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Perspectives in neutron physics research

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Abstract. Discovery of the neutron in 1932 by Chadwick ushered in a new era of scientific research and technology. The neutron is endowed with unique properties in its mass, life time, spin and magnetic moment etc and every important property has been used in the study of condensed matter, biological molecules, nuclear forces, stellar objects and other fields. Neutron has a wide range of applications in power production, breeding of fissile fuel, radiography, medicine and others.

Keywords. Neutron properties; spallation; plasma focus; breeding; neutron radiography.

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1. Introduction

It is seldom realised how important the discovery of neutron has been in our understanding of nature. Neutron by virtue of being a major constituent of the nucleus has been responsible for the subject of nuclear physics. Neutrons have not only been the key for nuclear transformations, production of isotopes, production of nuclear power and the like but are also fundamentally responsible for the characteristics displayed by the sun and the stars as we see them today.

In India Dr Raja Ramanna's name is synonymous with neutron physics. Having started his research career in King's college London using a small Ra-Be neutron source for fission physics studies, he has emerged as a pioneer in nurturing the field of neutron physics in our country. He set the pace in early fifties for the Indian scientists to do frontline research in the then emerging fields like solid state physics, nuclear physics, neutron physics and reactor physics using neutron as a research tool. He headed the groups that were responsible for providing high intensity neutron sources from reactors. The reactors APSARA, CIRUS, PURNIMA and latest DHRUVA have all been built under his guidance. India's first peaceful nuclear explosion was also his brainchild.

Neutron plays a very pivotal role as a research tool through some of its unique properties like charge neutrality, spin, magnetic moment etc. Therefore the first part of this review article is devoted to highlight these various properties. The second part of this review details the various techniques employed for the production of neutrons. It is emphasised that it is not merely the intensity alone but rather combination of number and energy that imparts special characteristics. Two applications have been cited at the end in some detail.

This article is dedicated to Dr Ramanna on the occasion of his 60th birthday but for whose vision and missionary zeal neutron physics would not have taken roots and grown to attain its present stature in India.

2. Discovery of the neutron

Lord Rutherford, the discoverer of the nuclear atom, made an amazing prophecy (Rutherford 1920) by stating

"Under some conditions it may be possible for an electron to combine much more closely with hydrogen nucleus (than in the neutral hydrogen atom) forming a kind of neutral doublet. Such an atom would have very novel properties. Its external field would be practically zero, except very close to the nucleus, and in consequence it should be able to move freely through matter. Its presence would probably be difficult to detect by the spectroscope and may be impossible to contain in a sealed vessel. On the other hand it should enter readily the structure of atom and may either unite with the nucleus or be disintegrated by its intense field, resulting possibly in the escape of a charged hydrogen atom or an electron or both".

The discovery of the neutron by Chadwick (1932) twelve years after the prophecy was the culmination of various investigations in several laboratories in Europe. It all started in 1930 when Bothe and Becker (1930) tried to detect nuclear disintegration with a needle counter. They bombarded various light elements like Li, Be and B with alpha particles from a Polonium source and measured the energies of gamma rays emitted from the samples. The gammas from Li were ascribed to nuclear excitation by the inelastic scattering of the alpha particles and that from boron was attributed to the fact that the residual carbon nucleus is in an excited state. Beryllium in particular gave gammas of very high energies of $\sim$ 5 MeV, and this was explained by Bothe and Becker saying that the nucleus was excited by the capture of alpha particle.

Two years later, Curie and Joliot used a much more powerful Pu-Be source to investigate further the Be $+ \alpha$ reaction. They observed that the radiation from Be ejected protons with kinetic energies around 5 MeV, when the foils containing hydrogenous material were inserted between beryllium and the ionization chamber. This lead to a difficult conclusion that in order to produce such energetic compton recoils, the gammas must have energies of the order of 50 MeV.

Shortly thereafter, in 1932, Chadwick who was a student of Lord Rutherford, measured energies and momenta of recoils from different materials using a pulse ionization chamber (figure 1) and explained all observations in terms of collisions, consistent with the laws of conservation, with a penetrating neutral massive particle slightly heavier than the proton. He christened the new particle the "neutron" (n) and its production by the bombardment of alpha particles on beryllium was described by the equation

$$Be^9 + He^4 \rightarrow C^{12} + n.$$

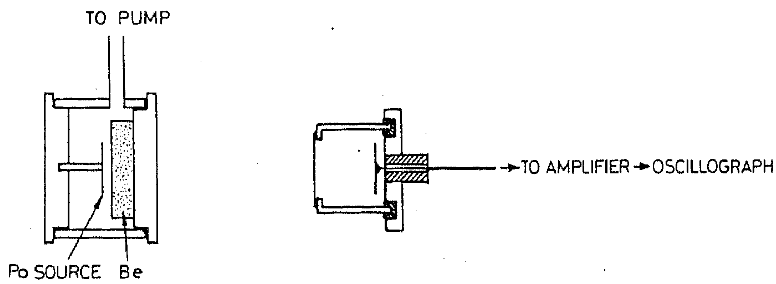

Figure 1. Experimental set-up used by Chadwick that led to the discovery of the neutron.

The discovery of neutrons resolved many puzzling questions *vis-a-vis* nuclear structure. Heisenberg immediately propounded that the nuclei contain only protons and neutrons. The discovery of the neutron gave birth to a new branch of physics called neutron physics.

3. Properties of neutrons

3.1 *Mass of the neutron*

Chadwick (1932) himself concluded from the study of recoil protons liberated by the neutrons, that the mass of the neutron is approximately equal to that of the proton, probably between 1·005 and 1·008. A more accurate estimation of the neutron mass (Chadwick and Goldhaber 1934) was made from the binding energy of the deuteron. The mass of the deuteron is equal to the sum of neutron mass m_n and proton mass m_p less the mass defect corresponding to the binding energy E_d. Thus

$$m_n = m_d - m_p + E_d/c^2.$$

From the known values of $m_d (= 2{\cdot}013554\,\text{amu})$, m_p $(= 1{\cdot}007226\,\text{amu})$ and E_d $(= 2{\cdot}225\,\text{MeV})$, the neutron mass turns out to be 1·008665 amu. Measurement of the photon energy emitted when slow neutrons are captured by hydrogen lead to further improvement in the neutron mass measurement (Knowles 1962). The accepted value (1982) for the rest mass of neutron is

$$m_n = 1{\cdot}008665012\,\text{amu}.$$

An interesting experiment to measure the neutron mass directly with free neutrons was proposed by Stedman (1968) and several others. A neutron moving with a velocity v is associated with it a wavelength given by

$$\lambda = h/(m_n v).$$

It is clear from this relation that h/m_n can be determined by measuring the velocity and wavelength of the neutrons. Time of flight technique was proposed to measure the velocity and the wavelength can be determined by Bragg reflection of the same neutrons in a single crystal.

