

A Review on the Principles and Application of Neutrons Scattering

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Abstract: The economy of the world today requires increasingly complex materials with specific properties to function perfectly. That is why, for nearly a century, neutrons have played a major role in increasing industries understanding of the material world. They allow physicists and engineers to study materials, revealing their atomic structures, dynamics, and magnetic properties to unravel how to make them stronger, lighter, and perform better. This work presents a review on principles and application of neutron scattering its importance in researching the properties of new materials critical to energy, therapeutic treatment, astronomy, radionuclide tracers, communication, and nanotechnology. The recent developments shown in this review provides information that can facilitate product development and improve the mechanics of new materials.

Keywords — Application of Neutrons, Neutrons scattering, Principles of Neutrons, *and* Reviewed information for product improvement.

I. INTRODUCTION

Neutrons have played a significant role in the characterization, development, and testing of materials over the past century. In 1994, the Nobel Prize in Physics was awarded to Clifford G. Shull and Bertram N. Brookhouse for their outstanding contribution to the impact of neutron scattering [1]. Neutron properties and interactions are described by nuclear physics [2]. Some elements occur in nature with only one stable isotope, while others have many stable isotopes [3]. Neutrons are produced copiously in the nucleus fusion and fission processes. They first and foremost contribute to the nucleosynthesis of chemical elements within stars through fusion, fission, and neutron capture processes. Neutron is essential for the production of nuclear power. Decades after the neutron was first discovered in 1932, neutrons were used to induce many different types of atomic transmutation. With the nuclear fusion discovery in 1938, it was recognized that if a fission event produced neutrons, each of these neutrons might cause further fission events in a surge known as a nuclear chain reaction.

II. HISTORICAL DISCOVERY OF THE NEUTRON

Neutron discovery occurred in the first half of the 20th century, with the creation of the nuclear bomb in 1945. In 1911, Rutherford's atomic model was made up of a small, positively charged core surrounded by a much larger, negatively charged cloud. In 1920, Rutherford assumed that the nucleus consisted of positive protons and neutrally charged particles, which were suggested to be electrons [2].

Oskar Klein introduced further quantum mechanical objections to the notion of electrons confined inside a nucleus in 1928. The noticeable properties of atoms and molecules were incompatible with the nuclear spin anticipated by the proton-electron hypothesis. Since both proton and electron carry an intrinsic spin of $\frac{1}{2} h$ there is no way to arrange an odd number of spin $+$ $\frac{1}{2} h$ to give a spin integer multiple of n [4].

In 1931, Walther Bothe and Herbert Becker [5] found that if alpha particle radiation from polonium falls on beryllium, boron, or lithium, an unusually penetrating radiation will be produced.

Chadwick won the Nobel Prize in physics for this discovery in 1935. Using kinematics, it was possible to determine the speed of the proton.

The Chadwick's equation:



On May 25, 1933, Chadwick held his Bakerian lectures, devoted to neutrons. He collected many results physicists had obtained on neutrons in almost a year and a half, mainly mentioning those obtained in Cambridge. Chadwick stated that the outstanding properties of neutrons are their ability to set in motion the atoms of matter through which they pass and their great penetrating power. Chadwick, moreover, dealt with the very interesting cases of fluorine and aluminum [6].

Such calculations had already been carried out by Massey in 1935, and he showed that the neutron-proton scattering cross-section was a function of neutron velocity. Attaining detailed knowledge on neutron-proton scattering as a function of velocity would help in obtaining information on such a still unsolved problem. From an experimental point of view, an investigation into the less swift neutrons had already revealed that the radius for the proton collisions continues to increase as the velocity of the neutron decreases. Now, the calculation of the neutron-proton elastic cross section led to the formula

$$Q = h^2 / TM^2V^2 \quad [2]$$

Where M is the reduced mass and v is the relative velocity. From a theoretical point of view, the neutron-proton elastic cross section increased as the neutron velocity decreased. Chadwick pointed out that, besides elastic collisions, inelastic collisions can also take place. He reported Feather's results on the transmutation produced by neutrons in nitrogen, oxygen, and carbon and stressed that γ -rays were emitted in such disintegration processes.

A. *Properties of the Neutron*

1. Neutrons that are free (outside a nucleus) are unstable and decay via beta decay. Disintegration of the neutron involves the weak interaction and is associated with a quark conversion (a down quark converted to an up quark).
2. Natural neutrons (the background of free neutrons) exist everywhere on Earth, and

they are caused by muons produced in the atmosphere where cosmic rays come into collision with particles of the earth's atmosphere.

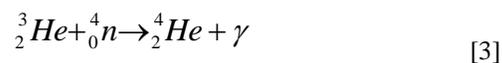
3. Neutrons can travel hundreds of feet in the air without any interaction. Neutron radiation is highly penetrating.
4. The mean square radius of a neutron is 0.8×10^{-15} m
5. The mass of the neutron is $939.565 \text{ MeV}/c^2$.
6. A neutron is $\frac{1}{2}$ spin particle with fermionic statistics.
7. A neutron has a non-zero magnetic moment.
8. Neutrons are neutral particles with no net charge.
9. t charge.
10. The mean life of a free neutron is 882 seconds.

B. *Neutron Source*

A neutron source is any device that emits neutrons, irrespective of the procedure used to produce the neutrons. The neutron source is used in the production of nuclear weapons, petroleum exploration, and nuclear power plants. Neutron service variables include the energy of the neutron emitted by the source, the rate of neutrons emitted by the source, the size of the source, the cost of owning and maintaining the source, and government regulation related to the source [7].

