Activity measurement of natural KCl salt

Radioactivity

Given isotopes of some elements are radioactive, meaning that one or more of their characteristics change spontaneously – without external effects - as a function of time, while emitting energy in the form of some corpuscular (particulate) or electromagnetic radiation.

One of the most frequent forms of radioactive radiation is β^- radiation which is made up of electrons originating from the decay of nuclear neutrons.

Activity (A) is the rate of radioactive decay – the number of decays per unit time of a radioactive sample:

$$A = -\frac{dN}{dt} = \lambda N$$

where N is the number of active nuclei/particles at a time t , and λ is the decay constant, the probability of decay per unit time.

The SI unit of activity is Bq (becquerel). 1 becquerel is the activity of a radiation source in which 1 decay occurs in 1 second. Thus 1 Bq = 1 s^{-1}.

In the simples cases activity decreases exponentially as a function of time (Fig. 1.):

$$A = A_0 e^{-\lambda t}$$

where A_0 is the activity at $t = 0$.

$$\lambda = \frac{\ln 2}{T_{1/2}}$$

where $T_{1/2}$ is called half-life – the time it takes for the number of active nuclei to half its original value. Radioactive isotopes are often characterized by half-life instead of λ. (for further details see the lecture notes).

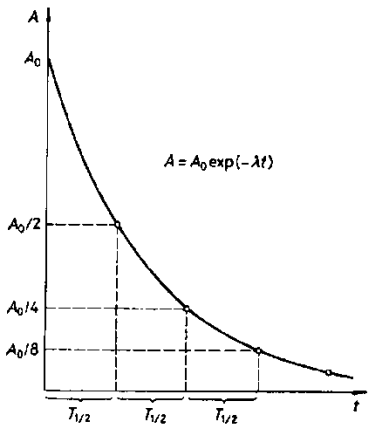

Fig. 1.
Change of activity as a function of time

Detection of radioactive radiation

Detectors used to detect radioactive radiation transform the incoming radiation to an electric signal (impulse) that can be processed by a counter. These detectors are classified according to the mechanism of signal generation: The most important nuclear detectors are:

Gas ionization detectors: the central part of the detector is a gas-filled capacitor, where the incoming radiation ionizes the non-conductive gas. The resulting discharges produce the electric signal. One of the most widely used gases is argon. Examples of gas ionization detectors are ionization chambers, proportional counter and the Geiger-Müller counter or GM tube.

Scintillation detectors: The scintillation method is based on the special characteristic of some materials to generate a flare of light (scintillation) in response to radiation. These flares of light are transformed to electric signals by a photocathode (see photocells). Examples of scintillator materials are NaI (to detect γ radiation), plastic scintillators (to measure β radiation), or ZnS (for alpha particles). Another technique is liquid scintillation counting where both the scintillator material and the isotope to be measured are dissolved in the liquid sample. This practice id used, e.g., to detect low energy (soft) beta emitters.

Semiconductor detectors: Regarding their structure, semiconductor detectors are large p-n or p-i-n semiconductor diodes. Electron - hole pairs are formed in the semiconductor detector when exposed to nuclear radiation. Voltage causes the electrons to migrate from the so-called depletion layer to the positive electrode and the holes to the negative electrode generating the electric signal.

Due to their mechanism, scintillation and semiconductor detectors can be used to identify also the energy of the radiation, unlike GM counters.

The number of the particles registered by the detectors is less than the number of the particles emitted by the radiation source. This is partly due to the usually linear geometric arrangement and partly to the fact that radiation is i) absorbed on the way from the source to the detector (absorption) and ii) diverted from its original direction (scattering), and iii) only a given percent of the particles that reach the detector actually generate a detectable signal. Thus the primary data should be strictly distinguished from activity. The number of information collected *n* during time *t* is called count. The measured particle intensity (*I*) or counting rate (counts during a given time) can be derived as $I = \frac{n}{t}$).

The unit of intensity is cps (counts per second) or cpm (counts per minute).
The relation between activity and intensity in a given experimental set-up is called gros counting efficiency (η):

$$\frac{n}{t} = I = \eta A$$

Statistical nature of radioactive decay

Radioactive decay is a statistical phenomenon, because the decay of a nuclei is a random process, characterized by a Poisson-distribution. Therefore, in nuclear investigations the standard deviation of a single measurement (s_n) can be calculated as:

$$s_n = \pm \sqrt{n}$$

where n is the count.

The standard deviation of a series of measurements can be given as:

$$s_{\bar{n}} = \pm \sqrt{\bar{n}}$$

where $\tilde{n}$ is the average of parallel measurement values.