3.2 *Charge of the neutron*

There is an abundance of evidence that the electric charge on the neutron if any (q_n) is approximately zero, as noted by Chadwick himself. Fermi and Marshall (1947) obtained an upper limit for the charge as 10^{-18} e from neutron scattering experiments on xenon. Shapiro and Estulin (1956) tried to deflect neutrons using strong electric fields but could not find any effect. Shull *et al* (1967) obtained an accurate value for the ratio of the neutron charge to that of the proton, using double crystal spectrometer, as

$$(-1{\cdot}9 \pm 3{\cdot}7)\,10^{-18}.$$

In a recent experiment at the Institut Laue-Langevin at Grenoble Gohler *et al* (1982) used a focussed beam of 220 m/sec neutrons to pass through an electric field of

5·9 kV/mm for a distance of 10 m and estimated the charge of the neutron as

$$q_n = -(1{\cdot}5 \pm 2{\cdot}2) \times 10^{-20}\, e,$$

where e is proton charge.

3.3 *Spin of the neutron*

The deuteron has spin 1 and no orbital angular momentum. Since the proton has spin $\frac{1}{2}$, it follows that the neutron must have spin $\frac{1}{2}$ or $\frac{3}{2}$. Schwinger (1937) showed that experiments on the scattering of neutrons by ortho and parahydrogen would permit determination of the neutron spin. Such experiments carried out by Halpern *et al* (1937) conclusively demonstrated that the neutron spin is just $\frac{1}{2}$.

3.4 *The magnetic moment*

The first measurement of magnetic moment of the neutrons was carried out by Alverez and Bloch (1940) using magnetic resonance technique. Cohen *et al* (1956) using a refined Rabi-method obtained a more accurate value for the neutron magnetic moment as $\mu_n = -0{\cdot}685039\, \mu_p$ (μ_p is the magnetic moment of the proton). The most accurate experimental value is due to Green *et al* (1979) obtained at ILL. This experiment has incorporated several innovations and improvements like use of cold neutrons (which allowed narrower resonance line widths), guide tubes and Ramsey separated oscillatory field magnetic resonance technique. The value for the neutron magnetic moment is

$$\mu_n = -0{\cdot}68497935\, \mu_p.$$

3.5 *The neutron lifetime*

One of the important properties of free neutron is its instability. Since the neutron decay is the most elementary example of the beta decay, measurements of neutron half-life are of special importance, particularly in the determination of weak coupling constants g_v and g_A. Neutron lifetime also plays a crucial role in astrophysics where it is central to the problem of helium production in the early universe (Taylor 1979). The neutron decays by weak interaction as

$$n \rightarrow p + e + \bar{\nu}$$

according to the radioactive law with a decay rate

$$\mathrm{d}N(t)/\mathrm{d}t = \lambda N.$$

In order to measure the half-life one has to determine the absolute number of neutrons in a well defined volume and obtain $\mathrm{d}N(t)/\mathrm{d}t$ from the measured rate of decay particles either protons or electrons from this volume. The neutron density within the beam is obtained with a high degree of precision using foil ($1/v$ detector) activation technique. The most formidable problem in any neutron lifetime experiment is to be able to detect the protons or electrons from the decayed neutrons in the presence of high gamma background.

Robson (1950) made the first serious attempt to measure its half-life accurately. He was able to detect both the decay particles, the proton and electron eliminating the background. The major uncertainty was the effective volume from which the decayed particles emerged. He obtained the neutron half-life as 12·8 ± 2·5 min. Sosnovsky *et al* (1959) carried out precise measurements and came out with a neutron half-life as 11·7 ± 0·3 min. The drawback in these experiments was that only a small fraction of the decays occurring in the source was recorded directly since the solid angle for the collection was small. Christensen *et al* (1972) using an 8 kG magnetic field were able to record all the decays. The magnetic field forces the decayed electrons leaving the beam to spiral about the field lines so that they eventually hit a large plastic scintillator. This measurement gave the half-life value as 10·61 ± 0·16 min. Byrne *et al* (1980) using "very cold neutrons" obtained 10·82 ± 0·16 min for the neutron half-life. The important features of this experiment were (1) a well-defined volume for the neutron beam (2) practically zero background, achieved by trapping the emerging protons for a significant time in an electromagnetic potential well before being released and detected. Figure 2 shows schematic of the experimental layout. Table 1 gives the basic properties of the free neutrons.

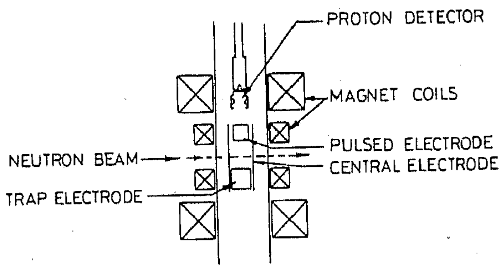

Figure 2. Experimental layout for the determination of neutron lifetime.

Table 1. Basic properties of the free neutrons.

Quantity	Value
Mass (m_n)	1·008665012 (0·011 ppm)
Charge (q_n)	$\leqslant (-1{\cdot}5 \pm 2{\cdot}2)10^{-20}\,e$
Spin J	$\frac{1}{2}$
Magnetic moment (μ_n)	−0·684979 35 (0·25 ppm)
Halflife (weighted average)	(10·68 ± 0·13) min
Ratio of weak interaction coupling constants (g_A/g_v)	−1·255 ± 0·006
Quantized properties	
Intrinsic parity	+1
Isospin	$\frac{1}{2}$
Baryon number	1
Lepton number	0
Strangeness	0
Charm	0
Bottomness	0
Topness	0

4. Neutron sources

Free neutrons do not occur in nature because of their short lifetime and therefore must be produced artificially. Neutrons form a part of the atomic nuclei of all elements (except hydrogen) where they are held together by short range nuclear forces. The neutrons can therefore be separated from the nuclei if the nucleus is somehow brought into an excited state whose energy exceeds the binding energy of the last neutron. Excitation of nuclei of selected isotope is generally accomplished by bombarding them with α particles, protons, deutrons or gamma rays. Table 2 gives binding energy of the last neutron for some important light nuclei.

