# An Introduction to the Physics of Nuclear Medicine

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**Laura Harkness-Brennan**
*University of Liverpool*

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*I dedicate this book to mum and Rachel.*

# Contents

# Preface

The complexity and vulnerability of the human body has driven the development of a diverse range of diagnostic and therapeutic techniques in modern medicine. The nuclear medicine procedures of positron emission tomography (PET), single photon emission computed tomography (SPECT) and radionuclide therapy are well-established in clinical practice and are founded upon the principles of radiation physics. This book will offer an insight into the physics of nuclear medicine by explaining the principles of radioactivity, how radionuclides are produced and administered as radiopharmaceuticals to the body and how radiation can be detected and used to produce images for diagnosis. The treatment of diseases such as thyroid cancer, hyperthyroidism and lymphoma by radionuclide therapy will also be explored.

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# Author biography

## Laura Harkness-Brennan

Dr Laura Harkness-Brennan is a Senior Lecturer in the Department of Physics at the University of Liverpool. She completed her PhD in 2010, which was a design study of the ProSPECTus Compton camera for nuclear medicine. In the same year, she also received the Shell and Institute of Physics Women in Physics Very Early Career Award. She now leads a team of researchers developing novel radiation detection and imaging techniques for medical physics and nuclear structure physics experiments. She has been a principal or co-investigator on over £5.3 million of external grant funding for this research. Laura teaches undergraduate and postgraduate courses in medical physics and nuclear instrumentation. She is a member of the Institute of Physics and a fellow of the Higher Education Academy. She is passionate about contributing to the public understanding of physics by engaging in outreach activities such as public lectures and family science days.

**Laura Harkness-Brennan**

# Chapter 1

## Introduction

Procedures that involve the production and administration of radionuclides to the body for either diagnostic or therapeutic purposes fall under the remit of *nuclear medicine*. This chapter will provide a revision of the building blocks of matter and their interactions, which is necessary to understand the topics discussed in later chapters. A brief overview of nuclear medicine will also be given.

### 1.1 Building blocks of matter

The building blocks of matter are illustrated in figure 1.1. Understanding the characteristics of these is important because the physical and chemical properties of all types of matter are determined by its constituents. All substances are made of *elements*, such as oxygen, sodium and lithium. The periodic table of the elements is shown in figure 1.2. Example elements that are of particular interest in nuclear medicine have been highlighted in yellow and will be referred to using their chemical symbols throughout the book. A list of these chemical elements and their symbols can be found in Appendix A. An *atom* is the smallest amount of the element to retain its chemical properties. The diameter of an atom is approximately 0.1 nm ($1 \times 10^{-10}$ m), which is a million times smaller than a single grain of fine sand. When at least two atoms of at least one element are present, they may be chemically bound together as *molecules*. One of the most essential molecules found on Earth is water, for which each molecule contains two hydrogen atoms and one oxygen atom, $H_2O$. Biological molecules of interest in nuclear medicine are usually constructed from various combinations of hydrogen, carbon and oxygen atoms.

An atom is composed of a positively charged *nucleus* and negatively charged *electrons*. The nucleus is formed from *protons* and *neutrons*, which together are known as *nucleons*. The total atomic and nuclear composition can be described by $^{A}_{Z}X_{N}$, where the *mass number, A*, is the total number of nucleons and the *atomic number, Z*, is given by the number of protons. The atomic number defines the type of chemical element, $X$. Nucleons are each composed of three quarks, which are the

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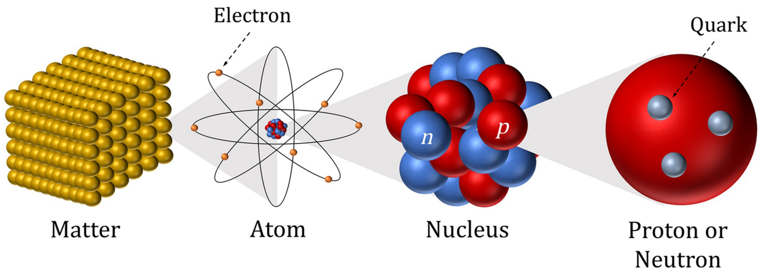


**Figure 1.1.** Illustration of the building blocks of matter.

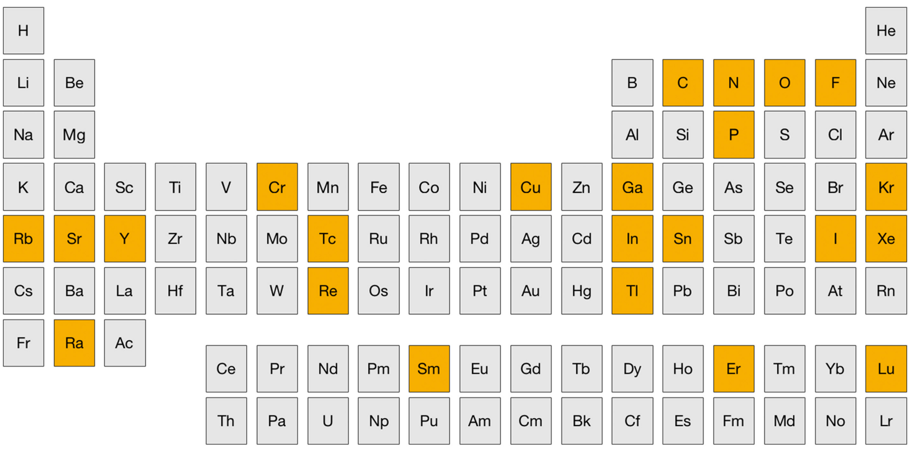


**Figure 1.2.** Periodic table of the elements, ordered by atomic number and grouped according to chemical properties. Example elements that have radioisotopes used in nuclear medicine are highlighted in yellow.

