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Experimental Demonstration of Fast Neutron Absorption Spectroscopy with Compact Laser-Driven Neutron Source

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Fast neutron absorption spectroscopy enables isotope-specific analysis with strong penetration and high sensitivity, but it is currently confined at traditional large size pulsed neutron sources, e.g., spallation sources and mobility electron accelerator-based neutron sources. While laser-driven neutron sources are more compact and feature shorter pulses, their use in fast neutron absorption spectroscopy has been hindered by two critical challenges: insufficient spectral energy resolution and poor in-beam γ -ray signal-to-noise ratio. To address these, we present the first experimental demonstration by integrating the single neutron counting time-of-flight technique with pulse shape discrimination. We achieved a 2% energy resolution at 0.5 MeV over an 11.3 m flight distance, thus clearly resolving magnesium (Mg) resonance peaks and their shapes at 0.268 MeV and 0.432 MeV. This experiment marks the first step toward the application of laser-driven fast neutron resonance spectroscopy for detecting low-Z elements, explosives (e.g., TNT, RDX) and flammable metals (e.g., Li, Na, K, Mg, Al), paving the way for higher-resolution nuclear data and flexible on-site non-destructive testing.

Over the past decades, neutron absorption spectroscopy has been extensively applied in temperature measurement, elemental analysis, and spatial radiography, etc [1–5]. Fast neutron absorption spectroscopy (FNAS) further offers superior penetration depth for isotope-specific diagnostics, making it particularly attractive for on-site non-destructive testing and explosive nuclide identification [6–10]. At present, FNAS experiments are primarily conducted at pulsed neutron sources, such as spallation and electron accelerator-based sources [11–13]. The reliance on such large-scale facilities presents two fundamental limitations: first, the immobility and limited beamtime restrict accessibility and flexible deployment; second, the intrinsic source time duration fundamentally limits the spectral energy resolution—for instance, some extremely narrow resonance lines (e.g., 1 keV in FWHM) require shorter-pulsed fast neutron sources and high-precision techniques [14], yet mainstream spallation sources (e.g., CSNS: 60 ns pulse, 1.6% resolution at 0.5 MeV [12]) still cannot resolve such lines. The immobility is particularly consequential for applications requiring on-site deployment, such as the

inspection of low-Z materials concealed behind high-Z shielding. For low-Z materials (e.g., C, H, O, N, Li, Na, K, Mg) concealed behind high-Z shielding (e.g., lead, steel), conventional X-ray diagnosis suffers from strong attenuation and poor electron-density contrast. Fast neutron absorption spectroscopy overcomes this by penetrating high-Z materials and exploiting the resonance signatures of these low-Z nuclei—features that exist only in the 0.1–10 MeV fast neutron range. Measuring the transmission spectrum provides a fingerprint for identifying explosives, drugs, nuclear material precursors, and flammable metals inside heavy containers—a key technology for counterterrorism and nuclear security.

Laser plasma accelerators (LPAs) have the characteristic of ultra-high acceleration gradients of 100s GV/m for electrons [15] and TV/m for ions. The LPAs based fast neutron sources combine the advantages of ultra-high peak flux, ultra-short time duration [14], compactness, and high repetition rate [16–18]. They can be realized through electron-driven photonuclear reactions and ions-driven nuclear fusion, (p, n) reactions [19–23]. Currently, it has been reported that the pulse duration of these fast neutron sources can be shorter than 100 picoseconds (ps). These pulsed fast neutron sources, after being moderated to the epithermal energy range, have been successfully used high-resolution epithermal neutron absorption spectroscopy measurements [24–28].

