I. Radioactive materials in the undergraduate laboratory

§ I.1 General safety aspects

In some of the experiments in the undergraduate physics lab a number of different radioactive sources is used. These sources are of low dose and hermetically sealed. However, it is generally accepted that exposure to radiation from radioactive sources, even in a small dose, is potentially harmful to your health. Therefore the presence/use of radioactive material will always present an extra risk factor.

Strict regulations apply to the use of radioactive samples in the laboratory to reduce these risks to an absolute minimum. By observing these regulations (see below) the extra dose of radiation you will receive in the laboratory will always be much lower than the dose you receive from natural causes. It is essential to be aware of and to understand any dangers and to strictly adhere to the applicable safety measures. Remember, not only your health might be at risk, but also of your co-workers.

There are also strict procedures for the safe disposal of hazardous material to prevent an uncontrollable spread of the material into the environment (with the risk of accidental exposure).

§ I.2 Isotopes

For proper identification of elements the following nomenclature and symbols are used. The *atomic number*, generally represented by the symbol Z, equals the number of protons in the nucleus. The *Z*-number largely determines the chemical properties of an element. Each element can have different *isotopes*. These isotopes have the same atomic number (number of protons), but have different numbers of neutrons N in the nucleus. The *atomic mass number* A is equal to the total number of particles $N + Z$ in the nucleus. Because of the large binding energies, the mass number is only an indication of the real atomic mass.
The atomic mass is usually expressed in *unified atomic mass units* (u) or *dalton* (Da). These two units are equal, and defined as 1/12 part of the mass of a carbon atom with atomic mass number 12 in its ground state: $1\ \mathrm{u} = 1\ \mathrm{Da} \simeq 1.66 \cdot 10^{-27}\mathrm{kg}$. For an element E with atomic number Z, the notation ${}^{A}_{Z}E$ or E-A is used (for example silver: ${}^{107}_{47}\mathrm{Ag}$ or Ag-107).

Some isotopes are *inherently stable*, which means that they will not decay over time. *Unstable* isotopes are referred to as *radioactive*, decaying in various possible ways by radiative emission, leaving behind a different isotope. The resulting isotope might be unstable as well which would lead to further decay.

On the internet, isotope specific information and on any of its decay processes can easily be obtained; specifically you may consult

http://atom.kaeri.re.kr/ton/.

In many cases element samples obtained from nature will contain a mixture of isotopes. Isotopic composition of natural samples can be found at
http://physics.nist.gov/PhysRefData/Elements/index.html.

§ I.3 Radioactive decay

The probability of decay of a radioactive nucleus is element-dependent and expressed by its decay constant λ. The probability dP for a nucleus to decay in the next time interval dt is given by the

product $dP = \lambda\, dt$. The number $dN(t)$ of a sample containing $N(t)$ radioactive nuclei which will decay in the next time interval $[t, t+dt]$ therefore equals $\lambda\, N(t)\, dt$. The resulting differential equation describing the decay process is then

$$\frac{dN(t)}{dt} = -\lambda\, N(t). \tag{1}$$

The solution of this equation (1) is given by

$$N(t) = N_0 \exp(-\lambda\, t) = N_0 \exp(-\, t/\tau), \tag{2}$$

using the notation $N_0 = N(t=0)$ and where τ is the (average) *life time* of the nucleus. Often, rather than specifying the λ or τ of the decay process, the *half-life time* $t_{1/2} = \tau \ln(2)$ is specified. The half-life time the time interval in which the number of radioactive nuclei reduces by a factor of two.

The decay rate or *activity* $A(t)$ of a sample of radioactive material (=source strength) is defined as

$$A(t) = -\frac{d}{dt} N(t), \tag{3}$$

which for a pure sample equals $N(t)/\tau$. Keep in mind that radioactive decay is a probability process: therefore, a quasi-continuous representation of a random decay process as used in the definition of activity $A(t)$ can only be justified for sufficiently high decay rates.

