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Review

New study of spallation reactions (Be + p) and (Sn + p) at 1.2 GeV per nucleon

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ABSTRACT

The aim of this study is to calculate neutron multiplicity per incident proton in the collision of 1.2 GeV energetic proton beams with Beryllium and Tin. These targets had been estimated using INCL4/ABLA physics models. The results of our Monte Carlo optimization study using MCNP.6 code gives several findings: the neutrons levels produced by Beryllium (Be) and Tin (Sn) respectively are 2.7n/p and 13 n/p; the neutron current scatter varies by the incident angles of the proton beam and the variation of the neutron intensity in the targets. This paper summarizes principles of the method that determine the spectrum of high-energy neutrons, which improve with precision neutron flux, current, and calculation yield.

Contents

1. Introduction

The basic principle of the accelerator-driven system (ADS) is to feed a subcritical medium composed of minor actinides by an external source of neutrons produced by spallation reactions. This spallation is made possible using a high-energy proton beam, which interacts with a suitable target source (Michaël, 2004).

Spallation physics play an important role in several areas such as nuclear waste management (Alexander, 2013; Liu, 2006), nuclear medicine (Tárkányi et-al. 2017) and energy (Schuurmans et al., 2003). However, high-energy physics is for several years a

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very interesting area of research, in addition, the construction of new accelerator models led to use the nuclear spallation had a new hardware platform, designs, and applications for the generation of neutron flux and neutron current based on charged particle beams (Fengjun Wu et al., 2016). In reality, neutron production is done by several methods such as nuclear reactors (Golabian et al., 2018; Didi et al., 2018a), neutron sources (Didi et al., 2017a,b,c) and neutron spallation (Didi et al., 2018e,f,g,h).

Currently, the developments of ADS are identified by each various elements that it comprises. For that, they are classified as either to the design (Cho, 1998), the process (Saban et al., 1996), the desired performances (Wang et al., 2016), the quality insurance and the system safety (Zup et al., 2018). However, necessary studies put in place to increase the ADS specificities quality: knowledge of the neutron characteristics of spallation targets (Graiciany et al., 2015; Zhang et al., 2017) and the multiplicity rate of neutrons related to the proton beams used (Didi et al., 2018e,f,g,h). Which, it is necessary and more obvious to take into consideration the motivation for the development of ADS. Obviously, spallation physics also includes a very important property in the choice of the target and the proton beam energy used. Indeed, several investigations are involved in improving the choice of the target and the incident particle beam in order to guarantee a more intense neutron production. (Didi et al., 2018e,f,g,h). Note that in spallation physics the module of the spallation target is the most innovative part of ADS. This component, therefore, brings a series of new technological challenges to solve. For this, the choice of the target must be relevant. ADS being a possible option to reduce the amount of nuclear waste, to promote stabilization of radioisotopes on the international scale and for a stable energy voice. There is a need for good computing tools to design these piloted systems by the accelerator and using an accepted and optimized spallation target (MCNP 6 code). It is in this vision we thought to carry out this research, which is associated with the transport code in which they are implanted. Several materials are studied. Among the materials most often cited as good candidates for a spallation target is Lead (Kumar et al., 2003; Feghhi et al., 2014). In this work, we are interested to study the spallation targets (Beryllium and Tin, due to the availability of the data of these Targets), used to an accelerator, because they are characterized by their productions of neutrons as a function of the incident proton beam.

