

# RADIOACTIVE DECAY

(57)

The radioactive decay of naturally occurring minerals containing uranium and thorium are in large part responsible for the birth of the study of nuclear physics.

These decay have HALF-LIVES of the order of the age of Earth, suggesting that the materials are survivors of an early period in the creation of matter by aggregation of nucleus; the shorter-lived nuclei have long since decayed away, and we observe today the remaining long-lived decays.

In addition to the naturally occurring radioactivity, we have also the capability to produce radioactive nuclei in laboratory through nuclear reactions.

This was done firstly by Irene Curie and Pierre Joliot in 1934, they used  $\alpha$  particle from the natural radioactive decay of Polonium (Po) to bombard aluminium, producing the isotope  $^{30}\text{P}$  (Phosphorus) which they observe to decay through the emission of positron emission with a HALF-TIME of 2.5 minutes.  $\alpha + \text{Po} \rightarrow ^{30}\text{P} \rightarrow \beta^+$  decay

For this work the Curie-Joliot team was awarded with the nobel prize for CHEMISTRY in 1935.

## THE RADIOACTIVE DECAY LAW

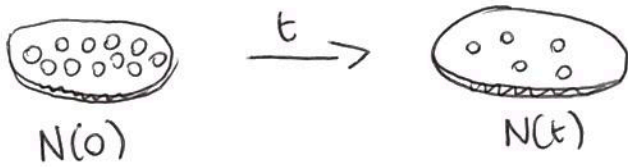
All the nuclei are "unstable". When <sup>they</sup> decay, they can undergo different decays ( $\alpha, \beta, \gamma$ ) but all of them follows the same exponential law. The exponential decay was observed after 3 years from the discovery of radioactivity in 1896.

It took several more years to understand that radioactivity represents changes in the individual atoms and not a change in the sample as a whole.

It took another 2 years to realize that the decay is statistical in nature.

That is impossible to predict when any given atom will disintegrate, and that this hypothesis leads directly to the exponential law. The lack of predictability does not bother most scientists today, but this early instance of it, before the developments of quantum theory, was apparently difficult to accept.

Let's suppose to have a certain sample of radioactive nuclei ( $N$ )



The number of decaying nuclei ( $dN$ ) in a certain time interval  $dt$  is proportional to  $N$ :

$$\frac{dN}{dt} \propto N \quad \Rightarrow \quad \frac{dN}{dt} = -\lambda N$$

The more we have the most probable is to observe a decay

Proportionality constant  
The sign  $\ominus$  indicates that the nuclei decay  
 $\lambda = \text{DISINTEGRATION CONSTANT} / \text{DECAY CONSTANT}$

$\lambda = \boxed{-\frac{dN/dt}{N}} \Rightarrow$  The probability to decay is ~~this is~~ a constant, regardless of the age of the atoms: this is the basic assumption of radioactive decay.

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

$$\int_{N_0}^N \frac{dN}{N} = -\lambda \int_{t=0}^{t=t} dt$$

$$\ln\left(\frac{N}{N_0}\right) = -\lambda t \quad \frac{N}{N_0} = e^{-\lambda t}$$

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

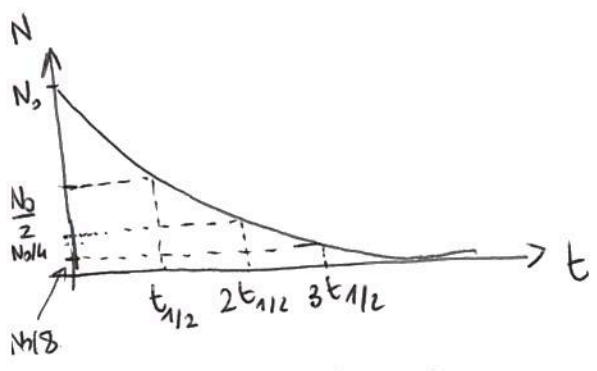
Exponential law of radioactive decay

$N_0$  gives the original number of nuclei present at time  $t=0$   
 $\lambda$  is a characteristic of the material.

