RADIOACTIVITY INDUCED IN TISSUES BY 600 MeV PROTONS

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GENEVA
1966
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M. Barbier, A. Hutton *) and A. Pasinetti **)
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ACKNOWLEDGEMENTS

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FIGURES
1. DEFINITION OF THE PHYSICAL PARAMETERS DESCRIBING INDUCED RADIOACTIVITY IN TISSUE

It is convenient to define parameters which are dependent on the activated material only, and independent of the experimental arrangement.

1.1 Induced activity per gram and unit flux at zero cooling time under saturation conditions

The activity per gram at cooling time $t_c$ for a target element $i$ with atomic number $A_i$, irradiated for a time $t_i$ in a flux $\Phi$ (expressed in particles per second and cm$^2$) is

$$\left( \frac{dn_s}{dt} \right) = \Phi \frac{N}{A_i} \sigma_i \left[ 1 - \exp \left( -\frac{0.693 t_i}{t_{1/2,s}} \right) \right] \exp \left( -\frac{0.693 t_c}{t_{1/2,s}} \right)$$

where $N = 6 \times 10^{-23}$ is Avogadro's number, $\sigma_s$ the production cross-section of the radioactive isotope $s$ considered, and $t_{1/2,s}$ the half-life of this isotope. At zero cooling time and with infinite irradiation time (saturation) the exponential functions on the right vanish. We will always refer to zero cooling time and saturation values when defining material parameters. So, when summing up over-all target constituents $i$, each present with a weight fraction $a_i$, we find for a particular isotope $s$

$$\left( \frac{dn_s}{dt} \right)_{t_c = 0} = \Phi N \sum_i a_i \frac{\sigma_{s,i}}{A_i} = \Phi C_s$$

where

$$C_s = N \sum_i a_i \frac{\sigma_{s,i}}{A_i}.$$
$C_s$ is thus a first characteristic parameter of the material constituting the target for the production of the particular isotope $s$. It is expressed in disintegrations per gram per sec per unit flux.

1.2 Counting rate and dose rate of a counter embedded in a large radioactive volume for unit flux, saturation, and zero cooling time

Once an object has a given activity it is useful to determine what is the radiation received from this object, which can have a given size and thickness, at a given distance, taking into account the kind of radiation emitted and its absorption in the object itself. Then this is what one measures experimentally.

For simplicity, we remain at saturation and zero cooling time.

Let $\epsilon_{s,k}$ be the probability of emission per decay of a particular radiation of type $k$ by isotope $s$, and $\mu_k/\rho$ the $1/e$ attenuation length in $g \text{ cm}^{-2}$ of this particular radiation in the target material.

Further, let $\Omega$ be the solid angle under which the detector used sees the radioactive body or sample.

One can prove that if the radioactive body is large compared to the attenuation length of the radiation emitted in the decay process, the number of quanta of this radiation per unit surface of the counter per unit time, i.e. the counting rate, at a location from which the radioactive body is seen under a solid angle $\Omega$, is given by

$$r = \frac{\bar{\phi}}{4\pi} \sum_i \frac{a_i}{A_i} \sum_s \left( \sum_k \frac{\epsilon_{s,k} \rho}{\mu_k} \right) \sigma_{s,i} \text{ sec}^{-1} \text{ cm}^{-2},$$

where summation over $i$ extends to all target constituents, over $s$ to all isotopes produced, and $k$ to all types of radiation emitted by these isotopes. $N$ is again Avogadro's number, $\bar{\phi}$ the irradiating flux, and $\sigma_{s,i}$ the production cross-section of isotope $s$, from target constituent $i$. Finally, $a_i$ is the weight fraction of target constituent $i$. The equation holds for $t_0 = 0$, $t_1 = \infty$. 

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p/ga
Here we recognize our previously-defined parameter $C_s$, so that $r$ becomes

$$r = \frac{1}{16\pi} \sum_s \sum_K \frac{\epsilon_{s,K} \rho}{\mu_K} C_s.$$

It is convenient to define as the relevant material constant

$$K_s = \sum_K \frac{\epsilon_{s,K} \rho}{\mu_K} C_s$$

from which we get the counting rate of a 1 cm$^2$ counter per second

$$r = \frac{1}{16\pi} \sum_s K_s \text{ sec}^{-1} \text{ cm}^{-2}.$$

Thus, $K_s$ is the flux of radiation quanta from the decay of isotope $s$ received by a unit surface viewing the radioactive body under a solid-angle $4\pi$ for unit irradiation flux, saturation conditions, and zero cooling time. Clearly, the formula is valid only for small $\Omega/4\pi$ values in this form giving a flux of radiation quanta per unit surface. However, it leads to a formula valid for solid angles, as large as desired, if one considers a counting volume presenting the same area in any direction, or if one goes over to absorbed doses instead of fluxes of radiation quanta across a surface, because the doses add algebraically.

Let $f_K$ be the factor indicating the number of radiation quanta of type $\kappa$ through the unit surface that will give an absorbed dose of 1 rad. Then we find the absorbed dose rate in rad/h from the radioactive sample to be at zero cooling time.
of bone and tissue of $3.0 \times 10^{-4}$ disintegrations/sec/g/unit flux. Converting this to rads of incident flux, we consider a very short irradiation time and apply the formula

$$\left( \frac{dn}{dt} \right)_{t=0} = \phi \cdot \frac{t_i}{t_{i/2}} \cdot 0.693 \left[ 2.5 \times 10^{-4} \right].$$

Thus for $t_i = 1$ sec, $\phi = 1$ rad/sec = $2.7 \times 10^7$ protons/cm²/sec, we find

$$\left( \frac{dn}{dt} \right)_{t=0} = 1.22 \times 10^{-3} \text{ disintegrations/g/rad of incident irradiation,}$$

which compares favourably with Legeay's value:

$$\left( \frac{dn}{dt} \right)_{t=0} = 0.73 \times 10^{-3} \text{ disintegrations/g/rad of incident irradiation.}$$

iv) $^{11}C$ in hair: Charalambus and Rindi defined a factor $K_1$ for $^{11}C$ in hair where

$$K_1 = \frac{1}{60C_s},$$

whence

$$C_s = \frac{1}{60K_1}.$$

For hair they find $K_1 = 0.93 \times 10^2$ with protons of 600 MeV. We now correct for $\eta, \epsilon$ to compare values of $C_s$. We put for $^{11}C$, $\epsilon = 2$. Charalambus and Rindi's counter, a scintillation box, had an efficiency of $\eta = 0.17$ (private communication). So we find from Charalambus' data $C_s = 5.4 \times 10^{-4}$, which agrees with our data for muscle = $5.0 \times 10^{-4}$.

5.2 Values found from beta counts

From the counts of the specimen irradiated for 20 minutes, we have calculated an independent estimate of the $C_s$ values for the various tissues and plexiglas, using the beta counter calibration for our special set-up described in Appendix B.
Table 7 gives the $C_s$ values found from the beta counts. They compare favourably with the $C_s$ values from the gamma counts given in the previous table.

6. DETERMINATION OF THE $C_s$, $K_s$ AND $L_s$ VALUES FOR THE WHOLE BODY FROM THE $C_s$ VALUES FOUND EXPERIMENTALLY FOR THE VARIOUS KINDS OF TISSUES

From the results obtained in the previous section ($C_s$ values for each kind of tissue) we can calculate a weighted value of the constants $C_s$, and subsequently $K_s$ and $L_s$, for the whole body. For this calculation we have taken the percentages for bone, muscle, and fat in the average human adult body, and lumped the rest of the weight as parenchymatous tissue, as indicated in Table 8.

Table 9 presents the weighted values of $C_s$ for the whole body. We have used the $C_s$ values from gamma counts, as listed in Table 6.

From these experimental values of $C_s$ found by the superposition of the data obtained directly from the various tissues exposed to the irradiation, one shall now calculate the other relevant parameters $K_s$ and $L_s$ for the whole body, which give the counting rate and the dose rate taking into account the absorption of the radiation emitted by the body itself.

Table 10 gives the constants $K_s$ and $L_s$ for the whole body. The $L_s$ values have been computed on the basis of the gamma counts only (which include the annihilation radiation from the $\beta^+$'s produced far from the surface), as one can check that in this case of radioactive tissue the contribution to the dose from the $\beta^-$ and $\beta^+$ escaping from the surface amounts to a few per cent only.

