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Plasma-Based Neutron Sources and Laser-Driven Acceleration Mechanisms

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Abstract: Three laser-plasma-based methods for neutron generation are explored. First, laser wakefield acceleration (LWFA) produces relativistic electron beams that generate neutrons via bremsstrahlung and photo-neutron reactions in a tungsten converter. Second, laser-driven deuterium-deuterium (D-D) fusion uses cryogenic deuterium ice targets irradiated by petawatt lasers to achieve extremely high plasma temperatures and neutron yields. Third, laser-ion acceleration involves accelerating ions (protons/deuterons) that collide with beryllium or copper converters, producing neutrons via nuclear reactions. A key advantage of using plasma is its ability to sustain extreme energy densities and electromagnetic fields, enabling compact, ultrafast, and high-flux neutron sources without the need for large-scale facilities. These methods are verified experimentally and through simulations, demonstrating compatibility with modern high-intensity laser systems.

Key words: Plasma physics, high-intensity laser pulses, laser-plasma interaction, electron acceleration, neutron generation.

1. Introduction

Neutrons are electrically neutral subatomic particles first identified by James Chadwick in 1932. Their discovery opened up new possibilities in nuclear physics and materials science. Just a few years later, in 1935, H. Kallmann and E. Kuhn performed the first neutron radiography experiment using a small-scale neutron source [1], marking the beginning of practical neutron applications. Since then, extensive research and technological advancements have significantly broadened the scope of neutron use across diverse scientific and industrial domains. Today, neutron sources serve critical roles in a variety of fields, such as neutron powder diffraction [2], oil and gas exploration [3], non-destructive neutron imaging [1], and boron neutron capture therapy for cancer treatment [4]. Due to their unique interaction characteristics with matter, neutrons are often irreplaceable in certain applications where conventional techniques like X-rays fall short. This makes them indispensable tools in both fundamental research and applied industrial practices. Among the various applications, neutron imaging stands out as a particularly well-established technique. Much like X-ray imaging, neutron imaging involves the creation of two-dimensional attenuation maps that reveal internal features of objects based on the interaction of radiation with matter. However, the two methods yield distinctly different image contrasts because of the fundamentally different ways in which neutrons and X-rays interact with elements. As shown in Fig. 1, X-rays are strongly attenuated in materials with high atomic numbers (high-Z), such as metals, due to their high electron density.

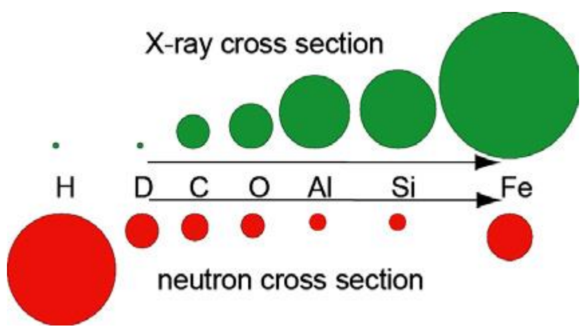

Fig. 1 Illustrative comparison of interaction cross-sections for neutrons and X-rays [5].

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In contrast, neutrons are more sensitive to low-Z materials and can penetrate deep into dense metals with relatively low attenuation. This contrast enables neutron imaging to uncover internal features in metallic components, such as jet engine blades, where X-ray imaging is ineffective. The same neutron-material interaction characteristics also make neutrons suitable for neutron powder diffraction, where they complement X-ray diffraction by offering access to different structural information, especially in light elements or magnetic materials. Both techniques provide diffraction patterns that help elucidate the crystal lattice structures of materials. The choice between neutron and X-ray diffraction methods typically depends on the elemental composition and specific features of the sample under study. Neutron sources can be categorized based on several criteria, including neutron energy spectrum, neutron flux, and source size. Of these, neutron flux is often the most critical parameter, as it directly determines the suitability of a neutron source for a particular application. Depending on the use case, neutron flux is characterized differently. For instance, in neutron powder diffraction, the flux is often specified as the number of monoenergetic neutrons per unit wavelength per square centimeter per second. A summary of various industrial applications and their corresponding neutron flux requirements is shown in Table 1 [1, 2, 4, 6]. Furthermore, neutron sources are classified into three main categories according to their energy:

