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Original Citation

Barlow, Roger , Ratcliffe, N, Cywinski, Robert, Bungau, Adriana and Edgecock, R. (2012) Optimising neutron production from compact low energy accelerators. In: Proceedings of the Third International Particle Accelerator Conference. IPAC 2012 . JACoW, New Orleans, Louisiana, USA, pp. 4154-4156. ISBN 978-3-95450-115-1

OPTIMISING NEUTRON PRODUCTION FROM COMPACT LOW ENERGY ACCELERATORS

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Abstract

There is currently much development in accelerator based methods to provide flexible and reliable neutron generators, in response to a decline in the availability of nuclear reactors. In this paper the focus is on neutron production via a low energy DC proton accelerator (1-10 MeV) and light target system. GEANT4 simulations are being used to study various aspects of target design, beginning with studies into light targets, such as lithium and beryllium, which are already in use. Initially the aim is to replicate these designs and benchmark these simulations with other models and experimental results before investigating how modifications can improve neutron production and tailor experimental geometries to specific applications such as neutron capture therapy and medical isotope production.

INTRODUCTION

There are two main methods of neutron generation: From a particle accelerator induced reaction or a nuclear reactor. Both methods are limited. However with the current views on nuclear technology and its many issues including logistics, flexibility and safety there is a drive towards developing and improving accelerator based sources for neutron production. There are many advantages to using accelerator based sources for neutron production. For example in medical applications an accelerator based source allows for much more flexibility ranging from an ease in logistics, being able to combine a treatment facility with a medical centre, to having more flexibility in selecting the energy range of the neutrons produced.

Many medical applications such as neutron capture therapies use thermal and epithermal neutrons which are best produced using low energy (less than 10 MeV) incident protons colliding with a light (low mass) target. The medical physics team at Birmingham University are implementing such methods of neutron production to develop a Boron Neutron Capture Therapy (BNCT) facility in the UK [1]. By firing a low energy ($\approx$ 3 MeV) proton beam at a thick lithium disc target with a fluental and graphite moderating block they have a working thermal/epithermal neutron source [2] [3].

This working target design has proved to be a good starting point for this work as the Birmingham team have both experimental [2] [3] results and previous model results generated using MCNP [1] with which to compare and benchmark our GEANT4 results, before going on to modify target designs and materials for our own applications. Additionally there seems to have been much discussion in the literature on which element, lithium or beryllium, would make the better target. There are several advantages and disadvantages associated with each element that need to be considered. While lithium has the preferable neutronic properties in terms of the neutron yield obtained under proton bombardment there can be several difficulties in practically implementing such a target due to mechanical and chemical properties, such as low melting point and poor heat conduction etc. In order to overcome these problems a more complex target assembly must be used, for example the Birmingham team have carried out extensive studies in which the lithium is attached to a suitable substrate whilst also providing an adequate cooling system to help combat the large amounts of power that get injected into the target by the proton beam [1]. In comparison a practical beryllium target design could be much simpler, even implemented as a single foil [4]. The price for these much better practical properties is a decrease in the neutronic properties, for example the beryllium neutron yield for an incident proton of 4 MeV is comparable to the lithium neutron yield at around 2.8 MeV [5] [6]. There has also been study of combining layers of these two elements to make a hybrid target to combine the advantages of each element whilst mitigating against the disadvantages of each individual element [7].

In this paper we present the results of simulations for both lithium and beryllium as single element targets for the GEANT4 validation process.

SETUP

The simulated data presented here has been obtained using a 0.7mm thick target disc with a diameter of 40mm in both lithium and beryllium. Simulations were performed with GEANT4 versions 4.9.4.p01 and 4.9.5.p01 using two physics lists, QGSP_BERT and QGSP_BERT_HP, as Bertini models are known to be more reliable at lower energy scales due to incorporated pre-compound models. A point like proton beam is fired in an energy range between 2 and 4 MeV. Results obtained from these simulations give a model count of the number of neutrons that are produced within and exit the target volume. Experimental work has also been done using similar targets and the available results can be used to benchmark our simulations.

RESULTS

For the first part of the validation process the lithium target simulation was used. Results obtained from these simulations using GEANT4.9.4.p01 with QGSP_BERT are shown in Fig. 1. These results gave the highest and most reliable neutron yields from the models employed. Experimental results from the Birmingham team can be seen in Fig. 2 [3]. A comparison of these plots shows that the functional form of the simulated data is significantly different from the experimental data. Moreover our results also give a much lower neutron yield (by approximately a factor of 10^4) than the experimental cross sections would suggest.

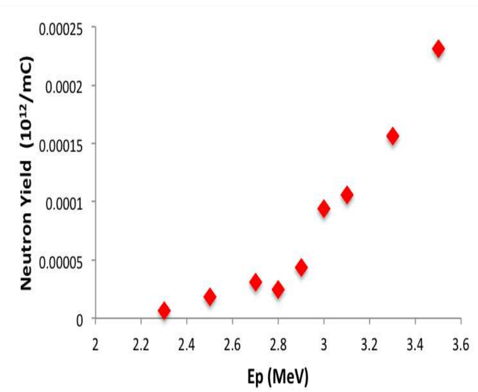

Figure 1: Simulation results of the lithium target using GEANT4.9.4.P01 with the QGSP_BERT model.