2. Materials and methods

Several Monte Carlo-based codes are used for neutron simulation such as FLUKA, GEANT4 and MCNP codes... In this study, we are interested in MCNP code developed by the Los Alamos Laboratory. The new Monte Carlo code MCNP.6 used in this research (Monte Carlo, 2013; Briesmeister, 2000; Monte Carlo, 2014). The code MCNP6 has the privilege of attaining the geometric description of the system. However, the case of deterministic codes is different because they necessitate simplifications, which are often necessary. We are used the INCL4/ABLA physics models, cross-sections from ENDF/B-VII.1 (Chadwick et al., 2006). INCL4/ABLA package is a caseless temporal cascading model is simulated the history of all particles undergoing binary collisions, imposed by an approach distance criterion minimum and subject to the Pauli blocking factor (Cugnon et al., 2001). ABLA is an advanced evaporation code (Schmidt, 2007; Yu et al., 2014). The INCL4/ABLA package is one of the most successful, reliable and popular tools for modeling particle interactions and high-energy nuclear reactions with matter (Yu et al., 2014, Leray et al., 2010, 2013b). We are interested in INCL4/ABLA package as it is very useful in high energy compared with other code such as the CEM model because it does not give the results in good agreement with the data (Engle et al., 2014; Chen et al., 2015).

The present work presents a new approach to obtain a good optimization of the yield and the neutron current generated by two types of targets Beryllium (Be) and Tin (Sn). In general, to produce the maximum of neutrons by spallation, based on the two aspects of importance (proton energy and target choice), the proton energy used in this research is 1.2 GeV and the dimensions

Table 1
Neutron multiplicity using MCNP.6 compared bay MCNPX and experience results for 0.8, 1, 1.2 and 1.4 GeV protons beam using Pb target.

	Neutron produced per proton			
	Pb (10.2*64)			
Proton Beam Energy (GeV)	MCNPX (Feghhi et al., 2014)	MCNP.6 Our results	Experience (Kumar et al., 2003)	Error %
0.8	14.733	15.169	13.5	11
1	18.695	18.398	17.5	4
1.2	21.933	22.110	22.3	5
1.4	24.698	26.013	26.3	1

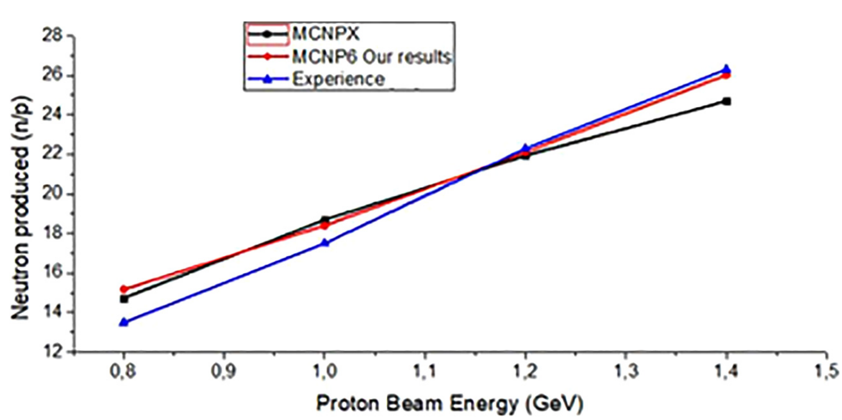

Fig. 1. neutron generation approved using MCNP.6 and compared with MCNPX and experience as a function of proton accelerator energy in Beryllium target.

of the two cylindrical targets are equal of 20.4 cm in diameter and 64 cm in height. We are interested in these dimensions since the majority of theoretical or experimental researches use the same target dimensions, which gives the agreement of the validation. In many scientific studies, one of the most frequently cited materials as good candidates for a spallation target is Lead. For this, we validated our research by experimental studies using this material (Pb) (Kumar et al., 2003; Feghhi et al., 2014). The main proposal of the present work is to study the neutron production in two types of spallation target (Beryllium and Tin) and to compare our work with experience work.

