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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 (∼25 meV) flux of ∼1010 n/s/µm2/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.

PACS numbers: Valid PACS appear here.

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 source 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 interaction of intense laser pulses (≥1018 W cm−2) with foil targets of micron-scale thickness produces ps bursts of 1012–14 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...
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 a significant thermal flux, as can be seen in Fig. 2(a).

During the characterisation, the proton flux was measured by the plastic scintillators, placed at near-threshold reaction of $^7$Li to peak around hundreds $^7$Li to peak around hundreds $^7$Li to peak around hundreds $^7$Li to peak around hundreds $^7$Li to peak around hundreds $^7$Li to peak around hundreds $^7$Li to peak around hundreds $^7$Li to peak around hundreds $^7$Li to peak around hundreds $^7$Li to peak around hundreds $^7$Li to peak around hundreds $^7$Li to peak around hundreds $^7$Li to peak around hundreds $^7$Li to peak around hundreds $^7$Li to peak around hundreds $^7$Li to peak around hundreds $^7$Li to peak around hundreds $^7$Li to peak around hundreds $^7$Li to peak around hundreds $^7$Li to peak around hundreds $^7$Li to peak around hundreds $^7$Li to peak around hundreds $^7$Li to peak around hundreds $^7$Li to peak around hundreds $^7$Li to peak around hundreds $^7$Li to peak around hundreds $^7$Li to peak around hundreds $^7$Li to peak around hundreds $^7$Li 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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/St/shot was produced within the detectable ranges for thermal (1 meV - 0.5 eV) and epithermal (0.5 eV - 65 eV) energies (see Table I). As the neutrons approach the thermal energy range, they tend to stay in thermal balance at the temperature $k_B T$ of the moderator with a Maxwellian distribution as $\phi(E) \propto E/(k_B T)^{3/2} \exp(-E/k_B T)$, 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 $k_B T$ 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 $^3\text{Li}(p,n)^7\text{Be}$ reaction[29], coupled to the Maxwellian proton spectra produced from the laser-irradiated foil. Simulations were carried out to study the effect of 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 ($\text{H}_2\text{O}$) moderator, a preliminary study was carried out using some other commonly used moderator materials. This included a 6 cm Heavy-Water ($\text{D}_2\text{O}$) moderator and 4 cm High-density Polyethylene (HDPE) moderator. In the latter case, a $^{65}\text{Cu}$ 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 $\text{D}_2\text{O}$ moderator produces a significantly lower thermal flux than the $\text{H}_2\text{O}$ moderator, which could be due to the difference in the moderator thicknesses, or due to the fact that $\text{D}_2\text{O}$ 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 $\text{D}_2\text{O}$ moderator was not possible in the experimental campaign due to lack of time. However, the preliminary data indicates its effectiveness is comparable to the $\text{H}_2\text{O}$ moderator. The HDPE moderator also shows a lower thermal flux compared to the $\text{H}_2\text{O}$ moderator, which suggests that $\text{H}_2\text{O}$ 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 significant improvement was made in the experimental setup, the neutron counts were insufficient for a meaningful analysis.

<table>
<thead>
<tr>
<th>Material</th>
<th>Neutron Flux (arb. units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{H}_2\text{O}$</td>
<td>$1.7 \times 10^6 \times (1.4 \pm 0.1) \times 10^4$</td>
</tr>
<tr>
<td></td>
<td>$1.9 \times 10^6 \times (1.9 \pm 0.3) \times 10^4$</td>
</tr>
<tr>
<td>$\text{D}_2\text{O}$</td>
<td>$1.3 \times 10^6 \times (3.4 \pm 0.5) \times 10^5$</td>
</tr>
<tr>
<td></td>
<td>$4.6 \times 10^6 \times (4.6 \pm 0.1) \times 10^5$</td>
</tr>
<tr>
<td>HDPE</td>
<td>$8.9 \times 10^6 \times (7.2 \pm 0.1) \times 10^5$</td>
</tr>
</tbody>
</table>

TABLE I. The neutron flux measured with different moderators.
significant 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 $10^{15}$ 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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![Graph](image-url)

**FIG. 4.** The background subtracted neutron spectra measured in the experiment for the H$_2$O moderator (as shown in Fig. 2(d)), compared with that obtained for 4 cm thick HDPE and 6 cm thick D$_2$O moderators.

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20. R. L. Lancaster, S. Kar, H. Habara, F. N. Beg, E. L. Clark, R. Freeman, M. H. Key, J. A. King, R. Kodama,
Lethargy (dN/du/sr)

Moderated neutron energy (eV)

0.5 MeV
1 MeV
2 MeV
3 MeV
5 MeV
10 MeV

Fast neutron Energy (MeV)

neutrons/primary

Moderator Thickness (cm)

7 cm
4.5 cm
1.5 cm

Catcher

Side View

Aluminium body and back plate

Bottom View

6 cm
SS
Plastic Holder

Stainless Steel

Thermal neutron Flux (arb. units)

Distance (cm)

-10                      -5                       0                       5                      10

Lethargy (dN/du/sr)

Moderated neutron energy (eV)

0.1 10 10^3 10^5 10^7

2 MeV 3 MeV 5 MeV 10 MeV

Fast neutron Energy (MeV)

0 2 4 6 8 10

Fast neutron Energy (MeV)

-10                      -5                       0                       5                      10

Distance (cm)

10

-3

10

-5

10

-7

10

-3

10

-4

10

-5

10

-6

10

-6

10

-5

10

-4