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It is a quantum fractal algorithmic universe

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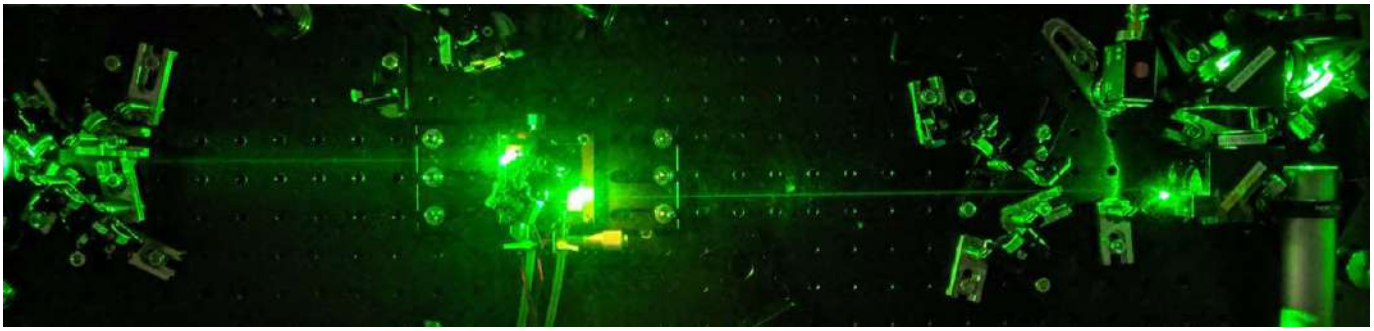
Cooling Positronium With Lasers

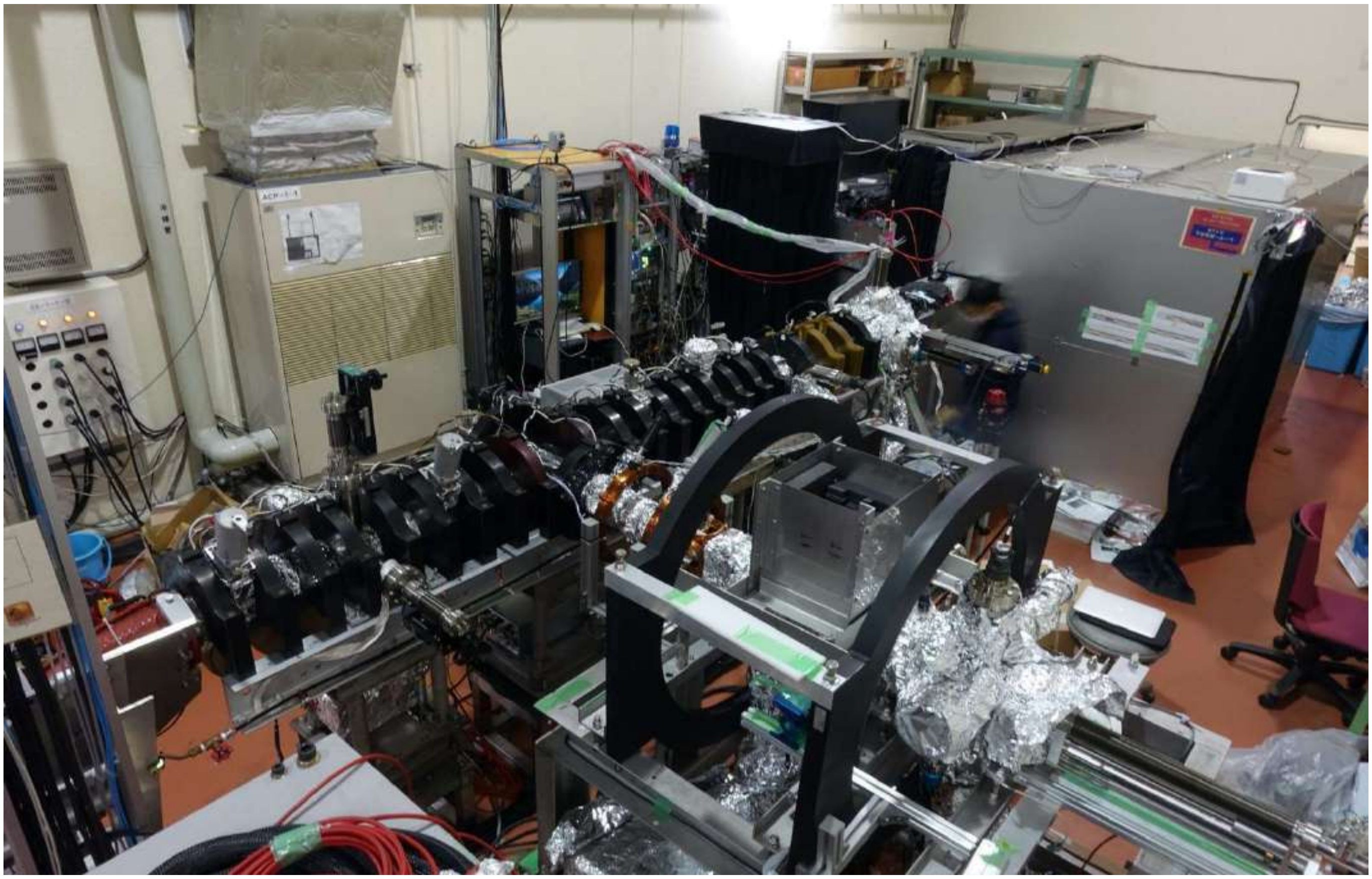
Most atoms are made from positively charged protons, neutral neutrons and negatively charged electrons. Positronium is an exotic atom composed of a single negative electron and a positively charged antimatter positron. It is naturally very short-lived, but researchers including those from the University of Tokyo successfully cooled and slowed down samples of positronium using carefully tuned lasers. They hope this research will help others explore exotic forms of matter, and that such research might unlock the secrets of antimatter.