§ I.4 Definitions

When dealing with risk factors it is of primary importance to define the relevant physical quantities. For risks involving exposure to radiation the following quantities are used.

- The **strength of a radioactive source** is expressed in **Becquerel**: $1\ \mathrm{Bq} = 1\ \mathrm{decay/s}$. Sometimes the outdated unit, the **Curie**, is used, $1\ \mathrm{Ci} = 3.7 \times 10^{10}\ \mathrm{Bq}$.
- The **dose** is the energy deposited in a material by radiation. It is expressed in **Gray**: $1\ \mathrm{Gy} = 1\ \mathrm{joule\ per\ kilogram}$ material.
- Especially when dealing with aspects of safety a measure of the effect of radiation on (human) tissue is important. The relevant quantity is **the equivalent dose**, which is measured in the unit **Sievert** (Sv). The conversion factor from Gray to Sievert depends on the type of radiation.

The following rules of thumb are used as estimates for the equivalent dose received per unit time from a source with an activity of $\boldsymbol{A}$ kilobecquerel *at a distance of* $\boldsymbol{d}$ meter *("whole body exposure").*

α-particles: under normal circumstances the effective range is so small that α-particles do not penetrate the skin, if they would reach your skin. However, α-particles cause great damage in case of *internal* contamination (with high risk if a leak would occur in the radioactive source).

β-radiation: $8 \times 10^{-3}\ A/d^2$ (μSv/hour).

γ- and röntgen (X-) radiation: $1.25 \times 10^{-4}\ E\, A/d^2$ (μSv/hour),
where E is the radiation energy in MeV ($= 1.6 \times 10^{-13}$ Joule).

neutrons: ϕ_1/d^2 (μSv/hour), where ϕ_1 is the dose per hour
at 1 meter distance from the source. No simple formula is available here.

The estimates above are conservative because they do not take into account such factors as additional absorption in clothing or in the air.

§ I.5 The law of squares

For radiation from a point source, the intensity decreases with d^2, the square of the distance d, provided this distance is not too small. Hence there are two good reasons to handle a source using tweezers instead of your hands: the distance to the source is larger and, if against all odds, a leak would occur you do not run the risk of getting radioactive material on your hands.

§ I.6 Biological effects and limits

Biological effects of exposure of humans to radiation have been studied primarily at high doses of radiation (for instance following a nuclear disaster). Much less is known about the consequences of low doses, such as occur in the laboratory. Yet it is generally assumed that low doses can be potentially harmful as well. Of special interest here are effects, which only become manifest many years after the exposure (such as cancer or consequences due to genetic defects). The likelihood of such problems increases with the dose received, regardless of whether the dose was received over a shorter or over a longer time period.

According to the "*Besluit Stralenbescherming Kernenergiewet*" (Radiation Protection Nuclear Energy Act) the maximum acceptable extra dose (above the inevitable background radiation from space, soil, buildings, etc.) for the most sensitive tissues (bone marrow, genitals) is $1\ \mathrm{mSv}$ per year. For the least sensitive tissue such as the skin this maximum is set at $20\ \mathrm{mSv}$ per year.

N.B. For professional radiological workers different regulations apply.

§ I.7 Laboratory sources

All the sources used in the undergraduate laboratory are *closed* sources: the radioactive material is welded into the carrier material or encapsulated in a foil. Of course you should never tamper in any way with a radioactive source. The table below contains an overview of the available laboratory sources and some further data. With the data given in the table below and the rules of thumb given above, the dose you receive in the use of a source can be estimated.

For comparison the dose of background radiation:

In the Minnaertbuilding: $0.1\ \mu\mathrm{Sv/hour}$,
At a height of $3000\ \mathrm{m}$: $0.4\ \mu\mathrm{Sv/hour}$.

