A Handbook of Nuclear Applications in Humans' Lives

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By

Farshid Tabbakh

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This book first published 2020

Cambridge Scholars Publishing

Lady Stephenson Library, Newcastle upon Tyne, NE6 2PA, UK

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

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ISBN (10): 1-5275-4336-6
ISBN (13): 978-1-5275-4336-2

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PREFACE TO THIS BOOK

Despite the increasing number of nuclear technology applications in today's world, viewpoints among people about nuclear technology and its significant contribution to building a modern society are very limited. For most people, Einstein's formula, $E=MC^2$ reminds them of the nuclear bomb; but, how many know that $E=MC^2$ also explains the mechanism of BNCT in cancer therapy or nuclear-generated electricity, both of which have raised the general level of comfort and health. It also explains the unlimited energy of the stars (fusion energy), which produces the cleanest, unlimited source of energy for humans. Fusion energy has been extracted at the laboratory level, driving several useful processes and applications. Another nuclear concept that needs to be introduced is radioactivity as a life-saving material. Radioactivity has saved many lives through smoke detectors and can play an important role in earthquake prediction too. These are just two of the countless examples of the positive role of radioactivity in human life, which can hopefully change the public perception of these concepts.

Radiation techniques have made a most significant contribution to human health and it is interesting to note that 12 of 15 Nobel prizes in medicine were awarded for radiation techniques. We can also point to nuclear techniques in agriculture increasing the amount of healthy food and reducing the number of hungry people on earth.

It is obvious that upgrading public knowledge and viewpoints about using nuclear techniques will lead to significant improvements in the economy of every society. For example, the establishment of electron irradiation facilities not only provides several utilities for the industrial, medical and environmental fields, but also has considerable social and economic results. To make electron beam usage more popular requires public knowledge enhancement. People should be informed that electron accelerators can improve the health and freshness of food and agricultural products; and can be used in contaminated and waste water treatments, pollutant removal, polymer modification and medicine. This information is important for people, especially for decision makers in developing countries, and has been collected here in this book. This book attempts to introduce a wide range of nuclear applications in almost all possible fields so as to increase public knowledge, especially among younger people and students, to develop a better view of nuclear science and its applications.

This book contains three chapters, with relevant introductions, which have been organized as follows.

Chapter 1 comprehensively describes nuclear concepts, phenomena and facilities, including their principles and corresponding applications in modern life. This chapter may be studied separately with the aim of introducing nuclear and radiation techniques and their uses.

Then, medical and non-medical applications are explained in chapters 2 and 3 respectively. In chapter 2, medical applications have been divided to into two parts: diagnostic and therapeutic.

In chapter 3, applications in non-medical fields have been introduced, including those for the environment, agriculture, farm animals, food, geophysics, industry, security, forensics, archaeology, cultural heritage and art. References relevant to each subject can be found at the end of the book.

It should be emphasized that while an attempt has been made to include all major nuclear techniques and applications, due to the wide range of applications and the fast growth of nuclear techniques, it is possible that some are not mentioned.

CHAPTER ONE

NUCLEAR CONCEPTS, TECHNIQUES AND DEVICES

Introduction

This chapter offers a relatively complete collection of all necessary information about peaceful nuclear technology and its impacts on modern society. Nuclear concepts, devices and techniques are countless, but this chapter highlights those items with applications in everyday life. As an example, there are various particles and sub-particles, and different types of nuclear reactors, radiation detectors, particle accelerators and plasma devices used in pure science and research, but those with applications in human society are described in this chapter.

Before introducing and explaining relevant nuclear techniques, methods and applications, there are a few important concepts that need to be explained. As such, before introducing the techniques, devices and applications, in this chapter a number of frequently used nuclear terms are explained—these are concepts like energy units, irradiation, particles, and isotopes, as well as the famous expression $E=MC^2$, which is considered one of the essential nuclear concepts in terms of its human applications.

