NUCLEAR PHYSICS

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Contents

Summary

The Bohr model of an atom depicts it as a nucleus consisting of neutral neutrons and positively charged protons surrounded by a cloud of negatively charged electrons. Nearly all the mass of the atom is in the centre of the atom, in the nucleus, which occupies only a very tiny space relative to the space occupied by the whole atom. The remainder of the atom is virtually empty except for the electrons. The proton number determines the particular element and is matched by an equal number of oppositely charged electrons. For the lightest elements the number of neutrons is approximately

equal to the number of protons while for the heaviest elements the ratio of neutrons to protons rises to about 1.5 to maintain the stability of the nucleus. Most individual elements have several different numbers of neutrons creating different isotopes of the same element.

A nucleus which has too many or too few neutrons is unstable and reverts to a stable condition by undergoing radioactive decay whereby the number of neutrons is adjusted by nuclear reactions within the nucleus and the emission of the surplus particles. The fact that a proton plus an electron makes a neutron allows for such reactions. The most common reaction (for an excess of neutrons in the nucleus) is the conversion of a neutron to a proton and an electron which is emitted as a β-particle. Also the heaviest elements are slightly unstable and gradually revert to lighter elements by emitting surplus neutrons and protons. The most common reaction is the emission of a single package of two protons and two neutrons known as an α-particle.

Radioactive decay is a stochastic process based on the current number of unstable nuclei in a sample of the material. Since the nucleus is transformed to another nuclide it no longer exists in its original form so the number in the sample and hence the decay rate decrease with time. This decrease is exponential and commonly measured as a half life during which time the activity or rate of decay decreases to half its value.

The protons and neutrons, collectively known as nucleons, are bound together in the nucleus by strong nuclear forces (analogous in a way to magnetic or gravitational attraction but very much stronger). Work input is required to separate the nucleons from one another. Conversely energy is released as they come together. This is the binding energy of the nucleus. The binding energy per nucleon is greatest for elements in the lighter mid range. Thus if a heavy element, such as uranium, fissions to become two mid range elements, surplus binding energy is released. This results in the useful energy which is exploited in a nuclear reactor.

1. Fundamental Concepts

1.1. Atomic Components

Nuclear physics is a relatively new science with the most significant developments occurring during the first half of the twentieth century. Niels Bohr (1885-1962) was a pioneer in this field and developed new concepts including the so called "Bohr Atom" which promotes the understanding of the structure of the atom as well as mechanisms of various chemical and nuclear reactions. Since nuclear reactions occur on such a minute scale as to be largely unobservable it is convenient to use such a model and others to describe various nuclear processes.

Atoms, according to the Bohr model, are made up of a nucleus of *protons* and *neutrons* which is surrounded by a cloud of *electrons*. Different *elements* have different numbers of protons in the nucleus while different *isotopes* of the same element have different numbers of neutrons in the nucleus. All isotopes of all elements are commonly known as *nuclides*. Hence there is a Chart of Nuclides showing all isotopes of all elements. The number of electrons (negatively charged) is always equal to the number of protons (positively charged). For the lightest elements, the number of neutrons in the nucleus is approximately equal to the number of protons but, for the heavier elements, the number of neutrons becomes progressively greater than the number of protons until, for the heaviest elements, the number of neutrons is approximately 50% greater than the number of protons.

The masses of a proton and a neutron are exceeding low being only about 1.67 x 10^{-27} kg (1.67 x 10^{-24} g). The mass of an electron is very much less being about 0.00091 x 10^{-27} kg (0.00091 x 10^{-24} g). The electron mass is thus practically negligible in comparison with a proton and a neutron. The neutron has a slightly greater mass than the proton since a neutron is effectively made up of a proton plus an electron. The mass difference between a proton and a neutron however is not equal to that of an electron due to energy effects.

Proton	1.67265 x 10^{-27} kg
Neutron	1.67495 x 10^{-27} kg
Electron	0.00091 x 10^{-27} kg

A proton has a positive charge of 1.602 x 10^{-19} coulombs and an electron an equivalent negative charge. A neutron, effectively being a proton and electron combined into a single particle, has no charge and is neutral. Thus neutrons are unaffected by the electrostatic charges developed by protons and electrons. Neutrons can therefore penetrate the electron cloud surrounding the nucleus of the atom and interact with the nucleus.

This leads to the fundamental difference between chemical and nuclear reactions. Chemical reactions are governed by the electron clouds of the respective atoms whereas nuclear reactions occur within the individual nuclei of the atoms themselves.

