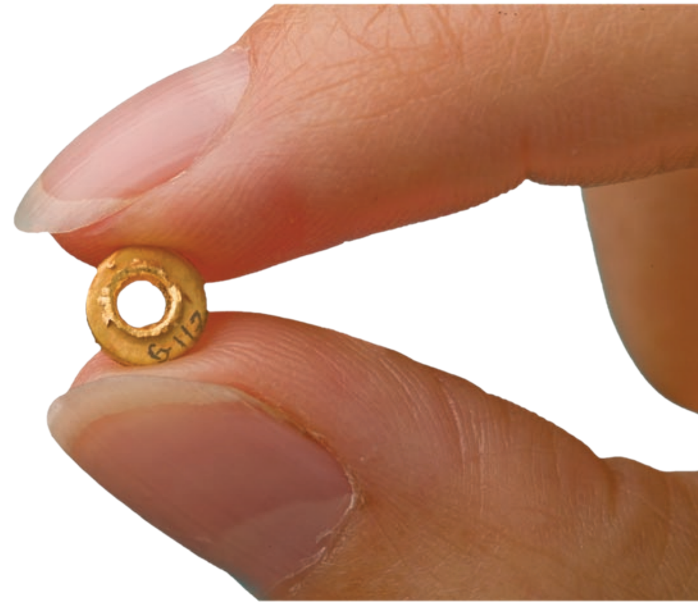
Mass-Producing Positrons



Livermore's new laser-based method to produce positrons uses targets made from a variety of high-atomic-number (high-*Z*) materials ranging in thickness from 250 micrometers to 3 millimeters. The 1-millimeter-thick gold target shown here was shot by the Laboratory's Titan laser. The best experimental results were achieved using the thickest targets.

HOW do black holes form? Where do gamma-ray bursts originate in space? Why does matter dominate over antimatter in the universe? No one really knows. However, through the study of positrons, the antiparticles of electrons, scientists believe they may gain insight into these complex astrophysical questions.

Positrons are elementary particles whose physical properties, such as spin and mass, are the same as electrons, except that positrons have a positive charge. For years, scientists have theorized that lasers could be used to generate positrons in a laboratory by "zapping" an ultrathin micrometer-size foil target made of a high-atomic-number (high-*Z*) material, such as gold or tantalum. Researchers at Livermore recently showed that targets thicker than a few micrometers are a more efficient mechanism for positron generation. Using an ultraintense, short-pulse laser and millimeter-thick targets, physicists Hui Chen and Scott Wilks have produced more than 100 billion positrons—an unprecedented number of laser-generated positrons.

Particle accelerators are typically used to generate positrons for antimatter research. Livermore's new laser-based method can generate similar numbers of positrons but in a fraction of the time—all positrons are generated in less than 100 picoseconds. With the capability of generating billions of positrons inside a small laboratory, scientists have a way of making antimatter more accessible, opening the door to new avenues of research. As a result, they may be able to uncover answers to some of the most perplexing questions about our universe. This new capability may also provide scientists with a better way to produce positronium—the short-lived bound state of an electron and a positron—which could enable the development of advanced, extremely high-powered gamma-ray lasers.

Larger Target, Greater Yield

Chen and Wilks began their research in 2003 as part of a project funded by Livermore's Laboratory Directed Research and Development (LDRD) Program. "At the time," says Chen, "researchers thought that only ultrathin foil targets could be used to create the hot electrons needed to generate positrons." For this earlier study, Chen and Wilks created an experimental method using ultrathin targets and developed instrumentation for detecting the positrons. The method required an intense laser to accelerate electrons to energies just over 1 megaelectronvolt. In what is known as the trident process, hot electrons interact with the nuclei of atoms within the target, producing a virtual photon that quickly converts to an additional electron and a positron.

Wilks, who designed the experiment for the LDRD project, used computer models to predict the number of positrons that would be generated as a function of the thickness of the target and the intensity of the laser. Chen, who performed and led the experiment, devised a detection scheme for positrons based on an existing electron spectrometer. They conducted their test on a laser at the Rutherford Appleton Laboratory in England. "We were allowed just one shot on the laser," says Chen. "Unfortunately, it yielded only a hint of a positron signal."

For their current LDRD study, Chen and Wilks improved their experimental design and detection methods. These experiments were performed in Livermore's Jupiter Laser Facility on the Titan laser, which was completed in 2006, one year after the team's initial experiments in England. Titan has a unique long- and short-pulse capability: A high-energy, petawatt short-pulse (subpicosecond) beam is coupled with a kilojoule long-pulse (nanosecond) beam. (See *S&TR,* January/February 2007, pp. 4–11.) With Titan, the team had a local, more accessible tool for proving their experimental design.