Multipass amplifier. This eerie green glow comes from the amplification of laser light used to cool positronium. Image credit: Yoshioka et al. CC-BY-ND

Some of our universe is missing. You may have heard such a bizarre statement if you've read much about cosmology in the last few decades. The reason scientists say this is because almost all the stuff we see in the universe is made from matter, including you and the planet you're standing on. However, for a long time we've known about antimatter, which as the name suggests, is sort of the opposite of regular matter, in that antimatter particles share the same mass and other properties of their matter counterparts, but have an opposite charge. When matter and antimatter particles collide, they annihilate, and it's widely believed they were created in equal amounts at the dawn of time. But that's not what we see now.

“Modern physics only accounts for a part of the total energy of the universe. The study of antimatter might help us account for this discrepancy, and we've just taken a big step in this direction with our latest research,” said Associate Professor Kosuke Yoshioka from the Photon Science Center. “We have successfully slowed and cooled down exotic atoms of positronium, which is 50% antimatter. This means that for the first time, it can be explored in ways previously impossible, and that will necessarily include a deeper study of antimatter.”



Positron source. To make positronium, you first need positrons, which are made in a particle accelerator. This apparatus is where positrons from the accelerator are collected to combine with electrons to form positronium. Image credit: Yoshioka et al. CC-BY-ND

Positronium sounds like something straight out of science fiction, and despite being very short-lived, it is very much a real thing. Think of it like the familiar atom hydrogen, with its central, positively charged and relatively large proton and tiny, negatively charged electron in orbit, except you swap the proton for the antimatter version of the electron, the positron. This yields an exotic atom which is electrically neutral but doesn't have a large nucleus; instead the electron and positron exist in mutual orbit, making it a two-body system. Even hydrogen is a multibody system, as a proton is really three smaller particles, called quarks, stuck together. And because positronium is a two-body system, it can be completely described by traditional mathematical and physical theories, making it ideal to test predictions with extreme accuracy.

