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Laser-generated nanosecond pulsed neutron sources: scaling from VULCAN to table-top

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Abstract. Neutron production capabilities of table-top laser accelerated protons based on data from a high-energy single-shot large laser are addressed. Recently, McKenna *et al* (2005 *Phys. Rev. Lett.* **94** 084801) have analysed the energy spectrum for a beam of protons accelerated on the VULCAN laser. In this paper, we present a new analysis of the same experiment which demonstrates, for the first time, production levels in excess of 10^9 neutrons per laser shot within a nanosecond pulse through (p,xn) reactions on lead targets. We have used this ^{nat}Pb(p,xn) conversion analysis approach to make predictions on the neutron production capabilities of table-top laser systems. Neutron spectra for current state-of-the-art table-top lasers have been calculated, and we have estimated that current systems are capable of producing 10^6 neutrons per second in nanosecond pulses. Furthermore, we have found that nanosecond neutron pulses at a rate of 5×10^9 neutrons per second are possible with the next generation of table-top lasers currently under construction.

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1. Introduction

The ability to induce a variety of nuclear reactions with high-intensity lasers has been demonstrated recently in several laboratories [2, 3]. Laser-induced activation [4]–[6], transmutation [7], fission [8] and fusion [9]–[11] have been demonstrated without recourse to reactors or other traditional neutron sources. These results came as a consequence of several technological breakthroughs in the field of high-intensity lasers in the last decade, which made laser intensities in the focal spot above $10^{19} \text{ W cm}^{-2}$ possible. Under these conditions, the laser beams generate plasmas with a temperature greater than 10 billion degrees (10^{10} K). The interaction of high-intensity laser light with this plasma on a surface of a thin solid target generates collimated jets of high-energy electrons and protons [12]. Experimental studies on thin foil targets with thicknesses greater than the wavelength of the laser light have demonstrated the production of beams of protons with energies up to 58 MeV, using a large single-shot kilojoule laser with a wavelength of $\sim 1 \mu\text{m}$ and an intensity of $3 \times 10^{20} \text{ W cm}^{-2}$ [13]. Two aspects are of particular interest: the proton energy attained and the high-conversion efficiency between the laser energy and the proton beam. In the above studies, a conversion efficiency of 12% was obtained [13].

Taking into account the high-proton energies, high laser to proton energy conversion efficiency and short proton pulse length, the (p,xn) reactions in high Z materials seem to be a promising option for a novel fast pulsed neutron source. Recently, McKenna *et al* [1] showed that a beam of protons accelerated in an experiment on the large single-shot VULCAN laser closely resembles the expected energy spectrum of evaporative protons (below 50 MeV) produced in GeV-proton-induced spallation reactions. In his work McKenna *et al* showed that laser-generated proton beams could be used for the study of residual isotopes in lead spallation target. In this paper, we present a new analysis of laser-generated proton reactions on lead with a view to characterizing the neutron emissions in both the above-mentioned VULCAN experiment and in experiments with high-repetition terawatt table-top lasers. This characterization of the neutron production capability is significant due to the possible application of this technology for compact generation of pulsed neutrons with table-top lasers. Due to the relatively high-proton generation efficiency on solid targets such sources could be significantly stronger than other neutron sources generated with the interaction of femtosecond laser pulses with deuterium clusters [14], where neutrons are generated directly from deuterium fusion or deuterium–tritium fusion reactions in laser heated plasma. Such cluster fusion sources are capable of yields up to 10^5 fusion neutrons per joule of incident laser energy [15].

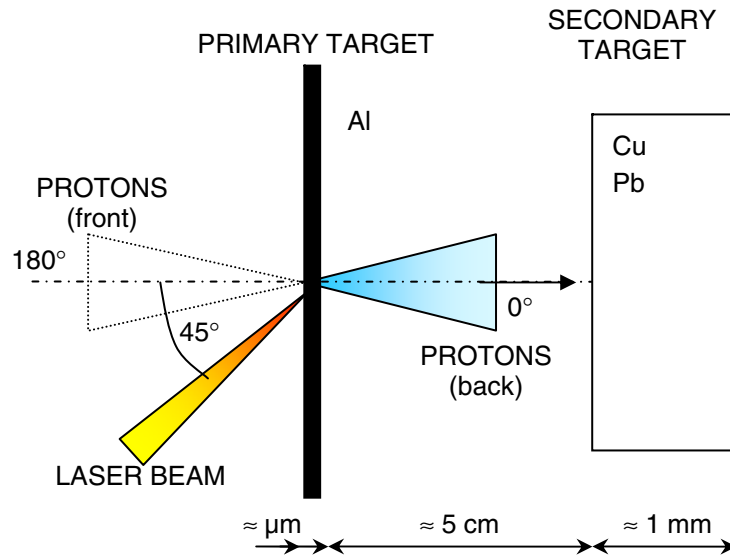


Figure 1. General layout for proton acceleration experiments using high-intensity lasers. The laser beam was focused on a thin aluminium target and protons accelerated from the back of the primary target were caught by thick secondary targets. These were used for proton beam diagnostics and/or neutron production.

