Positron and gamma-photon production and nuclear reactions in cascade processes initiated by a sub-terawatt femtosecond laser

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We demonstrate theoretically that sub-terawatt lasers are capable of producing, through specially arranged cascade processes in optimal targets, substantial amounts of nuclear radiation (positrons, gamma-photons, neutrons, and fission fragments). © *1997 American Institute of Physics.* [S0003-6951(97)02350-4]

Numerous proposals to induce nuclear transformations by intense lasers (see, e.g., Ref. 1) predicted exceedingly small output of ''nuclear radiation'' (positrons, gamma-photons, neutrons, and fission fragments), even for the laser intensity still out of reach. In fact, efficient production of nuclear radiation was not the subject of those proposals; as a result, optimal choice of processes and targets was not addressed. Recently, we have shown theoretically[2] that *already available* laser intensities are sufficient for producing, through a specially arranged cascade of processes, practically useful ultrashort-pulse, high-flux nuclear radiation with possible applications in material science, medicine, and nuclear engineering. High nuclear radiation yield predicted in Ref. 2 presumes, however, laser power of tens of terawatt (TW), which is currently available only from a few unique systems. In the present letter, we concentrate on the opportunities provided by much more modest lasers, with the output power of ~ 1 TW. We demonstrate theoretically that even such, widely available lasers are capable of generating, through relativistic laser–plasma electrons interacting with optimal targets, noticeable amounts of nuclear radiation and could, therefore, be instrumental in proof-of-principle experiments for future practical laser-based sources of that radiation.

Since direct electron–positron pair production or nuclear transformations by a laser field apparently require exceedingly high intensities, the only presently practical road to producing nuclear radiation by a laser is using MeV electrons present in laser plasma at already available laser fields. The efficient generation of such electrons occurs in plasma of subcritical density (see below); at the same time, efficient pair production and nuclear transformations require the highest density possible, in other words, solid targets. Moreover, cross sections of electron-induced processes of interest are orders of magnitude smaller than those of the respective photon-induced reactions, which calls for using a Bremsstrahlung converter. The above arguments bring us to a *three-step cascade*: (i) generation of MeV electrons in subcritical laser plasma; (ii) Bremsstrahlung conversion of MeV electron energy into MeV photons in a high-Z solid target; and (iii) electron–positron pair production or photonuclear reactions. The energy thresholds of the third step determine the required energy of laser–plasma electrons, and therefore the feasibility of the entire scheme for a given laser intensity. Electron-positron pair production threshold is ≈ 1.02 MeV. To attain observable neutron output, we propose using the *lowest-threshold* neutron photoproduction processes: in beryllium $\gamma + {}^9\mathrm{Be} \rightarrow n + {}^8\mathrm{Be}$ ($E_\gamma > 1.7$ MeV) or deuterium: $\gamma + {}^2\mathrm{H} \rightarrow p + n$ ($E_\gamma > 2.2$ MeV). Beyond 5 MeV, electrons could also initiate nuclear photofission in actinides, with neutron and fission-fragment output.

Since solid targets are necessary for efficient generation of nuclear radiation, we will limit our consideration to plasmas generated on, and in a close proximity of, solid surfaces. Both theory and experiment indicate that a relatively thick (~ 50 μm) layer of subcritical plasma is necessary for efficient generation of MeV electrons. Indeed, if a sub-TW laser pulse interacts directly with a sharp edge of a solid, the suprathermal electrons could be characterized by an effective temperature[3] $T_e \approx mc^2(\sqrt{1+I\lambda^2/4}-1)$, with the laser intensity I in 10^{18} W/cm^2 and laser wavelength λ in μm. For $I \sim 10^{18}$ W/cm^2 attainable with a near-TW laser, $T_e \sim 0.06$ MeV—apparently too low to assure substantial presence of MeV electrons. Behind this relatively small value is the fact that the electrons are accelerated only within a skin depth $<\lambda$. At the same time, a substantial amount of electrons with kinetic energy up to 2 MeV was generated on solid targets at similar laser intensities, when the main laser pulse hit a significant layer of subcritical-density plasma above the solid surface.[4,5] The acceleration length is much larger in this case than in a sold-density plasma, while the acceleration force should not differ by much; one, therefore, could expect much higher electron energy. (The highest laser–plasma electron energy so far has been observed in strongly underdense plasma;[6] however, the multi-TW laser power required places those results, which are used in part in Ref. 2, outside the scope of this letter.)

