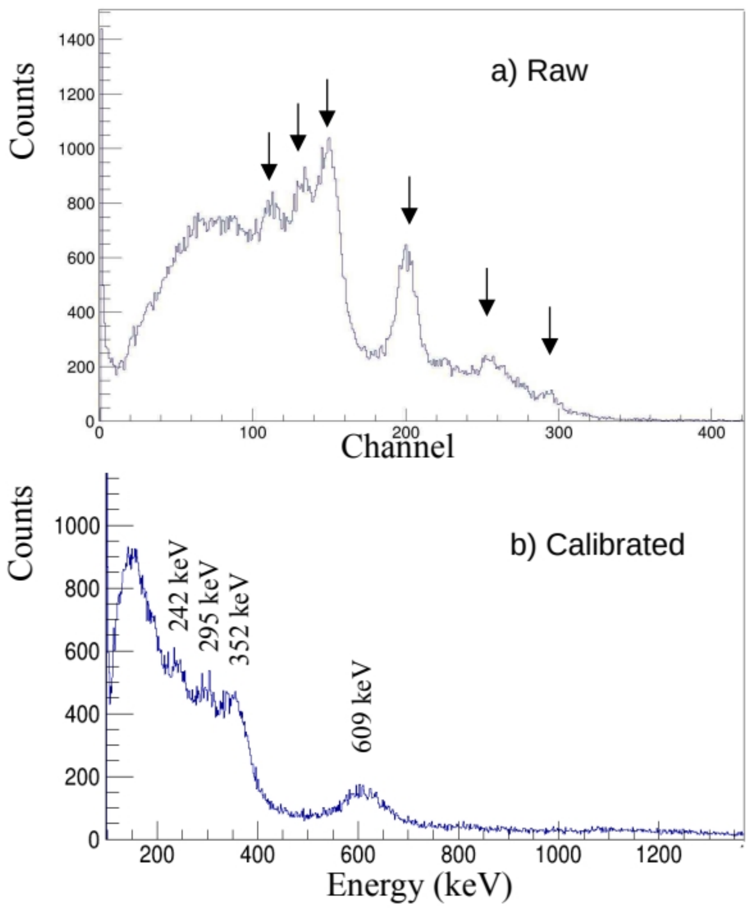


Figure 8 Decay of 222Rn and its daughters measured in air outside the well at Brunello. a) Shows the raw data before the energy calibration. The most prominent γ-rays occur at 242 keV, 295 keV, 352 keV, 609 keV, 1120 keV, 1377 keV and 1764 keV and they are marked by arrows. These peaks are identified and are related to the radon daughters. b) The same spectrum after the energy calibration.

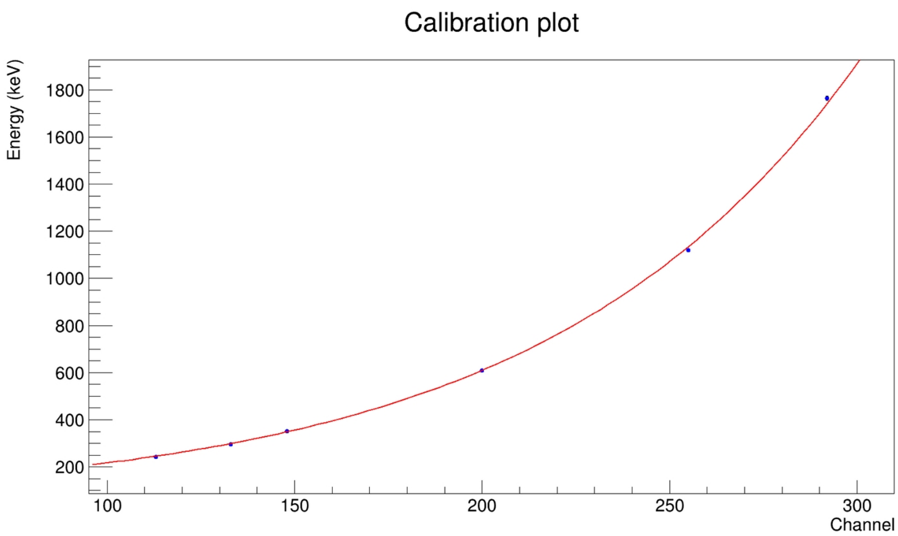


Figure 9 Calibration curve which shows the relationship between the energy deposition and the measured TOT values for Brunello.