- Cold neutron sources (low-energy neutrons)
- Thermal neutron sources (moderate-energy neutrons)
- Fast neutron sources (high-energy neutrons)

Thermal neutrons are the most commonly used and find wide application in neutron diffraction and imaging. Fast neutrons are predominantly used in active interrogation systems for detecting hidden nuclear materials, while cold neutrons are often employed in advanced techniques such as neutron interferometry, where longer wavelengths are beneficial for high precision measurements.

Table 1 Typical neutron flux requirements for various industrial and medical applications.

Applications	Needed neutron flux
Boron neutron cancer therapy	10^{12}-10^{13} n/s
Radiography	10^{11}-10^{12} n/s
Silicon doping	10^{13}-10^{14} n/s
Neutron radiography	10^{11}-10^{12} n/s

2. Conventional and Laser-driven Neutron Sources

Neutron sources are essential tools in various scientific, medical, and industrial applications. However, unlike light sources, the methods for generating high-flux neutron beams are quite limited. Currently, there are only two primary types of practical, high-flux neutron sources in widespread use: fission-based sources and spallation-based sources. Fission neutron sources, such as those operating in nuclear reactors, rely on the well-known chain reactions of fissile materials like uranium-235. When a U-235 nucleus captures a thermal neutron, it undergoes fission, releasing 2-3 additional neutrons on average. These secondary neutrons can further induce fission in neighboring nuclei, perpetuating the chain reaction. The excess neutrons produced in this process are then extracted from the reactor core and used as neutron beams. Facilities such as the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory (USA) and the Institute Laue-Langevin (ILL) in France are prominent examples of this type. The second main class, spallation neutron sources, is often regarded as a next-generation alternative to fission-based systems. These sources use particle accelerators, such as synchrotrons or linear accelerators, to accelerate protons (or sometimes electrons) to relativistic speeds. These high-energy particles are then directed onto a dense, heavy metal target, typically tungsten or uranium, inducing a spallation reaction. As a result, the target nuclei are broken into smaller fragments, releasing 20-30 neutrons per incoming GeV-scale proton. Notable examples include the Spallation Neutron Source (SNS) in the USA and the ISIS neutron and muon source in the UK. Although fusion-based neutron sources, such as those using deuterium-tritium (D-T) or deuterium-deuterium (D-D) reactions, also produce neutrons, they are still largely confined to research and proof-of-principle experiments, including those at the National Ignition Facility (NIF) and ITER in France. These fusion sources have not yet reached the level of practicality and routine usability of fission and spallation systems. Despite their effectiveness, traditional neutron sources suffer from significant limitations. They are large, expensive to build and maintain, and in many cases, subject to strict regulatory or geopolitical restrictions. As a result, access to such facilities is limited on a global scale [1]. In contrast, recent advances in high-intensity laser technology have given rise to laser-driven neutron sources, which promise a more compact and accessible alternative. Originally proposed over two decades ago, laser-based neutron generation remains an active area of research, with the majority of work still at the proof-of-concept stage. Nonetheless, these systems offer unique advantages that distinguish them from conventional neutron facilities. The core strength of laser-driven sources lies in the extremely high acceleration gradients achievable via laser-plasma interactions orders of magnitude greater than those of conventional RF accelerators, which are generally limited to about 100 MV/m due to material breakdown thresholds [7]. This allows for particle acceleration to comparable energy levels in a dramatically shorter distance, enabling tabletop-scale setups with the potential for portability and cost-effectiveness. Moreover, laser systems are inherently versatile. From a single laser-plasma platform, one can generate not only neutron beams but also high-energy electrons [8-14], ions [15], and X-rays [16], each offering a rich spectrum of applications in materials science, nuclear physics, medicine, and beyond. This multi-functionality further enhances the appeal of laser-driven platforms as next-generation radiation sources. Another key advantage is their ability to produce ultrashort neutron pulses, thanks to the femtosecond-to-picosecond durations of modern laser pulses. These short bursts lead to high temporal resolution, which is crucial for time-sensitive experiments and applications involving pulsed neutron beams. For instance, the rapid neutron capture process (r-process) a key mechanism responsible for the synthesis of heavy elements in astrophysical events can be experimentally studied in controlled laboratory settings using such intense pulsed sources [17]. Furthermore, laser-based neutron sources are being explored for advanced diagnostic imaging techniques, such as Fast Neutron Resonance Radiography (FNRR) [18]. This method uses a broad-spectrum, pulsed neutron beam to probe objects and detect light elements by leveraging the unique resonance features in their neutron cross-section spectra. By measuring the transmitted spectrum using Time-of-Flight (TOF) techniques, one can determine both the elemental composition and density distribution of the sample. This capability is particularly valuable in non-destructive testing, homeland security, and archaeology. However, such precision demands extremely short neutron pulses typically less than 1 nanosecond to minimize timing uncertainties and accurately resolve closely spaced resonance peaks. While conventional fission and spallation neutron sources continue to serve as the backbone of high-flux neutron science, laser-driven neutron sources offer a transformative vision for the future compact, multifunctional, and highly adaptable. As research advances and laser systems become more powerful and cost-efficient, these sources may soon become viable tools for a wide range of applications currently dominated by large-scale facilities.

