A CALCULATION OF THE NEUTRON EMISSION SPECTRA AND THE NEUTRON NUMBER PRODUCED BY $(p, n)$ REACTION FOR SOME THICK TARGETS COMPOSED OF HEAVY ELEMENTS FROM 0.5 GeV TO 3.0 GeV

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Abstract:

The calculation of neutron multiplicity and its energy spectra in $(p,n)$ reactions are very important and necessary for designing and manufacturing the target for an Accelerator Driven System (ADS). The neutron multiplicity in $(p,n)$ reactions on different thin targets with different proton beam energies has been presented in the JENDL-HE library. However, the target used in the ADS must be thick so that the number of neutrons produced is as large as possible. For this reason, we can’t directly use the results in the JENDL-HE library. In this paper, we calculate neutron emission spectra and multiplicity in $(p,n)$ reactions for some thick target nuclei including Pb\textsuperscript{204}, Pb\textsuperscript{206}, Pb\textsuperscript{207}, Pb\textsuperscript{208}, W\textsuperscript{180}, W\textsuperscript{182}, W\textsuperscript{184}, W\textsuperscript{186}, U\textsuperscript{235}, U\textsuperscript{238}, Au\textsuperscript{197} with proton beam energies ranging from 0.5 GeV to 3.0 GeV.

Keywords: neutrons, ADS, $(p, n)$ reaction

I. INTRODUCTION

The purpose of this work is to calculate the neutron energy spectra and the number of emitted neutrons from spallation reactions with different proton bombardment energies on different. 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 refs. [1], [2], [3] [4], [5], [6] the authors have showed different models to investigate the emitted neutrons.

Different from the previous work in refs. [1], [2], [3], in this work we use immediately the JENDL-HE nuclear data to calculate. It helps reduce significantly the computational cost. To use effectively the JENDL-HE nuclear data, we use the \textit{Screening effect model} to be presented in section II.3. First of all, in section II.1 we present the neutron emission spectra produced by the $(p, n)$ reaction for some spallation neutron target nuclei such as Pb, W, Ni, U, Au using proton beam energies from 0.5 GeV to 3.0 GeV using the database of JENDL-HE-2007. In section II.2 we present results of our calculations of the number of emitted neutrons in spallation reactions when the target considered is homogeneous and the incident proton energy doesn’t change during the interaction between incident protons and the target nuclei.
II. CALCULATION AND RESULTS

II.1. The neutron energy spectra

A computer program has been written to calculate the (p, n) reaction cross-sections basing on the following equation:

\[ \sigma_i(E, E', \mu) = \sigma(E_p) y_i(E_p) f_i(E_p, E_n, \mu) \]  

(1)

Where:

- \( i \) denotes one particular product
- \( E_p \) is the incident energy (eV)
- \( E_n \) is the energy of the product emitted (eV)
- \( \sigma(E) \) is the interaction cross section (barn)
- \( y_i \) is the product yield or multiplicity
- \( f_i \) is the normalized distribution with units (eV unit cosine\(^{-1}\))

Figures 1-4 show the neutron spectra from the (p, n) reaction on the \(^{206}\)Pb, \(^{186}\)W, \(^{238}\)U, \(^{197}\)Au nuclei, calculated at the proton energies from 0.5 to 3.0 GeV:

**Figure 1:** Neutron emission spectra of \(^{197}\)Au (p, n) reaction at 0.5 GeV to 3.0 GeV incident proton energy

**Figure 2:** Neutron emission spectra of \(^{186}\)W (p, n) reaction at 0.5 GeV to 3.0 GeV incident proton energy
II.2. The homogeneous model

The problem calculates the number of neutrons emitted from spallation reaction made as follows:

Assuming that we have a cylinder target with d thickness and r radius. To calculate the number of emitted neutrons from spallation reaction on a definite target element, we use proton beam with E energy. The incident proton energy range is chosen from 0.5 to 1.5 GeV with 0.1 GeV energy step. The reason of this choice is our calculation directed toward designing target for ADS. Many reasons for the choice of this interesting energy region will be showed from obtained calculation results latter. The energy region from 0.5 GeV to 1.5 GeV is interested very much. The chosen targets to calculate in this work are \(^{204}\text{Pb}\), \(^{206}\text{Pb}\), \(^{207}\text{Pb}\), \(^{208}\text{Pb}\), \(^{180}\text{W}\), \(^{182}\text{W}\), \(^{184}\text{W}\), \(^{186}\text{W}\), \(^{235}\text{U}\), \(^{235}\text{U}\), \(^{197}\text{Au}\). The target thickness is of equal proton mean path length in each target material at each proton energy. To decrease the heat of remain protons on target and to prolong the life time of targets, we choose the such target length. The target diameter is equal to the incident proton beam diameter. In this problem, we choose the target radius of four centimeters.

