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Measurement of Neutron Attenuation Through Thick Shields and Comparison with Calculation

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Los Alamos National Laboratory

Abstract

The large neutrino experiments conducted over the last several years at the Los Alamos Neutron Science Center (LANSCE) have provided the opportunity to measure the effects of neutron attenuation in very thick shields. These experiments have featured detectors with active masses of 6 to 150 tons and shield thicknesses ranging from 3000 to 5280 g/cm². An absolute measurement of the high-energy neutron flux was made from the beam stop in a neutrino cave at ninety degrees and nine meters from the beam stop. Differential neutron shielding measurements in iron were also performed, resulting in an attenuation length of 148 g/cm². These measurements allow for the testing of radiation shielding codes for deep penetration problems. The measured flux and attenuation length is compared to calculations using the LAHET Code System (LCS). These codes incorporate biasing techniques, allowing for direct calculation of deep penetration shielding problems. Calculations of the neutron current and attenuation length are presented and compared with measured values. Results from the shielding codes show good agreement with the measured values.

1. Introduction

The design of high-current hadron accelerator facilities requires the best possible estimates for neutron shielding. A shield that is too thick will waste resources needed for other parts of the program and will reduce the fluxes of desirable particles by increasing the distance to the detector. A shield that is too thin will result in unwanted neutron backgrounds in experimental detectors and additional radiation exposure to personnel.

The shielding considerations for proton accelerators operating in the Los Alamos Neutron Science Center (LANSCE) energy range (800 MeV) is controlled by the high-energy neutron cascade. The neutrons are attenuated by elastic and inelastic scattering. Elastic scattering is not an effective means of absorbing high-energy neutrons since there is little change in the neutron energy or direction for shields with moderate atomic numbers. However, below the lowest energy threshold for inelastic scattering, neutrons can build up and penetrate the shield in large numbers.
The large neutrino experiments at LANSCE offer more sensitive and expensive detectors than are usually used for shielding experiments. The detectors are well understood and the tracking information can be used to ensure that the neutrons are coming through the bulk shield and not through cracks or around corners.

There were two large neutrino experiments that measured neutrons in the neutrino cave at ninety degrees to the beam stop. E31 was a 6-ton water Čerenkov detector that used both ordinary and heavy water. This experiment measured neutron spectra at shield thickness of 4 and 5 meters and used the results to extrapolate the neutron background at the final shield thickness of 6.3 m. No neutrons were observed at 6.3 m in this experiment. A later experiment, E225, consisted of a 15-ton plastic scintillator-tracking detector. Because of the larger size and the longer exposure, E225 was able to measure the neutron current at a shield thickness of 6.5 m.

As a comparison, the neutron fluxes were calculated using the LAHET Code System (LCS). The recent modifications to the LCS code system, namely the incorporation of importance splitting, together with the dramatic advancement in computer processing speed, allow these neutrino experiments to be modeled completely using Monte-Carlo transport codes. These experiments provide a unique opportunity to benchmark these transport codes through very deep shielding.

2. Experimental Geometry Description

A general layout of the experimental area is shown in Figure 1. These experiments were conducted at the LANSCE neutrino experimental cave, located at the end of the Area A experimental area. The LANSCE accelerator is a linear proton accelerator capable of producing 1 mA of 800 MeV protons. The proton beam entered from the left and first passed through a 21-cm diameter spherical water degrader, used to increase the neutrino production (E225 only). Between the degrader and the beam stop are several isotope production targets. For the E31 experiment, these were modeled as four 4-cm thick aluminum disks, while for E225, nine 2.8-cm thick discs were used. The beam stop is a series of 21-cm diameter copper discs of various thicknesses, with water-cooling channels separating the concurrent discs. The total length of the copper in the beam stop is 60 cm.