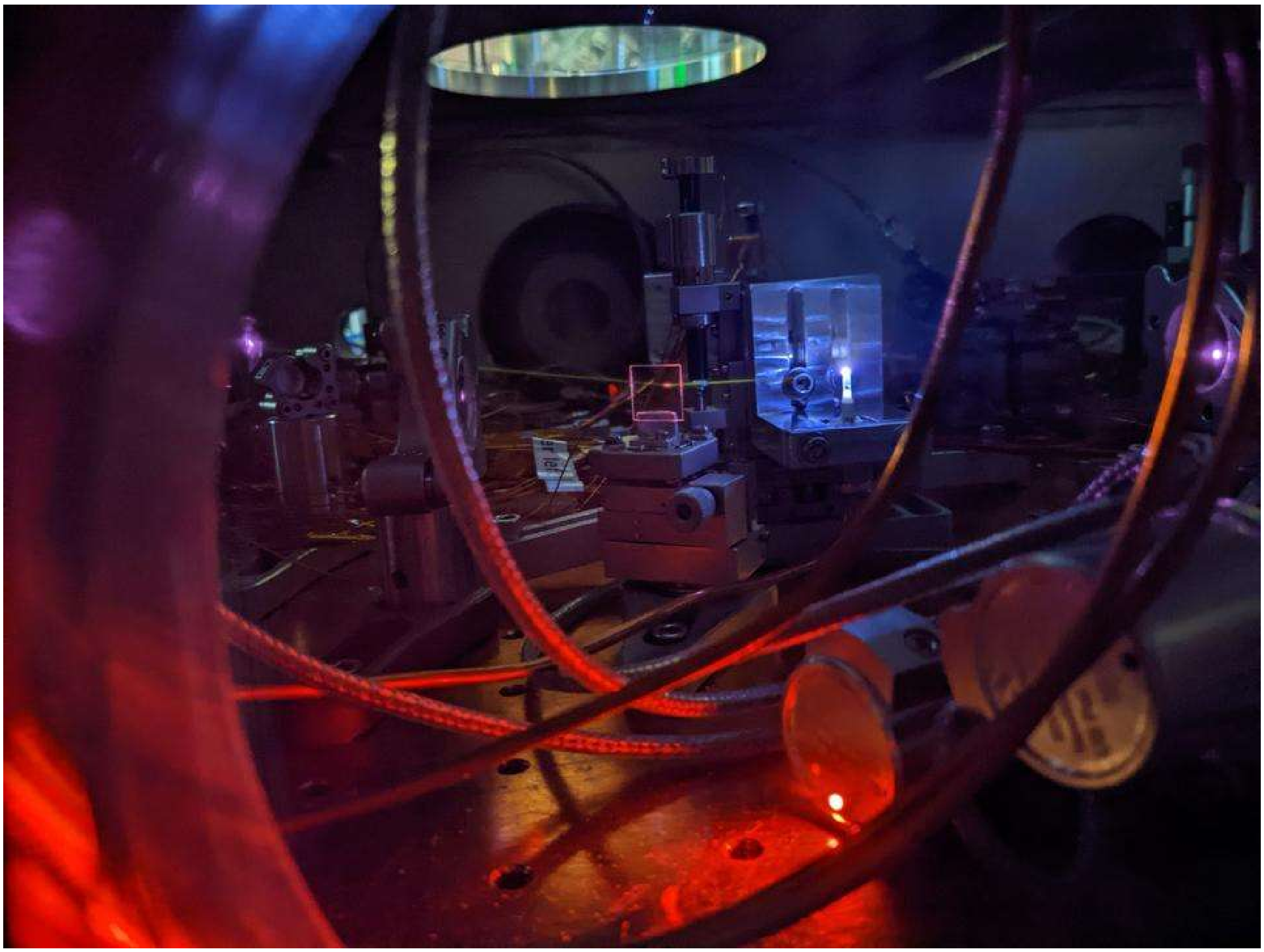
"For researchers like us, involved in what is called precision spectroscopy, being able to precisely examine the properties of cooled positronium means we can compare them with precise theoretical calculations of its properties," said Yoshioka. "Positronium is one of the few atoms made up entirely of only two elementary particles, which allows for such exact calculations. The idea of cooling positronium has been around for around 30 years, but a casual comment by undergraduate student Kenji Shu, who is now an assistant professor in my group, prompted me to take on the challenge of achieving it, and we finally did."