Other quantity which is useful to define is the HALF-TIME. Half time is defined as the period of time necessary for half of the nuclei present in the sample to decay.

$$N \rightarrow \frac{N_0}{2} \quad N(t) = N_0 e^{-\lambda t} \quad \frac{N_0}{2} = N_0 e^{-\lambda t_{1/2}} \quad e^{\lambda t_{1/2}} = 2$$

$$\lambda t_{1/2} = \ln 2 \quad \boxed{t_{1/2} = \frac{0.69}{\lambda}} \quad \equiv \text{HALF-LIFE } (t_{1/2})$$



It is also useful to consider the mean lifetime (or sometimes lifetime)  $\tau$ .  $\tau$  is defined as the average time that a nucleus is likely to survive before it decays. The number of nuclei that survive to time  $t$  is just  $N(t)$ , and the number that decay between  $t$  and  $t+dt$  is  $|dN/dt|dt \Rightarrow$

$$\tau = \frac{\int_0^{\infty} t |dN/dt| dt}{\int_0^{\infty} |dN/dt| dt} = \frac{1}{\lambda}$$

↑ TOTAL NUMBER OF DECAYS

We define probability density function

$$1 = \int_0^{\infty} c \cdot N_0 e^{-\lambda t} dt = c \cdot \frac{N_0}{\lambda}$$

$$c = \frac{\lambda}{N_0}$$

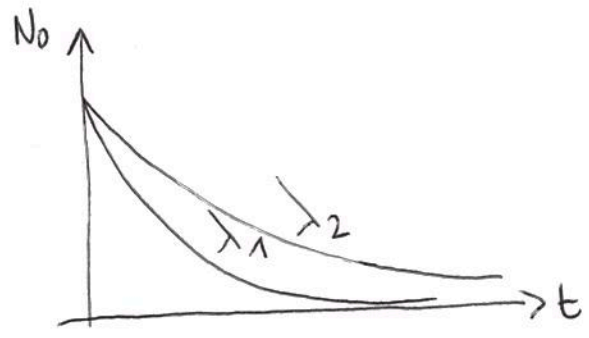
$$\tau = \langle t \rangle = \int_0^{\infty} t \cdot c \cdot N_0 e^{-\lambda t} dt = \int_0^{\infty} \lambda t e^{-\lambda t} dt$$

\* parts

$\Rightarrow$  lifetime is the inverse of decay constant.

$$t_{1/2} = \frac{0.69}{\lambda} = \tau \cdot 0.69 \Rightarrow \boxed{\tau = 1.44 t_{1/2}}$$

Mean lifetime > half-time =  $\frac{1}{\lambda}$



$$\lambda_1 > \lambda_2$$

$$\tau_1 < \tau_2$$

The exponential decay law allows us to predict the number of undecayed nuclei of a given type remaining after a time  $t$ . Unfortunately the law is limited useful because  $N_0$  is very difficult to measure.

Instead of counting the number of undecayed nuclei in a sample, it is easier to count the number of decays (by observing emitted radiations) that occurs between time  $t_1$  and time  $t_2$ .

Introducing the change  $\Delta N$  in the number of nuclei between  $t$  and  $t + \Delta t$

$$|\Delta N| = N(t) - N(t + \Delta t) = N_0 e^{-\lambda t} (1 - e^{-\lambda \Delta t})$$

If the interval  $\Delta t$  during which we count is  $\ll \lambda^{-1}$  ( $\Rightarrow \Delta t \ll t_{1/2}$ ) the high order terms in the expansion of the second exponential can be ignored,

$$|\Delta N| = \lambda N_0 e^{-\lambda t} \Delta t$$

Going differentials:

$$\left| \frac{dN}{dt} \right| = \lambda N_0 e^{-\lambda t}$$

Defining the activity  $A$  as the rate at which decays occurs in the sample

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

The initial activity  $A_0$  at  $t=0$  is  $A_0 = \lambda N_0$ .

The activity could have been obtained directly from the decay law formula, but in such way it should be more clear that measuring the number of counts  $\Delta N$  in a time interval  $\Delta t$  gives the activity of the sample ONLY IF  $\Delta t \ll t_{1/2}$ .