fundamental constituents. One of the most important particles in nuclear medicine is the *positron*, as it is released by radionuclides used in the diagnostic imaging procedure *positron emission tomography*. A positron is the *anti-particle* of an electron and as such has the same mass but an equal and opposite charge. A particle and anti-particle pair have the important property that they *annihilate* each other, producing energy. This is an example of matter-to-energy conversion, which is described by one of the most famous equations in physics, Einstein's equation, $E = mc^2$. In the annihilation of an electron and positron, $1.64 \times 10^{-13}$ Joules of energy is released. This energy can be more conveniently expressed as 1.022 MeV. The properties of protons, neutrons, electrons and positrons are given in table 1.1. As can be seen in the table, mass may be expressed in units of MeV $c^{-2}$, courtesy of $E = mc^2$.

## 1.2 Fundamental forces

Nature is governed by the four fundamental forces: *strong; electromagnetic; weak and gravitational*. Although all forces will play a role in nuclear medicine, it is the

**Table 1.1** Properties of particles relevant to nuclear medicine.

| Name | Symbol | Charge (C) | Mass (kg) | Mass (MeV $c^{-2}$) |
|---|---|---|---|---|
| Proton | p | $+1.6 \times 10^{-19}$ | $1.6726 \times 10^{-27}$ | 938.28 |
| Neutron | n | 0 | $1.6749 \times 10^{-27}$ | 939.57 |
| Electron | $e^-$ | $-1.6 \times 10^{-19}$ | $9.1094 \times 10^{-31}$ | 0.511 |
| Positron | $e^+$ | $+1.6 \times 10^{-19}$ | $9.1094 \times 10^{-31}$ | 0.511 |

first three that will be the most important, particularly in the discussion of radioactive decay processes:

**Strong force:** acts only on particles that are made from quarks, such as protons and neutrons. It is known as the *strong nuclear force* because it is responsible for binding together the nucleons within a nucleus. It is the strongest of the four forces (a relative strength of 1 in what follows) but acts only over a short range.

**Electromagnetic force:** acts on all electrically charged particles, with infinite range. It has a relative strength $\approx 10^{-2}$.

**Weak force:** acts on all particles but with an extremely short range. It has a relative strength $\approx 10^{-5}$. It is responsible for beta decay, which is an important radioactive decay process in nuclear medicine.

**Gravitational force:** acts on all particles, with infinite range. At the atomic scale, it is the weakest interaction, with a relative strength $\approx 10^{-39}$. It is important for large masses and is responsible for binding together the solar system.

## 1.3 Overview of nuclear medicine

Nuclear medicine is exclusively dedicated to administering radionuclides to patients for the purpose of diagnosis or therapy. In these procedures, radioisotopes are attached to a biological compound, which together form a *radiopharmaceutical* that accumulates in the body depending on its biokinetic response. This relies on the dedicated production of radionuclides for medicine, since naturally occurring radioactive materials do not undergo radioactive decay quickly enough. The imaging methods used for diagnosis are *single photon emission computed tomography (SPECT)* and *positron emission tomography (PET)*. The methods used to produce the images are slightly different but the underlying principles are the same. Photons are emitted, either directly from the radiopharmaceutical (SPECT), or following positron annihilation with an electron (PET) in the organ of interest. The photons interact in a radiation detector system surrounding the patient, which is used to locate and visualise the distribution of the radiopharmaceutical. The generated images are used to elucidate disease status, particularly in oncology, neurology and cardiology.

The treatment of diseases such as hyperthyroidism, neuroendocrine tumours and non-Hodgkin lymphoma by *radionuclide therapy* using radioactive sources is also an important aspect of nuclear medicine. This employs the same principle of the uptake

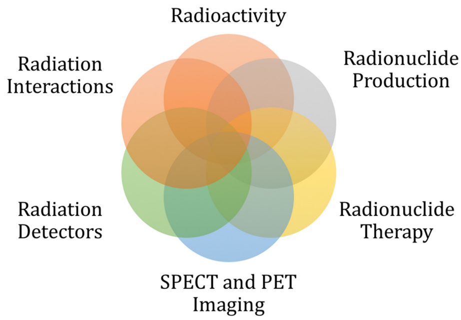


**Figure 1.3.** Overview of the foundations of nuclear medicine.

of the radiopharmaceutical to regions of interest in the body, such as within a highly-metabolic tumour. However, the objective of radionuclide therapy is to deliver lethal radiation doses to targeted tissue whilst minimising the dose to the surrounding tissue. This is achieved by using radionuclides that emit charged particles, since they will only travel up to a few millimetres in the tissue, which confines the region over which dose is delivered.

The physical principles of these diagnostic and therapeutic procedures will be discussed in detail in this book. However, the foundations will first be provided, which are an introduction to radioactivity, methods used to synthesise radionuclides, radiation interactions with matter and the detection of radiation. Understanding all of these topics is essential to appreciate the clinical application, as indicated by figure 1.3. We will begin with a short history of nuclear medicine.