Subpicosecond X-ray Pulses

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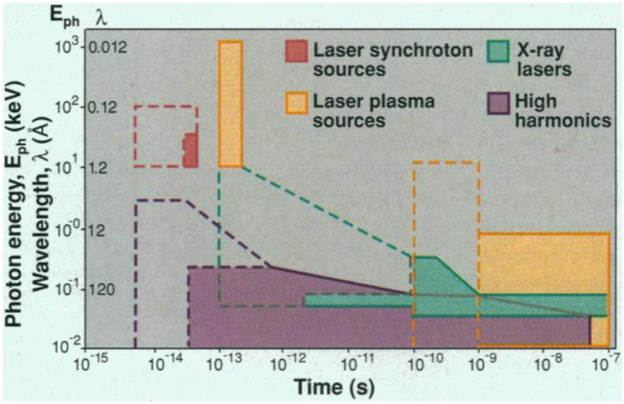
Progress has been made in the development of new sources of soft and hard x-ray radiation and in the construction of synchrotrons that can generate very bright x-rays. This opens new possibilities in physics, chemistry, and biology. One important part of such research is measurement of the dynamical response of systems. It is not enough to have intense x-ray radiation; it is also necessary to create this radiation with pulse durations comparable to the time response of the system of interest, which in many cases is on the order of less than a picosecond (typically 50 to 100 fs).

At present, such pulses can be created in the ultraviolet (UV) or infrared (IR) spectral regions (*1*) with extremely large power densities, exceeding 10^{18} to 10^{19} W/cm^2. However, to correlate dynamical information with high spatial resolution, one needs x-ray radiation with photon energies of 10 to 50 keV (a wavelength range of ~1 to 0.2 Å).

A new approach to the generation of ultrashort (300 fs) pulses of 0.4 Å x-rays is reported on page 236 of this issue (*2*). Schoenlein *et al.* have created such pulses by scattering a pulsed IR laser beam with a tightly focused electron beam. Although the measured flux of x-ray photons (5×10^4 photons per pulse) is somewhat small, this is promising, and in good agreement with theoretical prediction (*3*). An extended theory of the generation of such radiation, called the laser synchrotron source, was previously developed (*3*); it was shown that by interaction of a powerful subpicosecond laser with electrons having energy $E_e \approx 40$ MeV, 30-keV x-ray radiation can be generated. In effect, the electron beam is perturbed by the laser beam, generating x-rays in direction of the electron beam. [The first proof-of-principle laser synchrotron experiment was done at the Naval Research Laboratory (*4*), with backscattering from a 1-TW laser off of a 0.6-MeV electron beam. Radiation with an energy of about 20 eV was observed, which was also in agreement with theoretical predictions.]

There are two advantages of this approach. First, the system is compact in comparison with synchrotrons, in which the electron beam energy has to be ~300 times higher (~12 GeV) in order to generate 30-keV photons. Second, the achieved pulse duration of 300 fs for such energy photons is unique and can open up new areas for dynamical studies of crystals and biological systems.

How do these results compare with other short pulses of x-ray radiation? In the longer wavelength range (~10 to 100 Å), a good source of short pulses could be high harmonics (see figure) of UV or IR femtosecond laser pulses (*5*). With increasing power of femtosecond lasers, it might be possible to generate higher harmonics down to the 10 Å wavelength with reasonable efficiency (*6*). With increasing harmonic efficiency and increasing laser intensity, it probably will be possible to obtain coherent and tunable x-rays up to an energy of 3 to 5 keV in a 10-fs pulse, which should open a number of applications in biology, physics, and chemistry.



Presently available pulsed x-ray sources (solid lines) and extension of these sources in energy and time ranges (dashed lines) expected in near future.

