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Simulation of a Neutron Source at the KFSH&RC CS-30 Cyclotron

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Abstract. The aim of this work is to optimize the parameters of the CS-30 cyclotron neutron source at King Faisal Specialist Hospital & Research Center (KFSH&RC). The CS-30 cyclotron is a positive ion machine capable of accelerating protons with internal and extracted beam currents up to $100\mu A$ and $60\mu A$ respectively. Geant4 simulation toolkit based on Monte Carlo methods was used to study and compare the energy spectra and the angular distributions of the neutrons resulting from a 26.5 MeV proton beam on a 0.5 cm thick target Beryllium-9 with a 0.15 cm Copper-63 back stop.

1. Introduction

BNCT (Boron Neutron Capture Therapy) is a cancer treatment technique based on the reaction of ^{10}B with thermal or epithermal neutrons [1] used to produce an alpha particle ^{4}He and a ^{7}Li nucleus as shown in the following reactions [2, 3]:

$$^{10}\mathrm{B}^{+}\,\mathrm{n_{th}} \longrightarrow {}^{11}\mathrm{B}^{*} \longrightarrow {}^{4}\mathrm{He}(1.47\,\mathrm{MeV}) + {}^{7}\mathrm{Li}\,(0.84\,\mathrm{MeV}) + \gamma(0.48\,\mathrm{MeV})\;(93.7\,\%)$$
$$^{10}\mathrm{B}^{+}\,\mathrm{n_{th}} \longrightarrow {}^{11}\mathrm{B}^{*} \longrightarrow {}^{4}\mathrm{He}(1.78\,\mathrm{MeV}) + {}^{7}\mathrm{Li}\,(1.01\,\mathrm{MeV})\;(6.3\,\%)$$

The thermal neutron beam treats cancer when concentrated on affected tissue without destroying neighboring normal tissue [4]. Neutrons to be used with the BNCT cancer treatment technology are produced at the King Faisal Specialized Hospital and Research Center (KFSH&RC) using CS-30 cyclotron. In this work, the production of neutrons for the BNCT are simulated, studied and compared using a Geant4 (version 4.10.04) simulation code and ROOT.

2. CS-30 Cyclotron

The CS-30 cyclotron system at King Faisal Specialist Hospital & Research Center is designed for positive ion acceleration. It has been devoted for medical applications and research purposes since it was established in 1982 [5]. The cyclotron has a unique feature which is the capability to accelerate different particles in order to produce different beam currents [6].

3. Geant4 Simulation

The Monte Carlo simulation code is a toolkit used to simulate the passage, interaction and transport processes of particles through matter [7]. The physics list FTFP-BERT was used, which includes three models: Fritiof (FTF) model, Precom-pound (P) model and Bertini cascade (BERT) model [8]. A Geant4 code was developed to simulate the CS-30 cyclotron proton beamline and target as shown in figure 1.

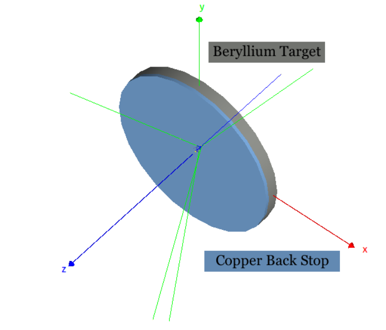

Figure 1. Visualization of proton interaction with target in Geant4

4. Results

4.1. Comparing Targets

For the first part of the validation process a comparison of simulated neutron production in both Beryllium-9 and Lithium-7 [9, 10] targets of similar dimensions bombarded by 26.5 MeV proton beams was made. Resulting energy spectra obtained from these simulations are shown in figure 2. In general, The $^9Be(p,n)$ gives higher neutron yield than $^7Li(p,n)$. The neutron energy spectrum of $^7Li(p,n)$ is softer and easier to be moderated. $^7Li(p,n)$ slows down fast neutrons to thermal energy levels more than $^9Be(p,n)$.

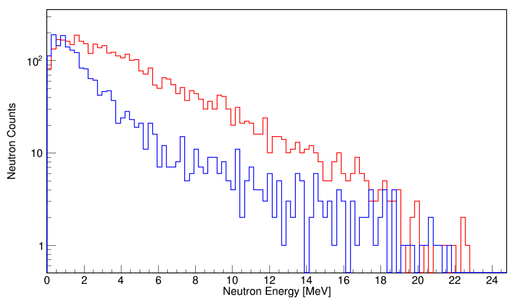

Figure 2. Neutron energy distribution in Beryllium target (red line) and Lithium target (blue line).

The neutron emission spectra is at different angles between 90° and 90° as shown in figures 3-6. The angle distribution contains a large number of neutrons in the proton beam direction, and number of neutrons decreases with broadening width of the scattering angles. The simulated results of the angular distributions are shown in figures 7-10. The results indicate that a large percentage of the yield is concentrated at the proton beam direction. The deviation from the beam direction decreases with increasing the energy.