3. Results

3.1. Validation

This study is theoretical research containing the results given by simulations; we are involved to make a validation. Table 1 shows two types of validation; the first is by a Monte Carlo simulation but with the code MCNPX (Feghhi et al., 2014) and the second, by the experience (Kumar et al., 2003). The tabulated results represent the spallation neutron yield for the Pb target using serval's proton beam energy, respectively 0.8 GeV, 1 GeV, 1.2 GeV,

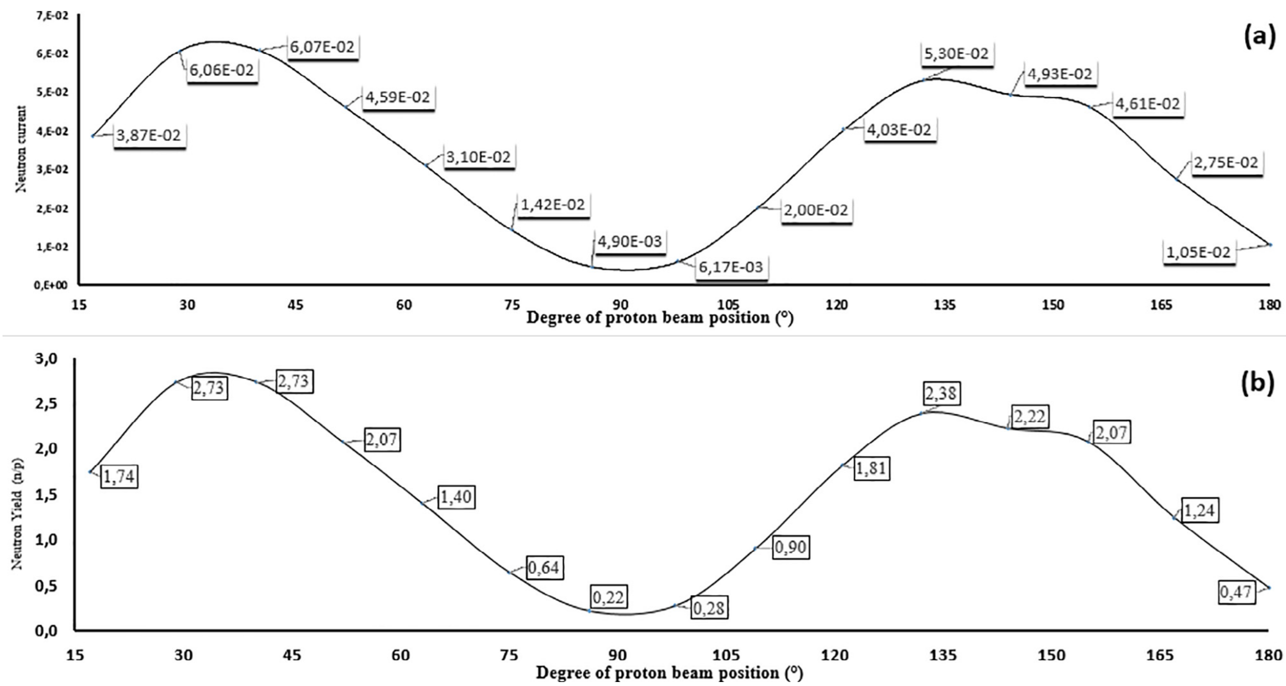

Fig. 2. The variation of current and neutron rate in the Beryllium target as a function of the incident angle of a proton beam energy of 1.2 GeV.

