LOW ENERGY FUSION FOR A SAFE AND COMPACT NEUTRON SOURCE

S. Albright* and R. Seviour, IIAA, University of Huddersfield, UK, HD1 3DH

Abstract

Neutrons are primarily produced at large international facilities using either spallation reactions or nuclear fission. There is a demand for small scale neutron production for use at hospitals and borders for a variety of applications. Isolated fission sources and sealed tube deuterium-tritium fusors are able to provide a reliable neutron flux at small scale but are impractical due to the associated radioactivity. A beam of protons or deuterons accelerated onto a thin target will undergo a fusion reaction resulting in the emission of a quasi-monochromatic neutron beam. The total flux and energy spectrum of the neutrons produced through fusion is primarily dependent on target material, target thickness, beam energy and projectile. The use of neutrons for security screening at border crossings, ports and airports has the potential to drastically improve threat detection and contents verification. Monte Carlo code MCNPX is being used to investigate the most suitable target and beam characteristics for a neutron source for security applications.

INTRODUCTION

There are many areas of both science and industry which use neutron beams. There is growing interest in using neutrons for medical applications, such as Boron Neutron Capture Therapy (BNCT) [1], and for security applications, such as Pulsed Fast Neutron Analysis (PFNA) [2]. Medical and security applications in particular are not easily served by current neutron sources which tend to be either large and expensive or have radiotoxicology concerns.

For use in medical and security environments two important properties of a neutron source are that it be:

- Compact: Hospitals and airports in particular have limited space available.
- Clean: Radiotoxicity must be kept to a minimum to protect operators and reduce necessary safeguards.

Recently there has been an increased interest in using low energy accelerators (¡10MeV) to produce neutrons. There are sealed tube neutron sources on the market at present (such as the ING013 produced by the VNIIAA [3]) which use a Tritiated Titanium target bombarded by a deuteron beam to produce a high flux of quasi-monochromatic neutrons at ≈ 14MeV. Sealed tube sources are not practical for mass deployment due to both the radiotoxicology of Tritium and the legislative controls around their use and transport [4, 5].

In this paper we present simulated results showing that fusion reactions are capable of providing neutrons suitable for a range of industrial applications. Keeping the energy of the incident particles low enables the use of small accelerators and choosing the projectile/target combination correctly will prevent build up of any long lived radioisotopes.

Proton induced fusion reactions were simulated in the Monte Carlo code MCNPX [6] to show the effect of varying target and beam parameters on the neutron beam. The optimum parameters of the neutron beam depend upon the application. Fusion based neutron sources have been shown to satisfy the requirements of two very different applications. For PFNA the primary concern is that the neutron spectrum be both narrow and high energy. For BNCT the neutrons are moderated into the epithermal region therefore the spectrum from the source is unimportant and only the total flux and size of the source are of concern.

The nuclear inventory package EASY-II [7], which uses the fispact-II code [8], has been used to investigate the build up of isotopes in targets to ensure no long-lived radioisotopes are produced. EASY-II enables the build up, decay, and subsequent re-activation of isotopes to be simulated reducing the risk of potentially hazardous decay and transmutation chains being unidentified.

APPLICATIONS

A brief description of two valuable applications of a fusion based neutron source is given along with details of the optimum neutron beam properties for both applications. The two applications discussed are BNCT, a cancer treatment, and PFNA, a security technique.

BNCT uses a boronated drug, preferentially taken up by tumour tissue, and then bombarded by epithermal neutrons. The reaction ^{10}B + n $\rightarrow ^{7}$Li + α causes a massive dose of radiation to be delivered to the tumour whilst leaving surrounding tissue relatively untouched. As BNCT requires epithermal neutrons the beam must be moderated, the sourced neutron spectrum is therefore unimportant and instead maximising the flux whilst minimising the size of the source is the principle concern.

PFNA is a security technique which uses a high energy, monochromatic neutron beam to stimulate the emission of prompt gammas (γs) from material. The γs emitted in PFNA are unique to the element being interrogated allowing the precise content of cargo to be identified. By pulsing the source a volume can be broken into voxels giving a 3D breakdown of what is in a container and where it is located. For PFNA it is important that the neutron beam be; high energy, to maximise prompt gamma emission and minimise transmutation rates; and monochromatic, to minimise both voxel sizes and uncertainties in gamma emission rates.

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[*] corresponding author: simon.albright@hud.ac.uk

ISBN 978-3-95450-138-0

MONTE CARLO SIMULATION

Monte Carlo code MCNPX has been used to demonstrate the effect of changing beam and target parameters on neutron spectrum. The parameters which can be varied are target element, target thickness, beam energy and projectile. The two elements discussed are Magnesium and Beryllium as the results are representative of what most targets will produce.