2. Neutron production with laser-accelerated protons at VULCAN

The recent proton beam production studies [1] made use of the petawatt arm of the large high-energy single-shot VULCAN Nd:glass laser at the Rutherford Appleton Laboratory, UK to focus laser light with a wavelength of $\sim 1 \mu\text{m}$ in a pulse of average duration 0.7 ps on to a thin primary target ($10 \mu\text{m}$ thick Al foil). The laser pulse delivered 400 J of light in a $7 \mu\text{m}$ diameter focal spot giving a peak laser intensity in the focus of $4 \times 10^{20} \text{W cm}^{-2}$. The typical broad energy spectrum of laser-accelerated protons was determined with copper plates positioned in front and behind the primary target as described in [16]. Two proton beams were accelerated in opposite directions normal to the primary target, but we only consider the beam at the back-end of the target for the neutron production analysis in the current work (see figure 1 for the general experimental layout). The measured proton spectrum, presented in the insert of figure 2, was found to exhibit a broad Boltzmann-like distribution with a temperature of 5 MeV [1]. The maximum detected proton energy was 42 MeV and the total number of protons accelerated to energies above 10 MeV was approximately 5×10^{11} .

By positioning a 1 mm thick, $5 \times 5 \text{cm}^{-2}$ sample of natural lead approximately 5 cm behind the primary target, the pulsed proton beam was used as a source of fast neutrons through several different (p,xn) reactions. This natural lead sample consisted of several isotopes (1.4% ^{204}Pb , 24.1% ^{206}Pb , 22.1% ^{207}Pb and 52.4% ^{208}Pb [17]). It should be noted, however, that the primary purpose of this experiment was the characterization of the proton beam, and that the setup was not therefore optimized for neutron production. Indeed, for an optimized neutron flux one would place the lead (or other high Z) converter closer to the primary target, in order to keep the neutron source diameter small.

The resultant neutron spectrum was determined in two different ways. Firstly, we calculated the neutron spectrum (presented in figure 2) using the known incoming proton spectrum,

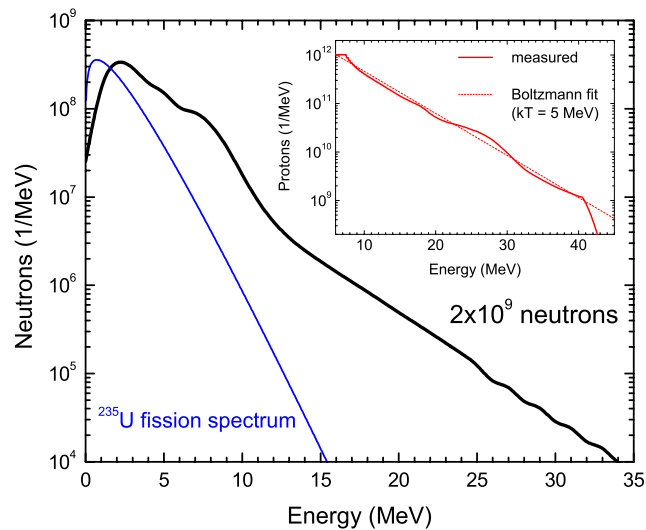


Figure 2. The calculated neutron spectra released in $^{\text{nat}}\text{Pb}(p,xn)\text{Bi}$ reactions in VULCAN experiment. The total number of neutrons per shot was determined also experimentally from the measured number of residual bismuth atoms in the lead target. Typical prompt ^{235}U fission spectrum is presented on the graph for comparison. Note that this ^{235}U spectrum was normalized to match the maximum of the laser-generated neutron spectrum. The insert shows the proton spectrum measured by copper foil activation technique and Boltzmann spectrum with a temperature of 5 MeV.

the proton stopping powers in lead and appropriately weighted cross-sections (presented in figure 3 [18]). We have taken into account only the most important (p,xn) reactions on ^{206}Pb , ^{207}Pb and ^{208}Pb which yield various bismuth isotopes (12 reactions in all as presented in table 1). As can be seen in figure 2, the neutron spectrum has a peak around 2 MeV with a long tail up to high energies which is small in magnitude and extends beyond a typical uranium neutron-induced fission spectrum. From this calculated spectrum, we see that the total number of neutrons released in the experiment was of the order of 2×10^9 neutrons per laser shot.

