Gamma Ray Activation of the Fermilab Pbar Target

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Abstract

A model for calculating induced radioactivity by a pulsed primary high energy beam has been developed. This model is consistent with the formalism for continuous beam by Barbier[1]. The method predicts the radioactivity of one of the earlier Fermilab antiproton production targets quite well.

I. INTRODUCTION

A quantitative understanding of the induced radioactivity in the parts of a high energy particle accelerator and particle detectors has been a topic of interest for a long time. A theory of induced radioactivity by a continuous beam of high energy particles on a thick target has been developed [1]. But the particle beams from a high energy synchrotron are pulsed, sometimes with pulse repetition rate of several seconds. For example, the proton beam used to produce pbars at Fermilab has pulse length of 1.6μ sec and a pulse separation of about 2.0 sec. In this report a model of residual gamma ray activity of a target which is exposed to pulsed beams is developed. An expression to be used in any such calculations is derived and applied to predict the activity of the Fermilab pbar source.

II. CALCULATION OF GAMMA-RAY ACTIVATION

When a high energy particle interacts with a nucleus it may be elastically scattered, knock out some nuclei or create some new high energy particles. The energetic secondary particles also induce nuclear reactions. This gives rise to nuclear and electromagnetic showers. Each nuclear reaction center is called a star. If the resulting nuclei are unstable, they will de-excite by boiling off neutrons, gamma rays, beta rays or by emitting internal conversion electrons. Each decay process will be characterized by its individual decay constant. A previous study[2] in the energy range from 3GeV to 30GeV on the formation cross sections for various radioactive nuclei in a copper target indicated no energy dependence. Based on similar observations on many target materials the cross-section for formation of any radioactive nucleus produced in the interaction of high energy particle has been parameterized [1]. However a more precise calculation might need additional experimental data on decay constants and formation cross sections in order to take into account the effect of every individual product.

Total gamma ray radiation dose rate D of a target in (R/hr), which is bombarded by high energy particle beam is,

$$D = -A\sum_j \frac{dN_j}{dt_c}\sum_k E_k(j)$$

$$= N_o A\sum_j \sigma_j \lambda_j \frac{1-e^{-\lambda_j t_I}}{1-e^{-\lambda_j t_p}} e^{-\lambda_j t_c}\sum_k \omega(E_{kj})E_k(j)$$

$$\int_V \frac{e^{-\mu(E_{jk})X(x,y,z)}\rho_s(x,y,z)}{4\pi(X+d)^2}dV \qquad (1)$$

where A is a constant to express results in terms of (R/hr). $\sum_j \frac{dN_j}{dt_c}$ is the activity of the source (a derivation of an expression for the pulsed primary beam is given in Appendix A). t_c, $E_\gamma(k)$, σ_j and λ_j are respectively the cooling time (sec), energy of gamma ray (MeV), the formation cross section of j (in mb/sr), radioactive decay constant for j (in sec^{-1}) N_o is the number of primary beam particles per pulse. t_p is the pulse repetition time (sec). $\mu(E_{jk})$ is the attenuation coefficient of the gamma ray in the target material(cm^{-1}). ρ_s is the star density of nuclear interactions (cc^{-1}). t_I is the total time (sec) that target has been irradiated with the primary beam. The constant A [3] is given by,

A = 1.297E-11/gm if X and d are in meters

A = 6.0E-10/gm if X and d are in ft

if the activity, $\sum_j \frac{dN_j}{dt_c}$ is given in units of Curies. Because of the spatial dependence of the star density in the target and geometry of the target, it is difficult to

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evaluate the integral in Eq. 1. However, one can incorporate these aspects into a Monte-Carlo code and estimate the dose rate exactly.