A more efficient way to generate the desired wavelengths is by means of soft x-ray lasers (*7*), which have an efficiency exceeding 10^{-5}. High brightnesses have already been demonstrated for x-ray lasers with photon energies of ~0.1 keV and 10^{14} to 10^{15} photons per pulse. The shortest wavelength achieved to date is 35 Å (~0.3 keV), but it is expected that lasing at a significantly shorter wavelength will be demonstrated soon. Soft x-ray lasers now produce pulses with durations of hundreds of picoseconds. This time can be shortened to a few picoseconds with the use of a powerful subpicosecond laser beam to generate lasing to ground state in ions. However, shorter pulses are not expected from existing x-ray laser schemes. Shorter pulses may be achieved when lasers making use of inner-shell lasing transitions are developed. These may also lead to lasing significantly below 10 Å in a compact system (*8*).

A complete discussion of short-pulse soft x-ray sources should also include laser-produced plasmas. A laser beam interacting with a solid, liquid, or gaseous target creates a high-temperature plasma that emits radiation characteristic of the target. Distribution of this radiation versus the energy of the photons (wavelength) depends on the laser power density on the target and the target material. For example, using a laser with a power density at the focal spot on the order of 10^{13} W/cm^2, one can ionize neon to a hydrogen-like state. Such ions emit strong spectral lines at 13.4 Å (0.92 keV) in the resonance transition (2*p*-1*s*), and at 11.6 Å (1.1 keV) in the 3*p*-1*s* transition. Significantly less laser power density (~10^{12} W/cm^2) is needed to generate hydrogen-like carbon from a solid carbon target with strong resonance line radiation (2*p*-1*s* transition) at 33.7 Å (0.37 keV) and at 28.4 Å (0.43 keV) in the 3*p*-1*s* transition.

In x-ray transmission microscopy of biological objects, the wavelength region of special interest is the so-called "water window" between 23 and 44 Å. In this region, the water absorption (oxygen absorption) is small in comparison with the absorption by carbon; therefore, the specimen can be imaged. For the generation of radiation in this region, high–atomic number targets are most suitable. For example, a lead target illuminated with a 10^{12} W/cm^2 laser pulse provides intensive, broadband radiation in the 20 to 40 Å region.

Recently, with the development of powerful subpicosecond lasers, it has become possible to efficiently create short pulses (in the range of 1 to 2 ps) of x-ray radiation by interaction of such laser beams with solid or gaseous targets (*9*). Very interesting results were obtained for the laser beam interacting with large (~100 Å) clusters in pulsed gas jets (*10*). It was shown that plasmas with electron temperatures far in excess of that for solid or regular gaseous targets were produced; therefore, it is possible to generate strong radiation in the vicinity of 6 Å (2 keV). Much shorter wavelength radiation (with photon energies up to 1 MeV) was also demonstrated in the interaction of subpicosecond laser pulses with solid targets (*11*, *12*). However, the number of photons in the range above 10 keV is very low. For practical purposes [such as for medical applications (*12*)],

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it would be necessary to significantly increase the repetition rate of the laser, in order to increase the average flux of the photons.

The results of Schoenlein *et al.* open a new avenue for ultrashort x-ray sources, tunable in a broad spectral range. Especially attractive is the compactness and short pulse duration of this new x-ray source. Only a relatively low photon flux (5×10^4 photons per pulse) has been obtained thus far, so only a very limited range of applications is currently possible. However, if this flux can be increased by several orders of magnitude, which is possible according to Schoenlein *et al.*, then a wide range of applications of such sources in industry, science, and medicine is possible.

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A Warped View of Time Travel

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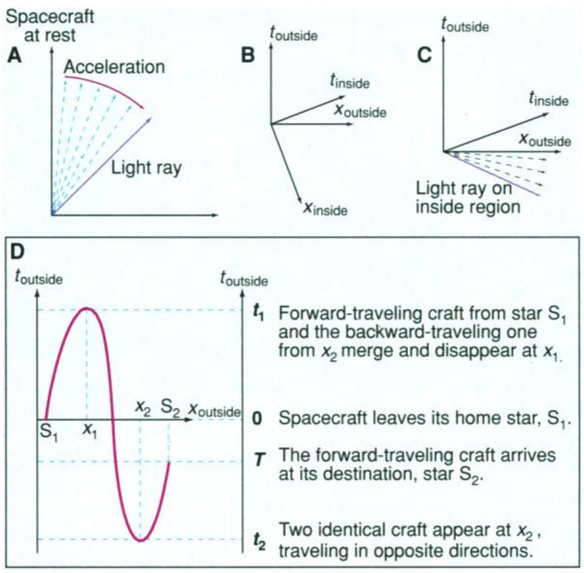
Physicists have long known that it is possible to jump forward in time. Einstein's special theory of relativity predicts that a moving clock ticks slower than one at rest, a phenomenon called time dilation (*1*). Thus, a person in motion ages slower than someone who is not, which would allow a traveler to leave Earth on a fast spacecraft and return just hours later as measured in his or her own time but years later according to terrestrial clocks. The traveler would effectively have jumped forward in time. In recent years, several researchers have attempted to extend this concept to grant a hypothetical time traveler access to not only the future but also the past.

