Measurements of Neutron Spectra and Doses in the Tevatron Tunnel for Up to 800 GeV Circulating Proton Beams

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Abstract

Measurements of the neutron fluence and energy spectra in the Fermilab tunnel during Tevatron operation are described. Multi-sphere neutron moderators and \(^{6}\text{Li} \cdot \text{I}(\text{Eu})\) scintillators, as well as other instruments, were used under various accelerator operating conditions. Comparison is made between neutron spectra derived from three unfolding codes and reasonable agreement is found. In addition to the usual slowing-down and thermal components, a prominent peak is evident at about 230 keV. About 30% of the fluence is between 0.1 and 1.0 MeV, with only \(-4\%\) above 10 MeV. The median energy is about 60 keV and the average quality factor is close to seven. Upper limits are also given for the dose due to photons and minimum ionizing particles.

INTRODUCTION

Little experimental information about neutron spectra or doses within high energy accelerator enclosures has been available up to now (1,2). Such information is potentially useful for a number of reasons. Knowledge of the spectrum can aid in shielding design, in understanding and reducing background in high energy physics experiments, and in designing new facilities in such a way as to minimize radiation damage to sensitive components. This last reason was the primary motivation for the measurements described below, which were done at the request of the Central Design Group for the Superconducting SuperCollider (SSC). The results described here are discussed more fully in reference 3.

EXPERIMENTAL METHOD

The measurement location was selected based on the absence of devices such as septa or beam scrapers that would contribute anomalously high losses. Since the primary measurement of interest for SSC purposes was beam losses under coasting beam running conditions at the maximum energy of the Tevatron (~800 GeV), the A-48 sector of the Fermilab ring was chosen as representative of a typical tunnel section. More information on the Tevatron can be found in reference 4.

A multi-sphere neutron spectrometer was used, consisting of eight neutron-moderating polyethylene spheres of various diameters surrounding \(^{6}\text{Li} \cdot \text{I}(\text{Eu})\) thermal neutron detectors. Figure 1 shows a plan view of the spectrometer array location, which spanned a length of 4.9 meters in the Tevatron tunnel, with the upstream end approximately 14 meters from the downstream end of a 4 meter long room-temperature straight section. The working hypothesis was that this straight section was the local source of primary beam interactions for the detected events. Figure 2, a cross sectional view of the tunnel, shows that the detectors were at the same elevation as the Tevatron ring on the opposite side of the enclosure, about 2 meters away.
Figure 1. Plan view of experimental set-up in the tunnel. Beam direction was left to right. (a) Overall view  (b) Detail of detector arrangement. Numbers indicate diameter of polyethylene moderators. The Th and Bi fission counters were near the 10" and 12" spheres.

Figure 2. Tunnel cross section showing relationship to Tevatron and Main Ring
Pulse height spectra from each of the eight $^6$Li scintillators were simultaneously collected in a multichannel analyzer. A typical spectrum for one detector is shown in figure 3. The peak near channel 57 is from thermal neutron capture on $^6$Li in the scintillation crystal. The number of counts in this peak for each detector are the quantities of interest for spectrum-unfolding.

Besides the multi-sphere spectrometer, the counting rate from an additional $^6$Li detector surrounded by a 12.7 cm. diameter moderator was used as a beam loss monitor to ensure that during the data acquisition period there were no large fluctuations in the counting rates. Two moderated BF$_3$ gas proportional counters, and parallel plate thorium and bismuth fission counters were used to obtain additional fluence and spectral information. The identical BF$_3$ counters, which have a relatively flat energy response, were located at the upstream and downstream ends of the spectrometer array to provide data on any variation in neutron flux as a function of the longitudinal position within the tunnel. The ratio of counts from these two flux detectors allowed a correction to be applied to the raw counts from each $^6$Li scintillator of the spectrometer based on an assumed linear variation of the flux with detector position. Note that this procedure assumes that the spectrum shape did not change with distance downstream.

