Neutron Physics

A Graduate Project Submitted to the
School of Graduate Studies
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In Partial Fulfillment of the Requirement for
the Degree of Master of Science in Physics

By

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Addis Ababa, Ethiopia

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DEPARTMENT OF

The undersigned hereby certify that they have read and recommend to the School of Graduate Studies for acceptance a project entitled "**Neutron Physics**" by **Abdu Ali** in partial fulfillment of the requirements for the degree of **Master of Science in Physics**.

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Abstract

This paper contains general introduction about neutron physics, sources of neutrons and its interaction with nuclei, absorption, moderation and detection of neutrons and some basic application of neutrons. By using the compound nucleus model, We have derived the reaction cross-section interms of the speed of neutron by considering scattering and resonance reaction of neutrons with a nucleus.

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Chapter 1

Introduction

The field of neutron physics has become an integral part of investigations into an array of important issues that span fields as diverse as nuclear and particle physics, fundamental symmetries, astrophysics and cosmology, fundamental constants, gravitation, and the interpretation of quantum mechanics. The experiments employ a diversity of measurement strategies and techniques, including condensed matter and low temperature physics, optics, and atomic physics, as well as nuclear and particle physics, and they address a wide range of issues. Nevertheless, the field possesses a coherence that derives from the unique properties of the neutron as an electrically neutral, strongly interacting, long-lived unstable particle that can be used either as the probe or as an object of study. By fundamental neutron physics, we mean that class of experiments using slow neutrons which primarily address issues associated with the Standard Model (SM) of the strong, weak, electromagnetic, and gravitational interactions and their connection with issues in astrophysics and cosmology.[7]

Neutrons experience all known forces in strengths that make them accessible to experimentation. It is an amusing fact that the magnitude of the average neutron interaction energy in matter, in laboratory magnetic fields, and near the surface of the Earth is the same order of magnitude for all forces except the weak interaction. The experiments include measurement of neutron-decay parameters, the use of parity violation to isolate

the weak interaction between nucleons, and searches for a source of time reversal violation beyond the SM. These experiments provide information that is complementary to that available from existing accelerator-based nuclear physics facilities and high-energy accelerators.

Free neutrons are unstable with a 15 minute lifetime but are prevented from decaying while bound in nuclei through the combined effects of energy conservation and Fermi statistics. They must be liberated from nuclei using nuclear reactions with MeV-scale energies in order to be used and studied. We define slow neutrons to be neutrons whose energy has been lowered well below this scale. The available dynamic range of neutron energies for use in laboratory research is quite remarkable. Thermodynamic language is used to describe different regions; a neutron in thermal equilibrium at 300 K has a kinetic energy of only 0.025 eV. Because its de Broglie wavelength (0.18 nm) is comparable to inter-atomic distances, this energy also represents the boundary below which coherent interactions of neutrons with matter become important. The most intense sources of neutrons for experiments at thermal energies are nuclear reactors, although accelerators can also produce higher energy neutrons.[7]

As the uncharged member of the nucleon pair, the neutron plays a fundamental role in the study of nuclear forces. Unaffected by the Coulomb barrier, neutrons of even very low energy (eV or less) can penetrate the nucleus and initiate nuclear reactions. In contrast to part of our lack of understanding of processes in the interior of stars results from the difficulty of studying proton -induced reactions at energies as low as keV. On the other hand the lack of coulomb interaction presents some experimental problems when using neutrons as a nuclear probe : energy selection and focusing of an incident neutron beam are difficult and neutrons do not produce primary ionization events in detectors(neutrons passing through matter have negligible interactions with the atomic electrons).

Basic researches with neutrons goes back almost to the earliest days of nuclear physics,and

it continues to be a vital and exciting research field today. For example,interference effects with neutron beams have permitted some basic aspects of quantum mechanics to be demonstrated for the first time. The electric dipole moment of the neutron should vanish if the neutron were an elementary particle or even a composite particle in which the binding forces were symmetric with respect to the parity and time-reversal operations. Many careful and detailed experiments have been done and all indicate a vanishing electric dipole moment, but the limit has been pushed so low (10^{-25}e.cm) that it is almost possible to distinguish among certain competing theories for the interactions among the elementary particles . The so-called Grand Unified Theories that attempt to unify the strong(nuclear), electromagnetic and weak($\beta - decay$) interactions predict that the conservation of nucleon number (actually baryon number) can break down and that a neutron could convert in to its anti-particle, the anti-neutron and then back again to a neutron. No evidence has yet been seen for this effect either,but current research is trying to improve the limits in our knowledge of the neutron-anti-neutron conversion frequency.[2]

1.1 The Neutron

A neutron is a tiny subatomic particle that can be found in practically all form of conventional matter. The only stable exception is the hydrogen atoms ,where it is bound closely with protons through the strong nuclear force , the strongest force in nature. Neutrons are responsible for about half the weight of conventional matter by volume. It can be seen as a proton and an electron smashed together. Because both of these particles have opposite charge of the same magnitude,their fusion result in charge less particle.This lack of charge can make neutron difficult to detect. Neutrons can sometimes behave charged in a limited way because their constituents, quarks, have small charges.

The neutron is a baryon and is considered to be composed of two down quarks and one up quarks. A free neutron will decay with a half-life of about 10.3 minutes but it is stable

if combined into a nucleus.The decay of the neutron involves the weak interaction.The neutron is about 0.2 percent more massive than proton, which translate to an energy difference of $1.29Mev$.The decay of the neutron is associated with a quark transfer motion in which a down quarks is converted to an up by the weak interaction. It is possible for proton to be transformed in to a neutron, but you have to a supply $1.29Mev$ of energy to reach the threshold for that transformation.[5]

1.2 Discovery of Neutron

The existence of neutron was first suggested by Rutherford in 1920. He thought that an electron could exist in a nucleus and could combine with a proton to form a neutron. Being electrically neutral, the neutron was very difficult to discover by methods of particle detection which depends on the deflection of the particles in a magnetic or electric field or on their ionization of matter.

In 1932, however, one of Rutherford's student, Chadwick demonstrated the existence of neutron, using an experiment first conducted by Bethe and Becker in 1930 and latter by Irene and Fredric Joliot. In the experiment a beryllium plate was bombarded by α-particles from a polonium source. This caused highly penetrating radiation to emanate from Be.

The reading on the detection (ionization chamber) was then noted. When a target containing large quantities of hydrogen (such as in the form of paraffin) was interposed between Be and detector, the reading was found to increase , rather than decrease as it was thought that it would, because of the expected absorption in paraffin. Chadwick showed conclusively that the penetrating radiation could not be γ-ray photons was initially suspected, but was that of a neutral particle,roughly equal in mass to the nucleus of the hydrogen atom (proton). He thus demonstrated that Rutherford's concept of the existence of the neutron was correct.[5]

The main characteristics of neutron:

- It is electrically neutral
- Having no orbital electron to cause emission or absorption spectra,it can not be seen on a spectrometer. i.e it is invisible
- It doesn't interact with electrons to any large degree. Thus it ionizes matter is mostly with nucleus in collision, causing some displacement of the nuclei or in absorption, causing the formation of other isotopes and subsequent induced radiations of various types.
- It exists permanently only in nuclei. Otherwise it is slightly, having a 13-minute half-life. If it is in a free state, it rapidly ejects a β-particle and a neutrino and transforms in to a proton.

1.3 Classification of Neutrons

For the purpose of study neutron interaction ; neutrons can be classified in various categories. Depending up on their energy neutrons are classified as:

1. Slow neutrons: are neutrons which have energy between 0 and 1000 ev

   a) Cold neutrons: Neutrons having energy very very small around $0.002ev$. These neutrons have high penetrability in crystaline and poly-crystaline materials

   b) Thermal neutrons : Neutrons which are in thermal equilibrium with the surroundings. The enery is not exactly known, but of the order of $E \sim kT$

   If $T = 300$K and $k = 1.33 \times 10^{-}16, then E \simeq 0.025\ ev$

   c) Epithermal neutrons: are neutrons whose energy is greater than $0.5ev$.

   d) Resonance neutron: are neutrons having energy between $1ev$ and $100ev$.

   2) Intermediate neutrons: are neutrons which have an energy 10^3ev to 5×10^5ev

   3) Fast neutrons :neutrons which have an energy range 0.5Mev to10Mev.

   4) Very fast neutron: neutrons having an energy range of 10Mev to 50Mev

5) Ultrafast neutrons: neutrons having an energy more than 50Mev.

Study of neutron interaction with matter requires the knowledge of neutron energy spectrum. For many applications the spectrum is poorly known. All neutrons are fast by birth and lose energy by colliding elastically with atoms in their environment and then after being slowed down to thermal energies they are captured by the nuclei of the absorbing medium.[3]

1.4 Protection From Neutron

Exposure to free neutrons can be hazardous,since the interaction of neutrons with molecules in the body can cause disruption to molecules and atoms, and can also cause reactions which give rise to other forms of radiation (such as protons). The normal precautions of radiation protection apply: avoid exposure stay as far from the source as possible, and keep exposure time to a minimum. Some particular thought must be given to how to protect from neutron exposure. However, for other types of radiation ,e.g. alpha particles ,beta particles or gamma rays, materials of a high atomic number and with high density make for good shielding ; frequently lead is used. However, this approach will not work with neutrons, since the absorption of neutrons does not increase straight forwardly with atomic number, as it does with alpha and gamma radiation . Instead one needs to look at the particular interactions neutrons have with matter. For example,hydrogen rich materials are often used to shield against neutrons, since ordinary hydrogen both scatter and slow neutrons. This often means that simple concrete blocks or even paraffin -loaded plastic blocks afford better protection from neutrons than do far more dense materials. After slowing, neutrons may the be absorbed with an isotope which has high affinity for slow neutrons with out causing secondary capture-radiation, such as lithium-6.

Hydrogen rich ordinary water affects neutron absorption in nuclear fission reactors: usually neutrons are so strongly absorbed by normal water that fuel-enrichment with

fissionable isotope is required. The deuterium in heavy water has a very much lower absorption affinity for neutrons than does protium (normal light hydrogen). Deuterium is therefore used in CANDU(CANada Deuterium Uranium)-type reactors, in order to slow (moderate) neutron velocity, to increase the probability of nuclear fission compared to neutron capture.

Chapter 2

Neutron Sources and Neutron Interaction

2.1 Neutron Sources

Neutrons are one of the most powerful probes for making the arrangement of atoms visible and for measuring the forces between them. The potential performance of a neutron source is basically the product of two quantities, the source strength which measures the flux of useful neutrons produced in the source and the instrumentation factor which measures how efficiently we can detect the scattered neutrons.

The first neutron sources were research reactors and a rapid progression in neutron source performance followed the reactor developments in the forties, fifties, and sixties. At the end of the sixties, this technology was fully mature and from the seventies until the late nineties, advances in the scientific utility of the technique derived mainly from improvements in instrumentation. Neutrons can also be produced by spallation. i.e. through bombardment of a heavy atom with intense beams of high energy protons ($\sim$ GeV or velocities $\sim$ 90 percent of the velocity of light). During the nineties, accelerator technology advanced to a state where spallation sources reached parity in scientific performance with the best high flux reactors and the new projects, now under construction or in development, promise significantly improved neutron source performance. Coupled with ongoing improvements in instrumentation, there are exciting prospects for new science.

