Scaling of Laser Fusion Experiments for DD-Neutron Yield

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Yields of neutrons produced in various laser fusion experiments conducted in recent decades are compared with each other. It has surprisingly been found that there is a possibility to make an overall elucidation of the variance in the number of neutrons produced in the various experiments. The common method is based on definition of the energy conversion efficiency as a ratio between the energy carried out by neutrons produced through the fusion reaction and the input energy given by laser energy, E, focused on a target. The neutron-yield – laser-energy (Y–E) diagram is the basic chart used to interpret the spread of experimental data in terms of the experimental efficiency of the laser-matter interaction. Experiments carried out using a single laser system show that laser energy dependence of the yield can be well-characterized by a power law, $Y = QE^{\alpha}$, where Q is the parameter reflecting possible dependence on the pulse duration, laser intensity, laser contrast ratio, focal geometry, target structure, etc. [1, 2]. Sorting the values of the neutron yields obtained in various experiments shows that the power law $Y = Q\,E^{1.65}$ is suitable to determine lines in the Y–E diagram each of them, where the value of Q is associated with quality of experimental conditions [3]. This sorting shows the order-of-magnitude differences in yields found in various experiments, which can be characterized by the value of the parameter Q. Due to the easy feasibility and the large number of DD fusion experiments performed, the overall Y-E diagram gives a chance to identify suitable laser systems for effective DD fusion experiments. It can, therefore, be assumed that some of the conclusions of these experiments could also be applied to the experimental arrangement suitable for optimizing $p^{11}B$ fusion.

Keywords: laser-plasma interactions, DD neutron yield scaling, DT neutron yield scaling, preplasma effect, hydrogen–boron fusion

INTRODUCTION

Many efforts have been devoted to optimizing the heating of fusion targets by laser pulses to initiate different fusion reactions producing e.g., neutrons and alpha particles through fusion DD, DT and $p^{11}B$ reactions that carry released energy [4–6]. One of the important objectives for developing a usable fusion energy source is just to find an effective way to enhance the laser energy coupling to the target in the context of inertial confinement fusion research [7]. On the other hand, plasma as a source of fusion neutrons produced by the reaction, $D + D \rightarrow He^3 + n$, may not only be produced by large laser facilities, but also by small laser devices. If the plasma is produced by laser pulses over the energy range from millijoules to dozens of kilojoules, then fusion neutrons are released from beam fusion and thermal fusion initiated by fast deuterons ($E_D > 20$ keV). A number of different experiments have shown that the value of neutron yield corresponding to this laser energy range varies from a few neutrons to trillions per laser shot.

Analysis of a wider range of experimental data from different research groups around the world have made it possible to obtain scaling laws, especially for certain types of experiments. The scaling properties are generally attributed to the laser power dependence, where the reaction rate, the density of the plasma and the projected range of the plasma particle in the target medium play a decisive role. However, given the different conditions under which laser plasma experiments are performed, it is useful to sort and compare the results of different fusion experiments based on the dependence of neutron yield on a wide range of laser energy [8, 9]. The large scatter of values in the publications presented so far indicates that laser parameters such as pulse energy, pulse duration and maximum intensity do not fully determine the fusion yield. Thus, fusion yield also depends on other factors affecting acceleration of ions, such as laser pulse shape, laser contrast ratio, focal geometry, target structure, pre-plasma formation, as well as non-linear processes occurring during the laser-plasma interaction. Despite the large number of parameters and processes that affect fusion yield, the experimentally observed dependence of neutron yield on laser energy appears suitable for finding the optimal experimental conditions required for practical use.

The laser energy dependence of the fusion yield has been characterized by a power law dependence, $Y = QE^{\alpha}$, on laser energy E, where Q is the parameter reflecting the processes occurring in such plasmas, as mentioned above [1, 2]. The experiment dealing only with fusion neutron yields from explosions of deuterium clusters irradiated with a 100-TW laser shown that the value of α can range from 1 to 2.3 and Q from 1,430 to 13,200, as reported in [2, 10, 11]. The first comparison of different experiments on deuterated solid targets showed that a typical fusion experiment can be included in the group of experiments where $Y(E) = 2,000 \times E^{1.65}$ [3]. The $Y = QE^{1.6}$ dependence was also used in Ref. [12] to indicate a similar trend. In this paper, we will report more experimental data supporting this trend in yield increasing as a function of laser energy for deuterated plasma. The dependence of Q on other parameters that together determine the position of the yield value in the Y-E diagram can be considered as a measure of the efficiency of the laser-matter interaction applied.

