# STUDIES OF RADIOACTIVITY AT HIGH ENERGIES

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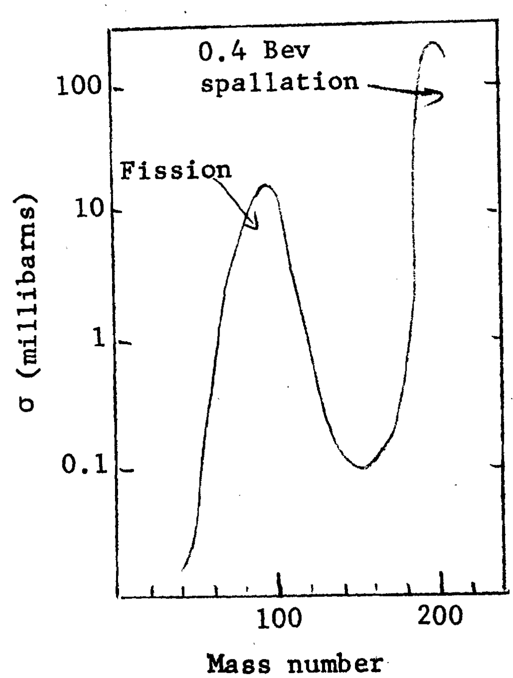
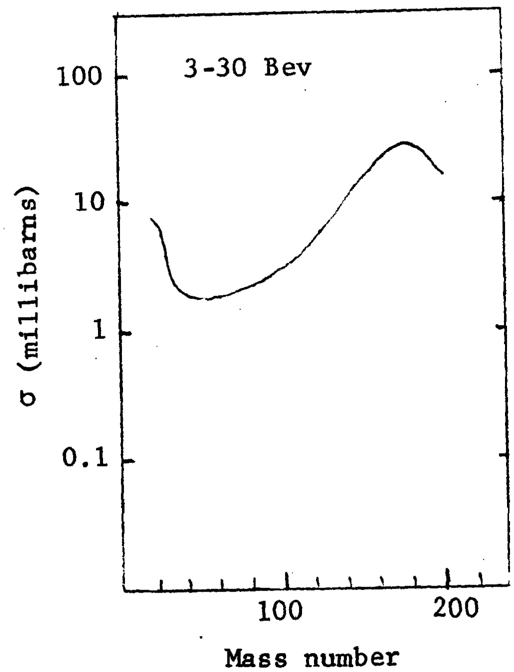
This report will deal with some of the problems connected with radioisotope production in components of, and shielding materials for, high-intensity, high-energy accelerators. Many of the points below are the result of calculations by, and conversations with, Dr. A. Galonsky of MURA. They have been adjusted to the adopted parameters, $10^{14}$ protons/sec (16 microamps) at 800 Bev (13 megawatts of beam power).

A general review of our present knowledge of the interactions of high-energy particles with complex nuclei should be helpful in the discussion of activation problems. Data are now available from the AGS and the CERN PS that show that the cross section, for production of a given isotope, from a given target element, is essentially independent of proton energy between 3 and 30 Bev. This is quite different from the marked changes in the yield patterns which are known to occur between 0.4 and 3 Bev. For a lead target these are shown in the following sketch. The pronounced fission peak observed at 0.4 Bev has essentially disappeared at 3 Bev and products of all mass numbers are produced with more or less the same cross section (within a factor of ten). We expect that at energies greater than 3 Bev the total cross sections of all target nuclei will be the geometric cross sections and, to the accuracy required for shielding calculations, the yield patterns for reactions induced by energetic pions,




neutrons, or antiprotons will not differ greatly from those of protons. The latter point is based on a very limited amount of experimental data.