We have made calculations for pbar target used in the 1988-89 collider run. Predictions have been compared with the available data. In all of the calculations the star densities have been generated by Monte-Carlo calculations using MARS10 [4] which uses a hadron nucleus interaction model. Further we assume that the source of radiation is situated at the center of the target. Thus in our model all gamma-rays undergo attenuation by the same amount of target material irrespective of the star location. This assumption is reasonable one for a cylindrically symmetric target with

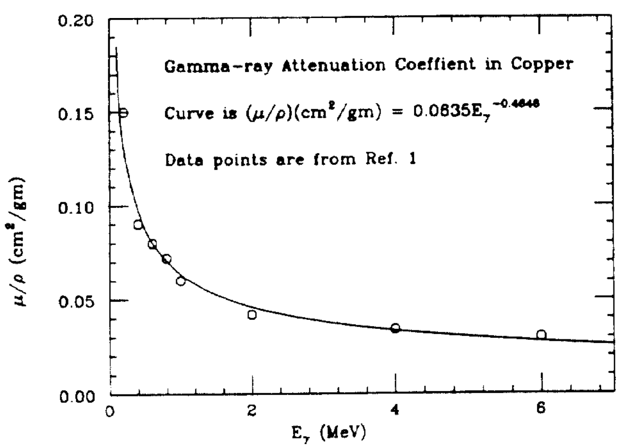

Figure 1. Gamma ray attenuation Coefficient in Copper. The curve represents a logarithmic fit to the data.

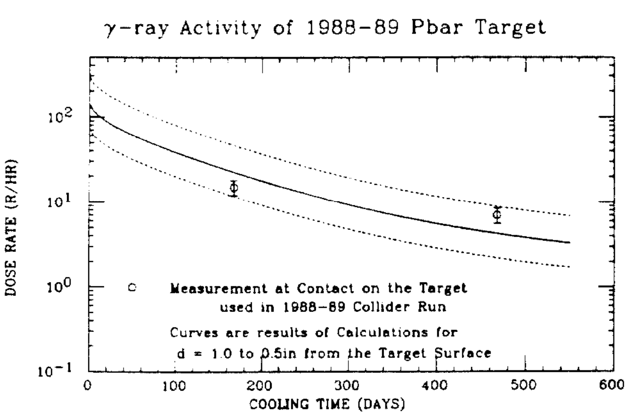

Figure 2. A comparison between predicted and measured radioactivity dose rate as a function of cooling time for one of the Fermilab pbar target

the beam along the axis and for a target with its dimension much smaller than the distance between the detector and the target surface. The gamma-ray attenuation coefficient, μ, can be obtained by a logarithmic fit to the data[1], which is shown in Fig. 1. About forty radioactive nuclei (with life time $\tau \geq 5$ min) have been taken into account in our calculations. Fig. 2 gives a comparison of the prediction and the measured value. The target was used for of 392 days with total of 292 days of irradiation and with an average N_o = 1.0E+12 p/pulse-sec. We calculated the number of stars in the target at about 4 per 120GeV proton. The calculated residual radioactivity is in good agreement with the data. However, several uncertainties exist in the method of measurement to get these data points. The radiation detectors used to measure target activities are known to have about 20% instrumental uncertainty in their measured values. Other large source of uncertainty could arise from the estimation of the distances between target to the detector. Also one has to notice that the beam axis in these targets were along a chord of a cylindrical rotating target with axis of rotation perpendicular to beam axis. Under these circumstances it is incorrect to assume the source of the gamma radiation is at the center of the target. Therefore only the data points labeled " dose rate at contact" have been used to compare with the predictions. Better data are essential to make better comparisons.

III. SUMMARY

A theory of induced radioactivity has been developed for pulsed primary high energy beam. The theory is consistent with the formalism for continuous beam by Barbier. Attempt has been made to compare predictions with the available data from targets used in the previous collider runs at Fermilab and a reasonable agreement is achieved.

REFERENCES

* Operated by the Universities Research Association, Inc., under contracts with U.S. Department of Energy.