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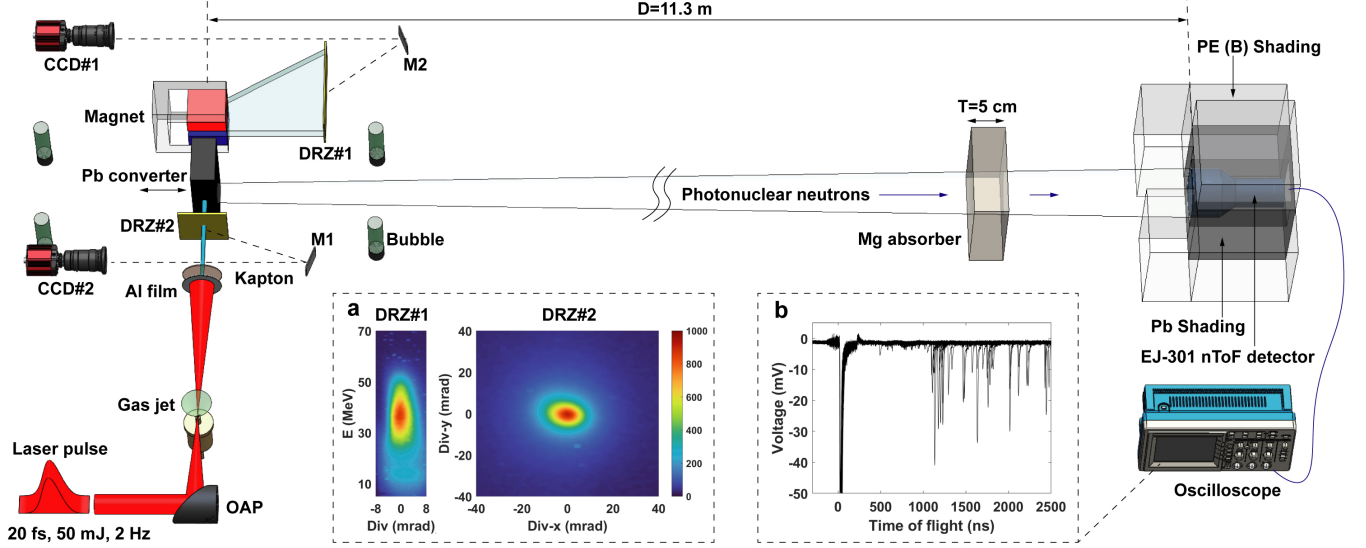


FIG. 1. **Schematic of the experimental setup.** The laser-plasma electron acceleration section is located in a vacuum, while neutron generation and diagnostics are conducted in air; these two environments are separated by a Kapton window. Electrons accelerated from the gas jet are characterized by DRZ#1 (for spectrum measurement) and DRZ#2 (for beam profile measurement), with representative results shown in the inset Fig.a. Photonuclear neutrons are generated using the Pb converter, pass through a 5-cm-thick Mg sample, and are measured by an EJ-301 scintillator with shielding at a flight distance of 11.3 m. The inset Fig.b shows a set (30 shots) of neutron Time-of-Flight signals recorded by an oscilloscope.

However, conventional fast neutron spectroscopy techniques (e.g., activation, recoil proton methods) suffer from poor energy resolution [29–31]. Similarly, high fast-neutron velocity causes signal pile-up and nonlinear amplitude-energy response in time-of-flight (ToF) measurements, also reducing resolution [32]. Moreover, in-beam gamma-ray background is hard to distinguish from fast neutrons, resulting in low spectroscopic signal-to-noise ratio. These challenges have hindered laser-driven FNAS from taking its first step toward practical applications.

In this work, for the first time, we experimentally demonstrated the laser-driven FNAS based on a repetitive compact laser electron accelerator [33–35]. To break through the above limitations, we employed the single neutron counting ToF technique to ensure a precision energy spectrum [36], further combining with the pulse shape discrimination technique to achieve a high signal-to-noise ratio. In consequence, the obtained FNAS can successfully resolve the characteristic resonance features of a magnesium (Mg) sample. Moreover, the transmittance analysis was conducted using experimental data, an exponential theoretical model, and Monte Carlo simulations for cross-validation. Here, the laser-driven neutron source features a short pulse duration (down to nanosecond), a broad energy range (0.1–10 MeV), compactness (10 m²), achieving a satisfactory energy resolution (2% at 0.5 MeV). Leveraging this source and its corresponding measurement techniques for FNAS offers new avenues for flexible, on-site applications in the fields of

non-destructive testing and element identification.