Since nuclear devices and facilities are used in a wide range of fields of study, in this chapter the principles of these systems are explained as simply as possible to give some background to those who are not very familiar with physics and the relevant principles. For example nuclear research reactors, synchrotron accelerators, plasma and nuclear modalities have relatively complicated structures and physics, but to understand their importance in industry and medicine, it is necessary to give some background about their operational principles first.

In this chapter, energy units, $E=MC^2$, irradiation and isotope concepts are described first. Then, particles, X-rays, gamma rays and radioisotopes are introduced, emphasizing their corresponding applications. A relatively complete list of radioisotopes and their area of usage can be found in this chapter. Plasma devices, fission and fusion reactors and particle accelerators (those with great importance in life) are introduced along with their uses. Tomographic techniques, nondestructive tests (NDT) and spectroscopy methods are also mentioned along with their applications. Two interesting nuclear techniques used in historical dating and astronomy are presented in the final part of this chapter.

As this chapter aims to include all possible nuclear techniques and applied concepts, including their principles, physics and applications, it can be studied separately.

As was pointed out in the PREFACE, though an attempt was made to introduce and describe all current nuclear techniques, along with their applications, due to the fast growth in nuclear applications in every field, it is difficult to include all of them in one book.

The complete contents of chapter 1 are presented on the next page.

The Complete Contents of Chapter One

Energy Units

$E=MC^2$ and its applications

Irradiation

Isotope

Particles, isotopes and photons

- Alpha particles (α) and applications
- Beta particles ($\beta^{\pm}$) and applications
- Deuteron particles (d^+) and applications
- Electron particles (e) and applications
  - Electron irradiation centre and applications
  - Transmission electron microscope (TEM) and applications
  - Electron back-scattered diffraction (EBSD) and applications
  - Scanning electron microscope (SEM) and applications
- Neutron particle (n) and applications
  - Neutron imaging and applications
  - Neutron therapy
  - Neutron activation analysis (NAA) and applications
  - Neutron diffraction and scattering applications
  - Neutron fluorescence and applications
- Proton particle (p) and applications
  - Proton Therapy
  - Proton Computed Tomography (pCT)
  - Proton Radiography
  - Proton Induced X-ray Emission (PIXE) Spectroscopy
  - Isotope Production
- Radioactive isotope/radioisotope/radionuclide
  - Radiotracers and applications
  - Nuclear batteries and applications
- X-ray and applications
  - X-ray diffraction (XRD) and applications
  - X-ray fluorescence (XRF) and applications
  - Compton scattering and applications
  - Compton backscattering and applications
- Gamma rays and applications
  - Gamma irradiation centres and applications
  - Gamma knife and applications

Plasma and applications

- ↘ Dense plasma focus (DPF) and application
- ↘ Inductively coupled plasma (ICP) torch and application
- ↘ Microwave plasma torch and application
- ↘ Arc discharge plasma torch and application
- ↘ Atmospheric pressure plasma jet and application
- ↘ Dielectric barrier discharge (DBD) and applications
- ↘ Corona discharge and applications

Fission reactions and fission reactors

- ↘ Nuclear power reactors and applications
- ↘ Nuclear research reactors and applications
  - ↘ Neutron activation analysis (NAA)
  - ↘ Radioisotope production
  - ↘ Boron neutron capture therapy (BNCT)
  - ↘ Geochronology
  - ↘ Semiconductor doping
  - ↘ Gemstone colouring
  - ↘ Neutron radiography
  - ↘ Material structure and dynamics
  - ↘ Positron sources
  - ↘ Testing
  - ↘ Gamma irradiation of plants and seeds
  - ↘ Nuclear validations
  - ↘ Evaluation of radioisotope production
  - ↘ Training

Fusion reaction and fusion reactors

Particle accelerators

- ↘ Van de Graaff
- ↘ Cyclotron (ion accelerator) and applications
- ↘ Electron accelerator and applications
- ↘ Linear accelerator (LINAC)
- ↘ Synchrotron and applications