Yoshioka and his team had several difficulties to overcome when trying to cool positronium. Firstly, there is the issue of its short life: one-ten millionth of a second.

Secondly, there is its extreme light mass. As it's so lightweight, you can't use a cold physical surface or other substance to cool positronium down, so the team used lasers. You may think lasers are very hot, but really, they are just packets of light, and it's the way the light is used that determines the physical impact it has on something. In this case, a weak and finely tuned laser gently pushes against a positronium atom in the opposite direction to its movement, slowing it down and cooling it in the process. Doing this repeatedly and in as little as one-ten millionth of a second cooled portions of positronium gas down to about 1 degree above absolute zero (-273 degrees Celsius), the coldest anything can get. Given positronium gas is at 600 kelvins, or 327 degrees Celsius, before cooling, this is quite a dramatic change in such a short space of time.
"Our computer simulations based on theoretical models suggest that the positronium gas might be even colder than we can currently measure in our experiments. This implies that our unique cooling laser is very effective at reducing the temperature of positronium and the concepts can hopefully help researchers study other exotic atoms," said Yoshioka. "This experiment used a laser in just one dimension, however, and if we utilize all three, we can measure the properties of positronium even more precisely. These experiments will be significant because we may be able to study the effect of gravity on antimatter. If antimatter behaves differently to regular matter due to gravity, it could help explain why some of our universe is missing."

Major Leap For Nuclear Clock Paves Way For Ultraprecise Timekeeping

The world keeps time with the ticks of atomic clocks, but a new type of clock under development — a nuclear clock — could revolutionize how we measure time and probe fundamental physics.



A powerful laser shines into a jet of gas, creating a bright plasma and generating ultraviolet light. The light leaves a visible white line as it interacts with leftover gas in the vacuum chamber. This process helps scientists precisely measure the energy needed to excite the thorium-229 nucleus, which is the core of a future nuclear clock. Credit: Chuankun Zhang/JILA

An international research team led by scientists at JILA, a joint institute of the National Institute of Standards and Technology (NIST) and the University of Colorado Boulder, has demonstrated key elements of a nuclear clock. A nuclear clock is a novel type of timekeeping device that would use signals from the core, or nucleus, of an atom. The team used a specially designed ultraviolet laser to precisely measure the frequency of an energy jump in thorium nuclei embedded in a solid crystal. They also employed an optical frequency comb, which acts like an extremely accurate light ruler, to count the number of ultraviolet wave cycles that create this energy jump. While this laboratory demonstration is not a fully developed nuclear clock, it contains all the key technology for one.

Nuclear clocks could be much more accurate than current atomic clocks, which provide official international time and play major roles in technologies and applications such as GPS and internet synchronization, and in financial transactions. For the general public, this development could ultimately mean even more precise navigation systems (with or without GPS), faster internet speeds, more reliable network connections, and more secure digital communications.

Beyond everyday technology, nuclear clocks could improve tests of fundamental theories for how the universe works, potentially leading to new discoveries in physics. They could help detect dark matter or verify if the constants of nature are truly constant, allowing for verification of theories in particle physics without the need for large-scale particle accelerator facilities.