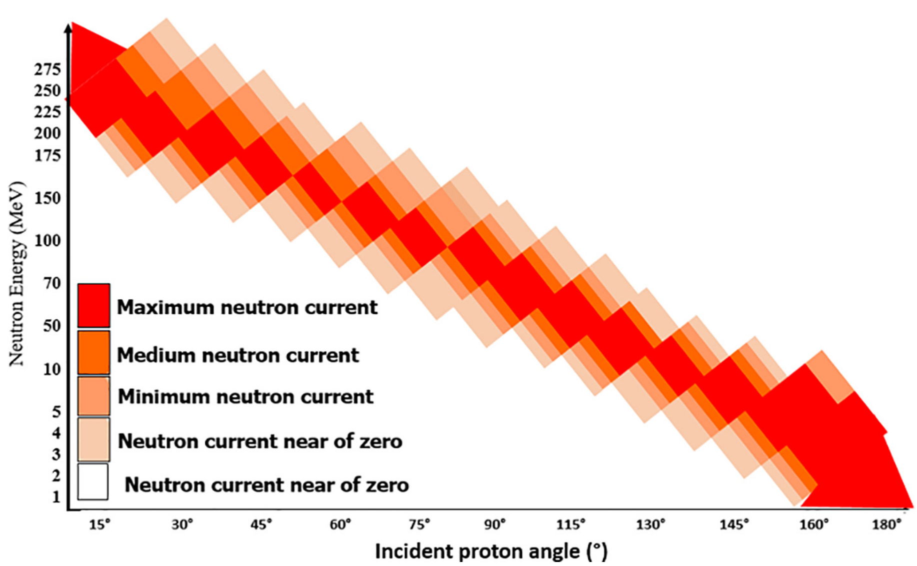

Fig. 3. The neutron current scattering produced by proton beam energy of 1.2 GeV in Be target as a function of incident beam angle and neutron energy.

and 1.4 GeV (Table 1). The results of a simulation using MCNP6 are summarized in (Table 1, Fig. 1), and calculated with a relative error.

The search for quantitatively predictive spallation codes must, therefore, go through the implementation of more restrictive experiments for the study of the spallation reaction.

This work was performed in order to determine the neutron current and neutron yield using the target of Beryllium (Be) and Tin (Sn). These targets are irradiated with 1.2 GeV proton beam. Fig. 1 shows the incident neutron energy normalized neutron yield. This figure illustrates the proton beam needed for neutrons production. From this figure, we can see clearly that the neutron yield for Lead (Pb) increases with beam energy.

Table 1 and Fig. 1 encourage us to search for new targets that can be used for accelerator-driven system design. We are interested to Be and Sn targets, so we are kept the 1.2 GeV energy and the same size of the Pb target geometry because these two parameters are widely used for the new design of the ADS.

3.2. Beryllium target

Fig. 2 shows the results of the distribution of the neutron yield (a) and current (b) as a function of the angle of the proton beam orientation. These zones give the neutron current produced for different degrees from 0° to 180° (the degrees represents the incident proton beam orientation with respect to the target, using tally F1) as a function of the neutron energy between 1 MeV and 275 MeV. The angular limits described by the C card, in this work the limited degrees are180° to 150°, 150° to 120°, (3) 120° to 90°, (4) 90° to 60°, (5) 60° to 30°, and (6) 30° to 0° with respect to the positive normal Monte Carlo (2014). Fig. 2 shows the variation of the neutron current in the Beryllium (Be) target as a function of the incident angle of the proton beam (Fig. 2a). The variation of the neutron yield is a positive periodic function. The variation contains two maximum values the first when the angle between 30° and 45° and the second when the angle between 120° and 155°, and a minimum value when the incident angle and perpendicular to the lower surface of the target (90°). The second part of (Fig. 2b) shows the variation of neutron rate per proton as a function of the incident angle, this pace reacts in the same way as the curve of the neutron current. Observe that the neutron rate is maximum when the angle of orientation between 30° and 45° is equal to 2.73n/p and between 120° and 155° is equal to 2.33n/p.

The understanding of the physical phenomena of a nuclear system is obviously closely related to the good knowledge of the neutron spectrum energy (between 1 MeV and 278 MeV) at any point and to any energy, for that, and after the spallation reactions under the effect of a proton beam of 1.2 GeV on Beryllium simulated by the code MCNP.6. Fig. 3 shows the variation of neutron current as a function of neutron energy and the angle of proton beam orientation relative to the target. We note from Fig. 3 that the neutron current is diagonally maximum (maximum when the neutron energy is minimal and the angle of proton orientation is maximum), and the neutron current is (maximum when the angle of minimum neutron orientation and maximum neutron energy). The red curve explains that the neutron current concentration is maximum (the red zone means that the neutron current is maximal).