Now what are the problems of stopping an 800-Bev beam with an average current of $10^{14}$ protons/sec (16 microamperes)? The problem of dissipating 13 megawatts of beam power will not be considered in detail. It can be handled by reactor-type engineering but may require some magnetic defocusing of the beam before the beam stop. For calculations of induced activities, we have to consider not only the primary beam but also, due to multiplication, a large number of secondaries of about 0.1 to 1 Bev in energy. We will assume a mean energy of 0.25 Bev per secondary. The primary beam, containing $10^{14}$ protons/sec, will produce $\approx$ 3200 secondaries per primary. Essentially all of these are stopped by nuclear interactions (ionization effects are very small). There will be $3.2 \times 10^{17}$ nuclear interactions per second. Fortunately, not all such interactions give radioactive products. The fraction of these collisions resulting in radioactivity with obnoxious properties depends upon the beam-stopper material and the definition of obnoxious. In $H_2$ the fraction is zero. In $Li^6$ it is close to zero since the major radioisotope produced is the innocuous $H^3$. Water might be a good choice when the heat-transfer problem is considered. The troublesome activities would be $Be^7$ and $H^3$. With aluminum, $Na^{22}$ would also be produced and the combined fraction of long-lived activities is $\sim 0.1$. Hence, for aluminum the equilibrium activity is of the order

$$(10^{14} \text{ protons/sec}) \text{ (3200 inel.coll./proton) (0.1 disintegrations/inel.coll.)}$$
$$= 3.2 \times 10^{16} \text{ disintegrations/sec} = 0.9 \text{ megacuries.}^{*}$$

This is substantially less than the equilibrium activity of the Brookhaven 25-Mw reactor. However, it is essential that the beam be extracted and stopped at some convenient point external to the accelerator, to prevent the entire accelerator becoming more or less uniformly radioactive to this extent.

The dose rate from such a beam stopper is not simple to calculate since the activity is produced, for normal incidence, deep below the surface of the material, hence many of the $\gamma$ rays are stopped before they emerge. Lin and Toyoda have performed a Monte Carlo calculation for 12-Bev protons incident on an iron beam stopper and have a dose rate of $\approx 40$ r/hr at a

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*The activity induced by neutron capture will depend very strongly on the medium. There will probably be $\sim 10^4$ neutrons generated for each 800-Bev proton. Hence, in the wrong material it would be possible to make $\sim 30$ megacuries.

distance of 1 meter and an intensity of 1 microampere (5-day-a-week operation for 1 year, 1-day cooling period). We have scaled their results to 800 Bev, assuming that the dose rate is proportional to both the intensity and the energy. We find that if this accelerator is operated 5 days per week for 1 year, then 1 meter from the beam stopper, the dose will be about 43,000 r/hr. This number may be incorrect by a factor of 2 or 4, but it will, in any case, be a large number.

In practice it will be impossible to extract all of the beam and some of the radioactivities will be produced in specific areas near targets or generally spread around the ring. The AGS has a general level of activity giving $\sim$ 1 mr/hr at 6 in. from the vacuum chamber, far from injection or target areas. At 1 meter the dose rate would be $\sim$ 0.15 mr/hr (1/r dependence assumed). A zero-order extrapolation from $10^{11}$/sec at the AGS to $10^{14}$/sec at 800 Bev, <u>keeping everything else the same</u>, gives

$$\left(\frac{0.15\ \text{mr}}{\text{hr}}\right)\left(\frac{10^{14}/\text{sec}}{10^{11}/\text{sec}}\right)\left[\left(\frac{\text{AGS circumference}}{\text{800-Bev circumf.}}\right)\left(\frac{\text{800 Bev}}{\text{AGS energy}}\right)\cong 1\right]$$

$$= (0.15)\left(\frac{10^{14}}{10^{11}}\right) = 150\ \text{mr/hr at 1 meter.}$$

If we wish to retain human access to those parts of the tunnel (about 99% of it) away from injection, extraction or targets, the fractional loss of particles must be reduced by a factor of $\sim 10^2$ as compared to the AGS. A factor of $10^2$ would leave 1.5 mr/hr at a meter and 10 mr/hr at 6 in.

We estimate the loss at the AGS as follows: 50% of the beam is lost at a target and results in $\sim$ 0.5 r/hr at a meter, average over 30 meters of circumference. The same loss, if distributed uniformly around the ring, would result in a dose rate reduced by 30 meters divided by $2\pi R$ = .04 or

20 mr/hr. Hence, the uniform loss that produces 0.15 mr/hr at a meter is

$$\left(\frac{0.15}{20}\right)(50\%) = 0.4\%.$$

At 800 Bev this loss would be $0.4 \times 10^{-3}\%$ or $0.4 \times 10^{-2}\%$, which corresponds to 1.5 mr/hr at a meter and is still tolerable.