These qualitative considerations are in agreement with the, conducted by us for the first time, three-dimensional (3D) PIC simulations of the interaction of a sub-picosecond, near-TW laser with a preformed extended ablation plasma near the critical surface. We employed our code VLPL[7] to model the ablating plasma with an exponential density profile along the laser beam axis, $n_e = n_c \exp(-x/d_p)$, where $n_c = 10^{21}$ cm^{-3} is the critical density for $\lambda \approx 1$ μm, and d_p

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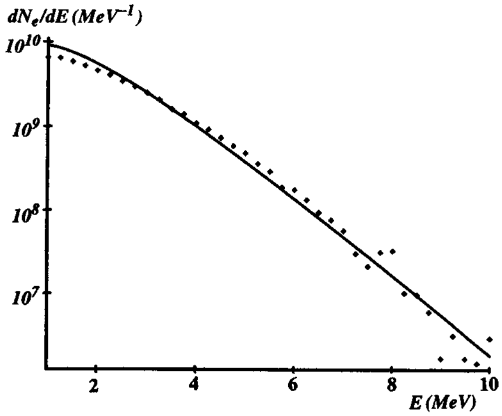

FIG. 1. Energy spectrum of MeV electrons that reach the critical surface of ablating laser plasma at sub-TW laser power. dN_e/dE—number of electrons in a 1 MeV interval at the energy E. Here crosses denote 3D PIC simulation results, while the solid curve represents the analytical fit.

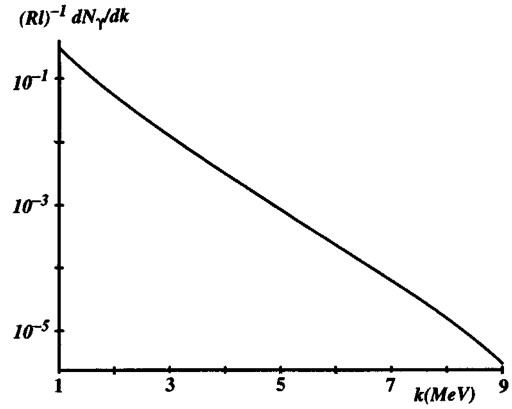

FIG. 2. The integrated-over-angle spectrum of the Bremsstrahlung radiation induced in a thin target by the MeV electrons from plasma generated by a sub-TW laser.

$=30\ \mu$m. We did observe, in particular, the vital role of the pre-formed subcritical plasma. Our results pertaining to self-focusing and channel formation have been reported in Ref. 8; most of the calculated electron energy spectra will be published elsewhere. Here we present (see Fig. 1) only the energy spectrum of the electrons that reach the boundary of the simulation region (behind the critical surface) with kinetic energy $E>1$ MeV. These electrons move largely in the direction of the laser pulse. This spectrum, which forms the basis of all quantitative estimates in this letter, contains a very substantial amount, $\sim 10^{10}$, of high-energy electrons—enough, as we show below, to generate observable, and perhaps even useful, amount of nuclear radiation in optimal targets. The first layer of such targets should consist of a low-Z ablation material (e.g., plastic) to facilitate formation of an extended plasma.

The second step of the proposed cascade is the Bremsstrahlung conversion; this process is also of interest by itself as a source of ultrashort pulses of intense x rays with numerous potential applications (see e.g., Ref. 9). Larger Bremsstrahlung yield requires a target thick for the incident electrons. Accurate calculations of Bremsstrahlung spectra in such targets require using Monte Carlo computer codes, see e.g., Ref. 10 and references therein. At this stage, however, it will suffice to obtain a simple analytical approximation for the Bremsstrahlung spectrum generated in a target *thin* for MeV electrons and therefore for MeV photons. The resulting positive conclusions on the feasibility of positron and γ-photon production could be made only stronger by considering thick targets; at the same time, our estimates of the neutron and fission output employ published results for thick targets.

The calculated electron spectrum fits fairly well the following expression:

$$dN_e/dE \approx \nu_0 E\ \exp(-rE), \quad \nu_0 \approx 3.03\times 10^{10}\ \text{MeV}^{-2}, \quad r\approx 1.20\ \text{MeV}^{-1}, \tag{1}$$

where dN/dE is the number of electrons in a 1 MeV interval at a given energy E (see Fig. 1). Neglecting changes in the electron bunch during its propagation in a thin target, we integrate the approximate expression for the integrated-over-angle Bremsstrahlung cross section from Ref. 11, $d\sigma/dk \approx aZ^2(k^{-1}-bE^{-1})$ (even for the low energy of interest, it reproduces to about 20% accuracy the results of Ref. 12), over the electron spectrum [Eq. (1)] to obtain (see also Fig. 2):

$$\frac{dN_\gamma}{dk} \approx n_a l \int_k^{E_0} \frac{d\sigma}{dk}\frac{dN_e}{dE}\, dE = Rlf_\gamma(k), \quad R=r^{-1}n_a aZ^2\nu_0, \tag{2}$$

$$f_\gamma(k) \approx \left(1-b+\frac{1}{rk}\right)e^{-rk}+\left(b-\frac{E_0}{k}-\frac{1}{kr}\right)e^{-rE_0},$$

where dN_γ/dk is the number of Bremsstrahlung photons radiated in the 1 MeV energy interval at the photon energy k; E_0 is the high-energy cut-off of the electron spectrum, assumed below at 10 MeV; Z, n_a, and l are the atomic number, the atomic density, and the thickness of the target, respectively; and $a\approx 11$ mbarn, $b\approx 0.83$.

