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of High Energy Muons and Neutrons\***

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## PERSONAL DOSIMETRY IN A MIXED FIELD OF HIGH ENERGY MUONS AND NEUTRONS

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### ABSTRACT

High energy accelerators quite often emit muons. These particles behave in matter as would heavy electrons and are thus difficult to attenuate with shielding in many situations. Hence, these muons can be a source of radiation exposure to personnel and suitable methods of measuring the absorbed dose received by these people is obviously required. In practical situations, such muon radiation fields are often mixed with neutrons, well-known to be an even more troublesome particle species with respect to dosimetry. In this paper, we report on fluence measurements made in such a mixed radiation field and a comparison of dosimeter responses. We conclude that commercial self-reading dosimeters and film badges provide an adequate measure of the absorbed dose due to muons.

### INTRODUCTION

At high energy proton accelerator laboratories, radiation exposure due to muons is often quite significant. The properties of such muon fields have been studied at Fermilab using scintillation telescopes (1, 2). The muon intensity has been observed to be peaked in the direction of the incident proton beam (350-800 GeV) in a cone typically less than six degrees FWHM. The nature of the high energy physics experiments that use particle beams incident on targets at rest in the laboratory frame of reference requires that the majority of the experimental apparatus be placed in, or very near, this cone. The signal cables leading from these particle detectors to areas of significant occupancy by experimenters are often restricted in length by pulse quality and delay considerations. Since muons, which have a rest energy of 105.7 MeV, behave in matter as would electrons of such large mass, they have very long ranges (e.g., about 700m of soil at 400 GeV). It is, therefore, generally impractical to use shielding to reduce dose equivalent rates in nearby areas. In specialized cases, magnetic fields are effective in reducing the muon fluence by deflection, but this technique is limited by the expense of magnets sufficiently large to deflect muons with momenta typically of the order of tens of GeV/c. Thus, high occupancy areas are sometimes locations of significant muon fluence. It is, therefore, necessary to be able to accurately assess the dose equivalents received by individuals in muon fields having poorly known energy spectra. This note presents a comparison of the response of dosimeters in a radiation field that is a mixture of muons and neutrons.

### PROPERTIES OF THE RADIATION FIELD

Figure 1 shows the geometry at the location where measurements were carried out. The muons arise primarily in the decay of pions formed by the interaction of 800 GeV protons from the Tevatron in two tungsten targets. The

radiation field at the location of the dosimetry measurements also includes neutrons emerging from the targets, beam dump, and associated iron and concrete shielding. The dosimetry measurements were made in a plane 4.3m above that of the beam. This location was not a high occupancy area but was chosen because the radiation field in this area, although of higher intensity, is similar in composition to that at locations typically occupied by personnel.

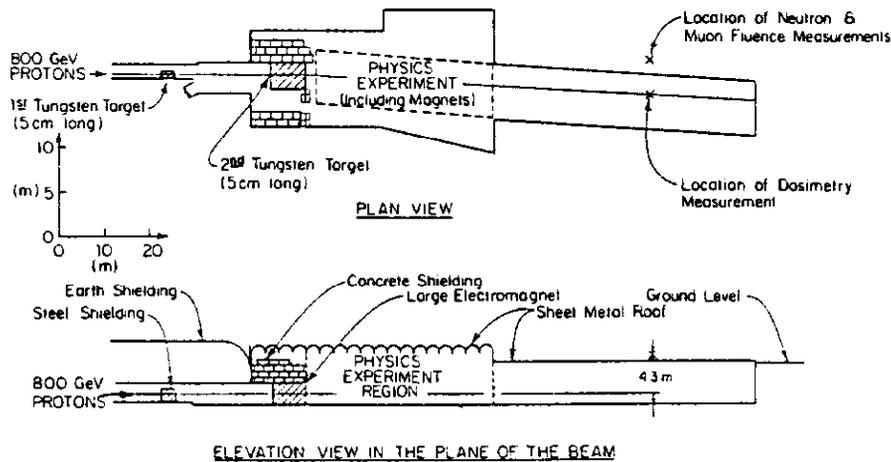


Figure 1: Geometry of the source of muons and the dosimetry measurements. The longitudinal scale differs from the transverse scale for both the plan and elevation views.

