

## LASER-INDUCED PARTICLE PRODUCTION AND NUCLEAR REACTIONS

P. L. SHKOLNIKOV and A. E. KAPLAN

*Department of Electrical and Computer Engineering,  
The Johns Hopkins University, Baltimore, MD 21218, USA*

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We show that electrons accelerated in plasma generated by available, or within reach, terawatt lasers can initiate positron and neutron production and a host of nuclear reactions. We propose and evaluate the environments and processes favorable for this phenomenon, which can be used to develop a practical table-top source of intense short pulses of positrons, gamma-photons, neutrons, and fission fragments.

The light intensity available with a number of table-top terawatt laser systems with sub-picosecond pulse length currently exceeds  $\sim 10^{19}$  W/cm<sup>2</sup> (see e.g. Ref. 1). In plasma generated by such intense light, the electron motion becomes relativistic. Indeed, the normalized energy of an electron in laser plasma,  $\gamma = E_{kin}/m_0c^2 + 1$ , is related to the intensity  $I$  of the laser with the wavelength  $\lambda$  as (see e.g. Ref. 2):

$$\gamma \approx 1 + (\lambda^2 I / 9 \times 10^{18})^{0.657} \quad (1)$$

where  $E_{kin}$  is the electron kinetic energy,  $\lambda$  is in  $\mu\text{m}$ ,  $I$  is in W/cm<sup>2</sup>, and the light is circularly polarized. It follows from Eq. (1) that for  $\lambda \sim 1 \mu\text{m}$  and  $I > 9 \times 10^{18}$  W/cm<sup>2</sup>, the electron kinetic energy exceeds its rest energy. Moreover, in plasma environment, electrons may be accelerated to a few MeV energy at substantially lower light intensities: in solid-density plasma — by inverse Bremsstrahlung or by strong electric fields at the solid-plasma interface,<sup>3</sup> and in underdense plasma — by large plasma waves.<sup>4</sup> In the latter case, with laser intensity of just  $6 \times 10^{18}$  W/cm<sup>2</sup>, electron energy of up to 44 MeV has been observed, and even higher energy predicted.<sup>4</sup> We show here that the energy of plasma electrons accelerated by available, or soon to be available, high-intensity lasers is sufficient for the feasibility of laser-induced particle production and nuclear reactions. To do that, we propose and evaluate the environments, targets, and processes favorable for this phenomenon that can be developed to a practical source of ultrashort-pulse, high-flux “nuclear radiation” (a shorthand for positrons, gamma-photons, neutrons,

and fission fragments), with important applications to material science, medicine, and nuclear technology; the latter may include gamma or neutron interrogation of radioactive waste, and the estimation of the effect of “full-scale” nuclear explosions on materials.

After early papers (see e.g. Refs. 2 and 5), the first to our knowledge proposal to generate nuclear radiation in laser plasma was published in 1987<sup>6a</sup> (see also Ref. 6b). Considered in Ref. 6a electrofission of uranium nuclei by plasma electrons moving in laser field promises, however, very low yield, while requiring laser intensity  $\sim 10^{21}$  W/cm<sup>2</sup>, which is still out of reach. We show here that with a different choice of reactions to initiate, the required laser intensity can be much lower, whereas the predicted output is high enough to be practically useful.

Among the nuclear reactions that can be induced by few-MeV electrons, directly or via Bremsstrahlung photons, the following processes have the lowest thresholds and are, therefore, the first candidates for generating nuclear radiation:

