CHARACTERISATION OF THE SPECTRA OF SPALLATION NEUTRON SOURCES THROUGH MODELLING

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Abstract

We have studied the properties of spallation neutrons produced by simulation of proton beams on simple lead targets. This is relevant for ADSR systems and other neutron sources. We provide a detailed description of the overall numbers of neutrons, their energy spectra, and spatial and angular distributions for proton energies between 100 and 1400 MeV, and find that these can be parametrised by simple forms.

INTRODUCTION

We study the number and nature of the neutrons produced by spallation, as simulated by the programs MCNPX [1] and Geant4 [2], in the hope that this will be useful in studies of ADSR reactors [3]. We consider a beam of protons falling on a cylindrical target, as shown in Fig. 1.

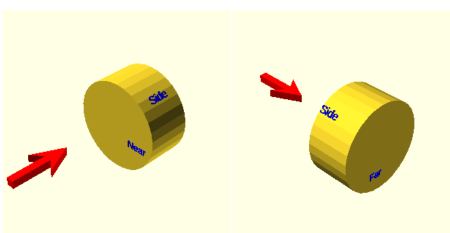

Figure 1: The target

The target is a cylinder of natural lead, of radius 30 cm and length 30 cm, where the 'Near', 'Far', and 'Side faces are as indicated. The beam is considered as monoenergetic, parallel and impinging on a single point. Numbers of particles simulated by MCNPX are typically 10^6 per run, and are usually such that statistical errors are negligible. Geant4 simulations (being slower) were of smaller numbers of particles. Preliminary results have been reported previously [4].

OVERALL NUMBERS

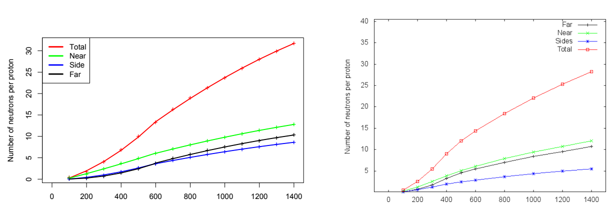

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Figure 2: Numbers of neutrons as a function of proton energy, as predicted by MCNPX (left) and Geant4 (right). Contributions from the different faces are shown

The two codes agree in predicting the increase of the overall number of neutrons with the energy of the proton beam, giving the often-quoted figure of about 30 neutrons per proton at 1 GeV.

It is hard to fit the curve with a single form, but two parabolas in the regions above and below 600 MeV provide a good description.

More neutrons emerge from the near face than the far face. This is somewhat counter-intuitive, but can be explained as the neutrons undergo many collisions in lead and 'forget' their original direction, and the near face receives the full energy of proton beam.

The total numbers from the two codes agree but there are small difference in the relative contributions from the end faces and sides which we are still trying to understand.

ENERGY SPECTRA

The description of the neutron energy spectra is different when one consider high energy or low energy neutrons, Figure 3 shows the energy spectra, as predicted by MCNPX, for neutrons for different proton energies, and they share an approximately exponential fall over a wide range, terminated by the actual proton energy. This can be neatly parametrised by $P(E) \propto \exp{(\alpha + \beta E + \gamma E^2)}(1 - (E/E_p)^\delta)$

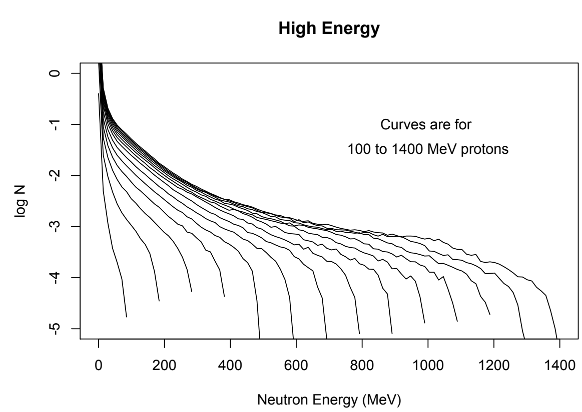

Figure 3: MCNPX predictions of the distributions in neutron energy for different proton energues

The predictions of Geant 4 agree, as is shown in Figure 4, which also shows how the spectra differ between the near, far and side faces.