The characteristics of the radiation field at this location were determined from measurements performed with various detectors which were mounted in a vehicle equipped with counting electronics. The neutron fluence as a function of energy was measured by a Bonner multisphere spectrometer (3, 4). The detector, called a phoswich, consists of an 8mm diameter by 8mm long  $^6\text{LiI}(\text{Eu})$  scintillation crystal embedded in a 12.7mm diameter by 12.7mm long plastic scintillator (5). It is placed at the center of one of a set of moderating polyethylene spheres of various diameters, and inserted into the radiation field; the procedure has been described a number of times (6, 7). The peak associated with neutrons in the pulse-height spectrum is clearly discernible above the charged particle background events even though large muon fluences are also observed (see below). In these measurements, the counting electronics were gated-on during the 23 second beam spill, which occurred once during each (approximately) 60 second accelerator cycle, and a precision  $^{10}\text{BF}_3$  long counter (8) provided the relative normalization for the individual Bonner sphere measurements. A threshold set on the long counter output rendered it insensitive to muons and  $\gamma$  rays.

If the energy-dependent multisphere response functions are known (9), the neutron fluence as a function of energy (i.e., the neutron spectrum) can be obtained from measured Bonner sphere counting rates by unfolding methods (see, e.g., 10). To gain some confidence in the reasonableness of the unfolded spectrum, we have used two programs, SWIFT (11, 12, 13), based on Monte Carlo techniques, and BUNKI (14, 15) an iterative recursion method. The unfolded spectra associated with a good fit to the data are shown in Fig. 2, plotted as fluence per unit logarithmic energy interval. The results from

SWIFT, shown as the points, are an average of the 100 best-fit spectra from the approximately  $7 \times 10^6$  sampled. While there are some energy bins at which the two spectra disagree, the general shape is similar for both. Of interest is the fact that, whereas about 20% of the total fluence is associated with thermal neutrons, almost 40% arises from those with energies above 100 keV. The general shape of this spectrum is similar to that measured external to a thick iron shield (7), a result which is not surprising given the present geometry. Figure 3 shows the contribution to the total dose equivalent as a function of neutron energy as determined by BUNKI. The fluence, absorbed dose, dose equivalent, and quality factor associated with the neutrons are shown in Table 1 for  $10^{12}$  protons incident on the target as measured by a secondary emission monitor (SEM) in the primary beam line. The values are based on the average of the results from the two fitting programs, BUNKI and SWIFT, and the errors are calculated as the standard deviation of the mean.

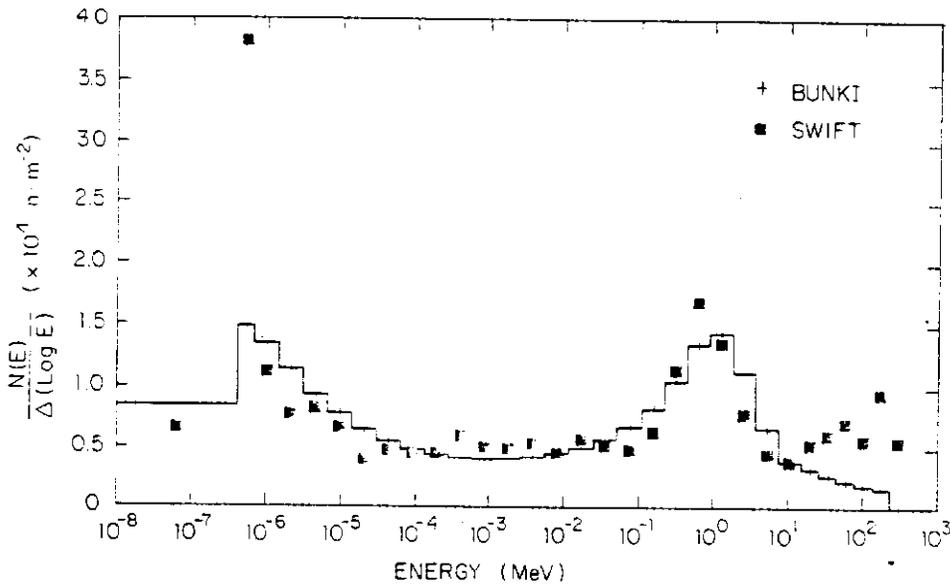


Figure 2: Neutron energy spectra determined from multisphere data.