4.1 *Neutron production by charged particle reactions and* (γ, n) *reactions*

Excited compound nuclei after the capture of charged particles can emit neutrons. The cross-sections for the reaction depend on the energy of the bombarding particle and on the value of the electrostatic barrier of the nucleus. The cross-section increases as the energy of the charged particle increases and reaches a maximum value equal close to the geometrical cross-section of the target nucleus.

4.1a (α, n) *reactions:* This reaction has historical importance because it was used in the discovery of the neutron. The reaction in general can be written as

$$\alpha + {}_{Z}X^{A} \rightarrow {}_{Z+2}X^{A+3} + n + Q.$$

The Q value is positive for exothermic reaction and negative for endothermic reaction. Some well-known examples are

$$\alpha + \mathrm{Be}^{9} \rightarrow \mathrm{C}^{12} + n + 5{\cdot}704 \text{ MeV},$$
$$\alpha + \mathrm{B}^{11} \rightarrow \mathrm{N}^{14} + n + 0{\cdot}158 \text{ MeV},$$
$$\alpha + \mathrm{Li}^{7} \rightarrow \mathrm{B}^{10} + n - 2{\cdot}79 \text{ MeV}.$$

Radioactive (α, n) *sources*

These were the first amongst the neutron sources and even today they are used widely. Polonium-beryllium, radium-beryllium, plutonium-beryllium and americium-beryllium

Table 2. Binding energy of the last neutron in light nuclei (Beckurts and Wirtz 1964).

Nucleus	Binding energy (MeV)	Nucleus	Binding energy (MeV)
H^2	2·225	B^{10}	8·440
H^3	6·258	B^{11}	11·456
He^3	7·719	C^{12}	18·720
He^4	20·577	C^{13}	4·937
Li^6	5·663	C^{14}	8·176
Li^7	7·253	N^{14}	10·553
Be^9	1·665	N^{15}	10·834
Be^{10}	6·814	N^{16}	2·500

Table 3. Characteristics of some α radioactive and spontaneous fission isotopes.

Isotope	Half-life (years)		Specific activity	
	α-dis-integration	Spontaneous fission	α-dis-integration (Curie/g)	Spontaneous fission, (fissions/sec/g)
^{210}Po	0·38	—	4650	—
^{226}Ra	1600	—	1	—
^{239}Pu	24360	$5·5 \times 10^{15}$	0·06	$1·5 \times 10^{3}$
^{241}Am	457·7	2×10^{14}	3	0·3
^{252}Cf	2·73	85·5	540	8×10^{11}

Table 4. Neutrons/sec for 1 g of α radioactive isotope for some (α, *n*) sources.

Isotope	Target material		
	Be	B	F
^{210}Po	$1·36 \times 10^{10}$	$3·35 \times 10^{9}$	$1·7 \times 10^{9}$
^{226}Ra	$1·70 \times 10^{7}$	$3·0 \times 10^{6}$	$3·0 \times 10^{6}$
^{239}Pu	$1·69 \times 10^{5}$	$4·28 \times 10^{4}$	$2·1 \times 10^{4}$
^{241}Am	$1·04 \times 10^{7}$	$2·49 \times 10^{6}$	$1·35 \times 10^{6}$
^{252}Cf	$2·39 \times 10^{9}$	$5·16 \times 10^{8}$	$3·40 \times 10^{8}$

are the important radioactive (α, *n*) sources. Table 3 gives characteristics of some α radioactive and spontaneous fission isotopes. Table 4 gives maximum specific output of neutrons for 1 g of radioactive isotope for some (α, *n*) sources.

4.1b *(d, n) reactions*: This is an extensively used reaction for the production of neutrons. The general equation for this reaction is

$$d + {}_{Z}X^{A} \rightarrow {}_{Z+1}X^{A+1} + n + Q$$

Typical examples,

$$d + H^2 \rightarrow He^3 + n + 3·26 \text{ MeV},$$
$$d + H^3 \rightarrow He^4 + n + 17·58 \text{ MeV},$$
$$d + Li^7 \rightarrow Be^8 + n + 15·02 \text{ MeV},$$
$$d + C^{12} \rightarrow N^{13} + n - 0·28 \text{ MeV},$$
$$d + Be^9 \rightarrow B^{10} + n + 4·36 \text{ MeV}.$$

Since the binding energy of the deuteron is small (~ 2·226 MeV/nucleon) the compound nucleus formed by the capture of deuteron is always found in a highly excited state and consequently almost all (*d, n*) reactions are exothermic. H^2(*d, n*) He^3 reaction is widely utilised for the production of monoenergetic neutrons because of expected good neutron yields for deuteron energies even below 1 MeV. The H^3 (*d, n*) He^4 is the best among (d, n) reactions for generating monoenergetic neutrons with high positive Q value.

4.1c *(p, n) reactions:* Like (d, n) reaction, this reaction has large neutron output compared to (α, n) reaction due to lower threshold energies. This reaction is extremely popular to produce monoenergetic neutrons with small proton energies. The general reaction is

$$p + {}_ZX^A \rightarrow {}_{Z+1}X^A + n + Q.$$

Generally lithium and tritium are used as targets for this reaction

$$p + \mathrm{Li}^7 \rightarrow \mathrm{Be}^7 + n - 1{\cdot}646 \text{ MeV},$$
$$p + \mathrm{H}^3 \rightarrow \mathrm{He}^3 + n - 0{\cdot}764 \text{ MeV}.$$

Assuming that this reaction is essentially due to β decay the Q value of the (p, n) reaction is

$$Q = E_\beta - Q_n,$$

where $Q_n = 0{\cdot}762$ MeV is the Q value of β decay of the neutron and E_β is the maximum energy of the β. Thus all (p, n) reactions are endothermic if the target nuclei are stable.

4.1d *(γ, n) reactions:* The emission of neutrons by the interaction of gamma rays with nucleus is known as nuclear photo effect. With increasing energy more complex reactions such as $(\gamma, 2n)$ (γ, p) and (γ, pn) etc are possible. The reaction equation is

$$\gamma + {}_ZX^A \rightarrow {}_ZX^{A-1} + n + Q.$$

The minimum γ energy required for this reaction to take place is equal to the binding energy of the neutron in the nucleus. The neutrons are monoenergetic if the γ-ray is monoenergetic. The threshold energy ranges from 10 to 20 MeV. The energy of the neutron can be calculated fairly accurately using the relation

$$E_{\text{neutron}} = M_R(E_\gamma - Q)/(M_R + m),$$

where M_R and m are the masses of target nucleus and the neutron respectively.