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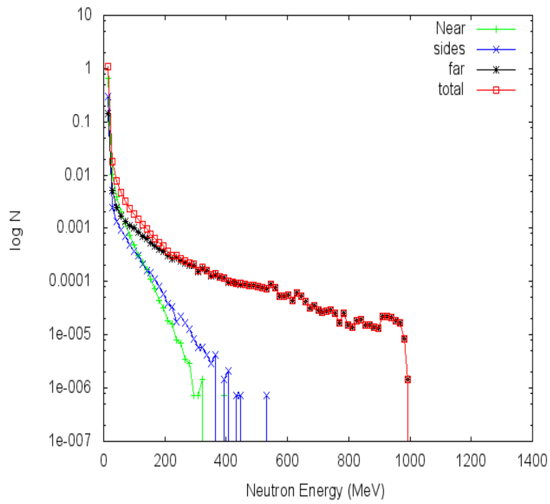

Figure 4: Distribution in E from Geant4 showing the contributions from different faces, for a 1000 MeV proton beam

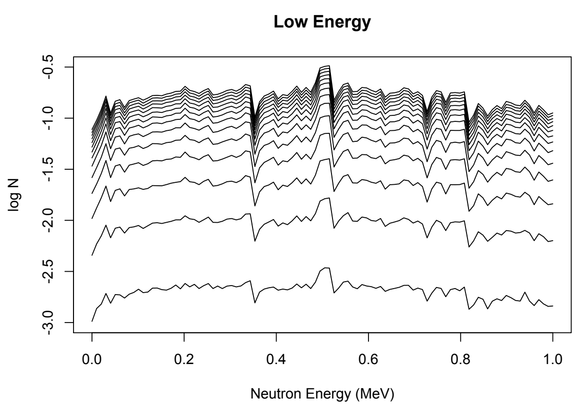

Figure 5: Low energy distributions in E from MCNPX

The logarithmic scale used in these figures may mislead: most neutrons emerging have, on this scale, low energies, and fall into the peak near $E = 0$. If the spectra are plotted in the low energy region, below 1 MeV, as is done in Figure 5, then different proton beam energies give spectra which are identical in shape but differ in magnitude. The irregularities are due to the structure of the neutron-Pb elastic cross section (This is further discussed in a later section).

Hence the predictions of Geant4 (Figure 6) are somewhat different, due to the different cross section libraries used. This plot also shows that the spectra from different faces are the same, in contrast to the high energy spectra of Figure 4

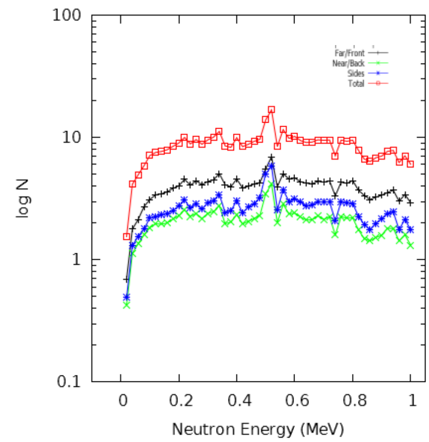

Figure 6: Low energy distributions in E from GEANT4

SPATIAL DISTRIBUTIONS

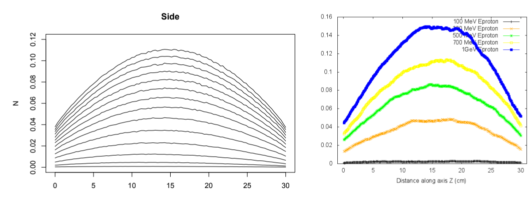

Figure 7: Distributions in z from MCNPX (left) and GEANT4 (right)

Figure 7 shows the predictions for the longitudinal position of neutrons emerging from the sides of the cylinder, for proton energies from 100 to 1400 MeV. The curves are well described by parabolas, with a centre which is almost at the centre of the cylinger, varying only slightly with proton energy

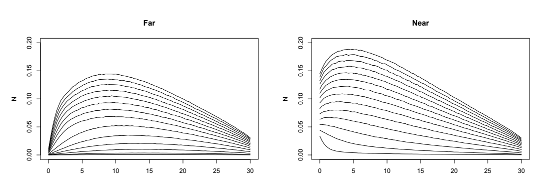

Figure 8: MCNPX predictions of radial distributions from the far face(left) and near face (right)

Figure 8 shows the radial distributions of particles emerging from the end faces. A first guess of a 2-dimensional gaussian, $P(r) \propto r\exp(-r^2/2\sigma^2)$, is not quite adequate: the curves for the far face can be parametrised by $P(r) \propto r^a \exp(-br - cr^2)$. For the near face, on the right, this is inadequate (particularly at low proton energies) due to a large number of neutrons emerging near $r = 0$, and the form $P(r) \propto (r - d)^a \exp(-br - cr^2)$ can be used.