The muon fluence at this location was determined from measurements with a pair of 6.4mm thick plastic scintillator paddles of transverse dimensions 203.2mm by 203.2mm, separated by a gap of 150mm which includes a 25.4mm thick aluminum plate used to reduce false coincidences due to delta rays. Standard electronics recorded both single and coincidence events. Scalers were gated "on" during both beam-on (23 second spill period) and beam-off time periods in synchronization with the accelerator cycle. Coincidence rates were about 75% of the singles rates; this reflects the reduced coincidence efficiency for detection of muons that are incident at angles other than  $90^\circ$  to the surface of the plates (1, 2). The muon fluence based on singles counting rates for  $10^{12}$  incident protons is shown in Row 2 of Table 1. Also shown are muon absorbed dose and dose equivalent, obtained from the measured fluence by use of the conversion factor of  $40 \text{ fSv}\cdot\text{m}^2$  and an assumed muon quality factor of unity (16). The table lists the fractions of the total fluence, absorbed dose and dose equivalent of the radiation field that are due to the neutrons and muons.

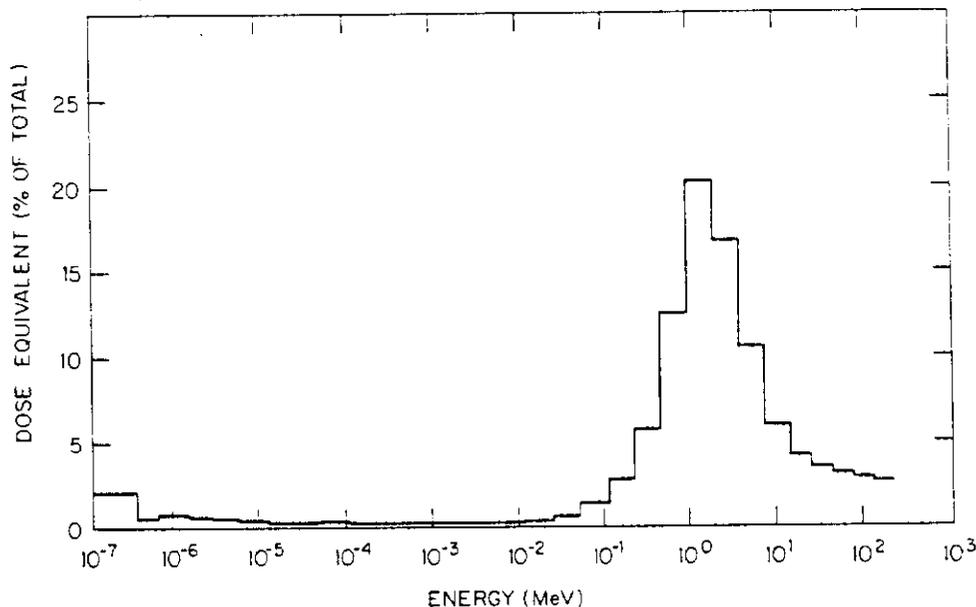


Figure 3: Neutron dose equivalent as a function of energy for the unfolded spectrum due to BUNKI shown in Figure 2.

Table 1. Results of muon and neutron fluence measurements using plastic scintillators and the multisphere technique normalized to  $10^{14}$  protons on target

Type	Fluence		Absorbed Dose		Dose Equivalent <sup>*</sup>		QF
	$m^{-2} \times 10^7$	Fraction	$\mu Gy$	Fraction	$\mu Sv$	Fraction	
Neutrons	$9.12 \pm 0.38$	0.62	$0.19 \pm 0.06$	$0.08 \pm 0.03$	$1.16 \pm 0.31$	$0.34 \pm 0.26$	$6.24 \pm 0.18$
Muons <sup>a)</sup>	5.62	0.38	2.25	0.92	2.25	0.66	1

<sup>a)</sup>Fluence based on singles counting rates. For fluence based upon coincidence rates, multiply by 0.75.