Laser Precision in Timekeeping

Atomic clocks measure time by tuning laser light to frequencies that cause electrons to jump between energy levels. Nuclear clocks would use energy jumps within an atom’s tiny central region, known as the nucleus, where particles called protons and neutrons cram together. These energy jumps are much like flipping a light switch. Shining laser light with the exact amount of energy needed for this jump can flip this nuclear “switch.”

A nuclear clock would have major advantages for clock precision. Compared with the electrons in atomic clocks, the nucleus is much less affected by outside disturbances such as stray electromagnetic fields. The laser light needed to cause energy jumps in nuclei is much higher in frequency than that required for atomic clocks. This higher frequency — meaning more wave cycles per second — is directly related to a greater number of “ticks” per second and therefore leads to more precise timekeeping.

But it is very hard to create a nuclear clock. To make energy jumps, most atomic nuclei need to be hit by coherent X-rays (a high-frequency form of light) with energies much greater than those that can be produced with current technology. So scientists have focused on thorium-229, an atom whose nucleus has a smaller energy jump than any other known atom, requiring ultraviolet light (which is lower in energy than X-rays).

In 1976, scientists discovered this thorium energy jump, known as a “nuclear transition” in physics language. In 2003, scientists proposed using this transition to create a clock, and but they didn’t directly observe it until 2016. Earlier this year, two different research teams used ultraviolet lasers they created in the lab to flip the nuclear “switch” and measure the wavelength of light needed for it.

In the new work, the JILA researchers and their colleagues create all the essential parts of a clock: the thorium-229 nuclear transition to provide the clock’s “ticks,” a laser to create precise energy jumps between the individual quantum states of the nucleus, and a frequency comb for direct measurements of these “ticks.” This effort has achieved a level of precision that is one million times higher than the previous wavelength-based measurement. In addition, they compared this ultraviolet frequency directly to the optical frequency used in one of the world’s most accurate atomic clocks, which uses strontium atoms, establishing the first direct frequency link between a nuclear transition and an atomic clock. This direct frequency link and increase in precision are a crucial step in developing the nuclear clock and integrating it with existing timekeeping systems.

The research has already yielded unprecedented results, including the ability to observe details in the thorium nucleus’s shape that no one had ever observed before — it’s like seeing individual blades of grass from an airplane.

The team presents its results in the Sept. 4 issue of the journal *Nature* as a cover story.

Toward a Nuclear Future

While this isn’t yet a functioning nuclear clock, it is a crucial step toward creating such a clock that could be both portable and highly stable. The use of thorium embedded in a solid crystal, combined with the nucleus’s reduced sensitivity to external disturbances, paves the way for potentially compact and robust timekeeping devices.

“Imagine a wristwatch that wouldn’t lose a second even if you left it running for billions of years,” said NIST and JILA physicist Jun Ye. “While we’re not quite there yet, this research brings us closer to that level of precision.”

The research team included researchers from JILA, the Vienna Center for Quantum Science and Technology, and IMRA America Inc.

Paper: Chuankun Zhang, Tian Ooi, Jacob S. Higgins, Jack F. Doyle, Lars von der Wense, Kjeld Beeks, Adrian Leitner, Georgy Kazakov, Peng Li, Peter G. Thirolf, Thorsten Schumm and Jun Ye. Frequency ratio of the ^{229m}Th nuclear isomeric transition and the ^{87}Sr atomic clock. *Nature.* Published online Sept 4, 2024. DOI: 10.1038/s41586-024-07839-6

Boosting The Frequency Of Sound Waves To Make The Next Generation Of Wireless Devices

Vincent Kerler, a second-year physics major in the College of Arts and Sciences, says he spent his summer running "a whole bunch of simulations to explore how mechanical waves move through a class of materials that convert mechanical stress into electricity and vice versa, or piezoelectric nanomaterials."