Y-E DIAGRAMS

To measure the fusion yield ranging from over roughly 12 orders of magnitude, from the lowest yields of a few DD neutrons per laser shot up to 10^{12} [13, 14], various calibrated low/high yield detection systems consisting of e.g., time-of-flight scintillation neutron detectors, nuclear track detectors, bubble and thermoluminescent dosimeters, and activation detectors are used. The total neutron yield into the solid angle of 4π steradian per laser shot is determined assuming that the neutrons are emitted isotropically although there is evidence that the emission from the plasma may not be perfectly isotropic. In addition, the spatial and energy distribution of neutrons is affected by neutron scattering through the passage of the interaction vessel [1, 15, 16]. Regardless of inaccuracies in total neutron yield determination
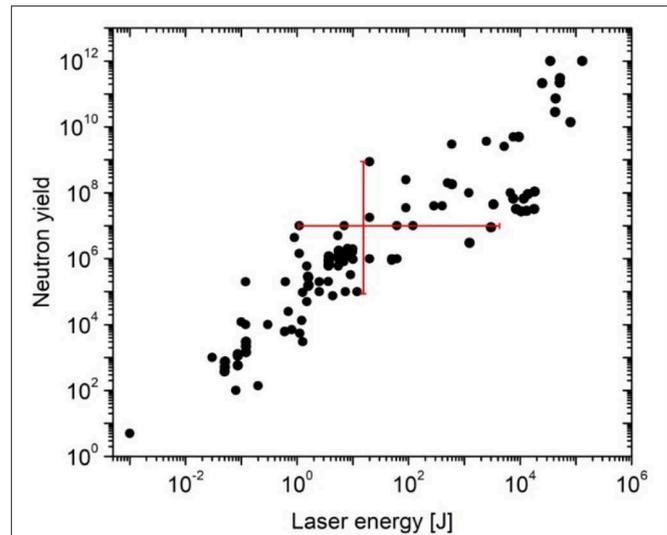

FIGURE 1 | Neutron yields from deuterated targets irradiated by various laser systems, data from References [1–3, 10, 14, 17–35]. Pitcher-catcher configurations are not displayed. In the case of anisotropic neutron emission, equivalent 4π neutron yields were calculated from peak neutron fluence.

and differences in a number of parameters determining laser interaction with target, neutron yield generally increases with increasing energy deposited by the laser on target, as **Figure 1**. The data presented are collected from a series of experiments dedicated to the interaction of fs-ns laser pulses with deuterated targets of various configurations, such as solid planar target, spherical target, cryogenically cooled target, clusters etc. [1–3, 10–12, 17–35]. Despite the large dispersion, these data show an increasing dependence of the neutron yield on laser energy. At the center of the data set, there is a large scattering of the neutron yield values: The yield ranges from 10^5 to 10^9 neutrons at deposited energy of 15 J. The horizontal-oriented line shows that the yield of 1×10^7 neutrons was achieved with both a high laser energy of 4,500 J and a low energy of 1 J. The 1 J-energy was clearly very effectively coupled to the fusing deuterons.

While it is not possible to retrospectively specify all the parameters that influenced the conversion of laser energy into fusion neutron energy, the experimental devices that provided both the largest and smallest yields can be characterized at least in part. Likewise, here it can be assumed that different lasers and targets were used to obtain maximum yield value in each experiment. Differences in experiments will be reflected by different values of the parameters of the above-mentioned power function $Y=QE^{\alpha}$. It is also obvious that in general a number of power functions can be fitted to experimental points shown in **Figure 1**, which differ in values of both parameters Q and α [1, 2].