3. High-energy Particle Generation via Laser-plasma Acceleration

The first step involves producing high-energy particles through laser-plasma acceleration mechanisms. Challenges at this stage include optimizing particle beam quality, increasing laser repetition rates, and minimizing laser system size for practical deployment.

Among these, beam optimization remains the most critical, as current experiments often exhibit instability, resulting in poor reproducibility. Achieving consistent results requires better control over experimental parameters, particularly laser intensity, focus quality, and target uniformity. High-intensity lasers are inherently difficult to stabilize, and achieving precise focus is frequently compromised by optical aberrations and environmental disturbances [19]. To reduce shot-to-shot variations in neutron output, it's essential to improve the stability of laser energy delivery, laser focusing precision, and target alignment. While significant advancements have been made in laser-electron acceleration, especially via the LWFA technique [9, 10, 20, 21], progress in laser-ion acceleration remains relatively limited.

Neutron production from accelerated particle beams

In the second phase, the high-energy particle beams generated from laser-plasma interactions are used to produce neutrons. This can be achieved through three primary schemes:

- Electron-driven neutron generation provides broad-spectrum, pulsed neutrons at high repetition rates, though with low conversion efficiency.
- Ion-driven schemes typically offer higher conversion rates and directional neutron emission influenced by the ion energy, converter material, and target design.
- Fusion-driven methods, capable of producing isotropic, monoenergetic neutron bursts, particularly from reactions such as D-D or D-T fusion.

Selecting the most suitable neutron generation approach and designing efficient converter targets optimized for neutron yield, energy spectrum, and beam directionality are key challenges at this stage.

4. Characterization and Application of Neutron Sources

The final step involves the diagnostic characterization of the laser-generated neutron beams and the development of application strategies. Compared to conventional fission or spallation sources, laser-based neutron beams have unique properties: they offer ultrashort temporal profiles, extremely high peak fluxes, and very compact source sizes. However, despite their intense instantaneous flux, the total number of neutrons per shot is relatively low, limiting their utility in experiments that require high integrated fluence. Moreover, scaling up the neutron output is constrained by the maximum deliverable laser energy, posing a fundamental limitation. Standard neutron moderation and transport methods used in traditional facilities are also ineffective here, as they would dilute the ultrashort pulse and broaden the emission region, negating the core advantages of laser-driven sources. This highlights the urgent need for alternative utilization strategies tailored specifically for laser neutron sources, such as time-resolved probing, localized diagnostics, or compact imaging systems that capitalize on the high brightness and short duration of these beams.