Tomography

- ↘ Magnetic resonance imaging (MRI) and applications
- ↘ Positron emission tomography (PET) and applications
- ↘ Computed tomography (CT) and applications
- ↘ Single photon emission computed tomography(SPECT)

Non-destructive tests (NDT) and applications

- Nuclear magnetic resonance (NMR)
- X-ray radiography and tomography
- Gamma ray radiography
- Synchrotron radiation
- Radiotracers
- Neutron radiography
- Proton radiography
- Electron transmission
- Nuclear resonance fluorescence (NRF)

Spectroscopy

- Transmission electron microscopy (TEM)
- Nuclear magnetic resonance (NMR)
- X-ray fluorescence (XRF)
- Gamma spectroscopy
- Mass spectroscopy
- X-ray photoelectron spectroscopy (XPS)

Nuclear dating

- Carbon-14 dating
- Radiometric dating

Nuclear astrophysics

Energy Units

In nuclear physics, the joule (J) is the SI unit of energy and the electron volt (eV) is also used as a non-SI unit of energy. Note the following equation:

1 (eV) = 1.602×10^{-19} (J)

In this book (as with other scientific books and papers in atomic and nuclear physics) the energy of particles both from accelerators or emitted from radioactive material are expressed in electron volts, which is defined as the energy obtained by an electron in a potential difference of 1 volt at a distance of 1 m. The energy units keV, MeV and GeV, which are frequently used in this book, are defined as follow;

1 keV = 1,000 eV

1 MeV = 1,000,000 eV

1 GeV = 1,000,000,000 eV

When talking about radiation safety and the effects of radiation on tissue, the absorbed radiation dose is defined as the energy (in joules) deposited in a unit mass of tissue, and is measured in grays (Gy). The gray is used in medical applications and the irradiation of food and agricultural products.

$E=MC^2$

$E=MC^2$ explains nuclear power. The nuclear energy released during fission or fusion reactions can be calculated by this formula, which was described by Einstein in 1932. When a heavy nucleus is divided into two lighter ones (fission fragments), the sum of the produced masses is smaller than the mass of the initial nucleus. This small, lost mass has been converted into energy and its value can be calculated according to $E=MC^2$. Also, in fusion reactions, there is a small amount of mass that is converted into energy because the two light nuclides fuse into a heavier nuclide, but the sum of the initial masses (before fusion) are more than the mass of the produced nuclide. Electricity generation; nuclear heat generation in cold countries; high pressure stream used in oil resources; and nuclear submarines all involve direct use of this formula, but obtaining energy from mass conversion in the form of neutron particles can also be found in many other useful reactions that indirectly use this formula. Boron neutron capture therapy (BNCT), which releases energetic alpha particles to treat tumors, and neutron generators from D-D fusion, which have several applications in medicine and industry, are examples of applications of mass to energy conversion.

Irradiation

Irradiation involves exposing various materials, the body, food and so on, to ionizing radiation: energetic electrons and other charged particles constitute directly ionizing radiation, while neutrons, X-rays and gamma rays are indirectly ionizing radiation. Irradiation can cause molecular links to fracture. Ionization radiation damages the DNA of cells (either directly or indirectly) through the formation of free radicals and reactive oxygen species. The irradiation process has many applications. Irradiation can be used as a catalyst in chemical reactions. Ionized molecules may initiate processes that can be used to form new substances. This method has been utilized for the industrial production of ethyl bromide, which is a volatile liquid used in the synthesis of organic materials. Matter may also be irradiated to modify its behavior or to induce beneficial properties. The molecules simply reform, realign or recombine in an altered format. For example, polyethylene molecules can be made to 'crosslink', giving the material the ability to stretch without breaking (see crosslinking in this chapter). This material is used as transparent packaging for food and other products.

