AN EXPERIMENTAL STUDY OF THE PENETRATION OF 10 AND 19.2 GEV PROTON RADIATION IN STEEL

by

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ABSTRACT

A thick steel absorber was irradiated with a narrow beam of 10 and 19.2 GeV protons. Measurements were made of the high energy flux using carbon-11 activation detectors and of radiation dose using ionization chambers along the beam line inside the absorber. Particle flux distribution perpendicular to the beam direction was also measured at several depths. The mean free path and radiation build-up in the absorber are given for the two proton energies.

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I. INTRODUCTION

Relatively little experimental information exists on the penetration of high energy proton radiation through materials that can be directly used for the calculation of the shielding required around a high energy accelerator. The design of a "biological" shield requires data on radiation build-up, radial spread, and attenuation of the radiation in the shielding material. The complexity of the interactions of high energy radiation with matter and consequently the large variety and spread in spectral distribution of the primary and secondary radiations produced in an absorber limits the amount of information that can be obtained from a single experiment.

The measurements described here were made in order to determine the distribution of the radiation flux and dose in a steel absorber from which mean free paths, build-up factors, and radial spread could be estimated for 19.2 and 10 GeV proton beams.

II. RADIATION MEASUREMENTS

The measurements were made in parallel with those described in part (1) (Ref. 1). The same absorber and beam layout were used.

High-energy particle flux was determined from measurements of the carbon-11 activity induced in plastic phosphors (Ref. 2). The carbon-11 activity is produced mainly by $^{12}C(n,2n)C^{11}$ and $^{12}C(p,pn)C^{11}$ reactions with contributions from $^3He^+p$ and $^3He^+n$ reactions.

The $^{12}C(n,2n)C^{11}$ reaction has a threshold at 20.4 MeV and a fairly constant cross-section above 50 MeV (Ref. 3). The $^{12}C(p,pn)C^{11}$ reaction has the same threshold and a constant cross-section from 150 MeV to several GeV (Ref. 4).
The plastic phosphors used were 20 mm thick disks of 42 mm diameter. The phosphors were counted on a shielded photo-multiplier using standard commercial counting equipment to determine the induced Gd activity. The decay of the 20.4 min. activity was followed over three half-lives (Ref. 5).

Particle radiation intensity was calculated from the induced activity either as a flux or as the total number of particles per second passing normally through the phosphor. The calculations were made assuming a chemical composition of (CH)\textsubscript{n} for the phosphor and a 29 mb cross-section for the production of Gd.

Radiation dose measurements were made with Baldwin-Farmer BD-11 condenser ionization chambers. These are air-filled "air equivalent" chambers with an integrated dose-range of 0-0.5 r. The chambers are normally calibrated with radium gamma radiation and the radiation dose was estimated assuming 1.06 r of gamma radiation equivalent to one rad in tissue. These chambers have been compared in other high energy particle beams, with a tissue equivalent ionization chamber (Ref. 6).

The results of these measurements are summarized below and indicate a reasonable "tissue equivalence" of the chamber to high energy radiation. The chambers will, however, under-estimate the fast neutron ($\sim$ 500 KeV - 15 MeV) by a factor of about 2.

**Summary of High Energy Particle Calibration of Air Equivalent Ionization Chambers**

<table>
<thead>
<tr>
<th>Radiation</th>
<th>T.E. Chamber Dose-Rate</th>
<th>BD-11 Chamber Dose-Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutron beam</td>
<td></td>
<td></td>
</tr>
<tr>
<td>max. energy 400 MeV</td>
<td>2.4 rad/hr.</td>
<td>2.3 rad/hr.</td>
</tr>
<tr>
<td>At depth of 20 g/cm\textsuperscript{2} in tissue-like material 400 MeV neutron beam</td>
<td>5.1 rad/hr.</td>
<td>5.3 rad/hr.</td>
</tr>
<tr>
<td>Air scattered, 600 MeV proton radiation</td>
<td>21.5 mrad/hr.</td>
<td>22.5 mrad/hr.</td>
</tr>
</tbody>
</table>
III. **ATTENUATION OF DIRECT BEAM**

The plastic phosphors were placed as accurately as possible on the beam centre line in the main stack of steel plates and were exposed for about one hour. The total number of protons entering the steel absorber was measured with coincidence counters and the time variation of beam intensity was monitored by the control ionization chamber near the stack. The particle intensity averaged over the cross-sectional area of a phosphor could then be related to the input beam intensity. The results for 10 GeV and 19.2 GeV are given in figure 1. This diagram shows the number of particles per second (as defined by the threshold and cross-section for C11 production) passing through a cylinder of 42 mm diameter concentric with the beam line for an input beam strength of one proton per second.

IV. **FLUX DISTRIBUTION IN THE ABSORBER**

Phosphors were also placed along lines perpendicular to the beam direction at depths of 10, 30, 50 and 120 cm of steel. From these activities it was possible to estimate the particle flux profiles perpendicular to the beam direction. The profiles of the 19.2 and 10 GeV radiation flux density are shown in figures 2 and 3. It is possible to make an estimate of the total number of particles crossing the air gaps between the steel plates by numerically integrating these profiles. The results of this integration are given below:

<table>
<thead>
<tr>
<th>Depth in steel cm</th>
<th>Total particles (capable of producing carbon-11) passing through plates per incident proton</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>19.2 GeV</td>
</tr>
<tr>
<td>10</td>
<td>$8.0 \pm 0.4$</td>
</tr>
<tr>
<td>30</td>
<td>$9.5 \pm 0.4$</td>
</tr>
<tr>
<td>50</td>
<td>$10.0 \pm 1.1$</td>
</tr>
</tbody>
</table>
V. DOSE MEASUREMENTS

Dose measurements were made on the beam line inside the main stack of steel plates. The total number of protons entering the stack during each exposure was measured with coincidence counters. The measured dose in millirads for a total beam input of $10^5$ protons has been plotted as a function of depth in fig.4.

