SPALLATION IS NOT THE ONLY FRUIT: LOW ENERGY FUSION AS A SOURCE OF NEUTRONS

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Abstract

Commercially there is a growing interest in applications of neutrons. Currently the majority of neutron sources are based at research institutions from either reactors or spallation sources. Smaller portable sources contain either fissile isotope or sealed fusors are available, although they either use or produce tritium, or other long lived decay products. As an alternative to the large facilities and the radio-toxicology of current portable sources research is being performed with an aim to produce a fusion based neutron source with neither of these concerns. We show that MCNPX is able to accurately reproduce (p, n) reactions for a number of light elements. Simulations of low energy proton reactions with light nuclei simulated with MCNPX and Geant4 are compared with experiment.

INTRODUCTION

Reactor based fission sources have been used for many years but the cost, infrastructure, and geographical footprint associated with building and maintaining nuclear reactors are very high, making then unsuitable for industrial applications. These same issues apply to spallation sources for the creation of neutrons.

Fusion based neutron sources operate by accelerating (at low energies) either protons or deuterons into a target material with $1 < Z < 20$. The precise energy required for the particle beam depends upon the target being used. Fusion sources can be constructed with massively lower costs than either fission or spallation facilities and also benefit from producing almost mono-chromatic neutrons. The most common fusion reaction used for neutron sources is the $T(d,n)^4He$ reaction, where deuterons are accelerated by 140KeV into a tritium target producing 14MeV neutrons.

Commercial sealed tube neutron sources are available, such as the ING-013 [1], using either the $D(d,n)^3He$ or $T(d,n)^4He$ reaction to produce neutrons. Theoretically any fusion reaction with 2 end products, like the $T(d,n)^4He$ reaction, will produce a monochromatic neutron beam however the design of the source, and the projectile energy, can cause a spread in the neutron energy.

Commercial sealed tubes can produce $> 10^9 ns^{-1}$ and have the advantage that once the generator is off no neutrons are produced. The problem with both the $D(d,n)$ and $T(d,n)$ reactions is that they either use, or produce, tritium. Tritium is a beta emitter and as a hydrogen isotope can easily enter the water table and atmosphere. Tritium is subject to quite stringent legislation under, amongst others, The Ionising Radiations Regulations 1999 (IRR'99) [2] and the High-activity Sealed Sources and Orphan Sources Regulations 2005 (HASSOSR'05) [3]. Problems with sealed tube sources are exacerbated by target ablation which reduces tube lifetime to hours for high-through put applications.

As an alternative to deuterium and tritium targets it is possible to use heavier elements such as Li, Be or O. Using the correct element removes the risk of producing tritium and removes the need for sealed tubes. Removing the need for sealed systems means that when a target has degraded too far it can be replaced without any other alterations being made to the system. By considering the effect of target thickness and beam energy on the neutron spectrum it will be possible to develop a combination with the peak in the neutron spectrum at the desired energy. This paper investigates neutron production via low energy proton/deuteron induced reactions which neither use nor produce tritium, these reactions would have fewer issues with the IRR'99 and the HASSOSR'05, whilst the low-energy would enable relatively cheap systems, with low geographical foot prints, infrastructure and longer lifetimes.

The ideal source should be monochromatic, pulsed, with tunable energy, which retains flux levels possible in a thick target. Development of alternative neutron sources would greatly expand the availability of neutrons to a wide range of applications (mining, medical, security). One such example that would greatly benefit from more widely available neutron sources is security screening of cargo. The traditional detection methods are limited and as threats increase more reliable technology is required, a recent study [4] found that operators missed 20% of potentially dangerous objects.

SIMULATIONS

Ratcliffe et al [5] showed that Geant4 was not able to reproduce low energy (p, n) reactions with the currently available models and so the decision was taken to use MCNPX. MCNPX is a versatile, general-purpose, Monte Carlo radiation transport code for modelling the interaction of radiation with target materials, the code treats an arbitrary configuration of materials in geometric cells. Pointwise cross-section data typically are used, although groupwise data is available. For neutrons, all reactions given in a particular cross-section evaluation (such as ENDF/B-VII) [6] are accounted for. Thermal neutrons are described by both the free gas and $S(\alpha, \beta)$ models [7]. MCNPX contains numerous flexible tallies: surface current/flux, volume flux (track length), point or ring detectors, particle heating, fission heating, pulse height tally for energy or charge deposition, mesh tallies, and radiography tallies.

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MCNPX is being used to simulate neutron production via proton/target fusion reactions. Initial simulations are being performed using the simplified case of a cylinder in a vacuum within a tally volume to provide energy and angular distribution of the produced particles.