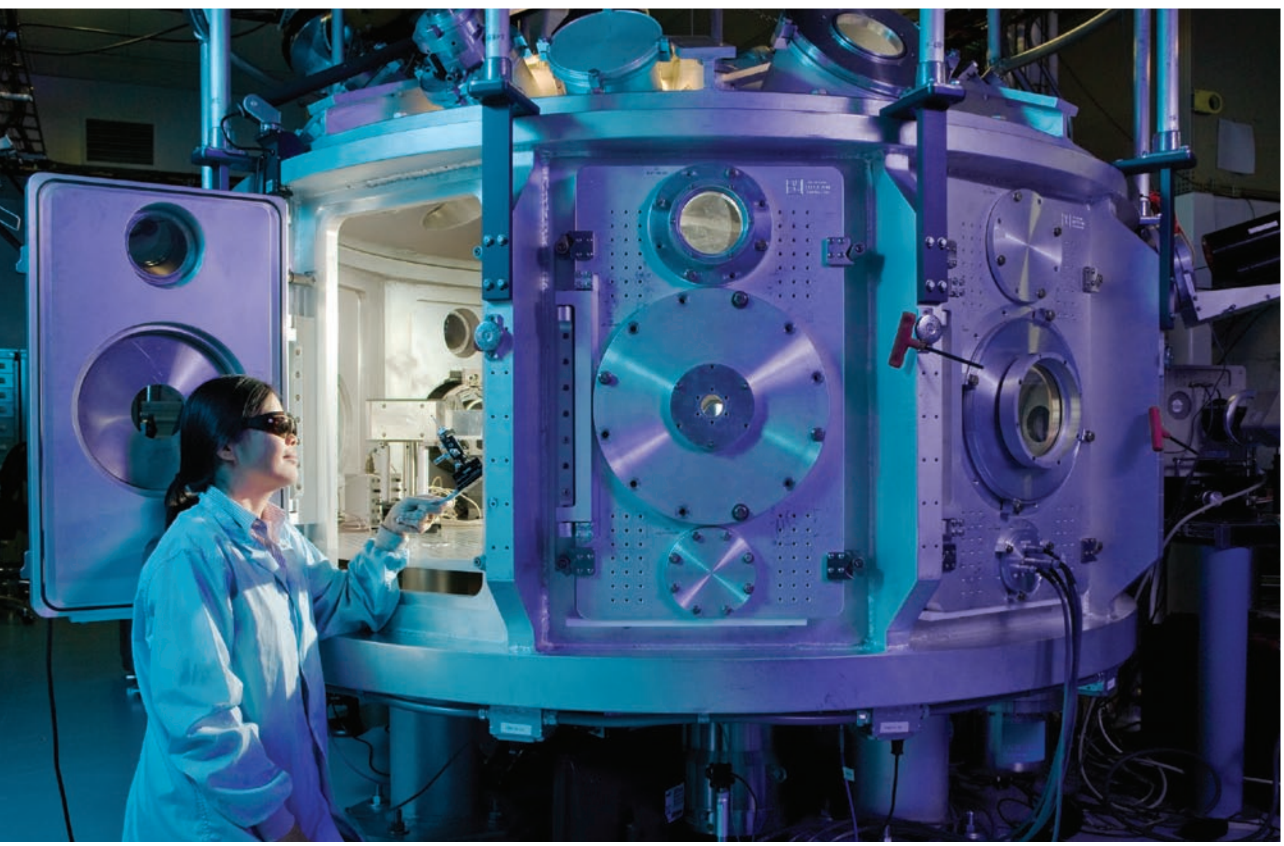
Initial experiments on Titan revealed new data on the distribution and energy of hot electrons interacting with materials. Wilks took these hot electron measurements and put them into a computational model. "The model calculated the electron distribution in the target, and how many positrons were produced in the process," says Wilks. "After reviewing the simulation results, I realized that irradiating thicker targets would result in orders of magnitude more positrons than seen in previous experiments."

The thicker targets increase the number of interactions that can occur inside the target. In addition, a different physical process—the Bethe–Heitler process—dominates in larger targets and promotes positron generation on a greater scale. To more accurately detect this abundance of antimatter, Chen redesigned the electron–positron spectrometers using more elaborate components to make them more sensitive to the positron signals.