(i) electron-positron pair production

$$\gamma + N \rightarrow N + e^+ + e^-, \quad (2a)$$

$$e^- + N \rightarrow e^- + e^+ + e^- + N, \quad (2b)$$

(ii) deuteron electrodisintegration

$$e^- + {}^2H \rightarrow p + n + e^-; \quad (3)$$

and (iii) neutron photoproduction in beryllium or deuterium

$$\gamma + {}^9Be \rightarrow n + {}^8Be, \quad (4a)$$

$$\gamma + {}^2H \rightarrow p + n. \quad (4b)$$

The thresholds are 1.2 MeV, 1.7 MeV, and 2.2 MeV for Eqs. (2a), (2b), (4a) and (3), (4b), respectively. (Process (2b) is called the “trident process”; both (2a) and (2b) require the presence of a nucleus  $N$  for the conservation of energy and momentum). Electrons accelerated beyond 5 MeV open additional opportunities discussed below. As it is seen from the Eqs. (2a)–(4b), we limit the scope of our paper to the processes initiated by the most abundant and energetic particles (electrons and  $\gamma$ -photons) produced in laser plasma; we do not attempt to address all conceivable reactions (such as those initiated by accelerated nuclei, protons, etc.)

Cross sections for the pair production (2a) on most nuclei can be found in e.g. Ref. 7; being proportional to  $Z^2$ , where  $Z$  is the charge of the nucleus, they are of order of  $1b = 10^{-24}$  cm<sup>2</sup> at the electron energy of a few MeV for the elements in the middle of the periodic table. The cross section of the trident, Eq. (2b), is given by Ref. 2 as:

$$\sigma_{tr} \approx 9.6 \times 10^{-4} (\alpha r_e Z)^2 (\gamma - 3)^{3.6}, \quad (5)$$

where  $\alpha = 1/137$  and  $r_e$  is the classical electron radius. The quantity  $\sigma_{tr}/Z^2$  grows very fast from 0 at the threshold ( $\gamma = 3$ ) to  $0.2 \mu b$  at  $E_{kin} \sim 2.5$  MeV. Deuteron

electrodisintegration cross section steadily grows from 0 at the threshold to  $\sim 70 \mu\text{b}$  at 40 MeV.<sup>8</sup> Cross section for both photoneutron processes, Eq. (4), jumps from 0 to  $\sim 2 \text{ mb}$  just above the threshold and then slowly decreases.<sup>9</sup> We will also need the Bremsstrahlung cross section; integrated over the angles, it is approximately equal [10] to:

$$\frac{d\sigma_\gamma}{dk} \approx \left(\frac{Z^2}{k}\right) a \left(1 - b \frac{k}{E_{kin}}\right) \quad (6)$$

where  $a \approx 11 \text{ mb}$ ,  $b \approx 0.83$ ,  $k$  is the photon energy. To calculate the rate of the processes under consideration (the number of the events per unit time), we use a well-known equation (in fact, a definition of cross section, see e.g. Ref. 2)

$$dN/dt = \sigma n_1 n_2 v V \quad (7)$$

where  $n_1$  and  $n_2$  are the density of projectiles (in most cases, electrons) and of the target particles (ions or atoms), respectively;  $V$  is the interaction volume; and  $v$  is the projectile velocity,  $v \approx c$  for relativistic particles.

We consider two qualitative different techniques to initiate nuclear reactions: by plasma electrons in the intense laser field, or by electrons already accelerated during laser-plasma interaction and now propagating through a solid target.

**Reactions initiated by quivering electrons.** The main advantage of this option is the high density of the projectiles: all the electrons in the laser focal volume participate. The yield, however, is limited by the available laser intensity. For all the estimations in this section, we assume the laser intensity of  $10^{20} \text{ W/cm}^2$ , which is within the reach of the next generation of ultrashort lasers. Some of the processes of interest would also occur, at much lower rates, at already available intensities.

Nuclear reactions can be initiated by quivering electrons in both underdense and solid-density plasmas. In underdense plasma, where plasma electron density is below the critical density  $n_{cr} = \pi/(r_e \lambda^2)$ , the interaction volume  $V$  is limited by the laser confocal parameter, which is quite large (typically from  $100 \mu\text{m}$  to  $1 \text{ mm}$ ); the density, however, is relatively low, below  $10^{21} \text{ cm}^{-3}$  for most lasers. On the other hand, in plasma of near-solid density (such plasmas are created on solid surfaces by intense femtosecond lasers), the interaction volume  $V$  is limited by the skin depth, which is much shorter than  $\lambda$ .