C. *Neutron Detectors*

The most common neutron detectors are of the proportional gas type. Neutrons have no charge and are non-ionizing. They are not as easily detected as X-rays. The detection method relies on the absorption of the neutron by an atom and the simultaneous emission of gamma rays. The most common is He^3 gas, which relies on the reaction.



From the equation above, stable isotopes of helium and γ -rays of specific energy are produced. Another gas suitable for this is BF_3 , which uses the absorption properties of the isotope ^{10}B . In thermal wavelength neutrons, the ^3He gas detector is considered the best, but in long wavelength neutrons, BF_3 is better, but it is hardly ever used now due to the technical difficulties of handling a corrosive and toxic gas. Because the capture cross-section of gases is minimal, He^3 detectors are usually filled above atmospheric pressure, e.g., 5 to 10 bar. They are

typically 10 to 15cm long and 2 to 5cm in diameter [8].

A recent development by the nuclear detector group at the ILL, Grenoble, has contributed to the production of single-tube He-gas detectors with positional sensitivity. By measuring the charge at both ends of a resistive anode wire, a larger magnitude of charge is observed, which is related to a shorter distance travelled by the pulse along the wire. These will have huge potential for high-resolution angle-dispersive power diffractometers (such as D2B) since they allow a greater solid angle to be estimated without comprising instrumental resolution, the asymmetry due to the curved Debye-Scherrer diffractions being removed via software binning of the 2-dimensional data to the conventional 1-dimensional power pattern [9].

Neutron multi-detectors are He³ gas-based. They are also filled with a dampening gas, such as a mixture of xenon (Xe) and methane (CH₄). The original multi-detectors consisted of an arrangement of vertical wires at fixed intervals. Usually the intervals are chosen so that they correspond to a nice angle in degrees, e.g., 0.1°. Recent developments to enhance the spacing interval have been one of the major contributions made to the development of micro-strips, which replace the traditional anode wires in these detectors.

Thus, one of the problems in detecting neutrons is the potential background from rogue γ -rays produced by neutrons from the pulsed source or the reactor, plus those generated by reactions with a monochromator or even the sample. Therefore, the electronics controlling the detector must be capable of differentiating the energy (or emission rate at pulsed sources) of the γ -rays so that only those generated in the detector are recorded. In addition, the detector must be shielded against the "cloud" of neutrons around the diffractometer. The shielding is very thick: many millimetres of polythene can help to moderate any fast neutrons, and the background neutrons will then be absorbed by B₄C-doped plastic or rubber.

1. Slow Neutron Detector: Widespread nuclear reactions with slow neutrons are in the energy range of about 0.1 eV to 0.5 eV. There are standard requirements for slow neutron detection. As in photon detection, the interaction cross-sectional area must be as large as possible to achieve high efficiency. Neutrons always produce secondary gamma rays by interacting either with surrounding

materials or detector materials. Thus, the quality-value of the interaction should be large to make the gamma-ray identification easy, and the kinetic energy of the products should be fully absorbed [10].

The three valuable interactions are B¹⁰ (n, α), Li⁶ (n, α), and He³ (n, p). The quality values are so large (compared to the neutron energy) that the interacting products cannot give information on the detected neutron. Thus, these detectors are very important for the pulse counting mode, and a time-of-flight spectroscopy technique must be employed for slow neutron spectroscopy to be achieved. The reaction products are emitted in opposite directions to maintain the linear momentum, and the energy of each product is also calculated by conservation of momentum and energy.

2. Boron-Based Detectors: The acclaimed boron-based neutron detector is the BF₃ proportional counter. In this detector, BF₃ gas acts both as a neutron detection material and a proportional gas. Diverse boron-containing gases, including BF₃, have a high concentration of boron, and their gas multiplication performance is extremely good. The intrinsic efficiency of a 30cm long detector (97% enriched ¹¹B) filled to 601 tons is 93% at thermal neutron energies (26 meV) in pulse height spectra from a BF₃ detector. Depending on the energy accumulation of each production, the total deposited energy within the gas volume changes.

When gamma rays interact, the resultant pulse height is the same as the pulse height of the neutron event due to full-energy deposition.

3. Helium-Based Detectors: The natural property of helium is the key component in a gas-proportional counter, and this is the most popular nuclear chamber compared to the ¹⁰B (n, α) interaction. The He³ (n, p) reaction has a more significant cross-section, which makes a He³ proportional counter an attractive alternative to a BF₃ proportional counter. The lower Q-value of the He³ (n, p) reaction makes gamma-ray identification more difficult than for a BF₃ counter.

D. Neutron Cross-Section

In particle and nuclear physics, neutron cross-section expresses the probability of interaction between an incident neutron and a target nucleus in combination with the neutron flux. It facilitates the calculation of the reaction rate, for instance, to derive the thermal power of a nuclear plant. The internationally agreed unit for measuring the cross-section is the barn,

which equals 10^{-29} cm^2 or 10^{-25} cm^2 . The more significant a larger neutron cross section is, the more likely the neutron will react with the target nucleus.

Isotopes (or nuclides) can be grouped according to their neutron cross-sections and how they react to an incident neutron. Nuclides that are likely to either decay and absorb a neutron or keep the neutron in their nuclei are neutron absorbers and will definitely have a capture cross section for that reaction. Isotopes that undergo fission are known as fissile fuel, and they have a corresponding fission cross-section, but the remaining isotopes that scatter have a scatter cross-section. Some isotopes, like uranium-238, have nonzero cross-sections of all three [11].

