A miniature thermal neutron source using high power lasers

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The continued improvement of high power laser technologies is recasting the prospects of small-scale neutron sources, to enable scientific communities and industries performing experiments that are currently offered at extensive accelerator-driven facilities. This paper reports moderation of laser-driven fast neutrons to thermal energies using a compact, modular moderator assembly. A significant thermal ($\sim$ 25 meV) flux of $\sim 10^6$ n/sr/pulse was measured from water and plastic moderators in a proof-of-principle experiment employing a relatively moderate power laser delivering 200 J on target in 10 ps. Using MCNPX simulations, the experimental results are reproduced and discussed.

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Soon after the discovery of neutrons by Chadwick in 1932[1], their potential to be employed in a wide range of applications were realised. While fast neutrons are beneficial for radiography[2] and material testing[3], the arena of neutron science mainly requires neutrons in epithermal (0.5eV to 100keV) and thermal (tens of meV) energy ranges. Epithermal neutron sources are of high interest for applications extending from imaging to fundamental science related to condensed matter physics[4–8] and biology[9]. Thermal neutrons, on the other hand, are used in multidisciplinary applications employing techniques such as thermal imaging[10], high-resolution neutron diffraction[11], small-angle neutron scattering[12], deep inelastic neutron scattering[13], and differential die away analysis[14].

While nuclear reactors in the early days were the primary sources of neutrons, many experiments indicated that the efficacy of a source is not only determined by its brightness, but also by its burst duration[15], leading to the quest for developing pulsed neutron sources. Consequently, pulsed spallation facilities started to provide neutron sources enabling deep-probing of matter from Angstroms to micrometre scale. However, the scale and operational cost involved in such accelerator-based facilities limit their availability to the scientific community. Advances in accelerator technologies have made it possible to construct compact accelerator-driven neutron sources[16] that can operate with relatively high performance at lower costs. These smaller sources can potentially play a significant role in research and development that were hitherto served by research reactors and spallation sources.

A new type of compact neutron source is emerging, which is based on the use of laser-driven ions. The in-

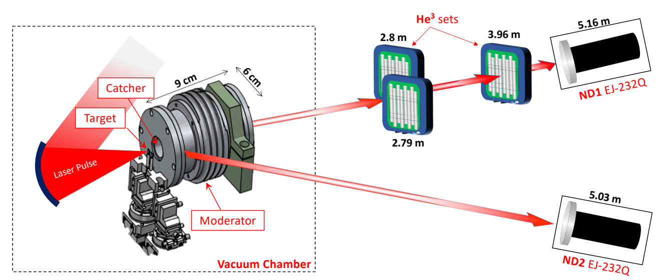

FIG. 1. Schematic of the experimental setup. Multi-MeV protons were generated in proximity to ^{7}Li catcher by irradiating the Vulcan laser on 20μm thick Au foils. The ^{7}Li cylinder of 1cm diameter and 2cm length was embedded in the moderator housing to maximise coupling of fast neutrons with the moderator material. The fast and moderated neutrons were diagnosed by two scintillator-based (ND-1 and ND-2) and three sets of ^{3}He proportional detectors. The distances of each detector from the moderator are mentioned above each detector.

teraction of intense laser pulses ($\geq 10^{18}$ W cm^{-2}) with foil targets of micron-scale thickness produces ps bursts of 10^{12-14} protons with MeV energies, which can be deployed efficiently to create brilliant sources of fast neutrons. The acceleration of light ions from a laser-irradiated foil takes place due to very large space charge field (sheath field of the order of TV/m) created by laser-accelerated hot electrons at the rear surface of the foil, in a mechanism known as Target Normal Sheath Acceleration (TNSA)[17]. By bombarding secondary targets (e.g. blocks of lithium, Beryllium or deuterated plastic) using the ions, nuclear reactions are triggered, producing high fluxes of beamed neutrons with multi-MeV energies[18–23].

