Possibility of Optically Induced Nuclear Fission

K. Boyer, T. S. Luk, and C. K. Rhodes

Laboratory for Atomic, Molecular, and Radiation Physics, Department of Physics,
University of Illinois at Chicago, Chicago, Illinois 60680

(Received 15 June 1987)

The process of nuclear fission induced by nonlinear radiative coupling to atomic electrons is considered. For 248-nm radiation at an intensity of $\simeq 10^{21}$ W/cm^2, highly relativistic currents are produced which can couple to the fission mode of nuclear decay. With irradiation for a time of $\simeq 100$ fs, the results indicate a fission probability of $\simeq 10^{-5}$ for ${}^{238}_{92}$U nuclei located at the surface of a solid target, a value several orders of magnitude above the limit of detection.

PACS numbers: 25.85.Ge, 32.80.Wr

Nuclear fission can be induced by electromagnetic interactions involving either photons or charged particles if sufficient energy is communicated to the nucleus enabling the system to penetrate the fission barrier. Known examples of electromagnetically induced fission are photofission,[1,2]

$$\gamma + A \xrightarrow[\sigma_{\gamma f}]{} f_1 + f_2 + \bar{\nu} n, \tag{1}$$

electrofission,[3]

$$e^- + A \xrightarrow[\sigma_{ef}]{} f_1 + f_2 + \bar{\nu} n + e^-, \tag{2}$$

and muon-induced fission.[4,5] It has also recently been proposed[6,7] that driven motions of atomic electrons arising from intense irradiation of atoms can couple energy to nuclear transitions occurring between bound nuclear states. This latter mechanism has some features in common with processes of nuclear excitation and deexcitation in which atomic electronic transitions play a role.[8-13]

The present work examines the possibility of optically induced nuclear fission of heavy elements arising from coupling to driven motions of atomic electrons produced by intense external radiation. The fission process is a particularly favorable one for the demonstration of nuclear excitation. It (1) generally has a large nuclear matrix element, (2) is a broad channel permitting coupling to spectral power over a wide range, and (3) involves a very large energy release comprising distinctive emissions. It will be shown that very large instantaneous fission rates may be generated in a considerable range of nuclear materials. If this can be achieved, extremely bright and *spatially localized* high-flux pulsed sources of fission fragments, neutrons, and γ radiation could be produced (e.g., $\gtrsim 10^{24}$ fission fragments/cm^2 s).

The acceleration of electrons to an energy sufficient to surpass the threshold of the fission reaction can be achieved in the focal region of an intense laser pulse.[14,15] The availability of an ultraviolet laser technology[16,17] capable of producing subpicosecond pulses with energies approaching the joule level in low-divergence beams at high repetition rates is making possible a regime of physical study concerning the behavior of matter at extremely high intensities[18,19] in the 10^{20}-10^{21}-W/cm^2 range. Since it can be shown[14,15] that intensities comparable to 5×10^{19} W/cm^2 at 248 nm will cause strongly relativistic motions to occur, the use of an intensity of $\simeq 10^{21}$ W/cm^2 would then generate relativistic electrons[14,15] with an energy sufficient ($\gamma \simeq 24$) to produce electrofission by the collisional mechanism represented by reaction (2). We also note that the bremsstrahlung produced collaterally by the fast electrons in the target material can also participate in the production of fissioning material through the photofission reaction (1). The influence of both of these processes is considered below for the case of a solid target composed of ${}^{238}_{92}$U.

Extant data[20-24] on photofission and electrofission of ${}^{238}_{92}$U enable a simple estimate to be made of the probability of fission caused by irradiation of material with 248-nm radiation at an intensity of $\simeq 10^{21}$ W/cm^2. The approach used parallels the classical procedure used in an earlier estimate[25] of the rate of excitation of atomic inner-shell electrons. We consider a plane solid uranium target with the ultraviolet radiation incident normal to surface. For this estimate, a pulse width with a duration $\tau \simeq 100$ fs and a focal area, positioned at the surface, of $\simeq 1$ μm in diameter are assumed. With the density of solid uranium as $\simeq 19$ g/cm^3, if all of the bound electrons were free and uniformly distributed, the average electron density in the material would be $\rho_e \simeq 4.4\times 10^{24}$ cm^{-3}. Since the projected driven motions of these electrons are highly relativistic at an intensity of $\simeq 10^{21}$ W/cm^2, the magnitude of the electronic velocity will be approximated by the speed of light c. Thus, the maximum driven particle current is given by

$$j \simeq c\rho_e \simeq 1.3\times 10^{35}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}. \tag{3}$$