The plots in Figure 1 and 2 show the change in neutron spectrum and flux with increasing beam energy. The very thin target used in these simulations (5μ m) meant that little energy was lost as protons travelled through the target. Since very little energy was lost the protons which reacted all had approximately the same energy.

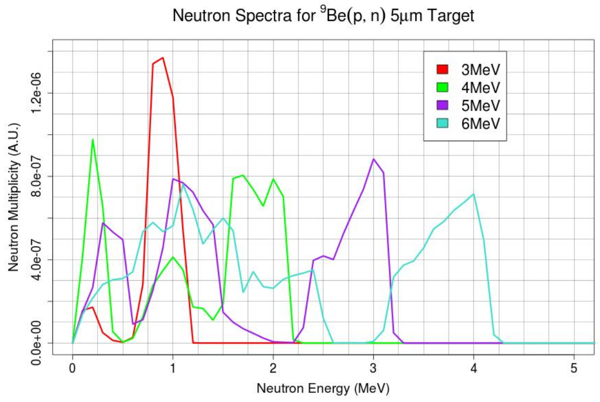

Figure 1: The neutron energy spectrum produced by a thin Beryllium target bombarded with protons with energy from 3-6 MeV.

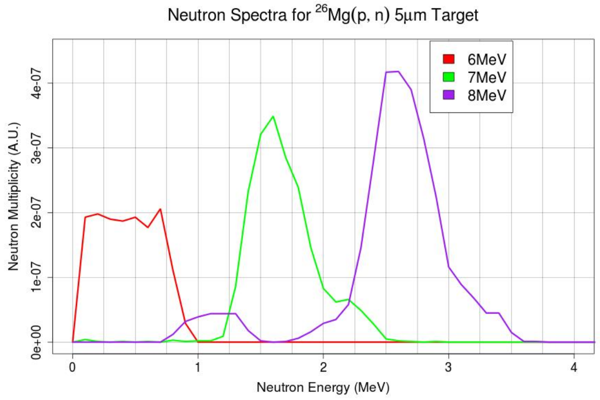

Figure 2: The neutron energy spectrum produced by a thin Magnesium target bombarded with protons with energy from 6-8 MeV.

The results in Figure 1 show that the ^{9}Be(p,n)^{9}B reaction very produces a broad spectrum of neutrons. Due to the spectral characteristics of a ^{9}Be target it would be most suited to an application like BNCT where the spectrum of the sourced neutrons is unimportant. The results in Figure 2 show that, for a thin target, the ^{26}Mg(p,n)^{26}Al reaction maintains a relatively narrow spectrum up to much higher beam energy and neutron energy than the ^{9}Be(p,n)^{9}B reaction. Due to the narrow spectrum the ^{26}Mg(p,n)^{26}Al reaction would be more suitable to an application like PFNA where spectral characteristics are the primary concern.

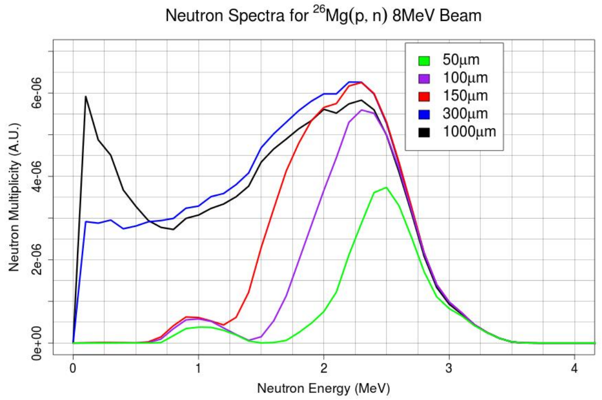

Figure 3: The neutron energy spectrum produced by a Magnesium target with thickness $50 - 1000\mu m$ bombarded by 8MeV protons.

The results plotted in Figure 3 show the impact of increasing target thickness on the neutron spectrum of the ^{26}Mg(p,n)^{26}Al reaction. The results in Figure 3 are characteristic of all accelerator based fusion reactions. As the thickness of the target increases the total flux and spectral width increase. Once the target is thick enough to slow incident projectiles below the fusion threshold energy the maximum neutron flux is reached ($\approx 300\mu$m in Figure 3), after this the only effect of increasing target thickness is increased neutron moderation.

ISOTOPE INVENTORY

As well as a thorough understanding of the neutron production properties of a target it is vital that the isotope production be well characterised. Under constant bombardment the target nuclei will transmute which may lead to a build up of radioactivity. Not only will the intended reaction occur (e.g. ^{26}Mg(p,n)^{26}Al) but other first generation reactions (e.g. ^{26}Mg(p,α)^{23}Na) and higher generation reactions (e.g. ^{26}Mg(p,n)^{26}Al(p,n)^{26}Si). The presence of additional decay channels and the production of higher generation isotopes poses a potential threat to the safety, and therefore applicability, of a fusion based neutron source.

