NEUTRON SPALLATION STUDIES FOR AN ACCELERATOR DRIVEN SUBCRITICAL REACTOR

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Abstract

Nuclear power production can benefit from the development of more comprehensive alternatives for dealing with long-term radioactive waste. One such alternative is an accelerator-driven subcritical reactor (ADSR) which has been proposed for both energy production and for burning radioactive waste. Here we investigate the effects of the size of the ADSR spallation target on the total neutron yield integrated over the neutron energy and emission angle. The contribution to the total neutron yield from the (n, xn) neutron interactions is evaluated at proton beam energies between 0.4 and 2 GeV. Calculations have been carried out with the GEANT4 simulation code using the Liege intranuclear cascade model and the results are compared to the the LAHET/MCNP code package predictions.

INTRODUCTION

Due to their inherent safety features and waste transmutation potential, accelerator driven subcritical reactors are the subject of research and development in many countries around the world. The ADSR consists of three parts: the accelerator, spallation neutron target and sub-critical reactor core. The spallation target is at the heart of any accelerator driven system.

Because the ADSR is operated in a subcritical state, the target system has to provide the neutrons needed to sustain fission. These are generated by the spallation process resulting from high energy protons impacting the spallation target installed at the centre of the core. Therefore the target materials must have high neutron production efficiency. One of the best candidate target material is lead or a lead/bismuth eutectic.

In the present work, the GEANT4 simulation code [1] has been used to calculate the total neutron yield for spallation reactions in Pb for proton energies between 0.4 and 2 GeV. The results of this work provide also a benchmark of the GEANT4 simulation results against the MCNP/LAHET (RAL model) code output published in reference [2].

COMPUTATION DETAILS

GEANT4 provides an extensive set of hadronic physics models for energies up to 10 - 15 GeV, both for the intranuclear cascade region and for modelling of evaporation. In MCNP/MCNPX codes, the Bertini model is used by default for nucleons and pions, while the ISABEL model is used for other particle types [3]. The Bertini model does not take into account the nuclear structure effects in the inelastic interactions during the intranuclear cascade and therefore the code modelling of interactions at energies much below 100 MeV is questionable [2]. This becomes an important issue when dealing with thick targets, as although the primary neutrons are produced by the high energy proton beam, these are relatively low energy neutrons which can produce further spallation processes inside the target leading to secondary neutrons.

For the Geant4 simulations, we selected the Liege intranuclear cascade model together with the independent evaporation/fission code ABLA. This model has been added recently to the Geant4 code and has been validated against experimental data for spallation processes in many different heavy elements [4]. This model is valid for proton, neutron, pion, deuteron and triton projectiles of energies up to 3 GeV and heavy target materials (Carbon - Uranium). It models the Woods-Saxon nuclear potential, Coulomb barrier, non-uniform time-step, pion and delta decay cross sections, delta decay, Pauli blocking and utility functions, making it an independent code. The Liege model is largely free of parameters and is preferred by validation and, compared to the other theoretical models available in Geant4 (Binary and Bertini being currently the most widely used), it is more data driven [5].

The MCNPX data with which our GEANT4 simulations are compared have been taken from reference [2]. In all the simulations described below, a 60 cm long Pb target was considered.

RESULTS

Figure 1 shows the dependence of the number of neutrons on the target radius, both for neutrons produced and leaving the target volume. This is shown separately for the primary neutrons generated by the initial protons, secondary neutrons generated by the primary neutrons inside the target and the total number of neutron induced. It can be seen that the main “source” of neutrons inside the target is not the initial proton, but the primary neutron.

The big difference in the number of produced neutrons and the number of neutrons leaving the target volume is due to the absorption of low energy generated neutrons. While the Bertini model does describe accurately the proton induced spallation processes, there is concern over its validity in describing the low-energy neutrons induced spallation. This model is the default MCNPX intra-nuclear cascade model for protons and neutrons, and has been chosen by the authors in reference [2]. The spallation neutrons en-

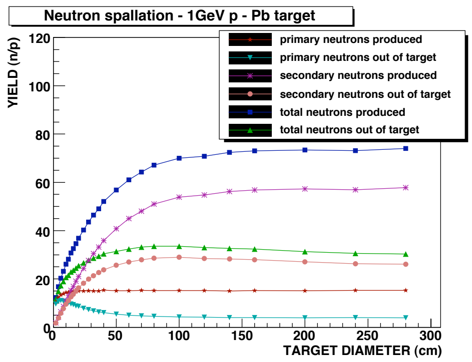

Figure 1: The variation of the calculated total neutron yield with the target radius (GEANT4).