The lateral shield consisted first of 36 cm of water-cooled steel next to the beam stop, followed by 55 cm of steel plate (density 7.8 g/cm³). Figure 1 shows where, during part of the E225 run cycle, 35 cm of this iron was replaced with 30.5 cm of depleted uranium. Next, additional steel plate was placed out to a distance of 4.2 m from the beam line. Additional shielding consisting of counterweights from an Atlas missile silo door were stacked to complete the bulk shielding between the beam stop and the detector, as well as forming the side shielding for the detector. One of these plates was weighed and its dimensions measured to determine the density. The measured density was 7.18 g/cm³. The center of the neutrino

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*LAHET is a registered trademark of the Regents of the University of California, Los Alamos National Laboratory.
detector was located 9 m from the beam line centered at the beam stop. At most, a total of 5280 g/cm\(^2\) of shielding was between the beam stop and the detector.

Prior to the water degrader, the proton beam passed through two graphite targets, 3 cm, and 6 cm long respectfully. These targets were located well before the beam stop (> 40 m) and any neutrons from these targets were rejected by the detector electronics. However, these targets effected the beam profile. The proton spectrum incident on the degrader was determined by running a 797 MeV proton beam through 9 cm of graphite. The result is a Gaussian proton spectrum with an average energy of 764 MeV and full-width half-maximum of 2 MeV.

### 3. Monte-Carlo Calculations

The neutron current into the neutrino detectors was calculated using LAHET 2.8.3.\(^1\) LAHET is Monte-Carlo radiation transport code that calculates interaction probabilities and transportation parameters for protons, pions, muons, as well as neutrons above 20 MeV. The pre-equilibrium model following the intranuclear cascade was invoked for all calculations. The use of this model improves the agreement with neutron spectrum measurements at large angles.\(^2\) The rest of the LAHET parameters were set to their default values.

A total of 500,000 source protons were used in each problem. The calculations were performed in a multi-step process. Since LAHET either records all or none of the collisions and surface boundary crossings into a disc file, limits on computer disc space made it impractical to complete the calculations in one long run. Instead, the bulk of the problem was run in the initial stage during which particles that were transported to the last 20 cm of the bulk shield were written to a supplemental file to be used as a source file in the next step. To increase the statistics, the geometry of the neutrino experiments was modeled using cylindrical symmetry. The bulk shield was divided into 20-cm long sections to allow particle splitting as the particles traveled deeper into the shield.

In the second stage, the last shield section and beyond, including the detector, were modeled in three dimensions. In order to increase the number of particles directed at the detector, a program was written in which the particles from the first stage, together with their directional cosines, are rotated along the cylindrical surface of the source towards the detector. This effectively maps the cylindrical surface source to one confined to a 30-degree arc on the cylinder centered towards the detector. The detectors subtended at most 20 degrees, small compared to the arc length of the modified source.

### 4. Measurements and Results

#### 4.1 Differential Shielding Measurement

During the setup of the E31 experiment, a differential shielding measurement was performed with the 6-ton water Čerenkov detector.\(^3\) This detector was a cube, 1.8m on a side, and loaded with 96 photomultiplier tubes. The fast neutron flux (20 to 60 MeV) was recorded for shielding thicknesses of 4 m and 5 m, using the 7.18 g/cm\(^2\) steel counterweights as the
shielding material between the two distances. The results are summarized in Table 1. The ratio of the two neutron flux measurements was $128 \pm 6$. This results in an attenuation length of $148 \pm 2 \text{ g/cm}^2$ or 19.0 cm for steel with a density of 7.8 g/cm$^3$.

**Table 1**

**Differential Shielding Results**

<table>
<thead>
<tr>
<th></th>
<th>Rate per mC</th>
<th>Ratio</th>
<th>Attenuation Length (g/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4 m</td>
<td>5 m</td>
<td></td>
</tr>
<tr>
<td>E31 (counts)</td>
<td>$5 \pm 0.2$</td>
<td>$0.039 \pm 0.001$</td>
<td>$128 \pm 6$</td>
</tr>
<tr>
<td>LAHET</td>
<td>$7740 \pm 210$</td>
<td>$64.2 \pm 1.9$</td>
<td>$121 \pm 5$</td>
</tr>
</tbody>
</table>

These measurements were modeled using LAHET, and the results are also shown in Table 1. Neutrons entering the detector in the 20 MeV to 60 MeV energy range were tallied for both 5 m and 4 m of shielding. The ratio between the two calculations is $121 \pm 5$, a 6% difference from the measured ratio.

