

Radon concentration in room air

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1 Introduction

Radon produces one of the largest sources of natural radiation a typical human is exposed to. Many countries have laws limiting the allowable concentration of radon in room air. In this experiment, the concentration of radon in the laboratory air will be determined. The radioactive noble gas radon continuously emanates from the earth's crust into the air. In basements and mines, when no adequate ventilation is set up, radon can accumulate to such high concentrations that it increases the cancer risks to people working there. Radon is created from the decay of the primordial isotopes ^{232}Th und ^{238}U , which are present in rock and stone walls. Those isotopes have a long decay chain and all daughter isotopes remain at the location of the mother isotope until the chain reaches radon. The radon can emanate out of the rock into water and air. The radon then continues decaying to radioactive lead, bismuth, and polonium, all of which attach to fine particles of dust in the air so that people breath them in. They remain in the lungs until they decay, exposing people to the radiation.

One can determine the radon concentration in the air by collecting the dust from a room and measuring the dust's activity in an appropriate detector.

2 Theory

The decay of radioactive isotopes is determined by equation 1, where N is the original number of atoms and $\lambda = 1/\tau$ und τ is the lifetime of the isotope.

$$dN/dt = -\lambda N \tag{1}$$

In a decay chain, the number of atoms of the i -th isotope is given by equation 2.

$$dN_i/dt = \lambda_{i-1}N_{i-1} - \lambda_iN_i \quad (2)$$

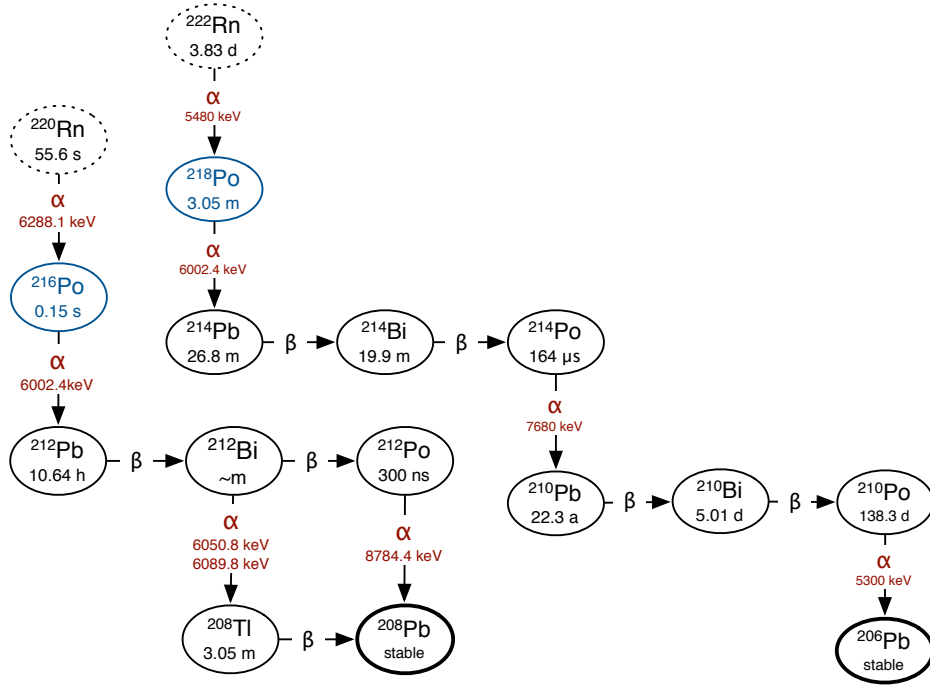


Figure 1: Zerfallsketten von ^{232}Th und ^{238}U ab deren Radon-Töchtern.

The decay chains of ^{232}Th and ^{238}U are shown in Fig. 1 starting from their radon daughters. Both radon isotopes have polonium and lead daughters, and the following discussion names only the element; the corresponding isotope can be filled in for either of the two chains. Since the lifetime of the primordial Th and U is much longer than those of all the daughters, the decay chains are in secular equilibrium, so that for arbitrary isotopes i and j in the same chain, equation 3 is true.

$$\lambda_i N_i = \lambda_j N_j \quad (3)$$

The secular equilibrium remains in tact as long as the chain is not broken.