These prospects will not be limited to materials science but also cover a wide variety of subjects from earth science to particle physics, from chemistry to engineering and from solid state physics to biology and medicine.[2],[3]

2.1.1 Radioisotope Sources

Although there are several types of neutron sources, the most convenient choice for university's laboratory work is isotopic neutron sources. Because they have a unique advantages of being small, portable, reliable and relatively cheap.

1) Spontaneous Fission: is a decay mode of some trans-Uranus isotopes during which two to four neutrons are released during this process. Californium(Cf) is a common example of these sources.

2)Two Component Sources : Based on (α,n) and (γ,n) reaction. They are composed of a long-lived radioactive isotope applying alpha particles or gamma photons and a target material of low atomic number. The neutrons are obtained by nuclear reactions as:

$$^{9}Be(\alpha, n)^{12}C$$

$$^{9}Be(\gamma, n)^{4}_{2}He \tag{2.1.1}$$

The main disadvantages of neutron sources of the latter type is the fact that very large gamma-ray activities must be used in order to produce neutron sources of attractive intensity. Therefore, the neutron appears in a much more intense gamma-ray back ground.

Due to energetic alpha particles are available from the direct decay of a number of convenient radio nucleides, it is possible to fabricate a small self contained neutron sources by mixing an alpha-emitting isotope with a suitable target material. Several different target material can lead to (α,n) reactions for alpha particle energies that are readily available in radioactive decay. The maximum neutron yield is obtained when beryllium is chosen as the target, Neutrons are produced through the reaction:

$$He + Be \longrightarrow C + n; Q = +5.71Mev \tag{2.1.2}$$

All the α-emitters of practical interest are actinide elements and investigation shown have that a stable alloy can be formed between the actinides and beryllium of the form MBe_{13}. Where M represents the actinide metals. Most of the sources listed in the table below. Therefore, are metallurgically prepared in the form of this alloy and each alpha particles has an opportunity to interact with beryllium nuclei with out any intermediate energy loss.

Source	Half-life	$E_\alpha$in Mev	Neutron yield/10^6 α-particle
^{239}Pu/Be	24000y	5.14	57(exp.)
$^{210}Po/Be$	138d	5.3	69(exp.)
$^{238}Pu/Be$	86y	5.48	79(cal.)
^{241}Am/Be	458y	5.48	70($exp.$)
^{244}Cm/Be	18y	5.79	100(cal.)
$^{242}Cm/Be$	162y	6.1	106(exp.)
^{226}Ra/Be	1602y	Multiple	502(exp.)
^{227}Ac/Be	21.6y	Multiple	702(cal.)

Table 2.1: Characterstics of Be(α,n) Neutron sources

The radioisotopes in the above table 1 except Ra and Ac involves simpler α-decay and the γ-decay back ground is much lower. The choice between these alternatives is made primarily on the basis of availability, cost and half-life.Due to this Am(458yrs) and Pu(86yrs) are widely used if high neutron yields are needed.[3]

The possible choice for radioisotope neutron sources are much more limited and are based on either spontaneous fission or on nuclear reactions for which the incident particle is the product of a conventional delayed process.

Many of the transuranic heavy nucleids have in appreciable spontaneous fission decay probability. Several fast neutrons are promptly emitted in each fission event. So a sample of such a radio-nuclei can be a simple and convenient isotopic neutron sources.Other products of the fission process are the heavy fission product, that is prompt fission gamma

rays and the beta and gamma activity of the fission product accumulated with in the sample.When used as a neutron source, the isotope is generally encapsulated in a sufficient thick container so that only the fast neutrons and gamma rays emerge from the source.

2.1.2 Photo neutron Sources

Is a process similar to the (α,n) sources. We can use the (γ,n) reaction to produce neutrons. The advantage of photo neutron production or source is that we can make the neutrons more nearly mono energetic. For example, ^{24}Na emits a γ of $2.76Mev$, absorption of which could be sufficient to overcome the neutron binding energy of ^{9}Be:

$$\gamma +^{9} Be \longrightarrow^{8} Be + n \tag{2.1.3}$$

The yield is acceptable (2×10^{6} neutrons per second per Ci of ^{24}Na), but the half life is short (15h). A longer lived isotope ^{124}Sb(60d) emits a strong γ whose energy just exceeds the ^{9}Be neutron binding energy: the emitted neutron has a much lower energy, about 24Kev.

2.1.3 Spontaneous Fission Sources

It is a common source of neutrons from isotopes such as ^{252}Cf. Neutrons are produced directly in the fission process, at a rate of about 4 per fission. The fission occurs in only about 3 percent of the decays (α-decay accounts the rest). The neutron energies are characteristics of fission-a continuous distribution an average energy of $1 - 3$Mev.

2.1.4 Reactor Sources

The neutron flux near the core of a nuclear fission reaction can be quite high typically 10^{14} neutrons per cm^2 per second. The energy spectrum extends to $5 - 7$ Mev but peaks at $1 - 2$Mev. These neutrons are generally reduced to thermal energies with in the reactor, but there are also fast neutrons present in the core. Cutting a small hole in the shielding

of the reactor vessel permits a beam of neutrons to be extracted into the laboratory for experiments. The high neutron fluxes from a reactor are particularly useful for production of radioisotopes by neutron capture,as in neutron activation analysis.

2.1.5 Nuclear Reaction Sources

There are of course many nuclear reactions that produce neutrons. These require an accelerator to produce a beam of particles to initiate the reaction,and thus they are not as convenient as the radioactive-decay. However, by carefully selecting the incident energy and the angle at which we observe the emitted neutron, we can obtain a reasonably mono-energetic beam of almost any desired energy .Some reactions that might be used are:[2]

$$
\begin{aligned}
&{}^{3}H(d,n)^{4}He, Q = +17.6Mev \\
&{}^{9}Be(\alpha,n)^{12}C, Q = +5.7Mev \\
&{}^{7}Li(p,n)^{7}Be, Q = -1.6Mev \\
&{}^{2}H(d,n)^{3}He, Q = +3.3Mev
\end{aligned}
\tag{2.1.4}
$$

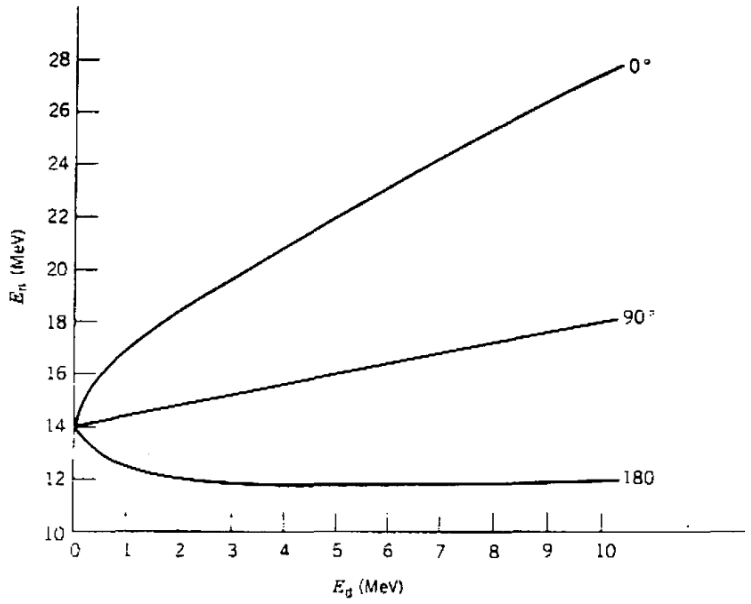

Figure 2.1: Neutron emitted in the $^3H(d,n)^4He$ reaction

This figure illustrates the dependence of the neutron energy for the first reaction on the incident energy and on the direction of the outgoing neutron.

2.2 Neutron Interaction

A nuclear reactor will not operate without neutrons. Neutrons induce the fission reaction, which produces the heat in CANDU(CANadan Deuterium Uranium) reactors, and fission creates more neutrons. The neutrons produced also engage in other reactions. It is important to know about these neutron interactions.

This section introduces five reactions that can occur when a neutron interacts with a nucleus. In the first two, known as scattering reactions,a neutron emerges from the reaction. In the remaining reactions,known as absorption reactions, the neutron is absorbed into the nucleus and something different emerges.

2.2.1 Elastic Scattering(n, n)

Elastic scattering resembles a billiard ball collision. A neutron collides with a nucleus, transfers some energy to it, and bounces off in a different direction. (Sometimes it absorbs the neutron and then re-emits it, conserving kinetic energy.) The fraction of its initial energy lost depends on whether it hits the target nucleus head-on or at an angle exactly like the cue ball striking a ball on the billiard table. The target nucleus gains the energy lost by the neutron, and then moves at an increased speed.[6]

Light nuclei are the most effective for slowing neutrons. A neutron colliding with a heavy nucleus rebounds with little loss of speed and transfers very little energyrather like firing the cue ball at a cannon ball. On the other hand, neutrons will not be scattered by the light electron clouds surrounding the nucleus, but will travel straight on much like baseballs through a fog.

2.2.2 Inelastic Scattering(n, nγ)

A neutron may strike a nucleus and be temporarily absorbed, forming a compound nucleus. This will be in an excited state. It may de-excite by emitting another neutron of lower energy, together with a gamma photon, which takes the remaining energy. This process is called inelastic scattering. It generally happens only when high energy neutrons interact with heavy nuclei and has little practical importance for reactor operation.[7]

2.2.3 Transmutation(n, p), (n, α)

A nucleus may absorb a neutron forming a compound nucleus, which then de-energizes by emitting a charged particle, either a proton or an alpha particle. This produces a nucleus of a different element. Such a reaction is called a transmutation.Transmutation is the transformation of one element into another by a nuclear reaction. Examples: Neutron-Proton Reaction (n, p) and Neutron-Alpha Reaction (n,α)

Oxygen-16 captures a neutron and emits a proton to form nitrogen-16: The product,

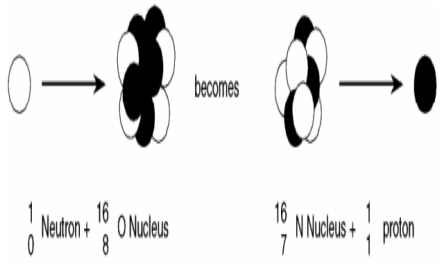

Figure 2.2: Neutron-Proton Reaction

nitrogen-16, is radioactive with a half-life of 7.1 seconds so this example is an activation reaction. N-16 is a beta emitter, but more important, it also emits very penetrating, high-energy gamma rays.

