INDUCED RADIOACTIVITY IN ACCELERATORS

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INTRODUCTION

A lot of attention has been paid recently to the activation of accelerators. The radioactivity induced by the flux of particles during the operation of the machine remains after the latter has stopped running. It constitutes a permanent danger to staff and restricts access to the equipment for operation, maintenance, repairs and alterations, in a way that is already being felt.

It is beginning to be realized that it is the activation level that will set a practical limit to the beam intensities of future machines. Accelerators are intended for constantly changing experimental work, involving frequent modifications in parts of the machine itself. For a series of investigations the accelerator cannot be operated as a box delivering a beam of primary particles. Depending upon the type of experiments in view, one must expect to run into a «barrier of radioactivity» that will dictate the maximum intensity of the internal beam if the machine is to remain a useful nuclear physics tool.

The principal methods for studying induced radioactivity will be outlined. These include measurements on a radioactive machine, experiments to establish the properties of various materials, and the calculation of radiation fields. Some experimental data collected at the CERN Synchro-Cyclotron will be given as an illustration.

1. ACCELERATOR ACTIVATION SURVEY

The first experiment to perform in order to study induced radioactivity on an accelerator is to measure the radiation level and its decay with time at different points in the machine hall.

Any gamma radiation detector can be used: Geiger-Müller tubes, scintillators, films, ionization chambers. However, as their response varies with energy, they should be calibrated for each radiation spectrum or location against the tissue equivalent ionization chamber, which can indicate the exact dose in rads. Also, the detector used should be fairly omnidirectional, as radiation will come from all directions in a machine hall.

Fig. 1. Lead protected counter.

The next step is to find out which parts of the machine are most active. For this it is necessary to place a collimator in front of the counter and shield it on all sides. Fig. 1 shows a lead protected counter, which can be pointed in any desired direction. If this device is equipped with a NaI crystal activity spectra from specific parts of the machine can be recorded.
Another task which has to be done frequently is to map the intensity of gamma radiation in very hot and possibly inaccessible spots, for instance between the pole pieces of a cyclotron. A plastic scintillator is recommended for very high counting rates. The shape of the scintillator can be spherical, as the counting rate is then independent of the distance from a plane of uniform activity. A plastic sphere, with a hollow light guide and a photomultiplier mounted on the end of a long pole, as used at CERN, is shown in Fig. 2.

For a better understanding of the distribution of activity in the machine, calculations of the flux falling on the pole pieces or accelerating cavities should be made, taking into account target position, mean scattering angle, multiple traversal, and focusing action of magnetic fields. Practical measurements of fluxes in hot regions can be made by placing small samples or wires in the machine to be activated. The distribution of activity along the wires shows the geometrical flux distributions. In this connexion, it is a good idea also to measure the dependence of the activity upon the depth of the activated material. This can be found by examining screws or bolts which were perpendicular to the surface.

Routine surveys should include radiation field measurements in the principal locations each time maintenance is carried out during a shut-down, for instance, in front of thin windows of the vacuum tank. In this way the general variation of the activity of the machine with time can be followed, and it can be stated whether the activation level has reached saturation or whether it will grow in the future, and levels to be expected for a given increase of the internal beam can be predicted.

II. THE PROPERTIES OF VARIOUS MATERIALS WITH RESPECT TO ACTIVATION

The high energy nuclear reaction cross-sections for building one element from another by the impact of a particle have been...
studied to a certain extent by the radiochemists. They form the basis of preliminary activation calculations, but need to be complemented by other experimental investigations on irradiated samples of various materials.

When irradiating samples, several things must be borne in mind. First, the irradiation time must be of the same order as the half-life of the newly formed elements which it is wished to study. Then the size of the sample must be chosen according to the scope of the experiment. Both small and large samples should be used. From small samples one can get the specific activity \( n \) in counts per gram and sec in the solid angle \( 4\pi \), the decay with time, the gamma energy spectral distribution, and the beta-activity. The counter efficiency should be determined with known sources of gamma radiation of several energies. Large samples are also useful because they give an opportunity of also measuring the absorption of the gamma radiation by the active material itself. A cylindrical shape is suitable with a section equal to the section of the detector and a length equal to two or three times the absorption length of the main gamma rays emitted. The sample should be placed on the axis of the detector, but some distance away from it in order to minimize geometrical effects due to the length of the sample. With these samples one can measure the danger parameter \( \frac{n}{\chi} \) (\( \chi \) being the mass absorption coefficient), the shape of the spectrum actually received from large active bodies and the radiological dose to which this spectrum corresponds. It is convenient to place these large samples against the tank wall outside the vacuum chamber and to measure them every maintenance day in order to record the growth of activity.

To illustrate all this, Figs. 3 and 4 show decay curves of various materials exposed to protons (in the cyclotron tank, at some distance from the target but at the same radius) and neutrons (outside the tank in a forward direction). The irradiation times were three months and six weeks respectively. The mean efficiency of the counter in the energy range was 8% so that the counts/gram-sec still have to be multiplied by 12.5 to give the specific activity \( n \) in photons/gram-sec in \( 4\pi \). Although they are interesting, these curves do not represent the exact situation in accelerators, where the irradiation time is much longer.