The number of decays in the interval from  $t_1$  to  $t_2$  is

$$\Delta N = \int_{t_1}^{t_2 = t_1 + \Delta t} A(t) dt$$

which is equals to  $A \cdot \Delta t$  only if  $\Delta t \ll t_{1/2}$

(i.e. if  $t_{1/2} = 1s \Rightarrow$  we observe the same # of counts in 1 min and in 1hr)

The activity of a radioactive sample is exactly the number of decays of the sample per unit time and decay/s is a good unit of measure, which is in the S.I. : Bq = 1 Becquerel = 1 decay/s.

Historically, the activity is also defined using the Curie (Ci) which counts the activity of 1 gram of radium:

$$1 \text{ Ci} = 3.7 \times 10^{10} \text{ decays/sec}$$

Note that the activity tells us the # of disintegrations per second; it says nothing about the kind or radiation emitted or their energy.

If we want to know about the effect of radiation on biological systems the activity is not a useful quantity.

It is important to note that the simple exponential law applies only to a limited number of circumstances. Under these circumstances, when a radioactive nucleus 1 decays with decay constant  $\lambda_1$  to STABLE nucleus 2, the number of present nuclei is:

$$N_1 = N_0 e^{-\lambda_1 t}$$

$$N_2 = N_0 (1 - e^{-\lambda_1 t})$$

The number of nuclei  $N_2$  starts at 0 and approaches  $N_0$  as  $t \rightarrow \infty$ ;  $N_1 + N_2 = N_0$ . If nuclei 2 are radioactive themselves then these simple equations do not apply.

Often it can happen that a given initial nucleus can decay in two or more different ways, ending in 2 different final states. The rate of decay into model a is determined by the partial decay constant  $\lambda_a$ , while decay mode b by the  $\lambda_b$  constant:

$$\lambda_a = -\frac{(dN/dt)_a}{N}$$

$$\lambda_b = -\frac{(dN/dt)_b}{N}$$

The total decay rate  $\frac{dN}{dt}$  is:

$$-\left(\frac{dN}{dt}\right)_t = -\left(\frac{dN}{dt}\right)_a - \left(\frac{dN}{dt}\right)_b = N(\lambda_a + \lambda_b) = N\lambda_t$$

Where  $\lambda_t = \lambda_a + \lambda_b$  is the total decay constant. Nuclii decay following the equation:

$$N = N_0 e^{-\lambda_t t}$$

We will NEVER observe an exponential decay of the activity with constant  $\lambda_a$  or  $\lambda_b$ . The relative decay constant  $\lambda_a$  or  $\lambda_b$  determine the probability for the decay to proceed by mode a or b

$$N_1 = N_0 e^{-\lambda_t t}$$

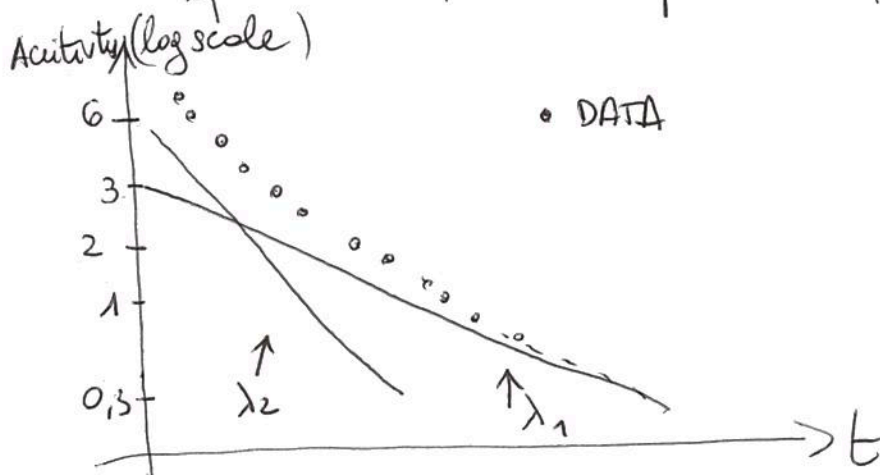
$$N_{2,a} = \left(\frac{\lambda_a}{\lambda_t}\right) N_0 (1 - e^{-\lambda_t t})$$

$$N_{2,b} = \left(\frac{\lambda_b}{\lambda_t}\right) N_0 (1 - e^{-\lambda_t t})$$

We cannot turn-off one decay in nature, thus  $\lambda_a$  and  $\lambda_b$  will never appear separated, and only ratios are possible.