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ANGULAR DISTRIBUTIONS

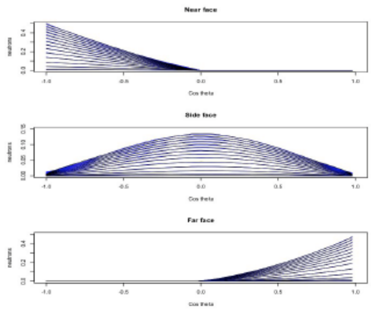

Figure 9: Distributions in $\cos\theta$ for the near face (top), sides (middle) and far face (bottom)

Figure 9 shows the MCNPX predictions for the polar angle ($\cos\theta$) distributions from the 3 faces. The end face distributions are adequately described by quadratics, the side face needs a quartic.

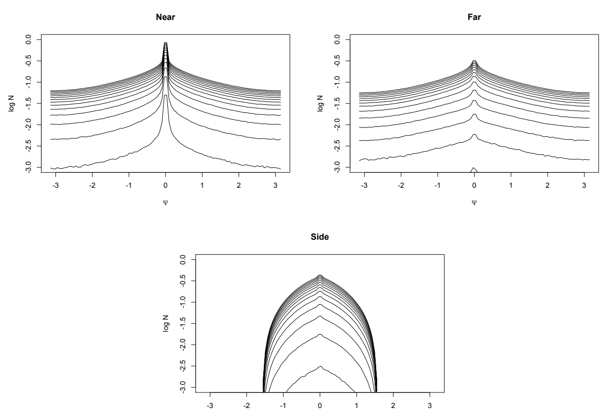

Figure 10: Distributions in ψ for the near face (top left),far face (top right) and sides (bottom)

Figure 10 shows the distributions in the angle ψ, the difference between the direction of travel (in the xy plane) and the azimuth where the neutron emerges. These contain two components, a wide variation, parametrisable by a simple polynomial, over the possible range (2π for the end faces and π for the sides) and a tight component near zero, which arises when a neutron emerges as a result of a single interaction. The relative size of the two components is strongly dependent on proton energy.

MODEL DEPENDENCE

We used the ENDF/B-V cross section tables [5]. We also tried the ENDL92 tables, which are provided in the release. Figure 11 shows the two total cross sections in the low energy (0-1 MeV) region, and Figure 12 shows the corresponding neutron spectra from MCNPX. The peaks in the former give dips in the latter. This underlines the sensitivity of the low energy spectrum to the cross section library used

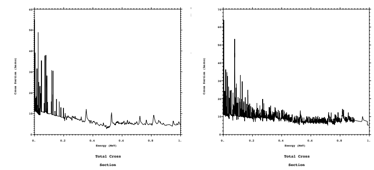

Figure 11: σ_{tot} for ENDF/BV (left) and ENDL92 (right)

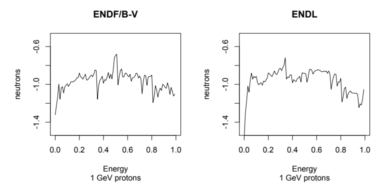

Figure 12: The low energy spectra produced by ENDF/BV (left) & ENDL92 (right)

Using Geant4 'out of the box' gave results considerably different from MCNPX: the default option to use models for cross sections is inapplicable for low energy neutrons, where resonances dominate. Hence a 'High Precision' model, using a cross section library, had to be used. We found the binary cascade `BIC_HP` model agreed better with the MCNPX predictions than `BERT_HP`, so we used that.

CONCLUSIONS

The analysis shows that the neutron spectra and properties produced by spallation are parametrisable by simple forms, with the exception of the low energy spectrum which is, however the same shape, whatever the proton energies.

It is believed that correlations between the quantities (such as those due to emergence from different faces) do not present a significant problem.

The parametrisation will depend on the target dimensions, but these dependences are slow and can be parametrised in their turn.

A complete parametrisation, which will enable studies of ADSR systems to be done without reference to the high energy spallation physics, is in preparation.

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