both samples and from down-hole logging, the higher permeability is unlikely to be related to its bulk properties, but probably reflects fracture permeability at least in a few zones. The temperature gradient in the hole is very low or even negative, which could reflect the vertical oceanic temperature structure on this steep-sided platform or slow seawater advection even in the low-porosity rocks.

Leg 118 has demonstrated the feasibility of drilling plutonic rocks with existing technology. There are many other favourable sites in fracture zones where sections of lower crust and upper mantle can be sampled. □

## Nuclear physics

# Laser-induced fission

*J.E. Lynn*

In the 50 years since the discovery of fission (Hahn, O. & Strassmann, F. *Naturwissenschaften* **27**, 11; 1939), powerful technologies based on the process have been developed, accompanied by detailed studies of the phenomenon. Many 'probes' for inducing nuclear fission have been found, the first being the neutron. Indeed, neutron-induced fission remains the basis of most uses of nuclear splitting. But other nuclear particles (protons, deuterons, $\alpha$-particles and heavier nuclei) and non-nuclear beams such as $\gamma$-rays, electrons and muons are also effective. Now, according to Boyer, Luk and Rhodes (*Phys. Rev. Lett.* **60**, 557–560; 1988), the possibility of inducing nuclear fission by ultraviolet light from an intense laser source should be added to this list. This would provide both a valuable tool for diagnosing the effects of intense fields on atomic electrons, and a bright point source of pulsed fission products and neutrons.

In principle, the possibility of inducing fission by light is not remarkable. The fission of nuclei heavier than iron is an exothermic reaction. Indeed, spontaneous fission is possible and is observed as a rare event for a few of the heaviest natural nuclei as well as for many artificial transuranic nuclei. But before splitting, a nucleus must first elongate from its equilibrium shape, an energy-expensive process creating a barrier against fission which even for uranium nuclei is 5–6 million electron-volts (MeV) high. Bombarding nuclear particles such as neutrons can provide most of this energy in the form of binding energy as they merge with the target nuclei, thereby creating excited compound nuclei with enough energy to overcome the fission barrier.

Non-nuclear beams provide the required energy directly to the target nucleus. Because such beams are of comparatively low intensity, the excitation process is by absorption of a single quantum of energy and, for electro-magnetic beams, this gives a requirement for radiation of very short wavelength. Suitable $\gamma$-ray beams are usually obtained by irradiating heavy-metal targets with electrons of several million electron-volts, but only a small fraction of the resulting *bremsstrahlung* quanta (photons) are of sufficiently high energy to induce fission at appreciable rates. Electron-induced fission results from inelastic scattering of the electron by the Coulomb field of the nucleus, which excites the nucleus to the required energy. The required electron energies for this form of fission are ~ 10 MeV or more.

Muon-induced fission is a mechanism of particular interest. What chiefly distinguishes the muon from the electron is its mass (it is about 200 times heavier than the electron) as well as its short life (2 ms). With nuclei it forms muonic atoms, the muon replacing an orbiting electron. Because of the large mass of the muon, the muonic orbits are very tightly bound and transitions between the orbits have correspondingly higher energy than electronic orbital transitions. The innermost muonic orbitals of very heavy atoms penetrate the nucleus, and there is very strong electromagnetic coupling between the nuclear and muon motion. Hence there is a high probability of a radiationless transition between the lowest muonic orbits sufficiently energetic to excite the nucleus to above its fission barrier.

The fission barrier of the muonic atom is greater than that of the bare nucleus by about 1 MeV owing to the change in muon binding energy following the increasing elongation of the nucleus that accompanies fission. The intra-orbital cascade following the absorption of a slowed muon into a muonic atom and the resulting fission occur very quickly. There is also a delayed fission process following the weak interaction of the muon with the nucleus, which transforms a proton into a neutron with the release of a large amount of excitation energy.

The process of optically induced fission, newly suggested by Boyer *et al.*, does not involve any similar form of direct electromagnetic coupling to the nucleus. The postulated mechanism is an indirect one in which the intense focused ultraviolet light acclerates the atomic electrons in the target material to highly relativistic energies and electron-induced fission of the nucleus follows. The laser light thus acts as a miniature electron accelerator. It has been calculated (Feldman, M.J. & Chino, R.Y. *Phys. Rev.* **A4**, 352; 1971) that a light intensity of $10^{12}$ W concentrated in a diffraction-limited focus would give an electric-field component of ~ $3\times10^{11}$ V $cm^{-1}$ and this would raise an electron to relativistic energies in a single pass. At such energies the magnetic component of the optical field would bend the electron to move forward to travel with the wave.

Boyer *et al.* believe that the electrofission resulting from a laser pulse of 1 J, $10^{-13}$ s duration focused in a spot of 1 μm diameter on the surface of a solid uranium target will give a fission probability of $10^{-5}$ per nucleus. The penetration of ultraviolet light into the metal is relaxed by relativistic corrections but still limited to ~ 0.02 μm. Thus about 8,000 fission events (equivalent to an energy yield of ~ 0.2 μJ) would occur in this spot.

As well as causing electrofission, the laser-accelerated electrons would produce *bremsstrahlung* electromagnetic radiation of sufficient energy to cause photofission. High-energy $\gamma$-rays penetrate about 1 cm into uranium, much further than light, and this would induce $10^6$ fissions following photoabsorption, but only about ~ 1,000 of the fission products would escape from the front surface of the target. The fission-product yield is dominated by the electrofission and the tiny volume in which it operates. The neutrons released by fission, on the other hand, are highly penetrating, thus the neutron yield is dominated by photofission, and the effective neutron source is spread over a large volume.

Although the report by Boyer *et al.* appears in the nuclear-physics section of *Physical Review Letters*, it seems unlikely that the main result of this phenomenon, if it is experimentally observed, will be to increase our understanding of the mechanism of fission, as the energy transferred by the scattered electron will be essentially unmeasurable. This is a pity because the spectroscopy of the mass and kinetic energy of the fission products should be highly measurable, given the small source size and short duration of the pulse, if suitable sub-picosecond time-of-flight techniques can be developed.

The relative ease and sensitivity of detection of fission events promise, however, to allow this phenomenon to be a valuable diagnostic technique for studying the coupling of intense laser light to atomic electrons. For applied physics, it gives the promise of an extremely small, pulsed source of fission-product nuclei and fast neutrons. Experimental realization may not be too far away, given that krypton-fluoride excimer lasers, yielding a wavelength of 248 nm, already operate at powers and pulse durations within an order of magnitude of those considered above (Schwarzenbach, A.P. *et al. Opt. Lett.* **11**, 499; 1986). □

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