Secondly, the number of γ -emitting residual nuclides in the lead was determined using γ -spectroscopy with a calibrated high-purity germanium detector. Following the γ peak identification based on the measured γ energies and half-lives, the net peak areas were used to calculate the number of each residual nuclide produced at the time of the laser shot (taking into account the detection efficiencies, decay branching ratios, gamma emission probabilities and half-lives). The main product nuclides were found to be close to the target nuclei, namely ^{206}Bi and ^{205}Bi , as can be seen in table 1, where all of the bismuth reaction products are listed. In smaller quantities, we also found isotopes of ^{204}Bi , ^{203}Bi , ^{202}Bi and ^{203}Pb . Due to their long half-lives the isotopes ^{207}Bi and ^{208}Bi were not detected with γ -spectroscopy. In total, more than 1.2×10^9 bismuth atoms were produced and measured. In order to produce this number of bismuth atoms, more than 1.6×10^9 neutrons had to be released in (p,xn) reactions on the natural lead target. The fact that this value is in agreement with the number of fast neutrons which we calculated above provides direct experimental justification for the validity of our first procedure. Since we have not taken into account neutrons released in the production of long-lived isotopes ^{207}Bi and

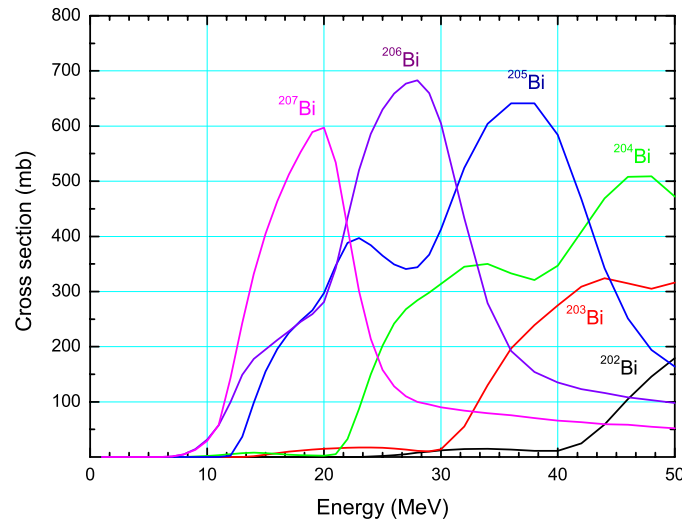


Figure 3. Cross-sections for the production of different bismuth isotopes from the natural mixture of lead isotopes taking into account (p,xn) and (p, γ) reactions (error bar on the cross-section value is about 20% [18]).

Table 1. Lists of identified reaction products from proton-induced reactions on lead. For each of the nuclides listed, at least six of the main emission lines were identified. Since lead has several stable isotopes, there can be several (p,xn) reactions leading to the production of one residual bismuth isotope. Reactions marked with {} are listed only for completeness, since it is highly unlikely that these high-threshold reactions occurred in our experiment. Due to their long half-lives the isotopes ^{207}Bi and ^{208}Bi were not detected with γ -spectroscopy.

Isotope	Half-life	List of possible reaction channels	Measured number of bismuth atoms
^{202}Bi	1.67 h	$^{204}\text{Pb}(p,3n)$, $\{^{206}\text{Pb}(p,5n)$, $^{207}\text{Pb}(p,6n)$, $^{208}\text{Pb}(p,7n)\}$	$1.94 \times 10^6(1 \pm 0.06)$
^{203}Bi	11.76 h	$^{204}\text{Pb}(p,2n)$, $^{206}\text{Pb}(p,4n)$, $\{^{207}\text{Pb}(p,5n)$, $^{208}\text{Pb}(p,6n)\}$	$2.13 \times 10^7(1 \pm 0.05)$
^{204}Bi	11.22 h	$^{204}\text{Pb}(p,n)$, $^{206}\text{Pb}(p,3n)$, $^{207}\text{Pb}(p,4n)$, $\{^{208}\text{Pb}(p,5n)\}$	$6.42 \times 10^7(1 \pm 0.05)$
^{205}Bi	15.31 d	$^{204}\text{Pb}(p,\gamma)$, $^{206}\text{Pb}(p,2n)$, $^{207}\text{Pb}(p,3n)$, $^{208}\text{Pb}(p,4n)$	$5.44 \times 10^8(1 \pm 0.05)$
^{206}Bi	6.24 d	$^{206}\text{Pb}(p,n)$, $^{207}\text{Pb}(p,2n)$, $^{208}\text{Pb}(p,3n)$	$5.71 \times 10^8(1 \pm 0.05)$
^{207}Bi	31.57 y	$^{206}\text{Pb}(p,\gamma)$, $^{207}\text{Pb}(p,n)$, $^{208}\text{Pb}(p,2n)$	
^{208}Bi	3.7×10^5 y	$^{207}\text{Pb}(p,\gamma)$, $^{208}\text{Pb}(p,n)$	
^{209}Bi	Stable	$^{208}\text{Pb}(p,\gamma)$	