After calculating the neutron current scatter as a function of energy and incident angle (Fig. 3), we are interested in understanding the type of neutron current produced in the Be target. Fig. 4 shows the neutron current variation as a function of the appropriate neutron energy going from 0 MeV up to 800 MeV; we studied a wider range of energy to favor our study more correctly. In a first view concerning the pace, note four important

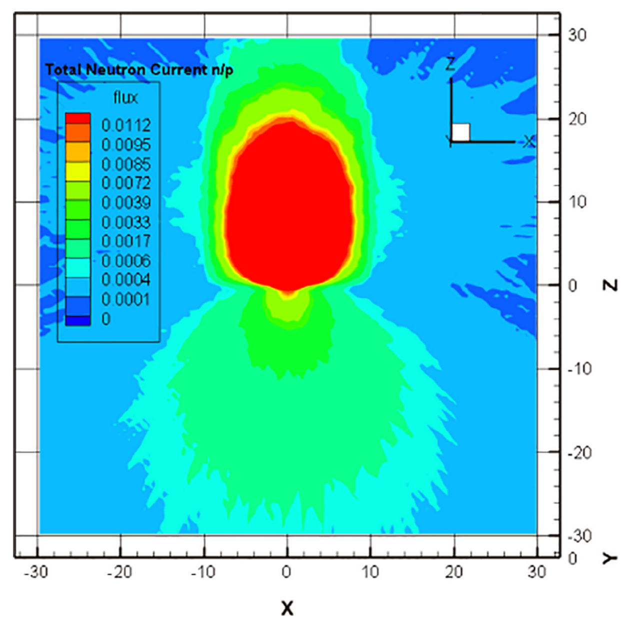

Fig. 5. Neutron current distribution, in Beryllium target Driven by 1.2 GeV proton Beam.

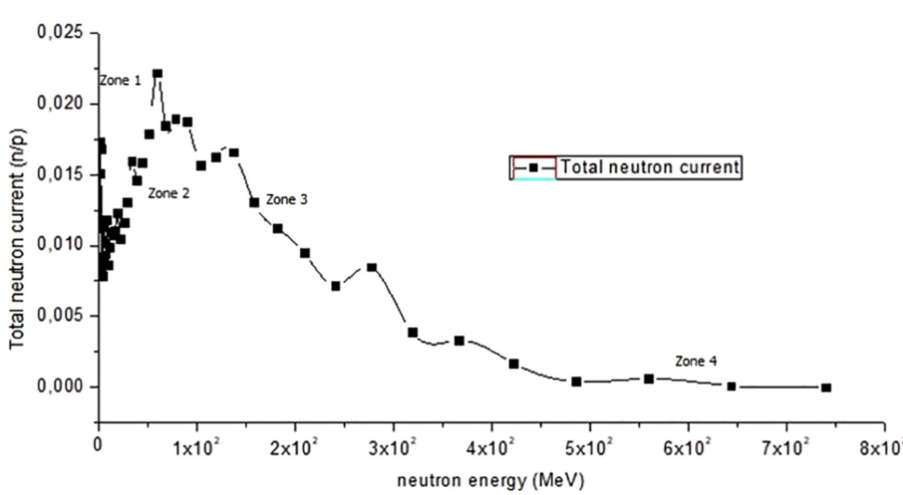

Fig. 4. The variation of neutron current as a function of the neutron energy in the Be target generated by a 1.2 GeV proton beam.

areas: the first zone is that of the thermal energy zone or more particularly less than 1 MeV points several points concentrated in this area, which means the phenomenon of slowing down the neutron. The second zone corresponds to the fast neutron energy range between 1 MeV and 75 MeV or notices a rapid increase in the neutron current level. The third zone is a long decrease with small fluctuations from 75 MeV to 400 MeV, and lately a zero zone from 400 MeV.

Using the application of the rectangular mesh, we divided the targets according to the three coordinates (50 * 50 * 50); the neutron flux is calculated for each point of the mesh. Fig. 5 shows the axial distribution of the neutron current in the Beryllium target driven by a 1 GeV energy proton beam.