Special relativity accurately describes objects moving close to the speed of light but makes no provision for gravity. Einstein formulated general relativity, which builds in the gravitational force by bending the flat space-time of the special theory (*2*). Scientists have since found some novel time machines in curved space-time, involving exotica such as black holes, wormholes, and even cosmic strings formed during the earliest moments of the universe's history (*3*).

In 1994 Alcubierre used general relativity to propose a way of curving space and time around a spacecraft so that it could reach speeds arbitrarily greater than that of light (*4*). The gravity-free flat space of special relativity prohibits superluminal travel, but in the general theory, the story is quite different. The flexibility of space-time introduced by gravity allows it the freedom to stretch, causing relative motion between two otherwise stationary observers. Alcubierre found that there is no limit to the rate at which space can change its size and shape in this way. His model involves a hypothetical spaceship surrounded by a bubble of warped space-time. This bubble is capable of contracting the space in front of the craft and expanding the space behind it, the net effect being to sweep the vessel swiftly to its destination. In between the expanding and contracting regions and far away from the craft, space-time is flat; the spaceship and its crew as well as distant observers are safely situated in zero-gravity flat space, through which the bubble of warped space containing the spaceship can move at limitless speeds. Everett has now shown how this "warp drive" could be implemented as a time machine (*5*).



A step back. (**A**) Acceleration of a spacecraft from rest to speeds less than light (dashed lines). (**B**) The regions inside and outside of the "warped" region are both flat, and the axes are rotated relative to one another by their relative motion. (**C**) If the spacecraft accelerates to sublight speeds within the bubble, it is possible for it to travel backwards through $t_{outside}$ (dashed paths). (**D**) Time travel as seen by a distant observer.

In special relativity, the speed of an object is constrained to be less than the speed of light. Physicists represent this on a space-time diagram (see figure, part A), which shows time t, distance x, and the path of a light ray. A spaceship at rest would simply move along the t axis. As it accelerates, its motion is described by one of the dashed lines, the direction of which rotates toward the light ray as the spacecraft travels faster.

With Alcubierre's warp drive, the situation is different. Inside the bubble, the spaceship is stationary with respect to the bubble and so moves along the t_{inside} axis (figure, part B). As Alcubierre has shown, the inside region is allowed to move relative to the outside with an unbounded speed, which allows the direction of t_{inside} to be rotated clockwise until it lies arbitrarily close to the $x_{outside}$ axis. In the inner flat region, special relativity holds, and the spacecraft is allowed to accelerate to any velocity less than light (figure, part C). Accelerating it to any one of the dashed trajectories takes its path across the $x_{outside}$ axis. An observer on the craft would then see $t_{outside}$ decrease; thus, time outside the bubble runs backwards.

Part D of the figure shows what this would look like to an outside observer of a spacecraft leaving star S_1, commencing time travel at t_1, finishing at t_2, and reaching star S_2 at a time T, less than zero. By reversing the roles played by stars S_1 and S_2, the ship can be made to travel in the opposite direction and arrive back at S_1 before it left. This suggests the intriguing possibility that engineers may one day be capable of building time machines without ever the need to harness exotic (and life threatening) astrophysical objects.

Aside from questions of technical feasibility, there are mixed reactions to some of the apparently bizarre consequences of time travel. Some argue for a "principle of self-consistency" (*6*), which requires all phenom-

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