7. IRRADIATION EXPERIMENT OF MICE IN A 600 MeV PROTON BEAM

In order to check the values obtained for the whole body by calculation from the results of the sample and tissue irradiations, we have
irradiated five mice, denominated A, B, C, D, E, with doses equal to 60, 900, 1200, 15,000 and 240,000 rads (the flux-to-rad conversion factor used was $2.7 \times 10^7$ protons cm$^{-2}$ per rad, which is valid at 600 MeV).

For the gamma measurements, we simply laid each mouse on the cap of the NaI(Tl) crystal. For the beta measurements we put the surface of the body of the mouse at the same distance from the counter as we did the surfaces of the various samples and tissues. We also registered the dose rate in mrad/h at the surface of mice D and E with a Teletector total 6112 of Foerstner, Ledenburg.

Figure 6 shows the $\gamma$ decay curves and also the dose rates measured under these conditions, and Fig. 7 gives the registered $\beta$ decay curves.

From the gamma decay curves, we have read off the activity values at cooling times of 30 min, 4 h, 15 h, 100 h, and reduced them to unit flux in order to be able to compare the results from all the mice. Table 11 presents these results which will be directly used in the next section.

8. COMPARISON OF THE EXPERIMENTAL DATA FROM THE IRRADIATION OF MICE WITH VALUES EXPECTED USING THE WHOLE-BODY PARAMETERS COMPUTED IN SECTION 6

8.1 Gamma counts

What we have done here is to calculate the gamma counts expected from the mice on the NaI(Tl) crystal using the $K_s$ values from Table 10 in order to compare them with the counts found experimentally. However, several corrections have to be made, due to the small size and particular geometry of the mice, which prevents us from using directly the theory valid for an infinite active body.

The following points are here of interest:

1) **Area.** The surface area of the mouse in contact with the crystal was in fact 22.5 cm$^2$. 

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p/gs
ii) **Thickness of mice.** The theory was calculated for an infinite body; for a man this will lead to an error of perhaps 10%; for a mouse of thickness 2 cm the correction to be applied for lack of attenuation is large. This correction is calculated from the theory of the dose rate experienced in front of an infinite radioactive layer of finite thickness, as given in Appendix B. The fact that the mouse body has not an infinite surface will, in fact, give a discrepancy which we will demonstrate later by a special calibration experiment.

iii) **The efficiency of the counter is defined as counts registered per disintegration in a point source.** By definition of our constant $K_3$, we calculate the number of photons leaving per unit surface of mouse. The efficiency we require is then the number of counts registered on the counter per total number emitted from the surface area of the mouse. So we have to multiply the old efficiency by a factor equal to the area of the mouse in contact with the counter divided by 2, as half of the photons go into the other half-space. For more details, see also Appendix B.

With these precautions we arrive at the expected number of counts for all the mice using the former $K_3$ values and the known irradiation fluxes and times, as shown in Table 12. These computed values are then compared with the mean experimental values for all mice from Table 10.

As we notice, the calculated sum is always higher by a factor 2 or 3 than the experimental mean.

To decide upon this point, we carried out a special calibration experiment. A small bag having the form of the mouse was filled with an equal weight of $K_2CO_3$. As one knows, natural potassium contains a certain proportion of natural $^{40}K$, which has a known emission rate for a gamma of 1.46 MeV. Using the same theoretical attenuation curve and calibration rules as before, we found experimentally a number of counts which was 2.57 times smaller than expected. This explains at least partially the discrepancy apparent in the last two columns of Table 12.
As an over-all conclusion one can say that the mice experiment confirms rather well the predictions for $K_3$ made on the basis of the measurements of the various samples of tissue.

8.2 Beta counts

To compare the beta counts from the irradiation of mice, we have followed a line somewhat different from the one taken with the gamma counts. Here we have directly reduced the experimental curves as well as could be done to give the value of parameter $C_3$. This we could do rather well for the $^{11}C$ counts in all mice, and for the $^{24}Na$ and $^{32}P$ counts in the most irradiated mouse B. The $^{16}F$ value could not be differentiated from the $^{11}C$ in all cases, which also introduces an error in the $^{11}C$ values. Table 13 presents the data together with the $C_3$ values for muscle from Table 7. The $\beta$ counts on mice are especially difficult to interpret because of the geometry involved. In view of this, the agreement is rather satisfactory.

It is obvious that the gamma counts give a better reading than the beta counts since the number of counts is higher.

8.3 Rad/hour counts

The geometry involved when counting the dose-rate in rad/h near the body of a mouse with the Relektor-type ionization chamber is somewhat intricate and merits a geometrical calculation. The mouse was $2b = 8$ cm long, and could be considered as a cylinder of radius $r = 1.5$ cm. The centre of the sensitive volume of the counter chamber when the counter face was in contact with the mouse's body was then $x = h_6$ cm from the axis of the mouse. We shall now assume that the whole mass of the mouse is concentrated on the cylinder axis and calculate the radiation field at 4 cm from the middle of this axis. Let $A$ be the total activity in photons/sec of the mouse, equally distributed on the axis. The registered counts $n$ at a distance $x$ from the axis is then
\[ n = \frac{A}{2b} \int_{-b}^{b} \frac{dz}{4\pi(x^2 + z^2)} \]

where \( z \) is the running coordinate along the axis. We find

\[ \frac{n}{A} = \frac{1}{4\pi b} \arctg \frac{b}{x} \]

where \( b \) is the half-length of the mouse, as geometrical efficiency of our arrangement. With this correction we arrive at the following experimental results taken at a cooling time of \( t_c = 3 \) h. The rad/h measured with our set-up reduced to unit flux were \( 2.27 \times 10^{-16} \) for mouse E and \( 2.5 \times 10^{-16} \) for mouse D. The whole-body \( C_3 \) values from Table 9, together with the correction factor just calculated for our set-up, would yield a predicted dose-rate of \( 2.74 \times 10^{-16} \) rad/h per unit flux.

9. PERSONNEL DOSIMETRY BY INDUCED ACTIVITY MEASUREMENTS ON THE BODY IN CASE OF RADIATION ACCIDENTS

9.1 Types of accidental exposures

Two sorts of accidental exposures could be considered as limiting cases. First, accidental exposure of short duration, at a high radiation level; second, unnoticed exposure of long duration at a low radiation level. The first occurs when a person is exposed to an accelerator beam or happens to enter a radiation area without noticing the danger, or if a sudden burst of radiation is released accidentally. The exposure is sometimes limited to one part of the body, as in the case of a beam. The other type of exposure can happen in the case of insufficient shielding.

The data derived in the earlier sections covers both kinds of accidents. In the case of a short burst, one must apply the mathematical treatment given in Section 1.3. In the case of a long irradiation, all isotopes, and not only the \(^7\)Be, can contribute to the knowledge, provided the measurements are taken sufficiently soon after the irradiation.
9.2 Practical measurement methods

Experimental procedures for investigating the radioactivity in the human body are numerous. We can quote here several of these, three of which are of particular interest because of their simplicity, and which apply to gamma counts from the whole body or a part of the body.

The first is the 1-metre radius arc method, in which the patient sits on a couch, the general line of which is approximately a circle of 1 m radius, at the centre of which is the counter.

The second is by placing the crystal on top of the thighs at the crotch and having the subject bent over the crystal so that the body almost completely surrounds the crystal. This also gives less background because of the shielding of the counter by the body itself.

The third is by placing the counter in contact with a part of the body. It is thus possible to make a plot of the distribution of the activity over each part of the body, as may be required in cases of local irradiation.

The fourth method is, of course, to place the person in a whole-body counter which has been suitably calibrated.

One can either note the total counts, and plot them, or take gamma-ray spectra and follow them in time.

Measurements of the induced activity in the human body, properly treated according to the general formula given in Section 1 and the calibration rules given in Appendix B, should normally yield the flux of particles $\phi$ to which the man has been subjected, provided the irradiation time is known, or the flux integral $\int \phi(t) dt$ if the irradiation was of short duration.