Results

Experimental setup. The experiment was conducted using the compact Ti: sapphire laser system at the SE-CUF, Institute of Physics, Chinese Academy of Sciences. The experimental setup is depicted in Fig. 1. A linearly polarized laser pulse with 2 Hz repetition rate, 800 nm central wavelength, 20 fs pulse duration (FWHM) and 50 mJ on-target energy, was tightly focused by an off-axis parabolic mirror with f-number 5.5. The focused near-Gaussian spot with $w_0 = 6.5 \mu\text{m}$ (containing $\sim 71\%$ of the laser power) yielded a peak intensity of $4.1 \times 10^{18} \text{ W/cm}^2$, corresponding to the normalized vector potential $a_0 \approx 1.38$. A De-Laval nozzle was used to produce the supersonic nitrogen gas (purity 99.999%) jet with a near-Gaussian density distribution with a radius of $150 \mu\text{m}$. The outflow nitrogen gas density can range from $1 \times 10^{17} \text{ cm}^{-2}$ to $5 \times 10^{19} \text{ cm}^{-2}$ by regulating the gas back pressure. The laser wakefield accelerated electron beam from the gas jet passed through a $14 \mu\text{m}$ Al foil and a $200 \mu\text{m}$ Kapton window. The DRZ screen #2 coupled with a CCD was used to record the electron beam profile. Subsequently, the electron beam that had penetrated the DRZ#2 entered the magnetic spectrometer, was deflected, and then recorded by DRZ#1. The typical energy distribution and angular distribution of the electron beam are shown by DRZ#1 and DRZ#2 in Fig. 1(a) respectively. The energy is mainly concentrated in the range of 30 to 50 MeV, which is favorable for driving the generation of photonuclear neutrons.

After moving in the 10 cm-thick lead (Pb) converter, the electron beam bombarded the converter (1 m away from the laser focal position). These electrons were deflected by the Coulomb field of Pb nuclei, producing bremsstrahlung γ -ray with critical energy extending to 10–20 MeV [37]. Subsequently, these high-energy γ -ray excite the Giant Dipole Resonance in Pb nuclei [38], generating photonuclear neutrons efficiently. One representative reaction for neutron generation is $^{208}\text{Pb}(\gamma, n)^{207}\text{Pb}$ with the γ -ray energy threshold of 8.395 MeV [39]. Four BD-PND bubble detectors were used to measure the angular distribution and yield of the photonuclear neutron source. An EJ-301 liquid scintillator with characteristic decay time of approximately 15 ns for neutron signal, shielded by boron-containing (20%) polyethylene (PE) and Pb, was employed to measure the neutron time-of-flight spectrum at a flight distance of 11.3 m and positioned at 90° to the electron beam propagation axis. The detector efficiency was calibrated offline by a ^{252}Cf fission source [32]. A 5 cm-thick Mg sample with natural isotopic abundance was positioned 30 cm upstream of the detector for FNAS. The reference spectrum without sample was also recorded for transmittance analysis.

Single neutron counting time-of-flight. The two challenges in achieving high-resolution and high signal-to-noise ratio FNAS are, respectively, realizing high-resolution energy spectrum measurement and distin-

guishing the γ -ray background noise in the spectrum. For fast neutron energy spectrum measurement, the commonly used methods at present include, the proton-recoil proportional counter, the ^3He ionization chamber and the nuclear activation method, which typically exhibit poor energy-resolution (~ 500 keV at 3 MeV) [29–31]. Another widely employed approach is the time-of-flight (ToF) technique—known for its fast response, high sensitivity, and excellent energy resolution [40]. Neutrons with different energies travel at different velocities, resulting in measurable time delays over a fixed flight distance. However, the neutron-induced scintillation signal exhibits a tens-of-nanosecond decay tail caused by intrinsic property of the organic scintillator, and its intensity depends non-linearly on both neutron flux and energy [32]. Multiple neutron signals tend to pile up under the high-flux condition, resulting in n-ToF waveform overlap and distortion, thereby diminishing the spectrum energy resolution derived from n-ToF waveform inversion [41]. Although the current-mode detection has been applied to mitigate signal distortion, signal overlap remains a significant challenge [42]. To overcome this issue, the n-ToF detector can operate in the single neutron counting mode [43], which utilizes a sufficiently long flight path to temporally separate individual neutron signals. This separation of arrival times in turn helps improve timing precision, as well as neutron energy precision.