VI. ERRORS AND CORRECTIONS

The true beam line was found to be off the nominal centre line by about 1° for the 19.2 GeV beam in the main absorber. Allowance was made for this, the correction being estimated from the beam distribution measurements. No corrections were applied for the divergence of the beam which was about 4 millirads.

Measurements were found to be reproducible at any one site to better than ±10% of the mean value. However, the possibility exists of systematic errors due to difficulties in placing the detectors exactly on the beam line. Positioning errors do not exceed ±5 mm; but because of the large variation of intensity with distance from the beam centre uncertainties in the measurements of up to 30% could result. Where counting statistics were poor, the counting standard deviation was combined with the positioning uncertainties to estimate the limits of the measured values.

VII. DISCUSSION

In the attenuation measurements the detector beam geometry was poor as the cross-sections of the detectors are larger
than the size of the incident beam. Therefore, the observed attenuation and build-up is a function of the detector size as well as of the radiation interactions. Extrapolation to "narrow beam" conditions is not feasible. However, for application to biological shielding, the measurements have a significance as the dimensions of the detectors reasonably resemble those of a critical organ in the body and would be similar to those used to determine the effectiveness of a shield. Under the conditions of the measurements, the following build-up and attenuation data are deduced for steel:

<table>
<thead>
<tr>
<th>Primary Proton Energy</th>
<th>Measurement</th>
<th>Build-up Factor</th>
<th>Mean free Path in steel $\rho=7.8 \text{ g/cm}^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>19.2 GeV</td>
<td>Particle flux above 20 MeV</td>
<td>3.5</td>
<td>170</td>
</tr>
<tr>
<td>10 GeV</td>
<td>&quot;</td>
<td>3</td>
<td>145</td>
</tr>
<tr>
<td>19.2 GeV</td>
<td>Radiation dose</td>
<td>15</td>
<td>155</td>
</tr>
<tr>
<td>10 GeV</td>
<td>&quot;</td>
<td>3.3</td>
<td>155</td>
</tr>
</tbody>
</table>

The mean free path is measured over the region of exponential absorption. The build-up factor is the quantity of radiation that would be found at zero depth if the exponential absorption line is continued back to zero divided by the measured value at zero depth.

The total particle flux through the steel plates, obtained by integrating the beam profiles at 10, 30 and 50 cm depth appears to remain constant over this range. The values found, 9 at 19.2 and 8 at 10 GeV compare favourably with the particle multiplication found.
for cosmic rays (Ref.7) and the value of 9 for all cascade nucleons per inelastic event at 3 GeV quoted by Lindenbaum (Ref.8).

The average number of shower particles at 20 GeV is about 4.4 (Ref.9) and at 10 GeV 3.0 (Ref.10), indicating that most of the cascade nucleons appear as low energy particles (< 100 MeV) and are not counted amongst the shower particles. The number of high energy protons is estimated to be 0.5 to 1 per inelastic event. The integrated flux of particles determined by carbon-11 activation in the phosphors is higher than the integrated number of minimum ionizing particles measured with nuclear emulsions. In addition, some of these minimum ionizing tracks in emulsions must be attributed to electrons from electromagnetic cascades produced by high-energy gammas from $\alpha$ decay. About an equal number of gamma rays is present in the electromagnetic cascades which can produce C$^{11}$ by C$^{12}$ ($\gamma$,n) C$^{11}$ reactions. At a depth of 10 cm of steel, a shower produced by gamma radiation of up to 1 GeV has already passed its maximum. The gamma radiation capable of producing the above reaction is therefore already in equilibrium in the first gap (behind 10 cm steel) with the number of the $\alpha$ produced. From the observed electron track density (Ref.1) from 10-30% of the C$^{11}$ could have been produced by gamma reactions. The medium energy ( > 20 MeV) neutrons which are not counted as neutral stars in the emulsion will also contribute to the observed C$^{11}$ activation. A total flux of 8 fast particles per incoming proton of 20 GeV is therefore not in disagreement with the results of reference 11.

The beam profile measurements are not extended far enough across the absorber to permit accurate profiles to be drawn. A quantitative estimation shows that after the initial build-up the flux contours form cylinders around the beam until the secondary radiation is attenuated and the contour crosses the beam line.
ACKNOWLEDGEMENTS

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BEAM INTENSITY AS A FUNCTION OF DEPTH IN STEEL

Particles per sec. for beam intensity of 1 proton per sec.

Thickness of steel cm

Fig. 1

19.2 GeV
10 GeV
FLUX DENSITY DISTRIBUTION ACROSS PLATES
19.2 GeV

Distance from beam line (cm) Fig. 2
FLUX DENSITY
DISTRIBUTION ACROSS PLATES
10 GeV

Distance from beam line (cm) Fig. 3
DOSE AS A FUNCTION OF DEPTH IN STEEL

Fig. 4