9.3 Other irradiating particles

The experiments we have made were with a pure beam of 600 MeV protons. It is known that the spallation cross-sections for light-weight elements do not vary appreciably with energy above this value, so that our results should also be valid for protons of kinetic energies above 600 MeV.
In all the high-energy region, where radioactivity is induced mainly by nuclear spallation reactions, it is also known from nuclear chemistry work that the nuclear reaction cross-sections for neutrons and pions are practically equal to those for protons. Figure 8 shows a plot of the total inelastic cross-sections of the elements versus their atomic number for protons, neutrons, and pions of either sign. As one can see, they lie practically all on the same straight line. The total inelastic cross-sections for bombardment with H\textsubscript{2}, He\textsubscript{3}, and He\textsubscript{4} ions are also shown. They lie on a line parallel to the preceding one, a factor 2.4 higher up. Thus our results are also applicable to these particles; the fluxes calculated with our formula for protons have only to be divided by a factor 2.4 to find the actual ones, as the activity per particle will be correspondingly higher.

9.4 Calculation of the absorbed dose in tissue from the flux measurement

From the knowledge of the flux times irradiation time yielded by the activity measurements, one has now to deduce the dose in rads which this flux has actually produced in the tissue that it entered.

Various authors have investigated the number of particles per cm\textsuperscript{2} falling normally on the surface of water, which will produce 1 rad absorbed dose at this surface. Figure 9 shows these fluxes in rad\textsuperscript{-1}cm\textsuperscript{-2} plotted as a function of energy from 1 to 10\textsuperscript{5} MeV for neutrons, pions, protons and deuterons, and alphas (this last curve is valid in carbon, not water).

Using the curves in Fig. 9, one can immediately tell the surface dose received in rads in tissue, for a flux time integral deduced from the induced radioactivity.

Another point of interest is that the surface dose is not necessarily the highest absorbed dose which occurs in the subject's organs. Actually there is some build-up of the number of high-energy particles penetrating through matter, because of the production of secondaries. Also, charged particles can be decelerated to less than the minimum ionization energy and ionize more. Measured dose build-up curves for
a pure 600 MeV proton beam, a pion spectrum with energies up to 70 MeV, and a neutron spectrum with energies up to 600 MeV are shown in Fig. 10. They are all reduced to 1 at the surface. These curves give an idea of the dose which can be received in organs at a given depth below the surface of the body. They are valid for irradiating fluxes normal to the surface.

9.5 Biological damage to tissue

The absorbed dose in rads which gives the energy deposited per gram of tissue, is not sufficient, at the high energies considered by us, to give an idea of the biological damage involved. For this, a knowledge of the radiobiological efficiency of the corpuscular radiation is required. This factor, multiplying the absorbed dose in rads, gives the equivalent dose to produce a similar biological damage with X-rays. The result is the so-called rem-dose.

At low energies (up to a few MeV) charged particles mainly deposit energy by ionization, and the rad and rem doses coincide. However, as the charged particle energy increases, nuclear reactions are always more frequent and the radiobiological efficiency is found to increase. Neutral particles are found to have a radiobiological efficiency very different from one at all energies.

Up to the present, the RBE is not well known at high energies. Computations up to 400 MeV for protons and neutrons, and some experiments up to 900 MeV with protons and neutrons exist. One experimental point exists for pions at 80 MeV. From all this data, both theoretical and experimental, which are represented by points in Fig. 11, we have tentatively drawn the dotted curves, partly inspired by the curves of Fig. 9, in an attempt to predict the rem-values for the various particles up to 1 GeV. Above this energy, no serious prediction can apparently now be made.
9.6 Construction of the typical gamma decay curve of
body activity for short-burst irradiation and
unit time flux integral using a 3" x 3" NaI(Tl) crystal.

The calculation of dose from a short burst of irradiation proceeds
on the basis of the photon flux per cm$^2$ of the detector, which was

\[ r = \frac{\phi}{t_i} \cdot \frac{\Omega}{4\pi} \cdot \sum K_s \exp \left( -\frac{t_a}{T_s} \right) \cdot \frac{0.693}{T_s^{1/2}} \text{ counts/sec}. \]

We take here $\phi t_i = 1$ part/cm$^2$ and $\Omega/4\pi = 1/2$. The number of counts
registered will be $r$ times the efficiency of the counter. This efficiency
$\eta$ is different for each isotope and is defined as the number of counts
per disintegration. For our purposes we will measure $r \cdot \eta \cdot a$, where $a$
is the area of the counter (here 45 cm$^2$). Table 14 contains the whole-
body $K_s$ times $0.693/T_s^{1/2}$,s values and the $\eta$ values.

We computed the theoretical curve for unit integrated flux, i.e.
1 proton/cm$^2$, which we present in Fig. 12. Then for any case of
irradiation we can determine the dose by comparison.

The sensitivity of the method depends on the isotope which can be
measured, in other words on the time one waits after the irradiation
to make the measurements. It also depends whether one uses total
counts of the counter, or takes a spectrum.

A typical background for a 3" x 3" crystal pressed against a man's
chest and shielded by a lead cylinder of 2 cm thickness in our labora-
tory room is 120 counts/sec. If one takes a spectrum, the sum of the
background counts in the channels under the 0.51 MeV peak amount to
10 c/sec, and the peak-to-total ratio for 0.51 MeV is 0.65.

Let us assume we do the measurement two hours after the burst
irradiation, and measure the 0.51 MeV peak from $^{11}$C and $^{18}$F. By com-
parison with the scale in Fig. 12, we see that the background conditions
are equivalent to an integrated flux of $1.2 \times 10^8$ protons/cm$^2$, cor-
responding to a 4.5 rad or 12 rem dose in the case of total counts, and
of $1.5 \times 10^7$ protons/cm$^2$, corresponding to a 0.6 rad or 1.5 rem dose in
the case where we take the spectrum.
ACKNOWLEDGEMENTS

Thanks are due to Mr. F. Hoffmann for help in the experiments, in various computations, and for drawing the graphs.

* * *
From the irradiation experiment of natural calcium (Section 4) we obtained the sum of the cross-sections for production of $^{24}\text{Na}$, $^{43}\text{K}$, and $^{28}\text{Mg}$ which have comparable half-lives. By applying Rudistam's formula, $^{28}\text{Mg}$ can be shown to be produced in negligible quantities and also their effect will be small because the number of gammas per disintegration is small.

To separate the $^{24}\text{Na}$ and $^{43}\text{K}$ isotopes, we have taken an energy spectrum. The counts in the two $^{24}\text{Na}$ peaks and the two $^{43}\text{K}$ peaks were integrated and multiplied by the total-to-peak ratios for the particular energies taken from Fig. 13, which is valid for a 3" x 3" NaI(Tl) crystal.

For $^{24}\text{Na}$ from natural calcium, considered as formed only of $^{40}\text{Ca}$, we arrive at a value of 1.7 mb.

For the isotope $^{43}\text{K}$, which cannot be made by spallation from $^{40}\text{Ca}$, we assume that the parent is the $^{44}\text{Ca}$, which has a natural occurrence of 2.06%. With this weighing factor we find a cross-section of 25 ± 3 mb.
COUNTING EFFICIENCY

B.1 Efficiency of the gamma counter

Figure 14 shows the efficiency of the gamma counter versus gamma-ray energy for a non-absorbing thin source placed on the top of the crystal housing. The efficiency \( \eta \) is defined counts per gamma emitted in the source. We read off the efficiency to be \( \eta = 0.27 \) for \( E_Y = 0.51 \text{ MeV} \) (\(^{11}\text{C}, ^{18}\text{F}, ^{7}\text{Be}\)). For \(^{24}\text{Na}\), which emits two photons with energies \( 1.37 \) and \( 2.75 \text{ MeV} \) we take a mean value of \( \eta = 0.18 \).

B.2 Efficiency of the beta counter

First the dead-time correction is applied as usual, with the factor \( 1/(1-nt) \), \( n \) being the number of counts per second and \( t \) the dead-time in seconds, here \( 2 \times 10^{-4} \).

As we have often to deal with thick samples, which cause some gamma background counts, we decided to use a \( 4 \text{ mm aluminium plate} \) as screen and call beta counts the difference between the numbers measured without and with this screen. The sample surface was also a circle with a diameter of \( 2.2 \text{ cm} \) placed at \( 1.5 \text{ cm} \) from the front face of the counter tube, which had itself a diameter of \( 2.8 \text{ cm} \) (Philips GW 18536 tube).

