NUCLEAR INTERACTIONS

R.A. Chaplin
University of New Brunswick, Canada

Keywords: Nuclear Interactions, Nuclear Cross Sections, Neutron Energies, Fission and Fusion

Contents

1. Neutron Interactions
1.1. Neutron Production
1.2. Elastic Scattering (Elastic Collision)
1.3. Inelastic Scattering (Inelastic Collision)
1.4. Radiative Capture
1.5. Nuclear Transmutation (Charged Particle Reaction)
1.6. Neutron Producing Reaction
1.7. Fission
1.8. Neutron Flux
1.9. Neutron Energy
2. Nuclear Cross Sections
2.1. Microscopic Cross Sections
2.2. Macroscopic Cross Sections
2.3. Number of Nuclei
2.4. Reaction Rate
2.5. Summary
2.5.1. Macroscopic cross-section
2.5.2. Neutron Flux
2.5.3. Reaction Rate
3. Neutron Scattering and Capture
3.1. Neutron Attenuation
3.2. Mean Free Path
3.3. Scattering Characteristics
3.4. Absorption Characteristics
3.5. Radiative Capture Model
3.6. Cross Sections
4. Neutron Moderation
4.1. Neutron Energy Changes
4.2. Logarithmic Mean Energy Decrement
4.3. Definitions
4.3.1. Mean Logarithmic Energy Decrement ξ
4.3.2. Macroscopic Scattering Cross Section Σ_s
4.3.3. Slowing Down Power
4.3.4. Moderating Ratio
5. Fission and Fusion
5.1. Energy Release
5.2. Fission

5.3. Fission Characteristics
5.4. Fission Products
5.5. Neutron Energy Spectrum
5.6. Delayed Neutrons
5.7. Fission Process Summary
Glossary
Bibliography
Biographical Sketch

Summary

When a heavy element, such as uranium, fissions into two mid range elements, binding energy is released. Furthermore since the neutron to proton ratio is about 1.5 for the heaviest elements but in the range of 1.2 to 1.3 for mid range elements there is a surplus of neutrons after a fissioning process. Some heavy elements fission spontaneously at a very slow rate due to inherent instability.

However fissioning can be induced by adding energy to the nucleus of some elements. This can be done by allowing the nucleus to capture a free neutron which then adds sufficient binding energy, as it combines with the nucleus, to cause the nucleus to become highly unstable and to split into two parts with additional free neutrons. These components fly apart with high kinetic energy which is subsequently degraded to produce heat.

Free neutrons interact with the nuclei of other materials in various ways, the most common being absorption and scattering. Scattering results in the transfer of some energy and the neutron continues to move through the medium but at a lower energy and hence lower velocity.

Neutrons being uncharged do not interact with the electron cloud surrounding the nucleus and, since the nucleus occupies such a tiny space within the atom, the probability of interaction is quite low. This probability is not necessarily related to the size of the nucleus but is measured as a cross section in units of area. The cross sections of different nuclei vary widely and may be greater or smaller than the projected area of the nucleus itself.

To maintain an ongoing chain reaction of nuclear fissions to release energy at least one free neutron from a previous fission must go on to induce fission in another fissile element such as uranium. The probability of this occurring can be enhanced by reducing the velocity of the neutron so that, when encountering a fissile nucleus, it spends more time in the immediate vicinity of the nucleus.

Thus surplus neutrons produced by fission are made to pass through a suitable medium, known as a moderator, where their velocity is reduced by multiple scattering collisions with moderator nuclei. They then re-enter the fissile fuel to produce at least one further fission. Some neutrons are absorbed by various nuclei.

This process is carefully balanced to ensure the steady and continuous release of energy. Since only about 200 MeV or 32 pJ is released by each fission, many parallel processes as described above must occur simultaneously.

1. Neutron Interactions

1.1. Neutron Production

Neutrons can be created by the integration of an electron and a proton. Furthermore a free neutron will in time disintegrate into a proton and an electron. Neutrons interact with the nuclei of atoms in various ways and may also be produced by the nuclei of certain atoms. The most common source of neutrons is the fissioning process where a heavy nucleus splits into two lighter nuclei. This fissioning of nuclei and the subsequent interaction of the resultant neutrons with other nuclei are the fundamental processes governing the production of power from nuclear energy. Knowledge of these processes is important in the study of nuclear engineering.