In addition to the 20 MeV to 60 MeV energy range, the results from LAHET were used to calculate the attenuation length for other energy groups. Table 2 summarizes these results. Below 100 MeV the ratios between the 4-m and 5-m shielding calculations were just outside the statistical errors. The last two energy groups showed a slight decrease in the attenuation length. These results were confirmed by the E31 measurements, in which the shape of the measured spectra at 4 m and 5 m of shielding was found to be the same.

**Table 2**

**Differential Shielding Results for Several Energy Groups**

<table>
<thead>
<tr>
<th>Energy Range (MeV)</th>
<th>Rate per mC</th>
<th>Ratio</th>
<th>Attenuation Length (g/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4 m</td>
<td>5 m</td>
<td></td>
</tr>
<tr>
<td>20 - 60</td>
<td>$7740 \pm 210$</td>
<td>$64.2 \pm 1.9$</td>
<td>$121 \pm 5$</td>
</tr>
<tr>
<td>60 - 100</td>
<td>$5010 \pm 160$</td>
<td>$44.0 \pm 1.4$</td>
<td>$114 \pm 5$</td>
</tr>
<tr>
<td>100 - 200</td>
<td>$9600 \pm 250$</td>
<td>$72.9 \pm 2.2$</td>
<td>$132 \pm 5$</td>
</tr>
<tr>
<td>200 - 400</td>
<td>$2350 \pm 130$</td>
<td>$16.6 \pm 1.0$</td>
<td>$142 \pm 12$</td>
</tr>
</tbody>
</table>

**4.2 Depleted Uranium-Steel Comparison**

In experiment E225, a 3 m x 3 m x 3.4 m sandwich detector was used, comprised of 40 layers, each with 2.5 cm (2.5 gm/cm²) of NE114 scintillator and 6.0 cm of flash chamber. Neutron-produced recoil protons were detected by running without an upper level discriminator that normally vetoed proton signals. The trigger requirement in E225 was at least a three-layer coincidence, corresponding to minimum proton energy of 150 MeV, making the detector sensitive to neutrons in the 150-400 MeV energy range. The detector had an average density of 0.47 g/cm³ and a hydrogen-carbon ratio of 1.39:1.
During this experiment, 35 cm of steel near the beam stop was replaced with 30.5 cm of depleted uranium. This change in the shielding configuration resulted in a reduction of the measured proton-recoil event rate from $56 \pm 2$ events per mA-hr to $25 \pm 2$ events per mA-hr. The experimental reduction factor is $0.45 \pm 0.04$.

This shielding change was also modeled using LAHET. Using the same geometry as before, 35 cm of steel was replaced with 30.5 cm of depleted uranium and 4.5 cm of air. Neutrons in the energy range of 150 MeV to 400 MeV crossing the front face of the detector were counted. These results are summarized in Table 3. The reduction factor calculated with LAHET is $0.524 \pm 0.031$. The DU to steel ratio is slightly higher for LAHET than the measured ratio, but still in close agreement.

### Table 3

<table>
<thead>
<tr>
<th></th>
<th>Rate per mA-hr</th>
<th>DU/Steel Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30.5 cm DU</td>
<td>35 cm Steel</td>
</tr>
<tr>
<td>E225 (counts)</td>
<td>$25 \pm 2$</td>
<td>$56 \pm 2$</td>
</tr>
<tr>
<td>LAHET</td>
<td>$183 \pm 8$</td>
<td>$350 \pm 12$</td>
</tr>
</tbody>
</table>