We have now to define the efficiency of our beta counter, and we do it as follows. We call this efficiency the number of counts registered per beta particle leaving the surface.

We have now to find experimentally the efficiency for our particular tube and geometrical arrangement as a function of maximum beta-ray energy emitted in the decay.

This we did by comparison with the gamma counter, whose efficiency is known, using isotopes which are both beta and gamma emitters such as \(^{11}\text{C}, ^{18}\text{F}, ^{24}\text{Na}\) and \(^{40}\text{K}\), of effectively infinite thickness for the betas. The theory of the comparison is given below. We use the following symbols:
\[ A = \text{activity/g of sample} \quad \rho = \text{density} \]
\[ t = \text{thickness} \quad a = \text{area} \]
\[ \mu_\beta = \text{attenuation coefficient for electrons} \]
\[ \eta_\gamma = \text{efficiency of gamma counter in c/disintegration} \]
\[ \eta_\beta = \text{efficiency of beta counter in c/particle leaving surface} \]
\[ \epsilon_\gamma = \text{number of gamma per disintegration} \]
\[ \epsilon_\beta = \text{number of beta per disintegration} \]
\[ n_\gamma = \text{counts measured on gamma counter (c/g)} \]
\[ n_\beta = \text{counts measured on beta counter (c/g)} \]

Then the number of disintegrations is \( MA \), and we have

\[ \eta_\gamma = \frac{n_\gamma}{MA \epsilon_\gamma} = \frac{N_\gamma}{A \epsilon_\gamma} \]

where \( N_\gamma \) is the number of \( \gamma \) counts per gram. For "infinite" sample, the number of betas leaving the surface per unit area is

\[ \frac{1}{2} A \cdot \frac{2\mu_\beta}{\mu_\beta} \]

For finite samples we apply an attenuation factor \([E]\), so that

\[ \eta_\beta = \frac{n_\beta \cdot 2\mu_\beta}{A \rho \cdot \epsilon_\beta \cdot \epsilon_\gamma} \cdot \frac{1}{[E]} \]

and

\[ \frac{\eta_\beta}{\eta_\gamma} = \frac{n_\beta \cdot 2 \cdot \mu_\beta}{\rho \cdot \epsilon_\beta \cdot \epsilon_\gamma} \cdot \frac{\epsilon_\gamma}{N_\gamma} \cdot \frac{1}{[E]} \]

\[ \frac{\eta_\beta}{\eta_\gamma} = \frac{2}{a} \cdot \frac{\mu_\beta}{\rho} \cdot \frac{n_\beta}{N_\gamma} \cdot \frac{\epsilon_\gamma}{\epsilon_\beta} \cdot \frac{1}{[E]} \]

Now the attenuation factor \([E]\) can be measured as a function of sample thickness with increasing quantities of KCl, containing the natural \( ^{40} \text{K} \) isotope.
The experimental result of the efficiency measurement with various thicknesses of KCl as a function of the thickness $t$ times $\mu$ is shown in Fig. 15. This curve is to be normalized to 1, for infinite thickness.

Measurements were now made with artificial sources of $^{14}$C, $^{19}$F and $^{24}$Na with results as presented on Fig. 16, which shows the efficiency of our $\beta$ counting arrangement as a function of the maximum beta-ray energy produced in the decay. These efficiencies lay between 0.45 and 0.56 counts per particle leaving the surface.

B.3 Correcting factors to be applied to counting rates for finding the constant $C_s$

The beta counter efficiency was simply defined as counts per particle leaving the surface. Let $(\frac{dn}{dt})_{t=0} = 0$ be the total number of counts from the isotope $s$ registered on the counter at zero cooling time. Then we have

$$\left( \frac{dn_s}{dt} \right)_{t=0} = \frac{\eta_s}{2} \cdot \left( \frac{E}{\mu} \right) \cdot \epsilon_\beta \cdot a \cdot [E] \cdot A$$

where $[E]$ is the attenuation factor to allow for the finite thickness of the sample, and $A$ is the activity per gram, that is,

$$A = C_s \Phi \left[ 1 - \exp \left( \frac{0.693 t_1}{t_{1/2}} \right) \right]$$

and $a$ is the area of the sample. So we find the constant $C_s$ from the experimental results, as follows:

$$C_s = \frac{(\frac{dn_s}{dt})_{t=0}}{\epsilon_\beta \eta_\beta} \left( \frac{\mu}{\rho} \right) \cdot \frac{2}{a} \cdot \frac{1}{[E]} \cdot \frac{1}{\Phi} \cdot \frac{1}{1 - \exp \left( \frac{0.693 t_1}{t_{1/2}} \right)}$$

$$C_s = (a_{s})_{t=0} \left[ \left( \frac{\mu}{\rho} \right) \cdot \frac{1}{\epsilon_\beta} \cdot \frac{1}{\eta_\beta} \cdot \frac{2}{a} \cdot \frac{1}{\Phi} \cdot \frac{1}{1 - \exp \left( \frac{0.693 t_1}{t_{1/2}} \right)} \right] \cdot [E]$$

* * *
CALCULATION OF DOSE TO TISSUE
FROM THE DECAY OF THE RADIOACTIVE
ISOTOPES FORMED THEREIN BY PRIMARY FLUX

For each radio-nuclide we can calculate the total number \( a_s \) of disintegrations per gram of tissue taking place during an infinite time. As the decay is exponential, we simply have to multiply by the delay constant \( T = 0.693 \ t_{1/2} \) and we find

\[
a_s = \left( \frac{dn}{dt} \right)_{t_c = 0} \cdot T.
\]

We then multiply by \( \varepsilon_{s,\gamma} \), which is the number of photons per disintegration of type \( \gamma \) from isotope \( s \).

Then we multiply by the energy of the \( \gamma \) rays expressed in ergs, giving the total energy \( e \) of the radio-nuclides of the type \( s \)

\[
e = a_s \cdot \sum \varepsilon_{\nu} E_{Y,\nu},
\]

summing over all photon-types \( \nu \) emitted by isotope \( s \).

We remember that 1 rad corresponds to an energy deposit of 100 erg/g^2. Let \( c \) be the conversion factor

\[
c = 10^2 \ \text{erg g}^{-1} \ \text{rad}^{-1}.
\]

We assume that the dose \( d_s \) from isotope \( s \) deposited in a cubic centimetre is equal to all the energy radiated by the radio-nuclides located in this same cm^3. This means we have an infinite medium and neglect surface effects. So we have

\[
d_s = c^{-1} a_s \sum \varepsilon_{s,\nu} E_{Y,\nu} \ \text{rads}.
\]
The total dose will be
\[ d = \sum_s c_s \frac{1}{4000} \sum_s a_s \left( \sum_{\nu} \epsilon_{s,\nu} E_{\gamma,\nu} \right) \]

Let us now consider that the flux is on for a very short time \( t_i \ll T \). Then
\[ a_s = \left( \frac{dn}{dt} \right) T_s = \bar{\Phi} C_s \frac{t_i}{T_s} \quad T_s = C_s \Phi t_i \]

where \( \bar{\Phi} t_i \) is total dose in numbers of protons/cm.

Using the accepted value 1 rad = 2.7 \times 10^7 protons/cm at 600 MeV, we can compare the dose \( d \) from \( \gamma \) rays from spallated nuclides with the incident dose \( d_0 \) assumed given in a short time. We seek the ratio

\[ \frac{d}{d_0} = \frac{\text{dose from induced activity}}{\text{dose from activating flux}} = \frac{\text{dose from induced activity in rad per rad of incident flux}} \]

and find

\[ \frac{d}{d_0} = \left( \frac{2.7 \times 10^7}{4000} \right) \sum_s C_s \left( \sum_{\nu} \epsilon_{s,\nu} E_{\gamma,\nu} \right) \]

\[ \frac{d}{d_0} = \left( 2.7 \times 10^5 \right) \sum_s C_s \left( \sum_{\nu} \epsilon_{s,\nu} E_{\gamma,\nu} \right) \]

where \( C_s \) is the constant derived in Section 1, i.e., the number of disintegrations per gram per incident flux particle/cm for a spallated isotope \( s \), and \( \epsilon_{s,\nu} \) is the number of photons of type \( \nu \) from isotope \( s \) with energy \( E_{\gamma,\nu} \).