Isotopes with a large scatter cross-section and low mass are good neutron moderators. Nuclides that have a large absorption cross-section are neutron poisons if they neither undergo decay nor are fissile. A poison that is correctly inserted into a nuclear reactor to control its reactivity in the long term and improve its shutdown margin is called a burnable.

1. Target type Dependence: The neutron cross-section is dependent on the type of target particle. For example, the capture cross-section of hydrogen-2 (referred to as deuterium) is much smaller than that of hydrogen-1. That is why some reactors use heavy water (in which most of the hydrogen is deuterium) in place of ordinary water as a moderator: fewer neutrons are lost by capture inside the medium, enabling the use of natural uranium instead of enriched uranium. This is the principle of a CANDU reactor.

2. Type of Reaction Dependence: The likelihood of interaction between an incident neutron and a target nuclide, independent of the type of reaction, is expressed with the help of the total cross section σ_T . However, it may be helpful to know if the incoming particle bounces off the target (and therefore continues travelling after the interaction) or disappears after the reaction. The scattering and absorption cross sections σ_S and σ_A can be determined, and the total cross section will be the sum of the two partial cross sections.

3. Absorption Cross Section: If absorption takes place when the neutron bombards the nuclide, the atomic number will move up on the table of isotopes by one position. For instance, U-235 will become U-236*, with the * indicating that the nucleus is energized. This energy has to be released, and the release can take place through several mechanisms.

1. The most effective way to release energy is when the neutron is ejected by the nucleus. If the neutron is ejected, it acts immediately in the same way as other scattering events.

2. The nucleus may emit gamma radiation.

3. The nucleus may emit β^- decay, when a neutron converts into a proton, an electron, or an electron-type antineutrino (antiparticle of the neutrino).

4. About 81% of the U-236* nuclei are so energized that they undergo the fission process to unleash the energy as a kinetic motion of the fission fragments, also emitting between one and five unbound neutrons.

5. Nuclei that undergo fission as their predominant decay method after neutron capture include U-233, U-235, U-237, Pu-239, and Pu-241.

6. Nuclei that absorb neutrons predominantly and then emit Beta particle radiation lead to new isotopes. Thorium (Th-232) absorbs a neutron and becomes Th-233*, which emits a Beta particle and becomes Pa-233, which emits another Beta particle to become U-233.

7. Isotopes that undergo Beta emission change from one element to another, but those that undergo gamma or X-ray emission do not change.

4. Scattering Cross-Section: Scattering cross-section can also be divided into coherent scattering and incoherent scattering, which is caused by spin dependence. Since neutrons interact with the nuclear potential, the scattering cross-section varies for different isotopes of the element. A very prominent example is hydrogen and its isotope, deuterium. The total cross-section for hydrogen is over ten (10) times that of deuterium, primarily due to the considerable incoherent scattering length of hydrogen, which is due to its spin dependence. Metals also tend to be relatively transparent to neutrons. Aluminum and zirconium are the two best examples of incoherent scattering.

5. Incident Particle Energy Dependence: For a given target and reaction, the cross-section strongly depends on the neutron speed. In extreme cases, the cross-section can be at low energies (threshold energy) or at high energies.

[11] takes a cross-section observed and recorded either at a given energy or averaged using a variation in energy range. The plot presented shows that the fission cross-section of uranium 235 is low at high neutron energies and becomes higher at low neutron energies. Such physical limitations explain why most operational nuclear reactors use neutron

moderators to reduce the neutron's energy and thus increase the probability of fission, which is essential to producing energy and sustaining the chain reaction.

A simple equation for the estimation of the energy dependence of any kind of cross-section is provided by the Ramsauer Model. This is based on the suggestion that the size of a neutron is proportional to the breadth of the probability density function, the position where the neutron is likely to be, and De-Broglie's wavelength.

III Applications of Neutron

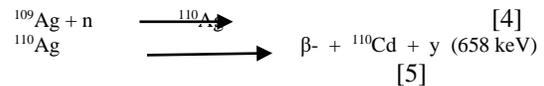
A. Neutron Activation Analysis (NAA)

Neutron Activation Analysis (NAA), discovered in 1936, is an essential technique for quantitative multi-element analysis of major, minor, trace, and rare elements. The initial step in neutron activation analysis is irradiating a sample with neutrons in a nuclear reactor or sometimes from other neutron sources. A stable nucleus absorbs one neutron and becomes a radioactive nucleus. The concentration of the stable element in the sample is measured by detecting the decay of these nuclei. The radioactive nuclei emit characteristic gamma rays. Detection of specific gamma rays (of specific energy) indicates the presence of a particular element. Suitable semiconductor radiation detectors may be used for quantitative measurement. The concentration of various component elements in a given sample can be analyzed by computer data reduction of gamma-ray spectra. Sequential instrumental neutron activation analysis allows quantitative measurement of up to 35 elements in a small sample of 5mg to 100mg. The lower detection limit is in parts per billion or parts per million, depending on the element [12].

The Oregon State TRIGA Reactor (OSTR) is a water-cooled reactor that uses uranium and zirconium hydride fuel elements in a circular grid array for research [13]. This reactor core is enclosed by a ring of graphite that reflects neutrons into the core. The core is positioned near the bottom of a 22-foot-deep, water-filled tank, and the tank is enclosed by a concrete monolith that acts as a radiation shield and structural support. The reactor's operations are licensed by the U.S. Nuclear Regulatory Commission to generate a maximum steady-state power of 3000 MW.