Fig. 5 shows the results obtained by the Mesh Tally technique, giving each approved neutron energy in the geometry of the beryllium target a visual interest.

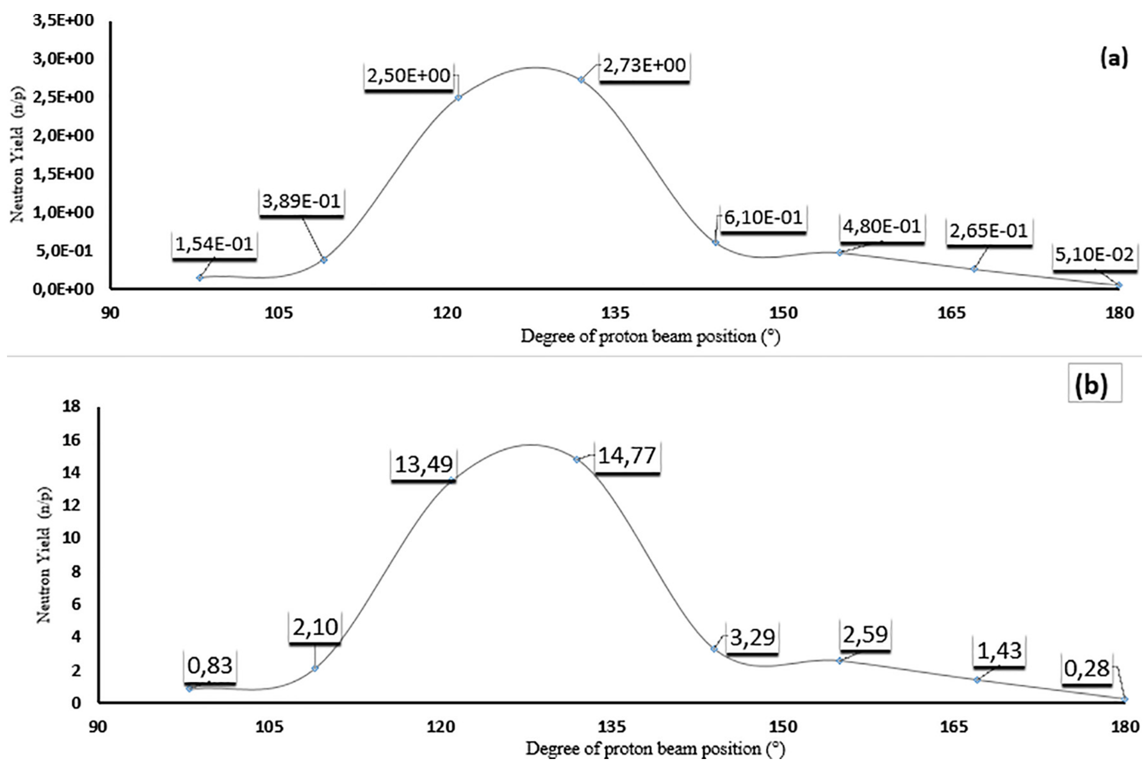

Fig. 6. The variation of current and neutron rate in the Tin target as a function of the incident angle of a proton beam energy of 1.2 GeV.