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Appendix A

INDUCED RADIOACTIVITY BY A PULSED HIGH ENERGY BEAM

Let N_o be the number of incident particles per pulse and let the time intervals between two successive pulses be t_p. As a result of interaction between the beam and the target many radioactive nuclei are formed. Let σ_j be the cross section for formation of the radioactive nucleus 'j'. The radioactive nuclei may be formed in their ground state or in any of their excited states. But the excited nuclei decay to their ground state very rapidly (with a characteristic life time of the order of few nsec or psec) resulting in a burst of gamma rays within a few microseconds of the beam interactions. The unstable nuclei in their ground state or in a meta-stable state undergo spontaneous radioactive decay. The number of radioactive nuclei of the type 'j' formed in an elemental volume dV = dxdydz at the end of the interaction of the first beam pulse is given by,

$$(dN_j)_1 = N_o dS \sigma_j \quad (1)$$

where dS = ρ_s(x,y,z)dV is the number of stars in the volume dV. By the end of the second pulse the number of radioactive nuclei 'j' left is,

$$(dN_j)_2 = N_o dS \sigma_j (1 + e^{-\lambda_j t_p}) \quad (2)$$

where λ_j is the radioactive decay constants. Similarly extending this for n pulses the total number of radioactive nuclei left not decayed are

$$(dN_j)_n = N_o dS \sigma_j (1 + e^{-\lambda_j t_p} + e^{-2\lambda_j t_p} + ... + e^{-(n-1)\lambda_j t_p})$$

$$(dN_j)_n = N_o dS \sigma_j \frac{1 - e^{-\lambda_j n t_p}}{1 - e^{-\lambda_j t_p}} \quad (3)$$

Let us assume that the irradiation is stopped after time $t_I = n_I t_p$ and target is let to cool for time t_c. The the number of radioactive nuclei left are

$$(dN_j) = N_o dS \sigma_j \frac{1 - e^{-\lambda_j t_I}}{1 - e^{-\lambda_j t_p}} e^{-\lambda_j t_c} \quad (4)$$

The long term radioactivity comprises essentially that arising from gamma decays alone. To calculate the residual radioactivity we have to take into account the total number of gamma rays (including annihilation of antiparticles into gamma rays) from each nucleus, ω(E_{kj}), with gamma ray energy E_k. Finally these newly emitted gamma rays at (x,y,z) in the target will be self attenuated by the target material. Let $\mu(E_{jk})$ be the attenuation coefficient of the gamma rays. Let X(x,y,z) be the thickness of the target material through which a gamma ray travels before it is being detected by a detector at a distance d from the target. Then

$$dN_j = N_o \sigma_j \frac{1 - e^{-\lambda_j t_I}}{1 - e^{-\lambda_j t_p}} e^{-\lambda_j t_c}$$

$$\sum_k \omega(E_{kj}) \frac{e^{-\mu(E_{jk}) X(x,y,z)} \rho_s(x,y,z)}{4\pi (X+d)^2} dV \quad (5)$$

The instantaneous gamma decay rate of this isotope is obtained by differentiating Eq. 5 with respect to t_c.

$$-\frac{dN_j}{dt_c} = N_o \sigma_j \lambda_j \frac{1 - e^{-\lambda_j t_I}}{1 - e^{-\lambda_j t_p}} e^{-\lambda_j t_c}$$

$$\sum_k \omega(E_{kj}) \frac{e^{-\mu(E_{jk}) X(x,y,z)} \rho_s(x,y,z)}{4\pi (X+d)^2} dV \quad (7)$$

Thus the total gamma-ray activity of the target will be the sum of activities of all gamma rays coming from different types of radioactive nuclei and the star densities integrated over entire target volume. Then we will get

$$-\sum_j \frac{dN_j}{dt_c} = N_o \sum_j \sigma_j \lambda_j \frac{1 - e^{-\lambda_j t_I}}{1 - e^{-\lambda_j t_p}} e^{-\lambda_j t_c}$$

$$\sum_k \omega(E_{kj}) \int_V \frac{e^{-\mu(E_{jk}) X(x,y,z)} \rho_s(x,y,z)}{4\pi (X+d)^2} dV \quad (8)$$

The above equation could be tested for a continuous beam. In Eq. 3 we find that for a continuous beam N_o has to be replaced by $N_o \delta t$ and set the limit δt to zero. Then

$$dN_j = N_o \sigma_j \frac{(1 - e^{-\lambda_j t})}{\lambda_j}$$

which is identical to one in Ref. 1. This confirms the consistency of the formalism for pulsed primary beams.