Neutrons captured by boron-10 cause the following reaction:

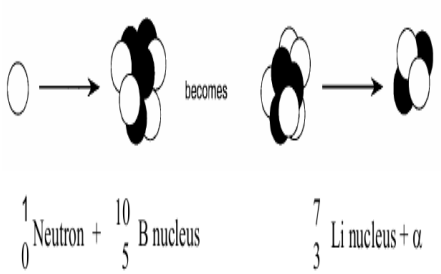

Figure 2.3: Neutron-alpha(n,α) reaction

2.2.4 Radiative Capture(n, γ)

This is the most common nuclear reaction. The compound nucleus formed emits only a gamma photon. In other words, the product nucleus is an isotope of the same element as the original nucleus. Its mass number increases by one.

Examples The simplest radiative capture occurs when hydrogen absorbs a neutron to produce deuterium (heavy Hydrogen)

The deuterium formed is a stable nuclide. However, many radiative capture products are radioactive and are beta-gamma emitters.Deuterium itself undergoes a radiative capture reaction to form tritium; The tritium isotope is unstable and is a major radiation hazard in CANDU reactors. Stable cobalt-59 undergoes radiative capture to form highly radioactive Co-60:

$$^{59}_{27}Co +^{1}_{0} n \longrightarrow^{60}_{27} Co + \gamma \tag{2.2.1}$$

Cobalt-60 has a long half-life (5.25 years) and emits very penetrating gamma radiation when it decays, making it a serious hazard among activated corrosion products. Normal steel usually contains a small amount of cobalt, but the concentration in reactor grade materials is limited to reduce the radiation hazard.Cobalt-60 is an isotope commonly used in radiation treatment of cancer.[6]

2.2.5 Fission

A nuclear fission is a nuclear reaction in which the nucleus of an atom splits into smaller parts (lighter nuclei), often producing free neutrons and photons (in the form of gamma rays). The two nuclei produced are most often of comparable size.

The following examples illustrate a convenient short hand notation for these reactions.[6]

$$^{1}_{0}n +^{2}_{1} H \longrightarrow^{2}_{1} H +^{1}_{0} n \longrightarrow^{2}_{1} H(n,n)^{2}_{1}H \tag{2.2.2}$$

$$^{1}_{0}n +^{238}_{92} U \longrightarrow^{238}_{92} U +^{1}_{0} n \longrightarrow^{238}_{92} U(n,n)^{238}_{92}U \tag{2.2.3}$$

$$^{1}_{0}n +^{16}_{8} O \longrightarrow^{16}_{7} N +^{1}_{1} p \longrightarrow^{16}_{8} O(n,p)^{16}_{7}N \tag{2.2.4}$$

Chapter 3

Absorption , Moderation And Detection of Neutrons

3.1 Absorption and moderation of neutrons

Neutron absorption is the process in which an atomic nucleus will absorb a neutron. Many different atomic nuclei will do this, and different nuclei will present a larger or smaller target for the neutron .

As a beam of neutron travels through a bulk matter, the intensity will decreases as neutrons are removed from the beam by nuclear reactions. For fast neutrons, many reactions such as (n,p)(n,α) or (n,2n) are possible, but for slow or thermal neutrons the primary cause of their disappearance is capture,in the form of the (n,γ)reaction.Often the cross sections for these capture reactions are dominated by one or more resonances, where the cross section becomes very large.

Beams of neutron can be produced from a variety of nuclear reactions. We can not accelerate neutrons as charged particles, but we can start with high-energy neutron and reduce their energy through collisions with atoms of various materials. This slowing of neutron is called "**Moderating**" the neutrons.

In crossing a thickness dx of a material, the neutrons will encounter ndx atoms per unit surface area of the beam of the material. Where n is the number of atoms per unit volume of the material. If σ_t is the total cross section (including scattering processes, which will tend to divert neutrons from the beam), then the loss in intensity I is :

$$dI = -I\sigma_t n dx \tag{3.1.1}$$

And the intensity decreases with absorber thickness according to an exponential relationship:

$$I = I_0 e^{-\sigma_t n x} \tag{3.1.2}$$

Keep in mind that this expression refers only to mono energetic neutrons-the original intensity of neutrons of a certain energy decreases according to eq(3.1.2). Off course , we may at the same time be creating neutrons of lower energy (by scattering for example), which may have a very different cross section but this effect does not included in the above equation .We therefore,can not use it reliably to calculate the decrease in the total number of neutrons, only the change in intensity of those with the given initial energy.
Let's consider a non-relativistic, elastic collision between neutron of initial energy E, mass m and velocity v with a target of mass M initially at rest . Then from conservation of energy and linear momentum, the ratio between the final neutron energy $E^{'}$ and the initial energy E is given by:

$$\frac{E^{'}}{E} = \frac{M^2 + m^2 + 2mMcos\theta}{(M+m)^2} \tag{3.1.3}$$

For neutron scattering from a nucleus of mass A, we substitute m=1 and M=A

$$\frac{E^{'}}{E} = \frac{A^2 + 1 + 2Acos\theta}{(A+1)^2} \tag{3.1.4}$$

where θ is the scattering angle in the center of mass system but E and $E^{'}$ are measured in the laboratory system. For no scattering angle ($\theta = 0$),the above equation gives .

$$\frac{E^{'}}{E} = 1, \tag{3.1.5}$$

The maximum energy loss occurs for a head on collision ($\theta = 180^0$):

$$\left(\frac{E^{'}}{E}\right)_{min} = \left(\frac{A-1}{A+1}\right)^2 \tag{3.1.6}$$

Notice that for $A = 1$(scattering from hydrogen), the neutron gives all its energy to the struck proton. For neutrons energies of about $10Mev$ and below , the scattering is mostly S-wave and thus (in the center of mass system) largely independent of θ. The value of $E^{'}/E$ are uniformly distributed between $E^{'}/E = 1$ and the minimum value given by the above equation 3.1.5 and shown in figure 3.1a. Because each neutron will scatter many times , we must repeatedly calculate the energy loss. In the case of the second scattering, the incident neutrons are no longer mono energetic but rather are distributed as shown in figure 3.1a. we can approximate this effect by considering each interval of width $\triangle$E to be a new generation of approximately mono energetic neutrons giving shown in figure 3.1b. Continueing this process , we obtain the succeeding generations of energy distribution shown in figure 3.1c.[2]

To make the calculations more quantitative, we define the parameter ζ to represent the average value of $log(E/E^{'})$, the average logarithmic energy decreament after a single collision :

$$\begin{aligned} \zeta \quad &= \left[log\frac{E}{E'}\right]_{av} \\ &= \frac{\int log\left[\frac{(A+1)2}{A^2+1+2Acos\theta}\right]d\Omega}{\int d\Omega} \end{aligned} \tag{3.1.7}$$

Where dΩ is the elements of solid angle in the center of mass system .Here again we assume the scattering to be isotropic. Carrying out the integration gives :

$$\zeta = 1 + \frac{(A-1)^2}{2A} log\frac{A-1}{A+1} \tag{3.1.8}$$

For large A ($A > 10$) this formula can be approximated to :

$$\zeta = \frac{2}{A+2/3} \tag{3.1.9}$$

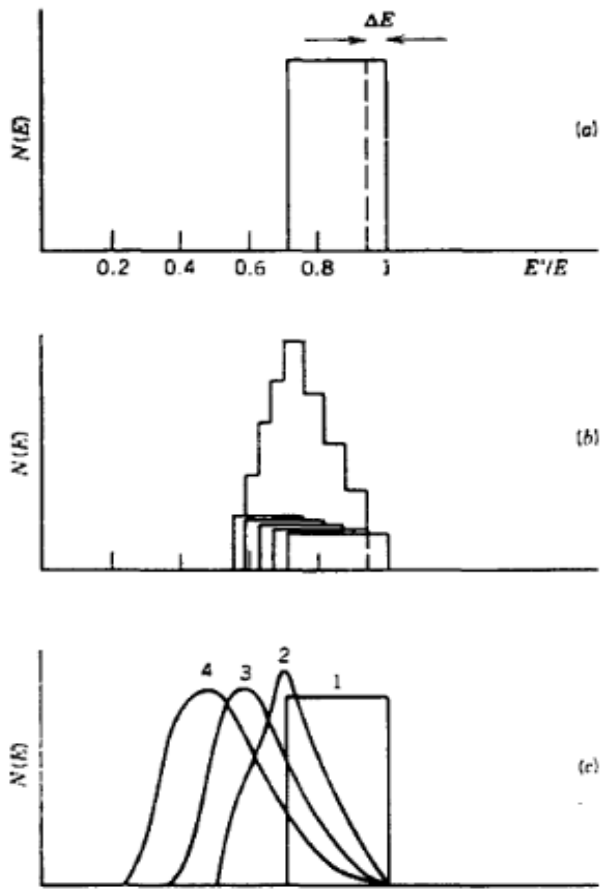

Figure 3.1: a) A mono energetic neutron of energy E gives after a single s-wave scattering from ^{12}C,a flat distribution of laboratory energies E' from 0.72E to E (b) dividing the scattered distribution in to five narrow ,nearly mono energetic distribution of width ΔE we get after a second scattering the five flat distributions shown,whose sum is the peaked distribution c) An exact calculation of the energy distribution after 1,2,3 and 4 scatterings

Heavy elements are poor moderators and light elements are good moderators, because for the value of A is enough large the energy loss fraction is very very smal or negligible.

If n_c is a number of collisions to reduce energy from E to $E^{'}$,

$$n_c = \frac{\ln(E/E^{'})}{\zeta} \tag{3.1.10}$$

And then the slowing down power is given by :

$$SDP = \zeta \sigma_{sca} N, \tag{3.1.11}$$

And the moderating ratio (MR) is given by:

$$MR = \frac{\zeta \sigma_s N,}{\sigma_a N,} \tag{3.1.12}$$

Where σ_s and σ_a are the scattering and absorption cross-section respectively. If σ_s is large SDP is also lare and if σ_a is large SDP is small. The average value of $logE^{'}$ is decreased after each collision by an amount ζ and after n collisions, the average value of $logE^{'}$ is $logE^{'}_n$:

$$logE^{'}_n = logE - n_c\zeta \tag{3.1.13}$$

which follows directly from equation 3.1.10. The following table 2 shows the value of ζ for some commonly used moderators. If our goal is to reduce the average neutron energy from that which is typical for neutrons emitted in fission (E$\sim$ $2Mev$) to that which is characterstics of thermal motion ($E^{'}_n \sim 0.025ev$), the number of generations of collisions is also shown in the table below.[1] The previous calculation has assumed that the atoms

Nucleus	ζ	n (for thermalization)
^1H	1.00	18
^2H	0.725	25
^4He	0.425	43
^{12}C	0.158	110
^{238}U	0.0084	2200