While filtering the dust out of the air, $V \text{ m}^3/\text{s}$ of air are blown through the filter. The air contains ρ_{Po} and ρ_{Pb} of Po and Pb atoms per m^3 . The number of atoms of the direct radon daughter Po collected in the filter is

determined by the accumulation from the air and its radioactive decay, giving rate equation 4,

$$dN_{Po}/dt = \epsilon_f \rho_{Po} V - \lambda_{Po} N_{Po} \quad (4)$$

where ϵ_f is the efficiency of the filter to collect the dust. Since the radon is not retained in the filter, but just the radon daughters, this process breaks the secular equilibrium.

The number of atoms of the next daughter in the decay chain, Pb, is feed both by accumulation from the air and vrom the decay of the Po that is already trapped on the filter. The differential equation for Pb is then given by equation 5.

$$dN_{Pb}/dt = \lambda_{Po} N_{Po} + \epsilon_f \rho_{Pb} V - \lambda_{Pb} N_{Pb} \quad (5)$$

The decay of a radon-daughter isotope is determined in this experiment by measuring the emitted gamma radiation. Figures 5 and 6 show the decay lines of the relevant isotopes. Of particular interest are the Pb lines that accompany this isotope's beta decay.

The number of detected lead decays can be used to calculate the Pb concentration in the air by using equation 6.

$$\begin{aligned} N_\gamma = & \epsilon_f \epsilon_d R \rho_{Pb} V \\ & \cdot \left[\left\{ \frac{1}{\lambda_{Po}} + \frac{1}{\lambda_{Pb}} + \frac{\lambda_{Pb}}{\lambda_{Po}(\lambda_{Po} - \lambda_{Pb})} + \frac{\lambda_{Po} e^{-\lambda_{Pb} T_f}}{\lambda_{Pb}(\lambda_{Pb} - \lambda_{Po})} \right\} (e^{-\lambda_{Pb} t_1} - e^{-\lambda_{Pb} t_2}) \right. \\ & \left. + \left\{ \frac{\lambda_{Pb}}{\lambda_{Po}(\lambda_{Pb} - \lambda_{Po})} (1 - e^{-\lambda_{Po} T_f}) \right\} (e^{-\lambda_{Po} t_1} - e^{-\lambda_{Po} t_2}) \right] \quad (6) \end{aligned}$$

The variables are labeled as follows:

V : Air throughput of the filter unit in m^3/s .

ϵ_d : Detection probability for a gamma particle at this energy

R : Branching ratio for emission of a gamma particle of this energy

T_f : The duration for which the air was filtered.

t_1, t_2 : The start and stop time of the data collection with the HPGe detector, measured in seconds from the time the air filter was turned off.

Equation 6 is shown graphically in figure 4.

3 Setup

An air filter unit is used to blow room air through a HEPA filter. The radon daughters attached to dust particles will be trapped in the filter. The gamma decay lines of those radon daughters are then detected using a high purity germanium detector (HPGe detector). Germanium detectors have a very good energy resolution, so that gamma lines of the relevant isotopes can be well-separated from background. Figures 2 and 3 show schematically a HPGe detector setup and how it is connected to the data collection computer.

4 What you should know before starting

The experiment takes place in room 3519 of the Physik I building. Radioactive sources are present in this room, so please do not bring any food or beverages!

Do bring a USB memory stick to save the data. Also bring some means to create a calibration curve: Either squared paper, a ruler and a calculator, or a laptop with analysis software.

Please make sure you are familiar with:

1. Concepts: Primordial nuclide, decay chain, equilibrium reactions, secular equilibrium
2. Decay chains of ^{232}Th and ^{238}U .
3. Concepts and equations related to radioactive decay (Half-life, lifetime, decay energy, branching ratio, decay spectrum);
4. Working principle of a germanium detector.