The quality factor (QF) of the mixed neutron and muon radiation field was measured by use of a recombination chamber. The procedure has been described previously (6, 7, 17). Briefly, the response (current or charge, I measured at the anode) of a special high pressure ion chamber (Model REM-2 Chamber, Radiation Dosimetry Instrument Division, ZZUJ, "Polan," Bydgoszcz, Poland) is measured over its operating potential range, V (20-1200 volts), and is fit to the equation

$$I = kV^N,$$

where k is a constant dependent upon the chamber and absorbed dose.

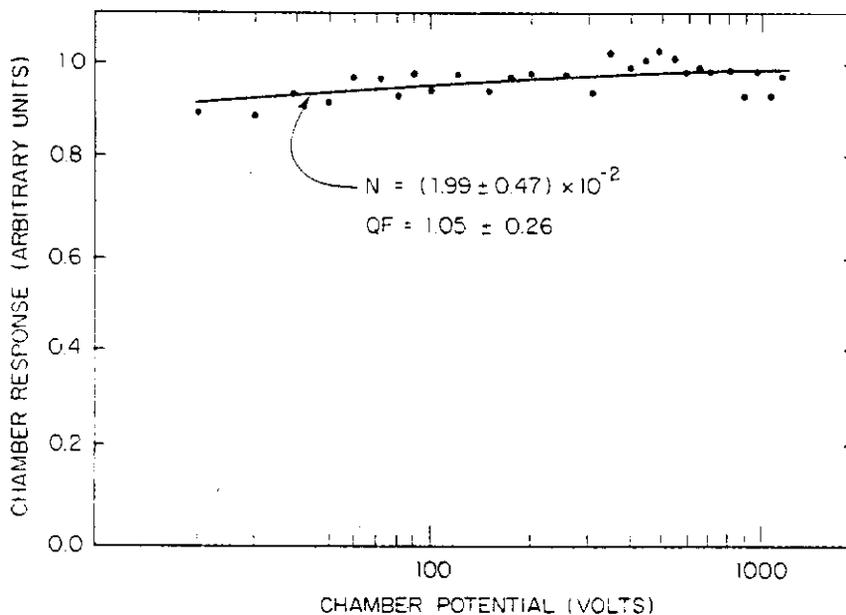


Figure 4: Recombination chamber response as a function of chamber potential.

Figure 4 shows the measured response and the resultant fit. As noted previously (6, 17) the value of N from the fit is correlated with the QF. For the value of N shown, the QF based upon the power law fit in Fig. 6 of (6) is  $1.05 \pm 0.26$ . This can be compared to the average value of  $1.42 \pm 0.15$  based upon the individual neutron and muon QF's shown in Table 1, weighted by the appropriate absorbed dose fractions.

## DOSIMETER AND FILM BADGE MEASUREMENTS

The responses of self-reading pocket dosimeters (Model 862, 0-200mR Gamma and X-ray Dosimeter, Dosimeter Corporation of America, P.O. Box 42377, Cincinnati, OH 45242, USA) and the film badges (Model P1 Dosimeter, R. S. Sandauer, Jr. & Co., 2 Science Road, Glenwood, IL 60425, USA) were determined in this radiation field, and compared to the total (both neutron and muon) absorbed dose measured with a tissue equivalent ion chamber of Fermilab design and calibration (18). These chambers have a digital readout calibrated with a  $^{137}\text{Cs}$  source to produce one logic pulse per exposure of  $6.45 \times 10^{-9} \text{ C kg}^{-1}$  (25  $\mu\text{R}$ ) in air. Similarly, the self-reading pocket dosimeters read out in the

traditional units of mR ( $1 \text{ mR} = 2.58 \times 10^{-7} \text{ C kg}^{-1}$  in air) and are calibrated with photons up to  $^{60}\text{Co}$  energies for their designed use in photon radiation fields. Since the ratio of muon stopping power in tissue (16) to that in air (nitrogen) (19) for energies between one and 800 GeV is  $1.07 \pm 0.05$ , an apparent reading of one Roentgen on the self-reading pocket dosimeter corresponds to a tissue absorbed dose of  $9.5 \times 10^{-9}$  Gy. We assume that the average energy per ion pair in air and tissue due to muons is the same as for photons.