Fig. 2a displays a typical oscilloscope waveform of single neutron counting ToF spectrum. Two well-separated pulses are observed, corresponding to the prompt γ -ray and the neutron, respectively. A total of 8,096 shots of data were collected at a repetition rate of 2 Hz and 1075 of signals were accumulated, with the Mg sample placed in the neutron flight path. The time spectrum was reconstructed with bin width $\delta t = 80$ ns, as shown in Fig. 2b. The neutron source pulse duration is estimated to be 9 ns considering the converter thickness and photonuclear neutrons energy distribution [44, 45]. Neutrons in the energy range of 0.1 to 0.55 MeV were selected for spectral analysis to encompass the characteristic resonance absorption features of magnesium. Both statistical and systematic uncertainties are accounted and presented as error bars in Fig. 2b. Distinct resonance features at the dip near 1200 ns can be observed in Fig. 2b, which corresponds to the neutron energy of 0.43 MeV based on the n-ToF calibration. However, further analysis is required to improve the signal-to-noise ratio, thereby clarifying these resonance characteristics.

Pulse shape discrimination. We evaluated the influence of multiple-scattered neutron and γ -ray on the resonance absorption spectroscopy. In our setup, the broad neutron spectrum, short flight distance, and lack of beamline moderation collectively minimize the impact of multi-scattered neutrons. We further confirmed it by moderation distance calculation [46] and Monte-Carlo simulation. Regarding γ -ray interference, the prompt

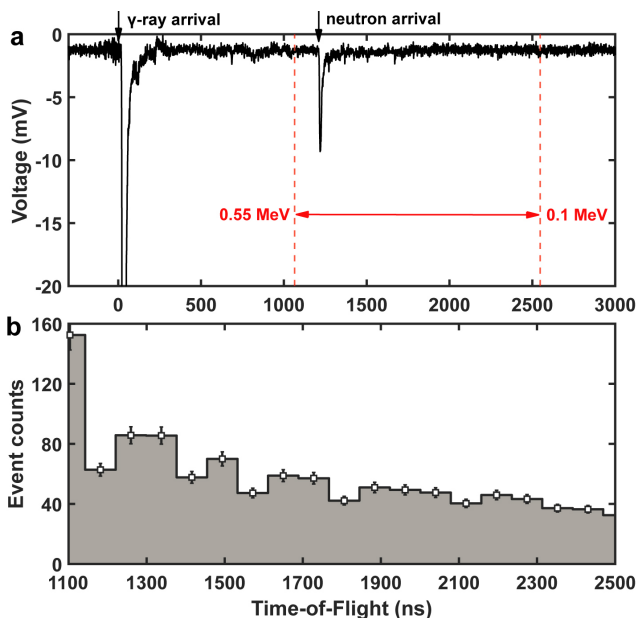


FIG. 2. **Results of Time-of-Flight measurement.** **a** A typical Time-of-Flight spectrum for single-neutron counting. The black arrows mark the arrival time of γ -ray (set as zero time) and neutron, while the red dashed lines indicate the neutron energy range of interest corresponding to 0.1–0.55 MeV. **b** The Time-of-Flight spectral distribution for the arrival time of the neutron signal, with Mg absorber in the flight path.

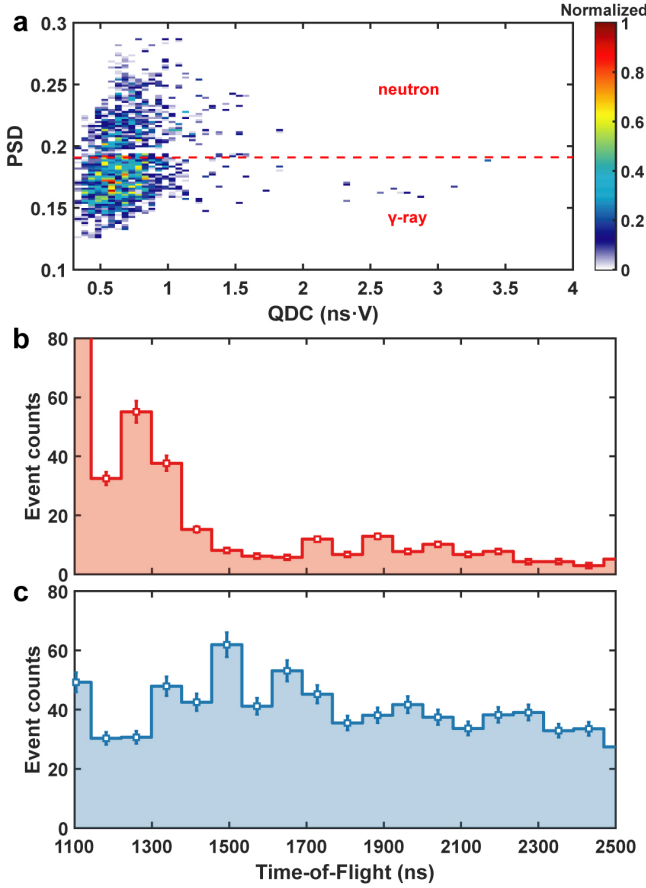


FIG. 3. **Pulse Shape Discrimination results.** **a** PSD-QDC distribution of the recorded signals, where the upper cluster corresponds to neutron events and the lower cluster to γ -ray events. **b** Neutron Time-of-Flight spectrum extracted from the signals after PSD discrimination. **c** Corresponding γ -ray Time-of-Flight spectrum.