The number of emitted neutrons from spallation reaction on a target is calculated by formula:
Where:

\[ N_n = N_p, N, d \sum_{j}^{32} \frac{d\sigma(\mu, E_p, E_n)}{dE} \]

\[ \mu = \cos \theta; \mu [-1, +1] \]

In JENDL library, emitted neutrons are distributed at 32 energies.

In section II.2, we consider the homogeneous target in which the number of incident protons and the incident proton energy don’t change during interaction between incident protons with target nuclei. This is a rough approximation and the defect of this model will be improved by the screening effect model presented in section II.3.

In this model, we consider that the number of initial incident protons (is \( N_0 \)) doesn’t change during interaction between incident protons with target nuclei. The target size was fixed at constant for each proton beam energy. That means the target thickness (d) is chosen equal to proton mean path length (\( \bar{R}_p \)) in each material at each incident proton beam energy. The radius of the proton beam (r) was kept constant at 4cm and the number of emitted neutrons at proton energies in range starting from 0.5 GeV up to 3.0 GeV was calculated by program written in MATLAB 7.0 language.

Now we present our calculation results for the number of emitted neutrons in \(^{206}\text{Pb}, \, ^{186}\text{W}, \, ^{238}\text{U}, \, ^{197}\text{Au}\) targets with proton energy range in starting from 0.5 GeV to 3.0 GeV as follows:

**Fig.5:** The number of emitted neutrons from spallation reaction calculated with \(^{206}\text{Pb}\) in range of proton energies from 0.5 GeV to 3.0 GeV

**Fig.6:** The number of emitted neutrons from spallation reaction calculated with \(^{186}\text{W}\) in range of proton energies from 0.5 GeV to 3.0 GeV
Fig. 7: The number of emitted neutrons from spallation reaction calculated with $^{238}\text{U}$ in range of proton energies from 0.5 GeV to 3.0 GeV

Fig. 8: The number of emitted neutrons from spallation reaction calculated with $^{197}\text{Au}$ in range of proton energies from 0.5 GeV to 3.0 GeV

Assuming the figure 5 is examined. We can see that the number of emitted neutrons is increasing with growth of incident proton energy:

For example at $E_p = 0.5$ GeV, we have the number of emitted neutrons $N_{n1} = 2.97 \times 10^{18}$ neutrons while at $E_p = 0.6$ GeV we have the number of emitted neutrons $N_{n2} = 4.11 \times 10^{18}$ neutrons, since then we have $\frac{N_{n2}}{N_{n1}} = 1.38$. That means the number of emitted neutrons at 0.6 GeV of incident proton energy has increased 1.38 times than the number of emitted neutrons at $E_p = 0.5$ GeV has been.

From figure 5, it’s clearly seen that the number of emitted neutrons at 3.0 GeV proton bombardment energy is 13.67 times as many the number of emitted neutrons as at 0.5 GeV proton bombardment energy etc….Calculated results with $^{186}\text{W}$, $^{238}\text{U}$, $^{197}\text{Au}$ targets are similar to that obtained of $^{208}\text{Pb}$ target.

From calculation results we can draw the conclusions that the number of emitted neutrons from spallation reaction depends on the incident proton energies and target materials. The higher incident proton energy is, the more number of emitted neutrons is.

II.3. The screening effect model

When proton beams enter to a medium, their current intensity will be reduced due to ionization effect, scattering effect…therefore their energy also will reduce. In section II.2 we haven’t mentioned those effects and now in this section, assuming the target is divided into sub-layers at the value of energies that corresponded to neutron cross-section given by JENDL-HE library.