Figure 2 shows a DD-neutron Y-E diagram, where for simplicity, only 5 lines $Y = QE^{1.65}$ are plotted, for Q ranging from 14 (Y_{SGG}) to 7.5×10^6 (Y_{BL-h}). In addition, those experimental data that relate to those lines are presented. One of these experiments dealing with deuterium cluster targets irradiated with 100 fs pulses, see Ma04 label, gave the dependence
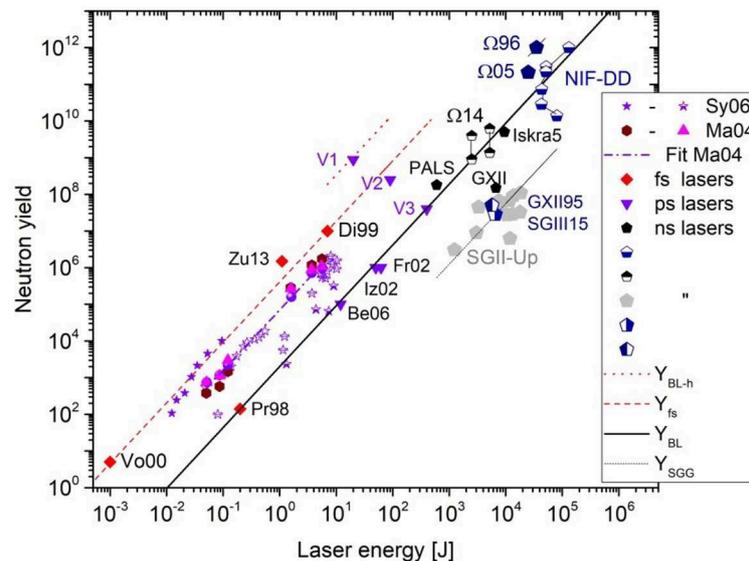
FIGURE 2 | Selected DD-fusion experiments associated with laser energy dependence of fusion neutron yields obeying the power law $Q \cdot E^{1.65}$, where $Q_{SGG} = 14$ (short dash line), and $Q_{BL} = 2,000$ (solid line), $Q_{fs} = 7.1 \times 10^4$ (dash-dot line) for explosions of deuterium clusters [2], $Q_{fs} = 4.1 \times 10^5$ (dash line) and $Q_{fs} = 7.5 \times 10^6$ (dot line). Data from References: Ma04 [2], Sy06 [10], Vo00 [13], Pr98 [17], Be06 [18], Iz02 [19], Fr02 [28], Zu13 [33], Di99 [34], V1 [25], V2 [26], V3 [27], PALS [20], Ω14 [22], Iskra5 [21], NIF-DD [23], Ω05 [31], Ω96 [14], SGII-Up [12], GXII [29], GXII95 [32], and SGIII15 [30].

$Y = 7.1 \times 10^4 \cdot E^{1.6}$ [1, 2]. The efficiency of this experiment given by the value of the Q parameter was higher by a factor of ≈ 35 than that of experiments involving the PALS experiment, which matches the solid line $Y_{BL} = 2,000 \cdot E^{1.65}$ [3]. The PALS experiment revealed a non-linear interaction of a 350-ps pulse with plasma [36], which resulted in the production of up to 4 $\times 10^8$ DD neutrons per shot, see PALS label [20]. The analysis showed that the central-of-mass velocity of ions was much higher than their temperature: $E_i \gg kT_i$, i.e., $kT_i \approx 1$ keV, proton kinetic energy of ≈ 1–4 MeV, and energy of deuterons reached a value of about 3 MeV [3, 37].

The last dependence Y_{BL} is associated with experiments where the self-focusing due to the interaction of laser beam with pre-plasma occurs spontaneously or in a controlled manner. In the case of yield labeled Pr98, a nanosecond pre-pulse was used to produce pre-plasma, which allowed a measurable neutron yield to be gained by self-focusing the main femtosecond pulse [17]. The yield labeled Be06 is a result of experimental study devoted to the effect of pre-pulses with various durations on the neutron yield in laser picosecond plasma [18]. Another experiment labeled Iz02 is the result of the effect of the pre-pulse on yield, where the pre-pulse delivered 10^{-4} of energy of the main 500 fs-pulse to the target [19]. Even in this case, the main pulse interacted with a pre-formed plasma.