The threshold for the electron energy for electrofission in ${}^{238}_{92}$U is approximately 10 MeV. Since the electrofission cross section[21,16] σ_{ef} is in the range of $\simeq 1$ mb for ^{238}U, the transition rate is $\sim j\sigma_{ef} \simeq 1.3\times 10^8$ s^{-1} which, for a pulse length τ of $\simeq 10^{-13}$ s, gives a total transition probability for electrofission of

$$P_{ef} \sim j\sigma_{ef}\tau \simeq 10^{-5}. \tag{4}$$

From the known systematics of nuclear-fission barrier heights,[2,26,27] some heavier materials like $^{252}_{98}\mathrm{Cf}$, and particularly certain isomers,[28] are expected to have threshold electron energies somewhat less than that characteristic of $^{238}_{92}\mathrm{U}$. However, since the photofission and electrofission processes generally go mainly through the $E1$ giant dipole resonance, a consideration of the sum rule for these transitions[29,30] suggests that the cross sections for the electrofission process for other heavy materials will not vary more than a factor of 10 from the value corresponding to uranium.

The volume of material involved in this interaction depends upon the depth of penetration of the ultraviolet field into the plasma. Since the critical electron density n_c is 1.6×10^{22} cm^{-3} at 248 nm, a value more than 200-fold less than the density estimated for the plasma under consideration, the uranium plasma is highly overdense. However, since the driven motion of the electrons is strongly relativistic, the penetration length of the external field has significant relativistic corrections which extend the propagation into the normally forbidden overdense region.[31] The dielectric constant ϵ for this case can be written as

$$\epsilon = 1 - \frac{\omega_p^2}{\omega^2}\left[1+\frac{e^2E_0^2}{m^2c^2\omega^2}\right]^{-1/2}. \tag{5}$$

In Eq. (5) ω_p is the customary plasma frequency, E_0 the peak value of the radiative electric field, ω the frequency of the wave, e the electronic charge, and m the mass of the electron. For an intensity of $\simeq 10^{21}$ W/cm^2, ω_p corresponding to a plasma density $\rho_e \simeq 4.4\times10^{24}$ cm^{-3}, and ω for 248 nm, the resulting skin depth[32] δ for damping of the propagation is $\delta \simeq 20$ nm. For these conditions, we have ignored collisions and estimate that the electrons have a total energy[14,15,33] γmc^2 corresponding approximately to $\gamma \simeq 24$ and, therefore, experience a change in the relativistic factor $\Delta\gamma \simeq 23$ due to the acceleration by the ultraviolet field. This magnitude of $\Delta\gamma$ is consistent with the maximum value that can be achieved by laser acceleration at a given power, regardless of the focusing conditions or the wavelength of irradiation.[15] For our case, in which the total power is $\simeq 10^{13}$ W, the maximum magnitude[15] of $\Delta\gamma$ is $\Delta\gamma_{\max} = 164$.

From the discussion given above, it is possible to estimate the energy of the fission yield that would be generated by irradiation of a solid uranium ($^{238}_{92}\mathrm{U}$) surface with a single pulse. The fission yield Y_{ef} corresponding to the electrofission channel can be written as

$$Y_{ef} = \rho_0 A \delta P_{ef} \Delta E_f \tag{6}$$

in which ρ_0 is the uranium atom density, A the focal spot area, δ the skin depth, P_{ef} the electrofission probability, and ΔE_f the average fission energy. With $\Delta E_f \simeq 165$ MeV and the other parameters as discussed above, $Y_{ef} \simeq 0.2$ μJ, or equivalently, approximately 8400 fission events. A similar outcome would be expected from a $^{232}_{90}\mathrm{Th}$ target.[34]

