# Radioactive Decay

In 1896 Henry Becquerel discovered a formerly unknown type of radiation, which is emitted by atomic nuclei. As we know today, this radioactive radiation can consist of $\alpha$ particles (Helium nuclei), $\beta^+$ or $\beta^-$ particles (positrons or electrons), $\gamma$ quanta (high-intensity radiation), or other particles. It can be found in natural radioactive elements such as uranium and radium, which are among the heaviest elements. Nowadays, a large number of lighter radioactive nuclei are produced in "artificial" nuclear reactions.

## Theory

Nucleons (protons and neutrons) stick together because of a strong attractive short-range force (*strong interaction*), which prevents the nucleus from falling apart in spite of the repulsive Coulomb force between the protons. Stable nuclei are possible for certain combinations of proton and neutron numbers only. The two numbers are more ore less equal with a slight dominance of neutrons for heavy nuclei.

Unstable isotopes disintegrate into a stable nucleus (usually not of the same element), possibly passing by several unstable intermediate nuclei. The decay is accompanied by the emission of radiation.

The number of disintegrations per second is proportional to the number of active nuclei: $\Delta N = -\lambda \cdot N \cdot \Delta t$

The *decay constant* $\lambda$ is characteristic for the decay of a given nucleus. For short time intervals, $\lambda$ is the probability that the nucleus will decay during the time $\Delta t$.

The relative change in the number of active nuclei is constant for equal intervals of time. This is typical for an exponential decay. It follows that the number of active nuclei after the time $t$ is given by

$$N(t) = N_0 \cdot e^{-\lambda t}.$$

The *half life* of a decay is related to the decay constant:

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

The half-lives of different radioactive elements span a range from smallest fractions of a second to more than $10^9$ years.

The *activity* of a radioactive sample is the number of disintegrations per second:

$$A(t) = \left|\frac{\Delta N}{\Delta t}\right| = \lambda N$$

$[A]$ = 1 disintegration per second = 1 Bq (Becquerel)

Activity is also measured in terms of a unit called *curie* (Ci), in honour of Marie (1867 – 1934) and Pierre (1859 – 1906) Curie: 1 Ci = $3.7 \cdot 10^{10}$ Bq.

It is impossible to predict the time when a given nucleus will disintegrate. Instead, we only know the probability that it will do so in the next second. As a consequence, measurements of the activity of a radioactive sample are always subject to statistical fluctuations (which has nothing to do with measurement errors).

The probability that from a sample of $N$ active nuclei exactly $x$ will disintegrate during the time is given by the *binomial distribution* (for large $N$):

$$P_N(x) = \binom{N}{x} p^x q^{N-x},$$

where $p = \lambda\,\Delta t$ is the probability that a nucleus will decay during the time $\Delta t$ and $q = 1 - p$ is the probability of the inverse event.

For weak samples, the binomial distribution can be approximated by the *Poisson distribution*, under certain conditions also by the *normal distribution* (see "Formeln, Tabellen, Begriffe", p. 121 ff.). In the latter case the *standard deviation* corresponds to $\sqrt{N}$.

## Experiments

**Goals:** You know and understand the decay law and the random nature of radioactive decay. You can operate a Geiger-Müller counter to determine the activity.

**Demo 1:** **Detecting radioactive radiation**

**Devices:**

- Wilson chamber
- Poster ("Messung radioaktiver Strahlung")

**Observations:**

a Observe and sketch some of the traces in the Wilson chamber.

b Study the poster and take notes.

**Tasks:**

1. Explain how a Geiger-Müller counter works.
2. Describe a second method used to detect radioactive radiation.

**Demo 2:** **Decay of radon 220**

**Devices:**

- Ionisation chamber, electrometer and plotter
- thorium source emanating radon 220

**Measurements:** Your teacher will demonstrate the experiment to you. You will receive a plot of the activity of the radon sample as a function of time.

**Analysis:**

1. Look up and explain the radioactive decay chain that leads from thorium 232 to radon 220 and its daughter nucleus.
2. Determine the half life of radon 220 from the decay diagram. Compare the value to the accepted value.

**Experiment 1:** **Mass of radioactive sample**

**Devices:**

- Radioactive source (Na 22 or Sr 90)
- Geiger-Müller counter

**Measurements:**

a Measure the diameter of the counter tube's front window. Place the source 20 cm away from the window.

b Remove the protective cap from the source and measure the time it takes to measure 500 events. reattach the protective cap immediately.

c Repeat the measurement for a distance of 10 cm.

**Analysis:**

1. Look up the characteristics (radiation type, half life, …) of the radioactive material you used in your measurements.
2. Calculate the source's activity from the measured event rate and the diameter of the counter window. Compare the results of the two measurements and give a reasonable explanation for the difference.
3. Calculate the mass of the active substance in the source. Do you expect the correct mass to be greater or smaller than the calculated value? Give reasons for your answer.

**EXPERIMENT 2:** **Binomial distribution**

DEVICES:
- Dice

MEASUREMENTS: Throw 20 times with 24 dice ("active nuclei"). Each time write down the number of dice showing six spots ("disintegrations").

ANALYSIS:
1. Determine the average and the value of maximum occurrence from your data. Compare the measured to the expected values.
2. Graph a histogram showing how many times every number of six spots occurred.
3. For every number of six spots calculate the theoretical value using the binomial distribution. Add the corresponding bars to the histogram.

**EXPERIMENT 3:** **Variation of decay numbers**

DEVICES:
- Radioactive source (Cs 137 or Am 241)
- Geiger-Müller counter

MEASUREMENTS:

A Place the source immediately in front of the counter window. Measure 50 times the number of events in 5 s.

B Redo the measurements for 25 times 10 seconds.

ANALYSIS:
1. Compare expected value, mean and and value of maximal occurrence between the two sets of data.
2. Draw a histogram of the two data series.
3. Explain how experiment 3 relates to experiment 2.

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REQUIREMENTS: For a short report, work at least on the exercises of the two demonstrations and one of the three experiments. The complete interpretation is required for a full report.

Hand in your report and the lab notes by Tuesday, 28 June 2011.