^{208}Bi , we may consider 2×10^9 neutrons released per laser shot as a conservative estimate for the number of neutrons produced. This corresponds to an estimate for the neutron yield in the VULCAN experiment of 5×10^6 neutrons per joule of incident laser energy, which does not take into account the contribution from the proton beam in front of the primary target, which could double the neutron yield.

A neutron pulse generated by a pulsed laser diverges rapidly from the source due to its continuous energy spectrum. Even if the laser pulse was much shorter than 1 ps, the width of the neutron pulse at a distance of 1 cm from the source would be of the order of 1 ns, while

Table 2. In the table, an overview of available neutron strengths for different commercial neutron sources is presented. Data were taken from [24], from technical data provided by different producers of these sources on their web pages, and from personal communication with source operators.

Some research reactor sources	Flux for irradiation (neutrons cm ⁻² s ⁻¹)	Strength (neutrons s ⁻¹)
250 kW TRIGA (General atomics)	2×10^{13}	7.8×10^{15}
62 MW ILL (Institut Laue-Langevin)	1.5×10^{15}	1.9×10^{18}
250 MW ATR (Idaho National Laboratory)	1.5×10^{15}	7.8×10^{18}
Some spallation sources	Average flux	Peak flux
	(neutrons cm ⁻² s ⁻¹)	(neutrons cm ⁻² s ⁻¹)
SINQ at Paul Scherrer Institute ^a	10^{14}	10^{14}
SNS at Oak Ridge (under const.)	10^{15}	10^{17}
Compact and portable neutron sources	Average strength	
	(neutrons s ⁻¹)	
Radioactive neutron sources ^b	10^5 – 10^7	
Spontaneous fission sources ^c	Around 10^{10}	
Portable neutron generators ^d	10^8 – 10^{10}	

^aSINQ in Switzerland is operating continuously and not in pulses.

^bNeutron sources using (α ,n) reactions (e.g. ²²⁶Ra- α -Be) or radioactive photoneutron sources (e.g. ⁵⁴Mn- γ -D).

^cSpontaneous fission sources are usually small (e.g. few mg) and they emit fission neutrons at high-specific rate (e.g. 2.3×10^{12} neutrons per gram of ²⁵²Cf).

^dPortable neutron generators based on D-D, D-T or T-T reactions using RF heated plasmas as a source for fast ions.

the corresponding width 1 m away from the source would be more than 50 ns, neglecting any neutron moderation. This type of reasoning is in good agreement with the results reported by Lancaster *et al* [19]. They measured 100–200 ns long neutron pulses at a distance of 2.3 m away from the ⁷Li(p,n)⁷Be source on the VULCAN laser.

2.1. Traditional neutron sources and neutron applications

Today, neutron sources have an extremely broad range of applications in science and technology. First appearing in the 1950s, and after a half of century of development, they are now a ubiquitous tool in scientific research and in many practical applications, such as neutron activation analysis [20], nuclear geophysics [21], neutron radiography [22] and active neutron interrogation methods [23]. The neutron spectra and flux levels required in each of these applications can be quite varied which is one of the reasons that so many different neutron sources are available. For a complete overview of the more traditional neutron sources and their applications the reader is referred to [24], in addition to the references given above. We have provided a short summary of the most commonly used neutron sources in table 2.

These commercially available sources produce neutrons with a variety of flux levels by utilizing different nuclear reactions. For producing large quantities of neutrons, induced fission or

Table 3. Experimental results for neutron sources generated with laser-accelerated protons. Average neutron source strengths were calculated assuming one laser shot every 30 min. Peak neutron source strengths were estimated assuming 1 ns neutron pulse length.