The other iodine laser system, like the PALS one, producing pulses with duration of 250 ps and with total energy up to 10 kJ is the ISKRA-5 12-channel laser system [21]; see Iskra5 label in **Figure 2**. The yield reaching a value up to 5×10^9 DD-neutron per shot was produced with energy of 10 kJ delivered to the inverted-corona target, where the ion kinetic energy was converted into thermal energy at a temperature of 10–20 keV.

It is obvious that even this yield value matches the line $Y_{BL} = 2,000 \cdot E^{1.65}$.

The values of the absolute yields of DD neutrons tagged with Ω label were taken from two experimental campaigns at OMEGA. As targets where used the glass capsules 880 µm in diameter, 2.0 µm thick, and filled with 3.6 atm D_2 and 7.9 atm D^3He gas, and with 9.3 atm of D_2 gas which were irradiated with 60 laser beams providing ≈ 2.5 and ≈ 5.2 kJ, respectively [22].

The highest number of 1×10^{12} DD-neutrons from an "exploding-pusher" powered by 130.6 kJ laser energy were achieved at the National Ignition Facility [23]. Most of the "exploding-pushers" tagged with NIF-DD label follow the power law dependence on laser energy, $Y_{BL} = 2,000 \cdot E^{1.65}$, well, as **Figure 2** shows.

Important experimental results marked with V1, V2, and V3 labels were obtained using the Vulcan laser system [25–27]. These experiments using 0.9–1.2 ps laser pulses have shown that the neutron yield can decrease with increasing laser energy. In the case of the V3 experiment, there could be such conditions under which the interaction of the main laser pulse with the pre-plasma could initiate different processes that consume laser energy at the expense of acceleration of deuterons and, thus, neutron yield. The pre-plasma was produced by a pre-pulse of the main 400 J laser pulse irradiating the target with a peak focused intensity of 4×10^{20} Wcm^{-2} at a contrast ratio of $\sim 5 \times 10^{-8}$ [27]. A higher yield was observed when a lower laser energy of 90 J was focused on the target with the peak laser intensity of 5×10^{19} W/cm^2 at a contrast ratio of 10^{-7} [26]. The highest yield was achieved with low energy of 20 J and intensity of 10^{19} W/cm^2 [25]. In this case, it can be assumed that no pre-plasma was produced due to the low contrast ratio. The value of this neutron yield of 7×10^7

neutrons/sr, see V1 label, is higher by a factor of ≈12 than that obtained with the pulse energy of 400 J [25, 27]. In the latter case, it can be assumed that the pre-plasma probably plays an insignificant role.

Figure 2 also shows that measured scaling of fusion yield as a function of laser energy may differ from $Q E^{1.65}$ in individual experiments. Although the Sy06 data presented by four types of asterisks (★ - ☆) were scaled by a power law with exponent varying from 2 to 2.2 in [1, 2, 10] and quadratic dependency was used to analyse them using hydrodynamic scaling and other methods [11, 24], it is clear that inserting them into the metadiagram shown in Figure 2 supports the overall trend of energy dependency represented by the $Y = Q E^{1.65}$ relationship. Using this dependency also allows us to approximately quantify the effectiveness of other experiments in the frame of the metadiagram, for example the SGII-Up experiment, as already stated in [12]. This experiment was devoted to the plasma compression with the use of eight laser beams that delivered 12-kJ energy in 2 ns on a CD_2 flat target at the ShenGuang-II Upgrade (SGII-Up) facility. As stated in [12], the highest yield of about 1×10^8 neutrons achieved at 12-kJ energy is in good agreement with the yield observed at 600-J energy delivered in 350 ps on a CD_2 flat target at the PALS facility. The yield values obtained in the GXII95 and SGIII15 cryogenic experiments also match the Y_{SGG} line [29, 30]. The metadiagram also shows other experimentally observed yields of DD-neutrons which were produced with higher as well as lower efficiency in comparison with our basic power law dependence on laser energy $Y_{BL} = 2{,}000 \cdot E^{1.65}$. The efficiency of production of 1×10^{12} DD neutrons with 35 kJ laser energy delivered by the OMEGA laser system is higher by a factor of ≈16 than the basic one with $Q = 2{,}000$, see Ω296 label [9].