The superconducting Tevatron and conventional Main Ring share the same tunnel. It was therefore necessary to inhibit data acquisition when the Main Ring was operating due to the higher losses associated with it. The inhibit signals were derived from selected Tevatron clock events processed through a custom built gating module (5). The gate signal of primary interest for this work allowed data acquisition when the Tevatron was operating with coasting beam at its maximum energy of 800 GeV and no Main Ring operations were occurring.

**UNFOLDED SPECTRA**

The neutron spectrum unfolding problem is well known. It requires the solution of the following equation:

$$C_r = \int N(E) \ R_r(E) \ dE$$

where $C_r$ is the counting rate in a detector surrounded by a moderating sphere of radius $r$, $N(E)$ is the neutron spectrum and $R_r(E)$ the energy-dependent response functions. In practice the equation is solved in its discretized form:

$$C_r = \sum \ N(E_i) \ R_r(E_i) \Delta E_i$$
where \( N(E_i) \) is the neutron fluence in the \( i \)th energy bin \( \Delta E_i \), and the response functions are obtained from separate calculations. We use the response functions of Sanna (6) to unfold the spectra.

Because of the inherent problems in spectrum unfolding (i.e. solving an under-determined system of equations with solutions that are sometimes ill-conditioned) we have chosen to use three different computer programs to derive spectra from the measured counting rates: BUNKI uses the SPUNIT iterative recursion procedure along with a choice of different starting solutions (7), LOUHI is a constrained least-squares method that allows user-controlled constraint conditions (8), and SWIFT is based on a Monte Carlo method that allows a broad sampling of possible neutron spectra with no a priori assumptions about their character, apart from non-negativity (9,10).

**Tevatron Spectra**

Figure 4 shows an example of the measured counting rates (open circles) for an 800 GeV run as a function of moderator diameter. The solid curve is for the best-fit spectrum unfolded with the LOUHI program. The dashed curves represent calculated responses if 100% of the fluence is assumed to be in the indicated energy bins. Figure 5 compares spectra derived from the three unfolding codes plotted versus the neutron energy (in lethargy units). In general, the quality of the fits to the measured counting rates are similar for the spectra obtained from the three codes. We observe that SWIFT tends to produce somewhat higher and narrower structures. Although the shapes of the spectra may vary somewhat, the areas under the respective curves do not vary significantly.

![Figure 4](image)

**Figure 4 - Comparison of measured (open circles) and calculated (solid line) detector responses. Other curves show relative response for three representative neutron energies.**

The dominant feature of the spectra for 800 GeV operation is the prominent peak near 0.23 MeV (see Figure 5). Only about 4% of the fluence is greater than 10 MeV, about 30% is between 0.1 and 1.0 MeV, and about 21% is below 1 eV. These numbers are averages for several runs. Figure 6 illustrates these results where a spectrum is expressed as the cumulative percentage of fluence and absorbed dose (tissue), plotted as a function of neutron energy. The apparent scarcity of high energy neutrons was confirmed by the small counting rates from the thorium and bismuth fission counters which have neutron detection thresholds of ~2 and ~50 MeV respectively.

Table 1 compares the neutron fluence, absorbed doses, and quality factors obtained from the three unfolding codes for several different 800 GeV runs. Reasonable agreement was found between the codes for these derived quantities, although there was a tendency for SWIFT to
Figure 5. Comparison of spectra derived from three unfolding codes (BUNKI, LOUHI, SWIFT) for Tevatron 800 GeV coasting beam.

give slightly higher quality factors. When averaged over all runs the quality factor was ~6.9. We also note that the average of the multisphere fluence measurements (normalized to the circulating proton beam intensity) were consistent with the average fluence obtained from the two moderated BF3 counters once allowance was made for the ~20 keV detection threshold of those counters. The

Figure 6. Neutron spectrum expressed as a cumulative percentage of fluence and tissue absorbed dose. 800 GeV data.
agreement was within ~20% for the 800 GeV runs. Better agreement could not be expected since
the difference between the upstream and downstream BF3 counters themselves was often ~20%
and in a few cases was even larger.