4.1e *Radioactive (γ, n) sources:* The γ energy of most of radioactive substances rarely exceeds 3 MeV and therefore (γ, n) reactions are possible only in beryllium ($Q = -1{\cdot}665$ MeV) and deuterium ($Q = -2{\cdot}225$ MeV). The drawbacks of these sources are their small yields and short half-life of the emitters. The target should be several centimeters thick to have good neutron output since cross-section for (γ, n) is small. Sb^{124}-Be neutron source is most widely used in practice due to the comparatively large half-life ($60{\cdot}9d$) of antimony.

4.2 *Neutrons from charged particle accelerators*

Accelerator-based neutron sources have distinct advantage in that the neutron source strength and its energy can be controlled with ease. Further, the source can either be continuous or pulsed.

Acceleration of charged particles like protons, deutrons and α's is based on the interaction of their charge with an electric field. Essentially an accelerator is a device in which the charged particles acquire the required energy by passing through a number of small potential differences whose sum is equal to the required V.

Accelerators are classified into different categories such as electrostatic, high frequency and induction accelerators depending on the way the electric field is generated to accelerate charged particles. Van de Graaff and Cokroft-Walton cascade generators belong to the first type where the charged particles acquire energy determined by the difference in potential between the electrodes.

Most important accelerators like cyclotron, microtron, synchrotron, synchrocyclotron and linear accelerators belong to the second group. In these accelerators, the particles interact with the high frequency electric field or cavity resonator through which they pass. Finally in the last group, the particles are accelerated under the action of an eddy electric field produced due to electromagnetic induction. Betatron is an example of this type of accelerator.

Van de Graaff generator: This is mainly used to accelerate protons and deuterons upto few MeV for production of monoenergetic neutrons using (p, n) and (d, n) reactions. Typical beam current is about 10 μA from continuous mode operation and is about 10 mA in the pulsed mode operation.

Cascade generator: This is similar to Van de Graaff except it differs in generating the high voltage. These are mostly used for generating small voltages to produce neutrons from $H^2(d, n)He^3$ or $H^3(d, n)He^4$ reactions.

Cyclotron: Protons and α particles can be accelerated to hundreds of MeV in cyclotrons. These energetic particles are used to produce neutrons using (p, n) or (α, n) reactions.

Other accelerators: Synchrocyclotron, synchrotron isochronous cyclotron (azimuthal variation of field) and linear accelerators are basically meant for getting very high energy particles.

Electron accelerator: These accelerators can be used to accelerate electrons upto energies equal to 50–100 MeV. On striking a target, these electrons give intense bremsstrahlung with a continuous spectrum. The bremsstrahlung in turn produces neutrons by (γ, n) processes. Bombarding a thick uranium target with 40 MeV electrons of about 1 mA current yields 10^{14} n/sec.

4.3 *Neutrons from research reactors*

Research reactors operating the world over are the main sources of copius supply of neutrons. The built-in facilities in the reactor enable carrying out a number of experiments simultaneous with the production of radioisotopes. Typically a 10 MW thermal reactor produces about $7{\cdot}5 \times 10^{17}$ neutrons per second. Unfortunately only a small fraction of this source is actually available to the experimenter. Hence the continued endeavour is to evolve and optimize core designs that would maximize the neutron flux ϕ which is defined as the number of neutrons passing through unit area in all directions in each second. The physics aspects of the reactor are basically characterized by this flux.

Since the neutrons in the reactor have a broad distribution of energy, from 0 eV to 10 MeV, the flux is a function of energy E of the neutron. Thus $\phi(E)\,dE$ is the flux of the neutrons. Three regions of energies are identified within the spectrum.

(a) *Thermal neutrons*: ($E < 0{\cdot}2$ eV). These neutrons are in thermal equilibrium with the moderator atoms and their energy distribution follows a Maxwellian form given by

$$\phi(E)\,\mathrm{d}E = \frac{2\pi n}{(\pi kT)^{3/2}}\left(\frac{2}{m}\right)^{1/2} E\exp(-E/kT)\,\mathrm{d}E,$$

where n is neutron density, k is Boltzmann's constant, m is neutron mass and T, the temperature of the medium in degrees Kelvin.

(b) *Resonance neutrons*: (0·2 eV $< E <$ 0·5 MeV). In this range, the neutron spectrum is determined by the neutrons being slowed down by elastic collisions with the moderator nuclei. In this region the spectrum follows the behaviour

$$\phi(E)\,\mathrm{d}E = \frac{(\text{constant})\,\mathrm{d}E}{E}$$

(c) *Fast neutrons*: ($E >$ 0·5 MeV). These neutrons have more or less the same energy distribution as that of fission neutron spectrum which is given by

$$N(E) \approx \exp(-E)\sinh(2E)^{1/2} \qquad (E \text{ in MeV}).$$

The intensity of each of these components depends upon the type of reactor, its operating power and the point inside the reactor. The major limiting factor to have thermal fluxes better than 10^{15} neutrons/sec/cm^2 is the power density which is controlled by various requirements of heat transfer, heat transport and stability of core materials under irradiation. Two representative types of reactors will now be considered.

Research reactors fuelled with natural uranium and moderated with heavy water are in operation in different countries. Indian reactor CIRUS, Canadian reactors NRX and NRU and French reactor EL2 are examples of this type of reactors.

The second type of reactors are fuelled with highly enriched uranium and moderated with light water. Material testing reactor of US and other swimming pool reactors are examples of this category.

Table 5 gives the different components of the flux at the core centre for these reactor types operating at 10 MW.

A simple expression (Spinrad 1966) can be derived which relates the core average flux to the core parameters like critical mass, core volume and power density to select the type of reactor to have increased fluxes.

The core average flux ϕ, is related to the power density P_d(MW/l) and the macroscopic fission cross section Σ_f as

$$\phi = \frac{P_d \times 3{\cdot}3 \times 10^{13}}{\Sigma_f}.$$

Table 5. Flux components in typical research reactors operating at 10 MW.