### 4.3 Absolute Neutron Current

The data from E225 were also used to determine an absolute neutron current into the detector. A Monte Carlo calculation, using the Kent State code for neutrons on scintillator, was done to determine the detector response. Neutrons were generated normal to the detector face with uniform initial position and with energies between 50 MeV and 400 MeV. The data were then fit to a cubic equation to obtain the efficiency as a function of neutron energy with the following result:

$$\varepsilon(E) = -0.3879 + 5.7 \times 10^{-3} E - 1.411 \times 10^{-5} E^2 + 1.156 \times 10^{-8} E^3$$  \hspace{1cm} (1)

This functional form for the efficiency was used to integrate over an assumed energy distribution for the incident neutrons:

$$\phi(E) = \phi_0 E^{-\gamma} \quad E_{\text{min}} \leq E \leq E_c$$

$$\phi(E) = \phi_0 \left(C_0 + C_1 E + C_2 E^2 \right) E^{-\gamma} \quad E_c < E \leq E_{\text{max}}$$  \hspace{1cm} (2)

where $E$ is the neutron energy and $\gamma$ is the spectral index. The constants are determined by the continuity of the flux and the first derivative at the junction energy $E_c$ and the condition that the flux vanish at $E = E_{\text{max}}$. The junction energy is taken to be two-thirds of the maximum energy.
$E_{\text{min}}$ is about 20 MeV, well below the region of interest. Measurements typically give a spectral index of $\gamma = 1.8$. This shape was tested with results from a later experiment (E645), and found to be in good agreement with Equation 2 for $\gamma = 1.8$ and $E_{\text{max}} = 400$ MeV.

The average efficiency for the $(150, E_{\text{max}})$ energy group is defined as

$$\langle \varepsilon \rangle = \frac{\int_{150}^{E_{\text{max}}} \varepsilon(E)\phi(E)dE}{\int_{150}^{E_{\text{max}}} \phi(E)dE} \tag{3}$$

This average efficiency was found to be $\varepsilon = 0.29$.

The neutron current can be calculated from the proton recoil rate. Using an event rate of $56 \pm 2$ per mA-hr, and a detector efficiency of 0.29, the neutron rate in the energy range 150 MeV to 400 MeV is 193 neutrons/mA-hr. This rate can be compared to the LAHET calculated rate of 350 neutrons/mA-hr. The calculated result is within a factor of two, a remarkable agreement considering the shield is over 33 attenuation lengths thick, corresponding to a reduction factor over 14 orders of magnitude.

As mentioned earlier, the average efficiency to the detector was calculated using an assumed neutron spectrum. The neutron spectrum determined by LAHET can be used to calculate an updated average efficiency. This spectrum is shown in Figure 2. The average detector efficiency using this spectrum is $\varepsilon = 0.26$. The number of neutrons entering the detector based on this average efficiency is $215 \pm 8$ per mA-hr, for a measured to calculated ratio of 1.6, closer still to the measured value.

5. Conclusion

The differential neutron current was measured at 4 m and 5 m of steel and compared to calculations using the LAHET radiation transport code. The calculations were found to be with close agreement with the measured data. Data was also taken comparing depleted uranium with steel shielding. The LAHET calculations over estimated the DU/steel ratio by 16%. An absolute measurement of the number of neutrons entering the detector was also measured and compared to calculations. In this case, LAHET overestimated the number of neutrons by 80%, based on the shape of the neutron spectrum assumed by the experimenter. If the neutron spectrum calculated by LAHET is used to calculate the average detector efficiency, LAHET overestimates the absolute neutron current by only 60%.

Acknowledgements

The authors thank Laurie Waters, Phil Ferguson, and the E31 and E225 experimental collaborations, without whom this work would not be possible. This work was supported by the U. S. Department of Energy.
References


5 Ibid.

Figure 1. Source and shield geometry for the E225 Experiment at the LANSCE beam stop. The geometry for the E31 experiment was similar except steel was used in place of the uranium and there was less cast steel shielding between the beam stop and the detector.

Neutron Spectrum into the E225 Detector

Figure 2. Neutron spectrum into the E225 detector calculated with LAHET.