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Table 1
Neutron fluence, absorbed dose and quality factors for several 800 GeV runs
(a=BUNKI, b=LOUHI, c=SWIFT)

<table>
<thead>
<tr>
<th>Run</th>
<th>Neutron Fluence</th>
<th>Tissue Absorbed Dose</th>
<th>Quality Factor</th>
<th>Avg. QF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(10^{-3}) n-cm(^{-2})</td>
<td>(micro-rad)</td>
<td>(a)</td>
<td>(b)</td>
</tr>
<tr>
<td>1</td>
<td>2.98 2.97 2.87</td>
<td>6.2 11.8 6.0</td>
<td>6.41</td>
<td>6.16</td>
</tr>
<tr>
<td>2</td>
<td>6.84 6.80 6.85</td>
<td>10.7 9.9 13.7</td>
<td>7.08</td>
<td>7.45</td>
</tr>
<tr>
<td>3</td>
<td>5.35 5.35 5.28</td>
<td>10.0 12.5 11.0</td>
<td>6.34</td>
<td>6.26</td>
</tr>
<tr>
<td>4</td>
<td>12.3 12.2 12.1</td>
<td>18.0 17.0 25.0</td>
<td>6.64</td>
<td>7.00</td>
</tr>
</tbody>
</table>

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Main Ring Spectra

Data were also taken during periods of Main Ring operations at energies from 8 to 150 GeV. It was necessary to gate off the data acquisition for the first 0.85 to 1.5 seconds of a Main Ring acceleration cycle due to the extremely high counting rates at the 8 GeV injection energy. Of the three unfolding codes used, SWIFT tended to produce a somewhat higher thermal component but otherwise the unfolded spectra had similar properties and closely resembled those obtained for the Tevatron runs at higher beam energies; a prominent peak near 0.26 MeV, less than 2% of the fluence greater than 10 MeV, about 28% between 0.1 and 1.0 MeV, and 22% less than 1 eV. Note that these fluence percentages are averages that were determined from Main Ring spectra obtained under a variety of operating conditions. The details can be found in reference 3. A typical spectrum is shown in Figure 7.

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Figure 7. Unfolded spectrum from LOUHI for a Main Ring run over the acceleration cycle from 8 to 150 GeV.
Comparison with Theoretical Spectra

It is interesting to compare our measured spectra with theoretical ones in the literature. Figure 8 shows a spectrum for 800 GeV coasting beam compared to two spectra calculated by O'Brien (15). The open points are calculated at a depth in soil of 1000 gm-cm$^{-2}$, while the starred points are calculated at a depth of 500 gm-cm$^{-2}$ in iron. Based on the comparison, it seems reasonable to conclude that the peak near 230 keV that is seen experimentally is related to a "filtering" of the neutrons by the iron laminations in the Tevatron magnets. Similar results are reported elsewhere at this conference for a thick iron shield (16). The finer structure in the calculated spectrum is most likely due to details of the neutron elastic scattering cross section energy dependence (resonances, etc.). Such details are not expected to be detectable in an inherently low resolution system such as the multi-sphere spectrometer. The lack of agreement at lower and higher energies might be explained by details of the geometry and materials within and around the accelerator tunnel (e.g., soil, concrete), but this is difficult to verify experimentally.