Since a highly relativistic current of electrons is produced in a dense plasma having ions of a high charge Z by the interaction of the oscillating electrons with the solid target, it is expected that a substantial quantity of energetic bremsstrahlung will be generated, some of which will be in the energy range ($\simeq 10$ MeV) corresponding to the photofission[20,21] process (1). Furthermore, since $\sigma_{\gamma f} \sim 10^2\sigma_{ef}$, the contribution of the photofission channel may not necessarily be negligible. In order to evaluate this contribution, we will assume that the plasma conditions are such that a fraction of $\simeq 10^{-3}$ of the incident radiative energy is channeled into energetic bremsstrahlung.[35,36] For an incident energy of $\simeq 1$ J, this bremsstrahlung would then account for $\simeq 1$ mJ, an estimate that is based on the measured scaling of hard x-ray production in studies of fusion plasmas.[35] If it is further assumed that all of this bremsstrahlung can participate in the photofission reaction, then $\simeq 10^9$ quanta are available. Given the photofission cross section of $\simeq 10^{-25}$ cm^2, this leads to the production of $\simeq 50$ fissions in the active volume, a value considerably less than that estimated for the electrofission mechanism. However, since the range[37] of the bremsstrahlung is $\simeq 1$ cm in solid uranium, an additional $\simeq 10^6$ fissions would be produced in a much larger region in the material surrounding the focal volume. Of those, only that fraction within the fission-fragment range[38] of $\simeq 5$ μm of the surface would produce escaping fission ions. This would be $\simeq 10^3$ particles. A major fraction of the neutrons produced ($\simeq 10^6$), however, would escape from a sample[39] with dimensions comparable to 1 cm. These estimates indicate that the detectable fission-fragment yield may contain a significant contribution from photofission. The total neutron production, however, is probably dominated by the photofission reaction. In terms of the fission yield originating in the focal volume, it seems likely that that would be governed mainly by the electrofission mechanism. Experimentally, a yield of the magnitude estimated, even if reduced by a factor of $\simeq 10^3$, could be readily detected.

A substantial quantity of fast uranium ions should be produced by electrostatic acceleration at the surface of the sample. This arises from the tendency of the relativistic electrons to be expelled from the region of high intensity, since the electron trajectories are curved by the magnetic $\mathbf{v}\times\mathbf{B}$ force so that their velocities are nearly parallel with the propagation vector $\mathbf{k}$ of the incident wave.[14,15] In rough approximation, it appears, for irradiation at $\simeq 10^{21}$ W/cm^2 at 248 nm, that this feature could lead to nearly full expulsion of the electrons from the first skin depth of the focal region, and possibly somewhat beyond, into a region further below the surface of the solid by the radiation pressure. It we assume complete ionization of the uranium atoms in this surface region, a high and nearly uniform planar charge density is created over a spatial extent of approximately 1 μm^2. Furthermore, since the heavy uranium ions are inertially confined to positions near their original sites on the surface for a time on the order of $\simeq 100$ fs, a positively charged ion near this surface will experience a strong electric repulsive force. For sufficiently short times and small distances from the surface, this field E_z is of constant magnitude and directed normally outward from the surface with a value given approximately by

$$E_z \simeq \tfrac{1}{2}\rho_z \tag{7}$$

in which ρ_z is the surface charge density. For fully ionized uranium ($Z=92$) having a lattice constant $r_0 \simeq 0.33$ nm, the field E_z is evaluated as

$$E_z = Ze/2r_0^2 \simeq 5.9\times 10^9 \text{ V/cm}. \tag{8}$$

If we further assume that this constant field extends for a distance normal to the surface of $\simeq 100$ nm, a length roughly one-tenth of the focal spot size, then an ion of charge Z passing through that field will acquire a kinetic energy ϵ_k of approximately

$$\epsilon_k = ZeE_z l. \tag{9}$$

For $Z=92$, ϵ_k is 5.4 MeV with a corresponding kinetic velocity of

$$v_k \simeq (Ze/r_0)(l/M)^{1/2} \tag{10}$$

in which M denotes the mass of a uranium ion. From Eq. (10) we see that a time-of-flight measurement of the ion current would carry direct information on the distribution of charge states formed by the interaction at the surface of the target, a physical parameter directly related to the electrofission rate. An impurity of hydrogen atoms on the surface of the target would make possible a calibration of the scale length l through a measurement of the proton component of the time-of-flight signal.