The maximum acceptable dose is $1\ \mathrm{mSv/year}$, which amounts to $0.5\ \mu\mathrm{Sv/hour}$ at $2000\ \mathrm{hour}$ of exposure per year.

Radioactive sources used in the undergraduate laboratory

Label BU0-	Source Nr	Nuclide	$T_{1/2}$ (year)	Production date	Strength (original) (kBq)	Strength **04-July-11** (kBq)	SGR[1] (μSv m^2/(MBq h))
150	212	Am 241	432.	01-Jan-90	185.	179.	
154	11511	Am 241	432.	01-Jan-90	185.	179.	0.02
155	215	Am 241	432.	01-Jan-90	185.	179.	
333	008/10	Am 241/Be	432.	22-Mar-10	1.85E+07	1.85E+07	(reaction neutron source)
118	47499	Co 57	0.74	01-Dec-03	3.70E+04	3.08E+01	0.03
335	1429651	Co 60	5.27	01-Apr-10	533.	452.	0.36
132	AG864	Cs 137	30.07	05-Feb-86	3831.	2130.	0.10 (via Ba-137m)
116	47391	Fe 55	2.73	01-Nov-03	370.	51.	0.0003
334	1429652	Na 22	2.60	01-Apr-10	398.	285.	0.33
134	EVA106	Ra 226	1600.	01-Jan-87	48.	48.	
135	TV106	Ra 226	1600.	01-Jan-87	333.	330.	
136	W523	Ra 226	1600.	01-Jan-87	333.	330.	
137	20342	Ra 226	1600.	01-Jan-87	185.	183.	
138	12132	Ra 226	1600.	01-Jan-87	185.	183.	
139	17122	Ra 226	1600.	01-Jan-87	185.	183.	
140	6992	Ra 226	1600.	01-Jan-87	185.	183.	
141	14666	Ra 226	1600.	01-Jan-87	185.	183.	
121	B1401	Sr 90	28.8	01-Jun-65	185.	61.	
122	31422	Sr 90	28.8	01-Jan-69	185.	66.	
123	13950	Sr 90	28.8	01-Jun-80	185.	87.	
124	19280	Sr 90	28.8	01-Jan-85	185.	98.	(electron emitter)
125	18395	Sr 90	28.8	01-Jan-89	185.	107.	
126	15981	Sr 90	28.8	01-Jan-89	185.	107.	
127	19926	Sr 90	28.8	01-Jan-89	185.	107.	
143-149		Th 232[2]	1.40E+10	01-Jan-87	185.	185.	0.36 (7x squeeze bottle)

[1] SGR: specific gamma-ray constant

[2] 7 $\times$ PE squeeze bottles containing Thoriumoxide

§ I.8 Equivalent dose and dosimeter readings

We consider here only *X*-ray and γ radiation (electromagnetic radiation), which, because of its potential penetration depth, will be most often encountered in the practice. The *equivalent dose* for exposure to electromagnetic radiation from an external point source is given by (see § I.4),

$$\text{Eq. dose/time} = 1.25 \times 10^{-4} \frac{(E/[\text{MeV}])(A/[\text{kBq}])}{(d/[\text{m}])^2}\ \mathbf{\mu Sv/h}. \tag{4}$$

Note the work format of this equation where the relevant physical quantities are made dimensionless by dividing the quantity explicitly by the applicable unit and specifying the unit for the result. The unit $\mathbf{\mu Sv/h}$ can be directly expressed in the more easily recognized unit $\mathbf{J/(kg\ s)}$:

$$\text{Eq. dose/time} = \frac{1.25 \times 10^{-10}}{3600} \frac{(E/[\text{MeV}])(A/[\text{kBq}])}{(d/[\text{m}])^2}\ \mathbf{J/(kg\ s)}. \tag{5}$$

In this equation the absorption by human tissue is taken into account. However, in working with a *pen dosimeter* a different unit is encountered, **R** (*Röntgen*) which in terms of SI-units is given by

$$1\ \text{R} = 2.58 \times 10^{-4}\ \text{C/kg}. \tag{6}$$

To relate the two quantities (*equivalent dose* and *dosimeter reading* in $\mathbf{C/kg}$) it is important to recognize the relationship between *delivered (absorbed) energy* and the *equivalent charge released by processes of ionization* in the absorption of the radiation in a dosimeter.