Experiment (reference)	Lancaster [19]	Yang [27]	Yang [27] ^a	This paper
Reaction(s) used	${}^7\text{Li}(p,n){}^7\text{Be}$	${}^{\text{nat}}\text{Zn}(p,xn)\text{Ga}$	${}^7\text{Li}(p,n){}^7\text{Be}$	${}^{\text{nat}}\text{Pb}(p,xn)\text{Bi}$
Laser energy (J shot ⁻¹)	69	230	230	400
Measured neutrons (neutrons shot ⁻¹)	2×10^8	$\approx 10^{10}$	5×10^{10}	2×10^9
Average strength (neutrons s ⁻¹)	10^5	$\approx 10^7$	2×10^7	10^6
Peak strength (neutrons s ⁻¹)	2×10^{17}	$\approx 10^{19}$	5×10^{19}	2×10^{18}

^aNeutron value for ${}^7\text{Li}(p,n){}^7\text{Be}$ case was determined by convolution of the measured proton spectrum with known cross-section.

spallation reactions are typically used, whilst smaller flux levels are possible through spontaneous fission or fusion based sources. The neutron flux is the usual measure of the strength of such sources and is defined as the number of neutrons passing through a unit surface per second. In general, it depends on the position within a large, extended source like a reactor or on the distance from a smaller point-like source. For the purpose of characterizing a neutron source, it is also important to discriminate between peak and average neutron flux. For a pulsed source, the average neutron flux is obviously lower than its peak value (for example, the peak flux of the Spallation Neutron Source currently under construction at the Oak Ridge laboratory in the USA will be $10^{17} \text{ cm}^{-2} \text{ s}^{-1}$, while the average neutron flux will be around $10^{15} \text{ cm}^{-2} \text{ s}^{-1}$). For the smaller, portable neutron sources, which are invariably point-like in nature, one usually characterizes their strength in terms simply of neutrons per second (the flux being dependent on distance from the source).

The neutron production analysis presented above, together with values quoted in recent publications (see table 3 for more references), show that current large laser systems like VULCAN are capable of producing approximately 10^{10} neutrons per shot. Taking into account the low-repetition rates of such large laser systems (i.e. one shot every 30 min) this means that the average strength of these laser-generated neutron sources is between 10^6 and 10^7 neutrons per second. This value is small compared to large-scale neutron sources, but it is comparable to the typical strength of compact neutron sources. One of the significant possible advantages of laser-generated neutron sources is their extremely short pulse durations (of the order of ns), which are at least an order of magnitude smaller than neutron pulse durations in traditional sources. For this reason, the peak neutron strength of the laser-based sources is similar to those which can be achieved with dedicated high-flux reactors. These short pulse durations could be useful in applications where prompt and delayed neutron and gamma emissions from irradiated materials have to be distinguished (e.g. prompt neutron material damage repair studies). Furthermore, the small diameter of the neutron beam produced with a laser source, which could be smaller than 1 mm under optimized conditions (i.e. with the converter close to the primary target), is yet another advantage. Short pulse duration and small source size would be of great advantage for many of the applications in the above-mentioned technology fields.

3. Neutron sources with table-top laser accelerated protons

In our discussion thus far, we have shown that laser-based neutron sources through (p,xn) reactions are comparable with, and in many respects more favourable than, current compact and portable neutron sources. However, due to their low-repetition rate and large size, single-shot lasers are clearly not suited for applications where there are mobility or space (not to mention cost) constraints. On the other hand, current terawatt table-top laser systems (e.g. Astra-Gemini laser at Rutherford Appleton Laboratory, UK or laser at the University of Jena, Germany) are much smaller, normally operate at repetition rates of 10 Hz but are still capable of accelerating protons to high enough energies to induce (p,n) reactions in low-threshold materials [25]. In this section, using similar methods to those explained above, we make estimates of the neutron production capabilities for current and future table-top laser systems. Our estimates are based upon data from our proton acceleration experiments on the table-top laser in Jena [26].