In this paper, we report the production of an intense

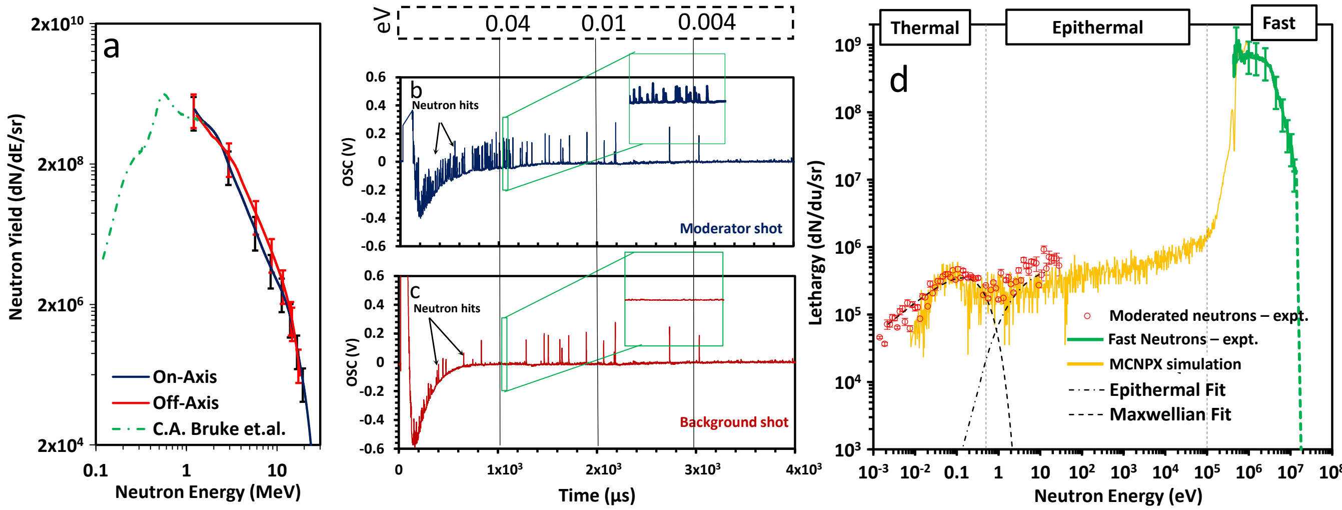

FIG. 2. **(a)** Typical fast neutron spectra produced in the experiment using the ^{7}Li(p,n) reaction, measured by ND-1 (on-axis) and ND-2 (35° off-axis). The dash-dotted green line shows the expected (based on the data reproduced with permission from Phys. Rev. C 10, 1299 (1974). Copyright 1998 American Physical Society) spectral profile of the sub-MeV neutrons produced predominantly by the p-Li reaction at near-threshold, which could not be measured by the plastic scintillators. **(b)** Raw data obtained by the ^{3}He proportional counters for 7 cm thick (from the end of the ^{7}Li catcher) H_2O moderator is shown, compared with the raw data obtained from a shot with an empty moderator housing shown below in **(c)**. The inserts show zoomed-in views of small sections of the raw data. The neutron hits are identified by the voltage spikes in the output signal of the ^{3}He detectors. The background subtracted neutron spectra obtained using the full set of ^{3}He detectors for the H_2O moderator is shown in **(d)**, along with the spectral profile obtained by the MCNPX simulation using an input fast neutron spectra that mimics the spectra shown in (a).