Earlier work on laser-fusion targets appears to confirm the generation of energetic ions by a surface mechanism of this type. Fast deuterium ions produced from solid CD_2 targets with picosecond irradiation at 1.06 μm have been observed[40] in approximate agreement with Eqs. (9) and (10). For a reasonable choice of parameters ($Z=1$, $l=1$ μm, and $r_0 \simeq 2a_0$), Eq. (9) gives $\epsilon_k = 64$ keV, while the measured value[40] was $\simeq 65$ keV.

Nuclear fission of heavy elements is predicted to be induced by the irradiation of solid targets with ultraviolet energy at an intensity of $\simeq 10^{21}$ W/cm^2. The fission events should be readily observable through the detection of fast fission fragments, fission neutrons, and γ radiation from excited fission product. For a pulse of $\simeq 100$-fs duration, a fission probability of $\simeq 10^{-5}$ is estimated for solid ${}^{238}_{92}\text{U}$. We note that recent calculations[41] of a related process involving transitions between bound nuclear states also gives transition probabilities in this general range. Fast highly charged ions of the parent material should also be produced in considerable numbers at the surface. Finally, the ease of detecting single fission events endows this technique with sensitivity to test the character of the atomic response to intense coherent fields, a question of fundamental significance.

This work was supported by the U.S. Office of Naval Research, the U.S. Air Force Office of Scientific Research under Contract No. F49620-85-K-0020, the Innovative Science and Technology Office of the Strategic Defense Initiative Organization, the Lawrence Livermore National Laboratory, under Contract No. 5765705, the National Science Foundation under Grant No. PHY-84-14201, and the Los Alamos National Laboratory under Contract No. 9-X54-C6090-1. Discussions with J. C. Solem are warmly acknowledged. One of us (C.K.R.) also wishes to acknowledge fruitful conversations with J. C. Solem and M. S. Weiss on the fission process.

---

[1] R. O. Haxby, W. E. Shoupp, W. E. Stephens, and W. H. Wells, Phys. Rev. **59**, 57 (1941).

[2] Robert Vandenbosch and John R. Huizenga, *Nuclear Fission* (Academic, New York, 1973), p. 112.

[3] J. D. T. Arruda-Neto and B. L. Berman, Nucl. Phys. **A349**, 483 (1980).

[4] S. Polikanov, in *Dynamics of Nuclear Fission and Related Collective Phenomena,* edited by P. David, T. Mayer-Kuckuk, and A. van der Woude, Lecture Notes in Physics Vol. 158 (Springer-Verlag, Berlin, 1982), p. 67.

[5] E. Teller and M. S. Weiss, Lawrence Livermore National Laboratory Report No. UCRL-83616, 1979 (unpublished); E. Teller and M. S. Weiss, in *A Festschrift for Maurice Goldhaber,* edited by G. Feinberg, A. W. Sunyar, and J. Weneser (New York Academy of Sciences, New York, 1980), p. 222.

[6] L. C. Biedenharn, G. C. Baldwin, K. Boyer, and J. C. Solem, in *Advances in Laser Science–I—1985,* edited by W. C. Stwalley and M. Lapp, AIP Conference Proceedings No. 146 (American Institute of Physics, New York, 1986), p. 52.

[7] G. A. Rinker, J. C. Solem, and L. C. Biedenharn, Los Alamos National Laboratory Report No. LA-UR-86-4187, 1986 (to be published).

[8] M. S. Freedman, Annu. Rev. Nucl. Sci. **24**, 209 (1974).

[9] R. J. Walen and C. Briancon, in *Atomic Inner-Shell Processes,* edited by B. Crasemann (Academic, New York, 1975), Vol. 1, p. 233.

[10] D. Kekez, K. Pisk, and A. Ljubicic, Phys. Rev. C **34**, 1446 (1986).

[11] K. Otozai, R. Arakawa, and M. Morita, Prog. Theor. Phys. **50**, 1771 (1973).

[12] T. Izawa and C. Yamanaka, Phys. Lett. **88B**, 59 (1979).

[13] V. I. Gol'danskii and V. A. Namoit, Yad. Fiz. **33**, 319

(1981) [Sov. J. Nucl. Phys. **33**, 169 (1981)].

[14] E. S. Sarachik and G. T. Schappert, Phys. Rev. D **1**, 2738 (1970).

[15] M. J. Feldman and R. Y. Chiao, Phys. Rev. A **4**, 352 (1971).

[16] J. H. Glownia, G. Arjavalingham, P. P. Sorokin, and J. E. Rothenberg, Opt. Lett. **11**, 79 (1986).

