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RESEARCHERS CREATE MATTER FROM LIGHT

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HIGH-ENERGY PHYSICS

Normally two beams of light do not interact with each other unless they are passing through a nonlinear material. Yet the demonstration of a positron-electron pair created from photon-photon scattering -- reported last September -- occurred in a vacuum. To make the process work, a team of research scientists from four institutions had to carefully manipulate high-energy laser and electron beams at the Stanford Linear Accelerator Center (SLAC; Palo Alto, CA), which effectively made the vacuum nonlinear enough to produce and generate a five-photon mixing process.

"It's like nonlinear optics," explained David Meyerhofer of the Laboratory for Laser Energetics at the University of Rochester (Rochester, NY). "In a second-harmonic conversion, I can convert two photons into one photon. In this case, we have a five-photon mixing process, if you will, of four [2 eV] photons mixed with a [30 GeV] gamma photon. [But] the output is not a photon. It's a pair [of particles]."

Meyerhofer and 19 other scientists from the University of Rochester, Princeton University (Princeton, NJ), University of Tennessee (Knoxville, TN), and SLAC co-authored an article in Physical Review Letters describing the first-ever creation of matter from light in a vacuum.[1]

The idea behind the process is more than 60 years old, and the necessary parameters are precisely specified by quantum-electrodynamic (QED) theory, which describes the quantum-mechanical interaction between electrons and photons. So, despite the metaphysical, magical, and even religious ideas associated with the words "creation of matter," the real achievement of the research team at SLAC was in doing something that people had only talked about doing for more than six decades.

A vacuum can be made to behave as if it were a nonlinear optical material when the electric field strength within it reaches the QED critical field strength of 10^{16} V/cm, Meyerhofer said. In terms of laser intensity, the QED field strength can also be expressed as 10^{29} W/crn^{2}. Because the highest laser intensities reported to date are only in the 10^{21} range, the researchers had to bounce a high-energy laser beam off the higher-energy electron beam at SLAC as the first step in a two-collision process.

In the first collision between the 2-eV laser beam and the 46-GeV electron beam, the electron beam acts essentially like a moving mirror that reflects the laser photons back into the laser beam. The first collision also takes advantage of a relativistic Doppler effect (Compton scattering) to shorten the wavelength and increase the intensity of the laser photons, which are transformed into 30-GeV gamma photons.

In the second collision, between the 30-GeV photon and four 2-eV laser photons, the short-wavelength gamma photon increases the field strength at the center of momentum to the critical QED field strength, thereby producing a nonlinear vacuum condition and the five-photon mixing process that produces the particle pair. A look at the parameters and tolerances required to achieve it makes it easy to understand why this feat took more than 60 years to accomplish.

First, to work efficiently with the electron beam produced by the linear accelerator at SLAC, the source laser had to provide both high peak power and high average power. To do this, the researchers at the University of Rochester devised a terawatt laser that could operate continuously at 0.5 Hz. The design included the first glass-slab amplifier combined with a chirped-pulse amplification laser (see figure on p. 30).

The all-glass laser system was installed by the Rochester team at SLAC for the experiment. It produces 1.5-ps, 1054-nm pulses at energies of more than 2 J and at almost 1 J when frequency-doubled to 527 nm, which is the wavelength used for the experiment.

Pulse synchronization

Laser design was not the toughest challenge in getting the system to work, however. The trick was in synchronizing the 1.5-ps laser pulses with 7-ps electron bunches hurtling down the 3km-long linear accelerator (linac). To synchronize the two energy beams within picosecond tolerances, the researchers phaselocked the laser to the RF trigger for the linac. The linac RF signal was fed to the laser over a 600-m optical cable. The signal was then divided by four and used to drive the modelocker in the laser oscillator, Meyerhofer said. A commercial phase comparator (from Lightwave Electronics; Mountain View, CA) was also used to maintain synchronization between the phase of the RF signal coming in and the phase of the laser signal going out.

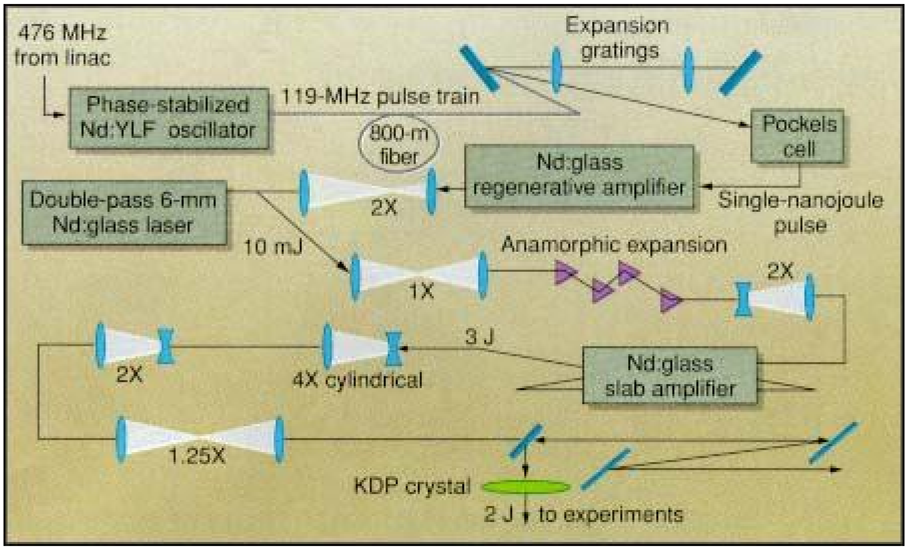
"We had to do quite a bit of work to get the noise on the overall system -- the RF, the laser, and how we ran the cavity-low enough to be able to synchronize down to the couple of picosecond level," Meyerhofer said.

Finally, the whole system had to be reliable enough to operate for 24 hours a day, one week at a time, according to Theo Kotseroglou, a SLAC physicist who gave a presentation on the 0.5-Hz terawatt laser in October at the annual meeting of the Optical Society of America (Long Beach, CA). Reliability was important partially because of limited accelerator availability, which only allowed the team one week of accelerator time about every eight months.

During that one week, several experiments had to be performed, and a considerable amount of time had to be spent in tuning the system to within the picosecond tolerances required for successful collisions between the laser and electron beams. Even when everything was lined up, the probabilistic nature of quantum phenomena yielded a relatively small cross section or probability of making pairs.

"Under the best conditions you make a little more than a pair per hundred shots," Meyerhofer said. "At half a hertz, a hundred shots is [about] three minutes, and that's only when everything was tuned up perfectly." In their published work based on a week of linac time, the team reported a total of 106 +/=14 particle pairs.

Considering that it took more than 60 years of thinking before anything got started, a week of strenuous fiddling and tweaking for just three minutes worth of results may not be all that bad.



: All-glass laser system with chirped-pulse amplification in a glass-slab amplifier was designed by researchers at the University of Rochester to produce high peak power and high average power for

light-scattering experiments. To facilitate collisions between laser photons and electrons from a linear accelerator, the laser system was phase-locked to the electron-beam RF source.

REFERENCE

1. D.L. Burke et al., Phys. Rev. Lett., 79(9), 1626 (Sept. 1, 1997).

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