Table I gives the values of this ratio for the isotopes \(^7\text{Be}, ^{11}\text{C}, ^{24}\text{Na}\), and their sum.

One sees that \( d/d_0 \) has the order of magnitude \( 10^{-5} \) for these main isotopes. Another contribution of the same order is expected from the betas.

* * *
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Elements distribution in total body of the standard man, Health Physics 2, 146 (1960).
Table 1

Percentages by weight of various tissues in whole body of an average human adult

<table>
<thead>
<tr>
<th>Tissue</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bone without marrow</td>
<td>10</td>
</tr>
<tr>
<td>Fat</td>
<td>14.9</td>
</tr>
<tr>
<td>Muscle</td>
<td>43.7</td>
</tr>
<tr>
<td>Blood</td>
<td>7.7</td>
</tr>
<tr>
<td>Kidneys</td>
<td>0.43</td>
</tr>
<tr>
<td>Liver</td>
<td>2.4</td>
</tr>
<tr>
<td>Skin and subcutaneous tissue</td>
<td>8.7</td>
</tr>
</tbody>
</table>

Table 2

Chemical composition of tissues in the human adult in % of weight

<table>
<thead>
<tr>
<th>Element</th>
<th>Whole body</th>
<th>Bone</th>
<th>Fat</th>
<th>Muscle</th>
<th>Kidney</th>
<th>Liver</th>
<th>Hair</th>
<th>Skin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen</td>
<td>65.0</td>
<td>40</td>
<td>11</td>
<td>71</td>
<td>71.6</td>
<td>72.3</td>
<td>23.6</td>
<td>66.7</td>
</tr>
<tr>
<td>Carbon</td>
<td>18.0</td>
<td>7.7</td>
<td>77</td>
<td>5.8</td>
<td>4</td>
<td>15.5</td>
<td>49.1</td>
<td>11.6</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>10.0</td>
<td>5</td>
<td>12</td>
<td>9.5</td>
<td>9.4</td>
<td>11.2</td>
<td>7.6</td>
<td>9.8</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>3.0</td>
<td>1</td>
<td>12</td>
<td>9.5</td>
<td>9.4</td>
<td>11.2</td>
<td>7.6</td>
<td>9.8</td>
</tr>
<tr>
<td>Calcium</td>
<td>1.5</td>
<td>14.0</td>
<td>0.007</td>
<td>0.02</td>
<td>0.012</td>
<td>0.012</td>
<td>0.020</td>
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<tr>
<td>Phosphorus</td>
<td>1.0</td>
<td>5.05</td>
<td>0.22</td>
<td>0.14</td>
<td>0.21</td>
<td>&lt;1</td>
<td>0.065</td>
<td></td>
</tr>
<tr>
<td>Potassium</td>
<td>0.2</td>
<td>0.06</td>
<td>0.36</td>
<td>0.175</td>
<td>0.215</td>
<td>0.215</td>
<td>0.107</td>
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<tr>
<td>Sulphur</td>
<td>0.25</td>
<td>-</td>
<td>0.25</td>
<td>-</td>
<td>0.19</td>
<td>3.6</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Sodium</td>
<td>0.15</td>
<td>0.18</td>
<td>0.072</td>
<td>0.175</td>
<td>0.19</td>
<td>0.19</td>
<td>0.16</td>
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<tr>
<td>Chlorine</td>
<td>0.15</td>
<td>0.19</td>
<td>0.066</td>
<td>0.22</td>
<td>0.16</td>
<td>0.16</td>
<td>0.30</td>
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<tr>
<td>Magnesium</td>
<td>0.05</td>
<td>0.105</td>
<td>0.023</td>
<td>0.021</td>
<td>0.022</td>
<td>0.022</td>
<td>0.014</td>
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<td>Iron</td>
<td>0.006</td>
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<tr>
<td>Manganese</td>
<td>0.00003</td>
<td>0.3</td>
<td>0.17</td>
<td>0.05</td>
<td>0.06</td>
<td>0.205</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Copper</td>
<td>0.0002</td>
<td>1.19</td>
<td>0.41</td>
<td>0.125</td>
<td>0.166</td>
<td>0.71</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Iodine</td>
<td>0.00004</td>
<td></td>
<td></td>
<td>0.03</td>
<td></td>
<td></td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Tin</td>
<td>0.00004</td>
<td></td>
<td></td>
<td>0.08</td>
<td></td>
<td></td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Aluminium</td>
<td>0.005</td>
<td>0.5</td>
<td>0.24</td>
<td>0.015</td>
<td>0.042</td>
<td>0.16</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>
Table 3

Production cross-sections for protons with kinetic energy around 600 MeV (millibarns)

<table>
<thead>
<tr>
<th>Isotope Target</th>
<th>$^7$Be</th>
<th>$^{11}$C</th>
<th>$^{13}$N</th>
<th>$^{19}$F</th>
<th>$^{22}$Na</th>
<th>$^{24}$Na</th>
<th>$^{27}$Mg</th>
<th>$^{28}$Mg</th>
<th>$^{31}$Si</th>
<th>$^{32}$P</th>
<th>$^{33}$P</th>
<th>$^{35}$S</th>
<th>$^{38}$S</th>
<th>$^{42}$K</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{12}$C</td>
<td>10</td>
<td>30.7</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>$^{14}$N</td>
<td>11.3</td>
<td>20</td>
<td>4.75</td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{16}$O</td>
<td>10.7</td>
<td>9</td>
<td>6.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{23}$Na</td>
<td>13</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{24}$Mg</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{27}$Al</td>
<td>4.6</td>
<td>3.3</td>
<td>0.36</td>
<td>(7.7)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>$^{32}$S</td>
<td></td>
<td></td>
<td></td>
<td>(7)</td>
<td>(10)</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{35}$Cl</td>
<td></td>
<td></td>
<td></td>
<td>2.2</td>
<td>(4.3)</td>
<td>7.1</td>
<td>0.2</td>
<td>37</td>
<td>6.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{34}$P</td>
<td>(4)</td>
<td>(8.1)</td>
<td>(13)</td>
<td>(5.7)</td>
<td>(1.03)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{39}$K</td>
<td>(2.7)</td>
<td>(4.3)</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{40}$Ca</td>
<td>(1.15)</td>
<td>(3.84)</td>
<td>1.72*</td>
<td>(1.7)</td>
<td>(0.29)</td>
<td>(5.4)</td>
<td>(23.2)</td>
<td>(9.4)</td>
<td>(16)</td>
<td>(0.007)</td>
<td></td>
<td></td>
<td>25*</td>
<td></td>
</tr>
<tr>
<td>$^{44}$Ca</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{53}$Mn</td>
<td>(0.33)</td>
<td>(0.53)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>$^{54}$Fe</td>
<td>(0.29)</td>
<td>(0.46)</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<td></td>
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</tr>
<tr>
<td>$^{63-65}$Cu</td>
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<td>0.03</td>
<td></td>
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<td></td>
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<td></td>
</tr>
</tbody>
</table>

*) measured value, see Appendix A.
Table 4

Constants $C_s = N_0/A$ for pure target elements

<table>
<thead>
<tr>
<th></th>
<th>O</th>
<th>C</th>
<th>N</th>
<th>Ca</th>
<th>P</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{14}C$</td>
<td>$3.38 \times 10^{-4}$</td>
<td>$15 \times 10^{-4}$</td>
<td>$8.6 \times 10^{-4}$</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$^{13}N$</td>
<td>$3.4 \times 10^{-4}$</td>
<td>$2.5 \times 10^{-4}$</td>
<td>$2.0 \times 10^{-4}$</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$^{19}F + ^{31}S$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>$3.1 \times 10^{-5}$</td>
<td>$5.3 \times 10^{-5}$</td>
<td>$3.9 \times 10^{-5}$</td>
</tr>
<tr>
<td>$^{24}Na + ^{28}Mg + ^{43}K$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>$3.7 \times 10^{-5}$</td>
<td>$12 \times 10^{-5}$</td>
<td>$7.8 \times 10^{-5}$</td>
</tr>
<tr>
<td>$^{7}Be$</td>
<td>$4.1 \times 10^{-4}$</td>
<td>$5 \times 10^{-4}$</td>
<td>$4.35 \times 10^{-4}$</td>
<td>$2.53 \times 10^{-4}$</td>
<td>$3.18 \times 10^{-4}$</td>
<td>$2.7 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