The precisely structured molecules essential to life do not benefit from irradiation. The changes introduced may not only disrupt the life form, they may also cause its death. This provides irradiators with some of their most beneficial and commercially important applications: the preservation of food stuffs and the sterilization of medical supplies. The bacteria and other life forms that infect and infest these products may be destroyed by irradiation. Substances, such as human and animal waste, can also be sterilized by irradiation. In the following sections, irradiation facilities with electrons and gamma rays have been described in detail with their applications in many aspects of life.

Isotopes

Another important and frequently used concept in nuclear physics is that of the different isotopes of a nucleus. The nucleus of atoms contains neutrons and protons. The number of protons in each atomic nucleus is permanent and defines the atomic number of the element. For example, the atomic numbers of hydrogen and oxygen are 1 and 8 respectively. This means that there is 1 proton in a hydrogen nucleus and there are 8 protons in an oxygen nucleus. Another nucleon in atomic nuclei is the neutron and the number of neutrons for one atomic nucleus is variable. According to the different numbers of neutrons in a nucleus (while the protons are stationary) different numbers of isotopes can be found for that nucleus or element. The isotopes of an element have the same chemical properties, but differ in their nuclear properties.

Some isotopes exist naturally (some radioactive and some stable) and some isotopes can only be made artificially. Later on in this book, unstable isotopes, different types of isotopes, different production techniques and different applications are introduced.

Particles, Radioisotopes, X-rays and Gamma Rays

When talking about particles in nuclear physics, it may come to mind that particles are only parts of the atom and have little to do with human life. Particles have more than a purely physical importance and they have applicable uses in everyday life. In this section, the following particles are defined and their applications are mentioned. Then the nuclear techniques, methods, and devices relevant to these applications are introduced. The particles referred to in this book include: alpha, beta (β^- and β^+or positron), deuteron, electron, neutron and proton.

It is necessary to emphasize that although there is no difference between an electron particle and a beta- particle, electrons have an atomic origin (orbital electrons of atoms) and can be produced from filaments (see X-ray tube in this chapter), while beta- particles have a nucleic origin and are released by the mechanism of nuclear decay. Accordingly, due to the different origins of these two particles, they have different applications and are therefore introduced separately in this book. X-rays and gamma rays are introduced, including their origins and various applications. Then radioisotopes, including their types, production methods and applications, such as nuclear batteries and radiotracers, are comprehensively described in the related subsections.

Proton Particle (p)

A fundamental particle with a positive charge located in the nuclei of atoms and with a mass of (1.6726231×10^{-27} Kg). The electrical charge of a proton is (1.60217733×10^{-19} C). The number of protons in an atom's nucleus (called the atomic number) determines the element. The proton was discovered by Rutherford in 1906. Free protons in the form of an accelerated beam can induce important nuclear reactions for isotope production. For example, fluorine-18 (F-18) used in PET imaging can be produced through proton bombardment of oxygen-18 to form the reaction: O-18 (P, n) F-18. The proton must have enough energy to induce this reaction.

Applications of protons

- Proton therapy (also see chapter 2)
- Proton computed tomography (pCT)
- Proton radiography
- Proton induced X-ray emission (PIXE) spectroscopy
- Isotope production using a cyclotron accelerator for medical imaging modalities, like PET and SPECT (see radioisotopes in this chapter)

Radioisotope production using proton particles is explained in the sections on cyclotron accelerators and radioisotopes. Proton applications in therapy, tomography, radiography and proton induced X-ray emission are introduced in the following.

Proton Therapy (Hadron Therapy)

The aim of proton therapy is to deliver high doses of ionizing radiation in the form of energetic protons to tumors, similar to other conventional nuclear methods using photons (X-rays) and alpha particles etc. (introduced in this chapter). The first clinical test was achieved in 1954. In proton therapy, the incident proton beam will rapidly lose energy in tumor cells with limited affect on normal tissue in comparison to treatments using photons (such as a gamma knife). Also, protons can be easily focused in a magnetic field, whereas photons and neutrons are not able to be focused. This makes proton therapy a useful radiotherapy method for cancer treatment to any depth in a patient due to its high penetration, focusable beam, high energy deposition into tumors and minimized side effects from scattering. Accordingly, it is suitable for treating small tumors and also for treating children because it causes limited damage to normal cells surrounding the tumor. Lung, prostate, brain, liver, breast, head and neck, etc. can all be treated by proton beam therapy.