burst of thermal neutrons from a laser-driven miniature neutron source. The ^{7}Li converter in our experiment was embedded in the moderator housing, as shown in Fig.1, which not only made a compact design (compared to the setup used by Mirfayzi *et. al.* in ref. [24]), but also allowed an efficient coupling of fast neutrons into the moderator. The proton beam produced by the TNSA mechanism exhibits a quasi-Maxwellian energy spectrum. Hence the large population of few-MeV protons generates large numbers of sub-MeV neutrons near the threshold of the endothermic ^{7}Li(p,n)^{7}Be reaction[25–27]. These neutrons can be efficiently moderated to thermal energies, compared to the multi-MeV neutrons which drive the thermal neutron sources at the spallation facilities. The moderator assembly was designed in a modular form to allow flexibility of changing moderator thickness, as well as with the provision of cryogenic lines wrapped around the moderator (as can be seen in Fig. 1) for the production of ultra-cold neutrons. Deploying commonly used moderator materials (such as light water (H_2O), heavy water (D_2O) and polyethylene) at room temperature, a significant thermal flux of the order of 10^6 n/sr/pulse was measured, in agreement with Monte-Carlo simulations.

The experiment was carried out by employing the VULCAN laser at the Rutherford Appleton Laboratory, STFC, UK [28]. The 10 ps FWHM laser pulse with energy of ∼200 J was focused on 20 μm Au foils down to a ∼7 μm FWHM spot (containing ∼35% of incident laser energy) by a f/3 off-axis parabola, delivering peak intensity of $\sim 5\times 10^{19}$ W/cm^2 on the target. The protons accelerated from the foils were allowed to impinge on the ∼2 cm thick ^{7}Li converter embedded in the moderator housing, placed at ∼5 mm from the foil. In the first part of the experiment, fast neutron spectra were measured using two calibrated EJ-232Q plastic scintillators[29] along the 0° (henceforth called ND-1) and 35° (henceforth called ND-2) directions with respect to the proton beam axis. During the characterisation, the ^{7}Li was placed inside an empty moderator assembly in order to estimate the background neutron signal in the ^{3}He detectors (as shown in Fig. 2(c)), produced by the moderator housing. A fast neutron flux of the order of 10^9 n/sr for neutron energy $E_n \geq 1$ MeV was measured by the plastic scintillators, as shown in Fig. 2(a). The plastic scintillators cannot provide information on the spectrum for sub-MeV neutrons, due to their low sensitivity in this energy range. However, one could expect the neutrons produced by the near-threshold reaction of ^{7}Li to peak around hundreds of keV with a tail of distribution extending down to keV energies[25–27], as shown in Fig. 2(a).

By filling the moderator with light water (H_2O) at room temperature, a significant increase in neutron signal at the thermal region was detected, as shown in Fig.2(b), compared to the shot shown in Fig.2(c) taken with an empty moderator assembly. Fig.2(d) shows the moderated neutron spectrum produced per laser shot by the coupled water moderator. This spectrum was obtained by averaging 162 measurements taken over several shots,

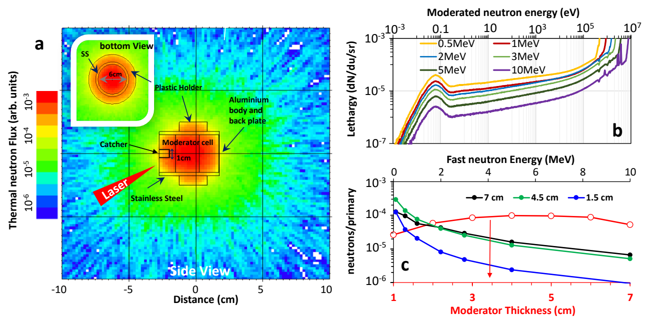

FIG. 3. **(a)** Flux distribution of thermal neutrons, of energy 1 meV to 0.5 eV, across the mid-plane of the water moderator, as produced by MCNPX simulation using a fast neutron spectrum mimicking the one shown Fig.2(a). The insert shows the neutron flux distribution across the face of the moderator. **(b)** Comparison between simulated neutron spectra at the detector positioned 10 cm from the moderator, for different input neutron energies. **(c)** Thermal flux at the detector for : (red) - different moderator thickness (bottom abscissa) using the fast neutron spectra mimicking the one shown in Fig.2(a); (black, green and blue) - moderators of thickneesess 7 cm, 4.5 cm and 1.5 cm respectively, while varying the energy of the fast neutrons incident on the moderator (upper abscissa).