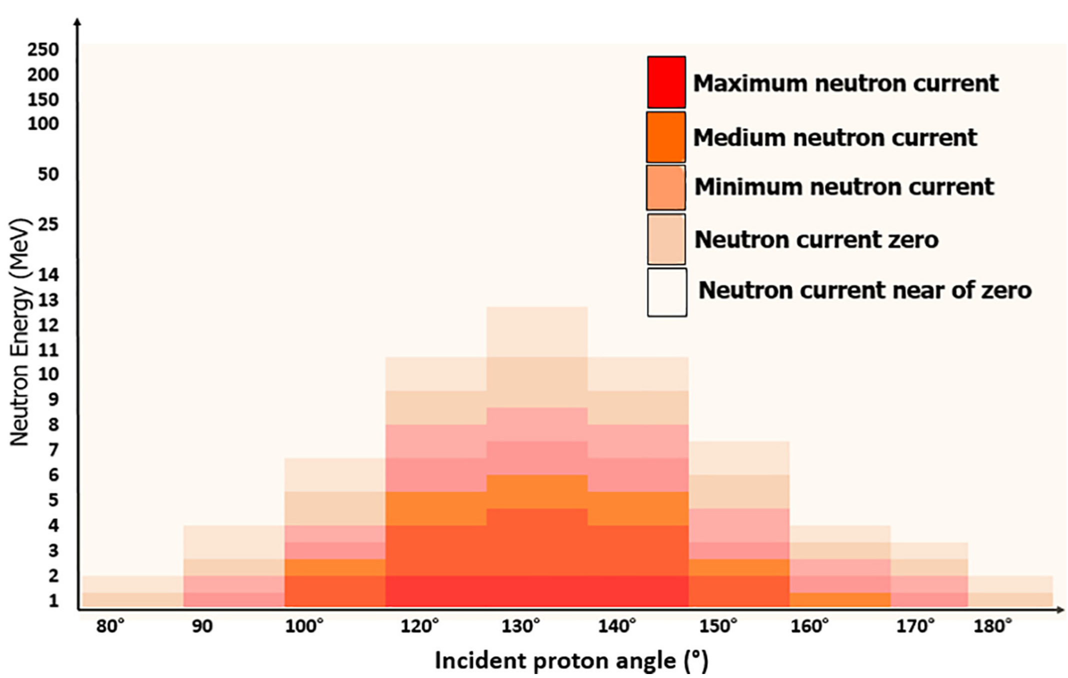

Fig. 7. neutron current scattering produced by a proton beam energy of 1.2 GeV in Sn target as a function of incident beam angle and neutron energy.

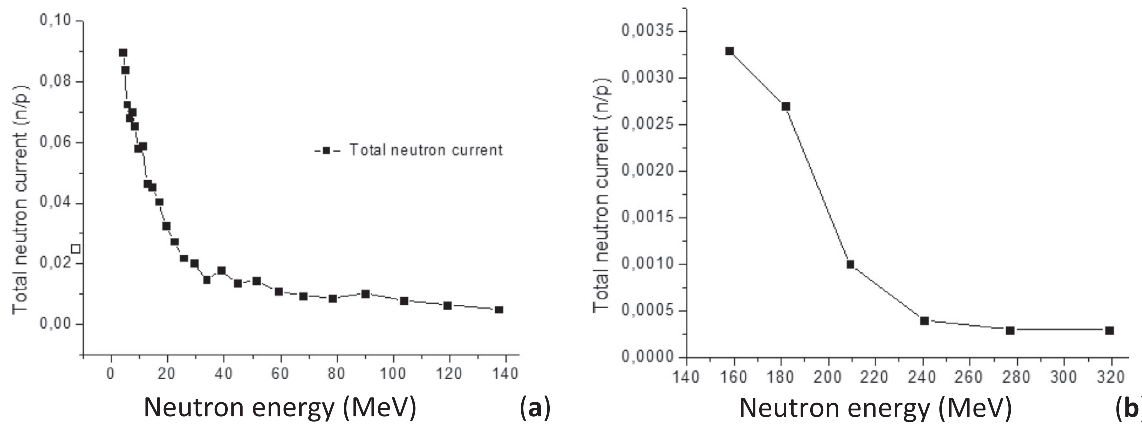

Fig. 8. The variation of neutron current as a function of the neutron energy in the Sn target generated by a 1.2 GeV proton beam.