Median and Effective Neutron Energies

Table 2 shows the median energies of the fluence and absorbed dose distributions determined from the 50% values of curves like that of Figure 6. Values of the fluence-median energy varied between 59 and 110 keV for four types of gating conditions. Values for the absorbed dose median energies were higher and had a smaller spread (490 to 690 keV). In addition, the average kerma factor (absorbed dose to tissue divided by neutron fluence) were used to determine an effective neutron energy. Values derived using the tabulation of Caswell et al. (11) are also shown in Table 2. It is interesting to note the relatively small values of these effective energies.
Table 2
Median and effective neutron energies for several runs

<table>
<thead>
<tr>
<th>Type of run</th>
<th>Energy (GeV)</th>
<th>Number of runs</th>
<th>Median energy (MeV)</th>
<th>Eff. energy (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>fluence</td>
<td>dose</td>
</tr>
<tr>
<td>Tevatron a</td>
<td>800</td>
<td>4</td>
<td>0.059</td>
<td>0.61</td>
</tr>
<tr>
<td>Tevatron b</td>
<td>800</td>
<td>12</td>
<td>0.059</td>
<td>0.69</td>
</tr>
<tr>
<td>Tevatron c</td>
<td>150</td>
<td>1</td>
<td>0.110</td>
<td>0.49</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td>0.061</td>
<td>0.66</td>
</tr>
</tbody>
</table>

Main Ring

8-150

5

0.051 0.62

0.38

a - Coasting beam with small losses
b - all runs
c - coasting beam at injection energy

DOSE FROM MINIMUM IONIZING PARTICLES

Charged particles from the high energy cascade (pions, muons) are expected to be largely minimum ionizing and their energy loss rate is ~1.2 MeV gm−1 cm−2. For the LiI scintillator used in this experiment such a particle would deposit about 6.2 MeV when crossing a diameter of the crystal. For a broad, monoenergetic beam perpendicular to the scintillator axis the energy loss distribution rises from zero (corresponding to tangential incidence) to a sharp maximum for the diametral path(12)(see Figure 9). Since no such enhancements were seen in the pulse height distributions in this energy region, and because photon and neutron contributions are expected to be important in this same pulse height region, it was only possible to set an upper limit on the dose due to minimum ionizing particles. Using the pulse height spectrum from the detector surrounded by the 18 inch diameter sphere since it had the fewest counts in the region of interest, the ratio of minimum ionizing dose (in LiI) to neutron dose (in tissue) was found to be less than 0.077±0.030. This ratio was derived from 18 (unselected) Tevatron runs made under a wide variety of conditions.

Figure 9. Observed pulse height distribution (open circles) for LiI, showing idealized distribution for minimum ionizing particles in a cylindrical detector and an assumed $E^{-2}$ photon spectrum.
DOSE FROM PHOTONS

To estimate an upper limit for the dose to LiI from photons, we assume a pulse height distribution proportional to $E^{-2}$ which is suggested by the track length distribution from shower theory (13,14). Such a shape is indicated in Figure 9. By normalizing such a curve to an experimental pulse height distribution and integrating between suitable limits an upper limit can be obtained on the photon dose to LiI. The dose is proportional to

$$\int_{E_1}^{E_2} E \ast E^{-2} \, dE$$

where we explicitly include in the above integral the energy weighting of the assumed photon spectrum, for clarity. The energy interval for the integration was chosen to be 0.3 to 30 MeV. The lower limit was based on the fact that photons much below this would be highly attenuated by the iron in the accelerator magnets, while for energies much greater than 30 MeV the energy transfer efficiency declines since the range of the electrons from photon interactions begins to exceed the size of the LiI crystal. Using data from a detector moderated by a 5.08 cm. diameter sphere, we found that the ratio of photon dose (in LiI) to neutron dose (in tissue) was 1.12±0.050 when averaged over 17 Tevatron runs. For the four selected runs of coasting beam given in Table 1 the ratio was 1.24±0.50. We emphasize again that these ratios must be considered only as upper limits under the stated assumptions since there are clearly other processes for energy deposition in the LiI that have not been discussed and are difficult to estimate (e.g. capture gamma-rays, fast neutron reactions).

REFERENCES


12. W.P Swanson, Appendix G to reference 3.