The groups $^{19}F + ^{31}S$ and $^{24}Na + ^{28}Mg + ^{43}K$ could not be split into their components during the experiments due to the similarity of half-lives.
Table 5

Weighted $C_s$ values for whole body, also split according to the elements present in the body

<table>
<thead>
<tr>
<th></th>
<th>O</th>
<th>C</th>
<th>N</th>
<th>Ca</th>
<th>P</th>
<th>S</th>
<th>Sum (whole body)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{11}\text{C}$</td>
<td>$2.2 \times 10^{-4}$</td>
<td>$2.7 \times 10^{-4}$</td>
<td>$0.26 \times 10^{-4}$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>$7.23 \times 10^{-4}$</td>
</tr>
<tr>
<td>$^{13}\text{N}$</td>
<td>$1.56 \times 10^{-4}$</td>
<td>$0.45 \times 10^{-4}$</td>
<td>$0.06 \times 10^{-4}$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$^{16}\text{F} + ^{31}\text{Si}$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>$4.65 \times 10^{-7}$</td>
<td>$5.3 \times 10^{-7}$</td>
<td>$0.98 \times 10^{-7}$</td>
<td>$1.09 \times 10^{-6}$</td>
</tr>
<tr>
<td>$^{24}\text{Na} + ^{28}\text{Mg} + ^{43}\text{K}$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>$5.55 \times 10^{-7}$</td>
<td>$12 \times 10^{-7}$</td>
<td>$1.95 \times 10^{-7}$</td>
<td>$1.95 \times 10^{-6}$</td>
</tr>
<tr>
<td>$^7\text{Be}$</td>
<td>$2.67 \times 10^{-4}$</td>
<td>$0.9 \times 10^{-4}$</td>
<td>$0.13 \times 10^{-4}$</td>
<td>$0.04 \times 10^{-4}$</td>
<td>$0.03 \times 10^{-4}$</td>
<td>$0.01 \times 10^{-4}$</td>
<td>$3.78 \times 10^{-4}$</td>
</tr>
</tbody>
</table>
## Table 6

Cs values for various animal tissues and other materials found from the gamma counts

<table>
<thead>
<tr>
<th>Substance</th>
<th>t_{irr}</th>
<th>$^{11}$C + $^{13}$N</th>
<th>$^{16}$F + $^{31}$S</th>
<th>Na + Mg + $^{43}$K</th>
<th>$^{7}$Be</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bone</td>
<td>5 min</td>
<td>$4.5 \times 10^{-4}$</td>
<td></td>
<td></td>
<td>$5.3 \times 10^{-4}$</td>
</tr>
<tr>
<td></td>
<td>20 min</td>
<td></td>
<td></td>
<td>$1 \times 10^{-5}$</td>
<td>$3.5 \times 10^{-4}$</td>
</tr>
<tr>
<td></td>
<td>40 min</td>
<td>$3.5 \times 10^{-4}$</td>
<td></td>
<td>$1.4 \times 10^{-5}$</td>
<td>$3.1 \times 10^{-4}$</td>
</tr>
<tr>
<td></td>
<td>3 h 15 min</td>
<td>$1.2 \times 10^{-5}$</td>
<td></td>
<td>$2 \times 10^{-5}$</td>
<td>$4 \times 10^{-5}$</td>
</tr>
<tr>
<td></td>
<td>7 h 28 min</td>
<td></td>
<td></td>
<td>$1.4 \times 10^{-5}$</td>
<td>$3.1 \times 10^{-4}$</td>
</tr>
<tr>
<td></td>
<td>best value</td>
<td>$4.5 \times 10^{-4}$</td>
<td>$1.2 \times 10^{-5}$</td>
<td></td>
<td>$1.4 \times 10^{-5}$</td>
</tr>
<tr>
<td>Liver</td>
<td>20 min</td>
<td>$5 \times 10^{-4}$</td>
<td></td>
<td>$0.62 \times 10^{-6}$</td>
<td>$2.9 \times 10^{-4}$</td>
</tr>
<tr>
<td>Kidney</td>
<td>20 min</td>
<td>$3.6 \times 10^{-4}$</td>
<td></td>
<td>$0.33 \times 10^{-6}$</td>
<td>$2.4 \times 10^{-4}$</td>
</tr>
<tr>
<td>Muscle</td>
<td>20 min</td>
<td>$5 \times 10^{-4}$</td>
<td></td>
<td>$0.21 \times 10^{-6}$</td>
<td>$2.5 \times 10^{-4}$</td>
</tr>
<tr>
<td>Fat</td>
<td>20 min</td>
<td>$14.3 \times 10^{-4}$</td>
<td></td>
<td></td>
<td>$3.8 \times 10^{-4}$</td>
</tr>
<tr>
<td>Plexiglas</td>
<td>20 min</td>
<td>$13.6 \times 10^{-4}$</td>
<td></td>
<td></td>
<td>$3.4 \times 10^{-4}$</td>
</tr>
<tr>
<td>Carbon</td>
<td>20 min</td>
<td></td>
<td></td>
<td></td>
<td>$4.1 \times 10^{-4}$</td>
</tr>
<tr>
<td></td>
<td>3 h 15 min</td>
<td>$10.9 \times 10^{-4}$</td>
<td></td>
<td></td>
<td>$3.9 \times 10^{-4}$</td>
</tr>
</tbody>
</table>
Table 7

C values for various tissues and other materials found from the beta counts

<table>
<thead>
<tr>
<th></th>
<th>$^{14}C + ^{13}N$</th>
<th>$^{18}F + ^{31}Si$</th>
<th>$^{24}Na + ^{28}Mg + ^{43}K$</th>
<th>$^{32}P + ^{33}P + ^{35}S$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bone</td>
<td>$9.7 \times 10^{-4}$</td>
<td>$4.68 \times 10^{-5}$</td>
<td>$2.07 \times 10^{-5}$</td>
<td>$2.22 \times 10^{-5}$</td>
</tr>
<tr>
<td>Muscle</td>
<td>$4.12 \times 10^{-4}$</td>
<td>$1.83 \times 10^{-6}$</td>
<td>$5.58 \times 10^{-7}$</td>
<td>$4.33 \times 10^{-7}$</td>
</tr>
<tr>
<td>Liver</td>
<td>$5.05 \times 10^{-4}$</td>
<td>$2.26 \times 10^{-6}$</td>
<td>$7.73 \times 10^{-7}$</td>
<td>$5.61 \times 10^{-7}$</td>
</tr>
<tr>
<td>Kidney</td>
<td>$4.97 \times 10^{-4}$</td>
<td>$2.5 \times 10^{-6}$</td>
<td>$8.16 \times 10^{-7}$</td>
<td>$4.33 \times 10^{-7}$</td>
</tr>
<tr>
<td>Fat</td>
<td>$1.41 \times 10^{-3}$</td>
<td>$-$</td>
<td>$-$</td>
<td>$1.9 \times 10^{-7}$</td>
</tr>
<tr>
<td>Plexiglas</td>
<td>$1.83 \times 10^{-3}$</td>
<td>$2.0 \times 10^{-6}$</td>
<td>$5.44 \times 10^{-8}$</td>
<td>$1.7 \times 10^{-7}$</td>
</tr>
</tbody>
</table>

Here we expect that the $^{18}F$ value will be too high due to the $^{31}Si$, which produces few $\gamma$ ($\epsilon = 0.07$), but the $\beta$ produced are of high energy and have a larger effect.
### Table 8
Tissue percentages taken for calculation of whole-body parameters

<table>
<thead>
<tr>
<th>Tissue</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muscle</td>
<td>43%</td>
</tr>
<tr>
<td>Fat</td>
<td>14%</td>
</tr>
<tr>
<td>Bone</td>
<td>10%</td>
</tr>
<tr>
<td>Rest (parenchyma)</td>
<td>33%</td>
</tr>
</tbody>
</table>

### Table 9
Weighted values of $C_s$ for whole body, constructed from the $C_s$ values for the various tissues obtained with the gamma counts