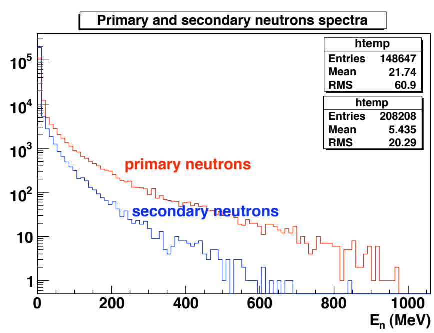

Figure 2: Spallation neutrons energy spectra (GEANT4).

ergy spectrum is shown in Fig. 2, for a 1 GeV proton beam and a 20 cm diameter target. There are 14.8 primary neutrons per incident proton with an average energy of 21.7 MeV and 20.8 secondary neutrons per projectile with an average energy of 5.4 MeV.

Figure 3 shows the variation of the total number of neutrons escaping the target per incident proton, for different proton beam energies and different target diameters. The number of neutrons increases steadily with the target diameter, reaching a plateau at about 100 cm diameter.

The leakage of high-energy ($E_n > 20$ MeV) neutrons per incident proton as a function of target diameter is shown in Fig. 4. The average energies of the spallation neutrons from the (n, xn) interactions is 6 MeV (see Fig. 2) and since the increase in total neutron yield with target diameter in Fig. 3 is due primarily to the contribution of these neutrons, they will not contribute to the leakage of high-energy neutrons and hence the decrease in the number of high-energy neutrons with increasing target diameter shown in Fig. 4.

Also of interest is the cumulative spectral distribution of all the neutrons escaping the target volume. Figure 5 shows the distribution of the number of neutrons above energy E_n per incident proton, for a 1.6 GeV proton beam. It can be seen that the majority of these neutrons have energies below 100 MeV.

The proton leakage cumulative spectral distribution for 1.6 GeV protons is shown in Fig. 6. The energy of the

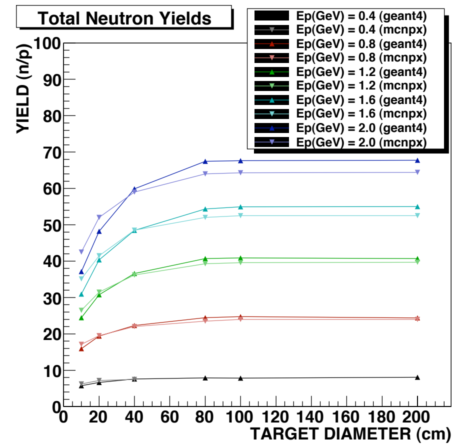

Figure 3: The variation of the total neutron yield with the target diameter for different proton energies (GEANT4 vs MCNPX).

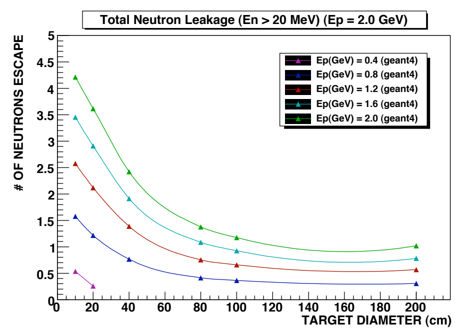

Figure 4: The leakage of high-energy neutrons versus target diameter for different proton energies (GEANT4).

protons escaping the 10 and 20 cm targets extends almost to the initial proton energy, for protons escaping from the back end without undergoing an inelastic scattering, while for the 100 cm target the proton energy loss is at least 0.7 GeV.

Figure 7 shows the comparison between the Geant4 and MCNPX predictions for the total number of protons and high-energy neutrons escaping from the target per incident

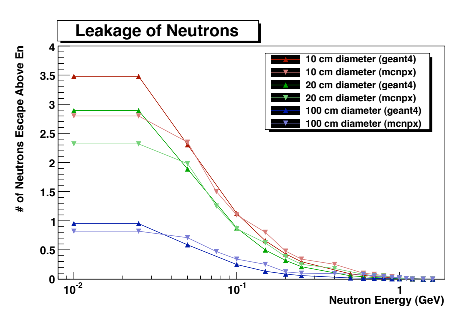

Figure 5: The cumulative energy spectrum of neutrons escaping from the target (GEANT4 vs MCNPX).