Due to the strong Z dependence, the second layer of an optimal target must consist of a high-Z material. Tantalum ($Z=73$, $n_a\approx 5.7\times 10^{22}\ \text{cm}^{-3}$) is frequently used in Bremsstrahlung converters; for a Ta target, $R\approx 8.4 \times 10^{10}\ \text{cm}^{-1}\,\text{MeV}^{-1}$. The stopping distance of electrons with the energy just above the Be photoneutron threshold in Ta is about 0.07 cm;[13] we may safely assume the thickness of a ''thin'' target at 0.1 of that, $l=0.007$ cm in Eq. (2). Based on Eq. (2), we expect, in particular, $\sim 8 \times 10^7$ photons with the energy above 1 MeV. This amount of γ photons can create 30 μGy exposure even under the assumption of an isotropic distribution, and therefore could be observed using detectors intended for high-energy flash radiography (e.g., Ref. 9 reports recording radiographic images at 1.5 μGy); moreover, one may hope that a sub-TW laser with the repetition rate in the kHz range could become a practical source of radiation for this imaging technique.

Propagating inside a Ta target, Bremsstrahlung photons [Eq. (2)], will produce positrons. To roughly evaluate the amount of positrons created, we neglect the contributions from electromagnetic showers; then

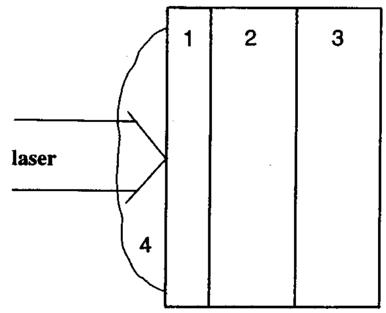

FIG. 3. Optimal target for a laser-based nuclear radiation source (not to scale). (1) a low-Z ablation layer, (2) a high-Z Bremsstrahlung converter (e.g., Ta), and (3) a neutron production layer (Be or D); (4) pre-formed plasma.

$$N_{\text{pair}} \sim n_a \int_{1.022}^{E_0} \frac{dN_\gamma}{dk} \frac{\sigma_{\text{pair}}(k)}{\mu(k)} dk \simeq n_a R l \mu_0^{-1} \overline{\sigma_{\text{pair}}}, \qquad (3)$$

$$\overline{\sigma_{\text{pair}}} \equiv \int_{1.022}^{E_0} f(k) \sigma_{\text{pair}}(k) dk,$$

where $\overline{\sigma_{\text{pair}}}$ is the pair-production cross section, σ_{pair}, averaged over the Bremsstrahlung spectrum. We have made use of the fact that the total photoabsorption coefficient μ is almost flat in the energy range of interest in high-Z materials (see e.g., Ref. 14), $\mu \approx \mu_0$. Using Ref. 15, we obtain for a Ta target that $\overline{\sigma_{\text{pair}}} \approx 0.28$ barn, which yields (with $\mu_0 \sim 2$ cm^{-1}) $\sim 5 \times 10^6$ positrons/pulse. The positron spectrum, immediately after the pair production, would have a maximum around 500 keV.

Although we have substantially underestimated the actual amount, the output is not only easily detectable but also potentially useful. Indeed, with the laser repetition rate of 10 kHz, one could expect an average intensity of the laser-based positron source to be close to ~ 1 Ci—on a par with that of an ^{22}Na source,[16] but with potentially much smaller radiation hazard.

For *neutron production* at the relatively low electron energies of interest here, a Ta/Be a Ta/D_2O target could be optimal, with laser plasma above the Ta surface. Extensive calculations relating incident electron energy and neutron yield in these targets presented in Ref. 17; for the electron energy above 5 MeV. For an order-of-magnitude estimate, we have extrapolated Fig. 3 in Ref. 17 down to the deuterium photoneutron threshold by an exponential (in fact, the neutron yield drops somewhat slower, so we again underestimate the output). Integrated over the energy spectrum of Eq. (1), that extrapolation yields $\sim 4 \times 10^4$ neutrons per pulse, with the neutron energy in the MeV range. This amount of neutrons, while hardly enough for any applications, should not present any difficulties for detecting.

We have come, therefore, to the conclusion that efficient production of γ photons and positrons needs a two-layer target (an ablation layer and a high-Z material), while neutron production for a near-TW laser would require an additional layer (Fig. 3).

Since the electron spectrum [Eq. (1)] extends beyond the energy threshold of nuclear photofission in uranium, we expect some amount of fission neutrons generated in a uranium target. Normalizing the experimental data given in Ref. 18 to the conditions of Ref. 19 (where electron energies above 10 MeV are considered), and numerically integrating them with Eq. (1), we estimate that about 4000 prompt neutrons/pulse could be obtained in a 1-cm-thick uranium target, which means about 1300 fission events/pulse.

In conclusion, we demonstrate theoretically that widely available sub-terawatt femtosecond lasers are capable of generating, through relativistic laser–plasma electrons interacting with optimal targets, a substantial amount of nuclear radiation and, therefore, can be instrumental in proof-of-principle experiments for future laser-based practical sources of that radiation.

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