while normalising the signal with respect to the fast neutron flux produced in respective shots measured by the ND-2. The normalisation factor for each shot was obtained by comparing with the most significant shot in the given dataset. The data shows a significant neutron flux of the order of 10^6 n/Sr/shot was produced within the detectable ranges for thermal (1 meV - 0.5 eV) and epithermal (0.5 eV - 65 eV) energies (see Table [1]). As the neutrons approach the thermal energy range, they tend to stay in thermal balance at the temperature k_BT of the moderator with a Maxwellian distribution as $\phi(E) \propto E/(k_BT)^{3/2}\ exp(-E/k_BT)$, where k_B is the Boltzmann's constant. Fig.2(d) shows the fits to the spectrum for both epithermal ($1/E$) and thermal (Maxwellian) distributions, with the k_BT calculated as 25 meV, corresponding to a temperature of 25 °C.

Monte Carlo N-Particle eXtended (MCNPX)[30] simulations were carried out to provide insight into the experimental data. The simulations were set up by mimicking the moderator assembly used in the experiment, with a detector placed at 10 cm from the exit face of the moderator. As expected, the moderator produces a fairly isotropic flux distribution of thermal neutrons, as shown in Fig.3(a). As the neutrons are moderated primarily by elastic scatterings with hydrogen, the moderated flux strongly depends on the energy of the fast neutrons and subsequently on the thickness of the moderator. As can be seen in Fig. 3(b) and (c), the lower the energy of the neutrons incident on the moderator, the higher is the thermal flux produced by the moderator for a given thickness. Due to the higher effectiveness of moderators for lower input energies, the thermal flux produced in our case was favoured significantly by the near-threshold ^{7}Li(p,n)^{7}Be reaction[25], coupled to the Maxwellian proton spectra produced from the laser-irradiated foil. Simulations were carried out to study the effect of moderator thickness on thermal neutron flux for our experimental condition (using the fast neutron spectrum produced by the Li catcher, shown in Fig. 2(a)), and the result is shown in Fig.3(c). As can be seen, moderation to thermal energies in our case reaches an optimum for moderator thicknesses of a few centimetres. For sufficiently thick moderators, on the other hand, the thermal neutron flux tends to drop eventually (see Fig.3(c)), as expected due to the absorption of neutrons by the moderator material (primarily by hydrogen). As shown in Fig. 2(d), the moderated neutron spectrum from the MCNPX simulations carried out for our experimental setup (mimicking the fast neutron spectrum shown in Fig. 2(a), including the sub-MeV part (dash-dotted green line), and the moderator shown in Fig. 1) matches closely with the experimental data, not only in connection to the spectral profile over the thermal region but also in terms of the measured flux at those energies.

In addition to the light water (H_2O) moderator, a preliminary study was carried out using some other commonly used moderator materials. This included a 6 cm Heavy-Water (D_2O) moderator and 4 cm High-density Polyethylene (HDPE) moderator. In the latter case, a ^{63}Cu ring was placed around the catcher to fill the gap and to act as a neutron reflector and multiplier for the high energy fast neutrons produced at the catcher. As can be seen in Fig. 4, the D_2O moderator produces a significantly lower thermal flux than the H_2O moderator, which could be due to the difference in the moderator thicknesses, or due to the fact that D_2O performs better as a reflector than a moderator. On the other hand, hydrogen has a higher neutron absorption at thermal energies compared to the Deuterium. A detailed study of the D_2O moderator was not possible in the experimental campaign due to lack of time. However, the preliminary data indicates its effectiveness is comparable to the H_2O moderator. The HDPE moderator also shows a lower thermal flux compared to the H_2O moderator, which suggests that H_2O is probably one of the preferred moderator materials for laser-driven neutron sources.