Table 3.1: Moderating Properties of Various Nuclei

from which the neutrons scattered to be at rest. This is certainly a good approximation for Mev neutrons ,but as thermal energies are approached. We find the thermal motion of the atoms of the moderator to be comparable to the speeds of the neutrons.The scattering in this case is better analyzed using statistical mechanics, and we can simply assume that after a sufficient time the neutrons will reach thermal equilibrium with the moderator at a temperature T. In this case the neutrons are described by a Maxwellian speed distribution:

$$f(v)dv = 4\pi n\left(\frac{m}{2\pi kT}\right)^{\frac{3}{2}} v^2 e^{\frac{-mv^2}{2kT}} dv \tag{3.1.14}$$

where f(v) gives the fraction of neutrons with speed between v and v + dv .Here m is the mass of neutrons and n is the total number of neutrons per unit volume.Rewriting this in terms of energy gives:

$$f(E)dE = \frac{2\pi n}{(\pi kT)^{\frac{3}{2}}} E^{\frac{1}{2}} e^{\frac{-E}{kT}} dE \tag{3.1.15}$$

Where f(E) is the fraction of neutrons having energy between E and E+dE. This shows the thermalizing effects of even a few generations of collisions [2]

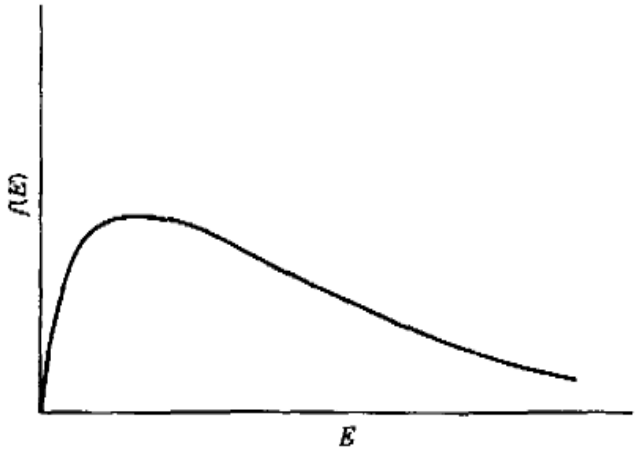

Figure 3.2: Maxwellian energy distribution ,a representation of the neutron energy spectrum after many scatterings

3.2 Neutron Detectors

A neutron detector does not record the presence of neutron directly but responds to secondary radiation (generally fast charged particles) which is emitted when the neutron undergoes a nuclear reaction in the detector medium. Because neutrons produce no direct ionization events ,neutron detectors must be based on detecting the secondary events produced by nuclear reactions , such as (n,p),(n,α),(n,γ) or (n,fission), or by nuclear scattering from light charged particles which are then detected. For slow and thermal neutrons ,the (n,p),(n,α) or (n,fission) reaction on light nuclei are among those most commonly used in

detectors.The process of neutron detection begins when neutrons, interacting with various nuclei, initiate the release of one or more charged particles. The electrical signals produced by the charged particles can then be processed by the detection system. Detectors employing either the recoil or reaction mechanism can use solid, liquid, or gas-filled detection media. Although the choice of reactions is limited, the detecting media can be quite varied, leading to many options.

The energy information obtained in neutron detection systems is usually poor because of the limitations of the available neutron-induced reactions. Recoil-type counters measure only the first interaction event. The full neutron energy is usually not deposited in the detector, and the only energy information obtained is whether a high or low-energy neutron initiated the interaction. Reaction-type counter take advantage of the increased reaction probability at low neutron energies by moderating the incoming neutrons. But knowledge of the initial neutron energy before moderation is lost. The energy recorded by the detector is the reaction energy (plus some of the remaining initial neutron energy). Thus, in general, neutron detectors provide information only on the number of neutrons detected and not on their energy. Information on the range of detected neutron energies can usually be inferred from the detector type and the surrounding materials.

Some of neutron detectors are gas-filled proportional counter, scintillators, fission chambers, ^{10}B-lined chamber and other types of neutron detectors. Gas-filled detectors were among the first devices used for radiation detection. They may be used to detect either thermal neutrons via nuclear reactions or fast neutrons via recoil interactions. After the initial interaction with the neutron has taken place, the remaining detection equipment is similar, although there may changes in high-voltage or amplifier gain settings to compensate for changes in the magnitude of the detected signal. Gas-filled thermal-neutron detectors use either BF_3 or ^3He. In the case of BF_3, the gas is enriched in ^{10}B. Fission chambers are a variation of the gas-filled counters ,which detect neutrons that induce fissions in fissionable material, coated on the inner walls of the chamber. Often

the exterior appearance of fission chambers is quite similar to that of other gas counters, although they are also available in smaller diameters or in other shapes. The fissionable material is usually uranium highly enriched in ^{235}U. Detectors lined with ^{10}B lie between ^{3}He and $^{10}BF_3$ proportional counters and fission chambers in terms of neutron detection efficiency and gamma-ray insensitivity. Structurally, ^{10}B-lined detectors are similar to fission chambers with the neutron-sensitive material, boron, plated in a very thin layer on the walls of the detector. Plastic and liquid (organic) scintillators are often used for fast-neutron detection because of their fast response and modest cost. Fast response is particularly beneficial for coincidence counting applications where the ratio of real to accidental coincidence events can have a significant impact on the statistical precision of measurement. Although organic scintillators have response times of a few nanoseconds, the coincidence resulting time for;assay applications is usually dictated by the dynamic range of neutron flight times (tens of nanoseconds) from the sample to the detectors. (A 500-keV neutron will traverse a flight path of 1m in 100 ns). The resolving times of coincidence counting systems that moderate fast neutrons prior to detection, on the other hand, are dominated by the dynamic range of times (tens of microseconds) required for thermalization.

The major disadvantage of organic scintillators in nondestructive assay applications is their high gamma-ray sensitivity. Detection probabilities for neutrons and gamma rays are comparable, and the pulse-height spectra resulting from monoenergetic radiation of both types are broad and overlapping. Hence, pulse height alone yields little information about particle type. In certain organic scintillators, however, electronic pulse-shape discrimination techniques can be used to effectively distinguish between neutron and gamma-ray interactions.

Some scintillators are manufactured with neutron-active material added to achieve enhanced neutron detection capability. The purpose is to achieve more localized and more rapid detection of neutrons than is possible with gas counters. Gadolinium, ^{10}B, and ^{6}Li

are typical materials loaded into the scintillator. The neutron-active material initiates the light production by releasing energetic charged particles or gamma rays when the neutron is captured. After the initial interaction with the neutron occurs the detection process is the same as if the light were produced by a gamma ray. Because the scintillator is also a gamma-ray detector, its gamma-ray sensitivity is generally very high. There are however, several possible configurations with good neutron detection efficiency and low gamma-ray sensitivity.[11],[12]

For slow and thermal neutrons ,detectors based on the (n,p),(n,α) reactions provide a direct means for observing neutrons from the signal left by the energetic p or α resulting from the reaction.The isotopes ^{10}B is commonly used,by producing an ionization chamber or a proportional counter filled with BF_3 gas or lined with boron metal or a boron compound.The reaction is

$$^{10}B + n \longrightarrow^{7} Li^* + \alpha$$

Where the ^7Li is preferentially left in an excited state with energy 0.48Mev(Natural boron consists of about 20 percent of the isotope ^{10}B ,so materials enriched in ^{10}B increase the efficiency of the detector). For thermal neutrons ,the cross section is about 3840b,a very large value and the cross section follows the 1/v law up to about 100Kev,so the dependence of cross section on incident energy is featureless(no resonances are present).

There is also an other advantage of the 1/v dependence of the cross section. Suppose we are observing a collimated beam of neutrons or an isotropic flux (perhaps near the core of a reactor) that has a velocity distribution of n(v)dv neutrons per unit volume with speeds between v and v + dv. The flux passing through a detector will be n(v)vdv and if the counter contain N boron nuclei each with cross section σ.The probability per second of an interaction (or counting rate, if we are able to detect and cout every interaction) is

$$dR = N\sigma n(v)vdv \tag{3.2.1}$$

this is for neutrons of speed between v and v + dv, but for neutrons of all speeds, the

total counting rate is

$$R = \int N\sigma n(v) v dv \tag{3.2.2}$$

$$= NC \int n(v) dv \tag{3.2.3}$$

Where the last step assumes that $\sigma \propto v^{-1}$,so that the product σ v is the constant C. The integral then gives the total number of neutrons per unit volume n , and the counting rate is

$$R = NCn \tag{3.2.4}$$

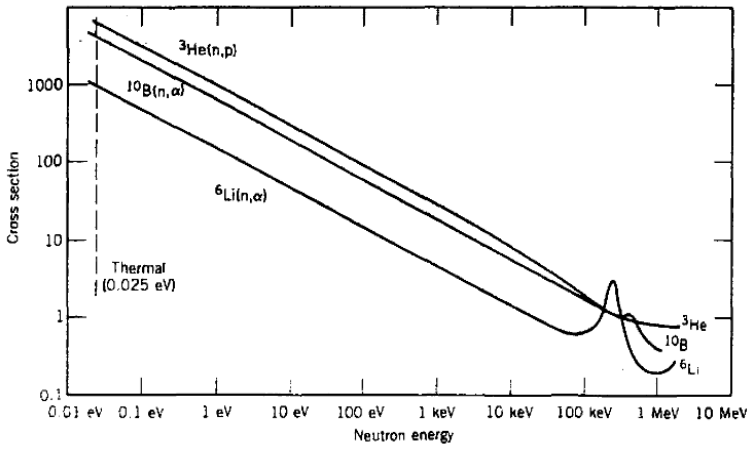

Figure 3.3: Neutron Cross sections for $^3He(n,p)$,$^{10}B(n,\alpha)$ and $^6Li(n,\alpha)$.The cross section shows the 1/v behavior for $E < 1$ Kev.But begins to show resonances above 100Kev.

That is,R is directly proportional to the neutron density for any distribution of velocities as long as we can neglect any distribution to the neutron flux out side the 1/v region of cross section.

The Q value for the reaction leading to the ^7Li excited state is $2.31Mev$, and for incident neutrons of kinetic energy small compared with this value.Momentum conservation requires the sharing of energy between ^7Li and α so that the α is given a kinetic energy of $1.47Mev$. The kinetic energy of the incident neutron ,if it is in ev or even Kev range ,Will not substantially this value . Unless either particle strike the wall,we will detect

simultaneously the ^7Li (T =$0.84Mev$) as well and the neutron then leaves as its signature a $2.31Mev$ energy loses in the counter .Because we can not measure Mev energies to ev or Kev precision in a proportional counter . We can not use such a device to measure such a low neutron energies.

Other similar devices are based on $^6Li(n,\alpha)$, with Q =$4.78Mev$ and $\sigma = 940b$ for thermal neutrons ,and $^3He(n,p)$ with Q =$0.765Mev$ and $\sigma = 5330b$.

Another way of measuring neutron intensities is by exposing the neutrons a material which becomes radioactive after neutron capture and which has a know capture cross sections for neutrons of particular energy. If we remove the material from the neutron flux and measure the induced radioactivity (using a γ detector), we can determine a neutron flux.

Among the earliest devices used for determining neutron energies were mechanical devices,for example the velocity selector, a rotating shatter made of a highly absorbing material ,such as Cd for thermal neutrons .this device is practical only for velocities in the thermal region, but it can be used to select neutrons from a continuous velocity distribution such as is produced by a reactor.