In the absence of large plasma waves (electrons accelerated by such waves will be considered in the next section), the rate of the positron generation in the trident process, Eq. (2b), is conveniently calculated in the units of positrons per  $ns$  by using Eq. (13) from Ref. 2:

$$\frac{dN}{dt} \left(\frac{e^+}{ns}\right) \approx 0.15 \lambda^{-1} Z^2 Z_i^{-1} l^3 \left(\frac{n_e}{n_{cr}}\right)^2 (\gamma - 3)^{3.6} (\gamma^2 - 1)^{1/2} \gamma^{-1}. \quad (8)$$

Here  $Z_i = n_e/n_i$ ,  $\lambda$  is in  $\mu\text{m}$ ,  $l^3$  is the interaction volume in the units of  $\lambda$ , and  $n_i$  and  $n_e$  are the ion and electron density, respectively; laser polarization is assumed

circular. For relativistic electrons of interest, the last two terms in Eq. (8) can be dropped, since  $(\gamma^2 - 1)^{1/2}\gamma^{-1} \approx 1$ . For frequently used Nd:YAG laser ( $\lambda \approx 1 \mu\text{m}$ ) and reasonable values of  $l^3 \sim 10^5$  (for the focal spot of  $10 \mu\text{m} \times 10 \mu\text{m}$  and the laser confocal parameter of  $\sim 1 \text{mm}$ ),  $Z_i \sim 10$ ,  $Z^2 \sim 300$  (argon), in an underdense plasma with  $n_e/n_{cr} \sim 0.8$ , one obtains from Eq. (9) that about  $10^4$  positrons would be generated by a picosecond pulse. This number does not include the contribution of the two-stage process, Bremsstrahlung followed by pair production, which is negligible for underdense plasma.

In solid-density plasma, with  $n_i \sim 5 \times 10^{22} \text{cm}^{-3}$ , and  $Z_i \sim 10$ , and estimating the relativistic skin depth<sup>6</sup> as  $\sim 220 \text{\AA}$ , one obtains  $\sim 10^6$  positrons per picosecond pulse created via the trident process on the surface of a uranium target. In this case, however, the above-mentioned two-step process  $e^- \rightarrow \gamma \rightarrow e^+e^-$  completely dominates. Indeed, the Bremsstrahlung cross section for photons with the energy above the pair-production threshold  $k_0 \approx 1.2 \text{MeV}$ , as derived from Eq. (6), is:

$$\sigma_\gamma \approx aZ^2[-\ln(r) - b(1-r)], \quad r \equiv E_{kin}/k_0 \quad (9)$$

which yields  $\sigma_\gamma \approx 0.3aZ^2 \sim 28 \text{b}$  for  $E_{kin} \sim 2.5 \text{MeV}$  ( $I \sim 10^{20} \text{W/cm}^2$ ), and the number of such photons generated in the skin layer, according to Eq. (7), as  $N_\gamma \sim \sigma_\gamma n_e n_i c \tau V$ ,  $\tau$  being the pulse length. While propagating in the solid, these photons generate electron-positron pairs in the amount of

$$N_{pair} \sim N_\gamma \sigma_{pair} n_i \mu^{-1}, \quad (10)$$

where  $\mu$  is the photon absorption coefficient. For our order-of-magnitude estimates, we will treat the Bremsstrahlung photons as having the same energy, at the midpoint between  $E_{kin}$  and  $k_0$ , in this case  $\sim 2 \text{MeV}$ . We estimate the absorption coefficient using e.g. Ref. 11, Fig. 7.10 as  $\mu \sim 1.6 \text{cm}^{-1}$ . This yields  $N_{pair} \sim 6 \times 10^9$  in 20 ps, with full domination of the two-step process.