3.1. Laser light to proton and proton to neutron conversion efficiencies

Neutron production efficiency is a product of the laser light to proton efficiency (ε_{Lp}) and the proton to neutron conversion efficiency (ε_{pn}). We can calculate ε_{pn} for our experiment at VULCAN as a ratio between the number of protons (5×10^{11}) with energies above 10 MeV that have reacted in the lead sample and the number of produced neutrons (2×10^9). This gives us the efficiency $\varepsilon_{pn} \approx 4 \times 10^{-3}$ for a laser irradiance of $4 \times 10^{20} \text{ W } \mu\text{m}^2 \text{ cm}^{-2}$ and energy on the target of 400 J. This ε_{pn} can be easily understood if we look into the basic processes behind the conversion. To generate neutrons, protons must interact with the target nucleus via a neutron generating nuclear reaction. The probability for the nuclear reaction can be described in terms of the mean free path (Λ) parameter defined as: $\Lambda = 1/\Sigma = 1/N\sigma$, where Σ is the macroscopic and σ is the microscopic cross-section of the reaction in question and N is the atomic density of the material. Charged particles like protons experience continuous energy loss when they pass through matter and hence have a limited range (R) in solids. For protons with energies below a few hundred MeV, R is a few orders of magnitude smaller than any Λ for proton-induced nuclear reactions. In this energy range, we can introduce a ratio between both parameters as a simplistic measure to estimate the proton to neutron conversion efficiency: $\varepsilon_{pn} \approx R/\Lambda$. Calculated values of ε_{pn} for lithium, lead and uranium are presented in figure 4, together with the Λ and R used in the calculations.

It can be seen that for protons at 5 MeV in Li the range is approximately 1 mm and the Λ for Li (p,n) reactions is 50 cm. Thus, we can estimate that less than 1 in 500 protons will induce (p,n) reactions resulting in ε_{pn} being smaller than 0.002. Moreover, we can see that ε_{pn} in Li is at its highest value for protons of ~ 5 MeV. Higher reaction probabilities can be found in Pb at proton energies above 15 MeV. ε_{pn} in Pb is greater than 1% for proton energies above 30 MeV. This fact suggests that we need higher proton energies for efficient neutron generation. At this intensity lead is not the preferred choice for neutron productions (as was shown by Yang *et al* [27]). Higher neutron yields can be achieved with lithium or another target with (p,xn) cross-sections peaked at lower energies. For the VULCAN experiment described in this paper, we calculated the average energy of the protons contributing to the (p,xn) reactions in lead (above 10 MeV) to be 15 MeV. The ε_{pn} for this average proton energy is approximately 10^{-3} . This value is in good agreement with the measured conversion efficiency of 4×10^{-3} , if we take into account the simplicity of the approach used.

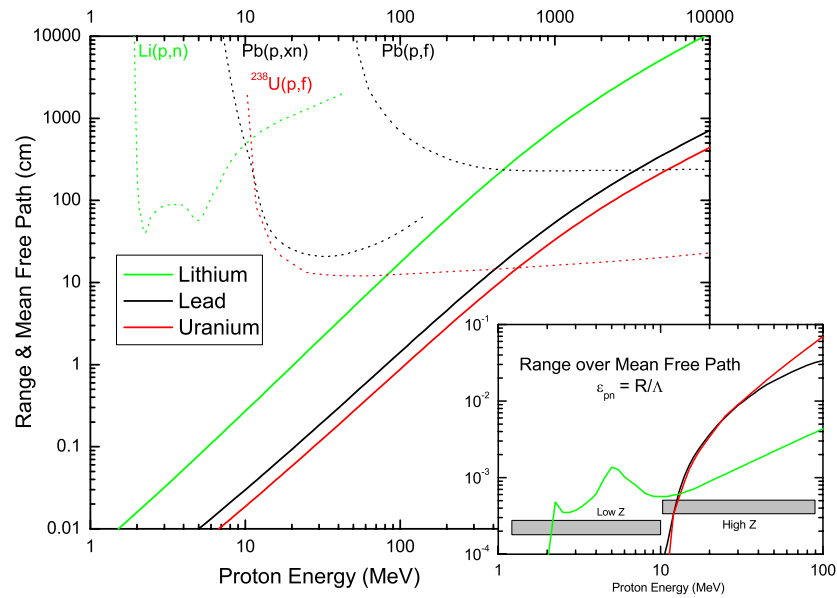


Figure 4. Proton ranges (R , —) in three different metals together with mean free paths (Λ ,) for neutron generation reactions in the same materials as a function of incoming proton energy. In the small insert the ratio between R and Λ as a function of proton energy is shown. This ratio is directly related to the efficiency of proton to neutron conversion ε_{pn} in different materials. Li and Pb are two typical materials used for neutron production and we have included U as a typical fissionable actinide material for which proton transmutation is also very interesting. The proton ranges were calculated with SRIM-2003 [38] and evaluated cross-section data for proton induced reactions were retrieved from EXFOR [39].