General Principles: In typical NAA, stable nuclides (AZ, the target nucleus) undergo neutron capture reactions in a flux of incident neutrons. The

radioactive nuclides (A+Z, the compound nucleus) produced in this activation process usually decay by emission of a beta particle (β^-) and gamma ray(s) with a unique half-life. A high-resolution gamma-ray spectrometer can detect these delayed gamma rays in the presence of the artificially induced radioactivity in the sample for both qualitative and quantitative analysis. The incident neutron hits the target nucleus, which captures the neutron and converts it into a compound nucleus. The latter immediately emits radiation called prompt gamma radiation and forms the radionuclide, which then kicks out a beta particle and emits delayed gamma radiation (emitted after some time delay). The natural sodium Na^{23} target is taken as a specific example. On neutron capture, it is converted to radioactive sodium Na^{24} . The usual procedure involves placing the samples to be analyzed with a number of suitable standards into the neutron field produced by a research nuclear reactor. The samples are then analyzed using an appropriate gamma-ray detector system. The Na^{24} decays to stable Mg^{24} with the release of gamma rays with energies of 1368.53 and 2754.09 kiloelectron volts (keV). On striking a suitable detector, the gamma ray energies are converted to an electrical signal known as a count in an energy spectrum. The accumulation of gamma counts at a particular point generates a curve. The area of which is proportional to the standards allows the establishment of a relationship that can be used to determine the abundance of a particular element or elements. The energies of the delayed gamma rays help in identifying component sample elements. The count of gamma rays of specific energy indicates the amount of element in the sample. For example, when a silver sample is irradiated, a fraction of the Ag^{109} atoms will capture a neutron and become Ag^{110} . The radioactive Ag^{110} atoms have a half-life of 24.6 seconds. Beta decay of Ag^{110} atoms to Cd^{110} occurs 4.5% of the time with the emission of a 658 keV gamma ray. The number of silver atoms present in the original sample can be determined by measuring the count of 658 keV gamma rays emitted from the sample in a given time interval after irradiating the sample.



1. Advantages and Limitations: As most samples are entirely transparent to both the probe (the neutron) and the analytical signal (the gamma ray), NAA is free of matrix interference. NAA does not require sample pretreatments such as digestion or dissolution because reagent or laboratory contamination is minimized, but

interferences can still occur when different component sample elements produce similar gamma rays. Interference can be circumvented by choosing alternate gamma rays or by counting after the shorter-lived nuclide has decayed. Other interferences can occur if another type of nuclear reaction simultaneously produces the radionuclide of interest in addition to the simple neutron capture process described here. Sensitivities and accuracy depend on the concentration of the element and radionuclide parameters (i.e., parent isotope abundance and gamma-ray abundance) present in the sample. Element sensitivities vary from 10^{-3} to 10^{-10} grams per gram of sample. Accuracy is usually between two and ten percent of the reported value, depending on the element analyzed and its concentration in the sample. The detection limit for a particular element depends upon the measured count rate (R) of the monitored gamma ray and the background radiation. As seen from the equation, the calculated count rate (R) for a given isotope and consequently the S/N (signal-to-noise ratio) can be increased by any combination of the following:

1. Increasing the detector efficiency (moving the sample closer to the detector)
2. Increasing the irradiation time (TI)
3. Decreasing the decay time (TD).

In many cases, the accuracy of the measurement can be improved by increasing the measurement time (TM), which enhances the overall signal or total number of counts (RTM). The bulk matrix is another common limitation of instrumental NAA. When it produces an extensive background that masks the signal of interest, the S/N becomes very low and the detection limit is greatly reduced. Time delays or chemical separations are employed to minimize this effect.

2. Applications: Advances in semiconductor detector systems and improvements in nuclear reactors have widened the scope of neutron activation analysis. A solid testament to the reliability and accuracy of NAA is its use in analyzing the lunar samples from the Apollo missions. Instrumental neutron activation analysis and radiochemical neutron activation analysis have made it possible for high-sensitivity and non-destructive determination of trace element concentrations in the bulk of a sample. Neutron activation analysis has been successfully used in research as diverse as nutrient uptake in plants, petro-genetic modelling of geologic phenomena,

identification of impurities in new metals and alloys, environmental monitoring, and analysis of forensic evidence for criminal and civil cases. Small samples (as small as a few micrograms) of 30 to 35 major, minor, and trace elements are routinely analyzed by instrumental neutron activation analysis. Radiochemical neutron activation analysis techniques, although destructive to the sample, enhance the number of determinable elements and rely on the assumption that different isotopes of the same element exhibit similar properties in any chemical process.

Different thickness gauges exploit the fact that gamma rays intensity decreases when they pass through a material. This process is employed in typical industrial applications such as:

1. The automobile industry: to test steel quality in the manufacture of cars and to obtain the proper thickness of tin and aluminum
2. The aircraft industry: to check for flaws in jet engines
3. Construction: to gauge the density of road surfaces and sub-surfaces
4. Pipeline companies test the strength of welds.
5. Oil, gas, and mining companies to map the contours of test wells and mine bores.
6. Cable manufacturers should check ski lift cables for cracks.