Under the guidance of Yue Jiang(left), a Ph.D. candidate in the Charlie Johnson research group in the School of Arts & Sciences, Vincent Kerler (right) conducted this work through the Penn Undergraduate Researching Mentoring Program, a 10-week opportunity from the Center for Undergraduate Research and Fellowships. The program provides rising second- and third-year students with $5,000 awards to work alongside Penn faculty.

His goal? To identify the best crystal structures and material compositions that could reduce reflections and lost power, thereby enhancing the performance of mechanical waves in wireless communications devices like cell phones.

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“What we want is to have the wave propagate through the crystal without really bouncing back at that boundary because that’s where energy gets lost,” says Kerler, who is from Columbus, Ohio. “So, I used software to model the behavior of the waves in our materials and specifically looked at how crystal lattice structures, sizes, and gradients impact their properties and reduce reflection at the boundaries.”

Specifically, Kerler is looking at ultrathin films, where their extent is much larger than their actual thickness, that have a coupling between the mechanical stress and their electromagnetic properties.

“If you deform them, you get a voltage across them, or, if you put a voltage across them, there might be deformation,” Kerler says.

“This new, exciting area of condensed matter physics,” Johnson says, “pretty much started with two of my Penn colleagues, Gene Mele and Charlie Kane, who popularized the concept of topological insulators. These are materials where the topology—a kind of geometry that focuses on the properties of space that are preserved under continuous transformations—plays a critical role in how electrons move within a crystal.”

Their work laid the foundation for a new understanding of quantum mechanics, “but it didn’t stop there,” Johnson says, “as researchers soon realized that the same principles could be applied to other types of waves, not just electrons.”

Johnson explains that his lab is interested in getting these mechanical waves, which are essentially sound waves the researchers call phonons, to operate at higher frequencies. The higher frequencies are analogous to the electromagnetic spectrum, the set of wave-based data transmission that radios, mobile phones, and other wireless devices use.

“What Vincent learns from these simulations might possibly be useful in current and future generations of cell phones because the frequency of the sound wave that we’re working with right now is of the order of one gigahertz, which is right in a cell phone band,” Johnson says.

Though the work involved hours of running simulations, often waiting as long as three hours for results, Kerler found it rewarding.

“It’s a slow process, but seeing patterns form in the data is really exciting,” he says. “My enthusiasm for the project really grew as I saw how small tweaks in the crystal structure could lead to significant changes in wave behavior. Again, it’s not fast work, and there were moments where I had to scrap an entire week’s worth of tests, but when things start to come together it’s so worth it.”