Another special case where we can use the exponential law is represented by a mixture of isotopes with 2 different life time:

eg.  $^{64}\text{Cu}$  (12.7h)  $^{61}\text{Cu}$  (3.4h) such mixture cannot be chemically separated, but studying the activity it is possible to understand which fraction of the sample is formed by the 2 isotopes.



Assuming that at large t only the contribution for the longest-living isotope is present is possible to fix  $\lambda_1$  and then, by fitting, extract the  $\lambda_2$  contribution.

2 Problems that can be solved using the activity exponential law (60)

PROBLEM 1

A sample of  $^{14}\text{C}$ , whose lifetime is 5730 y, has a decay rate of 14 disintegration per minute per gram of natural carbon.

A fossil is found to have a radioactivity of 4 disintegrations per minute per gram of its present carbon. How old is the fossil?

→ APPLICATION OF RADIOACTIVE DECAY LAW

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

$$R_0 = 14$$

$$R = 4$$

$$\Rightarrow 4 = 14 e^{-\lambda t} \quad e^{-\lambda t} = \frac{4}{14}$$

$$\lambda t = \ln\left(\frac{14}{4}\right)$$

$$t = \tau \ln\left(\frac{14}{4}\right) = 5730 \text{ y} \cdot \ln\left(\frac{14}{4}\right) \approx 7178 \text{ y} \\ \approx 10^4 \text{ y}$$

PROBLEM 2

Given that the half time of thorium is  $14 \cdot 10^{10}$  years, calculate the time period required for 10% thorium to be disintegrated

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

10% disintegrated  $\Rightarrow$  90% remains

$$\Rightarrow N(t) = 0,90 N_0 = \frac{90}{100}$$

$$\frac{9}{10} N_0 = N_0 e^{-\lambda t}$$

$$\lambda t = \ln\left(\frac{10}{9}\right)$$

$$\frac{0,69}{t_{1/2}} t = \ln\left(\frac{10}{9}\right) \Rightarrow t = \frac{1,4 \cdot 10^{10} \text{ y}}{0,69} \cdot \ln\left(\frac{10}{9}\right)$$

$$= 2,1 \cdot 10^9 \text{ y}$$

# QUANTUM THEORY OF RADIO ACTIVE DECAY

The energy levels obtained by solving Schrödinger equation for time-independent potentials are all STATIONARY STATES: a state which is stationary will NEVER make transition (i.e. decay) to other states.

We can allow a quantum system to be found sometimes in one state and sometimes in another state by making a mixture  $\psi = a\psi_1 + b\psi_2$  with probability  $|a|^2$  and  $|b|^2$  for  $\psi_1$  and  $\psi_2$ .

The time independent potentials,  $V_1$  and  $V_2$  are independent from time  $\Rightarrow$  do not correspond to decaying states.

$\Rightarrow$  We have to follow another way to solve the problem. The potential is assumed to be of the form  $V + V'$  where  $V$  is the potential which gives stationary states and  $V'$  is a weak additional potential that can cause transitions between states.

If we solve the Schrödinger equation neglecting  $V'$ , we obtain the static  $\psi$ . These wave functions can be used to calculate the transition probability between states.

The probability is the decay constant  $\lambda$ , and it is given by Fermi's golden rule:

$$\lambda = \frac{2\pi}{\hbar} |V'_{fi}| \rho(E_f)$$

where  $V'_{fi} = \int \psi_f^* V' \psi_i d\tau$ . Given the initial and final states functions  $\psi_i$  and  $\psi_f$ , it is possible to evaluate the "matrix element" of  $V'$  and then evaluate the transition probability.

$\rho(E_f)$  also influence the transition probability.

$\rho(E_f) \equiv$  DENSITY OF FINAL STATES. It is the number of states per unit energy intervals at  $E_f$ . It has to be included because if final state  $E_f$



is a single isolated state  $\Rightarrow$  the decay probability will be much smaller than it would be in the case of a large number of states near  $E_f$ . 61

The number of final states accessible for the decay is

$$dN_f = g(E_f) dE_f$$

There are 2 components to the density of final states: 1) the final nuclear state 2) the emitted radiation. Let's consider in turn each of the 2.