B. Neutron Interaction with Matter

Since neutrons are electrically neutral, they can penetrate matter more deeply than electrically charged particles of comparable kinetic energy; therefore, they are valuable probes of bulk properties. Neutrons interact with atomic nuclei and magnetic fields from unpaired electrons. Neutrons can cause pronounced interference and energy transfer effects in scattering experiments. Unlike x-ray photons with similar wavelengths, which interact with the electron cloud surrounding the nucleus, neutrons interact primarily with the nucleus of the atom itself. This interaction is described by Fermi's pseudo potential in arbitrary dimensions. Neutron scattering and absorption cross-sections vary unduly from isotope to isotope.

Also, depending on the isotope, the scattering can be incoherent or coherent. Among all isotopes, hydrogen has the highest neutron scattering cross-section. Also, important elements like carbon and oxygen are well visible in neutron scattering. This is in marked

contrast to x-ray scattering, where cross-sectional area increases with atomic number. Thus, neutrons can be used to analyze materials with low atomic numbers, like surfactants and proteins, at particle accelerator sources with high intensity, although they may cause the structures to change. The nucleus provides a concise range, with isotopic potential varying randomly from isotope to isotope, making it possible to tune the nuclear scattering contrast to suit the experiment.

The scattering almost always has elastic and inelastic components, but fractional elastic scattering is given by the Debye-Waller factor or the Mossbaver Lamb factor [14]. To attain a precise velocity, i.e., an accurate energy and De-Broglie wavelength, of the neutron beam is important; such single-energy beams are termed monochromatic. Monochromaticity is achieved either with a crystal monochromator or a time-of-flight mass spectrometer. In the time-of-flight approach, neutrons are sent through a segue of two spin slits, and only neutrons of a particular velocity are selected. There has also been the development of spallation sources, which can help create a rapid pulse of neutrons. In this method, the pulse contains scattered neutrons of different velocities, and these velocities can be determined afterwards by measuring the time of flight of the neutron between the samples in the neutron detector.

C. Neutrons in Material Science

Since neutrons are electrically neutral, they can penetrate matter more deeply than electrically charged particles of comparable kinetic energy; therefore, they are valuable probes of bulk properties. Neutrons interact with atomic nuclei and magnetic fields from unpaired electrons. Neutrons can cause pronounced interference and energy transfer effects in scattering experiments. Unlike x-ray photons with similar wavelengths, which interact with the electron cloud surrounding the nucleus, neutrons interact primarily with the nucleus of the atom itself. This interaction is described by Fermi's pseudopotential in arbitrary dimensions. Neutron scattering and absorption cross-sections vary unduly from isotope to isotope.

Also, depending on the isotope, the scattering can be incoherent or coherent. Among all isotopes, hydrogen has the highest neutron scattering cross-section. The study of neutrons is of great significance in material science because neutrons have unique properties that make them an ideal probe for studying the dynamics and structure of materials. Neutrons are uncharged

particles, which mean they can penetrate materials without being deflected by electric fields, unlike charged particles such as electrons or ions. This property allows neutrons to probe the internal properties and structure of materials without damaging or altering them.

Moreover, neutrons have a unique sensitivity to light elements such as hydrogen and lithium, which are difficult to detect using other techniques. This property is significant in the study of biological molecules and polymers, where hydrogen atoms play a critical role in determining the function and structure of these materials.

Neutron scattering techniques, such as neutron diffraction and neutron spectroscopy, provide detailed information about the atomic structure, molecular structure, dynamics, and interactions of neutrons with materials. This information is essential for understanding the properties and behaviour of materials in various applications, including energy storage, catalysis, drug delivery, and advanced materials for electronics, sensors, and photonics.

1. Neutron Imaging: Neutron imaging is a valuable tool in material research due to its unique ability to penetrate materials without damaging them. This makes it possible to study the internal structure and behaviour of materials under real-world conditions, which can provide insights into their properties and behaviour [15].

Application of Neutron Imaging: There are some specific areas of application for neutron imaging in material research. They include:

1. Characterization of porous materials: Neutron imaging is used to study the properties and internal structure of porous materials such as foams, rocks, and ceramics. This can provide information about their connectivity, fluid flow behaviour, and pore size distribution.

2. Investigation of composite materials: Neutron imaging can be used to analyze the internal structure and properties of composite materials such as metal-matrix composites, polymer composites, and ceramic-matrix composites. This can provide information about their distribution of phases, microstructure, and defects.

3. Study of battery materials: Neutron imaging can be used to analyze the nature of materials used in batteries, such as lithium-ion batteries. This gives information about the distribution of lithium ions

within the battery, which aids in the optimization of battery performance.

4. Analysis of welding operations: Neutron imaging can be used to examine the behaviour of materials during welding processes. This can provide details about the formation of defects such as voids and cracks, which can help improve welding processes.

5. Investigate corrosion: Neutron imaging can be used to study the action of materials under corrosive conditions. This can provide information about the propagation and formation of corrosion, which can help develop strategies to mitigate or prevent corrosion.

Overall, neutron imaging is an important tool in material research that can provide unique insights into the behaviour of materials under a variety of conditions [16].

D. Industrial Application of Neutron

Neutron imaging is a valuable tool in material research due to its unique ability to penetrate materials without damaging them. This makes it possible to study the internal structure and behaviour of materials under real-world conditions, which can provide insights into their properties and behaviour [15].