γ -ray burst does not overlap with the delayed neutron signal and can serve as a zero-timer, as shown in Fig. 2a. However, in-beam γ -rays, generated from neutron capture and inelastic scattering processes, mix with fast neutron signals and reduce the signal-to-noise ratio. We applied the pulse shape discrimination (PSD) technique to effectively distinguish neutron signals from in-beam γ -rays. Since γ -ray interaction with the scintillator primarily produces fast scintillation light, whereas neutron interaction yields delayed light, we employed the charge comparison method to implement PSD [32, 47]. An 80 ns time gate following the neutron signal peak was applied to extract the long charge integration component Q_L , recorded as the Charge-to-Digital Converter (QDC) value. Similarly, a 20 ns gate was used to obtain the short charge component Q_S . The PSD value was calculated as $PSD = \frac{|Q_L - Q_S|}{Q_L}$. We calibrated it with Marrone's signal shape model to validate the effectiveness [48]. The resulting PSD-QDC distribution derived

from the experimental data is shown in Fig. 3a, where neutron and γ -ray events are separated by a threshold $PSD = 0.195$, obtained by optimizing the figure of merit $FoM = S/(\Gamma_e + \Gamma_p)$ where S is the difference between the two centroids of the neutron and gamma peaks, and Γ_e and Γ_p is the FWHM of the gamma and neutron peaks [47]. Through the n- γ discrimination, 735 γ -ray events have been screened out from 1,075 pulses in the spectrum of Fig. 2b. The time spectrum of γ -ray events, which constitutes the primary background noise component in the measured spectrum of Fig. 2b, is shown in Fig. 3c. The extracted high signal-to-noise ratio neutron time spectrum is presented in Fig. 3b, from which the resonance dips near 1200 ns and 1600 ns can be distinguished more clearly.

Analysis. The neutron kinetic energy E_n can be calculated from the time delay Δt and flight distance L , using the expression: $E_n = \frac{1}{2} \cdot m_n \cdot \left(\frac{L}{\Delta t + \frac{L}{c}} \right)^2$, where m_n is the neutron rest mass and c is the speed of light. Taking into account the source duration, scintillator geometry, and instrument response, the energy resolution is estimated to be 2% at 0.5 MeV, based on the formula $\delta E = \sqrt{\frac{(\gamma+1)^3 E^3}{m_0 L^2} \delta t_n}$, and $\delta t_n = \sqrt{(\delta t_1)^2 + (\delta t_2)^2 + (\delta t_3)^2}$, where δt_1 is the source pulse duration, δt_2 is the spread time of neutron transiting the scintillator, and δt_3 is the instrumental response of the detection system [40, 49]. The refined precise neutron energy spectrum is presented in Fig. 4a with 0.02 MeV energy bin. The dip features of the experimental spectrum align well with the cross-section data shown in Fig. 4b [50]. Moreover, according to the energy spectrum and ToF detector response efficiency, the total number of 0.1~0.55 MeV neutrons reaching the detector after the absorber is 340. Further considering the neutron source's 4π spatial uniformity and detector acceptance solid angle of 6.15×10^{-5} sr, the source's average yield in the aforementioned energy range is approximately 3.5×10^5 n/shot (based on the detector neutron counts without the Mg sample).

