MCNPX Calculation and the Neutron Multiplicity for Beryllium Reflected Targets up to 4 GeV Protons

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ABSTRACT

The calculation of neutron multiplicity for (p,n) reactions are very important and necessary for designing and manufacturing the target for an Accelerator Driven System (ADS). In this paper, calculations were made for the neutron residual nuclei and neutron multiplicity in (p,n) reactions for some thick target nuclei including lead Pb, lead bismuth eutectic Pb+ Bi (volume ratio being 45:55) and Tungsten (W) using MCNPX. The effect of adding a Beryllium layer at the downstream end of the block is studied. The proton beam energy extended from 0.4 up to 4.0 GeV.

Key Words: Accelerator driven system, Spallation reaction, MCNPX, Neutron multiplicity, Spallation products.

1. INTRODUCTION

The purpose of this work is to calculate the number of emitted neutrons from spallation reactions with different proton bombardment energies on different targets with different material and thicknesses. Our special interest is in the number of neutrons emitted from spallation reactions with different incident proton energies on some thick targets used in designing the Accelerator Driven System (ADS). In fact, the design of targets is a key issue to be investigated for designing an ADS, and its performance is characterized by the neutron spectra and multiplicity in (p, n) reactions. For instance, in references 1 to 6 the authors have showed different models to investigate the emitted neutrons. Alternatively, in the present work the code MCNPX 1 to 4 was used.

The present work and calculation are about a proton beam colliding with the cylindrical blocks of lead Pb, lead bismuth eutectic Pb+ Bi (volume ratio being 45:55) and Tungsten (W). Spallation targets each of size d x L = 30 x (5:50) cm² and on adding a layer of Beryllium (⁴Be) of size 2RxL = 30x10 cm² at the downstream end of the blocks. The beam is introduced axially at 5 cm dip in the target so that neutrons produced in backward direction are not lost. The target geometry is shown in figure 1.

The purpose of introducing layer of Be- is to reflect those neutrons which may otherwise escape the block from the downstream end. On their reflection at larger angles they are directed towards the fuel assembly which in case of real design may exist outside of the cylindrical spallation targets. The Be- reflector may first of all scatter out escaping neutrons at larger angles so that many of them enter the fuel assembly instead of escaping out and secondly it marginally increases their number through (n, 2n) reactions. The schematic design of such assembly is given in figure 1. In table 1 the results of N/P from the MCNPX Code for the fixed proton beam energy, 3 GeV and different cylindrical targets with and without the Be- reflector are given for the sake of comparison. Aiming at selecting the optimum geometry of the target by choosing the optimum length (thickness) and diameter, a study was made, first of all, for the neutron multiplicity (n/p) as a function of the target length (X=5:50 cm) at different proton energies (0.4:4.2 GeV), to get the optimum length. Then a study was made for neutron multiplicity (n/p) as a function of the target diameter (D=2R=5:30 cm) at different proton energies (1.0:4.0 GeV), to get the optimum diameter.
Fig. (1) Target design of ADS.

Table (1) Comparison of the results of average neutron multiplicity per beam proton ( N / P )
calculated using MCNPX Code for the bare target assemblies of Pb , Pb+Bi and W- and on
adding 10 cm length of Be- reflector. (Target length, L=35 cm and radius R=7.5 cm).

<table>
<thead>
<tr>
<th>Target material</th>
<th>Pb</th>
<th>Pb+Be</th>
<th>PbBi</th>
<th>PbBi +Be</th>
<th>W</th>
<th>W + Be</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutron multiplicity</td>
<td>56.5</td>
<td>57.237</td>
<td>53.41</td>
<td>54.120</td>
<td>75.46</td>
<td>75.8725</td>
</tr>
</tbody>
</table>

2. MCNPX MONTE CARLO CODE

For the definition of the source term for ADS, it is necessary, besides the knowledge of the time
evolution of the spallation reaction, the description of the transport of the secondary particles in the
media is essential to calculate the number of neutrons escaping from the target, its energy and angular
distribution, the energy deposited in the target and the spallation products. These calculations are
accomplished with Monte Carlo simulation of the space transport of those secondary particles (2, 3).
Among several codes, there are LAHET, developed by Los Alamos, and FLUKA, developed by
CERN. Recently the code “MCNPX version 27e” was developed by Los Alamos National Laboratory,
being internationally one of the most used codes to realize this type of calculation, and it is the one
used by us to perform our calculations.

3. MCNPX CODE RESULTS

3.1 Target Geometry Optimization

Figures 2, 3 and 4 show the neutron multiplicity (n/p) normalized to the unit beam energy as a
function of the target length (X=5:40 cm) at different proton energies (0.4:4.0GeV) for lead $^{82}$Pb, lead
bismuth eutectic $^{82}$Pb+$^{83}$Bi (volume ratio being 45:55), and tungsten $^{74}$W targets respectively.
Fig. (2) The neutron multiplicity (n/p) normalized to the unit beam energy as a function of the target thickness at different proton energies (1.0-4.0 GeV) for lead target $^{82}\text{Pb}$

Fig. (3) Neutron multiplicity (n/p) normalized to the unit beam energy as a function of the target thickness different proton energies (1.0-4.0 GeV) for lead bismuth eutectic target $^{82}\text{Pb}+^{83}\text{Bi}$ (volume ratio being 45:55)

It may be seen from the figures 2, 3 and 4 that for our case, the large target thickness (X>35 cm) the increase of neutron multiplicity becomes slower. So for (X=35 cm) is the optimum or standard target length (thickness) for our calculations. Hence, the neutron multiplicity (n/p) as a function of the target diameter (D=2R=5:30 cm) at different proton energies (1.0-4.0 GeV) is studied. Figures 5, 6, and 7 show the neutron multiplicity (n/p) as a function of the target diameter (D=5:30 cm) at different proton energies (1.0-4.0 GeV) for lead $^{82}\text{Pb}$, lead bismuth eutectic $^{82}\text{Pb}+^{83}\text{Bi}$ (volume ratio being 45:55), and tungsten $^{74}\text{W}$ targets respectively.
Fig. (4) The neutron multiplicity (n/p) normalized to the unit beam energy as a function of the target thickness at different proton energies (1.0:4.0 GeV) for Tungsten$^{74}$W target.