Summarizing the laser-fusion experiments, the highest laser fusion yields by cryogenic targets were 1.9×10^{16} neutrons from deuterium-tritium (DT) implosions driven with 1.5 MJ laser pulses [38], as Figure 3 shows. We note that the values of the DT-neutron yield shown in Figure 3 are presented without a correction taking into account differences in DD and DT fusion reaction cross sections, although in the case of a thermonuclear reaction at a certain temperature, the fusion probability of the deuterium-tritium reaction is nearly by a factor of 100 larger than that of the deuterium-deuterium reaction [29]. If this factor is taken into account, then the values of DT-neutron yields achieved at the OMEGA and NIF experiments (tagged with 11–15 labels) are shifted to the Y_{BL} line that determine the results of standard DD-fusion experiments. Figure 3 shows only a few experimental results concerning the DT-neutron yields. It may be noted that, for example, other values reported by R. S. Craxton et al. [48] are located between points 2–5 and 10–11.

The configuration of the experimental points in the Y-E diagram shows relationships and connections between experiments of completely different levels that can be hardly to be expected. It is obvious that the empirical yield dependence on laser energy, $Y = QE^{1.65}$, is the simplest dependency that can be used to characterize experimental values obtained for an energy range exceeding 9 orders of magnitude. It is also a fact that when the fusion experiments described above were conducted with the use of high-quality laser pulses with a sufficiently high contrast
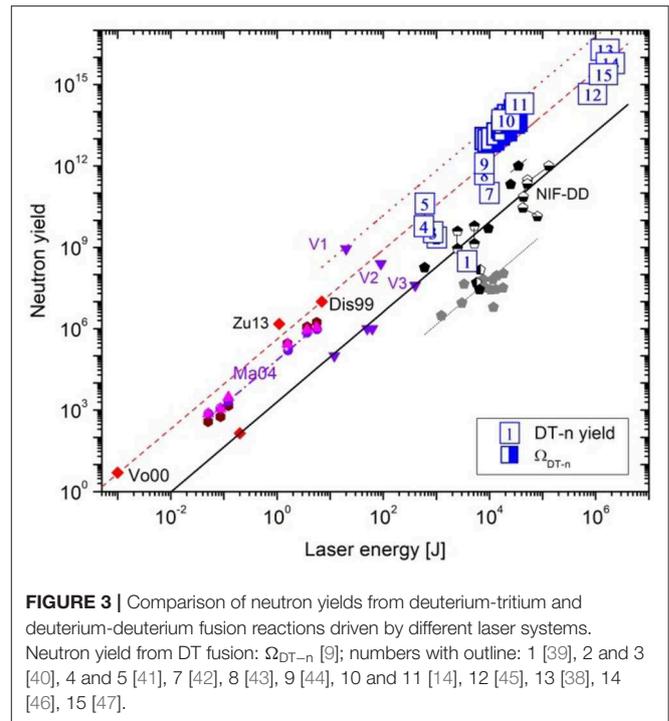

FIGURE 3 | Comparison of neutron yields from deuterium-tritium and deuterium-deuterium fusion reactions driven by different laser systems. Neutron yield from DT fusion: Ω_{DT-n} [9]; numbers with outline: 1 [39], 2 and 3 [40], 4 and 5 [41], 7 [42], 8 [43], 9 [44], 10 and 11 [14], 12 [45], 13 [38], 14 [46], 15 [47].

ratio, fusion gains at a given laser energy increased by more than four orders of magnitude [25]. The use of the power law dependence on laser energy reduces all processes that determine the conversion of laser energy to the production and acceleration of fusion ions to only two parameters Q and α. For a given energy, the Q coefficient allows comparing the efficiency of different laser systems, which is given by the number of neutrons per joule of laser energy. For a given parameter Q, the $\alpha = 1.65$ coefficient indicates the non-linearity dependence of yield on laser energy delivered to the target within the entire experimental point configuration. Regardless of low or very high laser intensities, "cleaner" experiments are needed to elucidate other values of α that have been observed in some experiments [1, 2].