Type	ϕ_f	ϕ_{epi}	ϕ_{th}
NRX	2×10^{12}	10^{12}	3×10^{15}
MTR	1×10^{14}	10^{13}	1×10^{14}
DHRUVA	5×10^{2}		2×10^{13}

The Σ_f is further related to critical masses and the core volume V as

$$\Sigma_f = \frac{N_0 \sigma_f}{A}(M/V),$$

where N_0 is Avagadro's number, σ_f is the microscopic fission cross-section and A is the molar mass of the fuel. Substituting this in the first equation

$$\phi = \frac{(3{\cdot}3 \times 10^{13})A}{N_0 \sigma_f}\frac{P}{M},$$

where P is total power. Thus it is clear from these equations that to get high flux, one should attempt to have a highly dilute core (M/V is small) or a small critical mass depending on whether power density or power is the limiting factor.

The beam tubes

Beam tubes are provided to make neutron beams available outside the reactor for carrying out the experiments. These tubes are normally cylindrical aluminium or zircalloy pipes which penetrate the shield in the horizontal direction to reach either the core or reflector or any other location to satisfy the experimental requirement. The neutron current density that can be obtained from such a tube can be calculated as follows. If A is the front surface area of the beam hole and ϕ is the flux at that surface, then the number of neutrons entering the beam per second is $\phi A/4$. If l is the length of the beam tube, then the neutron current density J at the tube exist is

$$J = \phi A/4\pi l^2.$$

Beam tubes are normally positioned tangential to the core to reduce the gamma ray background. Pure thermal beams are extracted from the thermal column. For getting

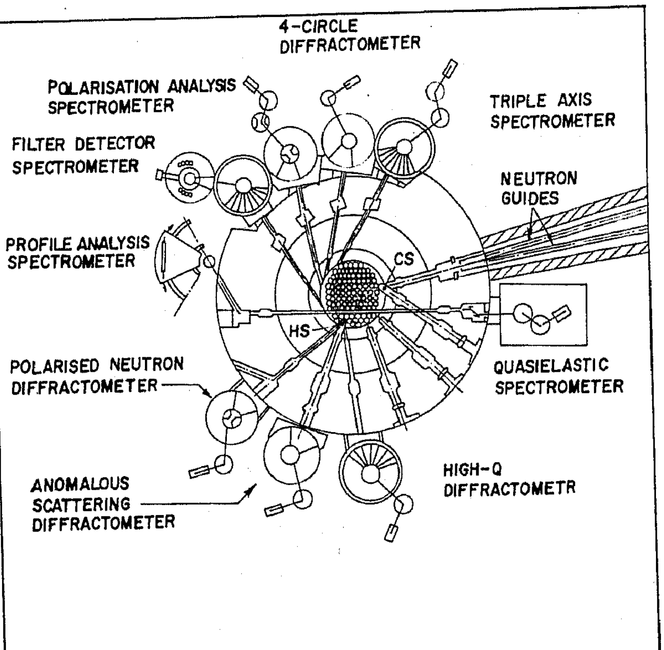

Figure 3. Schematic layout of the various neutron beam tubes in the reactor *Dhruva*.

epithermal beams the tangential tubes are located nearer the core and cadmium filters may be used to suppress the thermal neutrons present. Gamma ray intensity can also be reduced with lead filters. Figure 3 shows the various beam tube locations and the proposed experiments in the reactor *Dhruva* which is undergoing commissioning tests at BARC.

4.4 *Spallation neutron sources*

As early as in 1947 E O Lawrence conceived the idea of using energetic charged particles (from accelerators) in conjunction with a target to produce neutrons. The next important milestone in this direction was a detailed design study by Wilson *et al* (1965) of AECL, Canada, of an intense neutron generator (ING) in the early 1960s. Subsequently, different laboratories including BNL, ORNL and LASL have undertaken programmes in this challenging field.

For all practical purposes spallation reactions are inelastic nuclear reactions in which one of the two collision partners is a complex nucleus (target) and the energy available is several times the interaction energy between the nucleons in the nucleus. Thus, if the incident energy exceeds something like 50–100 MeV per nucleon, it is referred to as a spallation reaction. Spallation reactions are described in terms of the two-step model suggested by Serber (1947). In the first step the incident high energy particle enters the target nucleus and interacts with some of the nucleons in the target in what is known as an intranuclear cascade. In this process few nucleons will be knocked out of the nucleus. The excited residual nucleus deexcites in the second step of this model emitting a number of single nucleons. The first stage is known as 'fast' stage, knock on stage or cascade stage. Similarly the second stage is referred to as slow stage, deexcitation stage or evaporation stage.

The yield of such spallation neutrons is a function of: (a) incident particle type and energy (b) target material and its size and geometry. Figure 4 shows some results of experiments conducted with the protons from the 3 GeV cosmotron at BNL. It can be seen that the neutron yield from U targets is twice that from lead target. This is simply due to fast fission effect in ^{238}U.

The neutron yield calculations have been carried out by Monte-Carlo code called HETC (high engergy transport calculations) (Chandler 1972) developed at ORNL. This

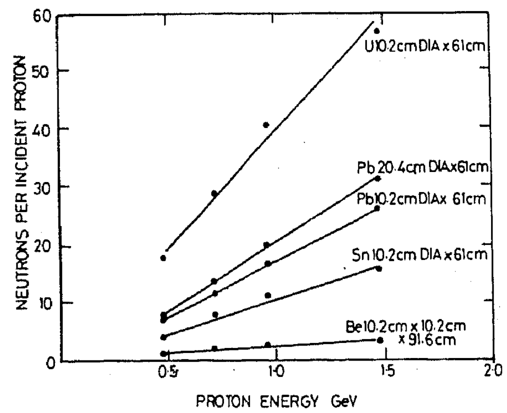

Figure 4. Neutron yields obtained by bombardment of heavy targets with high-energy protons.

code is a high energy version of an earlier code designated NMTC (nuclear meson transport code) (Coleman 1970). Detailed system analysis carried out at BNL and AECL indicate that: (i) the optimum proton energy is likely to be between 800 MeV and 1 GeV (ii) the optimum beam current is about 300 mA.

Linear accelerators capable of accelerating a steady continuous beam of protons at a current of ~ 100 mA are available today. Synchrotron is another potential candidate for getting high energy charged particle beams. Table 6 gives a number of spallation neutron source facilities.