Another way of measuring velocities is through a variant of a time- of flight technique. If we have neutrons in a short pulse ,we can time their travel over a distance of several meters (Thermal neutrons have $v = 2200m/s$, and the time of travel is thus an easily measurable to 10^{-3}s). For higher energies,longer flight path of order $100m$ and increased sensitivity of short timing techniques can give accurate velocity measurements for neutrons up to Mev energies.The initial pulse of neutrons for a timing measurement can be provided by a " chopper " of the kind as shown in the figure ,or else by a pulsed-charged particle accelerator, in which the neutrons are produced through reactions such as stated in chapter two.If the initial pulse includes a wide range of velocities, the start-stope technique using a time to amplitude converter can display the energy spectrum of neutrons .

Very precise energy determination can be done in the thermal region using crystal

diffraction. Thermal neutrons have a de Broglie wave length of about $0.1nm$,about the same as the spacing between atoms in a crystal lattice. If a beam of thermal neutrons is incident on a crystal, the wave nature of the beam will be revealed through a set of interference maxima that occur at angles determined by the Bragg condition:

$$n\lambda = 2dsin\theta \tag{3.2.5}$$

where d is the lattice spacing ,n the order of the interference maximum and θ is the angle of incident.and reflected beams make with the surface of the crystal. This technique ,which is used frequently to study the crystalline properties or atomic spacing of materials .

For measurements of energies of fast neutrons, the most common method is to use the recoil following elastic scattering between the neutron and a light target (H,^{2} H,^{3} He,^{4} He, etc).This elastic scattering was previously discussed in neutron moderation . We can show that the scattered neutron has a continuous range of energies from $E' = E$ down to the minimum value given in equation 3.1.6. The struck nucleus has a corresponding recoil energy ranging from zero to maximum

$$E_R = E - E' \tag{3.2.6}$$

$$(E_R)_{max} = E - (E')_{min} \tag{3.2.7}$$

$$= E\frac{4A}{(A-1)^2} \tag{3.2.8}$$

For hydrogen ,$(E_R)_{max} = E$,while for $^3He, (E_R)_{max} = 0.75E$.

The proton recoil signal is normally observed by using a scintillating material that is reach in hydrogen, such as plastic or an organic liquid.The scintillator therefore serves as both the proton target for the neutron and the detector for the recoiling proton. Taking in to account the energy resolution of the scintillator and geometrical effects, the observed energy spectrum for mono energetic neutrons looks like the continuous distribution shown in the following figure. If the incident neutrons have several distinct energy components, the unfolding of the superimposed spectra of recoils may be difficult.

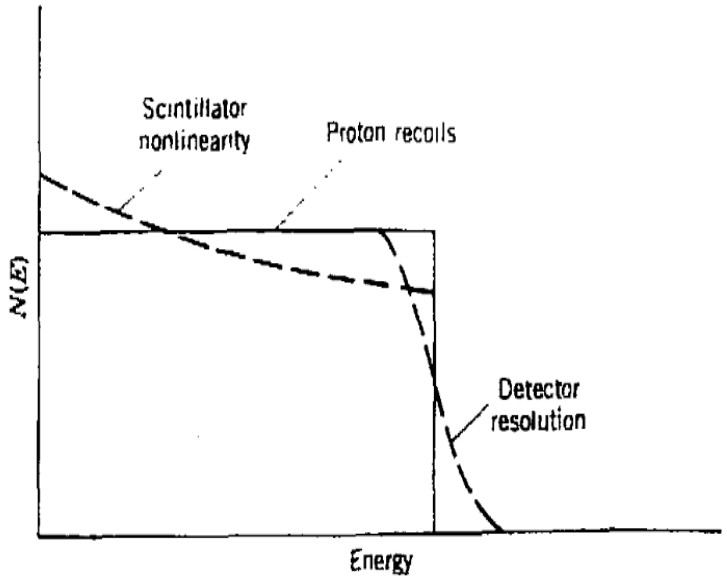

Figure 3.4: An ideal spectrum of proton recoils(from monoenergetic incident neutrons) can be distorted by detector resolution and scitillator nonlinearity

The efficiency of proton recoil scintillation detectors for Mev neutrons can be of the order of 50 percent.

3.3 Neutron Reaction and Cross Section

Cross section is a measure of the probability for a reaction between two particles to occur.Units of cross section is barn which has a dimension of area analogy with target size.Microscopic cross section defines probability of reactions between neutron and an individual particle or nucleus.example ^{235}U. Where as a macroscopic cross section defines a probability of interaction between neutron and some bulk materials, i.e, concrete. This types of cross section is related to a mean free pathλ, where λ is the average path length in material between two collisions.

3.3.1 Scattering and reaction cross section

In order to see some details of reaction cross section more thoroughly, let us take the Z-axis to be the direction of the incident beam and assume it can be represented by a plane wave e^{ikz} corresponding to momentum $P = \hbar k$. The out going particles will be represented by spherical waves and so the manipulations become easier if we express the incident plane wave as a super position of spherical waves:

$$\Psi_{inc} = Ae^{ikz} = A\sum_{\ell=0}^{\infty} i^l(2l+1)j_\ell(kr)p_\ell(cos\theta) \tag{3.3.1}$$

Where A is an appropriate chosen normalization constant .The radial functions $j_l(kr)$ are spherical Bessel functions ,which are solutions to the radial part of the schrödinger equation. In a region far from the target where the nuclear potential vanishes, the angular functions $p_\ell(cos\theta)$ are Legendre polynomials such that:

$$p_0(cos\theta) = 1$$

$$p_1(cos\theta) = cos\theta$$

$$p_2(cos\theta) = \frac{1}{2}(3cos^2\theta - 1) \tag{3.3.2}$$

This expansion of incident (and eventually the scattered) wave is called the partial wave expansion, with each partial wave corresponding to a specific angular momentum ℓ, such a procedure is valid if the nuclear potential is assumed to be central. If a particle of momentum p interacts with impact parameter b, then the semi-classical relative angular momentum will be :

$$\ell\hbar = pb \tag{3.3.3}$$

$$b = \frac{\ell\hbar}{p} = \frac{\ell\lambda}{2\pi}$$

Where $\lambda/2\pi$ represents a reduced de Broglie wave length . According to quantum mechanics ℓ can only be defined in integer units and thus the semi-classical estimate should

be revised some what. That is particles with angular momentum between $0\hbar$ and $1\hbar$ will interact through impact parameters between zero and $\lambda/2\pi$ and thus effectively over an area(cross section) of at most $\pi(\lambda/2\pi)^2$,with $\hbar \leq \ell \leq 2\hbar$,the cross section is a ring of inner radius $\lambda/2\pi$ and outer radius $2\lambda/2\pi = \lambda/\pi$ and thus of area $3\pi(\lambda/2\pi)^2 = 3(\lambda/2)^2/\pi$. We can thus divide the interaction area in to a number of zones each corresponding to a specific angular momentum ℓ and each having area $\pi[(\ell+1)(\lambda/2\pi)]^2 - \pi(\ell\lambda/2\pi)^2 = (2\ell+1)\pi(\lambda/2\pi)^2$ We can estimate the maximum impact parameter for nuclear scattering to be about $R = R_1 + R_2$ (the sum of the radii of the incident and target nuclei) and thus the maximum ℓ value likely to occur is $R/(\lambda/2\pi)$ and the total cross section is correspondingly:

$$\sigma = \sum_{\ell=0}^{2R\pi/\lambda} (2\ell+1)\pi(\lambda/2\pi)^2 = \pi(R+\lambda/2\pi)^2 \tag{3.3.4}$$

This is a reasonable estimate, for it includes not only an interaction distance R,but also it allows the incident particles wave nature to spread over a distance of the order of $(\lambda/2\pi)$, making the effective interaction radius $(R+\lambda/2\pi)$.

When the wave is far from the nucleus, the $j_\ell(kr)$ have the following convenient expansion:

$$j_\ell(kr) = \frac{sin(kr-\ell\pi/2)}{kr}, (kr \gg \ell) \tag{3.3.5}$$

$$= i\frac{e^{-i(kr-\ell\pi/2)} - e^{i(kr-\ell\pi/2)}}{2kr} \tag{3.3.6}$$

So that,

$$\psi_{inc} = \frac{A}{2kr}\sum_{\ell=0}^{\infty} i^{\ell+1}(2\ell+1)\left\{e^{-i(kr-\ell\pi/2)} - e^{i(kr-\ell\pi/2)}\right\}p_\ell(cos\theta) \tag{3.3.7}$$

The first term in bracket , involving e^{-ikr} represents an incoming spherical wave converging on the target, while the second term in e^{ikr} represents an out going spherical waves given in a plane wave.

The scattering can affect only the out going wave, and can affect it in either of the two ways; through a change in phase and through a change in amplitudes. The change in amplitude suggests that there may be fewer particles coming out than there were going in, which may appear to be a loss in the net number of particles. However, keep in mind that, the wave function represents only those particles of momentum $p = \hbar k$. If there is inelastic scattering or some other nuclear reactions, the energy or even the density of the out going particles may change.

It is there fore not surprising that there may be fewer particles in the e^{ikr}term following inelastic scattering. It has become customary to refer to a specific set of conditions (exclusive of directions of travel) of the outgoing particles and residual nucleus as a reaction channel. The reaction may thus proceed through the elastic channel or through any one of many inelastic channels. Some channels may be closed to the the reacting particles, if there is not enough energy or angular momentum to permit a specific final configuration to be reached.