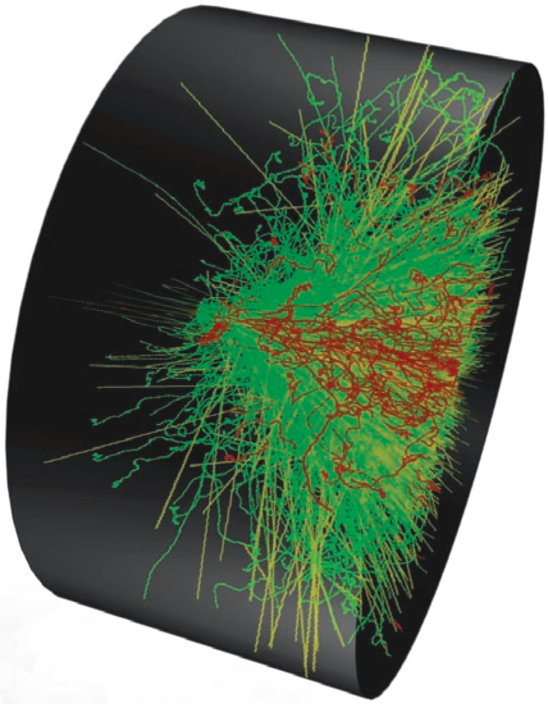
Producing Particle Pairs

Chen developed new, larger targets using a variety of materials, from aluminum to gold. The targets ranged in thickness from 100 micrometers to 3 millimeters. Each target was shot with two laser pulses in close succession. The first pulse lasted a nanosecond and delivered 100 joules of energy to the target. This initial blast created a plasma on the surface of the material that contained electrons and ions. The second laser shot was an ultraintense pulse—10^{19} watts of energy per square centimeter—that lasted only picoseconds but was powerful enough to accelerate electrons within the plasma. "For other studies, this plasma is not always ideal because researchers want to accelerate the electrons to lower energies," says Chen. "We can get three or four times more positrons by using the plasma to generate 10- to 100-megaelectronvolt higher-energy electrons." These electrons are blasted into the target, which acts as a catalyst to induce particle interactions.

Within the target material, the electrons move at relativistic speeds with kinetic energies ranging from 6 to 100 megaelectronvolts. Through the Bethe–Heitler process, these high-energy electrons lose energy as they interact with the material's nuclei, resulting in the emission of high-energy bremsstrahlung photons. These photons in turn interact with the high-*Z* nuclei, which enables some of the high-energy photons to split into electron–positron pairs (matter and



Inside Livermore's Jupiter Laser Facility, physicist Hui Chen conducts positron experiments on Titan, a laser that couples a high-energy, petawatt short-pulse (subpicosecond) beam with a kilojoule long-pulse (nanosecond) beam.



Simulations show the electron-positron-photon shower from a positron experiment. When the laser strikes the target (from the left), high-energy electrons (green) are generated that then lose energy as they interact with the target material's nuclei, emitting high-energy bremsstrahlung photons (yellow). Some of the high-energy photons then interact with the nuclei, creating pairs of electrons and positrons (red). A number of positrons then leave the target (out the right) and are detected by positron spectrometers. (Rendering by Kwei-Yu Chu.)

antimatter) based on Einstein's $E = mc^2$ formula that relates energy and matter. The energies of the photons are proportional to the energies of the decelerating electrons as they interact with the material. The higher the energy, the more likely the bremsstrahlung photons will produce electron–positron pairs, a large fraction of which are inevitably blasted out the back of the target in a plasma jet.

The positron energy in the plasma jet was measured by two of the redesigned spectrometers positioned at various angles around the back of the target. However, the plasma jet does not contain the total amount of positrons generated, such as those still in the target. The data recorded from the spectrometers is compared with computer simulations to infer how many pairs were created overall. Chen and Wilks directly detected more than 1 million particles per laser shot. They infer that a total of about 100 billion positron particles were produced. Using targets less than 200 micrometers thick, the research team found that the positron signal fell below the detection limit of the spectrometers. The most successful results were produced using 1- to 3-millimeter-thick gold targets.

A Wealth of Possibilities

The new method for positron generation designed by Chen and Wilks has the potential to advance antimatter research. Studying the gamma rays produced when positrons and electrons annihilate each other may help researchers better understand gamma-ray bursts that occur in space. In addition, the method could be used to generate a high-yielding positron source for particle accelerators. The method could also provide a more efficient way to generate positronium gas. Current production methods require positronium gas to be contained in magnetic traps that must be filled repeatedly to obtain the amount needed for research purposes. "Instead of producing positronium gas in small increments over time, we can in principle produce the amount needed for research in a few picoseconds," says Chen.

"The results of this experiment are so new, we have not even begun to investigate all the potential applications," says Wilks. In the meantime, scientists have a new mechanism by which they may be able to unravel antimatter's secrets. While it may be decades or longer before scientists know enough about antimatter to significantly increase their understanding of the origins of our universe, the research done by Wilks and Chen could move them one step closer to the answers.

—Caryn Meissner

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