A heavy nucleus such as Uranium-235 will occasionally fission spontaneously into two lighter nuclei. A heavy nucleus such as this has about one and a half as many neutrons as protons in the nucleus. A mid-range nucleus however has only about one and a third as many neutrons as protons in its nucleus. Thus, when a heavy nucleus fissions into two lighter nuclei, not as many neutrons are required to maintain a stable configuration in the nucleus and some neutrons are rejected immediately the fission occurs. Generally two to three neutrons are emitted during the fission process.

In a nuclear reactor, fissile nuclei such as Uranium-235 and Plutonium-239 are induced to fission by having their nuclei excited beyond the level of stability. This is done by subjecting them to the influence of free neutrons. Free neutrons interact with various nuclei in different ways causing a range of different reactions of which fission is just one. Most interactions involve scattering (non-absorption) or capture (absorption) of the neutrons and a transfer of energy. These reactions are important in maintaining and controlling the fission reactions in nuclear reactors.

1.2. Elastic Scattering (Elastic Collision)

Elastic scattering occurs when a neutron strikes a nucleus and rebounds elastically. In such a collision kinetic energy is transmitted elastically in accordance with the basic laws of motion. If the nucleus is of the same mass as the neutron then a large amount of kinetic energy is transferred to the nucleus. If the nucleus is of a much greater mass than the neutron then most of the kinetic energy is retained by the neutron as it rebounds. The amount of kinetic energy transferred also depends upon the angle of impact and hence the direction of motion of the neutron and nucleus after the impact.

1.3. Inelastic Scattering (Inelastic Collision)

Inelastic scattering occurs when a neutron strikes and enters a nucleus. The nucleus is excited into an unstable condition and a neutron is immediately emitted but with a lower energy than that of the entering neutron. The surplus energy is transferred to the nucleus as kinetic energy and excitation energy. The excited nucleus subsequently returns to the ground state by the emission of a γ-ray. Such collisions are inelastic since all the initial kinetic energy does not reappear as kinetic energy. Some is absorbed by the nucleus and subsequently emitted in a different form (γ-ray). The emitted neutron may or may not be the one that initially struck the nucleus. In simplistic terms the neutron can be considered simply to be bouncing off an energy absorbing nucleus.

1.4. Radiative Capture

Radiative capture can be considered to be similar to the initial process leading to inelastic scattering. A neutron strikes and enters a nucleus. The nucleus is excited but the level of excitation is insufficient to eject a neutron. Instead all the energy is transferred to the nucleus as kinetic energy and excitation energy. The excited nucleus subsequently returns to the ground state by the emission of a γ-ray. The incoming neutron remains in the nucleus and the nuclide increases its number of neutrons by one. This is a very common type of reaction. It leads to the creation of heavier isotopes of the original element. Many of these may be radioactive and decay over time in different ways.

1.5. Nuclear Transmutation (Charged Particle Reaction)

Nuclear transmutation is similar to radiative capture and inelastic scattering. A neutron strikes and enters a nucleus. The nucleus is excited into an unstable condition but a particle other than a neutron is emitted. The emitted particles are either protons or α-particles. This leaves the nucleus still in an excited state and it subsequently returns to the ground state by the emission of a γ-ray. In this process the total number of protons in the nucleus is reduced by one for proton emission and by two for α-particle emission. The original element is thus changed or transmuted into a different element.

1.6. Neutron Producing Reaction

Neutron producing reactions occur when one or two additional neutrons are produced from a single neutron. As before a neutron strikes and enters a nucleus. The nucleus is excited into an unstable condition as with inelastic scattering but two or three neutrons instead of only one neutron are emitted. The still excited nucleus subsequently returns to its ground state by the emission of a γ-ray. This is an uncommon reaction occurring in only a few isotopes.

1.7. Fission

Although spontaneous fission occasionally occurs, fission is generally induced by neutrons. A neutron strikes and enters a heavy nucleus. The nucleus is excited into an unstable condition as with most of the foregoing interactions. In this unstable condition the nucleus splits into two new mid-range nuclei usually of unequal mass. Since these new nuclei do not need as many neutrons for stability some neutrons are emitted immediately. The surplus binding energy drives the new nuclei (fission fragments) and neutrons away from one another with high velocity. The new nuclei subsequently lose their kinetic energy by ionizing reactions with the surrounding nuclei through which they pass and return to their ground states by emission of γ-rays. They are invariably still unstable with too many neutrons and subsequently decay usually by β-particle and γ-ray emission. The high energy neutrons lose energy by scattering collisions with nuclei of the surrounding medium and are subsequently generally captured by other nuclei to produce one of the reactions described in this section.