1) Nuclear state:

Solving Schrodinger equation for time-independent potential  $V$  gives us the stationary state of the nucleus:  $\Psi_a(\vec{r})$ . The time dependent w.f. is:

$$\Psi_a(\vec{r}, t) = \Psi_a(\vec{r}) e^{-i E_a t / \hbar} \quad (1)$$

$E_a$  = Energy of the state.

The probability of finding a state in "a" is  $|\Psi_a(\vec{r}, t)|^2$  which is time-independent.

To be consistent with the radioactive decay law (i.e. probability to decay which goes like  $e^{-t/\tau}$ )

$$|\Psi_a(t)|^2 = |\Psi_a(t=0)|^2 e^{-t/\tau_a} \quad \tau_a = \frac{1}{\lambda_a}$$

Equation (1) can be rewritten as:

$$\Psi(\vec{r}, t) = \Psi(\vec{r}) e^{-i E_a t / \hbar} e^{-t/\tau_a}$$

Including the "real" exponential term has a price: we lose the ability to determine exactly the energy of the state.

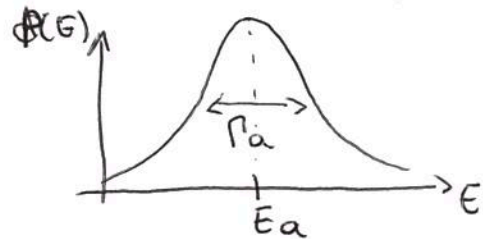
(Heisenberg energy-time uncertainty principle: If we the state lives forever  $\Rightarrow \Delta t \rightarrow \infty \Rightarrow$  The energy is determined without error because  $\Delta E \rightarrow 0$ )

If the state lives on average for a time  $\tau$ , its energy is undermined:

$$\Delta E \sim \frac{\hbar}{\tau}$$

The discussion can be more rigorous calculating the distribution of energy states. The probability to observe in the energy interval between  $E$  and  $E+dE$  in proximity of  $E_a$  is given by square distribution:

$$P(E)dE = \frac{dE}{(E-E_a)^2 + \Gamma_a^2/4}$$



↑  
Width of the  
state  $a \Leftrightarrow$  inability to determine  
 $E_a$  precisely

If we cannot determine the energy of the nuclear states, can we speak of transitions between distinct levels? Yes, because the width of nuclear levels are small compared with their energy spacing.

Nuclear states have a lifetime  $\gtrsim 10^{-12}$  s  $\Rightarrow \Gamma < 10^{-10}$  MeV while the separation energy is of the order of  $\approx 10^{-3}$  MeV

$\Rightarrow$  It is reasonable to speak of discrete pseudo-stationary states because their separation is larger than their width

$\Rightarrow$  The nuclear states do not contribute to the density of final states, because there is only one state that can be reached in a given decay process.

It is then the

2) Emitted Radiation that contributes to  $\rho(E_f)$ !

Finally we can make some general comments regarding  $\rho(E_f)$ .

If we observe only the probability to form the nuclear state  $E_f$ , then we must consider all possible radiations of energy  $E_i - E_f$ .

The radiation can be emitted in ANY direction and in ANY state of polarization.

To solve the equation of decay law we assumed  $\lambda$  to be 1) small (64)  
 2) constant in time. These two conditions are the same made to derive Fermi's Golden Rule. If  $V'$  is time independent, also  $\lambda$  will be time independent, and the effect of  $V'$  is

$$\Psi_a \rightarrow \Psi_a + \frac{V'_{ba}}{E_b - E_a} \Psi_b$$

Probability to decay of a SINGLE NUCLEUS

And the system has a probability  $|V'_{ba}|^2$  to be found in state  $b$ : this can be seen on the decay probability.

To apply Fermi's Golden Rule, the probability of decay must be small, so that the amplitude of  $\Psi_b$  is small. If the decay probability were large then there would have been enough radiation to induce reverse transition  $b \rightarrow a$  through the resonance absorption process, and the system would then oscillate.

The final connection between the effective decay probability for an ensemble of a large number of nuclei and the microscopic decay probability computed from Q.M. of a single nucleus requires the assumption that each nucleus of the ensemble emits its radiation independently of all the others. We assume that the decay of a given nucleus is independent of the decay of its neighbors.