Since at  $10^{20} \text{W/cm}^2$  the energy of quivering electrons is above the threshold of the deuterium electrodisintegration, Eq. (3), one can in principle expect the generation of neutrons (and protons with keV kinetic energy) in the laser focal region. The cross section of this process, however, is very small,  $\sim 1 - 10 \mu\text{b}$  for  $E_{kin}$  of interest, which results in the negligible output of neutrons in underdense deuterium plasma. (The neutron production by deuteron-deuteron collisions is not considered here.) The neutron output might be much higher, again due to the two-step process  $e^- \rightarrow \gamma \rightarrow n$ , in solid beryllium covered by a thin high- $Z$  film. Indeed, at the first stage,  $N_\gamma \sim 2 \times 10^{10}$  photons with the energy above the photoneutron threshold of  $\sim 1.7 \text{MeV}$  would be generated in a small volume of uranium solid-state plasma on beryllium surface. Equation (10) with  $\sigma_{\gamma n} \sim 2 \text{mb}$  instead of  $\sigma_{pair}$  yields then  $N_n \sim 10^6$  neutrons in about 20 ps by Bremsstrahlung photons propagating into the solid. This represents the peak neutron flux  $\sim 6 \times 10^{16} \text{cm}^{-2}\text{sec}^{-1}$  — on a par with neutron fluxes from reactor sources (see e.g. Ref. 12).

**Accelerated electron bunches.** Laser intensity of  $\sim 10^{20}$  W/cm<sup>2</sup> assumed above is not immediately available, except for inside a relativistic plasma channel,<sup>13,6b</sup> where, however, there are relatively few electrons. Short-duration pulses of electrons accelerated beyond 1 MeV by lasers in solid-density plasma<sup>3</sup> and, to much higher energy, in underdense plasma,<sup>4</sup> have already been reported at the intensities an order of magnitude lower. Although the amount of such electrons is currently many orders of magnitude smaller than that of quivering electrons at the same laser intensity, the positron and neutron production cross sections are much higher for higher electron energy. An important additional advantage of these electrons over the quivering electrons is that the former retain their relativistic energy long after the laser pulse disappears, so that the amount of nuclei available for interaction is limited only by the penetration depths of the electrons and produced by them Bremsstrahlung photons. Also, the only, to our knowledge, published estimates of the amount of suprathreshold electrons above 2 MeV (the energy necessary for substantial rate of nuclear radiation) generated in a solid-density laser plasma<sup>14</sup> dealt with plasma and laser parameters drastically different from those we are interested in. We will, therefore, limit ourselves to discussing the feasibility of nuclear reactions of relativistic electrons accelerated in underdense plasma by wave-breaking.<sup>4</sup>

In the experiments, Ref. 4b,  $\sim 1.5 \times 10^8$  electrons are emitted at the energy between 8 and 44 MeV in  $\sim 10^{-4}$  sr angle, as can be inferred from Ref. 4b, Fig. 2. The energy spectrum of the electrons is almost flat between 8 and 30 MeV, and then drops towards 40 MeV. One could estimate the number of positrons generated by these electrons via the two-step process in a uranium target as  $\sim 10^8$  per pulse — an order of magnitude below the estimate obtained above for quivering electrons, but still substantial. For neutron production, the advantage of higher electron energy is even more clear: much smaller amount of electrons produces a very substantial — and already attainable — neutron yield. Using a photoneutron target optimized for neutron interrogation of nuclear waste<sup>15</sup> (Ta Bremsstrahlung converter, Al electron stopper, and heavy water photoneutron converter), one can expect  $\sim 10^5$  neutrons generated in  $\sim 1$  ns, the estimate based on Fig. 3 in Ref. 16. Even larger amount of neutrons can be generated in a high- $Z$  solid target,<sup>16</sup> in particular in natural uranium. Indeed, e.g. Ref. 17 indicates the neutron yield of  $\approx 6 \times 10^{-3}$  neutrons/electron in  $\sim 1$  cm thick uranium target for  $E_{kin} \sim 20$  MeV, i.e.  $\sim 10^6$  total neutron yield in 30 ps (the time necessary for the electrons to cross the target), or the peak intensity of  $3 \times 10^{16}$  n/sec. These neutrons, as well as Bremsstrahlung photons, could be used for, e.g., real-time radiography and computer tomography of nuclear waste; laser-produced plasma would replace an electron accelerator in the design of such applications described in Ref. 15.