1.8. Neutron Flux

Neutrons created by fission pass freely through solid material since atoms consist mainly of empty space. They have no charge and so are not affected by the charged electron cloud surrounding the nucleus. Furthermore the nucleus is so small compared with the size of the atom that the chance of the neutron colliding with it is extremely small. In a uniform material the neutrons travel randomly in all directions and some measure of their number or influence is required. A convenient parameter is *neutron flux*.

Neutron flux φ is defined as the number of neutrons per unit volume n multiplied by their velocity v.

$$\varphi = nv \quad (1)$$

Neutron flux so defined has units of number per unit area per unit time. This can be considered as the number of neutrons passing through a particular cross sectional area in any direction per second.

If the neutrons travel in a parallel beam the area through which the neutrons pass may be considered to be at right angles to the beam and the given area will then be equal to the cross sectional area of the beam. This is the case in irradiation experiments where a beam of neutrons is directed out of a nuclear reactor through special ports which trap neutrons moving in other directions. Such a beam is known as a collimated beam.

Within the reactor the neutrons travel in all directions and the neutrons will pass through a given area in all directions and from both sides. This area is more difficult to define hence the definition of neutron flux as number multiplied by velocity.

1.9. Neutron Energy

During the fission process, in which a heavy nucleus splits into two fission fragments and some residual neutrons, some 200 MeV of binding energy is released. This appears as kinetic energy as the fragments and neutrons separate at high velocity. Most energy is carried by the fission fragments and is deposited as heat in the surrounding material as the fragments come to rest. The two or three residual or prompt neutrons carry away about 5 MeV as kinetic energy so on average a neutron produced by fission has an energy of about 2 MeV or 0.32 x 10^{-12} J. Considering that the mass of a neutron is 1.67495 x 10^{-27} kg its velocity can be calculated from the basic equation for kinetic energy E_{KE} where m is mass and V velocity:

$$E_{\mathrm{KE}} = \tfrac{1}{2}\, mV^2 \quad (2)$$

This gives an average velocity of about 20 x 10^6 m/s. This is the average based on an average energy of 2 MeV. The actual range of energies however can range from near zero to about 8 MeV as shown in Figure 12 giving velocities anywhere up to about 55 x 10^6 m/s.

These high energy neutrons interact with the nuclei of the medium through which they pass. In the process some are captured but most are scattered by elastic or inelastic collisions with the nuclei. Such scattering collisions result in a transfer of energy from the neutrons to the nuclei until the neutrons reach an equilibrium condition with the medium. In this condition the nuclei, being in a state of vibratory motion by virtue of their temperature, give as much energy to the neutrons as they receive from the neutrons. The neutrons are thus in thermal equilibrium with the medium and are said to be thermalized. Even though the medium may be at a uniform temperature, subsequent scattering collisions occurring in random directions relative to the motion of the nuclei, result in thermal neutrons having a range of energies above and below the thermalization energy as shown in Figure 1. This figure also shows the corresponding velocity distribution of the neutrons.