We account for the change in the ℓ^{th} out going partial wave by introducing the complex coefficient η_ℓ in to the out going term of equation 3.3.7

$$\psi = \frac{A}{2kr}\sum_{\ell=0}^{\infty} i^{\ell+1}(2\ell+1)\Big\{e^{-i(kr-\ell\pi/2)} - \eta_\ell e^{i(kr-\ell\pi/2)}\Big\}p_\ell(cos\theta) \tag{3.3.8}$$

The wave represents a superposition of the incident and scattered wave $\psi = \psi_{inc} + \psi_{sc}$. To find the scattered wave itself, we subtract equation 3.3.7 from equation 3.3.8, we got

$$\begin{aligned}\psi_{sc} &= \frac{A}{2kr}\sum_{\ell=0}^{\infty} i^{\ell+1}(2\ell+1)(1-\eta_\ell)e^{i(kr-\ell\pi/2)}p_\ell(cos\theta) \\ &= \frac{A}{2k}\frac{e^{ikr}}{r}\sum_{\ell=0}^{\infty}(2\ell+1)i(1-\eta_\ell)p_\ell(cos\theta)\end{aligned} \tag{3.3.9}$$

Because we have accounted for only those parts of ψ_{sc} with wave number k identical with the incident wave, this represents only elastic scattering.Now we can find the scattered current density:

$$\begin{aligned} j_{sc} &= \frac{\hbar}{2mi}\left(\psi^*_{SC}\frac{\partial\psi_{sc}}{\partial r} - \frac{\psi_{sc}\partial\psi^*_{sc}}{\partial r}\right) \\ &= |A|^2\frac{\hbar}{4mkr^2}\left|\sum_{\ell=0}^{\infty}(2\ell+1)i(1-\eta_\ell)p_\ell(cos\theta)\right|^2 \end{aligned} \tag{3.3.10}$$

And the incident current density is :

$$j_{inc} = \frac{\hbar\kappa}{m}|A|^2 \tag{3.3.11}$$

The differential cross section $d\sigma/d\Omega$ is the probability per unit solid angle that an incident particle is scattered in to the solid angle $d\Omega$; the probability $d\sigma$ that an incident particle is scattered in to $d\Omega$ is the the ratio of the scattered current density through $d\Omega$ to the incident current :

$$d\sigma = \frac{(j_{scattered})(r^2 d\Omega)}{j_{incident}} \tag{3.3.12}$$

Then the differential cross section is :

$$\frac{d\sigma}{d\Omega} = \frac{1}{4k^2}\left|\sum_{\ell=0}^{\infty}(2\ell+1)i(1-\eta_\ell)p_\ell(cos\theta)\right|^2 \tag{3.3.13}$$

To find the total cross section , we require the integral of the Legendre polynomials :

$$\int p_\ell(cos\theta)p_{\ell'}(cos\theta)sin\theta d\theta d\phi = \begin{cases} \frac{4\pi}{2\ell}, if \ell = \ell' \\ 0, if \ell \neq \ell \end{cases} \tag{3.3.14}$$

Thus

$$\sigma_{sc} = \sum_{\ell=0}^{\infty}\pi(\lambda/2\pi)^2(2\ell+1)|1-\eta_\ell|^2 \tag{3.3.15}$$

If elastic scattering were the only process that could occur ,then $|\eta_\ell| = 1$ and it is conventional to write $\eta_\ell = e^{2i\delta_\ell}$, where δ_ℓ is the phase shift of the ℓ^{th} partial wave. For this case ,$|1-\eta_\ell|^2 = 4sin^2\delta_\ell$ and hence

$$\sigma_{sca} = \sum_{\ell=0}^{\infty} 4\pi(\lambda/2\pi)^2(2\ell+1)sin^2\delta_\ell \tag{3.3.16}$$

For $\ell = 0$ this equation reduces directly to:

$$\sigma_{sca} = 4\pi\frac{d\sigma}{d\Omega} = 4\pi\frac{sin^2\delta_0}{k^2} \tag{3.3.17}$$

If there are other processes in addition to elastic scattering (inelastic scattering or other reactions) then equation 3.3.16 is not valid, because $|\eta_\ell| < 1$. We group all of the above processes together under the term reaction cross section σ_r,where we take "reaction" to mean all nuclear processes except elastic scattering. To find this cross section ,we must examine equation 3.3.8 to find the rate at which particles are "disappearing" from the channel with wave number k. That is , we find the difference between the incoming current and the outgoing current using,the 1^{st} and 2^{nd} terms in equation 3.3.8 respectively :

$$|j_{in}| - |j_{out}| = \frac{|A|^2\hbar}{4mkr^2}\left\{\left|\sum_{\ell=0}^{\infty}(2\ell+1)i^{\ell+1}e^{i\ell\pi/2}p_\ell(cos\theta)\right|^2 - \left|\sum_{\ell=0}^{\infty}(2\ell+1)i^{\ell+1}e^{-i\ell\pi/2}p_\ell(cos\theta)\right|^2\right\} \tag{3.3.18}$$

And the reaction cross section becomes:

$$\sigma_r = \sum_{\ell=0}^{\infty}\pi(\lambda/2\pi)^2(2\ell+1)(1-|\eta_\ell|)^2 \tag{3.3.19}$$

The total cross section including all processes is

$$\sigma_t = \sigma_{sc} + \sigma_r \tag{3.3.20}$$

$$= \sum_{\ell=0}^{\infty} 2\pi(\lambda/2\pi)^2(2\ell+1)(1-Re\eta_\ell) \tag{3.3.21}$$

From this result ,we should note that :

1) It is possible to have elastic scattering in the absence of other processes , that is, if $|\eta_\ell| = 1$,then equation 3.3.19 vanishes. It is not possible ,however,to have reactions with out also having elastic scattering . That is , any choice of η_ℓ for which $\sigma_r \neq 0$ for a

given partial wave automatically gives $\sigma_{sca} \neq 0$ for that partial wave. 2) For a "black disk" absorber as equation 3.3.4, in which all partial waves are completly absorbed up to $\ell = R2\pi/\lambda(\eta_{\ell=0})$ for complete absorption and unaffected for $\ell > 2\pi R/\lambda(\eta_\ell = 1)$ then,

$$\sigma_{sca} = \pi(R + \lambda/2\pi)^2 \tag{3.3.22}$$

And

$$\sigma_r = \pi(R + \lambda/2\pi)^2 \tag{3.3.23}$$

So that:

$$\sigma_t = 2\pi(R + \lambda/2\pi)^2 \tag{3.3.24}$$

The total cross section is twice the geometrical area.The explanation for this non classical effect can also be found in the "shadow" region, the target nucleus can not simply absorb and throw a sharp shadow.

3.3.2 Resonance Reaction

The compound nucleus model of nuclear reactions treats the unbounded nuclear states as if they formed a structureless continuum. That is,there may be discrete nuclear states ,but there are so many of them and they are so close together that they form a continuous spectrum. Each of these supposed discrete states is unstable against decay and therefore has a certain width; when the state are so numerous that their spacing is much less than the width of the individual states , the compound nucleus continuum results. To obtain a quantitative understanding of the formation of resonances, we represent the nuclear potential seen by the captured particle as a square well. The oscillatory wave functions inside and out side the well must be matched smoothly. Depending on the phase of the wave function inside the nucleus,the smooth matching can result in substantial variations between the relative amplitudes of the wave functions inside and out side the nucleus. In case (a) the incident particles has relative little probability to penetrate the nucleus and form a quasi bound state; in case (c), there is a very high probability to penetrate.As we

vary the energy of the incident particle,we vary the relative phase of the inner and outer wave functions.[2],[4]

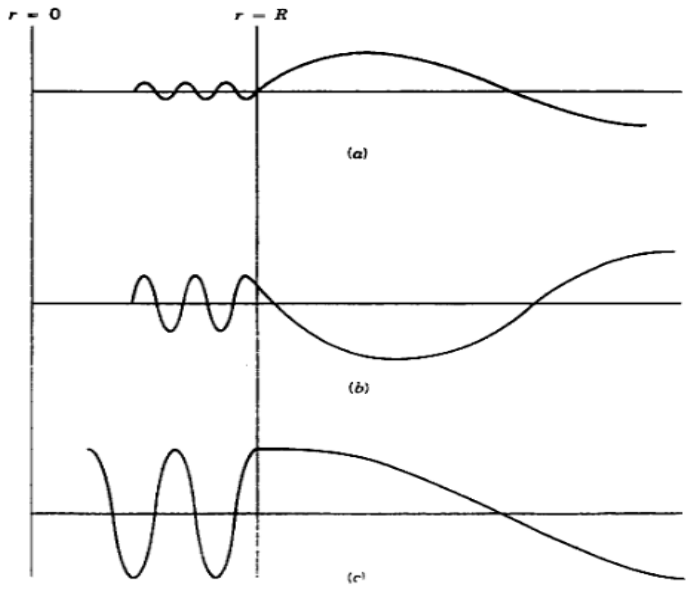

Figure 3.5: (a) Far from the resonance ,the interior and exterior wave functions match badly ,and little penetration of the nucleus occurs (b)As the match improves ,There is a higher probability to penetrate (c)At resonance the amplitudes match exactly,the incident particle penetrate easily and the cross section rises to maximum

In a single isolated resonances of energy E_R and width Γ, the energy profile of the cross section in the vicinity of the resonance will have the character of the energy distribution of any decaying state of life time $\tau = \hbar/\Gamma$. The resonance will occur where the total cross section has a maximum. From equation 3.3.21, assuming only one partial wave ℓ is important for the resonant state, there will be a scattering resonance where $\eta_\ell = -1$, corresponding to a phase shift $\delta_\ell = \pi/2$. The shape of the resonance can be obtained by expanding the phase shift about the value $\delta_\ell = \pi/2$. Better convergence of the Taylor series expansion is obtained if we expand the cotangent of δ_ℓ:

$$cot\delta_\ell(E) = cot\delta_\ell(E_R) + (E - E_R)\left(\frac{\partial cot\delta_\ell}{\partial E}\right)_{E=E_R} + 1/2(E - E_R)^2\left(\frac{\partial^2 cot\delta_\ell}{\partial E^2}\right)_{E=E_R} + ... \tag{3.3.25}$$

In which $(\partial cot\delta_\ell/\partial E)_{E=E_R} = -(\partial\delta_\ell/\partial E)_{E=E_R}$ Defining the the width Γ as :

$$\Gamma = 2(\frac{\partial\delta_\ell}{\partial E})^{-1}_{E=E_R} \tag{3.3.26}$$

Then it can be shown the second order term vanishes, and neglecting higher order term.

$$cot\delta_\ell = -\frac{(E-E_R)}{\Gamma/2} \tag{3.3.27}$$

Because Γ is the full width of the resonance, the cross sections should fall to half of the central value at $E-E_R = \pm\Gamma/2$. From the above equation, this occurs when $cot\delta_\ell = \pm 1$,or $\delta_\ell = \pi/4, 3\pi/4$ (compared with $\delta_\ell = \pi/2$ at the center of the resonance).The cross section depends on $sin^2\delta_\ell$,which does indeed fall to half the central value at $\delta_\ell = \pi/4$ and $3\pi/4$ From equation 3.3.27,we found that :

$$sin\delta_\ell = \frac{\Gamma/2}{\left[(E-E_R)^2 + (\Gamma/2)^2\right]^{1/2}} \tag{3.3.28}$$

And the scattering cross section becomes using equation 3.3,28 and 3.3.16

$$\sigma_{sc} = \pi(2\ell+1)/k^2 \frac{\Gamma^2}{(E-E_R)^2 + \Gamma^2/4} \tag{3.3.29}$$

This result can be generalized in two ways .First we account for the effective of reacting particles with spin .If S_a and S_x are the spins of the incident and target particles and if I is the total angular momentum of the resonance ,

$$I = S_x + S_a + \ell \tag{3.3.30}$$

Then the factor $(2\ell+1)$ should be replaced by the more general statistical factor :

$$g = \frac{2I+1}{(2S_a+1)(2S_x+1)} \tag{3.3.31}$$

Note that g reduces to $(2\ell+1)$ for spin less particles . The second change we must make is to allow for partial entrance and exit widths.If the resonance has many ways to decay ,then the total width Γ is the sum of all the partial width Γ_i :

$$\Gamma = \sum_i \Gamma_i \tag{3.3.32}$$

The Γ^2 factor in the denominator of equation 3.3.29 is related with to the decay width of the resonant state and therefore to its life time: $\Gamma = \hbar/\tau$ .The observation of only a single entrance or excite channel does not affect this factor, for the resonance always decays with the same life time τ.The Γ^2 factor in the numerator ,on the other hand ,is directly related to the formation of the resonance and to its probability to decay in to a particular exit channel.In the case of elastic scattering for which equation 3.3.29 was derived, the entrance and exit channels are identical.That is ,for the reaction $a + x \longrightarrow a + x$, we should use the partial widths Γ_{ax} of the entrance and exit channels:

$$\sigma = \frac{\pi g}{k^2} \times \frac{(\Gamma_{ax})^2}{(E - E_R)^2 + \Gamma^2/4} \tag{3.3.33}$$

