

---

**The  $^3\text{He}(\text{d},\text{p})\text{He}^4$  Nuclear Fusion  
Reaction as a Source of Mega-  
voltage Protons for the Production of  
Fluorine-18 for PET Applications.**

By  
Michael Paul Barnes  
BSc (Pro) (Hons)

Supervisors: Professor John O'Connor  
Assoc/Prof Martin Ebert

A Thesis submitted in the fulfillment of the  
degree of

**Master of Philosophy (Physics)**

*The University of Newcastle*

August 2009

---

---

## Declaration

I hereby declare that this work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. I give consent to this copy of my thesis, when deposited in the university library, being made available for loan and photocopying subject to the provisions of the Copyright Act 1968.

.....  
Michael Paul Barnes

October 2008

---

## Acknowledgments

I would like to take this opportunity to thank my two co-supervisors Professor John O'Connor and Associate Professor Martin Ebert for their wisdom, guidance and patience during this project. Their doors and email inbox's were always open to me when I required assistance, feedback or a reality check about my research. I feel I am a better researcher for their help.

---

# Table of Contents

|  |            |
|--|------------|
| <i>Declaration</i>   | <i>i</i>   |
| <i>Acknowledgments</i>   | <i>ii</i>  |
| <i>Table of Contents</i>   | <i>iii</i> |
| <b>1. Abstract</b>   | <b>1</b>   |
| <b>2. Aims and Motivation</b>  | <b>3</b>   |
| <b>3. Introduction</b>   | <b>4</b>   |
| <b>3.1 Positron Emission Tomography (PET) and its Applications</b>   | <b>4</b>   |
| 3.1.1 Clinical Applications of PET   | 5          |
| 3.1.1.1 Positron Decay   | 7          |
| 3.1.1.2 Annihilation   | 7          |
| 3.1.2 Positron Emitters  | 10         |
| 3.1.2.1 Fluorine-18  | 10         |
| 3.1.2.2 Other Positron Emitters  | 11         |
| 3.1.3 Fluorodeoxyglucose (FDG)   | 11         |
| 3.1.3.1 FDG Synthesis  | 12         |
| 3.1.3.2 FDG Dosage   | 13         |
| <b>3.2 The <math>^{18}\text{O}(\text{p},\text{n})^{18}\text{F}</math> Reaction</b>   | <b>13</b>  |
| <b>3.3 Cyclotron Production of Fluorine-18 Utilizing the <math>^{18}\text{O}(\text{p},\text{n})^{18}\text{F}</math> Reaction</b> | <b>15</b>  |
| <b>3.4 Alternate Production Methods of Fluorine-18</b>   | <b>17</b>  |
| 3.4.1 Alternate Methods using the $^{18}\text{O}(\text{p},\text{n})^{18}\text{F}$ reaction                                       | 17         |
| 3.4.1.1 Linear Accelerators  | 17         |
| 3.4.1.2 Lasers   | 18         |
| 3.4.2 Methods using alternate reactions  | 19         |
| 3.4.2.1 Cyclotrons   | 19         |
| 3.4.2.2 Nuclear Reactors and Van de Graaff Generators  | 20         |
| <b>3.5 The <math>^3\text{He}(\text{d},\text{p})^4\text{He}</math> Reaction</b>   | <b>21</b>  |
| <b>3.6 Helium-3 Ion Sources</b>  | <b>23</b>  |

---

|            |  |           |
|------------|--|-----------|
| 3.6.1      | Saddle-Field Ion Sources   | 24        |
| <b>3.7</b> | <b>Sputter Process</b>   | <b>26</b> |
| 3.7.1      | Introduction   | 26        |
| 3.7.2      | Sputter Yield  | 26        |
| 3.7.2.1    | Ion Energy   | 27        |
| 3.7.2.2    | Target Materials   | 28        |
| <b>3.8</b> | <b>Stopping and Range of Ions in Matter (SRIM) Monte Carlo Program</b> | <b>29</b> |
| 3.8.1      | Introduction   | 29        |
| 3.8.2      | The Science of SRIM  | 29        |
| 3.8.2.1    | Stopping of Ions in Compounds  | 29        |
| 3.8.2.2    | Stopping of High Energy Ions   | 31        |
| 3.8.3      | SRIM Accuracy  | 32        |
| <b>4.</b>  | <b>System Designs</b>  | <b>33</b> |
| <b>4.1</b> | <b>Practical considerations</b>  | <b>33</b> |
| 4.1.1      | Ease of Use  | 33        |
| 4.1.2      | Small size   | 34        |
| 4.1.3      | Safety   | 34        |
| <b>4.2</b> | <b>Economic considerations</b>   | <b>34</b> |
| <b>4.3</b> | <b>Yield Efficiency</b>  | <b>35</b> |
| <b>4.4</b> | <b>Designs</b>   | <b>35</b> |
| 4.4.1      | Deuterated Solid Target  | 35        |
| 4.4.1.1    | Alternative Plastics to Mylar  | 38        |
| 4.4.2      | Super heavy water Target   | 39        |
| <b>5.</b>  | <b>Calculations</b>  | <b>42</b> |
| <b>5.1</b> | <b>Introduction</b>  | <b>42</b> |
| <b>5.2</b> | <b>Nuclear Reaction Product Yield Calculations</b>                     | <b>42</b> |
| 5.2.1      | Proton Yield   | 43        |
| 5.2.2      | Helium-3 Current   | 43        |
| 5.2.3      | Concentration of Deuterium and the total Integrated Cross section      | 44        |
| 5.2.3.1    | Helium-3 Stopping-Power  | 44        |
| 5.2.3.2    | $^3\text{He(d,p)}^4\text{He}$ Reaction Cross sections                  | 46        |

