Light controls matter, matter controls x-rays

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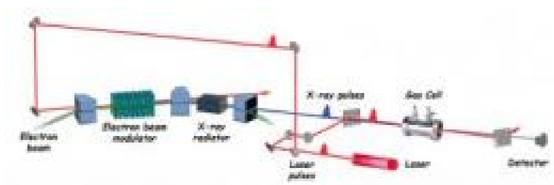

This is a simplified sketch of the experiment at the Advanced Light Source's femtosecond spectroscopy beamline. A laser oscillator generates femtosecond pulses that follow two paths. One path interacts with the synchrotron's electron beam to generate femtosecond x-ray pulses; the other (after a delay to insure synchronization) rejoins the x-ray pulses and copropagates with them through the gas cell. Credit: Lawrence Berkeley National Laboratory

Like playing a game of scissors-paper-rock, a team of scientists led by Thornton E. (Ernie) Glover of Lawrence Berkeley National Laboratory's Advanced Light Source (ALS), Linda Young of Argonne National Laboratory, and Ali Belkacem of Berkeley Lab's Chemical Sciences Division has used laser light to control x-ray beams - by first changing the material medium through which the x-rays pass.

As a new generation of powerful light sources comes online, intense x-ray beams may be able to control matter directly and allow one beam of x-rays to control another.

Using the ALS's femtosecond (quadrillionth of a second) spectroscopy beamline 6.0.2, Glover and his colleagues sent ultrashort pulses of laser light and higher-frequency x-rays together through a gas cell filled with pressurized neon. Excited by the laser pulses, the gas, which normally absorbs x-rays, became transparent to the x-ray pulses during their quick passage.

Schroedinger's lightbulb

"We were inspired by the interesting new science demonstrated in quantum optics experiments that use visible light to control visible light," says Glover. "One spectacular example is slowing light to a near standstill in some media. The ability to, in effect, stop light in a medium has potential applications for quantum information storage and processing."

Glover says another example of optical control is using visible light to induce transparency in a medium. "We embarked on our own research in the hope that it would lead to new and interesting ways to use x-rays as well as visible light."

Light's behavior in a medium like air or glass or water is determined by the interaction of its electromagnetic field with the medium's electrons. In a quantum-mechanical phenomenon called coherent superposition, a "pump" pulse of light couples two different material states so that when a subsequent "probe" pulse boosts an electron to either of the excited states, the electron ends up in both states simultaneously.

Although this had been done with visible light, no one had successfully controlled a probe x-ray pulse this way before the work of Glover and his colleagues. Higher-energy x-rays interact with electrons in different atomic shells and create excited states that decay a thousand times faster than those created by visible light - thus interrupting the attempt to form a coherent superposition and using it as a control mechanism.

"The superposition state has to last for a useful length of time," Glover explains. "But x-rays interact strongly with an atom's inner core electrons, and x-ray excitation of core electrons leaves holes behind which are filled by other, more weakly bound electrons so quickly that the superposed state lasts for only a femtosecond or so."

Glover says one approach to solving this short-lifetime problem is "by increasing the number of photons" - using very intense optical pulses to more strongly couple the material states. For a given laser pulse energy, the intensity increases as the pulse length decreases.

But to see the combined light-matter system, the x-ray pulse has to be at least as short or shorter than the laser pulse, and both pulses have to move through the medium together. These conditions are met by using synchronized pulses, measuring about 200 femtoseconds, of both optical light and x-rays.

A very special beamline

"Beamline 6.0.2 was the first and still one of only three places in the world where these experiments could be done," Glover says. The experiment's intense laser pulses created brief coherent superposition states in the dense neon gas inside the cell, which rendered the pressurized neon in the gas cell transparent to the x-rays.

"Quantum mechanicaly speaking, there is destructive interference between two absorption pathways and this reduces the absorption," says Glover. "That is, it makes the medium transparent." For the first time, optical pulses had been used to control how x-rays interact with matter.

The experimenters quickly put this ephemeral neon window to practical service, using it to measure the duration of the femtosecond-scale x-ray pulse to high accuracy more simply than has been possible before, with the added ability of shaping x-ray pulses on a femtosecond time scale.

"To our knowledge there are no other viable approaches to shaping x-ray pulses with femtosecond precision," Glover says. "By demonstrating a way to shape x-rays on the femtosecond time scale, we've opened the door to 'quantum control' experiments - now possible only with long-wavelength light - in the x-ray regime."

X-rays have element specificity - they can be tuned to talk to particular kinds of atoms in a molecule much more effectively than visible light can. "A number of advances seem possible," says Glover. "Shaping pulses on this time scale will be important in experiments that seek to control chemical reactions, phase transitions, and other phenomena."

Further afield may be the potential of using light to control the phase of x-ray pulses. It's difficult to fabricate perfect mirrors and zone plates for focusing x-rays, but that problem could be overcome by using lenses of gas controlled by light. Phase control over x-ray pulses could lead to new ways to make images of complex structures like protein crystals.

X-ray pulses whose shape, length, and intensity are precisely controlled might even be able to label individual atoms and follow them through a complex series of chemical reactions like photosynthesis. Says Glover, "We may be able to exert control over how matter evolves and what paths chemical reactions take."

In the next generation of light sources, using free-electron lasers to produce ultrabright, ultrafast, high-repetition-rate x-rays, such potential uses of the ability to control x-rays with light would open a dazzling panorama of understanding and control over the natural world.

More information: "Controlling x-rays with light," by Thornton E. Glover, Marcus P. Hertlein, Stephen H. Southwork, Thomas K. Allison, Jeroen van Tilborg, Elliot P. Kanter, Bertold Krässig, Hari R. Varma, Bruce Rude, Robin Santra, Ali Belkacem, and Linda Young, appears in the January 2010 issue of Nature Physics and is available online to subscribers at www.nature.com/nphys/journal/v … 1/abs/nphys1430.html

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