A radionuclide tracer, or radiotracer, is a small repetition of a system whose properties aid in the systematic study of that system. This means that its properties must be similar but different from the bulk. Radioactive isotopes emitting gamma rays or beta particles are excellent candidates for use as tracers to study the dynamical behaviour of biological, hydrological, and industrial systems. The primary attribute of a radioactive substance that makes it extremely useful as a tracer is its amenability to detection at low levels [17].

Radiotracer is ideally suited for fast diagnosis of faults in operating industrial systems and for studying the kinetics of industrial processes without having to shut down normal operations. This is not possible with other tracers. The most commonly used radionuclide tracer in industry is given in the table.

Table: The Most Commonly used Radionuclide Tracer in Industry

Isotope	Half-life	Chemical form	Application
Ar ⁴¹	109min	Argon	Gases
Na ²⁴	14h	Sodium carbonate	Aqueous solution

Br ⁸²	35h	Ammonium Bromide	Aqueous solution
La ¹⁴⁰	1.67d	Lanthanum chloride	Solid
Hg ¹⁹⁷	2.6d	Mercury metal	Mercury inventory

E. Fast neutron Capture and Neutron Therapy

1. Therapy of Cancer: Neutron radiation can be exploited for medical treatment because its radiation is both penetrating and ionizing. The radiation can have the unfortunate side effect of leaving the affected area radioactive. Neutron tomography is not a viable medical application, but neutron therapy utilizes high-energy neutrons greater than 20 MeV to treat cancer. Radiation therapy for cancer is dependent on the biological response of the cancerous cells to ionizing radiation. If the radiation beam is delivered in small sessions to damage cancerous areas, normal tissue will have time to rejuvenate itself, while tumour cells often cannot. Neutron radiation can release energy into a cancerous region at a rate that is an order of magnitude greater than gamma radiation. Beams of low-energy radiation are used in boron capture therapy to treat cancer. In boron capture therapy, the patient is treated with a drug containing boron, which assembles in the tumour to be targeted. The cancerous growth (tumour) is then bombarded with very low-energy neutrons (although often higher than thermal energy), which are collected by the boron-10 isotope in the boron. This produces an excited state of boron-11 that then decays to produce lithium-7 and helium particles that have sufficient energy to kill the cancer cell. The alpha particle, although it has a short range, can damage nearby cells. When therapeutic treatment is applied to the treatment of cancer, a neutron source with an intensity of the order of billion (10^9) neutrons per second per cm^2 is preferred, and such fluxes require a research nuclear reactor.

2. Neutron Treatment: Neutron therapy is an efficient form of radiation therapy. Treatment experience with cancer has shown that certain tumour types (pathologies) are complicated when conventional radiation therapy is used to kill the cancerous cells. These pathologies are "radio-resistant". Neutron therapy specializes in treating radio-resistant and inoperable tumours occurring anywhere in the body. Radiation therapy uses penetrating beams of ionizing radiation, primarily to treat malignant tumors. Conventional radiation therapy includes x-rays, photons, and electrons and is available at many hospitals and clinics. These beams are generated by electron accelerators or

from radioactive sources such as cobalt-40. Hadrons therapy includes protons and neutrons, and they are generated using deuteron or proton accelerators. The primary effect of ionizing radiation is to destroy the capacity of cells to divide. This is achieved by damaging their DNA strands. For photon, proton, and electron radiation, the damage is done primarily by activated radicals generated from atomic interactions. These types of radiation are called Low Linear Energy Transfer (LLET) radiation. Neutrons are High Linear Energy Transfer (HLET) radiation, and damage is done primarily by nuclear interactions. If a tumour cell is exposed to LLET radiation, there is a possibility of the cancerous cell repairing itself and continuing to grow. But with HLET radiation, the chance for a damaged tumour cell to repair itself is minimal.

In general, fast neutrons can control huge tumours because, unlike LLET radiation, neutrons do not depend on the presence of oxygen to kill the cancer cells. In addition, the biological effectiveness of neutrons is not affected by the time or stage in the life cycle of cancer cells, as it is with LLET radiation.

Because the biological effectiveness of neutrons is so high, the required tumour dose to kill cancer cells is about one-third of the amount required with photons, protons, or electrons. An entire course of neutron therapy is administered in only 10^{-12} treatments, compared to 30^{-40} treatments needed for LLET radiation.

F. Application in Astronomy (the Neutron Star)

A neutron star consists of the collapsed core of a large (10^{-29} solar masses) star. Neutron stars are the densest and smallest stars known to exist. With a radius of 12 km, they can, however, have a mass of about thrice that of the Sun. They arise from the supernova explosion of a super-giant star, combined with gravitational collapse that compresses the core to a white dwarf star density. Most of the basic models for these objects imply that neutron stars are composed almost entirely of neutrons. They are supported against additional collapse by neutron degeneracy pressure; a phenomenon described by the Pauli Exclusion Principle. If the remnant is massive, the density which is more than an upper limit of the size of neutron stars at 2-3 solar masses will continue to collapse to form a black hole [18].

Neutron stars are scorching and typically have a surface temperature around 6.0×10^5 K. They are so

dense that a 3cm^3 container containing neutron-star material would have a mass of approximately 13 million tons, or a 2.5 million m^3 chunk of the Earth (a cube with edges of about 135 meters). They have strong magnetic fields, between 10^9 and 10^{16} times stronger than Earth's. The gravitational field at the neutron star's surface is about 3×10^{11} times that of the Earth [19].