---

|                |  |           |
|----------------|--|-----------|
| <b>5.3</b>     | <b>Fluorine-18 Yield</b>   | <b>46</b> |
| 5.3.1          | Useable Proton Current   | 47        |
| 5.3.2          | Helium3 and Proton Losses  | 48        |
| 5.3.3          | Concentration of Oxygen-18 and the Total Integrated Cross Section        | 49        |
| 5.3.4          | Proton Initial Energy Calculations                                       | 50        |
| 5.3.5          | Fluorine-18 yield calculation  | 56        |
| <b>5.4</b>     | <b>Deuterated Mylar Target</b>   | <b>57</b> |
| 5.4.1          | Sputtering   | 57        |
| 5.4.2          | Proton Attenuation   | 58        |
| 5.4.3          | Helium-3 and Proton Losses   | 59        |
| <b>5.5</b>     | <b>Super Heavy Water Target</b>  | <b>62</b> |
| 5.5.1          | Helium-3 and Proton Losses   | 63        |
| <b>6.</b>      | <b><i>Results and Discussion</i></b>                                     | <b>67</b> |
| <b>6.1</b>     | <b>Deuterated Target</b>   | <b>67</b> |
| 6.1.1          | Replacing Mylar with Plexiglas   | 69        |
| 6.1.2          | Target Degradation   | 71        |
| 6.1.3          | Effect of Unwanted Nuclear Reactions in the Deuterated Target system     | 73        |
| <b>6.2</b>     | <b>Super Heavy Water Target</b>  | <b>74</b> |
| 6.2.1          | Target Degradation   | 76        |
| 6.2.2          | Effect of Unwanted Nuclear Reactions in the Super-Heavy-Water System     | 77        |
| <b>6.3</b>     | <b>Issues common to both the Deuterated target and Super Heavy Water</b> |           |
| <b>Designs</b> |  | <b>78</b> |
| 6.3.1          | Radiation Protection   | 78        |
| 6.3.2          | Shielding  | 79        |
| <b>7.</b>      | <b><i>Conclusions</i></b>  | <b>81</b> |
| <b>8.</b>      | <b><i>References</i></b>   | <b>83</b> |

---

# 1. Abstract

Fluoro-deoxyglucose (FDG) labeled with fluorine-18 is commonly used in positron emission tomography (PET) imaging. PET imaging is a powerful tool used primarily in the diagnosis and management of cancer. The growth of PET has been limited partly by the difficulties associated in producing fluorine-18. This project involves a theoretical investigation of a novel method of producing fluorine-18 utilising proton generation via the  $^3\text{He}(\text{d},\text{p})^4\text{He}$  nuclear reaction.

Currently the most common method of producing fluorine-18 for PET is with a medical cyclotron that accelerates protons to mega-voltage energies. These protons are then directed onto a target rich in oxygen-18. This initiates the  $^{18}\text{O}(\text{p},\text{n})^{18}\text{F}$  reaction to produce fluorine-18. The  $^3\text{He}(\text{d},\text{p})^4\text{He}$  reaction, utilized for the present study, has a Q-value of 18.35 MeV and this results in protons being produced at energies similar to that produced in a medical cyclotron. This reaction was investigated as an alternative proton source for the  $^{18}\text{O}(\text{p},\text{n})^{18}\text{F}$  reaction. The expected advantage of this method over the cyclotron is that particles need only be accelerated to keV energies rather than the tens of MeV that a medical cyclotron accelerates protons to. This is expected to significantly reduce the cost and associated size of the system.

Two systems based on the  $^3\text{He}(\text{d},\text{p})^4\text{He}$  reaction were designed and calculations were performed to determine the respective yields of fluorine-18. The first system involved separate targets for the  $^3\text{He}(\text{d},\text{p})^4\text{He}$  and  $^{18}\text{O}(\text{p},\text{n})^{18}\text{F}$  reactions. Helium-3 ions are initially fired onto a deuterated plastic target. A heavy-water ( $\text{H}_2\text{O}^{18}$ ) target is placed immediately behind this plastic target to absorb mega-voltage protons produced by the reaction  $^3\text{He}(\text{d},\text{p})^4\text{He}$  in the plastic. The second system involved a single, super heavy water ( $\text{D}_2\text{O}^{18}$ ) target onto which helium-3 is fired so that both the  $^3\text{He}(\text{d},\text{p})^4\text{He}$  and  $^{18}\text{O}(\text{p},\text{n})^{18}\text{F}$  reactions can occur concurrently in the one target.

The input parameters of energy and beam current for the helium-3 beam required for the  $^3\text{He}(\text{d},\text{p})^4\text{He}$  reaction were selected on the basis of the performance

---

of currently available ion sources and in particular the saddle-field ion source. Practical considerations such as radiation safety, target degradation and lifetime and ultra high vacuum (UHV) issues were also investigated to further determine the feasibility of the two systems.

With the beam current and energy at the extreme limits of the saddle-field ion source it was calculated that insufficient fluorine-18 could be produced daily to supply a PET facility with FDG. It was also found that the high helium-3 beam currents and energy required to produce significant amounts of fluorine-18 resulted in prohibitive temperature rises in the targets that would likely result in target vaporization.