The most exciting new opportunity presented by plasma-accelerated electrons might be their ability to induce nuclear fission in actinides, the typical threshold being  $\sim 5$  MeV. Using again a uranium target  $\sim 1$  cm thick, taking into account the

$\sim 1/3$  ratio of the photofission to total neutron photoproduction in uranium,<sup>18</sup> and assuming that each fission creates two-three prompt neutrons, we expect the number of fission events initiated by fast electrons to be an order of magnitude smaller than the total number of generated neutrons. Therefore, the electron pulse observed in Ref. 4b will induce  $\sim 10^5$  fission events within  $\sim 30$  ps. Each such event generates  $\sim 185$  MeV  $\approx 0.03$  nJ energy practically instantaneously; therefore, we expect the fission energy output of about  $3 \mu\text{J}$  per laser pulse, or 0.1 MW of thermal power generated in the target. If the bunch of accelerated electrons is tightly focused, e.g. to  $1 \mu\text{m}$  spot size, this power would be deposited into a very small volume of  $\sim 10^{-8} \text{ cm}^3$ . Then, the flux of nuclear radiation through the walls of the interaction “tunnel” would be  $\sim 10^{24} \text{ cm}^{-2}\text{sec}^{-1}$ , very high compared to, e.g., typical reactor neutron fluxes (see, e.g., Ref. 12). One could in principle hope to use this burst of nuclear radiation to imitate, to some extent, the radiation of nuclear explosion, and to apply it to, e.g., simulation of the effect of the real nuclear explosion on various materials. Moreover, there are reasons to believe that the yield of MeV electrons reported in Ref. 4b is an order of magnitude smaller than the actual yield, and that the full electron energy spectrum stretches up to 70 MeV; if this is true, the nuclear radiation flux of  $\sim 10^{25} \text{ cm}^{-2}\text{sec}^{-1}$  is already attainable.

Further conceivable improvement in the efficiency of the electron acceleration by Raman scattering and, therefore, the increase in the intensity of the generated nuclear radiation, may appear possible in plasma waveguides developed at University of Maryland,<sup>19</sup> due to large increase in the laser propagation length in such waveguides. It is worth noting also that the conditions inside a relativistic plasma channel<sup>13</sup> (virtually bare nuclei in super-intense light) could facilitate yet another kind of nuclear reactions, laser-induced change of the isomeric content in a target with low-lying isomeric levels. For instance, the resonant excitation of the nuclear isomer<sup>229m</sup>Th by resonant  $\sim 4$  eV photons could occur at much higher rate than that estimated in Ref. 20.

In conclusion, we have theoretically shown that current or soon to be available laser-driven sources of relativistic electrons have strong potential for generating short-pulse intense nuclear radiation, including positrons, neutrons, gamma-photons, and fission fragments. We propose and evaluate the environments, targets, and processes favorable for this phenomenon which may become a practical source with important applications to material science, medicine, and nuclear technology; the latter may include gamma or neutron interrogation of radioactive waste, and the estimation of the effect of “full-scale” nuclear explosions on materials. In the future, we are going to address some alternative sources of nuclear radiation driven by strong electromagnetic pulses, in particular by ultrashort unipolar solitons.<sup>21</sup>

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