Researchers aim to identify subatomic relics of the Big Bang

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Chris Tully makes an adjustment to the PTOLEMY prototype. Credit: Elle Starkman/PPPL Office of Communications

Billions upon billions of neutrinos speed harmlessly through everyone's body every moment of the day, according to cosmologists. The bulk of these subatomic particles are believed to come straight from the Big Bang, rather than from the sun or other sources. Experimental confirmation of this belief could yield seminal insights into the early universe and the physics of neutrinos. But how do you interrogate something so elusive that it could zip through a barrier of iron a light-year thick as if it were empty space?

At the U.S. Department of Energy's Princeton Plasma Physics Laboratory (PPPL), researchers led by Princeton University physicist Chris Tully are set to hunt for these nearly massless Big Bang relics by exploiting a curious fact: Neutrinos can be captured by tritium, a radioactive isotope of hydrogen, and provide a tiny boost of energy to the electrons—or beta particles—that are emitted in tritium decay.

Tully has created a prototype lab at PPPL to detect Big Bang neutrinos by measuring the extra energy they impart to the electrons—and to achieve this with greater precision than has ever been done before. Spotting these neutrinos is akin to "detecting a faint heartbeat in a sports arena filled to the brim" said Charles Gentile, who heads engineering for the project, which Tully has dubbed PTOLEMY for "Princeton Tritium Observatory for Light, Early Universe Massive Neutrino Yield." Ptolemy was an ancient Greek astronomer who lived in Egypt during the first century.

Darkest, coldest conditions achievable

The task calls for measuring the energy of an electron with a precision comparable to detecting the mass of a neutrino, which until recently was thought to have no mass at all. Such measurements require the darkest, coldest conditions achievable in a laboratory and the use of quantum electronics—a discipline that deals with the effect of quantum mechanics on the behavior of electrons in matter—to detect the minute extra energy that a Big Bang neutrino would impart. Quantum mechanics describes the motion and direction of subatomic particles.

Why is the energy that a Big Bang neutrino provides so extraordinarily small? What's unique about these relics is that their wavelength has been stretched and cooled as the space-time we live in has expanded over approximately 13.7 billion years. This expansion has cooled a tremendous number of neutrinos to temperatures that are billions of times colder, and therefore less energetic, than those of neutrinos originating from the sun. When tritium captures these cold neutrinos, they create a narrow peak in energy that is just above the maximum energy of an electron from tritium decay.

The difficulty in identifying a Big Bang relic doesn't end there. Since neutrinos can take different forms, the height of the peak could be higher or lower by a factor of two, depending on whether the neutrino is like normal matter with a corresponding particle of antimatter—an antineutrino—or whether the neutrino is different and is in fact its own antiparticle. The extra height might not appear at all if neutrinos decay over billions of years into yet unknown, lighter particles.

Cutting-edge technology

Tully aims to show that the prototype for PTOLEMY, which is housed in a basement site at PPPL, can indeed achieve the precision needed to detect Big Bang neutrinos. The cutting-edge technology could then become the basis for a major experiment at PPPL to test long-held assumptions about the density of Big Bang neutrinos throughout the universe.

Confirming the assumptions could validate the standard model of the origin of the universe, Tully says, while refuting them could overturn the model and prompt new ideas about the Big Bang and its aftermath. Finding the neutrinos could also show if they could be a source of the invisible dark matter that scientists say makes up 20 percent of the total mass of the universe.

Such discoveries could be epochal. Could the project "make long-term contributions to the understanding of the universe?" Tully asks in presentations about PTOLEMY. "Absolutely!" he says. "We believe that we live in a sea of 14 billion-year-old neutrinos all around us. But is it true?"

The prototype at PPPL may hold the key to finding out. The device consists of a pair of superconducting magnets connected to opposite ends of a five-foot cylindrical vacuum chamber. A source containing a tiny bit of tritium sits inside one end of the chamber, with a calorimeter that Argonne National Laboratory is providing to measure electron energy set at the other end. The experiment will bind electrons from the tritium decay to magnetic field lines and pass them through filters in the vacuum chamber that will remove all but the highest-energy electrons, which the calorimeter will then measure.

Preventing "noise"

Great care will be taken to keep random thermal "noise" from disrupting the finely tuned equipment at each end of the experiment. Researchers will deposit the tritium on the nanomaterial graphene—a layer of carbon just one atom thick—to ensure that the electrons come off cleanly into the vacuum.

The calorimeter at the other end of the chamber will be connected to a dilution refrigerator set at between 70 and 100 millikelvins, a temperature 20 times colder than deep space and less than one-tenth of a degree above absolute zero. This deep-freeze will keep the calorimeter poised between a superconducting state—one in which electrons can flow with virtually no resistance—and a non-superconducting state with resistance to the flow of electrons. The delicate balance between these two states, combined with extremely low noise conditions achievable only with quantum electronics, will provide the sensitivity needed to precisely measure the energy of an electron that impinges upon the calorimeter. The setup will produce "the most precise electron-energy measurements ever made using calorimeter techniques," Tully said.

This experiment is "a perfect match for the competencies and capabilities that exist at PPPL," said Adam Cohen, deputy director for operations at PPPL and supervisor of the PTOLEMY project. Such qualities include know-how in handling tritium, a laboratory for synthesizing nanomaterial, decades of experience operating magnets and vacuum vessels, and space for an expanded experiment. "Chris and I talked about collaboration between PPPL and the University about three years ago," Cohen recalled. "Every time we pursue an activity with the campus it strengthens the bridge that exists between us."

Cross-fertilization

Looking ahead, Cohen sees PTOLEMY attracting new students, researchers and visitors, along with experts in high-energy physics, to PPPL. This could produce cross-fertilization with the Laboratory's core mission of advancing fusion and plasma science, he said.

For Tully, PTOLEMY could become the gateway to many avenues of research. "When one opens a new frontier of exploration," he noted, "there is no telling what will be found and learned."

Provided by Princeton Plasma Physics Laboratory

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