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$^{14}$C + $^{13}$N</th>
<th>$^{16}$F + $^{31}$Si</th>
<th>$^{24}$Na + $^{28}$Mg + $^{43}$K</th>
<th>$^{7}$Be</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muscle</td>
<td>$2.15 \times 10^{-4}$</td>
<td></td>
<td>$0.9 \times 10^{-6}$</td>
<td>$0.99 \times 10^{-4}$</td>
</tr>
<tr>
<td>Fat</td>
<td>$2 \times 10^{-4}$</td>
<td></td>
<td>$1.2 \times 10^{-6}$</td>
<td>$0.53 \times 10^{-4}$</td>
</tr>
<tr>
<td>Bone</td>
<td>$0.45 \times 10^{-4}$</td>
<td>$1.2 \times 10^{-6}$</td>
<td>$1.4 \times 10^{-6}$</td>
<td>$0.38 \times 10^{-4}$</td>
</tr>
<tr>
<td>Other parenchym. tissue</td>
<td>$1.42 \times 10^{-6}$</td>
<td></td>
<td>$1.55 \times 10^{-6}$</td>
<td>$0.89 \times 10^{-4}$</td>
</tr>
<tr>
<td>Sum (whole body)</td>
<td>$6 \times 10^{-4}$</td>
<td>$1.2 \times 10^{-6}$</td>
<td>$3.9 \times 10^{-6}$</td>
<td>$2.8 \times 10^{-4}$</td>
</tr>
<tr>
<td>Expected whole body from Table 5</td>
<td>$7.23 \times 10^{-4}$</td>
<td>$1.09 \times 10^{-6}$</td>
<td>$1.95 \times 10^{-6}$</td>
<td>$3.78 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

The agreement between the two last lines is good.
<table>
<thead>
<tr>
<th>Isotopes</th>
<th>$K_s$ gamma</th>
<th>$L_s$</th>
<th>$K_s$ beta</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{11}C + ^{13}N$</td>
<td>$1.57 \times 10^{-2}$</td>
<td>$1.49 \times 10^{-8}$</td>
<td>$2.9 \times 10^{-5}$</td>
</tr>
<tr>
<td>$^{19}F + ^{31}Si$</td>
<td>$3.05 \times 10^{-5}$</td>
<td>$2.86 \times 10^{-11}$</td>
<td>$8.75 \times 10^{-8}$</td>
</tr>
<tr>
<td>$^{24}Na + ^{28}Mg + ^{43}K$</td>
<td>$1.7 \times 10^{-4}$</td>
<td>$5.92 \times 10^{-10}$</td>
<td>$7.2 \times 10^{-8}$</td>
</tr>
<tr>
<td>$^7Be$</td>
<td>$4.23 \times 10^{-4}$</td>
<td>$4.03 \times 10^{-10}$</td>
<td></td>
</tr>
<tr>
<td>$^{32}P + ^{33}P + ^{35}S$</td>
<td></td>
<td></td>
<td>$9.0 \times 10^{-8}$</td>
</tr>
</tbody>
</table>
Table 11

Registered activities of mice normalized to unit flux at different cooling times, in counts/min

<table>
<thead>
<tr>
<th></th>
<th>Mouse A</th>
<th>Mouse B</th>
<th>Mouse C</th>
<th>Mouse D</th>
<th>Mouse E</th>
<th>Mean value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_c = 30$ min</td>
<td>$5.8 \times 10^{-5}$</td>
<td>$7.1 \times 10^{-5}$</td>
<td></td>
<td></td>
<td></td>
<td>$6.45 \times 10^{-5}$</td>
</tr>
<tr>
<td>$t_c = 4$ h</td>
<td>$2.87 \times 10^{-7}$</td>
<td>$1.06 \times 10^{-7}$</td>
<td>$0.71 \times 10^{-7}$</td>
<td>$1.12 \times 10^{-7}$</td>
<td>$1.05 \times 10^{-7}$</td>
<td>$1.36 \times 10^{-7}$</td>
</tr>
<tr>
<td>$t_c = 15$ h</td>
<td>$1.25 \times 10^{-8}$</td>
<td></td>
<td>$0.94 \times 10^{-8}$</td>
<td>$1.03 \times 10^{-8}$</td>
<td>$0.91 \times 10^{-3}$</td>
<td>$1.03 \times 10^{-3}$</td>
</tr>
<tr>
<td>$t_c = 100$ h</td>
<td></td>
<td></td>
<td>$2.13 \times 10^{-5}$</td>
<td></td>
<td>$2.24 \times 10^{-9}$</td>
<td>$2.18 \times 10^{-9}$</td>
</tr>
</tbody>
</table>

Table 12

Expected number of counts/min for various isotopes and cooling times for whole body per unit flux

<table>
<thead>
<tr>
<th></th>
<th>$^{14}C$</th>
<th>$^{18}F$</th>
<th>$^{24}Na$</th>
<th>$^{7}Be$</th>
<th>Sum</th>
<th>Mean value from experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_c = 30$ min</td>
<td>$2.0 \times 10^{-4}$</td>
<td>$1.7 \times 10^{-7}$</td>
<td>$6.6 \times 10^{-6}$</td>
<td>$4.1 \times 10^{-9}$</td>
<td>$2.06 \times 10^{-4}$</td>
<td>$6.45 \times 10^{-5}$</td>
</tr>
<tr>
<td>$t_c = 4$ h</td>
<td>$1.4 \times 10^{-7}$</td>
<td>$4.4 \times 10^{-8}$</td>
<td>$5.5 \times 10^{-9}$</td>
<td>$4.1 \times 10^{-9}$</td>
<td>$2.4 \times 10^{-7}$</td>
<td>$1.36 \times 10^{-7}$</td>
</tr>
<tr>
<td>$t_c = 15$ h</td>
<td>-</td>
<td>$6.84 \times 10^{-10}$</td>
<td>$3.4 \times 10^{-8}$</td>
<td>$4.1 \times 10^{-9}$</td>
<td>$3.83 \times 10^{-8}$</td>
<td>$1.03 \times 10^{-8}$</td>
</tr>
<tr>
<td>$t_c = 100$ h</td>
<td>-</td>
<td>-</td>
<td>$6.6 \times 10^{-10}$</td>
<td>$4.1 \times 10^{-9}$</td>
<td>$4.75 \times 10^{-9}$</td>
<td>$2.18 \times 10^{-9}$</td>
</tr>
</tbody>
</table>
Table 13

Experimental $C_b$ values deduced from the beta counts of the mice irradiation experiment together with the muscle value from Table 7

<table>
<thead>
<tr>
<th></th>
<th>$^{11}$C + $^{13}$N</th>
<th>$^{18}$F + $^{31}$Si</th>
<th>$^{24}$Na + $^{28}$Mg + $^{43}$K</th>
<th>$^{32}$P + $^{33}$P + $^{35}$S</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$3.59 \times 10^{-4}$</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>B</td>
<td>$1.76 \times 10^{-6}$</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>C</td>
<td>$2.1 \times 10^{-4}$</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>D</td>
<td>$1.68 \times 10^{-4}$</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>E</td>
<td>$1.04 \times 10^{-4}$</td>
<td>$7.74 \times 10^{-7}$</td>
<td>$1.31 \times 10^{-6}$</td>
<td></td>
</tr>
<tr>
<td>Muscle by B counter</td>
<td>$4.12 \times 10^{-4}$</td>
<td>$1.83 \times 10^{-6}$</td>
<td>$5.58 \times 10^{-7}$</td>
<td>$0.433 \times 10^{-6}$</td>
</tr>
</tbody>
</table>

Table 14

Parameters for short-burst irradiation

<table>
<thead>
<tr>
<th></th>
<th>$^{11}$C</th>
<th>$^{18}$F</th>
<th>$^{24}$Na</th>
<th>$^{7}$Be</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_s$</td>
<td>$0.693$</td>
<td>$8.9 \times 10^{-6}$</td>
<td>$3.2 \times 10^{-6}$</td>
<td>$2.2 \times 10^{-9}$</td>
</tr>
<tr>
<td>$\eta$</td>
<td>0.27</td>
<td>0.27</td>
<td>0.18</td>
<td>0.27</td>
</tr>
</tbody>
</table>
Table 15
Ratio of dose from decay of induced activity to incident dose