Simulations were carried out in EASY-II to identify the isotopes produced in a selection of targets under proton bombardment. After 72 hours of continual 8 MeV proton bombardment on ^9Be and ^{26}Mg targets the isotopes shown in Table 1 were identified. The ^9Be target would be expected to have no latent activity, the initial fusion reaction and subsequent decays are:

$$^9\mathrm{Be} + \mathrm{p} \rightarrow {}^9\mathrm{B} + \mathrm{n}$$

$$^{9}\mathrm{B}(t_{\frac{1}{2}} \approx 8 \times 10^{-19}\mathrm{s}) \rightarrow^{8} Be + \mathrm{p}$$

$$^{8}\mathrm{B}e(t_{\frac{1}{2}} \approx 6 \times 10^{-17}\mathrm{s}) \rightarrow 2\alpha$$

The extremely short half lives of the products in the decay chain prevents any latent activity building up in the target. Table 1 shows that under proton bombardment ^{9}Be will also produce the radioisotope ^{7}Be($t_{\frac{1}{2}} \approx$ 53d) through the interaction chain ^{9}Be(p,γ)^{10}B(p,α)^{7}Be.

Table 1: The Isotopes (Z>2) Produced after 72 Hours of 8 MeV Proton Bombardment of ^{9}Be and ^{26}Mg

^{9}Be	^{26}Mg
^{6}Li ^{7}Be($t_{\frac{1}{2}} \approx$ 53 d) ^{10}B	^{16}O ^{20}Ne ^{23}Na ^{24}Mg ^{25}Mg ^{26}Al($t_{\frac{1}{2}} \approx 7 \times 10^{5}$ y) ^{26m}Al ($t_{\frac{1}{2}} \approx$ 6 s) ^{27}Al

As ^{9}B decays nearly instantaneously and ^{26}Al has a very long half life it would at first be assumed that ^{9}Be was a preferred target in terms of radiotoxicology. The 2nd generation isotope ^{7}Be is potentially more dangerous than ^{26}Al as, due to the differing decay rates, a larger amount of ^{26}Al would be required to take the activity above safe limits. In an industrial environment, be it medical, security or other, the residual activity of the target must not exceed safe limits but different applications may have different limits.

FUTURE WORK

At present there are no Monte Carlo codes able to accurately simulate low energy deuteron interactions and proton interactions can only be reliably simulated with nuclear data files. There is a loose trend for more energy being released (and therefore lower acceleration voltages needed) in deuteron induced reactions than proton induced reactions. Due to the higher energy release deuterons may be a better projectile for applications which require a high energy neutron beam.

Whilst cross-sections are known for most (d, n) reactions the energy spectra and angular distributions of the emitted neutrons remain mostly unpublished. Additional experimental data will broaden the range of projectile/target combinations which are understood and so enable neutron sources to be more effectively tuned to the application.

CONCLUSION

Two potential applications of low energy fusion based neutron sources have been discussed. For example in medicine neutron can be used for the cancer treatment BNCT, this requires an epithermal neutron beam which can be achieved by moderating a higher energy beam. For BNCT the sourced spectrum is unimportant so instead a high flux, low energy (and therefore compact) source can be used. The discussed ^{9}Be(p,n)^{9}B reaction would be suitable for this application as even at 3 MeV a fair neutron flux is achieved.

In security the neutron scanning technique PFNA requires a high energy, monochromatic beam. As the spectrum of the beam is most important for PFNA it would be acceptable to use a lower flux target which has better spectral properties. A target with characteristics similar to the ^{26}Mg(p,n)^{26}Al would be suitable for this application.

For either of these technologies to become a reality a low-cost compact source of neutrons need to be developed, and a key way in which both of these conditions can be achieved is through the use and development of neutron sources that utilise low energy reactions. A concern with any device based on nuclear interactions is the production of radioisotopes. Whilst radioisotopes are produced by both ^{9}Be and ^{26}Mg the level of activity may not be sufficient to pose a safety concern.

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[3] website: http://vniia.ru/eng/ng/docs/ing_element_eng.pdf

[4] Ionising Radiations Regulations 1999
website: http://www.legislation.gov.uk/uksi/1999/3232/contents/made

[5] High-activity Sealed Radioactive Sources and Orphan Sources Regulations 2005
website: http://www.legislation.gov.uk/uksi/2005/2686/contents/made

[6] MCNP: Monte Carlo N-Particle Transport Code System Including MCNP6.1, MCNP5 1.60, MCNPX 2.70 and Data Libraries. Available from the Radiation Safety Information Computational Center (RSICC) at Oak Ridge National Laboratory as CCC-810.

[7] website: http://www.ccfe.ac.uk/EASY.aspx

[8] website: http://www.ccfe.ac.uk/assets/Documents/CCFE-R%2811%2911.pdf