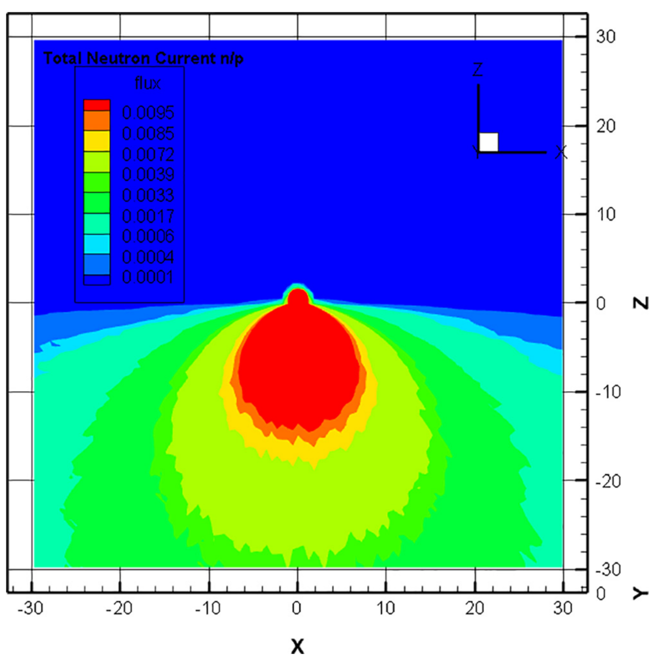

Fig. 9. Neutron current distribution, in Tin target Driven by 1.2 GeV proton Beam.

This method contains better configurations based on the model used and the maximum value of the yield. The color change in Fig. 5 represents a significant property directly related to the neutron type variety produced and the neutron distribution on the Beryllium target, using a 1.2 GeV proton beam.

3.3. Tin target

Fig. 6 shows the distribution of current (a) and yield (b) of neutron products in the Sn target due to 1.2 GeV protons, according to the angles of the proton beam and the Sn target.

In this figure, we can conclude that when neutron current increase (a) the yield neutron increase too (b). Neutron current scattering is a reflection of the nature of the target being studied; this remark is well explained by the analysis, which represents the neutron current cloud. This figure (Fig. 7) shows that the neutron current produced by the Tin target is maximum in the area of less than 4 MeV energy and between the angles of 100° and 160°, which is the opposite in the Beryllium target.

As before, we have concluded that the neutron current distribution applies by a certain mathematical law, after knowing this scientific reality we are interested to know the types of neutron comes into play. Fig. 8 is divided into two parts. These two parts are in function of the neutron energy; the first interval between 0 and 140 MeV (a) is represented by the variation of the neutron current, in this rate a rapid drop in the current level in the energy range between 0 and 25 MeV, followed by a significant stability from 25 MeV up to 140 MeV. The second interval (b) is between 140 MeV and 320 MeV, and there is a decrease in the current level over the entire energy range to zero values, the red zone means that the neutron current is maximum.

Fig. 9 represent the neutron current distribution generated by the target of Tin (Sn). The target studied is of radius 20.4 cm and height 64 cm. This target is bombarded by 1.2 GeV proton beam energy. As can be seen from the analysis of this figure that the variation of colors dispersed in a typical and clear way, this variation explains that the intensity of neutron current follows a certain mathematical theory: maximum in the middle of the target (30 cm of height of red color) and minimum at the end of the target.

4. Conclusion

In this study, we show that the variation of the proton penetration angle in the target has an effect on the neutron production. This variation depends on the target used, for example: using Beryllium target the neutron current is maximum when the proton penetration degree in the target is low and the neutron energy is more intense, the current also remains maximum when the penetration degree increases, Moreover, the neutron energy decreases. On the other hand, for the Tin target, the neutron current is maximally concentrated in medium degrees of neutron penetration and low neutron energy. The most important funding in this article is the application of the spallation models implemented in the MCNP.6 transport codes. From this work, we found that the method for determining the optimal configurations consists of the following: the target material, the incident proton energy, and the target geometry. In addition, we can conclude that the neutron generation in the target increases approximately linearly with the incident particle energy and with the selected target materials.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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