This assumption then allows us to have a confidence that the decay constant we measure in laboratory can be compared with the results obtained by Q.M. calculations.

# MEASURING RADIATION

The activity of a radioactive sample does not depend on the type of radiation or its energy.

⇒ Activity might be useful to compare two sources of the same isotope, but we can't compare different decays.

So what can we do?

Nuclear radiations have the common property of ionizing atoms with which they interact.

Let's start from X-rays and  $\gamma$ : Photons interact with the atoms of the air through many processes (Compton scattering, P.E. effect, pair production), each of them create an  $e^-$  of relatively high energy. The secondary electrons create other electrons.

The total electric charge  $Q$  on the ions produced in a given mass  $m$  of air is called exposure  $x$

$$x = \frac{Q}{m} \left[ \frac{C}{kg} \right]$$

charge of ions      AND MASS

More often the roentgen (R) unit is used. R is defined as the exposure resulting in an ionizing charge of 1 electrostatic unit in 1  $cm^3$  of air at  $T=0^\circ$  and 760 mm Hg of pressure ( $\Rightarrow m = 1,293 \cdot 10^{-6}$  kg)

$$1R = 2,58 \cdot 10^{-4} \frac{C}{kg}$$

Assigning one unit of electric charge to each ion, an exposure of 1R means that

$$\frac{2,5 \cdot 10^{-4} C/kg}{1,6 \cdot 10^{-19} C} = 1,61 \times 10^{15} \frac{\text{ion}}{kg} = 28 \cdot 10^9 \frac{\text{ion}}{cm^3}$$

are formed. To form a ion air  $\approx 34$  eV are needed  $\Rightarrow$  An exposure of 1R results in an energy absorption by the air of  $\approx 7,8 \cdot 10^{10} \frac{eV}{cm^3}$

A 1 MeV  $\gamma$  rays will produce  $\approx 30,000$  electrons/ions. A radioactive (63)

source will generally produce many  $\gamma$  at different energies

The exposure resulting from the source will depend on the number of decays and on the intensity and energy of each  $\gamma$ -ray.

The exposure will also depend on the ACTIVITY of the source, and on how far we are from that.

$$\underbrace{\frac{\Delta X}{\Delta t}}_{\text{EXPOSURE RATE}} = \Gamma \frac{A}{d^2}$$

↑ activity  
↑ distance from the source  
↑ constant

↳ depends on the nucleus which emits the  $\gamma$

Usually  $d$  is taken  $\approx 1 \text{ m}$   $\Rightarrow$  The unit of  $\Gamma = \frac{\text{R}}{\text{h}} / \frac{\text{Ci}}{\text{m}^2}$

Different materials react differently to the absorbed energy, so we

have to define ABSORBED DOSE (D). The unit of D is the 'rad':

(radiation absorbed dose) The S.I. unit of D is Gray (Gy)  $\equiv 1 \text{ J/kg}$

$$1 \text{ Gy} = 100 \text{ rad}$$

To define standards for radiation protection of human beings, it is necessary to have some measurement of biological effects to

different kinds of radiations.

The relative biological effectiveness (RBE), or the ratio of the dose of a certain radiation to the dose of x-rays that produces the same biological effect. RBE ranges from 1 (to x-rays) up to 20

for  $\alpha$ . RBE is difficult to measure, usually the quality factor QF is used. QF is calculated for a given type of radiation according to the energy deposited for unit length. It ranges on

The RBE.

The effect of a certain radiation on a biological system then depends on the absorbed dose  $D$  and on the quality factor  $QF$  of the radiation. The dose equivalent  $DE$  is obtained multiplying

the 2:

$$DE = D \cdot QF$$

The unit of  $DE$  is rem (roentgen equivalent man) and in the SI unit is the Sievert (Sv).  $1 \text{ Sv} = 100 \text{ rem}$

$1 \text{ rem} = 10^{-2} \text{ Sv}$

EXERCISE:

The human body contains on average about 18% of carbon and 0,27% of potassium.

Compute the intrinsic activity of the average person from  $^{14}\text{C}$  and  $^{40}\text{K}$ .