5 Performing the experiment

The radon decay products have different lifetimes. Thus it is important to first determine how long to operate the air filter for, and when and for how long to measure the gamma spectra of the HEPA filter.

First, install a new HEPA filter behind the front plate of the filter unit. Please make sure the filter is installed facing the right way as indicated by

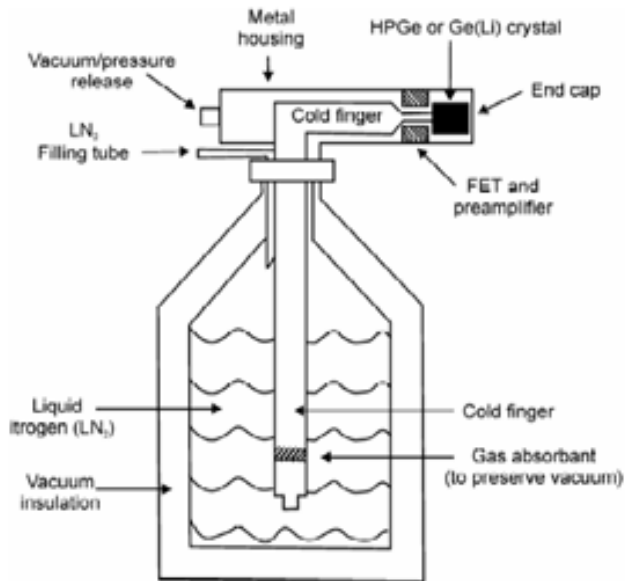


Figure 2: Germanium detector setup[2].

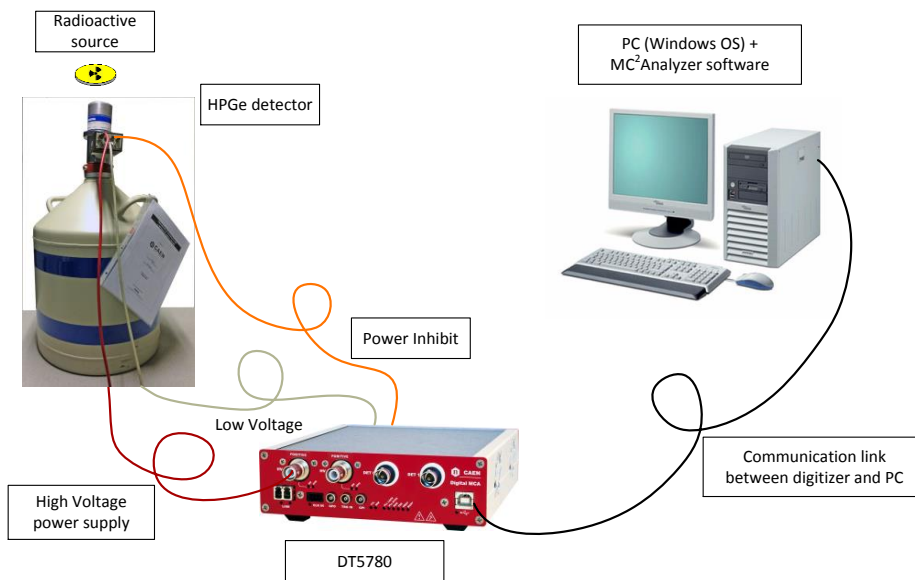


Figure 3: The germanium detector with its read-out system[3].

the arrows. Even though there are slots for other types of filters, we use only the HEPA filter here. Turn on the air filter unit on the highest setting.

Then, the germanium detector is set up. The detector is cooled with liquid nitrogen and already under high voltage. The data collection software on the computer is now turned on and connected to the detector. When starting data collection, the software will take the detector signals and produce an energy spectrum in which the decay lines of the radon isotopes will arise as peaks.

At first, you do not know which channel number in the spectrum corresponds to which energy. In order to find the peaks from the radon daughters, the detector has to be calibrated. We do this with calibration sources of known type and activity, which are available in the lab. The sources should be chosen to have decay lines in the same energy region as the radon lines of interest.