5. Instrumentation and Diagnostic Challenges

Accurate measurement and characterization of laser neutron sources pose additional challenges. Existing instruments are unable to directly measure the ultrashort neutron pulse durations (typically sub-nanosecond), as they are over a thousand times shorter than the pulses from conventional spallation sources. Moreover, fast neutrons, being neutral and weakly interacting, do not easily produce detectable signals in short timescales. As a result, critical information such as pulse duration and source size remains unknown in most current experiments. Diagnostics are typically limited to measuring neutron fluence (neutrons per steradian), while end-users often require characterization in terms of neutron brightness (neutrons/sec/cm^2/sr) for meaningful comparison with other sources. Although some estimates of neutron pulse duration have been inferred indirectly, such as via time-of-flight (TOF) measurements of associated ion beams [22], these methods have not yet been experimentally validated. Without precise knowledge of neutron birth time and emission geometry, it remains difficult to calculate accurate neutron flux, which is essential for benchmarking and guiding future development. Thus, there is a strong demand for new diagnostic tools and advanced detector technologies capable of resolving ultrafast, small-scale neutron emissions. These developments are vital for fully realizing the potential of laser-driven neutron sources and expanding their role in both fundamental research and applied technologies. A summary of typical schemes and a description of laser-based neutron sources are shown in Table 2.

6. Neutron Generation Via Laser-driven Ion Acceleration

Over time, numerous techniques have been developed and explored for producing neutrons through laser-plasma interactions. Among these, the most widely adopted approach involves utilizing ion beams primarily protons or deuterons accelerated by lasers through mechanisms such as target normal sheath acceleration (TNSA) [23] or the breakout afterburner (BOA) regime[24]. In the TNSA method, a high-intensity laser is tightly focused onto the surface of a thin metal foil, creating extremely strong electromagnetic fields that rapidly ionize the target material and generate a dense, hot plasma. The electrons, being lighter, absorb most of the laser energy and expand faster than the ions. As these energetic electrons exit the rear surface of the target, they establish an electrostatic sheath field that subsequently accelerates ions. The more recently discovered BOA mechanism [25] involves ultra-thin targets that undergo volumetric heating when irradiated by laser pulses. In this regime, the laser is capable of penetrating the thin foil and accelerating ions directly via relativistic effects. Compared to TNSA, BOA has demonstrated higher efficiency and improved neutron production [24]. However, implementing BOA requires laser pulses with extremely high contrast ($\sim 10^{11}$), which poses significant experimental challenges. These high-energy ion beams are then directed onto converter materials also referred to as catchers with high neutron yield cross-sections, where nuclear reactions lead to neutron emission. For instance, Willingale *et al*. [26] used a laser-accelerated deuteron beam directed at a deuterated plastic catcher positioned behind the primary target, resulting in neutron generation via the d(d, n)^3 He reaction. At Los Alamos National Laboratory (LANL), the BOA mechanism was employed using the Trident laser system, with beryllium-9 (^{9}Be) serving as the converter to generate neutrons through either the ^{9}Be(p, n)^{9}B reaction or deuteron breakup [24, 27]. Similarly, lithium-7 (^{7}Li) has been used as a converter in several studies [28-30], producing neutrons through the ^{7}Li(p, n)^{7}Be reaction. More complex reactions such as ^{7}Li(d, xn) have also been proposed [31]. Among various materials, beryllium-9 is frequently chosen due to its chemical stability and its high neutron conversion efficiency for both proton and deuteron beams.

Table 2 Summarizing the general scheme and challenges of plasma-based neutron sources.

Challenge	Description
Laser energy and repetition rate	High-energy, high-rep-rate lasers are needed for practical neutron flux.
Ion beam quality	Broad energy spread and divergence reduce reaction efficiency.
Target design	Optimizing primary and secondary targets for efficient neutron generation.
Thermal management	Repeated shots cause heating and damage to targets.
Neutron yield	Achieving sufficient yield for applications (e.g., $>10^9$ n/s).
Shielding and safety	Intense neutron radiation requires significant biological and equipment shielding.
Beam transport and focusing	Efficient ion transport to secondary targets is technically challenging.
Diagnostics	Real-time neutron diagnostics are essential and non-trivial.