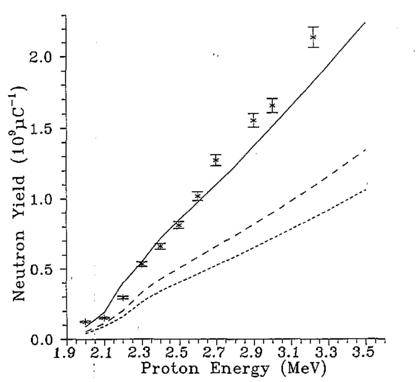

Figure 2: Total neutron yields from a pure thick lithium target (solid line and points). The dashed lines represent lithium compound targets that were also used in experiments by D. A. Allen and T. D. Beynon

In the second part of the validation the lithium disc was replaced by a beryllium disc of similar dimensions. Results obtained from the same Bertini model are shown in Fig. 3 and an experimental comparison can be seen in Fig. 4 [7]. The simulated results follow a similar curve to that shown by the experimental neutron yields from such a target. However the values are significantly lower. For example at 3 MeV the model results give a value of $0.0006{*}10^{12}$/mC , approximately 500 times lower than the value of $0.3{*}10^{12}$/mC obtained experimentally at the same proton energy. However results obtained from the Bertini HP model using an updated version of GEANT4 4.9.5.p01 are shown in Fig. 5. These results show a much better correlation with those in Fig. 4, both quantitatively and qualitatively with model and experimental results giving a neutron yield of approximately $1{*}10^{12}$/mC at 4 MeV.

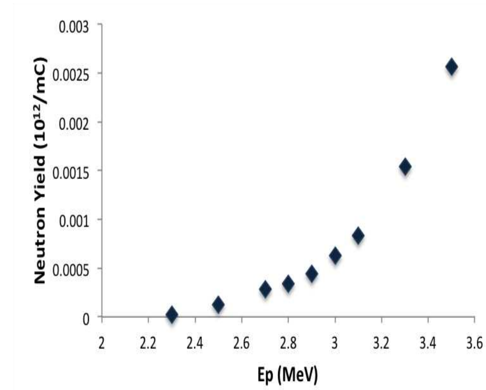

Figure 3: Simulation results of the beryllium target using GEANT4 version 4.9.4.p01 with the QGSP_BERT model.

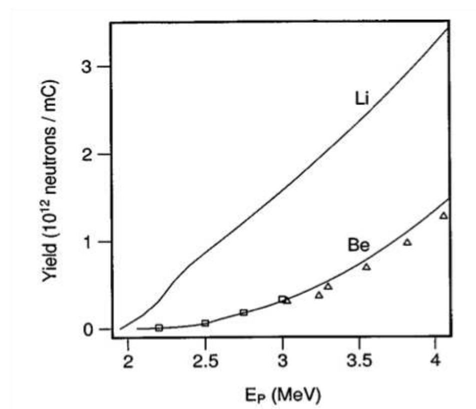

Figure 4: Total experimental neutron yields a for thick lithium target from cross-sections from [9] and a beryllium with data from [10]. Direct neutron yields for a beryllium target are from [8] (squares) and [11] (triangles).

Although the experimental data obtained from beryllium are well modelled, both quantitatively and qualitatively, by the GEANT4.9.5.p01 QGSP_BERT_HP simulations, attempts to use the same modelling procedures for the lithium target gave results which were no better than those obtained with the previous models.

CONCLUSIONS

For beryllium targets at least, both the energy dependence and the magnitude of the neutron yield resulting from the impact of low energy (2-4 MeV) protons are well modelled by the GEANT4.9.5.p01 QGSP_BERT_HP simulations, as can be seen in Fig. 5 where our simulations are compared with the experimentally obtained yields. For

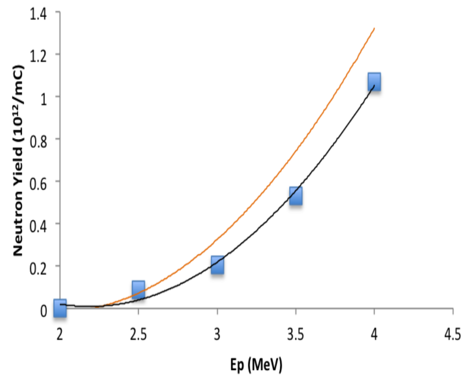

Figure 5: Overlay plot of experimental results (yellow line) for a beryllium target with those obtained using GEANT4.9.5.p01 with the QGSP_BERT_HP model (blue points with dark blue trend line).

lithium targets, however, neither the yield nor its dependence on proton energy are in agreement with experimental data. It is clear that there are significant issues with the physics embodied in GEANT4 at these rather low proton energies. Nevertheless the benchmarking of the GEANT4 simulations against the experimental results from beryllium give us some confidence in moving forward, at least with this target material, to develop more detailed geometrical models with which the production and delivery of thermal and epithermal neutrons for Boron Neutron Capture Therapy can be fully optimised. In so doing it is also important to understand for what materials, and at which energies the simulations begin to break down.

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