To further validate the experimental results and conduct transmittance analysis, a simplified theoretical calculation model is employed and the transmittance $T_{\text{theory}}(E)$ can be expressed as:

$$T_{\text{theory}}(E) = \prod_{i=1}^3 e^{-(\eta_i n_i l \sigma_i(E))}, \quad (1)$$

where natural isotopic abundances η_i are 0.79, 0.10, and 0.11 for ^{24}Mg , ^{25}Mg , and ^{26}Mg , respectively; the atom number density of natural magnesium n_i is $4.32 \times 10^{22} \text{ cm}^{-3}$; the target thickness l is 5 cm; The energy-dependent cross-section $\sigma_i(E)$ of the i^{th} magnesium isotope is taken from the ENDF evaluated nuclear data file [50], and is graphically presented in Fig. 4b. The exper-

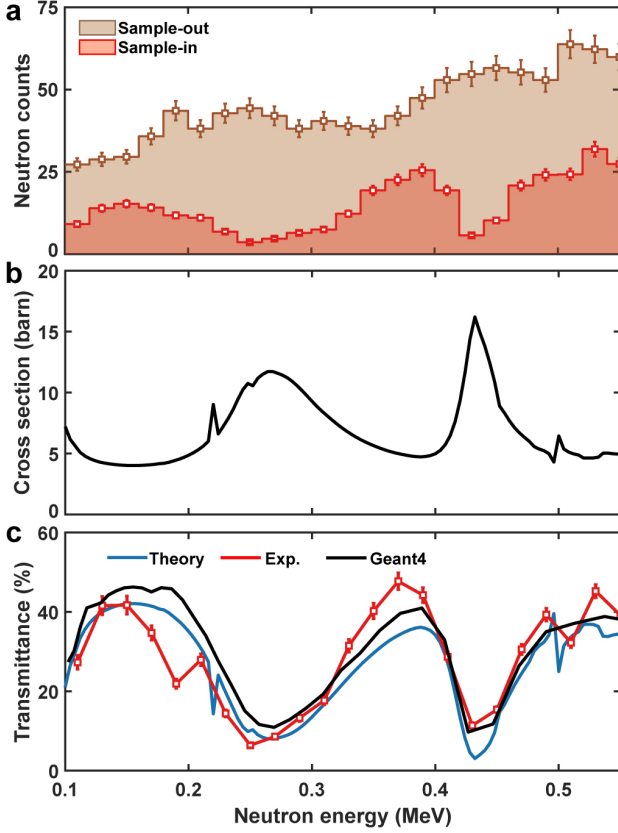


FIG. 4. **Fast neutron resonance spectroscopy results and transmittances in the neutron energy range of interest corresponding to 0.1~0.55 MeV.** **a** The fast neutron absorption spectrum of the magnesium sample. **b** The total neutron reaction cross-section of magnesium nuclides. **c** Transmittance for the Mg sample. The red/blue/black solid lines represent the experimental/theoretical/simulated results respectively.

imental transmittance was calculated as:

$$T_{\text{exp}}(E) = \frac{Y_{\text{in}}(E)}{Y_{\text{out}}(E)}, \quad (2)$$

with the same experimental setup and number of shots, $Y_{\text{in}}(E)$ and $Y_{\text{out}}(E)$ represent the neutron yields in each energy bin for the cases with and without the magnesium sample, respectively. The derived experimental transmittance T_{exp} (red solid line) and the theoretical value T_{theory} (blue solid line) are plotted in Fig. 4c for comparison.

To assess the agreement between the experimental and theoretical transmittance results, we performed the χ^2 analysis within each resonance dip. The statistic χ^2 was calculated as:

$$\chi^2 = \sum_{j=1}^n \frac{(T_{\text{exp},j} - T_{\text{theory},j})^2}{T_{\text{exp},j}}, \quad (3)$$

where $T_{\text{exp},j}$ and $T_{\text{theory},j}$ represent the experimental and theoretical transmittance values at the j^{th} energy bin,

and n is the number of data points in the selected region. Resonance dips at 0.268 MeV and 0.432 MeV were analyzed within FWHM energy ranges of 0.210–0.330 MeV and 0.370–0.510 MeV, respectively. The corresponding χ^2 values were 0.05 and 0.14, respectively. The χ^2 values indicate strong agreement between experimental and theoretical results, confirming the system's capability to accurately resolve the resonance features.

For further substantiation, we performed Monte Carlo simulations with the Geant4 code [51], based on the setup of the actual experimental geometry. The incident electron beam parameters—including energy distribution, charge, and divergence—were input according to the experimental measurements (Fig. 1). The simulation incorporated bremsstrahlung photon generation in the lead converter, followed by photonuclear reactions and neutron transport. The resulting transmittance curve T_{Geant4} (black solid line), shown in Fig. 4c, demonstrates good agreement with both theoretical calculation and experimental measurement. Additionally, the neutron yield estimated from the simulation was 3.2×10^5 n/shot (0.1 MeV to 0.55 MeV), consistent with the experimental result. However, there is still a slight deviation between the experimental and simulated transmittances, which originates from several sources. First, detector response nonlinearity and target inhomogeneity may introduce discrepancies. Second, background contributions from in-beam γ -rays cannot be entirely eliminated. Finally, statistical limitations arise from a relatively low neutron event count in our experiment.