As mentioned earlier, the experiment was designed to assess and demonstrate the feasibility of producing intense bursts of thermal neutrons employing high intensity, short laser pulses as a driver. Although a signifi-

	N_F (n/sr) $E_n \geq$1MeV	N_{Th} (n/sr) $\leq$ 0.5eV	N_{Ep} (n/sr) 0.5eV $\leq E_n \leq$ 65eV
H_2O	$\sim 1.7\times 10^9$	$(1.4\pm0.1)\times 10^6$	$(1.9\pm0.3)\times 10^6$
D_2O	$\sim 1.3\times 10^9$	$(3.4\pm0.5)\times 10^5$	$(4.6\pm0.1)\times 10^5$
HDPE	$\sim 8.9\times 10^8$	$(1.7\pm0.3)\times 10^6$	$(7.2\pm0.1)\times 10^6$

TABLE I. **The neutron flux measured with different moderators.**

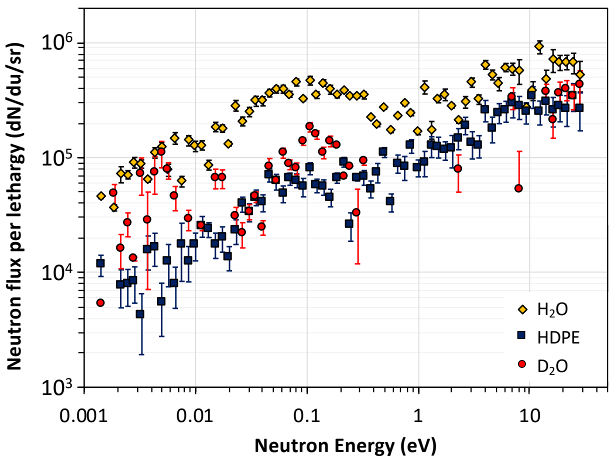

FIG. 4. The background subtracted neutron spectra measured in the experiment for the H_2O moderator (as shown in Fig. 2(d)), compared with that obtained for 4 cm thick HDPE and 6 cm thick D_2O moderators.

cant flux of thermal and epithermal neutrons was measured using a relatively moderate laser power in this experiment, there is considerable scope for improving further the thermal neutron flux by optimising the moderator design, as well as the fast input neutron source. The incident fast neutron flux can be significantly enhanced by increasing the energy and number of incident ions on the converter. In fact, fast neutron fluxes of the order of 10^{10} n/sr (orders of magnitude higher than produced in the current experiment) have been recently demonstrated[22, 23], which can be further improved by taking advantage of the ongoing developments in laser technology coupled to advanced laser-driven ion acceleration mechanisms[31–34]. In particular, the upcoming high repetition rate ($\sim$ 10 Hz) diode pumped [35], Petawatt-class lasers, such as HAPLS[36], offers the possibility of producing such intense bursts of neutrons at high repetition rates (10 Hz and beyond).

On the other hand, laser-driven fast neutron pulse has sub-ns duration at its source, which follows from the ps duration of laser-driven ion bursts. Therefore, the pulse duration of slow neutrons at a laser-driven neutron facility would be solely defined by the moderator design. Upon optimisation, shorter duration neutron pulses would allow shorter stand-off distances (compared to the typical tens of meters of source-to-sample distance at conventional facilities) without compromising the energy resolution, which in turn would lead a significantly higher flux delivered at the sample location[37]. In addition to the advantages of an intense source, a miniaturised moderator coupled to a μm-scale, laser-driven ion source also offers a significantly less hostile environment compared to any conventional accelerator-driven sources (large-scale or compact), opening possibilities of performing pump-probe experiments. While the thermal flux obtained in this proof-of-principle experiment is encouraging for some basic studies in the application areas mentioned above, with further developments and optimisation one can envisage scenarios in a near future in which laser-driven methods are used for more fundamental applications, complementing some of the works currently feasible only at large-scale facilities.

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