As soon as the star's core collapses, its rotation rate increases due to the conservation of angular momentum. A newly formed neutron star emerges and rotates up to several hundred times per second. Some neutron stars emit beams of electromagnetic radiation, and that makes them detectable as pulsars. Indeed, the discovery of pulsars in 1967 was the initial observational suggestion that neutron stars existed. The radiation from pulsars is assumed to emanate from regions near their magnetic poles. If the magnetic poles do not coincide with the rotational axis of the neutron star, the emission beam will sweep the sky. When observed from a distance, if the observer is somewhere in the path of the light beam, it will appear as pulses of radiation coming from a fixed location in space (the so-called lighthouse effect"). The fastest rotation rate for a neutron star is 715 times per second or 45,500 revolutions per minute, giving a linear speed at the surface on the order of 0.166 c.

There are more than 100 million neutron stars in the Milky Way. This figure is obtained by estimating the number of stars that have undergone supernova explosions. However, most are old and cold, and neutron stars can only be easily detected in certain conditions, such as when they are a part of a binary system or as pulsars [20].

Non-accreting and slow-rotating neutron stars are virtually undetectable; however, since the *Flourish Space Telescope's* detection of RX J185635-3754, a few nearby neutron stars that emit thermal energy in the form of radiation have been detected. Soft gamma stars are guessed to be a type of neutron star with very strong magnetic fields, known as neutron stars with fossil discs around them, or alternatively, magnetars.

Neutron stars in binary systems can undergo accumulation, which makes the system bright in x-rays, while the material falling onto the neutron star can form hotspots that revolve in and out, as seen in identified X-ray pulsar systems. In addition, such accretion can "recycle" old pulsars and potentially cause them to gain mass and spin up very fast,

forming the so-called millisecond pulsars. These binary systems will continue to evolve, and eventually their companions can become compact objects such as neutron stars or white dwarfs themselves, though other possibilities include the complete destruction of the companion through merger or ablation. The ablation of binary neutron stars is likely the source of short-duration gamma-ray bursts and a strong source of gravitational waves. Though, as of 2015, no direct detection of the gravitational waves from such an event was possible, gravitational waves have been incidentally detected in a system where two neutron stars orbit each other [21].

1. Formation: Any arrangement or category of star with an initial mass above 8 M_{\odot} has the potential to produce a neutron star. As the star drifts away from the main sequence, subsequent nuclear burning produces an iron-rich core. When all the nuclear fuel in the core has been completely used up, the core must be backed up by degeneracy pressure alone. Further accumulation and deposits of mass from shell burning cause the core to exceed the Chandrasekhar limit. Electron-degeneracy pressure is overcome, and the core collapses further, causing its temperatures to soar to over 5×10^9 K. At these temperatures, photodisintegration (the complete breaking up of iron nuclei into alpha particles by high-energy gamma rays) occurs. As the temperature increases, electrons and protons combine to form neutrons via electron capture, releasing a pool of neutrinos. Neutron degeneracy pressure halts the contraction when densities reach a nuclear density of 4×10^{17} kg/m³. In falling, the outer envelope of the star is terminated and flung outward by a flux of neutrinos produced in the creation of the neutrons, thereby becoming a supernova. The residue is a neutron star. If the remnant has a mass greater than about 3.5 M_{\odot} , it will further collapse to become a black hole [22].

As the core of a massive star condenses during a Type II supernova, Type Ib, or Type Ic supernova and collapses into a neutron star, it retains most of its angular momentum. Since it has only a tiny fraction of its parent's radius (and therefore its moment of inertia is sharply reduced), a neutron star is formed with a high rotation speed, which finally slows down after a very long period. Neutron stars are known to have rotation periods ranging from about 1.5 ms to 35 s. The neutron star's density also gives it a very high surface gravity, with typical values ranging from 10^{13} to

10^{14} m/s² (10^{12} times that of Earth). One of the reasons for such immense gravity is the fact that neutron stars possess an escape velocity ranging from

100,000 km/s to 150,000 km/s, that is, from a third to half the velocity of light. The neutron star's gravity accelerates falling matter to tremendous speeds. The force of its impact would probably destroy the object's component atoms, rendering all the matter identical to the rest of the neutron star [23-25].

2. Properties:

Mass and Temperature - A neutron star has a mass of at least 1.0 and perhaps up to 3.0 solar masses (M_{\odot}). In general, compact stars of less than 1.39 M_{\odot} (the Chandrasekhar limit) are white dwarf stars, whereas compact stars with a mass between 1.4 M_{\odot} and 3 M_{\odot} (the Tolman-Oppenheimer-Volkoff limit) are likely to be neutron stars (though there are a few tenths of a solar mass where the masses of low-mass neutron stars and high-mass white dwarfs can overlap). Between 3 M_{\odot} and 5 M_{\odot} , hypothetical transitional stars such as quark stars and electroweak stars have been proposed, but none have been shown to exist. Beyond 10 M_{\odot} , the stellar remnant will overcome the gravitational collapse, and neutron degeneracy pressure will usually occur to produce a black hole, though the smallest observed mass of a stellar black hole is about 5 M_{\odot} . The temperature inside a nascent neutron star is about 10^{11} to 10^{12} Kelvin. However, the huge number of neutrinos released carries away so much energy that the temperature of an isolated neutron star falls within a few years to around 10^6 Kelvin. Even at this lower temperature, most of the light generated by a neutron star is in the X-ray range [26-29].