4.5 *Dense plasma focus as a neutron source*

The dense plasma focus (Mather 1964; Fillipov 1962; Imshennik 1973) is an intense source of monoenergetic neutrons. Essentially this is a fast dynamic Z-pinch in which stored magnetic energy is rapidly converted into plasma energy and then compressed by its self-magnetic field. The device shown in figure 5 consists of two cylindrical electrodes in a coaxial configuration and a capacitor bank. The space between the electrodes is filled with deuterium gas at a pressure of few torr. The electrodes are connected to a high energy (1 kJ to 1 MJ), high voltage (20 to 80 kV), low inductance (~ 40 nH) capacitor bank through a spark gap. As soon as the spark gap is closed, the capacitor bank is discharged and the gas breaks down at the insulator, allowing a radial

Table 6. Spallation neutron source facilities.

Name	LAMPF	SIN	TRIUMF	ING	RUTH. LAB.	IPNS-I	KEK
Location	U.S.A.	Swiss	Canada	Canada	U.K.	U.S.A.	Japan
accr.	Linear	S.O.C.	Cyclotron	Linear	Sync	His	Sync
P energy	800 MeV	590 MeV	500 MeV	1 GeV	800 MeV	600 MeV	500 MeV
Avg. current	1 mA	100 μA	100 μA	65 mA	200 μA	—	1·5 μA
Target	W	Pb, Bi	Molten lead	Pb-Bi (liquid)	DEP, U	^{238}U	DEPT. U
N. yield/s	2×10^{16} n/sec	—	10^{16} n/sec	10^{19} n/sec	4×10^{16} n/sec	2×10^{15} n/sec	$1{\cdot}8 \times 10^{14}$
Pulse rate	120	Con/pulse	—	C.W.	50	45	20
Power cons	27 MW	6·8 MW	5·6 MW	100 MW	—	—	—
Target heat	200 kW	45 kW	38 kW	38 MW	450 kW	20 kW	2 kW

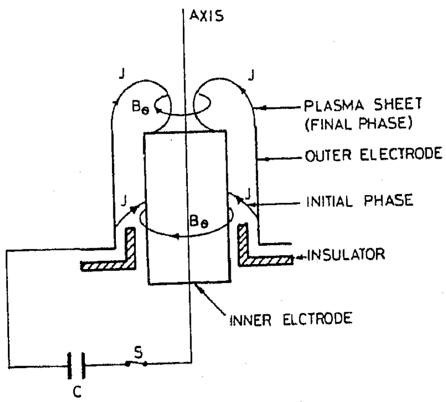

Figure 5. Schematic of a plasma focus discharge showing initial and final phases.

current to flow between the electrodes. This radial current produces an azimuthal magnetic field. The combination of the azimuthal field with a radial current produces $J \times B$ force on the ions away from the insulator. Thus as the current continues to flow the plasma front is accelerated along the z axis, ionizing the neutral gas it encounters. As soon as the plasma front reaches the end of the electrode, the axial momentum of the plasma causes the front to fold over the end and radially imploding towards the axis of central electrode creating a hot dense plasma focus typically about 2 mm in dia and 10 to 30 mm long. The discharge current at the time of focus formation can be as high as several hundred kiloamperes to a few mega amperes. Intense bursts of electrons, neutrons, ions, soft x-rays (< 10 keV) and hard x-rays (> 30 keV) are observed to emanate from the focus.

A unique feature of plasma devices is, irrespective of differences in design, the neutron yield N of all optimised plasma focus devices is found to obey a universal scaling law, namely that the yield is found to scale as the fourth power of peak discharge current (I) or as the square of the capacitor bank energy (E). Neutron yield (Conrad 1983) as function of plasma current for different focusses of various international laboratories including BARC (Shyam and Srinivasan 1978) is shown in figure 6. During the 1970s plasma focus devices have produced about 10^{12} neutrons per discharge from (D–D) reactions. With the present state of art 10^{14} neutrons per discharge can be achieved by dissipating about 300 kJ of stored energy.

4.6 *Classification of neutrons on the basis of energy*

Neutrons are classified as ultra cold neutron (UCN), very cold neutrons (VCN), cold neutrons (CN), thermal neutrons, epithermal neutrons and fast neutrons depending on their energy (or wavelength). Since each class of neutrons has a role to play in the basic research, one has to tailor the easily available neutrons of a given energy. Of all the

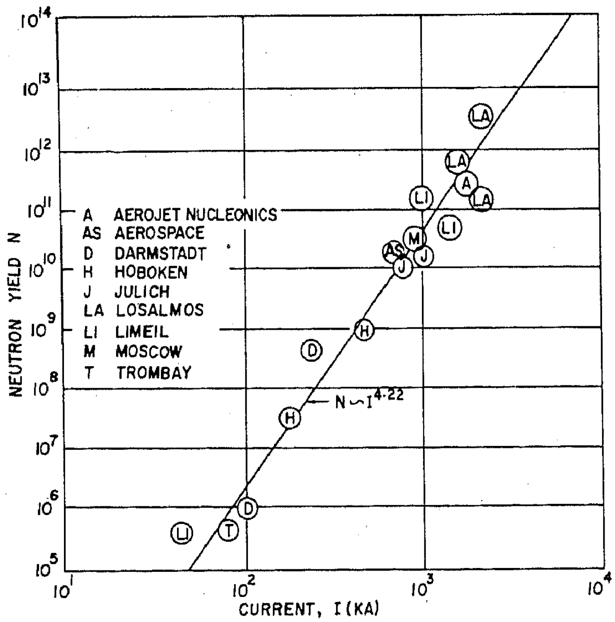

Figure 6. Neutron yield as a function of plasma current for different foci.

neutron sources UCN and VCN beams are difficult to get with good intensities.

A very useful relation between neutron velocity V (m/sec), de Broglie wavelength (Å) and the neutron energy E (eV) is given by

$$E\ (\text{eV}) = 5{\cdot}2 \times 10^{-9}\ V^2\ (\text{m/sec}),$$
$$= 8{\cdot}2 \times 10^{-2}\ \lambda^{-2}\ (\text{Å}).$$

Ultra cold neutrons: Neutrons entering a solid material from vacuum with energy E less than U_{eff} (called the locally averaged Fermi scattering potential for the material), with a corresponding velocity less than v_c or wavelength greater than λ_c will be reflected even at normal incidence. Such neutrons are called ultra cold neutrons (UCN). Typically for UCN $E \leqslant 2{\cdot}4 \times 10^{-7}$ eV, $v \leqslant 6{\cdot}8$ m/sec and $\lambda \geqslant 580$ Å.