7. Neutron Sources from Laser-induced Fusion Reactions

A promising approach for neutron generation involves initiating nuclear fusion reactions using high-intensity laser pulses. One method utilizes deuterium gas cluster targets, where powerful lasers are directed onto clusters formed from deuterium gas jets. Upon laser irradiation, the strong electromagnetic field rapidly ionizes the clusters by stripping off their electrons. This results in a Coulomb explosion where the positively charged deuterons repel each other and are accelerated to high energies. This method was first demonstrated by T. Ditmire and his team in 1999 [32], laying the foundation for laser-driven cluster fusion experiments. Another advanced technique for neutron generation is Inertial Confinement Fusion (ICF), which involves compressing a fuel target composed of a D-T mixture. This is achieved using some of the world's most powerful lasers, such as the NIF laser system (delivering up to 2.1 megajoules of energy) at Lawrence Livermore National Laboratory (LLNL) and the Omega laser (with 30 kilojoules) at the University of Rochester. These laser pulses irradiate the outer surface of a spherical capsule containing the D-T gas, producing an outward ablation. This ablation drives an inward shockwave that compresses and heats the fuel core to fusion-relevant conditions. Although originally developed as a means to study controlled thermonuclear fusion for energy production, ICF experiments also serve as a source of fusion neutrons under certain configurations. A third method involves laser-driven ion acceleration, where intense laser fields accelerate deuterons, and these energetic ions are then directed into a secondary target to induce fusion. This process, known as beam-target fusion, can yield neutron production depending on the ion energy and the nature of the target material. In each of these approaches, the underlying principle is the same: supplying sufficient kinetic energy to light nuclei (deuterons or tritons) to overcome their mutual electrostatic repulsion, the Coulomb barrier, and allow fusion to occur. The fusion reactions then release high-energy neutrons, commonly at the energy of 2.45 MeV for D-D reactions or 14.1 MeV for D-T reactions. In the case of deuterium cluster gas jet experiments, the target material is typically a supersonic gas jet of deuterium (D_2) or deuterated hydrocarbons like CD_4. The gas is either cryogenically cooled or cooled further through adiabatic expansion upon entering a vacuum, leading to the formation of nanometer-scale clusters (typically 1-10 nm in radius) [33]. When the laser hits these clusters, the intense field causes rapid ionization, and the resulting hot plasma electrons are expelled. The remaining positively charged cluster undergoes a Coulomb explosion, converting stored potential energy into the kinetic energy of the ions. These high-energy deuterons can then collide and fuse within the expanding jet, producing a short, intense pulse of fusion neutrons, which are largely monoenergetic and centered around 2.45 MeV. This laser-cluster fusion method has several advantages, including its simplicity, relatively compact setup, and the ability to produce ultrashort bursts of neutrons, which are useful for time-resolved studies in material science and nuclear diagnostics. Additionally, it offers a path toward tabletop neutron sources for scientific and medical applications, provided challenges related to neutron yield and repetition rate can be addressed in future developments.

