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The study offers a recipe for researchers at the Extreme Light Infrastructure (ELI) high-power laser facility to follow to produce matter from light. Pictured is the L3-HAPLS advanced petawatt laser system at the ELI Beamlines Research Center. Photo courtesy of Lawrence Livermore National Laboratory.

Making Matter Out of Light: High-Power Laser Simulations Point the Way

A few minutes into the life of the universe, colliding emissions of light energy created the first particles of matter and antimatter. We are familiar with the reverse process—matter generating energy—in everything from a campfire to an atomic bomb, but it has been difficult to recreate that critical transformation of light into matter.

Now, a new set of simulations by a research team led by UC San Diego's Alexey Arefiev point the way toward making matter from light. The process starts by aiming a high-power laser at a target to generate a magnetic field as strong as that of a neutron star. This field generates gamma ray emissions that collide to produce—for the very briefest instant—pairs of matter and antimatter particles.

The study published May 11 in *Physical Review Applied* offers a sort of recipe that experimentalists at the Extreme Light Infrastructure (ELI) high-power laser facilities in Eastern Europe could follow to produce real results in one to two years, said Arefiev, an associate professor of mechanical and aerospace engineering.

“Our results put scientists in a position to probe, for the first time, one of the fundamental processes in the universe,” he said.

Harnessing high power

Arefiev, Ph.D. student Tao Wang and their colleagues at the Relativistic Laser-Plasma Simulation Group have been working for years on ways to create intense, directed beams of energy and radiation, work that is supported in part by the National Science Foundation and Air Force Office of Science Research. One way to accomplish this, they noted, would be to aim a high-power laser at a target to create a very strong magnetic field that would throw off intense energy emissions.

High-intensity, ultra-short laser pulses aimed at a dense target can render the target “relativistically transparent,” as the electrons in the laser move at a velocity very close to the speed of light and effectively become heavier, Arefiev explained. This keeps the laser’s electrons from moving to shield the target from the laser’s light. As the laser pushes past these electrons, it generates a magnetic field as strong as the pull on the surface of a neutron star—100 million times stronger than Earth’s magnetic field.

To say this all happens in the blink of an eye is a vast overstatement. The magnetic field exists for 100 femtoseconds. (A femtosecond is 10^{-15} of a second—a quadrillionth of a second.) But “from the point of the view of the laser, the field is quasi-static,” said Arefiev. “Then again, from the point of view of the laser, our lives are probably longer than the life of the universe.”

A high-power laser in this instance is one in the multi-petawatt range. A petawatt is a million billion watts. For comparison, the Sun delivers about 174 petawatts of solar radiation to the Earth’s entire upper atmosphere. A laser pointer delivers about 0.005 watt to a Power Point slide.

Previous simulations suggested that the laser in question would have to be high powered and aimed at a tiny spot to produce the required intensity to create a strong enough magnetic field. The new simulations suggest that by increasing the size of the focal spot and boosting the laser power to around 4 petawatts, the laser’s intensity could remain fixed and still create the strong magnetic field.

Under these conditions, the simulations show, the laser-accelerated electrons of the magnetic field spur the emission of high-energy gamma rays.

“We did not expect that we didn’t need to go to a crazy intensity, that it’s just sufficient to increase the power and you can get to very interesting things,” said Arefiev.

Particle pairs

One of those interesting things is the production of electron-positron pairs—paired particles of matter and antimatter. These particles can be produced by colliding two gamma-ray beams or colliding one gamma-ray beam with blackbody radiation, an object that absorbs all radiation falling on it. The method produces a lot of them—tens to hundreds of thousands of pairs born out of one collision.

Alexey Arefiev, an associate professor of mechanical and aerospace engineering at the UC San Diego Jacobs School of Engineering.

Scientists have performed the light-into-matter feat before, notably in one 1997 Stanford experiment, but that method required an extra stream of high-energy electrons, while the new method "is only light used to produce matter," said Arefiev. He also noted that the Stanford experiment "would produce one particle pair about every 100 shots."

An experiment that uses only light to create matter more closely mimics conditions during the first minutes of the universe, offering an improved model for researchers looking to learn more about this critical time period. The experiment could also provide more chances to study antimatter particles, which remain a mysterious part of the universe's composition. For instance, scientists are curious to learn more about why the universe appears to have more matter than antimatter, when the two should exist in equal amounts.

Arefiev and his colleagues were encouraged to do these simulations now because the laser facilities capable of carrying out the actual experiments are now available. "We specifically did the calculations for the lasers that have not been available until recently, but now should be available at these laser facilities," he said.

In an odd twist, the simulations proposed by the research team could also help the ELI scientists determine whether their lasers are as intense as they think they are. Firing a laser in the multi-petawatt range at a target only five microns in diameter "destroys everything," said Arefiev. "You shoot and it's gone, nothing is recoverable, and you can't actually measure the peak intensity that you produce."

But if the experiments produce gamma rays and particle pairs as predicted, "this will be a validation that the laser technology can reach such a high intensity," he added.

Last year, the UC San Diego researchers received a U.S. National Science Foundation grant that allows them to partner with ELI researchers to carry out these experiments. This partnership is critical, Arefiev said, because there are no facilities in the United States with powerful enough lasers, despite a 2018 report from the National Academies of Sciences warning that the U.S. has lost its edge in investing in intense ultrafast laser technology.

Arefiev said the ELI laser facilities will be ready to test their simulations in a couple years. “This is the reason why we wrote this paper, because the laser is operational, so we are not that far away from actually doing this,” he said. “With science, that is what attracts me. Seeing is believing.”

Paper Title: Power scaling for collimated -ray beams generated by structured laser-irradiated targets and its application to two-photon pair production.” Co-authors include Xavier Ribeyre and Emmanuel d’Humières of the University of Bordeaux-CNRS-CEA; Daniel Stutman of the Extreme Light Infrastructure-Nuclear Physics (ELI-NP)/Horia Hulubei National Institute of Physics and Nuclear Engineering and Johns Hopkins University; and Toma Toncian of the Institute for Radiation Physics, Helmholtz-Zentrum Dresden-Rossendorf.

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