Very Cold Neutrons: Neutrons with the velocity $6{\cdot}8\ \text{m/sec} \leqslant v \leqslant 100\ \text{m/sec}$ are referred to as very cold neutrons. These neutrons are reflected at angles $< 90°$. The corresponding energy and wavelengths are

$$2{\cdot}4 \times 10^{-7}\ \text{eV} \leqslant E \leqslant 5{\cdot}2 \times 10^{-4}\ \text{eV},$$
$$580\ \text{Å} \geqslant \lambda \geqslant 12{\cdot}6\ \text{Å}.$$

Cold neutrons: These neutrons are reflected at very small angles of incidence and have velocities around 800 m/sec with a corresponding energy of 0·0033 eV and a wavelength of 5 Å.

Although UCN's, VCN's and CN's exist as the low energy fraction of the Maxwell-Boltzmann distribution, it is almost impossible to extract them directly. So it is normal practice to generate these sources from a fast source by down scattering in a good converter or cold source at appropriate temperature.

Thermal neutrons: Neutrons which are in thermal equilibrium with the surrounding medium and follow Maxwellian distribution for neutron density with energy.

Epithermal or resonance neutrons: Neutrons in the energy range from about 0·2 eV to 500 keV belong to this category. The spectrum is determined by the neutrons being slowed down by elastic collisions with the moderator nuclei.

Fast neutrons: Neutrons with energy from 500 keV to 20 MeV.

Super fast neutrons: Neutrons possessing energy greater than 20 MeV.

5. Applications

The important properties of the neutron are its mass, charge neutrality, spin, magnetic moment and lifetime against β decay etc. These unique properties have made the neutron an ideal tool for the scientist to probe the unknown mysteries of the nature. The ever expanding research areas where the neutron is playing a dominating role encompasses the physical sciences, biological sciences, medical sciences, earth sciences, agricultural sciences not to mention its important role in nuclear power production and other industrial applications (Schofield 1982).

Exhaustive research work over the years on structural studies and dynamical properties of condensed matter using neutrons has been pursued at BARC (Iyengar 1973). Study of properties of magnetic materials using the inherent magnetic moment of the neutron (Satya Murthy and Madhav Rao 1981), production and applications of polarised neutrons (Satya Murthy and Madhav Rao 1984) will also be not discussed here.

One of the most outstanding applications of the neutron is in power production through fission chain reactions in a reactor. The behaviour of the neutron population in such a reactor can be obtained by solving the Boltzmann neutron transport equation in seven variables. The input to solve the transport equation is the neutron cross-section data. Ramanna *et al* (1956) developed the pulsed neutron technique in our country to generate thermal cross-section data for moderators and coolants. The impact of nuclear research on the future technology of nuclear power was discussed by Iyengar (1979). In view of the availability of excellent text books (Bell and Glasstone 1970) we will not discuss this topic also.

5.1 *Sub-Lawson fusion systems for power production and breeding*

In all likelihood, the first generation commercial fusion reactors are to be fuelled with a mixture of deuterium (D) and tritium (T) (Hirsch 1975; Ramanna 1984) wherein about 14·1 MeV out of 17·6 MeV energy released in the fusion reaction will be carried away by the neutrons liberated in the reactions. The tokamak and the tandem mirror are the top contenders in the field (Ramanna 1984). The plasma zone of any such device is surrounded by a medium, known as blanket, wherein the 14 MeV neutrons leaking out of the plasma zone deposit their energy for the subsequent generation of power. A conceptual design of a fusion reactor based on a magnetic confinement is shown in figure 7. For a pure fusion system to be economical, it is expected that the power amplification factor Q (fusion output power/power in the plasma) should be of the order of 10 (Dolan 1982). Such high Q values are unlikely to be achieved in the near future without further technological breakthroughs.

The hybrid concept (Lidsky 1975) in which fusion and fission systems are coupled exploits the fact that fusion reactions are neutron rich but energy poor while fissions are energy rich but neutron poor. The two hybrid concepts that are vigourously pursued are (Maniscalce 1981): (a) hybrid blankets or fast fission blankets and (b) symbiotic blankets or suppressed-fission blankets. These two concepts are shown schematically in figure 8.

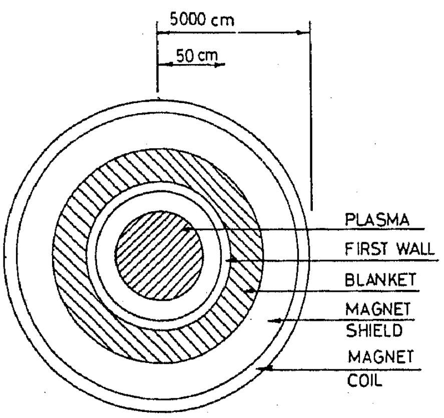

Figure 7. Conceptual design of a fusion reactor based on magnetic confinement.