Fig. (5) The neutron multiplicity (n/p) as a function of the target diameter (D) at different proton energies (1.0:4.0 GeV) for lead target $^{82}$Pb.

Fig. (6) Neutron multiplicity (n/p) as a function of the target length (D=5:30 cm) at different proton energies (1.0:4.0 GeV) for lead bismuth eutectic target $^{82}$Pb+$^{83}$Bi (volume ratio 45:55).
Fig. (7) The neutron multiplicity \( n/p \) as a function of the target diameter \( (D=5.30 \text{ cm}) \) at different proton energies \((1.0:4.0\text{GeV})\) for Tungsten \(^{74}\text{W}\) target.

It can be seen from the figures 5, 6, and 7 that for the large target diameters, \((D > 15 \text{ cm})\) the increase of neutron multiplicity becomes slower. It may be pointed out that the neutron multiplicity changes faster with the length than the diameter of the target. This is because of the fact that the hadronic cascade has highly limited transverse momentum. Hence, we can find that the standard target length is \((X=35 \text{ cm})\) and diameter \((D=15 \text{ cm})\). Now we can study the neutron multiplicity for a target of geometry \((X=35, D=15 \text{ cm})\) as a function of the incident neutron energies for lead \(^{82}\text{Pb}\), lead bismuth eutectic \(^{82}\text{Pb}+^{83}\text{Bi}\) (volume ratio being 45:55), and tungsten \(^{74}\text{W}\) targets respectively, see figure 8.

Fig. (8) Neutron multiplicity as a function of the neutron energies.

Comparing the results of non-fission \(^{82}\text{Pb}\), \(^{82}\text{Pb}+^{83}\text{Bi}\) and \(^{74}\text{W}\)- targets, it is clear that \(^{74}\text{W}\)- is a better neutron source when compared with \(^{82}\text{Pb}\). It is known that \(^{74}\text{W}\)- is very costly and hard in milling for shaping etc. Secondly, from the point of modeling by a mathematical code parameters of \(^{82}\text{Pb}\) are better available. Thirdly, number of escaped from \(^{74}\text{W}\)- spallation target is only 20% higher than \(^{82}\text{Pb}\)-target and on using Be-as reflector with \(^{82}\text{Pb}\)- even this difference of 20% is marginalized. Captured neutrons are no longer useful for fission. In general, \(^{82}\text{Pb}\)- is a good choice technically than \(^{74}\text{W}\)- even if it is used in molten condition as melting point of \(^{74}\text{W}\)- is very high compared to \(^{82}\text{Pb}\). Comparing \(^{82}\text{Pb}+^{83}\text{Bi}\) eutectic again \(^{82}\text{Pb}\)- is better because \(^{82}\text{Pb}+^{83}\text{Bi}\) suffers from the higher radio-activity due to Polonium but slightly worse than the eutectic with melting point being 123 °C for the eutectic and 327.5 °C for the \(^{82}\text{Pb}\).
3.2. Spallation Products

One aspect of major importance in spallation reactions is the residual nuclei (or spallation products). In this section, results of isotopic yield in a thick PbBi target (L=35cm, R=7.5cm) bombarded by 3GeV proton are simulated by MCNPX with BERTINI Dresner and ISABEL Dresner (Fig. 9).

Figure (10) shows that the residual nuclei production estimated by these models is a bit close. In the fission area both models are in good agreement, already in the spallation area we noticed great agreements.

4. THE NEUTRON VALUES

The cost of the proton accelerator is an important parameter when designing a neutron spallation source to have a comparative, or to evaluate a merit figure, an interesting parameter is the “neutron value”, which is defined as the number of produced neutrons normalized to the unit beam energy per incident particle. Figure 11 illustrates such parameter.
From the above result it can be noticed that a maximum occurs in the range of energy of 0.8-1.2 GeV, therefore this is the range of energy of the protons that gives a maximum “neutron value”, defining the optimum conditions, as far economy is considered.

Fig. (11) Average neutron multiplicity per unit energy (GeV) and per incident proton as a beam energy

5. CONCLUSION

Calculations in the present work show that:

- The best target geometry is length X=35 cm and diameter D=15 cm.
- The best operating energy is E=3 GeV.
- The best target material is lead bismuth eutectic ⁸²Pb+⁸³Bi (Volume ratio being 45:55).

Both the curves, (n/p) vs. (L) and (n/p) vs. (D) tend towards saturation and such information is very useful in designing INSS for ADSS. At this state of the present work, it was not possible to infer on the efficiency in the predictions of the models for residual nuclei production, such stage this being accomplished and comparisons with experiments. 0.8:1.2 GeV is the range of energy of the protons that gives a maximum neutron value.

REFERENCES