Density and Pressure - Neutron stars have overall densities of 3.7×10^{18} to 5.9×10^{18} kg/m³ (i.e., 2.6×10^{15} to 4.1×10^{15} times the density of the Sun), which is similar to the approximate density of an atomic nucleus of 3×10^{17} kg/m³. The neutron star's density varies approximately from 1×10^9 kg/m³ in the crust, increasing with depth to about 6×10^{17} to 8×10^{17} kg/m³ (denser than an atomic nucleus). A neutron star is so dense that one tablespoon (10 millilitres) of its matter would have a mass of over 10.5×10^{12} kg (that is, 2400 tonnes per 1 nanolitre), about 1200 times the mass of the Great Pyramid of Giza. The pressure increases from 3×10^{43} to 1.6×10^{45} Pa from the inner crust to the centre, or core.

The equation of state of matter at such high densities is not exactly known because of the theoretical difficulties associated with extrapolating the likely behaviour of quantum chromodynamics, superfluidity, and superconductivity of matter in such states, along with the empirical difficulties of observing the characteristics and dynamics of neutron stars that are at least hundreds of parsecs away.

Giant Nucleus - A neutron star has similar properties to those of an atomic nucleus, including its density, and is composed of nucleons within an order of reasonable magnitude. In popular scientific observations, neutron stars are therefore sometimes described as super giant nuclei. However, in other respects, atomic nuclei and neutron stars are quite different. In particular, a nucleus is bonded together by the strong interaction force, whereas a neutron star is held together by gravity, and thus the structure and density of neutron stars can be more variable [30-31].

Magnetic Field - Neutron stars have strong magnetic fields. The field strength on the surface of neutron stars has been estimated to have a range of 10^8 to 10^{15} gauss (10^4 to 10^{11} tesla). In comparison, the magnitude at Earth's surface ranges from 0.25 to 0.65 gauss (25 to 65 microtesla), making the field at least 10^8 times as strong as Earth's magnetic field. The disparities in magnetic field strengths are probably the main factor that allows different types of neutron stars to be distinguished by their spectra, and explains the oscillation of pulsars. Magnetars also known as neutron stars have the strongest magnetic fields, in the range of 10^8 to 10^{11} tesla and have become the acknowledged hypothesis for neutron star types; anomalous X-ray pulsars (AXPs) and soft gamma repeaters (SGRs).

The origins of the strong magnetic field are yet unknown due to its ambiguous nature. One hypothesis is that of the conservation of the original magnetic flux, which takes place during the formation of the neutron star (flux freezing). If an object has a specific magnetic flux over its surface area and that surface area contracts to a smaller one, but the magnetic flux is conserved, then the magnetic field would correspondingly increase. In addition, a collapsing star begins with a much larger surface area compared to a resulting neutron star, and the conserved magnetic flux will result in a far stronger and more stable magnetic field than the neutron star. However, this simple idea does not fully explain the magnetic field strengths of neutron stars.

Pulsars - Neutron stars are detected and classified from their electromagnetic radiation. Neutron stars are usually observed through pulsed radio waves and other electromagnetic radiation, and neutron stars observed with pulses are called pulsars.

Pulsars' radiation is thought to be caused by particle acceleration near their magnetic poles, which need not be aligned with the rotational axis of the neutron star. It is thought that a large electrostatic field builds up near the magnetic poles, leading to electron emission. These electrons are magnetically accelerated along the field lines, leading to curvature radiation, with the radiation being strongly polarized towards the plane of curvature. In addition, high-energy photons can interact with lower-energy photons and the magnetic field for electron-positron pair production, which, through electron-positron annihilation, leads to further high-energy photons.

The radiation emanating from the magnetic poles of neutron stars can be described as magnetospheric radiation, in reference to the magnetosphere of the neutron star. It is not to be confused with magnetic dipole radiation, which is emitted because the magnetic axis is not aligned with the rotational axis and has a radiation frequency the same as the neutron star's rotational frequency. If the axis of rotation of the neutron star is different from the magnetic axis, external viewers will only see these beams of radiation whenever the magnetic axis points towards them during the neutron star's rotation. Therefore, periodic pulses are observed at the same rate as the rotation of the neutron star.

Non-pulsating Neutron Stars - In addition to pulsars, neutron stars have also been identified with no apparent periodicity in their radiation. This seems to be a characteristic of the X-ray sources known as Central Compact Objects in supernova remnants (CCOs in SNRs), which are thought to be young, radio-quiet isolated neutron stars.

Spectra - In addition to radio emissions, neutron stars have also been identified in other parts of the electromagnetic spectrum. This includes visible light, near infrared, ultraviolet, X-rays, and gamma rays. Pulsars observed in X-rays are known as X-ray pulsars if they are accretion-powered, while those identified in visible light are known as optical pulsars. The majority of neutron stars detected, including those identified in optical, X-ray, and gamma rays, also emit radio waves. The Crab Pulsar produces electromagnetic emissions across the spectrum. However, there are neutron stars called

radio-quiet neutron stars, with no radio emissions detected.

IV Conclusion

This work presented a review of recent developments in neutrons in material science, which is crucial to finding solutions to a whole array of new technological and sociological demands in such areas as energy, health, national security, and the environment. Neutron scattering is an effective technique for studying the properties and structure of materials at the molecular and atomic levels. It is particularly suitable for material research because neutrons are reactive to different types of atoms and have the ability to penetrate deep into materials without damaging them, providing information about their inner structure without destroying the sample. This is because of their responsiveness to light elements, non-destructive nature, versatility, and penetration depth.

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