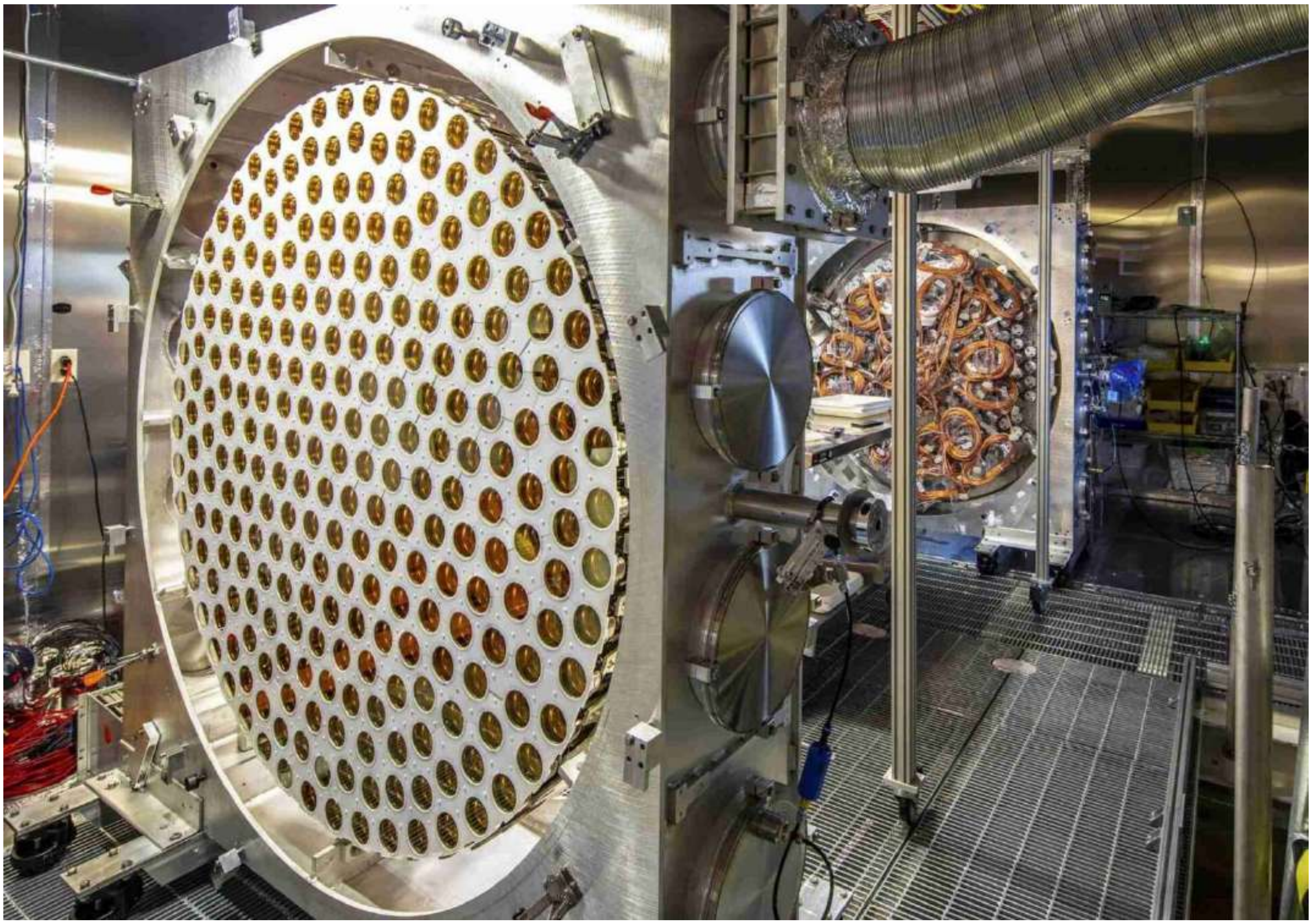
Looking ahead, the next steps in Kerler’s research involve further refining these simulations to achieve even more precise control over wave behavior. As Johnson points out, “If we could do better at bringing the energy in, then that would make all of our experiments better.” This could involve transitioning from the theoretical models that Kerler is working with to physical experiments at the Singh Center for Nanotechnology’s nanofabrication facility.

In addition, the team is exploring the use of advanced materials, such as scandium-doped aluminum nitride, which offer the promise of even higher piezoelectric coupling and, therefore, higher frequency resonances.

“There’s still so much more to explore, and I’m really fascinated by the potential of these materials,” Kerler says.

New Record Set In The Search For Dark Matter—With A Major Assist From Rochester Scientists

Thanks to a data acquisition system developed at the University of Rochester, scientists have searched more widely than ever before for the elusive makeup of so-called dark matter.



GROUND ZERO: Lower (left) and upper photomultiplier tube arrays are prepared for LZ at the Sanford Underground Research Facility in Lead, South Dakota. Image credit: Matthew Kapust / Sanford Underground Research Facility

The result was announced by Lawrence Berkeley National Laboratory, which leads an experiment using the world's most sensitive dark matter detector, the LUX-ZEPLIN (LZ), from 4,850 feet below the surface at the Sanford Underground Research Facility in South Dakota.