Cyclotrons and synchrotrons are the two main facilities that deliver collimated proton beams in therapeutic applications. CT is one of the modalities used for tumor tomography and electron density measurement that is important for proton therapy and radiation dose calculation because the protons will directly interact with orbital electrons to finally stop. In the proton therapy process, the protons must stop and deliver their entire energy to the tumor. CT information and related analysis by means of the Bragg peak concept leads to precise calculations and planning to ensure efficient proton beam delivery.

Due to the production of secondary radiation from the interaction of protons with matter, such as gamma rays and neutrons, it is necessary to protect the patient and equipment in proton delivering facilities using properly designed shields.

Proton Computed Tomography (pCT)

Proton computed tomography (pCT) is a diagnostic imaging modality with benefits for proton therapy. As mentioned above, X-ray CT is used to construct an image of a tumor identified for proton treatment, but this leads to errors in predicting the proton stopping range in tissue and is thus not sufficiently accurate for planning proton therapy. As such, using protons instead of X-rays for diagnosis and imaging was suggested in the late 1970s by Ken Hanson. pCT is used to construct an accurate electron density map for therapeutic purposes by measuring the energy loss of high energy protons as they pass through the body in several directions. The machine rotates around the object while silicon trackers are used to study proton trajectories; the residual energy of the proton beam is measured using a calorimeter.

Proton Radiography

Proton radiography is like X-ray radiography in some respects. The protons that pass through the object under study will lose energy and may be absorbed or scattered by the coulomb forces from the nuclei of the object, depending on its material properties such as atomic number, electron configuration and density. To form the image, the emergent beam passes through a series of magnetic lenses to focus the beam and form the image. A magnetic lens is a coil with an electric current that produces a magnetic field around the coil area (in and out). These magnetic fields are able to bend the passing charged particles and a divergent beam when passing through this area will be converged and focused, like an optical lens focusing a light beam.

The protons that pass through the objects (not scattered or absorbed) emerge from the object and form an image on the image plate located after the magnetic lenses.

As mentioned previously, material properties, like atomic number and density, can affect a proton's passage through the material, meaning that both the material's amount and type can be studied simultaneously.

Protons are ideal probing particles as they can be detected with 100% efficiency and with multiple time detection. This is useful for rapid multiple time radiography for advanced hydrotest facilities and thick object (metal) radiography, neither of which are not possible with X-ray radiography.

Proton Induced X-ray Emission (PIXE) Spectroscopy

Spectroscopy using X-rays is an atomic spectroscopic technique induced by protons. It is used for minor element analysis in different complex matrices applicable to metallurgy and environmental studies. In this technique, a low energy proton (from a Van de Graaff accelerator) is emitted towards the target (sample) and the spectrum of the generated characteristic X-ray can be detected by a semiconductor detector, which measures the concentration of the elements in the sample. Interdisciplinary problems from fields including environmental studies, material studies, biology, biomedicine, archaeology and geology can be completed using neutron activation analysis.

Neutron Particle

A neutron is an elementary particle with no electric charge (neutral) and a mass of $1.6749286 \times 10^{-27}$ kg. Its mass is 2.5 electron masses heavier than a proton particle. The neutron was discovered by Sir James Chadwick in 1932. Except for the nucleus of hydrogen, which has a single nucleon (one proton), neutrons exist in all atomic nuclei. The hydrogen isotopes, deuterium and tritium, have one and two neutrons respectively. The difference in the neutron number in a nucleus defines the different isotopes of a single element. Neutrons play very important roles in nuclear reactions and applications.