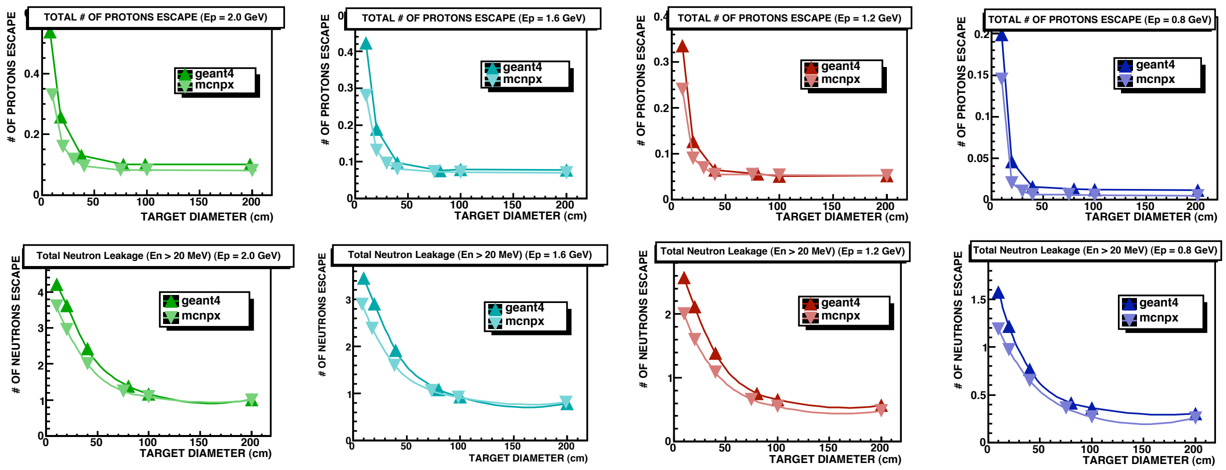

Figure 7: Protons and high-energy neutrons leakage from the target vs target diameter (GEANT4 vs MCNPX).

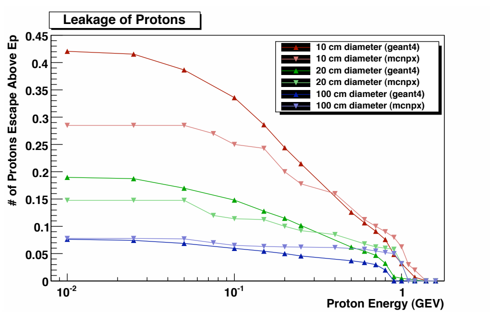

Figure 6: The cumulative energy spectrum of protons escaping from the target (GEANT4 vs MCNPX).

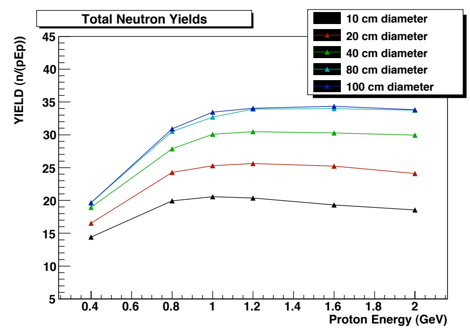

Figure 8: The total number of neutrons escaping from the target per unit of proton energy (GEANT4).

proton, for a 1.6 GeV proton beam. The Geant4 prediction of the neutron leakage from targets of 10, 20 and 100 cm diameter is 3.4, 2.9 and 0.9 neutrons per projectile, while the MCNPX predictions were 2.8, 2.3 and 0.8 neutrons respectively.

As expected, there is a sharper decrease in the proton leakage with increasing target diameter than in the case of neutron leakage. The flat region at diameters above 50 cm represents the protons escaping from the front and back ends of the target. For 1.6 GeV protons, the Geant4 prediction of the proton leakage from targets of 10, 20 and 100 cm diameter is 0.42, 0.19 and 0.078 protons per projectile. The MCNPX predictions [2] were 0.28, 0.13 and 0.076 protons per projectile.

Figure 8 shows the mean neutron multiplicity per unit of proton energy for different target diameters. It has a broad maximum at around 1 GeV and then falls slightly at higher energies for the 10 cm diameter target.

CONCLUSION

The total neutron yields from spallation processes inside Pb targets were computed and comparisons were made between the Geant4 and MCNPX predictions. The two code predictions are in reasonably good agreement, however in almost all cases Geant4 gives results that are higher than the MCNPX predictions, especially for the low energy neutrons which, according to the MCNPX results, are more likely to be absorbed inside the target.

The optimum proton beam energy was found to be around 1 GeV, for which there is no significant increase in the total neutron yield for target diameters larger than 40 cm.

REFERENCES

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[4] Status of INCL/ABLA codes in Geant4 (Apr08), Geant4 Hadronic WG meeting, April 24th, 2008,

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