(Assume  $m_{\text{human}} \approx 70 \text{ kg}$ ; 0,012% of Potassium is  $^{40}\text{K}$ ;  $\frac{^{14}\text{C}}{^{12}\text{C}} = 1,3 \times 10^{-12}$ )

$t_{1/2}(^{14}\text{C}) = 5730 \text{ y}$        $t_{1/2}(^{40}\text{K}) = 1,25 \cdot 10^9 \text{ y}$

$$m(^{14}\text{C}) = 70 \text{ kg} \cdot 0,18 \cdot 1,3 \cdot 10^{-12} = 1,64 \cdot 10^{-11} \text{ kg} = 1,64 \cdot 10^{-8} \text{ g}$$

$$N(^{14}\text{C}) = \frac{N_A}{A} \cdot m(^{14}\text{C}) = \frac{6,023 \cdot 10^{23}}{14} : 1,64 \cdot 10^{-8} = 7,05 \cdot 10^{14} \text{ ptc}$$

$$A(^{14}\text{C}) = \frac{\ln 2}{5730 \cdot 3,14 \cdot 10^7 \text{ s}} \cdot 7,05 \cdot 10^{14} = 2760 \text{ Bq}$$

$\approx 3 \cdot 10^3$        $\Rightarrow \sim 3000 \text{ Bq/seconds}$

$$m(^{40}\text{K}) = 70 \text{ kg} \cdot 0,27 \cdot 1,2 \cdot 10^{-4} = 2,27 \cdot 10^{-5} \text{ kg} = 2,27 \cdot 10^{-2} \text{ g}$$

$$N(^{40}\text{K}) = \frac{6,023 \cdot 10^{23}}{40} \cdot 2,27 \cdot 10^{-2} = 3,4 \cdot 10^{20} \text{ ptc}$$

$$A(^{40}\text{K}) = \frac{\ln 2}{1,25 \cdot 10^9 \cdot 3,14 \cdot 10^7 \text{ s}} \cdot 3,4 \cdot 10^{20} = 6030 \text{ Bq}$$

$\approx 6000 \text{ Bq/s}$

"NATURAL DOSE"  
 $\approx 370 \text{ Bq/kg}$

$^{14}\text{C}$  is  $\approx 1/2$  of all the genetic cells;  $^{40}\text{K}$  is not a DNA component (64)

A  $^{14}\text{C}$  atom decays inside DNA  $\approx 50$  times  $\times$  seconds  $^{14}\text{C} \rightarrow ^{14}\text{N} + \bar{\nu} + e^-$

### EXERCISE

Calculate the internal dose per year that you receive from the  $^{14}\text{C}$  contained in your body. The  $^{14}\text{C}$  emits  $\beta^-$  radiation with an energy of 152 keV. The  $t_{1/2} (^{14}\text{C}) = 5730 \text{ y}$

$$D = \frac{E}{M} \cdot A = \frac{152 \text{ keV}}{70 \text{ kg}} \cdot 2720 \text{ Bq} = 5910 \frac{\text{keV}}{\text{kg} \cdot \text{s}}$$

$$1 \text{ eV} = 1,6 \cdot 10^{-19} \text{ J}$$

$$D = 9,5 \cdot 10^{-13} \frac{\text{J}}{\text{kg} \cdot \text{s}} = 9,5 \cdot 10^{-13} \frac{\text{Gy}}{\text{s}}$$

$$D(1 \text{ y}) = 9,5 \cdot 10^{-13} \text{ Gy/s} \cdot 3,14 \cdot 10^7 \text{ s} = 3 \cdot 10^{-5} \text{ Gy} = 30 \mu\text{Gy}$$

### EQUIVALENT

Dose limit:

- general public = 0,5 rem =
- working with radiation = 5 rem

Dose for x-ray of the chest = 0,05 rem  
of tooth = 0,002 rem

Killing dose: 100 rem (From WWII nuclear bomb)

FOR  $\beta^-$   $QF = 1 \Rightarrow$  Because of  $^{14}\text{C}$  we receive  $30 \mu\text{Si} \equiv 30 \cdot 10^{-6} \cdot 10^{-2} \text{ rem} = 3 \cdot 10^{-5} \text{ rem}$