The question of laser light to proton conversion efficiency is more specific and has not yet been properly answered. The few studies on this subject (e.g., [28]) indicate a correlation between ε_{Lp} , the laser pulse energy E and the laser irradiance $I\lambda^2$. Or, in other words, ε_{Lp} is a function of $I\lambda^2\tau_{laser}$, where τ_{laser} is the pulse duration of the laser pulse. For laser pulse energy of 100 J and irradiance of $10^{20} \text{ W cm}^{-2} \mu\text{m}^{-2}$ the measured ε_{Lp} around 10% is usually found in reports (e.g. [29, 30]). However; for $E \approx 1 \text{ J}$ and $I\lambda^2 \approx 10^{18} \text{ W cm}^{-2} \mu\text{m}^{-2}$ data on ε_{Lp} as low as 0.001% [31] and as high as 0.7% [28] were reported. These large experiment-to-experiment variations are related to different laser contrasts and pulse durations, to different target foils and to the different proton energy measurement techniques used. In addition, ε_{Lp} also depends on primary target thicknesses and was shown that it can be influenced by controlling the hydrogen-containing surface layers [32]. For the design of applications using laser-accelerated ions this efficiency is very important and will be addressed in our future studies. One significant conclusion from these studies is that short pulse lengths τ_{laser} on table-top lasers are disadvantageous for the laser to proton conversion efficiency.

3.2. High intensity table-top laser development

The current state-of-the-art table-top laser at University of Jena operates at 10 Hz repetition rate and delivers approximately 1 J of light to a target with a focal irradiance of $10^{19} \text{ W } \mu\text{m}^2 \text{ cm}^{-2}$.

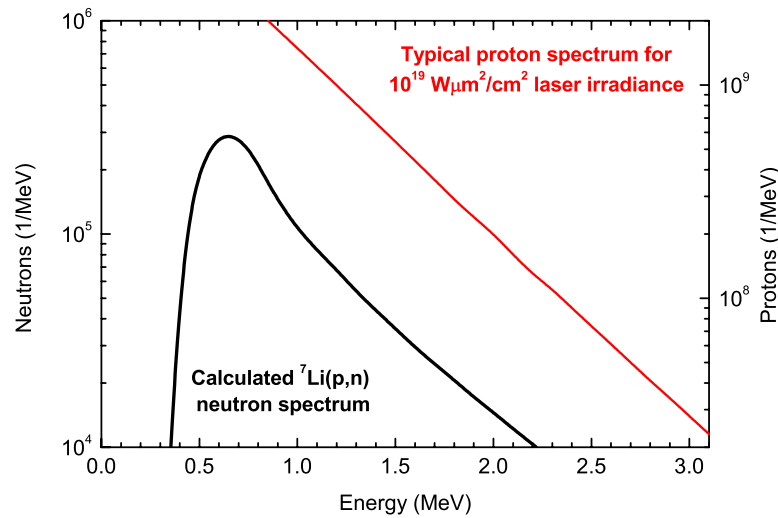


Figure 5. The calculated neutron spectra released in ${}^7\text{Li}(p,n)$ reactions for typical proton spectrum accelerated by $10^{19} \text{ W } \mu\text{m}^{-2} \text{ cm}^{-2}$ laser irradiance of a thin metal foil. We assumed the protons relevant to (n,p) reactions ($E > 1.9 \text{ MeV}$) to be Boltzmann distributed with approximate temperature of 500 keV. Maximum measured proton energy for terawatt table-top laser in Jena was 3.1 MeV and the number of protons above 1.9 MeV was 10^8 . The total number of neutrons per shot calculated from this spectrum is 1.5×10^5 .

Proton acceleration up to around 3 MeV has been achieved with this laser [26], which is enough for inducing (p,n) reactions in lithium (NB ${}^7\text{Li}$ (p,n) reaction has a threshold value of 1.88 MeV). The efficiency ε_{Lp} for such table-top devices is, according to available data [28], higher than 10^{-5} , and the proton to neutron conversion efficiency ε_{pn} for protons with energies between 2 and 3 MeV is 4×10^{-4} (see figure 4). Using our phenomenological analysis procedure, we can therefore conclude that such a table-top laser system with a thick Li target can produce 10^5 neutrons per shot. A simulated neutron spectrum for this setup based on measured proton beam parameters is presented in figure 5. This neutron spectrum spans the range 0.5–1 MeV, with a peak around 0.65 MeV, and has an associated total number of neutrons of 1.5×10^5 . Therefore, we may conclude that neutron yields produced by such a source is at the very least 10^5 neutrons per joule of laser energy or 10^6 neutrons per second, which is comparable with neutron yields produced by cluster fission sources generated with the interaction of femtosecond laser pulses with deuterium clusters [14, 15].

