Bursts of photonuclear reactions in the application of intense ultrashort light pulses to matter

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Bursts of electron-photonuclear reactions during the application of intense ultrashort light pulses to matter are studied.

A new field of optics—the optics of subpicosecond and femtosecond pulses of ultrahigh power density, beyond 10^{18} W/cm^2 (power densities up to 10^{21} W/cm^2 and even higher are being discussed) (Refs. 1–4, for example)—has recently begun a rapid development in several major scientific centers in the US (the Universities of Rochester and Illinois), West Germany (the Max-Planck Institute), the USSR (Moscow State University and the Lebedev Physics Institute), etc.

It has been mentioned[1] that the electrons of outer atomic shells can be immediately stripped off the atomic cores in such strong fields, since the optical field strength satisfies $E > E_{\rm B} \approx e/a_{\rm B}^2 \approx 10^7$ absolute units (10^{17} W/cm^2), while the atomic cores (especially the inner-shell electrons) remain only slightly perturbed, since the fields of the internal shells are $E_{\rm in} \approx Ze/a_{\rm in}^2 \approx Z^3 E_{\rm B}$. Since the orbital radius is $a \approx a_{\rm B}/Z$, the relation $E_{\rm in} \gg E_{\rm B}$ holds (at an atomic number $Z > 50$, we find $E_{\rm in} > 10^5 E_{\rm B}$) (the subscript B means the first Bohr radius of hydrogen).

At $E \approx m\omega c/e \approx mc^2/e\lambda \approx 2 \times 10^8$ absolute units (10^{19} W/cm^2), however, at a wavelength $\lambda \simeq 10^{-5}$ cm, the velocities of the ejected electrons become relativistic. Boyer and Rhodes[1] have pointed out that such electrons can excite the inner shells of atoms, and they can do this with a probability far higher than in a multiphoton process involving the optical field itself. Calculations were carried out in Ref. 4 on the excitation of inner atomic shells by such electrons.

We wish to call attention to the possibility of observing bursts of photoelectron-nuclear reactions as a result of the appearance of such electrons during the application of light pulses.

The thresholds for photonuclear and electron-photonuclear reactions lie at photon and electron energies on the order of a few MeV. Their efficiency increases sharply as the energy is raised to several tens of MeV.

To evaluate the burst of a reaction stemming from the appearance of such electrons in a medium, we can make direct use of the resultant yield of reactions during the application of an electron beam to a target. We also find the results generated by the photons created by these electrons. In many cases, photonuclear reactions have cross sections far larger than electron-nuclear reactions (e.g., $\sigma_{\gamma f} \approx 10^2\ \sigma_{ef}$, but the difference may decrease when the multiplicity of electron collisions is taken into account). For example, the resultant yield of neutrons from $(\gamma n)(\gamma f)(en)(ef)$ reactions is known[5] for the direct application of an electron beam to matter. The yield

N_n/N_e (expressed in MeV) increases nearly linearly with the electron energy ϵ_e, from $N_n/N_e \approx 2\times 10^{-3}$ at $\epsilon_e \approx 10$ MeV to $N_n/N_e \approx 10^{-2}$ at an energy $\epsilon_e \approx 40$ MeV.

Electrons acquire such energies as they go abruptly into a regime of free oscillations. Their energy $\epsilon_e \approx e\lambda E$ requires fields $E \approx 2\times 10^9$–10^{10} absolute units (i.e., at power densities $I \approx (E^2/4\pi)c \approx 10^{21}$–$3\times 10^{22}$ W/cm^2).

If the energy at the laser pulse, Q, is given, the number of these electrons which are formed will be $N_e \approx Q/\epsilon_e \approx 10^{13}$ at $\epsilon_e \approx 10$ MeV and $Q \approx 10$ J. We would thus have a yield of 3×10^{10} neutrons in a time $\tau > 10^{-12}$ s. Even under these conditions, internal energy evolution may become a significant fraction of the incident energy. Such agents can be used to introduce short bursts of neutrons, γ radiation, and relativistic electrons. High electron densities will make it possible to carry out experiments with neutrons, with the conversion of nuclei, and the production of isotopes. Such agents should be accompanied by the appearance of strong Coulomb fields, $E \sim \epsilon_e/ea_f \approx 30$ GV/cm with $\epsilon_e \approx 30$ MeV, a focus of radius $a_f \approx 10$ μm, and a burst of acceleration of ions by the high electron pressure to velocities $u_i \approx \sqrt{\epsilon_e/M_i} \approx 3\times 10^9$ cm/s to 3×10^8 cm/s at $M_i \approx (2\text{–}300)M_p$.

The use of tubular beams or hollow objects would make it possible to achieve a "cumulative" concentration of such ion streams and to achieve an energy release of high concentration through processes which occur at high densities and high temperatures.

The estimates presented here are given for intense bursts of nuclear reactions at power densities $I \approx 10^{21}$–10^{22} W/cm^2. The observable beginning of such processes should occur at vastly lower power densities, $I \approx 10^{19}$–10^{20} W/cm^2. The reasons are that the relativistic electron energy depends only weakly on the flux density, $\epsilon_e \sim \sqrt{I}$; there is a conversion of electrons into γ rays; and the threshold energy for photonuclear processes is low (a few MeV).

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[2]C. H. Rhodes, Science **229**, 1345 (1985).
[3]S. V. Krayushkin, Author's Abstract, Dissertation, Physics Faculty, Moscow State University, 1987 (see the summary table on lasers of this type).
[4]I. L. Beĭgman and B. N. Chirkov, Pis'ma Zh. Eksp. Teor. Fiz. **46**, 314 (1987) [JETP Lett. **46**, 395 (1987)].
[5]K. H. Beckurts and K. Wirtz, Neutron Physics, Springer, New York, 1964.

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