Neutron Production

The (p, n) reactions can produce neutrons through two distinct channels, compound nucleus and direct production. Compound nucleus production involves the projectile and target fusing resulting in an excited state which then relaxes through the emission of a neutron. Direct production involves projectiles at higher energies stimulating the emission of a neutron without the formation of a compound nucleus. For a fusion based neutron source it is desirable to remain in an energy regime where direct production is not a factor.

In the simplest approximation a (p, n) reaction will produce a perfectly mono-chromatic neutron beam where the neutron energy E_n is given by:

$$E_n = \frac{Q + E_p}{M_{CN}} M_{DN} \tag{1}$$

Where Q is the mass-energy difference between the initial and final state, E_p is the proton energy, M_{CN} is the mass of the compound nucleus and M_{DN} is the mass of the decay nucleus. In practice even for a perfectly mono-energetic proton beam the neutron beam is still not perfectly mono-chromatic for a number of reasons most significantly the Fermi motion of nucleons acts to broaden the peak as well as the existence of meta-stable states and additional decay channels which can introduce lower energy peaks.

Verification work was performed using the $^7Li(p, n)$ reaction as there is a substantial amount of literature available for it, specifically the Liskien and Paulsen data set [8] which has been compiled into a look up table for use in MCNPX. Comparison of the angular distribution (Figure 1) and neutron spectrum (Figure 2) for this reaction showed good agreement between experiment and simulation and therefore we were confident that in at least some cases the (p, n) reaction could be accurately simulated.

Having verified that a degree of accuracy was possible alternative targets were investigated, not all elements are available in the ENDF libraries used by MCNPX and so the elements available for simulation were limited. The TENDL libraries [9] are able to provide data for those elements not available through ENDF however these are also not completely reliable. At present only materials for which there is experimental data available for comparison can be simulated however this still provides ample opportunity for investigating the applicability of some targets to PFNA.

Simulations of (p, n) reactions have been performed with a range of beam energies and target thicknesses for several target materials. The neutron flux and spectrum for

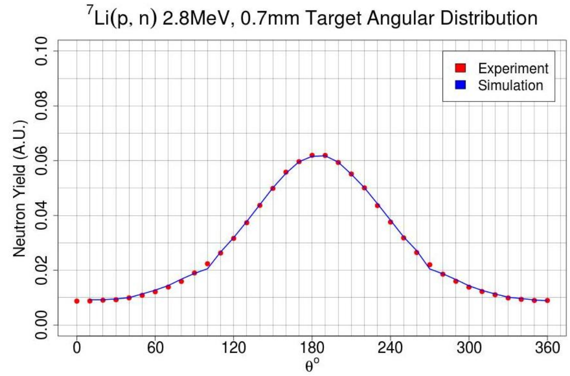

Figure 1: The simulated (blue line) and experimental (red points) angular distribution of neutrons in the $^7Li(p, n)$ reaction where 180^o is the straight through direction.

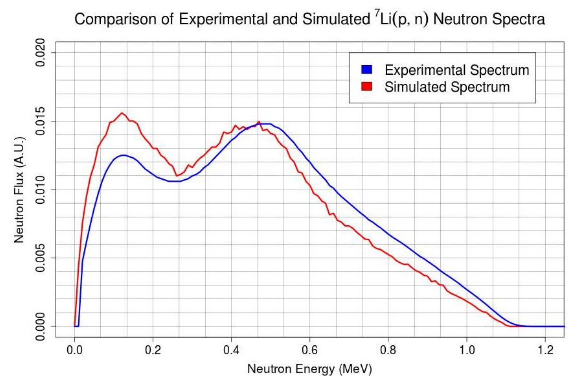

Figure 2: The simulated (red line) and experimental (blue line) neutron spectrum from the $^7Li(p, n)$ reaction.

$^9Be(p, n)$ and $^{26}Mg(p, n)$ are discussed with the effects of both beam energy and target thickness demonstrated.

The $^9Be(p, n)$ reaction shows multiple energy peaks rapidly emerging as E_p is increased, as can be seen in Fig. 3, this is most likely due to the production of additional ejectiles and/or meta-stable states. Unlike ^9Be the spectrum from ^{26}Mg (Fig. 4) maintains monochromaticity upto much higher proton energies and higher neutron energies, specifically where $E_n \approx 3MeV$ for $^{26}Mg(p, n)$ shows a fairly narrow spectrum there are multiple peaks present in the $^9Be(p, n)$ spectrum.