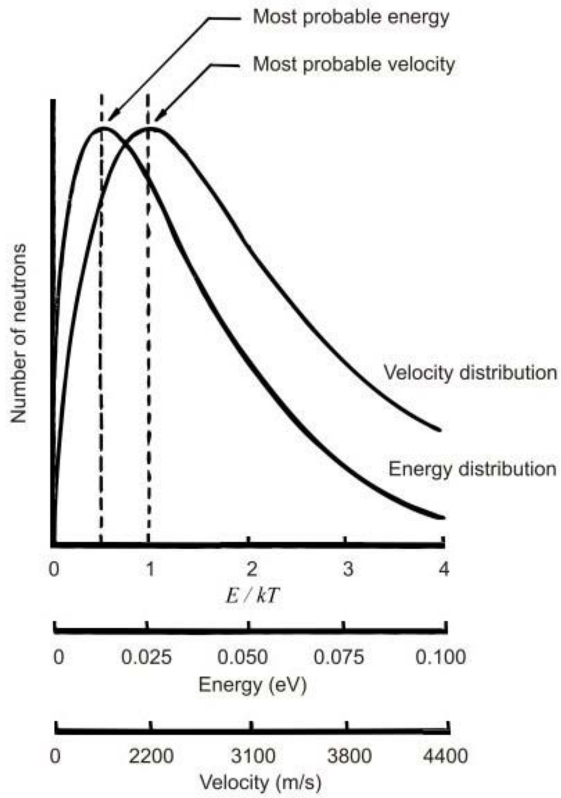

Figure 1. Energy and velocity distribution of thermalized neutrons

This is a Maxwellian distribution with the energy E given in terms of the Boltzmann constant k and temperature T as well as in electron-volts while the velocity V is given in meters per second. The Boltzmann constant is as follows:

$$k = 13.8 \times 10^{-24} \text{ J/K}$$

$$k = 86.2 \times 10^{-6} \text{ eV/K}$$

The average energy E_{ave} and the most probable energy E_{mp} of the neutrons are given by:

$$E_{ave} = (3/2)\,kT$$
$$E_{mp} = ½\,kT$$

In neutron studies however the most probable velocity V_{mp} is considered. This is given by:

$$V_{mp} = [2kT/m]^{1/2}$$

Hence the corresponding neutron energy E is given by:

$$E = kT \quad (3)$$

All thermal neutrons in a system are considered to have this velocity which is then given by:

$$½\,mV^2 = kT$$

At an ambient temperature of 20°C or 293K this velocity is 2200 m/s and the corresponding energy is 0.025 eV. These are the values traditionally used in neutron scattering calculations involving thermal neutrons.

-
-
-

Bibliography

El-Wakil, M.M. (1993), *Nuclear Heat Transport*, The American Nuclear Society, Illinois, United States. [This text gives a clear and concise summary of nuclear and reactor physics before addressing the core material namely heat generation and heat transfer in fuel elements and coolants].

Foster, A.R., and Wright, R.L. (1983), *Basic Nuclear Engineering*, Prentice-Hall, Englewood Cliffs, New Jersey, United States. [This text covers the key aspects of nuclear reactors and associated technologies. It gives a good fundamental and mathematical basis for the theory and includes equation derivations and worked examples].

General Electric (1989), *Nuclides and Isotopes*, General Electric Company, San Jose, California, United States. [This reference booklet contains a complete chart of the nuclides with all their properties (structure, isotopic mass, half-life, decay modes, absorption properties, etc.) as well as explanatory supporting text].

Glasstone, S. (1979), *Sourcebook on Atomic Energy*, Krieger Publishing Company, Malabar, Florida, United States (original 1967), Van Nostrand Reinhold, New York, United States (reprint 1979). [This is a classic text (over 100 000 English copies sold and translated into seven other languages). It covers all aspects of atomic theory and nuclear physics from the initial development to the first commercial power reactors of several different types. It is an excellent historical reference].

Glasstone, S. and Sesonske, A. (1994), *Nuclear Reactor Engineering*, Chapman and Hall, New York, New York, United States. [This text, now in two volumes, covers all aspects of nuclear physics and nuclear reactors including safety provisions and fuel cycles].

Knief, R.A. (1992), *Nuclear Engineering: Theory and Technology of Commercial Nuclear Power*. Hemisphere Publishing Corporation, Taylor & Francis, Washington DC, United States. [This book gives a concise summary of nuclear and reactor physics before addressing the core material namely reactor systems, reactor safety and fuel cycles. It is a good reference for different types of reactors and historical developments].

Krane, S.K. (1988), *Introductory Nuclear Physics*, John Wiley and Sons, New York, United States. [This text provides a comprehensive treatment of various aspects of nuclear physics such as nuclear structure, quantum mechanics, radioactive decay, nuclear reactions, fission and fusion, subatomic particles, etc.]

Lamarsh, J.R. and Baratta, A.J. (2001), *Introduction to Nuclear Engineering*, Prentice-Hall, Upper Saddle River, New Jersey, United States. [This book provides a comprehensive coverage of all aspects of nuclear physics and nuclear reactors. It has a good descriptive text supported by all necessary mathematical relations and tabulated reference data.]

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.. He has recently been appointed as Chair of the Department of Chemical Engineering.