Not every decay of the source is detected by the detector. The probability for detection generally depends on the decay energy and the location of the source. In order to later calculate how many gamma particles were emitted from the filter, the efficiency of the detector must be calibrated as a function of energy.

Before sources are brought out from the safe, think about which source is useful for calibration and how long the calibration needs to be.

You can create a new folder on the computer for your group into which all spectra are saved. The spectra can be saved in the format of the read-out software as well as in a pure ascii format.

Once the air was filtered for enough time, remove the HEPA filter and fold it as small as possible. Place the filter in front of the germanium detector where the calibration sources were before. Note down all times when devices were turned on and off.

The detector environment contains radon daughter isotopes. Thus, it is important to measure the background spectrum.

6 Analysis

energy calibration : The peaks in the spectra from the calibration sources are fit with a gaussian. Possible background is modelled by a line. The channel where the mean is located is plotted against the energy of the peak. This creates a graph which can be fit with a mathematical function. Think

about what function this should be and determine its parameters.

Efficiency calibration : The number of events registered by the detector at a given energy is given by the area of the peak. If the background is very small, the number of events in each channel belonging to the peak can be added up. The number of actual decays in the source can be calculated based on the documented activity of the calibration sources and the lifetime of the measurement. The ratio of detected versus actual number of decays is plotted in a graph as a function of the decay energy. Find a mathematical curve to fit this graph. Since the filter paper does not have the same dimension as the calibration sources, a correction factor must be calculated. Think about how the efficiency behaves with distance from the detector and how large the filter paper was.

Number of radon-daughter decays Identify the relevant Po and Pb decay lines in the spectrum of the filter paper. The number of events in each peak is determined by fitting a gaussian plus background to the peak. Remember to subtract the activity of the background spectrum at this energy. Use equation 6 in order to calculate the Pb concentration in the air (twice for the ^{222}Rn daughter, from the two clear peaks, and once for the ^{220}Rn daughter from the one good peak). The concentrations of ^{222}Rn and ^{220}Rn can then be determined from equation 3. Please give this in units of Bq/m^3 .

7 Write-up

The write-up should have the format of a scientific journal article and contain all information about materials, procedures, results and analysis that a typical physics student would need to understand the results.

It should contain:

1. The energy and efficiency calibration curves, fit with a mathematical function.
2. The spectra of the filter paper, where the x-axis should be energy and the relevant peaks labelled with the isotope that created them. The y-axis should be in units of events/time

3. A table of all the parameters for the peaks used (both from the calibration sources and from the filters), that is gross and net count rate, isotope, half-life, detection efficiency, branching ratio
4. Discussion of the systematic uncertainties in each part of the experiment (which ones are there, which are the dominant ones, how could this be improved?)
5. Compare the measured radon concentration with typical values.

Please keep in mind formatting

- Use the standard sections for scientific works.
- Cite a reference for all equations and figures that you have not created yourself. Number your references and list them at the end of the manuscript.

References

- [1] H.C. Evans, "Radioactivity of the air", Queen's University, Physics 352
- [2] <http://www.expertsmind.com> (Oct 2016)
- [3] CAEN MC² Analyzer User Manual Rev.1 (2015)