In air it takes *effectively* about $33.7\ \mathbf{eV}$ of energy to release one electron *e* ($\widehat{=}\ 1.6 \times 10^{-19}\ \mathbf{C}$). Using this information the formula given above for the equivalent dose can be converted in $\mathbf{C/(kg\ s)} \rightarrow \mathbf{R/s}$ (Note: absorption properties of energetic electromagnetic radiation by biological material are very similar to absorption in air; can you explain why?):

$$\begin{aligned}
\text{Eq. charge/time} &= \left(\frac{1.25 \times 10^{-10}}{3600}\right) \frac{(E/[\text{MeV}])(A/[\text{kBq}])}{(d/[\text{m}])^2} \left(\frac{1.6 \times 10^{-19}[\text{C}]}{33.7 \times 1.6 \times 10^{-19}[\text{J}]}\right) \mathbf{J/(kg\ s)} \\
&= \left(\frac{1.25 \times 10^{-10} \times 10^3}{3600 \times 33.7 \times 2.58 \times 10^{-4}}\right) \frac{(E/[\text{MeV}])(A/[\text{kBq}])}{(d/[\text{m}])^2}\ \mathbf{mR/s} \\
&= \left(\frac{1.25 \times 10^{-10} \times 10^3 \times 37}{3600 \times 33.7 \times 2.58 \times 10^{-4}}\right) \frac{(E/[\text{MeV}])(A/[\mu\text{Ci}])}{(d/[\text{m}])^2}\ \mathbf{mR/s} \\
&= 1.48 \times 10^{-7} \frac{(E/[\text{MeV}])(A/[\mu\text{Ci}])}{(d/[\text{m}])^2}\ \mathbf{mR/s},
\end{aligned} \tag{7}$$

where we used the conversion

$$1\ \mu\text{Ci} = 37\ \text{kBq}. \tag{8}$$

Example: consider a source with the following characteristics:

$A = 1\ \mu\text{Ci}$ (source strength)
$E = 1\ \text{MeV}$ (energy per emitted photon)
$d = 1\ \text{cm}$ (distance to source)

The *equivalent dose* amounts to:

$\frac{1.25 \times 10^{-4} \times 37}{(0.1)^2}\ \mathbf{\mu Sv/h}\ \approx\ 0.5\ \mathbf{\mu Sv/h}$ (which amounts to legal limit for *continuous* exposure).

Under these circumstances we need exposure over a period of almost 19 hours for a dosimeter to register $1\ \mathbf{mR}$.

Literature: de Bruin, M. "*Straling en stralingsdetectie*" (Radiation and radiation detection)

§ I.9 Safety regulations and precautions

The following rules/precautionary measures need to be observed **unconditionally** when you use a radioactive sample:

- The sources are located in a safe in Kruyt W225. The safe is normally locked: contact an assistant in case you need to use a radioactive source. Every person who uses a source is personally responsible for returning it to the safe as soon as possible (but in any case that same day).
- Only use a source when it is really needed. Never leave a source unattended (on a table or anywhere else).
- Only handle a source with the tweezers specifically meant for this purpose.
- Take extra care with sources that are covered with a thin foil (in some cases the thickness of this foil is less than 0.1 mm).
- Never remain longer than strictly necessary inside the circle indicated around the neutron source in Kruyt W225.
- Alert the amanuensis or assistant immediately, when there is any suspicion whatsoever that radioactive material may have been released. As a first measure in that case, use the control monitor to check your hands for radioactive contamination.