Discussion

The laser-driven neutron source in this work required 8096 shots (67 min at 2 Hz) to accumulate sufficient statistics. For a similar fast neutron resonance spectroscopy measurement, the CSNS Back n facility would need $\sim 30,000$ pulses (20 min at 25 Hz) [52]. The laser-driven source offers an inherently short pulse duration (~ 10 ns), yielding a limiting energy resolution of $\sim 2\%$ at 11.3 m, as shown by the orange solid line in Fig. 5, far better than the $\sim 10\%$ resolution of CSNS in its 410 ns mode [12]. The 60 ns mode of CSNS achieves better resolution but requires a 76 m flight paths, as blue solid line shown in Fig. 5. Looking forward, several straightforward pathways exist to further improve the performance. Repetition rate: Commercial laser electron accelerators already operate stably at 1000 Hz; upgrading our system to this repetition rate is a direct next step. Energy resolution: Reducing the converter thickness from 10 cm to 1 cm would compress the neutron pulse to ~ 1 ns, enabling an energy resolution better than 1% at 0.5 MeV with a flight distance of ~ 10 m, surpassing the best resolution of CSNS. Average flux: Combining high repetition rate, higher laser energy, and high efficiency electron beam generation regime offers a clear route to increase the average flux while maintaining short pulse duration. With a near term order of magnitude increase in laser

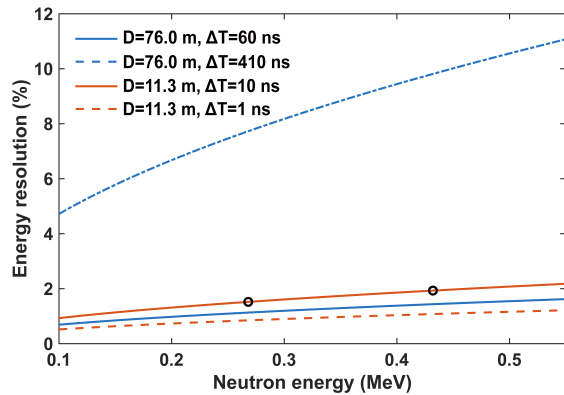


FIG. 5. **Limiting energy resolution for different neutron pulse durations and flight distances.** The blue dashed/solid lines correspond to the energy resolution of the double/single bunch mode of the CSNS back-n facility with a 76 m flight distance; the orange solid line represents the laser neutron source with a 10 ns pulse duration and an 11.3 m flight distance, while the orange dashed line corresponds to the laser neutron source with an optimized pulse duration of 1 ns. The energy resolutions at the key resonance energies of 0.268 MeV and 0.432 MeV are marked by open black circles on the resolution curve corresponding to our experimental conditions.

energy—a technology nearing maturity—the full spectrum fast neutron flux is expected to reach $\sim 10^{11}$ n/s, reducing acquisition time to ~ 1 s under the same statistical accuracy. Despite these advances, laser driven neutron sources will not match the average neutron flux of GELINA photon-fission ($\sim 10^{13}$ n/s) and CSNS ($\sim 10^{16}$ n/s) spallation facilities in the foreseeable future. However, they offer unique advantages in compactness (~ 10 m² footprint) and cost effectiveness (~ 2 million dollars), enabling fast neutron resonance spectroscopy to transition from large scale centralized facilities to field deployable and laboratory scale applications.

Although RF accelerators can also produce fs electron bunches, achieving an energy of tens of MeV and a repetition rate of >100 Hz simultaneously poses significant challenges. On one hand, the conventional RF acceleration gradient is only about 100 MV/m, requiring a several-meter-long accelerating structure to reach tens of MeV. On the other hand, fs bunches rely on complex techniques such as photocathode injectors and magnetic compression, while the high repetition rate of 100 Hz introduces substantial thermal loads and synchronization jitter, imposing stringent demands on beam quality, cooling, and feedback control. These factors make the overall system complex and cost-prohibitive, far more difficult than low-repetition-rate operation. In contrast, neutron sources driven by laser-accelerated high-repetition-rate, short-pulsed electron beams offer a new pathway for high-resolution fast neutron spectroscopy.