4.2.3 Komilio

By using the same method, the sensor at the Komilio site was also calibrated. Figure 10 shows the spectrum measured in air by the γ-ray sensor at Komilio. It shows a) the raw spectrum as a function of the TOT values (channels) and b) the calibrated spectrum which is shown as a function of deposited energy. The calibration curve is given in Figure 11.

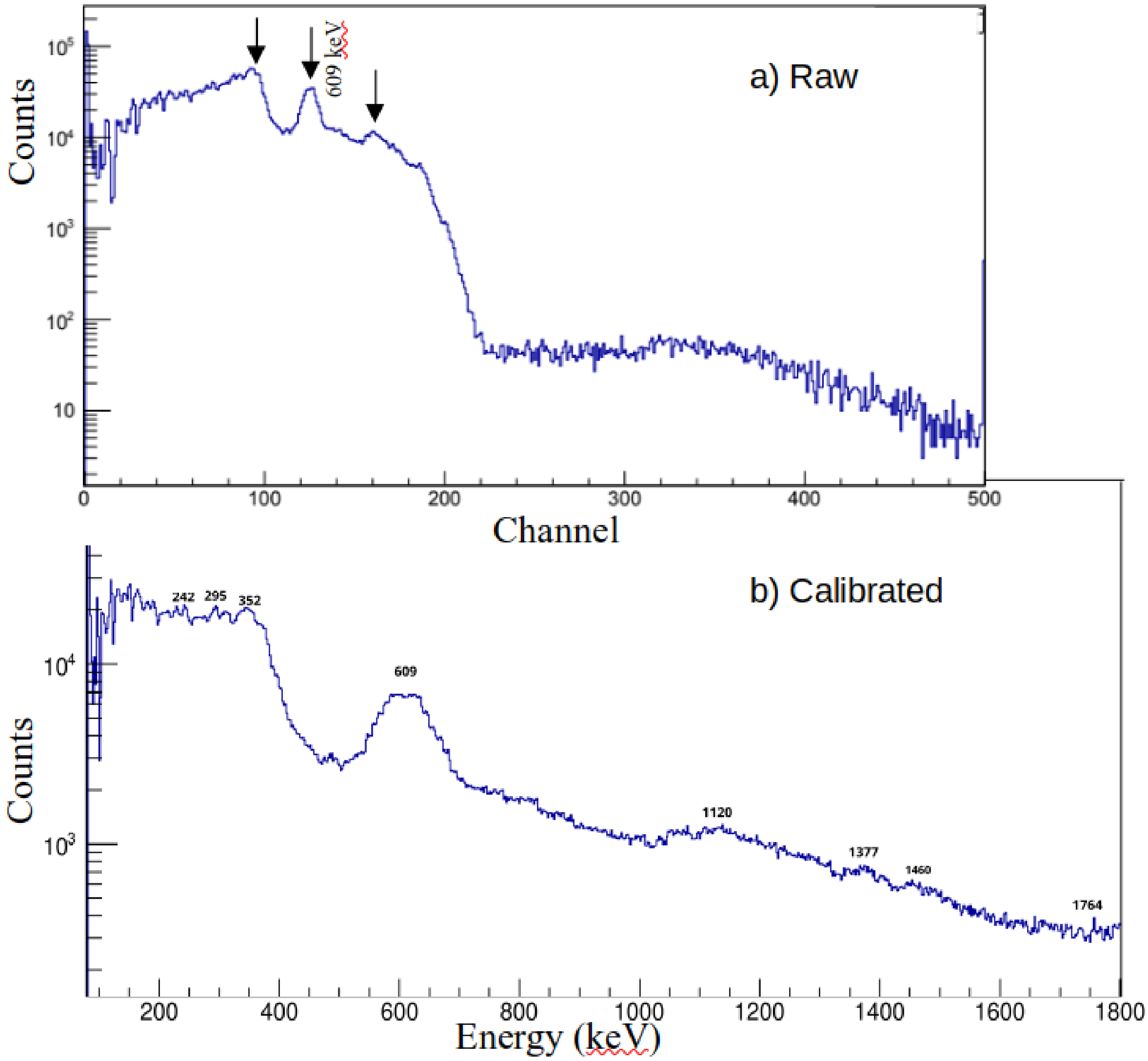


Figure 10 Decay of 222Rn and its daughters measured in air outside the well at Komilio. a) Shows the raw data before the energy calibration. The most prominent γ-rays occur at 242 keV, 295 keV, 352 keV, 609 keV, 1120 keV, 1377 keV and 1764 keV and they are marked by arrows. These peaks are identified and are related to the radon daughters. b) The same spectrum after the energy calibration.

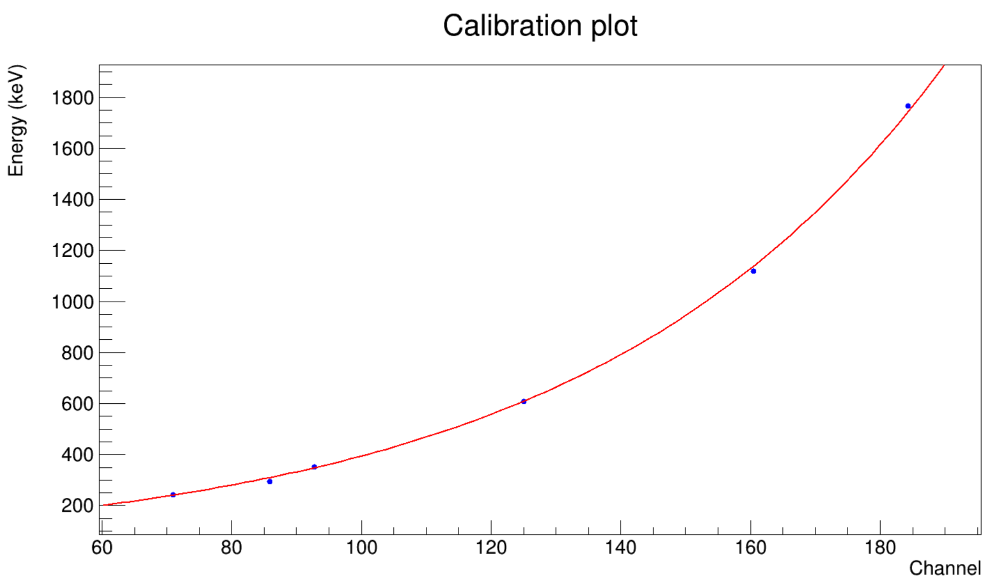


Figure 11 Calibration curve which shows the relationship between the energy deposition and the measured TOT values for Komilio.

5 Conclusions

Characterization and activity calibration of the first artEmis sensor was performed at SURO where we determined the sensor sensitivity to be 1 Bq/L. Another important result we obtained at SURO was that, due to the shielding effect of the water, contribution of standard airborne radiation, e.g. 40K can be disregarded and the total number of events in the γ-ray spectra can be connected to the radon concentration in the water. This result increases the sensitivity of the method and decreases the importance of a spectral analysis e.g. energy calibration, for all the sensors.

Nevertheless, a detailed energy calibration was performed for two of the six prototype sensors at the measurement sites in Lefkada in order to check the detector performance and the energy range sensors were covering. Furthermore, all the well-functioning sensors clearly showed the 609 keV γ-ray transition which is a clear indication of the presence of the radon daughters. This peak can be used monitoring possible changes in the calibration.

6 References:

[1] GEANT4—a simulation toolkit. Agostinelli et al., Nucl. Instrum. Meth. A 506 (2003) 250-303
[2] Converting vice to virtue: can time-walk be used as a measure of deposited charge in silicon detectors Nygren DR. Intern LBL Note. 1991.