DD AND p¹¹B FUSION EXPERIMENT AT PALS

The Prague Asterix Laser System (PALS) in Prague was used not only for the DD fusion experiments [3, 20] but also as a driver for the fusion reactions of hydrogen protons with the boron isotope ^{11}B releasing three alpha particles and energy of 8.7 MeV: p + ^{11}B = 3α + 8.7MeV [6, 43, 44]. First, A. Picciotto et al. obtained a high number of α particles (10^9 α/sr/shot) released from the plasma which was produced on a silicone target, doped by boron and enriched with hydrogen by an annealing process. The target was exposed to laser intensity of 3×10^{16} W/cm² (500-J energy in 0.3 ns (full-width at half-maximum, FWHM) [49]. Very high yield, well-above 10^{10} α/sr/shot, was obtained by L. Giuffrida et al. [6] when a 0.5-mm thick boron nitride targets were irradiated with 0.3 ns pulses delivering energy of

TABLE 1 | Yield of p + ^{11}B → 3α + 8.7 MeV and D + D → ^{3}He (0.82 MeV) + n (2.45 MeV) fusion reactions performed at the PALS facility.

Laser energy	Target	Yield/steradian /shot	Fusion product	References
500 J	hydrogenated Si target doped by ^{11}B	10^9	3α particles + 8.7 MeV	[49]
600 J	0.5-mm boron nitride	6.5×10^{10}	3α particles + 8.7 MeV	[6]
600 J	0.2–0.5 mm CD_2	3.2×10^7	2.45 MeV neutrons	[3, 20]

Laser pulse duration of 0.3 ns (FWHM), wavelength of 1,315 nm, focal spot diameter of 70 μm.

600 J. It has been shown that this yield of α particles is not thermonuclear in nature, but rather results from a beam-driven fusion process.

Table 1 shows the yields of α particles and DD neutrons released from the fusion plasma produced by the PALS laser. The first two rows show an increase in the number of α particles due to a change in the composition of the target. The number of α particles emitted per steradian and laser shot is three orders of magnitude higher than the number of DD neutrons produced with the same laser intensity and energy. If we consider the possibility of increasing yield by using a high-quality laser, as mentioned above, then the use of picosecond or shorter duration CPA- laser pulses that do not produce pre-plasma but initiate non-thermal fusion reactions in p^{11}B plasma could help solve a key problem for controlled nuclear fusion energy generation [50, 51].

CONCLUSIONS

In this work, we restricted our study on the scaling law of fusion yields, $Y = QE^{1.65}$, derived empirically from the available experimental data. The performed analysis showed that this function fits the largest number of experimental data on the energy scale covering 9 orders of magnitude, namely for the line with $Q = 2,000$. Published experimental data made it possible to classify individual experiments within a metadiagram

in such a way that the number of fusion reactions increases with increasing energy as $E^{1.65}$ at the same value of the Q coefficient. This coefficient summarizes the effect of all possible processes taking place during laser-target interaction on fusion neutron production. Then the part of E that is not converted into energy carried by fusion neutrons can be quantified by $1/Q$. In this case, the experiments tagged with Y_{fs} label are ≈200 times more productive than the Y_{BL} experiments and the V1 experiment is then even ≈3,700 times more productive than the Y_{BL} ones. The Y_{SGG} experimental configurations, on the other hand, are 25 times less productive than the Y_{BL} ones. It is obvious that in order to search for optimal conditions of a generation of fusion neutrons using some kind of laser system, it is appropriate to compare the observed $Y = Q\ Y(E)$ dependence with the experimental results of other experiments using metadiagram. The values of the Q coefficient offer the possibility of finding the effective acceleration of ions and the production of fusion neutrons and one can assume that they will also be valid in the case of proton boron fusion.

It goes without saying that every laser system used for a production of fusion neutrons has its own specifics that can be explained by many different sub-processes, as shown by many key works. However, the method presented allows each interaction laser system to be placed in the overall context of the laser-matter interaction.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

JK: wrote the manuscript. DK: reviewed the manuscript and collected experimental data. All authors contributed to the article and approved the submitted version.

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