We have for the first time demonstrated fast neutron

absorption spectroscopy using a compact laser-driven neutron source, which has a pulse duration of 9 ns, a repetition rate of 2 Hz, and a flux of 7×10^5 n/second within the 0.1–0.55 MeV energy range. The neutron spectrum was acquired via the single-neutron counting time-of-flight technique. Additionally, the pulse shape discrimination technique was implemented to effectively distinguish neutron signals from the in-beam γ -ray background. A neutron absorption spectrum with high energy resolution and a high signal-to-noise ratio was obtained, enabling clear identification of the characteristic resonance peaks of the magnesium sample at 0.268 MeV and 0.432 MeV—with an energy resolution of 2% at 0.5 MeV. Moreover, the transmittance derived from the experiment is in excellent agreement with the results of theoretical calculation and Monte Carlo simulation. This work highlights the advantages of the source's ultrashort duration and the system's compactness, thereby demonstrating strong potential for applications in non-destructive testing, and security screening.

Methods

Laser-driven neutron source. The experiment was performed using a compact Ti:sapphire laser system at the SECUF, Institute of Physics, Chinese Academy of Sciences. The laser delivered 20 fs, 50 mJ pulses at 800 nm with a repetition rate of 2 Hz. The beam was focused by an off-axis parabolic mirror (f/5.5) onto a supersonic nitrogen gas jet, reaching a peak intensity of 4.1×10^{18} W/cm². Laser wakefield acceleration produced electron beams with energies concentrated between 30 and 50 MeV and a total charge of several hundred pC. The electrons were directed onto a 10 cm thick lead converter located 1 m downstream, generating bremsstrahlung γ -rays and subsequently photoneutrons via giant dipole resonance. The neutron source operated in air, with a Kapton window separating the vacuum acceleration chamber from the beamline. A 5 cm thick natural magnesium sample was placed 30 cm upstream of the detector for transmission measurements. Neutron time-of-flight measurements were performed with an EJ-301 liquid scintillator positioned 11.3 m from the converter, shielded with boron-loaded polyethylene and lead. The detector efficiency was calibrated offline using a ²⁵²Cf fission source. A total of 8,096 laser shots were accumulated.

Neutron gamma pulse shape discrimination. To suppress in beam γ ray background arising from neutron capture and inelastic scattering, pulse shape discrimination was applied using the charge comparison method. Signals from the EJ 301 scintillator were integrated over two time gates: a short gate of 20 ns (Q_s) and a long gate of 80 ns (Q_L). The PSD parameter was calculated as $\text{PSD} = (Q_L - Q_s)/Q_L$. A PSD threshold of 0.195 was optimized by maximizing the figure of merit $\text{FoM} = S/(\Gamma_\gamma + \Gamma_n)$, where S is the separation between neutron and γ ray peaks, and Γ_γ , Γ_n are their full widths at half maximum. This discrimination removed 735 γ -ray events out of 1,075

recorded pulses, significantly improving the signal to noise ratio of the neutron ToF spectrum and enabling clear identification of magnesium resonance dips.

Monte Carlo simulations. Monte Carlo simulations were carried out with the Geant4 code to validate the experimental results and assist in transmittance analysis. The simulation geometry reproduced the actual experimental setup, including electron transport, lead converter, magnesium sample, and detector shielding. Input parameters for the electron beam (energy spectrum, divergence, and charge) were taken from experimental measurements. Bremsstrahlung production, photoneutron generation via the giant dipole resonance, and subsequent neutron transport were modeled using the QGSP-BIC-HP physics list and the ENDF/B-VII.1 nuclear data library for cross-sections.

Data availability

The data that support the findings of this study are available on request from the corresponding authors.

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Author contributions

J.F. and L.C. designed research; H.X., J.F., M.Z., B.S., J.W., and Y.L. performed research; H.X., J.F., and J.R., contributed new reagents/analytic tools; H.X., J.F., M.Z., B.S., J.R., G.Z., Y.L., X.L., and W.Y. analyzed data; L.C. facilitated the experiment and led the whole project; and H.X., J.F. wrote the paper.

Competing interests

The authors declare no competing interests.

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