8. Neutron Sources from Laser-accelerated Electrons

Neutrons can also be generated by utilizing relativistic electron beams produced from laser-based accelerators. In this method, high-energy electrons are accelerated typically through LWFA or direct laser acceleration (DLA) to relativistic velocities by interacting with gas targets under the influence of intense laser fields [7, 34]. Once these high-energy electrons collide with a dense, high atomic number (high-Z) material, such as tungsten or lead, they rapidly decelerate and emit intense bremsstrahlung radiation (X-rays in the MeV range). These bremsstrahlung photons can then interact with the nuclei in the converter or surrounding materials, initiating photonuclear reactions, namely (γ, n) or (γ, fission) processes. In the (γ, n) reaction, a high-energy photon knocks out a neutron from a stable nucleus, while in (γ, fission), the photon induces fission in heavy nuclei, such as uranium or thorium, releasing multiple neutrons. This approach is summarized in Table 3. In typical experimental setups, multi-tens-of-MeV electrons generated by LWFA are directed onto a converter target made of high-Z elements. As the electrons scatter and slow down within the target, they emit bremsstrahlung photons with energies comparable to the incident electron energies. When these photons exceed the binding energy of neutrons in nearby nuclei, they can be absorbed and trigger neutron release through photodisintegration reactions. While conceptually straightforward and technologically promising, the efficiency of this approach remains a limiting factor. The conversion efficiency from laser energy to high-energy photons through bremsstrahlung is typically less than 1%. In contrast, laser-driven ion sources (such as proton or deuteron sources) can achieve energy conversion efficiencies up to 10%. Furthermore, the nuclear reaction cross-sections for photoneutron and photo-fission reactions are generally much lower than for proton-induced (p, xn) reactions, resulting in reduced overall neutron yield [35]. Despite these limitations, laser-electron-driven neutron sources have unique advantages. The ultrashort pulse duration of LWFA electron beams allows for the generation of neutron pulses on femtosecond to picosecond time scales, enabling time-resolved nuclear and materials science experiments. Additionally, the compactness of laser wakefield accelerators makes them attractive for tabletop neutron sources, particularly for applications where portability and precision timing are important. To improve efficiency, researchers have also investigated advanced techniques such as Inverse Compton scattering (ICS). In this method, relativistic electrons interact with a counter-propagating laser beam. Due to the relativistic Doppler effect, low-energy photons from the laser are upshifted to high-energy gamma rays upon scattering. These gamma rays can then induce photonuclear reactions with higher photon energy control and potentially greater efficiency [36]. It should be noted that, although less efficient than ion-driven neutron sources, laser-accelerated electron beams offer an alternative path for generating neutrons, with advantages in beam quality, temporal resolution, and system compactness. Ongoing research aims to optimize target design, photon generation methods, and reaction pathways to improve their practical viability in scientific and applied fields.

Table 3 Schematic overview of electron-driven neutron source using LWFA.

Stage	Process	Description
Laser acceleration	LWFA	An intense femtosecond laser pulse propagates through low-density plasma (e.g., gas jet), generating plasma wave that traps and accelerates electrons to relativistic energies (10 MeV to a few hundred MeV).
High-energy electron beam	Relativistic electron beam generation	The LWFA process produces a collimated, high-energy, ultrashort electron beam suitable for downstream photon generation.
Converter target	Interaction with high-Z material	The electron beam is directed onto a high-Z target (e.g., tungsten, tantalum, or lead), where electrons are rapidly decelerated.
Bremsstrahlung radiation	Emission of MeV X-rays	As electrons decelerate in the high-Z material, they emit bremsstrahlung radiation (X-rays/gamma rays), with photon energies similar to the incoming electron energy.
Photonuclear reactions	(γ, n) or (γ, fission) reactions	Bremsstrahlung photons interact with atomic nuclei in the converter or surrounding material, inducing nuclear reactions such as (γ,n) to release neutrons.
Neutron output	Neutron emission	Neutrons are emitted with energies dependent on the nuclear reaction channel, typically in short bursts suitable for diagnostics or experimental use.

9. Summary

Laser-driven electron acceleration has emerged as a compelling pathway for generating neutron sources through photonuclear interactions. Utilizing techniques such as LWFA, femtosecond laser pulses can accelerate electrons to relativistic energies ranging from tens of MeV to several MeV [37, 38]. These high-energy electrons, when directed onto high-Z materials, produce intense bremsstrahlung radiation. The resulting X-ray and gamma-ray photons can induce neutron emission via photo-disintegration reactions like (γ, n) and (γ, fission), thereby serving as an effective neutron generation mechanism. Although the efficiency of electron-driven neutron sources remains lower compared to ion-driven schemes, largely due to the limited conversion efficiency of bremsstrahlung and smaller cross-sections of photon-induced nuclear reactions, the method offers unique advantages. These include the potential for compact, ultrafast, and highly collimated neutron sources, ideal for time-resolved studies and applications in nuclear physics, material science, and medical diagnostics. Recent advances in ICS and laser-plasma interaction techniques aim to enhance photon production efficiency and neutron yield, making electron-driven neutron sources increasingly viable for practical applications. Continued development of high-repetition-rate laser systems and optimized target configurations is expected to further close the performance gap with traditional ion-driven sources and unlock new frontiers in compact neutron science.

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