Whilst increasing the beam energy can be seen to affect both the flux and spectrum of the neutrons produced in fusion reactions the effect of target thickness must also be considered. A constant beam energy onto a target of varying thickness shows the dependence of spectrum and multiplicity on target thickness. Figure 5 shows the neutron energy spectra for a magnesium target of varying thickness under an 8MeV proton beam. As can be seen in Figure 5 increasing target thickness has two effects, up to a certain thickness (for Mg between $150\&300 \mu m$) the total neutron flux increases to a maximum and as the thickness increases the neutrons become moderated as they propagate through the target and the low energy end of the spectrum increases. In the extreme case of $1000 \mu m$ of Mg becomes the dominant part of the spectrum. The effect of target thickness

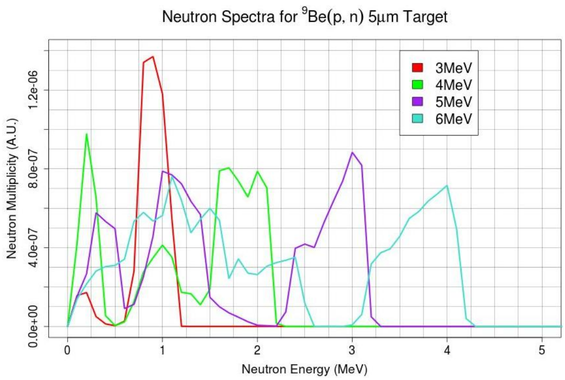

Figure 3: The neutron energy spectrum produced by a thin Beryllium target bombarded with protons with energy from $3-6MeV$.

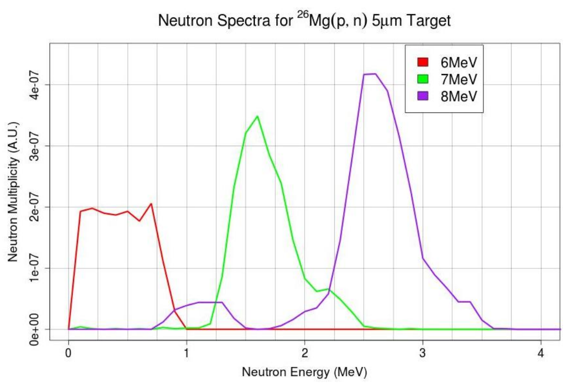

Figure 4: The neutron energy spectrum produced by a thin Magnesium target bombarded with protons with energy from $6-8MeV$.

seen in the $Mg(p, n)$ spectrum shows that whilst a thicker target will increase the neutron flux if the thickness is increased too far the effect on the spectrum becomes undesirable.

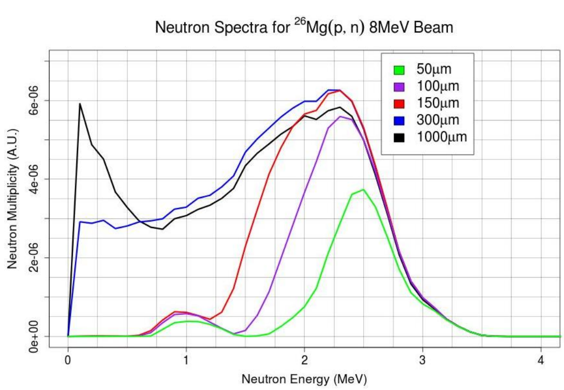

Figure 5: The neutron energy spectrum produced by a Magnesium target with thickness $50-1000\mu m$ bombarded by 8MeV protons.

FUTURE WORK

At present only (p, n) reactions can be simulated with MCNPX and some elements and isotopes are not available. As an alternative to the (p, n) reaction the (d, n) and (α, n) reactions can be used. Using a different projectile may increase the flux and energy of the neutrons without the associated chromaticity effects of increased beam energy and target thickness.

For security applications it is desirable to have as focused a neutron beam as possible to maximise the flux which passes through the suspect volume. By using the heavier element as the projectile and the lighter element as the target momentum conservation should result in a more focused neutron beam.

The (d, n) and (α, n) reactions and using the heavier element as the projectile all require experimental work due to the low availability of data which can be used for validation.

SUMMARY

There is a growing interest across multiple branches of industry in uses of neutrons. In particular neutron sources can be used for security as an augmentation of existing X-ray technology. The current generation of neutron sources, reactors, spallation machines and sealed fusors are not suitable for use in a security setting. We propose a small-scale fusion based neutron source which will avoid the cost and scale of large facilities and avoid the radioactivity of current compact devices.

Correctly operated a fusion neutron source can provide a high flux of mono-chromatic neutrons which can be used for a variety of industrial applications where current neutron sources are not suitable.

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