Table 1 shows proton mean path length ($R_p$), chosen target thickness and divided layers of target in each target material at proton energies in starting from 0.5 GeV up to 3.0 GeV.
Table 1: Proton mean path length, target length, divided layers of targets uranium, lead, gold and wolfram at proton bombartment energies from 0.5 GeV to 3.0 GeV

| E_p (GeV) | 238U | 206Pb | 197Au | 186W |
|----------|------|-------|-------|------|
|          | Rp (cm) | Target length (cm) | Layers | Rp (cm) | Target length (cm) | Layers | Rp (cm) | Target length (cm) | Layers |
| 0.5      | 13.0 | 6 | 19.7 | 20 | 6 | 11.5 | 11 | 6 | 11.3 | 11 | 6 |
| 0.6      | 15.8 | 16 | 7 | 25.9 | 26 | 7 | 15.1 | 15 | 7 | 14.8 | 15 | 6 |
| 0.7      | 19.9 | 20 | 7 | 32.5 | 32 | 8 | 18.9 | 19 | 8 | 18.6 | 19 | 7 |
| 0.8      | 24.1 | 24 | 8 | 39.4 | 39 | 9 | 22.9 | 23 | 8 | 22.5 | 22 | 9 |
| 1.0      | 32.8 | 33 | 10 | 53.7 | 54 | 10 | 31.3 | 31 | 9 | 30.8 | 31 | 9 |
| 1.5      | 55.8 | 56 | 10 | 91.5 | 91 | 11 | 53.3 | 53 | 10 | 52.5 | 52 | 10 |
| 2.0      | 80.6 | 80 | 11 | 13.0 | 130 | 12 | 76.0 | 76 | 11 | 74.8 | 75 | 11 |
| 3.0      | 129. | 129 | 13 | 200. | 200 | 13 | 121. | 121 | 12 | 120. | 120 | 13 |

We use the screening effect model to calculate the number of emitted neutrons from spallation reaction in 206Pb, 238U, 186W, 197Au target cases in range of proton energies starting from 0.5 GeV up to 3.0 GeV and a comparison of the results of the emitted neutron number in both models is presented in figures 9, 10, 11, 12 as below:

Figure 9: A comparison of the number of emitted neutrons from spallation reaction calculated with 206Pb bombarded with proton energies from 0.5 GeV to 3.0 GeV in the screening effect model and the homogeneous model

Figure 10: A comparison of the number of emitted neutrons from spallation reaction calculated with 197Au bombarded with proton energies from 0.5 GeV to 3.0 GeV in the screening effect model and the homogeneous model
Figure 11: A comparison of the number of emitted neutrons from spallation reaction calculated with $^{238}$U bombarded with proton energies from 0.5 GeV to 3.0 GeV in the screening effect model and the homogeneous model

Figure 12: A comparison of the number of emitted neutrons from spallation reaction calculated with $^{186}$W bombarded with proton energies from 0.5 GeV to 3.0 GeV in the screening effect model and the homogeneous model

Based on the obtained results from figs.9, 10, 11, 12 we can draw the following conclusions:

The number of emitted neutrons in the homogeneous model is higher than that in the screening effect model because when protons pass each sub-layer of target, proton energy decreases and the number of emitted neutrons decreases too.

The number of emitted neutron varies as a function of the target nuclei and as the energy of the incident particle calculated with the screening effect model compared with homogeneous model, reaching saturation around 1.5 GeV. This problem can be explained as follows: when proton bombarding energy is high enough (about from 1.5 GeV and over), proton can immediately interact with nucleons of target nuclei. The probability of primary particles such as $\pi^\pm, \mu^\pm, \ldots$ will increase. The higher incident proton energy is, the more energy for these channels will spend. Hence, from these results we can see that ADS technology needs only accelerator energy about from 0.5 GeV to 1.5 GeV. This is the energy region interested very much.

III. CONCLUSION

Heavy nuclei (Pb, W, U, Au) were chosen as a spallation target to obtain the hardest possible neutron energy spectrum (figures 1, 2, 3, 4). This is the need to optimize the fission probability of TRU (Transuranic elements). Indeed, in the fast neutron flux provide by the ADS all TRU can undergo fission, a process which eliminates them, while in a tradition reactor thermal neutron flux many TRU do not fission and thus accumulates as waste.
The number of emitted neutrons from spallation reaction calculated with different heavy targets bombarded with proton energy range in starting from 0.5 GeV up to 3.0 GeV is very useful data for designing a target for ADS. There are approaches to carry out this work [1], [2], [4], [5]. In this calculation, we suggest a simple calculation approach – We use JENDL-HE nuclear data with the screening effect model to establish our calculating and our approach reduces volume of calculation significantly. We hope this approach will be able to calculate spatial distribution of neutron from spallation reaction.

IV. REFERENCES

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