<table>
<thead>
<tr>
<th>Substance</th>
<th>$^7$Be</th>
<th>$^{14}$C</th>
<th>$^{24}$Na</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bone</td>
<td>$6.56 \times 10^{-6}$</td>
<td>$1.72 \times 10^{-4}$</td>
<td>$19.4 \times 10^{-6}$</td>
<td>$2.0 \times 10^{-4}$</td>
</tr>
<tr>
<td>Liver</td>
<td>$5.68 \times 10^{-6}$</td>
<td>$1.89 \times 10^{-4}$</td>
<td>$3.43 \times 10^{-6}$</td>
<td>$2.0 \times 10^{-4}$</td>
</tr>
<tr>
<td>Kidney</td>
<td>$4.77 \times 10^{-6}$</td>
<td>$1.39 \times 10^{-4}$</td>
<td>$4.97 \times 10^{-6}$</td>
<td>$1.5 \times 10^{-4}$</td>
</tr>
<tr>
<td>Muscle</td>
<td>$5.27 \times 10^{-6}$</td>
<td>$1.89 \times 10^{-4}$</td>
<td>$3.2 \times 10^{-6}$</td>
<td>$1.9 \times 10^{-4}$</td>
</tr>
<tr>
<td>Grease</td>
<td>$7.72 \times 10^{-6}$</td>
<td>$5.46 \times 10^{-4}$</td>
<td>--</td>
<td>$5.5 \times 10^{-4}$</td>
</tr>
<tr>
<td>Flexiglas</td>
<td>$7.04 \times 10^{-6}$</td>
<td>$5.19 \times 10^{-4}$</td>
<td>--</td>
<td>$5.3 \times 10^{-4}$</td>
</tr>
</tbody>
</table>
Figure captions

Fig. a, b: Decay of registered gamma activity of two series of mineral samples irradiated by 600 MeV protons.

Fig. 2: Decay of registered beta activity of two series of mineral samples irradiated by 600 MeV protons.

Fig. 3: Decay of registered gamma activity of various tissues irradiated by 600 MeV protons.

Fig. 4: Decay of registered beta activity of various tissues irradiated by 600 MeV protons.

Fig. 5: Decay of registered gamma activity of bone samples irradiated for different tissues by 600 MeV protons.

Fig. 6: Decay of registered gamma activity and dose rates of mice irradiated by 600 MeV protons.

Fig. 7: Decay of registered beta activity of mice irradiated by 600 MeV protons.

Fig. 8: Total inelastic cross-sections of the elements for various high-energy particles as a function of atomic number.

Fig. 9: Normal fluxes necessary to produce an absorbed surface dose of 1 rad in water (or carbon) for various particles as a function of their kinetic energy.

Fig. 10: Measured dose build-up curve inside water or tissue for 600 MeV protons, pions of 70 MeV energy emitted by a Be target struck by 400 MeV protons, and neutrons emitted by a Be target struck by 600 MeV protons.

Fig. 11: Normal fluxes necessary to produce a biological damage of 1 rem for various particles as a function of their kinetic energy.

Fig. 12: Typical gamma decay curve r, f, a of whole-body activity on a 3" x 3" NaI(Tl) crystal computed for a unit integrated flux of 1 proton/cm² and a solid angle Ω = 2π.

Fig. 13: Total-to-peak ratio in a gamma spectrum taken with a 3" x 3" NaI(Tl) as a function of photon energy.

Fig. 14: Efficiency of the 3" x 3" NaI(Tl) gamma counter in our experimental set-up as a function of gamma-ray energy in counts per photon emitted.
Fig. 15: Efficiency of $\beta$ counter set-up as measured with activated carbon and with natural KCl in counts registered per electron leaving the surface as a function of $\mu t$.

Fig. 16: Counting efficiency of our beta counter set-up as a function of the maximum beta-ray energy emitted in the decay in counts registered per particle leaving the surface.
Minerals

Irrad. time 3 h 15 min
Proton energy 600 MeV
Proton flux $1.8 \times 10^{10} \text{cm}^{-2} \text{sec}^{-1}$
Minerals

Fig 1b

Irrad. time 13 h 51 min
Proton energy 600 MeV
Proton flux $10^9 \text{cm}^2\text{sec}^{-1}$
Minerals  

Fig 2a

Irrad. time 3h15min
Proton energy 600 MeV
Proton flux 1.8 \(10^{10}\) cm\(^{-2}\) sec\(^{-1}\)

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Activity (cpm)</th>
<th>Count Area (cm(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ca</td>
<td>2.77</td>
<td>7.0</td>
</tr>
<tr>
<td>S</td>
<td>4.66</td>
<td>5.7</td>
</tr>
<tr>
<td>Bone</td>
<td>3.73</td>
<td>3.4</td>
</tr>
<tr>
<td>P</td>
<td>2.49</td>
<td>3.8</td>
</tr>
<tr>
<td>C</td>
<td>3.73</td>
<td>3.6</td>
</tr>
</tbody>
</table>
Irrad. time 13 h 51 min
Proton energy 600 MeV
Proton flux $10^9 \text{cm}^{-2} \text{sec}^{-1}$

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Activity</th>
<th>Emission</th>
</tr>
</thead>
<tbody>
<tr>
<td>KCl</td>
<td>2.66 gr</td>
<td>5.7 cm²</td>
</tr>
<tr>
<td>LiCl</td>
<td>1.28</td>
<td>4.6</td>
</tr>
<tr>
<td>Ca</td>
<td>2.58</td>
<td>6.4</td>
</tr>
<tr>
<td>S</td>
<td>2.70</td>
<td>2.0</td>
</tr>
<tr>
<td>P</td>
<td>1.46</td>
<td>2.8</td>
</tr>
</tbody>
</table>
Irrad. time 20 min
Proton energy 600 MeV
Proton flux $10^{10}$ cm$^{-2}$ sec$^{-1}$
Fig 4

Irrad. time  20 min
Proton energy  600 MeV
Proton flux  $10^{10} \text{cm}^{-2} \text{sec}^{-1}$
Sample area  3 cm$^2$
thickness  5 mm

Beta c/min-gr

Bone
Kidney, Liver
Muscle
Fat, Plexiglas

$t_c$
hours
Bone

Proton flux $10^{10} \text{ cm}^{-2} \text{ sec}^{-1}$
Proton energy 600 MeV

$T_i = 5\text{ min} \quad 20 \quad 40\text{ min} \quad 7\frac{1}{2} \text{ h}$
Irrad. time:

A: 1 sec, $1.6 \times 10^9$ Prot/cm$^2$-sec
B: 20 "  $1.2 \times 10^9$ "
C: 2 "  $1.6 \times 10^{10}$ "
D: 20 "  $2.0 \times 10^{10}$ "
E: 5 min, $2.2 \times 10^{10}$ "

Proton energy 600 MeV

Dose rate - mR/h
Mice

Irrad. time:

A:  1 sec, $1.6 \times 10^9$ Prot/cm$^2$sec
B:  20 "  $1.2 \times 10^9$ "
C:  2 "  $1.6 \times 10^{10}$ "
D:  20 "  $2.0 \times 10^{10}$ "
E:  5min, $2.2 \times 10^{10}$ "

Proton energy 600 MeV
Fig. 8

Graph showing the relationship between $\sigma_{inel}$ and $A_T$ for various particles:

- $\bullet$ protons $870$ MeV
- $\circ$ protons $55$ MeV
- $\bigcirc$ neutrons $300$ MeV
- $+$ positive pions $3$ GeV/C
- $-$ negative pions $4.3$ GeV/C
- $\triangle$ deuterons $160$ MeV
- $\ast$ He$_3$ $315$ MeV
- $\blacksquare$ He$_4$ $220$ MeV
- $\square$ He$_4$ $240$ MeV

Legend:
- $2^{1/3}$
- $(38.15 \pi A^{2/3})$
- $(15.9 \pi A^{2/3})$

Fig. II. 5
Fig 10

Build up factor

- 525 MeV neutrons
- 600 MeV protons
- 70 MeV pions

0.2  4  8  12  16  20  24  28  32 g/cm²
Fig 12

Whole body

Na I 3"x 3"

\[ \Omega = 2\pi \]

Integr. flux = 1 proton/cm\(^2\)
Total-to-peak ratio for NaI 3'x3'
Efficiency of NaI crystal at 0.75 cm

Energy of Gamma vs. Efficiency
Efficiency of beta counter

Counts per beta particle leaving the surface

Fig 16

%

$E_{\text{Beta max}}$

$18F$

$11C$

$40K$

$24Na$