Similarly for the reaction $a + x \longrightarrow b + y$ a different exit width must be used :

$$\sigma = \frac{\pi g}{k^2} \frac{\Gamma_{ax}\Gamma_{by}}{(E - E_R)^2 + \Gamma^2/4} \tag{3.3.34}$$

These two equations are examples of a Breit-Wigner formula for a shape of a single ,isolated resonance. Many elastic scattering resonances have shape slightly different from that suggested by the Breit-Wigner formula.This originates with an other contribution to the reaction amplitude from direct scattering ,the incident particle by the nuclear potential ,without forming the resonant state. The alternative process is called potential scattering or shape elastic scattering. Potential scattering and resonance scattering both contribute to the elastic scattering amplitude and interference between the two processes causes variation in the cross section . Interference can cause the combined cross section to be smaller than it would be for either process alone. It is therefore, not correct simply to add the cross sections for the two processes. We can account for the two processes by writing

$$\eta_\ell = e^{2i(\delta_{\ell R} + \delta_{\ell p})} \tag{3.3.35}$$

Where $\delta_{\ell R}$ is the resonance phase shift and $\delta_{\ell p}$ is an additional contribution to the phase

shift from potential scattering. From equation 3.3.15, we find the cross section as

$$\sigma_{sc} = \frac{\pi(2\ell+1)}{k^2}\left|e^{-2i\delta_{\ell p}} - 1 + \frac{i\Gamma}{(E-E_R)+i\Gamma/2}\right|^2 \tag{3.3.36}$$

Far from the resonance, $(E - E_R) \gg \Gamma/2$ the potential scattering term dominates,

$$\sigma \cong \sigma_{pot} = \frac{4\pi}{k^2}(2\ell+1)sin^2\delta_{\ell p} \tag{3.3.37}$$

At $E = E_R$, the resonant term dominates and

$$\sigma \cong \sigma_{res} = \frac{4\pi}{k^2}(2\ell+1) \tag{3.3.38}$$

Neutrons do not experience a coulomb barrier and can fuse at a very low energies. Infact the probability increases as the energy is reduced ,varying inversely as the neutron velocity. The effect is known as the '1/v' law, which was discovered by Fermi when he found that neutron induced reaction rates increased dramatically when he slowed the neutrons down.

Let us consider the 1/v dependence of the low energy neutron cross section. We obtain an estimate for the reaction cross section $\sigma_r = \pi(R + \lambda/2\pi)^2$ based on a total absorption model.A primary modification to this estimate would include the reflection of the incident neutron wave function at the nuclear surface-how likely is it that the incident particle will penetrate to the region of nuclear potential. The transmission probability for a rectangular potential barrier is given by

$$T = \frac{j_{transmitted}}{j_{incident}} = \frac{4k_2/k_1}{(1+k_2/k_1)^2} \tag{3.3.39}$$

Then the cross section is estimated as

$$\sigma = \pi(R + \frac{\lambda}{2\pi})^2\frac{\frac{4k_2}{k_1}}{(1+\frac{k_2}{K_1})^2} = \pi(R+\lambda/2\pi)^2\frac{4k_1k_2}{(k_1+k_2)^2} \tag{3.3.40}$$

Where $k_1 = \sqrt{\frac{2mE}{\hbar^2}}$ and$k_2 = \sqrt{\frac{2m(E-V_0)}{\hbar^2}}$ for a barrier of depth $-v_0$ For low energy neutrons ,$E \ll V_0$ and $k_1 \ll k_2$,also $\lambda/2\pi = k^{-1} \gg R$,so

$$\sigma \cong \frac{4\pi}{k_1k_2} \tag{3.3.41}$$

and since $k = p/\hbar = mv/\hbar$,we have the $1/v$ dependence of the cross section.

A similar result can be obtained from quite an other approach ,using the single level resonance formula, following neutron capture, the primary decay mechanism is $\gamma-$emission the probability for which is virtually independent of any small variation in the resonance or incident energy.We can therefore take Γ as independent of the neutron energy. The neutron width Γ_n which refers to the entrance channel,is dependent on the density of final states dn/dE available to the captured neutron, which is proportional to the velocity of neutron.This is some what similar to $\alpha-$decay in which the decay probability includes a factor proportional to v that originates from considering the frequency with which the α-particle presents itself to the nuclear barrier in preparation for decay.Far from the resonance ,$E \ll E_R$ and

$$\sigma \cong \frac{\pi}{k^2} \frac{\Gamma_n \Gamma}{E_R^2 + \Gamma^2/4} \propto \frac{1}{v} \tag{3.3.42}$$

,where $\Gamma_n \propto v$

As indicated by the cros sections plotted in figure 3.3, the 1/v law is followed quite accurately for reactions far from the resonance region.In the resonance region there is no exact theory for predicting the location of the resonances;the structure may be dominated by a single isolated resonance.

Chapter 4

Some Basic Applications of Neutron Physics

Neutrons plays an important role in many nuclear reactions.For example, neutron capture often results in neutron activation ,inducing radioactivity. Neutron capture reaction can be used to determine the energy and spin parity assignments of the capturing states. When the (n,γ)reaction occurs, the ground state (or a long-lived isomeric state) of $A^{'}$ is itself radioactive. We therefore accumulate activity of $A^{'}$ (usually with out bothering to observe the decay of $\gamma^{'}$s from the capture state). The activity builds up according to the following equation:

$$A_1(t) = \lambda_1 N_1(t) = R(1 - e^{-\lambda_1 t}) \tag{4.0.1}$$

Where N_1 is number of radioactive nuclei,λ_1 is decay constant, R is production rate and t is an irradiation time or a time required to decay the nuclei.

The above equation can be expressed in the following useful form:

$$A_1 = 0.602 \frac{\phi}{3.7 \times 10^{10}} \frac{m}{A} \sigma (1 - e^{-\lambda t}) \tag{4.0.2}$$

Where A_1 is the activity in Curies,m/A is dimensionless ratio between the mass of the target and its atomic mass, σ is the capture cross section and ϕ is the neutron flux in neutrons/cm^2/sec and t is the duration of the neutron bombardment.

This technique has a variety of applications with a known cross section(σ). But the most

common application is to use cases with known ϕ and σ to do qualitative analysis to determine m. After exposing an unknown sample to neutrons, we can observe many different radiations from the radioactive decays of those isotopes that can be produced by neutron capture.Careful measurements of the γ-ray spectrum permits the determination of which isotopes are present and at what quantities. Thus we can deduce the original quantities present in the irradiated sample. This technique is called Neutron Activation Analysis(NAA) and it has important applications in a variety of areas including environmental pollution research, Archeology and forensic science

In particular, knowledge of neutron and their behavior has been important in the development of nuclear reactors and nuclear weapons. The fissioning of elements like Uranium -235 and Plutonium-239 is caused by their absorption of neutrons.

Cold, thermal and hot neutron radiation is commonly employed in neutron scattering facilities, where the radiation is used in a similar way one uses X-rays for the analysis of condensed matter. Neutrons are complementary to the latter interms of atomic contrasts by different scattering cross sections;sensitivity to magnetism;energy range for inelastic neutron spectroscopy; and deep penetration into matter.

The developments of "neutron lenses" based on total internal reflection with in hallow glass capillary tubes or by reflection from damped aluminum plates has driven ongoing research in to neutron microscopy and neutron/gamma ray tomography. A major use of neutron is to excite delayed and prompt gamma rays from elements in materials .This forms the basis of neutron activation analysis (NAA) and prompt gamma neutron activation analysis (PGNAA). NAA is most often used to analyzed subterranean rocks arround bore holes and industrial bulk materials on conveyor belts. Another uses of neutron emitters is the detection of light nuclei,particularly the hydrogen found in water molecules. When a fast neutron collides with a light nucleus, it loses a large fraction of its energy .By measuring the rate at which slow neutrons return to the probe after reflecting of hydrogen nuclei, a neutron probe may determine the water content in soil.

4.1 Therapeutic Nuclear Medicine

The primary use of nuclear radiations in therapy is in the destruction of unwanted or malfunctioning tissue in the body ,such as cancerous tumor or an over acting thyroid gland. This effect originates with the ionizing ability of nuclear radiations. In essence, the destruction of tissue proceeds as follows:

1)The incident radiations ionize atoms in molecules of the irradiated material.This physical change occurs on a time scale of 10^{-16}s or less.

2)The ionized molecules participate in chemical reactions that give rise to free radicals or other exited molecules, and this occurs with in $(10^{-15} - 10^{3})$s.

3)Then this free radicals incorporated in to complex biological structures at the molecular level and altered their biological function.This change to become apparent, it may takes hours to years.

It is possible to have direct action by radiation on the biological sensitive molecules,because the human body is about 80 percents water. However, it is most likely that the radiation will produce ionization events with water molecules and water molecule can be ionized by incident radiation as :

$$H_2O \longrightarrow H_2O^+ + e^- \tag{4.1.1}$$

And the free electron can be captured by an other neutral water molecule to produce a molecule with excess negative charge:

$$H_2O + e^- \longrightarrow H_2O^- \tag{4.1.2}$$

Both H_2O^+ and H_2O^- are unstable ions and can dissociate as follows

$$H_2O^+ \longrightarrow H^- + OH^+ \tag{4.1.3}$$

$$H_2O^- \longrightarrow H^+ + OH^- \tag{4.1.4}$$

In each case, the result is an ion (H^-, OH^-) and a free radical(H^+, OH^+). The free radical is electrically neutral atom or molecules which has a free electron to participate in chemical bonding.this free electrons has a strong tendency to participate in to a chemical reactions ancd leads to a more stable paired configuration,these free radicals are extremely reactive with in about 10^{-6} seconds.They will react along the following paths in an environment of pure water :

$$H + H \longrightarrow H_2$$

$$OH^+ + OH^+ \longrightarrow H_2O2$$

$$H^- + OH^+ \longrightarrow H_2O$$

$$H_2O + H^- \longrightarrow H_2 + OH^+ \tag{4.1.5}$$

In organic matter, we can simplify the structure of a complex hydrogen containing biological molecule as the combination RH of a free radical R with hydrogen . The free radicals H^+ and OH^+ can combine with this molecules as :

$$OH^+ + RH \longrightarrow R^+ + H_2O$$

$$H^+ + RH \longrightarrow R^+ + H_2 \tag{4.1.6}$$

In either case, the result is the production of a free radical which may be parts of a biological more complex system(example chromosome) and may alter the function that system, possibly causes its death or alternatively changing the genetic information (genetic mutation).