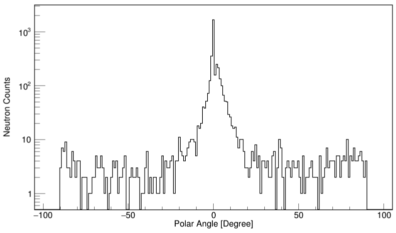

Figure 3. Polar angle distribution by ^{9}Be target.

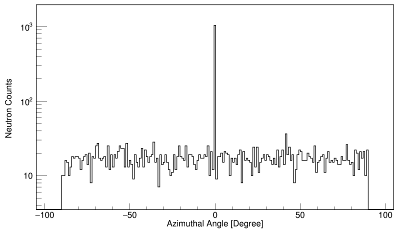

Figure 4. Azimuthal angle distribution by ^{9}Be target.

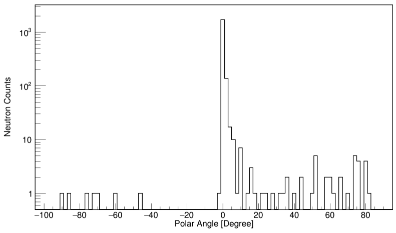

Figure 5. Polar angle distribution by ^{7}Li target.

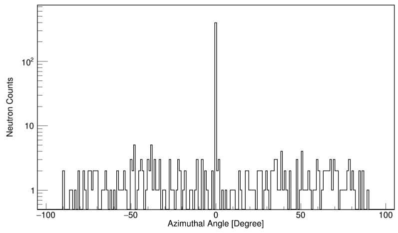

Figure 6. Azimuthal angle distribution by ^{7}Li target.

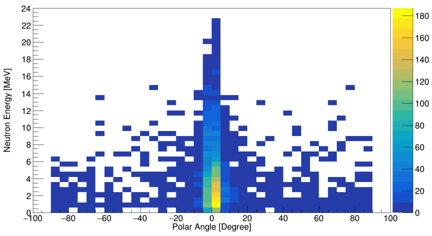

Figure 7. Energy versus polar angle distribution by ^{9}Be target.

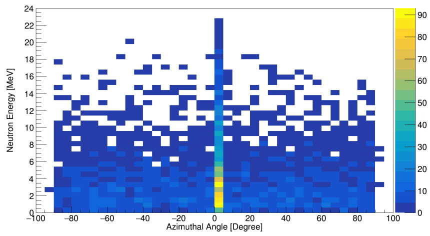

Figure 8. Energy versus azimuthal angle distribution by ^{9}Be target.

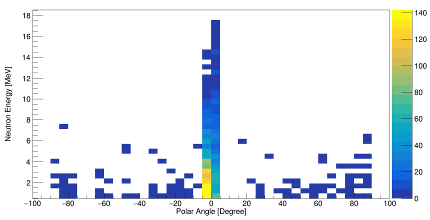

Figure 9. Energy versus polar angle distribution by ^{7}Li target.

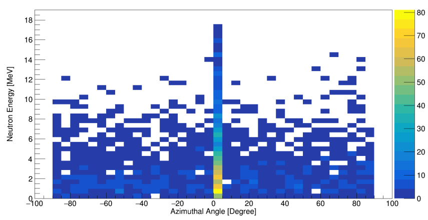

Figure 10. Energy versus azimuthal angle distribution by ^{7}Li target.

4.2. Comparing Beams

In the second part of the validation different proton beam energies as well as a deuteron beam were simulated and compared. Figure 11 clearly shows that the resulting neutrons are mostly fast neutrons that cover a wide spectrum of energies between 0 MeV to energies less than the incident proton energies. The polar angle distribution contains a large number of neutrons in the proton beam direction. The number of neutrons decreases with the broadening width of scattering angles and the increase of proton energy as shown in figures 12-15.

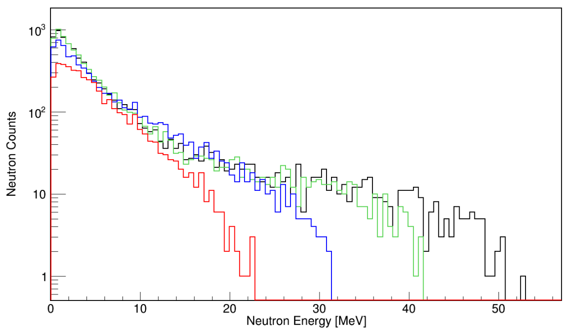

Figure 11. Neutron energy distribution proton-bombarding energies 26.5 MeV(red line), 36.5 MeV(blue line), 46.5 MeV(green line) and 56.5 MeV(black line).