Neutron energy classification

Thermal neutrons: these are neutrons in thermal equilibrium with the surrounding medium. Thermal neutrons have an energy of about 0.025 eV at room temperature (25°C).

Epithermal neutrons: these are neutrons with energy in the keV region.

Fast neutrons: fast neutrons are neutrons with high energy (above 1 MeV).

Neutron sources

Fission reactions: fission reactions produced in nuclear reactors are one of the primary sources of thermal and epithermal neutrons (see fission reaction in this chapter).

Fusion reactions: fusion reactions are the source of fast neutrons using fusion reactors such as TOKAMAK, dense plasma focus (DPF) devices (see fusion reaction in this chapter) and neutron generator devices. The neutron generator is a deuteron (deuterium ion) accelerator in which the accelerated deuterons strike a deuterated target (a composition of deuterium) and the induced D-D fusion reactions lead to fast neutron generation.

Radioisotope: alpha emitter radioisotopes like Cf-252, Am-241, Pu-238, Po-210 and Ra-226 combined with beryllium also produce neutrons and are called alpha-neutron sources. A gamma-neutron source is also possible by using H-2 or Be-9 under gamma ray irradiation. Another neutron source is based on the spontaneous fission of radioisotopes, like Cf-252, Pu-238 and Cm-242.

Photonuclear interaction: the bombardment of certain targets, like beryllium and deuterium, by gamma rays with energy of more than 2 MeV can generate neutrons through photonuclear interactions.

Accelerators (spallation): except for deuteron acceleration (described above), the proton bombardment of certain targets is able to generate neutrons. This is called spallation.

Neutrons interact with matter through the mechanisms of elastic scattering (with no energy transfer to the nucleus), inelastic scattering (partial energy transfer) or capture (captured by the nucleus). Neutrons are not a form of directly ionizing radiation because they do not interact with orbital electrons. Neutron-based applications can be found in imaging, medicine and industry, as detailed below.

Applications of neutrons

- Neutron activation analysis (NAA)
- Neutron energy deposition used in TOKAMAK (ITER) as a source of thermal energy
- Neutron radiography and imaging
- Neutron diffractometer
- Neutron spectroscopy
- Neutron therapy (by both thermal and fast neutrons)
- Neutron resonance fluorescence

These applications are explained, including the area in which they are used, in the following sections.

Neutron Activation Analysis (NAA)

The activation of an unknown sample by neutron irradiation in a nuclear research reactor allows us to obtain information about the microelements in the sample by detecting the characteristic induced radiations and gamma rays from atomic excitation (see nuclear fission in this chapter).

The age of an oil painting can be determined using NAA by measurement of Ra-226, Pb-210 and Po-210. NAA can allow material composition determination and microelement determination in metals; inorganic compounds; animal and plant tissues; soil, water and the surrounding environment; and medicine. It is also used in forensic studies, for example in the analysis of bullets fired from a gun.

Neutron Radiography, Imaging and Tomography

Radiography is an imaging technique using forms of radiation like X-rays, gamma rays and neutrons, etc. Neutron radiography is a promising technique in industrial non-destructive testing (NDT) and security inspections. Both thermal and fast neutrons are employed in different methods of neutron radiography. While, X-ray imaging and radiography has been used mostly for objects made of heavy elements, neutron radiography is suitable for imaging materials containing low weight elements like hydrogen. X-ray radiography cannot detect hydrogen compounds like polymers, explosive materials and so on. Therefore, neutron imaging techniques can provide information that is impossible to get through X-ray imaging. Since most neutron interactions are with lower weight nuclei (with masses near to the neutron's own), radiographic images obtained by neutron irradiation can show low weight elements precisely, including polymers, hydrocarbon materials and explosives. Another advantage of neutron radiography is in the investigation of materials inside lead containers without opening them—neutrons have limited interaction with lead atoms and can pass through such containers, while X-rays will be stopped by the lead walls. The scientific, industrial, agricultural, artistic, security and medical applications of neutron radiography are introduced in the following.