Definite information can only be expected from samples which have been irradiated to saturation point. In that case the relative position of the decay curves for the various materials and their shape could be completely different from those presented here. Long-term irradiation experiments are now in progress at CERN.

### III. THE CALCULATION OF THE ACTIVITY PER GRAM AS A FUNCTION OF THE FLUX

The purpose of this work is obviously to make it possible to calculate in advance the field of radiation in a given installation which has been exposed to the action of a given flux of high-energy particles. Once the cross-sections are known, one can first determine the activity per gram as a function of the flux received. Supposing the sample has been exposed to a constant flux \( \Phi \) during an irradiation time \( T_i \), then the number of active atoms of the element \( v \) per gram of matter at an instant \( t \) will be equal to

\[
N_v = \Phi \sigma_v \frac{N}{A} \int_0^{T_i} e^{-\frac{t-\tau}{T_v}} d\tau,
\]

where \( \sigma_v \) cm\(^2\) is the cross-section for the formation of the element \( v \), \( \Phi \) sec\(^{-1}\)-cm\(^{-2}\) the incident flux of particles, \( N \) the number of active atoms per gram of the element exposed to the flux (\( N = 6 \times 10^{23} \) is the Avogadro number and \( A \) the atomic weight in grams), and \( T_v \) the time constant of decay to \( 1/e \) of the activity formed (1.44 times the half-life). The factor \( \Phi \sigma_v \frac{N}{A} \) indicates the number of atoms formed per unit of time and this number decreases exponentially with the time constant \( T_v \) from the moment of formation \( \tau \) up to the present moment \( t \), the time being counted from the beginning of the exposure. What interests us is the activity itself, i.e. the number of atoms decaying per second. This can be obtained by deriving the above expression with respect to time. The total of all the elements formed should also be made on the \( v \) indexes, which gives:

\[
\sum_v \frac{dN_v}{dt} = 6 \times 10^{23} \Phi \frac{1}{A} \times \sum_v \sigma_v e^{-\frac{T}{T_v}} \left(1 - e^{-\frac{T_i}{T_v}}\right),
\]
Fig. 3. Decay of samples exposed to protons. Proton exposure 3 months.

Fig. 4. Decay of samples exposed to neutrons. Neutron exposure 6 weeks.
where \( T = t - T_1 \) is the time which has elapsed since the end of the exposure.

**IV. THE CALCULATION OF THE FIELD OF RADIATION**

When one has a block of active matter of a certain volume it is evident that part of the radiation coming from the interior will be absorbed before reaching the surface. This absorption should be taken into account when evaluating the radiation to which the staff are exposed. As a first approximation, it is sufficient to consider the mass absorption coefficient \( x \) (g\(^{-1}\).cm\(^2\)) for narrow beams and to suppose an exponential decay of the intensity \( N_\gamma \) of the radiation with the number of g/cm\(^2\) through which it has to pass:

\[
N_\gamma = N_0 e^{-x \rho x},
\]

where \( x \) is the path and \( \rho \) the density.

Once the activity per gram \( n \) and the absorption coefficient of the material irradiated \( \chi \) are known, it is only a question of geometry to calculate the field of radiation existing outside the active mass. Each element of volume \( dV \) sends a quantity of photons \( n dV \) into the solid angle \( 4\pi \). Let \( n \) represents the number of photons emitted in \( 4\pi \) per gram per second. To determine it, the mode of decay must be taken into account. If only one gamma is emitted per decay, \( n \) will be equal to \( \frac{dN_\gamma}{dt} \) for each element \( \nu \), and if there are two it will be doubled. If a positron is emitted which immediately recombines to give two 510 keV photons, it will also be doubled, etc. It is seen that \( n \) can be calculated from \( \sum \frac{dN_\gamma}{dt} \) by taking into account the mode of decay for each fission product and multiplying the corresponding cross-section \( \sigma_\nu \) by an appropriate coefficient. It can also be measured experimentally on an active sample. It is, at \( T = 0 \) and for infinitely long exposure

\[
n = \Phi \times 6 \cdot 10^{23} \times \frac{1}{A} \sum \sigma_\nu.
\]

The photon flux issuing from the element of volume evidently decays in inverse proportion to the square of the distance and in addition is exponentially attenuated along that part of its path which lies inside the radioactive material. The flux received by the detector is obviously proportional to the solid angle subtended by the active element of volume.

Since the active masses may be spread over a large area, it is advisable to assume that the detector is spherical and consequently presents the same cross-section in all directions. This simplifies the geometry and also the calculations. The number of photons reaching the sphere per second is then given by the volume integral

\[
N = \int \frac{\pi a^2}{4\pi x^2} \cdot e^{-x \rho x} \cdot n q dV,
\]

where \( a \) is the radius of the detector sphere, \( x \) the distance between the sphere and the active element of volume, \( x \) the portion of this distance which is inside the active element and \( V \) the active volume covered by the integral. The activity \( n \) may be a function of position.