There are at least two possible sources of the estimated 0.4% loss at the AGS: (1) rf mishandling, and (2) interactions and scattering in the residual gas. We estimate losses from the second effect assuming a pressure $P = 2 \times 10^{-6}$ mm Hg of air, acceleration time = 1.2 sec, and $\lambda$ for interactions and scattering = 6 gm/cm$^2$. Then the thickness traversed is 0.12 gm/cm$^2$ and the loss of protons is 0.12/60 = 0.2%. A conclusion consistent with the accuracy of these estimates is that all of the general activity at the AGS results from this effect.

A necessary, but not sufficient, requirement for helping "cool" the 99% of the 800-Bev tunnel which is not near extraction ports, etc., is a pressure of less than $10^{-9}$ mm Hg.

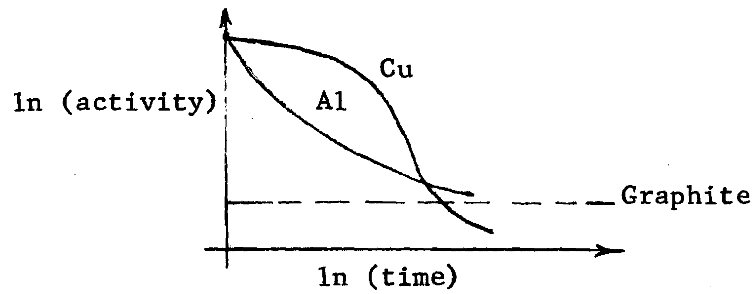
With such a small loss requirement other effects (Touschek?) may be important.

The choice of construction materials for the accelerator itself is important from the standpoint of induced activity. In heavy materials such as iron there is a wide distribution of yields and one makes many radioactive species. Light elements may be better. However, one will have to use iron for magnets. Aluminum might be used for coils, but, as will be shown, copper may be a better choice.

To examine the activation of common building materials, thin targets were bombarded in a zero-degree beam from a copper target which was bombarded by protons in the Cosmotron for about 60 hours. Gamma rays were counted from these materials after bombardment.

| | Relative gamma ray rate/gm | | | |
|---|---|---|---|---|
| Days after bombardment | Zn | Cu | Fe | Al |
| 12 | 8.3 | 4.8 | 9.3 | 2.3 |
| 30 | 4.3 | 2.6 | 4.0 | 1.8 |
| 90 | 2.3 | 1.3 | 1.2 | ~ 1.8 |

Note that 12 days after the bombardment, the aluminum activity was less than the copper activity but the situation was reversed after about 90 days.




In aluminum, it is the 2.6-year sodium 22 which accounts for the slow decay rate, while in copper many short-lived products are formed.

Fulmer, Toth and Ball have done similar work in connection with an 810-Mev cyclotron at Oak Ridge. They have discovered that lead decays quite rapidly and carbon is very good. They have calculated that if they line the pole tips of this cyclotron with a 4-cm thick layer of graphite, they will reduce the activity by a factor of ten. One reason for this large decrease is the small angle at which the scattered particles in the vacuum chamber enter this layer, which results in a long path in this material. Hence, a thin liner can be quite effective.

At present we are examining the activation of a variety of materials (Pb, Zn, Cu, Fe, Ti, $SiO_2$, $CF_2$, Al, graphite, stainless steel, and inconel) in a $\sim 0^{o}$ beam from an AGS target. Should there be significant differences between comparable structural materials, these data should help in the design of the high-energy machine to reduce activation.

Discussion

J.P. Blewett (BNL): How much lead would be required to shield a beam stopper to a safe level after it ceased to be used?

J.B. Cumming: For the iron beam stopper described above the dose rate was 43,000 r/hr at 1 meter. To reduce this to 1 mr/hr is a factor of $4.3 \times 10^{7}$ or $\sim$ 25 half-thicknesses. In lead, for a 1-Mev gamma ray, this is $\sim$ 25 cm.

L.C.L. Yuan (BNL): What activity will be induced in the air in the tunnel?

J.B. Cumming: I haven't calculated that specifically. In air spaces in beam lines you would get about 0.5 curies of $C^{11}$ per meter at $10^{14}$/sec. It is clear that one does not want any air gaps in beam lines for a 800-Bev accelerator.