Applications of neutron radiography, imaging and tomography

- Investigation of the interiors of wood and soil for moisture analysis (hydrogen detection)
- Research into rock formations, geological transport processes, minerals and soil assemblies
- Non-destructive testing of nuclear fuel elements and quality control
- Investigating the inside of metallic archaeological objects to understand historical techniques in metallurgy, precisely study the internal parts and also to improve preservation techniques
- Neutron radiography has been used in art and painting. For example, Rembrandt's oil paintings have been investigated using neutron radiography to make visible the underlying structures and assess signature reliability
- Neutron tomography of living things. The dose rate absorption for humans is high-risk and dangerous
- Fossil examination in archaeology
- Non-destructive mechanical engineering testing

- Non-destructive testing of the internal structure of electronic contacts
- Welding imaging and alloy investigation in materials research
- Explosive materials and drug detection in cargo
- Imaging of plants in plant science research

Thermal Neutron Therapy

Thermal neutrons can be used to induce certain reactions with injected boron in tumors to damage tumor cells. For a more detailed description, see the description of boron neutron capture therapy (BNCT) in applications of fission research reactors. Further explanation of BNCT is presented in chapter two.

Fast Neutron Therapy

A high energy proton accelerator can be used to produce fast neutrons. Neutrons can produce a higher dose than photons making for more efficient cancer therapy.

Neutron Diffraction and Scattering in Matter and Applications

Neutron beam scattering and diffraction by atoms can be used in a non-destructive process in modern material science to identify the magnetic structure and nuclear structure of materials. There are two methods.

Neuron diffraction: one technique utilizes a neutron scattering mechanism and diffraction measurement similar to that of X-ray diffraction (see XRD in this chapter) using Bragg's law and the neutron wave property. Due to the scale of the neutron's wavelength, which is similar to the spacing between the atoms and lattices, this particle is ideal as a method for material structure measurement. A neutron diffractometer (ND) has a number of advantages over an X-ray diffractometer (XRD): it does not depend on the atomic type (atomic number of the substances); it scatters strongly in the presence of hydrogen; and it has a high penetration depth. Neutron diffractometers are used in material science, crystallography, mineralogy, geochemistry, solid-state physics, biology and engineering

The diffractometer technique is used for measuring the distance between atoms in a crystalline sample in the range of a few angstroms (called wide angle diffraction); as well as precipitation, magnetic domains and macromolecules in solution at a larger scale (called small angle scattering) in the range of several hundred angstroms. Examples of small angle scattering in different fields include:

- Material science and polymers: atomic structures; stress-strain determination; phase separation in alloys or glasses; super-alloy morphology; ceramic microporosity; liquid crystals and gels.
- Biology: protein size and shape.
- Magnetism: correlations and domains or the flux line lattices in ferromagnetic superconductors.
- Geoscience: phase and texture analysis.
- Chemistry: new compound structure determination, time resolved reactions, etc.

The study of large scale structures by small angle scattering can be performed on surfaces, in thin film systems or multilayer systems by means of a neutron reflectometer, which measures the angle of the reflected neutrons from the layers or surfaces. It is used in:

- Material and polymer sciences: the study of crystal surfaces or polymer films; liquid-liquid interfaces, etc.
- Life sciences: biological membrane study
- Magnetism: thin film magnetism and magnetic data storage

Neutron spectroscopy: one can also use the properties of the neutron particle and the time-of-flight (TOF) technique to determine the kinetic energy of a neutron (velocity) through neutron spectroscopy. A neutron spectrometer measures a scattered neutron's velocity and thus its kinetic energy, which gives the dynamic structure of a system after determination of the structure using a diffractometer. Neutron spectroscopy can be used in many fields:

- Biology: studying the dynamics of gels, proteins and biological membranes.
- Material science: diffusion in superionic glasses; hydrogen-metal systems and ionic conductors; quantum liquids; crystal field splitting in magnetic areas; phonon density of states; phonon

dispersion in crystalline materials; spin wave dispersion; the dynamics of biological membranes; phase transition, etc.