**V. TWO EXAMPLES OF FIELDS OF RADIATION**

One case which occurs in practice is that of a field of radiation in the vicinity of a flat active layer of indefinite extent. One can give

![Fig. 5. Radiation field of an active layer.](image-url)
The element of volume becomes \( dV = -2\pi x^2 \sin \alpha \, d\alpha \). One obtains
\[
\frac{N}{\pi a^2} = nQ \int \sin \frac{\pi}{2} e^{-\pi D \cos \alpha} \, dV = \frac{n}{2} \int (1 - e^{-\pi D}) \sin \alpha \, d\alpha.
\]

In the event of the thickness \( T \) being infinite (all the half space being active) one finds
\[
\frac{1}{N} = \frac{1}{2} \frac{n}{\chi} \sec^2 \cdot \text{cm}^{-2}.
\]

When the layer has a finite thickness, it can be integrated in parts and one finds
\[
\frac{N}{\pi a^2} = \frac{1}{2} \frac{n}{\chi} \left[ 1 - e^{-\chi} - \frac{T}{\chi} Ei \left( \frac{-T}{\chi} \right) \right],
\]
where \( X \) is the length for attenuation of the radiation to \( 1/e \) and where the function
\[
-Ei(-x) = \int_{x}^{\infty} \frac{e^{-t}}{t} \, dt
\]
is well known in sine integral theory. Fig. 6 represents the expression is square brackets which shows how the field of radiation grows with the thickness of the active layer.

Another case which occurs in practice is that of an absorber for a high-energy particle beam. Let \( \pi R^2 \) be the cross-section of the beam presumed to be circular and let it fall perpendicularly on to the absorber. The value which it is necessary to calculate is the intensity of the activation radiation on the surface of the absorber at the centre of the area on which the beam falls. Cylindrical coordinates \( (r, z) \) centered in the beam on the surface of the absorber will be used. Since the penetration of the protons is generally much greater than the length of absorption of gamma rays, the active area can be taken to extend to infinity in the direction of the axis. One obtains
\[
\frac{N}{\pi a^2} = nQ \int_{0}^{\infty} R \int_{0}^{\infty} 2\pi r \, dr \, dz,
\]
where \( X = 1/\chi q \).

After integration as a function of \( r \) one has
\[
\frac{N}{\pi a^2} = \frac{n}{2} \left[ 1 - \int_{0}^{\infty} Ei \left( -\sqrt{\frac{R^2 + z^2}{X^2}} \right) \, dt \left( \frac{z}{X} \right) \right],
\]
an expression which should be graphically integrated for different \( R/X \) parameter values.

![Fig. 6. Radiation field versus thickness for active layer.](image_url)

Fig. 6 gives the shape of the quantity in square brackets as a function of \( R/X \), namely the variation of the intensity of the radiation with the radius of the beam cross-section (the beam flux but not its total intensity is presumed to remain constant). It is seen that one reaches about the same value for \( \frac{n}{2\chi} \) as in the previous case, as soon as \( \frac{R}{X} \) exceeds 1.

**VI. THE n/χ RATIO FOR DIFFERENT MATERIALS**

It was seen in the previous paragraph that the field of radiation is determined by the ratio \( n/\chi \) in addition to the geometrical conditions. Knowing the flux \( \Phi \), it can be calculated for different elements by using the radiochemical data available and taking into account the mode of decay and the energy of the gammas emitted. The absorption coefficient \( \chi \) depends
very little on the element concerned in a large area but it depends a great deal on the energy of the photon. The energy of the photons emitted by each fission product should therefore be considered and the cross-section $\sigma_\nu$ divided by the appropriate value of $\chi$.

This compilation was done for several elements and the quantity $\frac{1}{A} \sum \sigma_\nu / \chi_\nu$, which we call the «danger parameter» for the material, is given below. In drawing up this table, all fission products with a lifetime of less than a day were arbitrarily neglected.

$\frac{1}{A} \sum \sigma_\nu / \chi_\nu$ ratio for different elements.

<table>
<thead>
<tr>
<th>Element</th>
<th>$\Lambda$, gr</th>
<th>$\Sigma \sigma_\nu$, mb</th>
<th>$\frac{1}{A} \sum \sigma_\nu / \chi_\nu$</th>
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<tbody>
<tr>
<td>H</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Be</td>
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<td>15</td>
<td>$2.3 \times 10^{-27}$</td>
</tr>
<tr>
<td>C</td>
<td>12</td>
<td>10</td>
<td>1.2</td>
</tr>
<tr>
<td>O</td>
<td>16</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
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</tr>
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VII. CONCLUSION

Although this work is rather incomplete, it nevertheless gives some idea of the phenomena occurring when atomic installations are activated. The results already obtained make it possible to a certain extent to predict the fields of radiation to be expected when the primary fluxes and the geometrical arrangement of the activated elements are known. It will be advisable to do this before constructing any high energy accelerator of high intensity in order to be sure not to run into a «barrier of radiation» which would make the servicing of the machine impossible.

REFERENCES