1.2. Atomic Notation

The *atomic number* is designated Z. This is the number of protons in the nucleus. It also designates a particular element. The *neutron number* is designated N. This is the number of neutrons in the nucleus. Together neutrons and protons are termed *nucleons* and the *atomic mass number*, designated A, is the total number of nucleons in the nucleus. The atomic mass number is related to the *isotopic mass* (or atomic weight) of the element but is an integer whereas the isotopic mass (or atomic weight) is the actual mass of the particular isotope (or element). The usual way of designating a particular isotope X is as follows:

Isotope ${}^{A}\mathrm{X}_{Z}$
Element = X
Mass Number = A
Protons = Z
Neutrons = $A - Z$

Different isotopes of the same element are designated by the chemical symbol followed by the atomic mass number. For example C-14 is the carbon isotope having 6 protons and 8 neutrons in the nucleus.

1.3. Atomic Mass Scale

Since atomic masses are so minute, it is convenient to introduce a very small unit, known as the *atomic mass unit* (u), to simplify the arithmetic. This unit is defined by taking the mass of the neutral atom of the isotope carbon-12 to be precisely 12 u. From this, it follows that the equivalence between the atomic mass unit and the kilogram is:

1 u = 1.660566 x 10^{-27} kg

It should be noted at this point that this value of 12 u converted to kg is slightly less than the total mass of 6 protons and 6 neutrons. Some mass has disappeared in the assembly of the nucleus.

If the value of the atomic mass unit in kg given above is compared with the masses of a proton and neutron in kg it follows that the mass of both a proton and a neutron are slightly greater than 1 u. The masses of the atomic constituents in atomic mass units are:

Proton	1.0072765 u
Neutron	1.0086650 u
Electron	0.0005486 u

The isotopic masses of all other elements are given relative to Carbon-12. Isotopic masses for all isotopes are given in the Chart of Nuclides. The atomic weight M of an element is calculated by adding the products of the isotopic masses and the relative fractional abundances γ of the individual isotopes.

$$M = \gamma_{\mathrm{A}} M_{\mathrm{A}} + \gamma_{\mathrm{B}} M_{\mathrm{B}} + \gamma_{\mathrm{C}} M_{\mathrm{C}} + \ldots$$

Note that the isotopic masses are the total masses including electrons. If the mass of the nucleus only is required then the masses of electrons must be subtracted. For nuclear reaction equations where the same number of electrons appear on each side of the equation the masses of electrons may be neglected since they cancel one another.

1.4. Mass-Energy Equivalence

It is well known that energy E is related to mass m according to the following equation where c is the velocity of light. Hence mass can be converted into energy in a prescribed manner.

$$E = mc^2 \tag{1}$$

In the above section the mass of one atomic mass unit has been given as:

1 u = 1.660566 x 10^{-27} kg

The velocity of light is:

$c = 2.998 \times 10^{8}$ m/s

The energy equivalent of one atomic mass unit may therefore be calculated as follows:

1 u = 1.4925×10^{-12} J

In nuclear physics it is common to use *electron volts* (eV) or *mega-electron volts* (MeV) as a measure of energy where:

1 eV = 1.6022×10^{-19} J

Making this substitution gives the energy equivalent of one atomic mass unit as:

1 u = 931.5 MeV

In a nuclear reaction the masses of the interacting nuclei (isotopic mass minus mass of electrons) can be determined from the Chart of Nuclides and the masses of any free nucleons (protons and neutrons) added or subtracted. Any change in mass as a result of the reaction between nuclei and nucleons can then be directly converted into energy by this equivalence factor. This is then the energy required to produce the reaction or the energy released by the reaction. The latter process is what produces energy in a nuclear reactor.

1.5. Avogadro's Number

It is often required in nuclear engineering that the number of atoms or nuclei in a given sample of known mass be calculated. This number can be obtained from Avogadro’s Number given as:

$N_{\mathrm{A}} = 6.022 \times 10^{23}$

Note that to facilitate calculations it is better to write it immediately as:

$N_{\mathrm{A}} = 0.6022 \times 10^{24}$

This rationalizes the exponent and allows it to be easily cancelled by other exponents also written using the engineering notation for exponents.

The number of atoms N_{X} in a given sample of mass m is given by the following equation where m is the mass in grams and M is the atomic weight:

$$N_{\mathrm{X}} = \left(N_{\mathrm{A}} / M \right) m \qquad (2)$$

In many cases since the atomic mass number A is very nearly equal to the atomic weight M of an element the following approximate relationship may be used:

$$N_X \approx (N_A/A)m \qquad (3)$$

If the sample consists of a mixture of isotopes with one predominating then the atomic mass number of the predominant isotope may be used. For example the value of 238 may be used for low enriched uranium. This approximation gives results within an acceptable range of accuracy in engineering calculations where other simplifying assumptions are made.