Two separate dosimeter tests were conducted. For both cases, eight self-reading dosimeters supported vertically (as they typically would be worn by a person) in an aluminum holder 80mm by 140mm were placed directly upstream of the tissue equivalent ion chamber. These dosimeters have been verified to be relatively insensitive to neutrons from a Pu-Be source. Film badges were attached to the same holder. The film badge package contained both x-ray, beta, gamma film and Kodak NTA emulsion wrapped together so both muon and neutron absorbed doses were determined individually. The expectation being tested is that the "gamma" film accurately records the muon absorbed dose. The dimensions of the aluminum holder are very similar to those of the ion chamber. The spatial nonuniformity of the radiation field is insignificant over these dimensions. The pocket dosimeters were read out immediately, while the film badges were sent to the vendor for prompt processing (within two weeks after the exposure) to avoid possible fading of the NTA emulsion (20).

Table 2. Comparison of dosimeters with absorbed dose measurements using a tissue equivalent ion chamber, and the results of Table 1. The error determinations are explained in the text.

Instrument Type <sup>a)</sup>	Absorbed Dose ( $\mu\text{Gy}$ )			Normalized Absorbed Dose <sup>b)</sup>	
	Total	Muon	Neutron	Muon	Neutron
<u>TEST ONE</u>					
Ion Chamber	696	$638 \pm 17^c$	$56 \pm 17^c$	1.00	1.00
Pocket Dosimeters (8)		$734 \pm 16$		$1.16 \pm 0.05$	—
Film Badges (3)		$600 \pm 100$	$100 \pm 38$	$0.94 \pm 0.16$	$1.72 \pm 0.90$
<u>TEST TWO</u>					
Ion Chamber	704	$644 \pm 18^c$	$56 \pm 18^c$	1.00	1.00
Pocket Dosimeters (8)		$748 \pm 20$		$1.15 \pm 0.05$	—
Film Badges (5)		$600 \pm 100$	$75 \pm 13$	$0.93 \pm 0.16$	$1.27 \pm 0.50$

<sup>a)</sup> Number in parenthesis is number of instruments used

<sup>b)</sup> Normalized to ion-chamber values

<sup>c)</sup> Obtained from total absorbed dose by use of the fractions indicated in Table 1.

The results of the tests are summarized in Table 2. Errors assigned to the pocket dosimeter and film badge values are standard deviations. Neutron absorbed doses were derived from the dose equivalents reported by the vendor by removing a quality factor of eight appropriate to the Am-Be neutron field used in the calibration of the NTA emulsion.

As seen in Table 2, both the self-reading dosimeters and the film badges designed for the measurement of photon doses give results consistent with those in Table 1 for muons. The results based on the NTA film, on the other hand, suggest that the neutron component of the total absorbed dose is a factor of 1.3 to 1.7 times larger than was determined by measurements shown in Table 1. These NTA values are, however, likely to be overestimates since an enhanced film response is expected (20, 21) in the presence, as indicated in Fig. 2, of both thermal neutrons and those of energy higher than used by the vendor for calibration. Clearly, the strong energy dependence of the NTA film response makes it useful only as a rough indicator of neutron absorbed dose.

## CONCLUSION

It is seen that self-reading pocket dosimeters and ordinary film badges provide an adequately accurate record of absorbed dose and dose equivalent in a muon radiation field even where the energy spectrum is not well known. Any neutron contamination of such a field, however, will complicate the dosimetry considerably and will require a spectral determination for a satisfactory assessment. Future studies of both muon and neutron dosimetry should be done at high energy accelerator laboratories. At Fermilab, a beam of muons of known energy has recently been built and the authors hope to exploit it in extensions of this work.

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