The radiation may interact directly with the molecule RH with out the intermediate step of producing free radicals from water .this is accomplished by direct ionization followed by dissociation.

$$RH \longrightarrow RH^+ + e^-$$

$$RH^+ \longrightarrow R^- + H^+ \tag{4.1.7}$$

Again resulting in a free radical R^-.

If the irradiated material is rich in oxygen, an other set of processes is possible.

$$R^- + O_2 \longrightarrow RO_2^- \tag{4.1.8}$$

and the organic peroxyradical RO_2^- can interact with another RH molecule;

$$RH^- + RH \longrightarrow RO_2H + R^- \tag{4.1.9}$$

resulting in yet another free radical R^-,which can initiate a new set of processes(this is analogous to the chain reaction in neutron-induced fission). Another process that occurs with oxygen is

$$O_2 + e^- \longrightarrow O_2^- \tag{4.1.10}$$

Because O_2 has a larger electron affinity, the capture of the electron by O_2 not only can initiate an alternative set of chemical reaction but also can prevent the free electron from recombining with the original ions produced by the interaction of the radiation; thus the radiation damage is not able to be "*healed*" through the recapture of the electrons. This oxygen effect results in highly oxygenated tissue having a greater sensitivity to radiation and thus irradiated tissue that is rich in oxygen has a smaller survival rate than tissue that is less rich in oxygen. From the stand point of treatment of tumors with radiation,this is some what of unfortunate situation. For tumors generally have an inferior blood supply compared with normal tissue and thus less well oxygenated. The oxygen effect results in tumors being less sensitive to radiation than the surrounding tissue.

4.2 Interference and Diffraction with Neutrons

Beams of neutrons can provide an excellent way to observe effects depending on the wave behavior of material particles. We can see examples of the diffraction of nucleons

in scattering from nuclei, when the wave length of the incident particles is comparable to the nuclear size. By moving to other range of wave lengths however,we can observe effects such as single and double slit or thin film interference, which are more frequently demonstrated only with optical radiations.

Probably the most frequent application of neutron interference is in the diffraction of neutrons by crystals. The diffraction can be used to provide a source or a detector of mono energetic neutrons, or it can be used to study crystal structure of materials. For neutrons whose wave lengths are about the same order as the crystalline atomic spacing d, interference results in an apparent "reflection" from planes drawn through atoms of the lattice. Typically atomic spacing in solids are of order $0.1nm$ and a de Broglie wavelength of $0.1nm$ corresponding to thermal neutron energies. The choice of a particular set of reflection planes, is arbitrary; Corresponding to different angle θ and different spacing d. In three dimensions, we can specify the choice of planes with a set of indices that give essentially the number of fundamental lattice spacings along the three coordinate axes.

The intensity at any particular reflection may be a complicated function of crystal properties and neutron scattering amplitudes (which may involve coherent sums over different isotopes that may be present in the crystal).

The scattering sample in these case is a powder consisting of many micro crystals, so that all possible orientations are simultaneously observed.

An alternative approach would be to begin with a beam of neutrons containing a mixture of energies, such as might be obtained from a reactor.If the beam falls on a scattering crystal at a certain angle, we will observe mono energetic neutrons that satisfy the Bragg condition given in equation 3.2.5 (assuming that the same angle does not happen to satisfy the Bragg condition for a different wave length and set of crystal planes). If we change the angle θ slightly, the same Bragg condition will be satisfied for slightly a different wave length or energy. We thus have a neutron monochromator ,a source of neutron of any particular energy with a spread in energy determined by the angular spread of the beam.

Powder diffraction patterns can be used to deduce the type of crystal structures, as in the cubic lattice characteristics of nickel .Similar studies are possible for more complex systems,including the relatively disordered structures of liquids and glasses, and the exceedingly complicated structure of biological molecules.

The primary mechanism for neutron scattering is the nuclear scattering. An alternative mechanism is magnetic scattering in which the neutron magnetic moment scatters from the electronic magnetic moment.If it is possible to separate nuclear from magnetic scattering (for instance, by using polarized neutrons). It is possible to deduce magnetic structures ,which can be more complicated and more interesting than the physical arrangement of atoms in the lattice. The following figure shows the neutron diffraction pattern of MnO above and below the Neel temperature, which is for anti ferromagnet that the curie temperature is for ferromagnet. Below the Neel temperature , MnO is anti ferromagnet in which there are alternative layers with opposite spin orientations. (In a ferromagnetic structure ,all spins will be parallel). Figure 4.1 shows a representation of the structure.

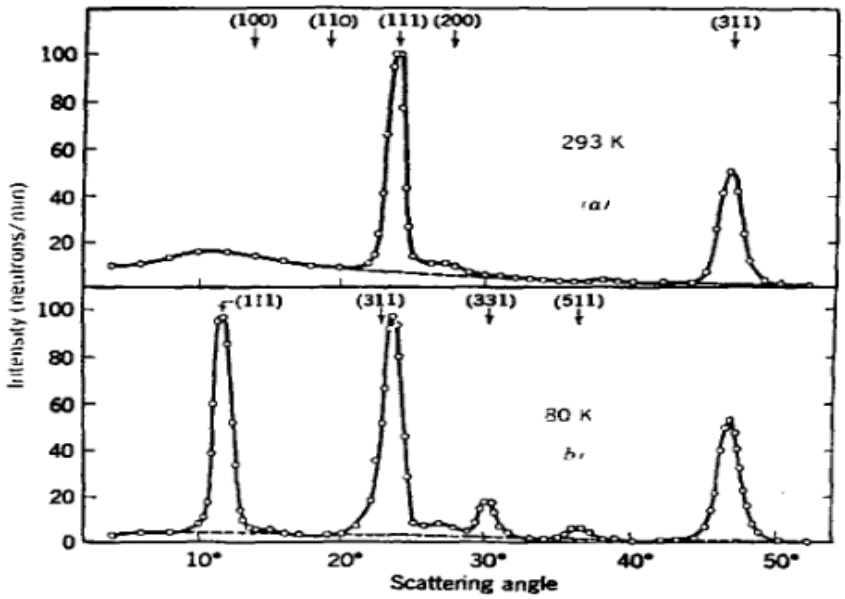

Figure 4.1: The neutron diffraction pattern of MnO above(a) and below(b) the antiferromagnetic transition temperature

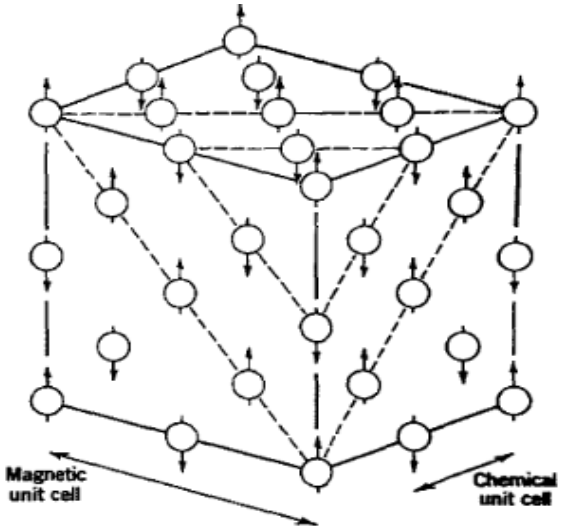

Figure 4.2: The crystal structure of MnO ,in the anti ferromagnetic structure, the lattice repeats over the distance of $2a$ (where a is the spacing of Mn atoms) while at high temperature the spins are all aligned and the lattice repeats over a distance of a

The basic distance needed for the structure to repeat itself (called unit cell dimension) is twice what it would be if we were above the Neel temperature where the the magnetic structure repeats in nano alternating fashion. There is a factor of two(2) difference in the basic distance d that appears in the Bragg equation and the result is that the peaks for magnetic scattering appear at values of θ such that $sin\theta$ is half what it would be for nuclear scattering.

The rare earth metals have rather similar crystal structures of the hexagonal type. But very different magnetic properties that also change with temperature as in the case of MnO. In some cases the electronic magnetic moment is perpendicular to the hexagonal plane.But may be modulated in unusual ways from one layer to the next, as for example several layers pointing up and then several down or else sinusoidally. In other structures, the electronic moment lies in the hexagonal plane, but it rotates through a certain angle from one layer to the next. These magnetic structures can be studied only through neutron diffraction.

Chapter 5

Conclusion

As we have discussed in this paper, there are different categories of neutron sources. Some of these are Photo neutron sources, Spontaneous fission sources, Reactor sources, Radioisotope sources and nuclear reaction sources. Photo neutron source (γ, n) is similar to (α, n) neutron sources, but in photo neutron source we can make the neutron nearly more mono energetic. Among these neutron sources, the isotopic neutron source is the most convenient choice for University's laboratory work. Because they have a unique advantage of being small, portable, reliable and relatively cheap.

Neutron interaction with nuclei can be categorized in to two. These are : scattering,in which a neutron emerges from the reaction and absorption in which the neutron is absorbed in to the nucleus and some thing different emerges.

Neutrons can be absorbed by the atomic nuclei. This process can be done by many atomic nuclei and different nuclei will present a larger or smaller target for the neutron. As a beam of neutron travels through a bulk matter ,the intensity will decreases as neutrons are removed from the beam by nuclear reactions. For fast neutrons, many reactions such as (n,p)(n,α) or (n,2n) are possible, but for slow or thermal neutrons the primary cause of their disappearance is capture,in the form of the (n,γ) reaction.

A neutron detector does not record the presence of neutron directly but responds to secondary radiation which is emitted when the neutron undergoes a nuclear reaction in the detector medium. Because neutrons produce no direct ionization events, neutron detectors

must be based on detecting the secondary events produced by nuclear reactions, such as (n,p), (n,α), (n,γ) or (n,fission), or by nuclear scattering from light charged particles which are then detected.For slow and thermal neutrons, the (n,p),(n,α) or (n,fission) reaction on light nuclei are among those most commonly used in detectors. The process of neutron detection begins when neutrons, interacting with various nuclei, initiate the release of one or more charged particles. The electrical signals produced by the charged particles can then be processed by the detection system.

For a good moderators, the value of A should be small, the average logarithmic energy decrement (ζ) should be large, the absorption cross-section (σ_a) should be small and the scattering cross-section (σ_{sca}) should be large. So, light nuclei are good moderators and heavy nuclei are poor moderaters.

The total cross-section for scattering interaction of neutrons is twice the geometrical area of the nucleus, it is apparently para-doxial result. This apparent paradoxial result is explained in terms of shadow scattering. In the geometrical optics,the obstacle cast the perfect shadow means no light behind the obstacle.

For a resonance reaction, the cross section decreases with increasing velocity of neutrons.Thus as the the neutron becomes slows down or moderated due to scattering process, absorption become more probable and this shows the $1/v$ behavior of reaction cross-section.

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This project is my original work, has not been presented for a degree in any other University and that all the sources of material used for the project have been dully acknowledged.

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