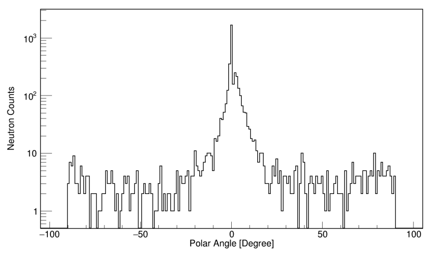

Figure 12. 26.5 MeV proton beam.

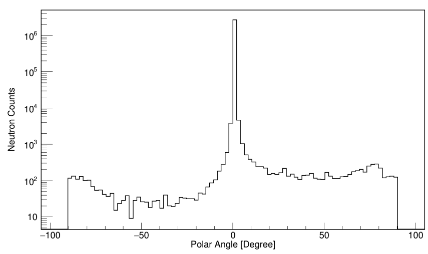

Figure 13. 36.5 MeV proton beam.

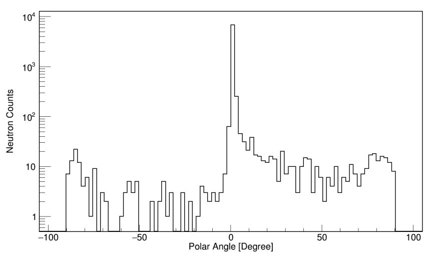

Figure 14. 46.5 MeV proton beam.

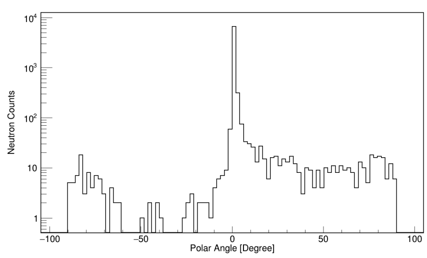

Figure 15. 56.5 MeV proton beam.

Another method of producing neutrons with a Beryllium target is the $^9Be(d,n)$ reaction where the Q-value is large and positive [11] so the spectra will extend to cover higher energy ranges than that of the deuteron beam. The resulting neutron yields are mostly fast neutrons with energies between 0.1 MeV to 17.6 MeV as shown in figure 16. The relationships between the energy distribution and the polar angular distribution of neutrons are shown in figure 17. The results indicate that most of the yield at different energies is concentrated at the deuteron beam direction which has a polar angle of 0°. However, the neutron yield decreases with increasing the energy and is equally distributed along all azimuthal angles between −90° to 90° except for the deuteron beam direction (0°), which has the most concentration as shown in figure 18.

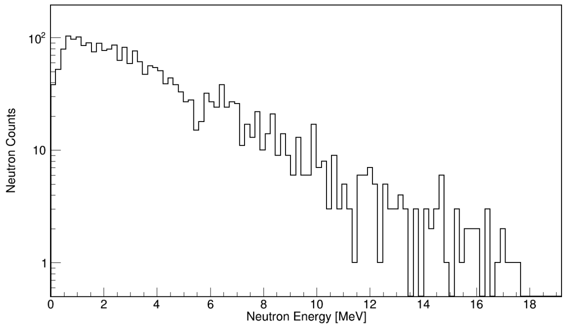

Figure 16. Neutron energy distribution by deuteron beam 15 MeV.

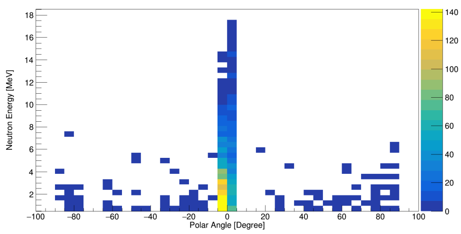

Figure 17. Energy versus polar angle distribution of neutrons.

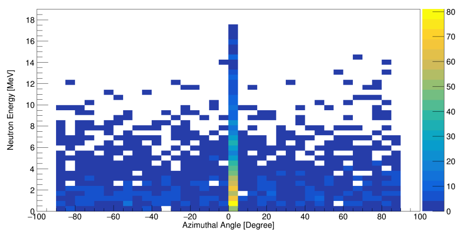

Figure 18. Energy versus azimuthal angle distribution of neutrons.

5. Conclusions

The neutron yield and the characteristics of the neutron spectra depend on the element of the target and the energy of the incident protons. The results indicate that the $^9Be(p, n)$ reaction is suitable to produce fast neutrons with energies between 1 to 22.6 MeV and are produced at an angle between −90° to 90° relative to the incident protons mostly at zero degrees which means it would be preferable to place the neutron detector facing the beam direction. Using Lithium-7 as an alternative target is beneficial to moderating the fast neutrons into thermal neutrons. The possibility of producing high energy neutrons was investigated by increasing the energy of the proton beam and using a deuteron beam.

6. Acknowledgements

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7. References

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