As an example of the use of this relationship consider the potential power output of the total consumption of 1 kg of pure Uranium-235 per day. The number of Uranium-235 atoms in 1 kg of pure fuel is:

$$N_X = (0.6022 \times 10^{24}/235) \times 1000$$

$$N_X = 2.562 \times 10^{24} \text{ atoms}$$

If this number of atoms is totally consumed (fissioned) in one day and if each fission produces 200 MeV of energy as a result of the mass deficiency arising in the fission reaction then energy is released at the following rate:

$$P = 0.005932 \times 10^{24} \text{ MeV/s}$$

If this is converted to watts and hence megawatts the rate of heat energy production is:

$$P = 950 \text{ MW}$$

If used in a nuclear power plant with a thermal cycle efficiency of about 30% this would be equal to approximately 300 MW of electrical power.

If in the above equation the atomic weight of Uranium-235 (235.043924) had been used instead of the atomic mass number (235) the difference in the answer would have been negligible.

2. Atomic Structure

2.1. Atomic Dimensions

The dimensions of atoms are extremely small and difficult to visualize. It is therefore necessary to draw a comparison and to compare the size of a complete atom with that of its nucleus.

The diameters of atoms range from about 75 picometers to about 500 picometers with the larger atoms generally being towards the bottom left hand side of the Periodic Table of Elements.

The radii and diameters of nuclei are given by the following formulae where A is the atomic mass number:

$$r = 1.25 \times 10^{-15} A^{1/3} m \quad (4)$$

$$d = 2.5 \times 10^{-15} A^{1/3} m \quad (5)$$

Considering Helium as an example the following dimensions are obtained:

Atom diameter = 100 x 10^{-12} m = 100 000 x 10^{-15} m

Nucleus diameter = 0.004 x 10^{-12} m = 4 x 10^{-15} m

The atom diameter is thus some 25 000 times that of the nucleus. It is evident therefore that the atom consists mainly of empty space in which there is a cloud of electrons and a very small and dense nucleus. Furthermore the neutrons and protons in the nucleus have a mass some 4000 times that of the electrons. This is an important concept when considering the passage of neutrons and other atomic particles through a material. Uncharged particles such as neutrons pass freely through the electron clouds of millions of atoms before eventually striking or interacting with a nucleus.

2.2. Energy Levels

The electrons surrounding a nucleus may be excited to discrete energy levels up to the energy level at which the electron is separated from the nucleus and ionization occurs. When an electron drops down from a certain energy level to another lower level or to the ground state, energy corresponding to the drop is emitted in the form of *x-rays*. The wavelength of these x-rays depends upon the associated energy drop. The wavelength λ of the x-ray is given by the following equation where h is Planck's constant (6.626 Js or 4.136 x 10^{-15} eVs), c is the speed of light and E is the energy drop of the electron.

$$\lambda = hc/E \quad (6)$$

The energy levels are usually measured in electron volts and excitation may be induced by electromagnetic influences. The nucleons within the nucleus behave in a similar manner. There are also discrete energy levels to which the nucleons can be excited. In dropping back to lower energy levels or to the ground state, the excess energy is emitted in the form of γ *-rays*.

These energy levels are measured in mega-electron-volts since the energy levels are roughly a million times greater than those for electrons. The excitation generally arises from particle interactions with the nucleus, for example absorption of a neutron or emission of a β -particle.

During the decay of radioactive isotopes, particles such as β -particles may be emitted. Since each such particle carries away a discrete amount of energy, it may leave the nucleus in an energy state higher than the ground state of the newly formed isotope. This excited isotope will then drop down to the new ground state by the emission of a γ -ray of appropriate energy. Invariably any nuclear reaction involving the absorption or emission of a particle by a nucleus results in the emission of a γ -ray.

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Biographical Sketch

Robin Chaplin obtained a B.Sc. and M.Sc. in mechanical engineering from University of Cape Town in 1965 and 1968 respectively. Between these two periods of study he spent two years gaining experience in the operation and maintenance of coal fired power plants in South Africa. He subsequently spent a further year gaining experience on research and prototype nuclear reactors in South Africa and the United Kingdom and obtained M.Sc. in nuclear engineering from Imperial College of London University in 1971. On returning and taking up a position in the head office of Eskom he spent some twelve years initially in project management and then as head of steam turbine specialists. During this period he was involved with the construction of Ruacana Hydro Power Station in Namibia and Koeberg Nuclear Power Station in South Africa being responsible for the underground mechanical equipment and civil structures and for the mechanical balance-of-plant equipment at the respective plants. Continuing his interests in power plant modeling and simulation he obtained a Ph.D. in mechanical engineering from Queen's University in Canada in 1986 and was subsequently appointed as Chair in Power Plant Engineering at the University of New Brunswick. Here he teaches thermodynamics and fluid mechanics and specialized courses in nuclear and power plant engineering in the Department of Chemical Engineering. An important function is involvement in the plant operator and shift supervisor training programs at Point Lepreau Nuclear Generating Station. This includes the development of material and the teaching of courses in both nuclear and non-nuclear aspects of the program.