- Chemistry: rotational tunneling in molecular crystals and vibrational states in solids.

As has been pointed out, these techniques have been used in many scientific fields including: fundamental physics; clean energy and environmental studies; pharmaceuticals; nanotechnology; material engineering and so on. It should also be mentioned again that neutrons have a more significant penetration depth than X-ray photons.

Applications of neutron diffraction and scattering in matter

- Magnetic excitation and magnetic order
- Heritage science: the significant penetration of neutrons into material has allowed them to be non-destructively used in understanding heritage and museum artefacts and fossils better. For example, the period and place of a ceramic fragment can be determined by studying its crystalline structure.
- Polymer research: neutrons can identify the structure of polymers and anti-reflective coatings; studying specific parts of complex molecular systems.
- Identifying the accurate structure of pharmaceutical compounds.
- Studying material structure and condensed-matter.
- Investigating and testing a material's strength.
- Anisotropy and quantum effects in solids and testing safety performance and stress-strain analysis (residual stress) of certain materials (at a depth that is not possible with XRD), such as components for nuclear reactors and aircrafts.
- Bioscience studies: studying antibody structures; studying the interaction of active parts of medicines with lipids and proteins and proteins and other macromolecules, etc.
- As hydrogen molecules display the largest scattering with neutrons, neutron scattering can provide information about the diffusion of hydrogen in metals used in fuel cells and hydrogen storage systems.
- Using neutron scattering in catalysis and the petrochemical industry.
- Neutron scattering in studying condensed noble gases, metals, superfluid mixtures and molecular hydrogen and deuterium.

Alpha Particle (α)

The alpha particle is the same as the nucleus of helium. It is a positively charged particle consisting of two protons and two neutrons. As such, its electrical charge is twice that of a proton and it has a mass four times bigger than a proton or a neutron. Its electrical charge is (3.20435466×10^{-19} C) and its rest mass is (6.6951034×10^{-27} Kg). Some radioactive isotopes are alpha emitters, such as Am-241 and radium-226. Alpha particles played an important role in Rutherford's famous experiment examining atomic structure. It also creates excitation along its path, which will cause X-rays to be emitted from an excited atom.

Since alpha particles are relatively heavy compared to other particles, they can create more ionization in matter at a shorter distance and deposit a considerable amount of energy in the form of heat inside a target. This characteristic of alpha particles has allowed it to be used in cancer therapy to effectively damage cancer cells. For example, in boron-neutron-capture-therapy (BNCT) alpha particles will be produced from incident thermal neutrons that damage tumor cells, or through injecting Ra-226 (an alpha emitter) directly into cancer cells. Alpha particles are able to induce a nuclear reaction, which is used for producing radionuclides such as Astatine-211 (At-211) via $^{209}Bi(\alpha,2n)^{211}At$, which is used for monoclonal antibody attachment in cancer treatment (see RIT in chapter2). $^{107}Ag(\alpha,x)^{109}Cd$ is used to produce Cadmium-109, which is used as a tracer and in XRF spectroscopy. The considerable heat produced through alpha energy deposition has helped in the design of nuclear batteries (thermoelectric radioisotope generators) used in space missions. The scattering of low energy alpha particles is used to identify the elements in a thin layer of material. Alpha particles are used in both material analysis and material development. Alpha particles for inducing nuclear reactions must be accelerated by cyclotron accelerators.

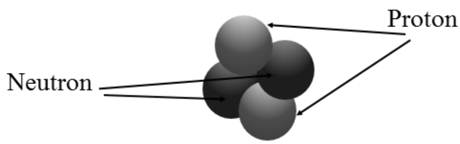

Figure 1-1: alpha particle consisting of two protons and two neutrons.