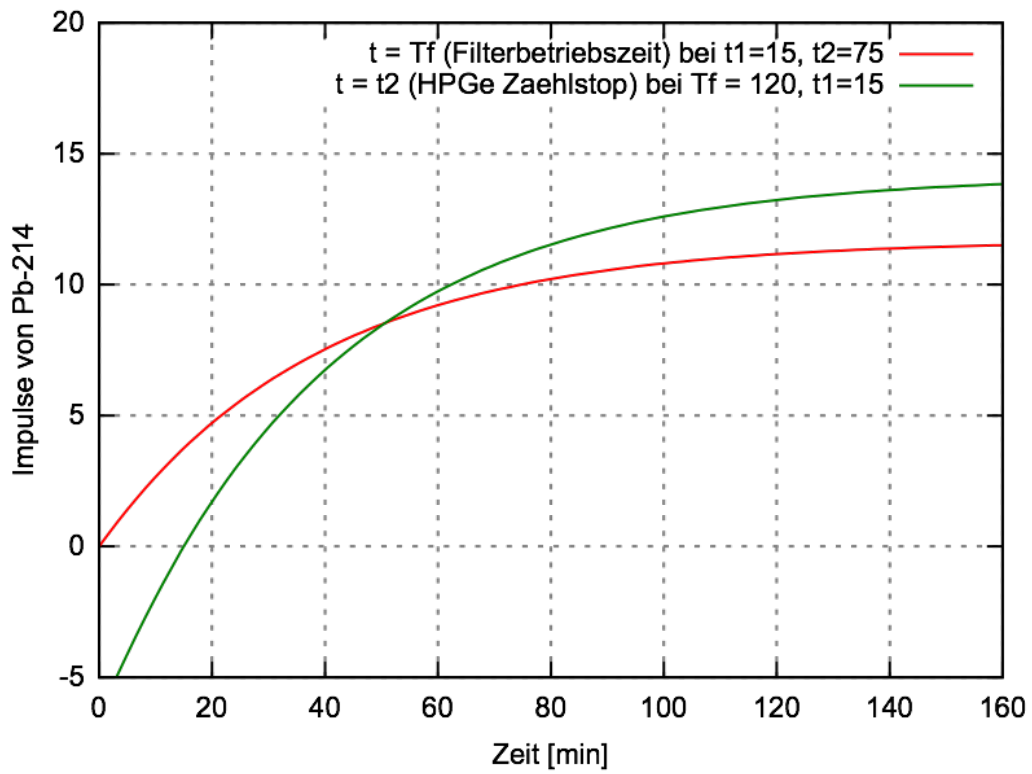


Figure 4: The number of counts (arbitrary scaling here) from the ^{222}Rn decay chain, calculated using Eq. 6 and shown as it depends on the operating time of the air filter and the counting time with the germanium detector.

Isotope	Half-life	Decay Gamma-ray Energy (keV)	Branching Ratio (%)	Decay Mode	
^{220}Rn	55.6 s	549.7	0.095	α	100%
^{216}Po	0.15 s	804.9	0.0018	α	100%
^{212}Pb	10.64 hr	77.1 238.6 300.1	17.5 43.6 3.34	β^-	100%
^{212}Bi	60.55 min	727.2 785.4 1620.6	6.65 1.11 1.51	β^-	64.1%
^{212}Bi	60.55 min	39.9	1.10	α	35.9%
^{212}Po	2.98×10^{-7} s			α	100%
^{208}Tl	3.05 min	72.8 75.0 84.8 277.4 510.8 583.1 763.1 860.4 2614.6	2.03 3.43 1.18 6.80 21.6 86.0 1.64 12.0 99.8	β^-	100%
^{208}Pb	stable				

Figure 5: Properties of the ^{220}Rn daughter isotopes.

Isotope	Half-life	Decay Gamma-ray Energy (keV)	Branching Ratio (%)	Decay Mode
^{222}Rn	3.82 d			α 100%
^{218}Po	3.11 min	837.0	0.0011	α 99.98% β^- 0.02%
^{214}Pb	26.8 min	77.1 241.9 295.2 351.9 785.9	10.8 7.46 19.2 37.1 1.09	β^- 100%
^{214}Bi	19.9 min	609.3 665.5 768.4 806.2 934.1 1120.3 1155.2 1238.1 1281.0 1377.7 1401.5 1408.0 1509.2 1661.3 1729.6 1764.5 1847.4 2118.5 2204.1 2447.7	46.1 1.56 4.88 1.23 3.16 15.0 1.69 5.92 1.47 4.02 1.39 2.48 2.19 1.15 3.05 15.9 2.12 1.21 4.99 1.55	β^- 99.98% α 0.02%
^{214}Po	1.64×10^{-4} s	799.7	0.0104	α 100%
^{210}Tl	1.3 min	298 797.7 860 1070 1110 1210 1316 2010 2360 2430	80 100 7 12 7 17 21 7 8 9	β^- 100%

Figure 6: Properties of the ^{222}Rn daughter isotopes.