Due to the relatively high cross-section for the (p,f) reaction in uranium and the (p,xn) reaction in lead, the ε_{pn} will reach approximately 1% for these reactions using laser accelerated protons with average energies around 30 MeV. The relation between proton energies and laser irradiance $I\lambda^2$ has been extensively studied by many authors. Clark *et al* [33], Mendonça *et al* [34] and Spencer *et al* [29] have showed that the maximum proton energy and mean proton energy are approximately proportional to $\sqrt{I\lambda^2}$. If we assume this scaling, a proton beam with a maximum energy of 100 MeV could be reached at $10^{21} \text{ W cm}^{-2} \mu\text{m}^{-2}$. Since the maximum proton energies are typically 5–10 times higher than the mean proton energies, we need $4 \times 10^{21} \text{ W cm}^{-2} \mu\text{m}^{-2}$ at large laser facilities like VULCAN to produce protons with 30 MeV mean energy.

This level of laser intensity is also likely to be achievable on diode-pumped table-top lasers systems in the near future. POLARIS [35]—a diode-pumped high-power laser system under construction at the University of Jena, due for completion in 2007—will deliver ultra-short pulses (150 fs) with a planned energy up to 200 J, a wavelength of 1030 nm and a predicted repetition rate of 0.1 Hz. Diode-pumped table-top lasers are not only smaller, they have also higher wall-plug efficiency than large lasers like VULCAN. Focusing this light to a spot with a diameter around $10\ \mu\text{m}$ will result in an irradiance of $10^{21}\ \text{W cm}^{-2}\ \mu\text{m}^{-2}$. If we assume a value for ε_{Lp} of 10% on a thin primary target and a value for ε_{pn} of 1% on thick lead target, POLARIS will be able to support a compact neutron source with around 5×10^{10} neutrons per pulse—that is to say, an average neutron strength of 5×10^9 neutrons per second.

4. Conclusions

The highly efficient conversion of laser light into fast protons, achieved with irradiation of thin solid targets, has opened up the possibility of generating pulsed neutrons in a completely new way. These sources are based on proton to neutron conversion in thick converter materials. Using a phenomenological approach based upon nuclear cross-section data and proton range calculations, we have estimated proton to neutron conversion efficiencies for different materials. We have shown that low Z materials like lithium can be used as proton to neutron converters in current laser systems with correspondingly low-proton energies (which has also been demonstrated by Lancaster *et al* [19] and Yang *et al* [27]). However, high Z materials, such as lead, are the materials of choice for efficient proton to neutron conversion for laser systems in the near-term future, when much higher proton energies will be available. Some authors [36, 37] have indicated that future laser systems will reach laser intensities well beyond $10^{21}\ \text{W cm}^{-2}\ \mu\text{m}^{-2}$, even up to $10^{24}\ \text{W cm}^{-2}\ \mu\text{m}^{-2}$, in the next decade. At these intensities proton energies will be high enough to initiate spallation reactions in high Z solid targets. Spallation reactions are even more efficient in neutron production than fission reactions, making for higher efficiency neutron generation. The characteristics of these neutron sources are an anisotropic neutron flux, a continuous energy spectrum and an extremely short pulse width.

By using a combination of experimental data [1] and phenomenological analysis, we have demonstrated that the VULCAN laser is capable of producing 2×10^9 neutrons per laser shot. Using the model we have developed for the VULCAN analysis, we have predicted that current state-of-the-art table-top lasers can generate neutron pulses with a rate of 10^6 neutrons per second by using lithium as a proton to neutron converter. We further predict that with the table-top lasers currently under construction, pulsed neutron sources with 5×10^9 neutrons per second (in pulses smaller than 1 ns) will be readily achievable. The extremely short neutron pulse length means that this could be a very promising neutron source for applications where precise time determination in nuclear reactions is important (e.g. pulsed fast neutron activation methods or prompt neutron material damage repair studies). Moreover, the short pulse length and strength of such neutron sources is also of interest for pulsed fast neutron interrogation methods. Finally we conclude that, given the current rate of evolution in laser technology, fast, cheap, flexible, pulsed neutron sources on the table-top scale will become available in the next few years.

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