Thus, the measured counts can be given as:

$$\bar{n} \pm \sqrt{\bar{n}}$$

If the n total count and the n_h background count are measured for the same length of time, the minimum net count (characterizing the source) which is still significant can be estimated as:

$$n_{\min} = n - n_h \geq 3\sqrt{\bar{n}_h}$$

Consequently, this is the minimum count, where the measured value can be considered as valuable information.

The standard deviation of the counting rate $I = \frac{n}{t}$

$$(sd)_I = \frac{(sd)_n}{t} = \frac{\pm\sqrt{\bar{n}}}{t} = \pm\sqrt{\frac{\bar{n}}{t^2}} = \pm\sqrt{\frac{I}{t}}\,.$$

Therefore

$$I \pm (sd)_I = I \pm \sqrt{\frac{I}{t}}\,.$$

Absorption of β-radiation

If radioactive radiation passes through any medium, its intensity weakens. The following equation describes the change of β^-–radiation intensity:

$$I = I_0 \cdot e^{-\mu' x}$$

where I_0 and I is the intensity of the radiation before and after passing through a medium.

x is the thickness of the absorbent [length],

μ' is the linear absorption coefficient [length^{-1}].

This equation is valid for continuous energy distribution β^--radiation.

Observations show that at a given energy the absorption coefficient for elements with low atomic number ($Z < 13$) is only influenced by the density of the absorbing medium. The $\frac{\mu'}{\rho} = \mu =$ weight absorption coefficient [length^2·weight^{-1}] for elements with low atomic number is approximately independent from the material of the absorbent. This approximation is acceptable for most calculations. The introduction of the mass absorption coefficient requires the multiplication of the thickness of the absorbent by its density: $\rho x = d$ = surface density [mass·length^{-2}].

Then

$$I = I_0 \cdot e^{-\mu' x} = I_0 \cdot e^{-\mu d}$$

To characterize the absorption of the radiation through a medium the half-thickness is defined, which is the thickness of the layer that reduces the intensity to half of its original value. Its relation to the absorption coefficient can be deduced the same way as the relation of half-life and the decay coefficient:

$$x_{1/2} = \ln 2/\mu' \quad ; \quad d_{1/2} = \ln 2/\mu \quad ;$$

Self-absorption of β$^-$-radiation in thick sample layer

It is a frequent phenomenon that the intensity and energy of the radiation already decreases in the sample layer itself.

Let's examine the intensity of the radiation leaving a sample with a thickness of x. The ratio of all decays taking place in the sample that depart perpendicularly to the upper surface of the sample is I_0.

Consequently, $(I_0/x) = i_0$ particles derive from a unit of thickness of a layer and $i_0 dx$ from dx unit thickness of a layer. A radiation originating from a dx elemi layer x distance from the surface weakens while passing through a layer of x thickness:

$$dI = i_0 \, e^{-\mu' x} dx \, .$$

Integrating this from 0 to x:

$$I = \frac{i_0}{\mu'}\left(1 - e^{-\mu' x}\right) = \frac{I_0}{\mu' x}\left(1 - e^{-\mu' x}\right) = \frac{I_0}{\mu d}\left(1 - e^{-\mu d}\right)$$

Measurement exercise:
Measurement of ^{40}K in natural KCl

A lot of natural radioactive isotopes (^{40}K, ^{87}Rb, ^{148}Sm, ^{176}Lu, ^{232}Th, ^{238}U stb.) have a long half-life, i.e., their activity does not change during the usual observation time.

The amount of nuclei of these elements deem unchanged during centuries. However, knowing their *A* and *N* values the decay constant and the half-life can be calculated.

^{40}K isotope emitts $E_{\beta max}$=1,33 MeV beta, as well as 0.05 MeV and 1.46 MeV gamma radiation. 0.0117% of natural K atoms are radioactive ^{40}K. The half-life of ^{40}K is $1.25 \cdot 10^9$ year.

Description of measurement

Sample preparation:

-Prepare two samples with substantially different mass between 5-12 g from KCl salt into the sample holders. Compress the salt well.

Detection of beta radiation:

- with GM counter.

Steps:

- measurement of the background with empty sample holder
- measurement of KCl samples at two different height

Detection time in every case is **3**x**5 minutes**.

- measurement of higher KCl content sample at higher position for 3 x10 minutes

Evaluation of the measured results:

1. Make sure to check the results are realistic: measure the ratio of the counts. (Let's round the averages to whole number.)

2. Calculate the absolute and relative (%) nuclear deviation of the counts and intensities. Expound the result.

3. Compare the measured values at different positions and with different amount of KCl.

4. Calculate the gross efficiency of ^{40}K measure for the used device.