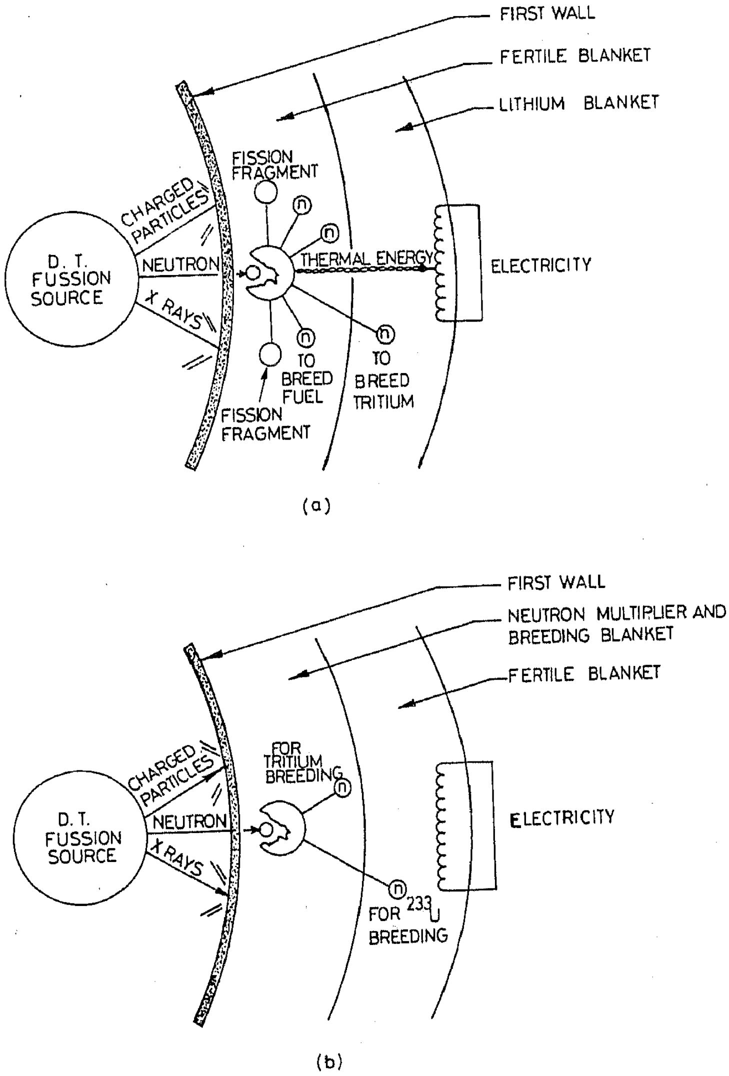

Figure 8. Schematic of hybrid and symbiotic blankets.

In the fast fission blanket system, the D-T fusion source is surrounded by a fertile material blanket. The fusion neutrons cause fast fissions in the fertile material, thereby amplifying the fusion energy and also multiplying the fusion neutrons. The fission energy will be utilized to generate power just like in any nuclear power reactor. One of the multiplied neutrons is needed to breed tritium from lithium situated in the blanket and the remaining are available for breeding fissile fuel from fertile materials like ^{232}Th and ^{238}U.

Suppressed fission blanket concept is essentially meant for producing fissile fuel from fertile materials. An additional non-fission neutron multiplying zone such as BeO, lead etc is placed between the D-T fusion source and the fertile blanket (Nargundkar *et al* 1984). The neutron multiplier also moderates the 14 MeV fusion neutrons to below fission threshold energy (1.5 MeV) before they reach the fertile zone, thus suppressing fissions in the blanket while breeding the fissile material.

Although the basic motivation for developing a fusion breeder is essentially the same as for the fission breeder *i.e.* to exploit the enormous energy potential of the world's abundant Th-232 and U-238 natural resources, there are important differences that make the fusion breeder a better choice. The following advantages are noteworthy: (i) Fusion breeder needs no fissile inventory. (ii) Power densities are 10 to 200 times less than those in the fission breeder. (iii) The fuel production and energy production can be separated. (iv) Fusion system can produce many times ($\sim$30) more net fissile product per unit power than a fast breeder. (v) Since enormous amounts of fissile fuel can be produced from fusion breeder, many fission reactor concepts can be adopted, not necessarily the fast breeders. (vi) Fusion neutrons can also be used to transmute the longlived radioactive fission waste products to less hazardous and toxic substances with reduced half-lives. This solves the vexing problem faced by the fission reactors. (vii) There are no safety problems since power is generated in a subcritical system.

5.2 *Neutron radiography*

Neutron radiography, a relatively new and powerful technique of producing images of objects, is finding applications in varied and diverse fields such as engineering, metallurgy, reactor technology, aerospace, medicine, ordnance and electronics etc. Hitherto the most established technique of flaw detection in industrial products was through x-ray radiography. However this method has limitations and fails to give required information under certain situations like locating light material behind or within heavy materials, testing of radioactive parts or irradiated fuel assemblies of power reactors, detection of hydrogeneous inclusions in materials and inspection of thick plates of heavy materials. In all these situations neutron radiography can be used successfully because the way neutrons interact with matter is totally different from the way x-rays interact. X-rays interact with the orbital electrons only and hence the attentuation coefficient increases with increasing Z unlike the neutrons which interact with the nucleus of the atom. Another important difference is the ability of the neutrons to distinguish between the isotopes of same element which is impossible with x-rays.

The technique of neutron radiography involves the placement of the sample under test in the path of a well-collimated beam of thermal neutrons and studying the transmitted beam modified by the attenuations within the sample. Since the photo-sensitivity of x-ray films to neutrons is very low, the transmitted neutron beam is made to fall on a suitable converter screen which in turn emits photographically sensitive radiations. These radiations finally expose a conventional x-ray film to give the required radiograph.

In the first method, the converter screen along with the x-ray film is placed behind the object under test and exposed sufficiently long to get the image. The converter screens are thin sheets of Rh, Gd, Cd, Sm or a suitable scintillator loaded with Li-6 or B-10. This method has some drawbacks if gamma ray background is present in the neutron beam or the specimen itself is radioactive. The second technique called the transfer method circumvents this problem. In this, a converter screen alone is exposed to the transmitted neutron beam and the screen becomes radioactive. The latent image of the specimen formed on the screen is then transferred to the photographic film in a separate place free from any background. Suitable converter materials, keeping the half-life in mind are In, Dy and Au.

The third technique of recent origin uses Li-6, B-10 or U-235 loaded screens to convert the thermal neutrons into alpha particles or fissions fragments. These charged particles fall on a special plastic material causing radiation damage along their paths.

The radiograph is obtained after etching the plastic sheet in a chemical solution. The advantages of this method are (i) totally gamma insensitive, (ii) no limitation on time of exposure and (iii) elimination of use of x-ray films.

In addition to what has been mentioned some specific applications in nuclear technology are: (a) testing of unirradiated nuclear fuel assembly to give qualitative information on assembly, voids, foreign materials and quantitative information on homogeneity, average density etc. (b) testing of irradiated fuel to give information on leaks, densification, swelling, migration and disintegration etc.

A dedicated neutron source reactor specially meant for neutron radiography applications is being set up at the Reactor Research Centre, Kalpakkam (Srinivasan *et al* 1979) for testing of fuel assemblies of fast breeder test reactor and for other related applications.

6. Conclusion

Neutrons by virtue of their unique and unparalleled properties have provided scientists and engineers with a tool to unravel the mysteries of nature. Every important property of the neutron has been exploited by the researchers to help probe into the fundamental properties right from understanding the nature underlying the nuclear forces to the formation and the structure of the stars. With further breakthroughs in technology more and more intense neutron sources tailored to specific needs will become increasingly available that would boost the neutron utility further both in the fields of basic and applied sciences. Neutrons have already contributed in a large measure to global human welfare and would undoubtedly continue to do so in an ever increasing manner in years to come. It is no prophecy therefore to predict that the neutron which celebrated its golden jubilee in the year 1982 will have many more jubilees in store in the future.

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