[17] A. P. Schwarzenbach, T. S. Luk, I. A. McIntyre, U. Johann, A. McPherson, K. Boyer, and C. K. Rhodes, Opt. Lett. **11**, 499 (1986).

[18] C. K. Rhodes, Science **229**, 1345 (1985).

[19] C. K. Rhodes, in *Giant Resonances in Atoms, Molecules, and Solids,* edited by J.-P. Connerade, J. M. Esteva, and R. C. Karnatak (Plenum, New York, 1987), p. 533.

[20] J. T. Caldwell, E. J. Dowdy, B. L. Berman, R. A. Alvarez, and P. Meyer, Phys. Rev. C **21**, 1215 (1980).

[21] F. Zamani-Noor and D. S. Onley, Phys. Rev. C **33**, 1354 (1986).

[22] D. H. Dowell, L. S. Cardman, P. Azel, G. Bolme, and S. E. Williamson, Phys. Rev. Lett. **49**, 113 (1982).

[23] H. Stroher, R. D. Fisher, J. Drexler, K. Huber, U. Kniessel, R. Ratzek, H. Ries, W. Wilke, and H. J. Maier, Nucl. Phys. **A378**, 237 (1982).

[24] K. A. Griffioen, P. J. Countyman, K. J. Knöpfle, K. Van Bibber, M. R. Yearian, J. G. Woodworth, D. Rowley, and J. R. Calarco, Phys. Rev. C **34**, 1375 (1986).

[25] C. K. Rhodes, in *Multiphoton Processes,* edited by P. Lambropoulos and S. J. Smith (Springer-Verlag, Berlin, 1984), p. 31.

[26] J. Aschanbach, R. Haeg, and H. Krieger, Z. Phys. A **292**, 285 (1971).

[27] J. R. Nix, Annu. Rev. Nucl. Sci. **22**, 65 (1972).

[28] R. Vandenbosch, Annu. Rev. Nucl. Sci. **27**, 1 (1977).

[29] F. E. Bertrand, Annu. Rev. Nucl. Sci. **26**, 457 (1976).

[30] *Giant Multiple Resonances,* edited by F. E. Bertrand (Advanced Academic, New York, 1980).

[31] P. Kaw and J. Dawson, Phys. Fluids **13**, 472 (1970).

[32] J. D. Jackson, *Classical Electrodynamics* (Wiley, New York, 1975), 2nd ed.

[33] L. S. Brown and T. W. B. Kibble, Phys. Rev. **133**, A705 (1964).

[34] H. X. Zhang, T. R. Yeh, and Lancman, Phys. Rev. C **34**, 1397 (1986).

[35] D. R. Bach, D. E. Casperson, D. W. Forslund, S. J. Gitomer, P. D. Goldstone, A. Hauer, J. F. Kephart, J. M. Kindel, R. Kristal, G. H. Kyrda, K. B. Michell, D. B. Hulsteyn, and A. A. Williams, Phys. Rev. Lett. **50**, 2082 (1983); A. Hauer *et al.*, in *Laser Interaction and Related Plasma Phenomena,* edited by H. Hora and G. Miley (Plenum, New York, 1984), Vol. 6, p. 479.

[36] R. A. Grandey, in *Strongly Coupled Plasmas,* edited by G. Kalman and P. Carini (Plenum, New York, 1978), p. 427.

[37] E. L. Chapp, *Gamma Ray Astronomy* (Reidel, Dordrecht, 1976).

[38] U. Littmark and J. F. Ziegler, *Handbook of Range Distributions for Energetic Ions in All Elements* (Pergamon, New York, 1980), Vol. 6, p. 482.

[39] J. R. Stehn, M. D. Golberg, R. Wiener-Chasman, S. F. Mughabghab, B. A. Magurno, and V. A. May, *Neutron Cross Sections,* BNL-325 (Associated Universities, Upton, New York, 1965), Vol. 3, Suppl. No. 2.

[40] G. H. McCall, F. Young, A. W. Ehler, J. F. Kephart, and R. P. Godwin, Phys. Rev. Lett. **30**, 1116 (1973).

[41] J. F. Berger, D. Gogny, and M. S. Weiss, Lawrence Livermore National Laboratory Report No. UCRL-96759, 1987 (to be published).