Eight students and researchers from the University of Rochester are part of the LZ collaboration, which consists of roughly 250 scientists from 38 institutions around the world. The Rochester group is led by Frank Wolfs, a professor in the Department of Physics and Astronomy.

"It is a reflection of the quality of our team that a small group such as ours can have such a major impact on one of the most intriguing problems in modern physics," Wolfs says.

5X better result with data acquisition system from Rochester

The galaxies of the universe are thought to be swaddled in dark matter. What has puzzled astronomers, though, is what makes up dark matter.

The prevailing theory is that it consists of WIMPs, or weakly interacting massive particles. Although no one has ever seen a WIMP, scientists at the LZ collaboration have been actively looking.

Now, according to the LZ collaboration, their search has probed deeper than any previous experiment partly because of the University of Rochester's contribution. The experiment's new result further limits what WIMPs could be.

"If you think of the search for dark matter like looking for buried treasure, we've dug almost five times deeper than anyone else has in the past," says Scott Kravitz, LZ's deputy physics coordinator and a professor at the University of Texas at Austin. "That's something you don't do with a million shovels. You do it by inventing a new tool."

One of the new tools is the digital electronics hardware for the LZ data acquisition system built in Rochester.

The hardware was developed by a small local electronics company, SkuTek Instrumentation, dedicated to serving physics researchers worldwide. The firmware for the data acquisition system was developed at the University of Rochester.

Leading efforts to better understand WIMPs

Overseeing the operation of the electronics system are senior scientist Dev Ashish Khaitan and senior research engineer Eryk Druszkiewicz of the University of Rochester.

"It is both exhilarating and humbling to build the tools that could help us unlock the deepest mysteries of the universe with the talented Rochester dark matter group," Khaitan says.

The Rochester group leads the efforts to explore unique couplings of WIMPs to baryonic matter and is pioneering the search for neutrino signals from distant core-collapse supernovae—a signal that might only occur three times per century in the Milky Way.

“It is exciting to be processing signals at rates in excess of half a terabyte per second continuously for years when trying to solve the puzzle of the universe’s composition,” Druszkiewicz says.

The latest result analyzes 280 days’ worth of data. The experiment plans to collect 1,000 days’ worth of data before it ends in 2028.

Work Starts On Machine To Solve One Of Science's Biggest Mysteries: Detecting Dark Matter Particles

University of Liverpool researchers are part of a UK collaboration that has begun designing a new device to detect the elusive dark matter particles thought to make up more than 85% of the content of the Universe.

Image credit: University of Liverpool

A preliminary award of £8 million from the UKRI Infrastructure Fund will support a consortium of UK universities, led by Imperial College London, to work with the Science and Technology Facilities Council (STFC) Boulby Underground Laboratory over the next three-and-a-half years.

As part of the world-leading Xenon Lux-Zeplin Darwin (XLZD) Consortium for dark matter research, the team will develop initial plans and design components for the world's largest and most advanced dark matter detector. Once completed, this international experiment could be hosted at the UK's deep underground science facility at Boulby mine in the North East of England.

A new frontier

One of the primary aims of the international XLZD Consortium is to build a definitive experiment to detect dark matter and explore its properties and origin.

The detector will consist of a large underground “thermos flask” containing up to 100T of liquid xenon, which scientists believe will react subtly with dark matter as it passes through the Earth. Tiny, but detectable, flashes of light will be generated as evidence of the presence of dark matter particles and recorded for scientists to analyse.

The experiment has the potential to change our understanding of physics in the same way that CERN’s Large Hadron Collider did when it detected the Higgs Boson particle in 2012. The XLZD observatory will explore the fundamental laws of physics but also acts as a telescope for the nature and composition of our universe, searching for dark matter particles and new neutrino physics.

Professor Sean Paling, Director and Senior Scientist at STFC’s Boulby Underground Laboratory said: “To discover, or even be able to rule out the existence of dark matter, will be an enormous leap for science and transform our understanding of the cosmos.

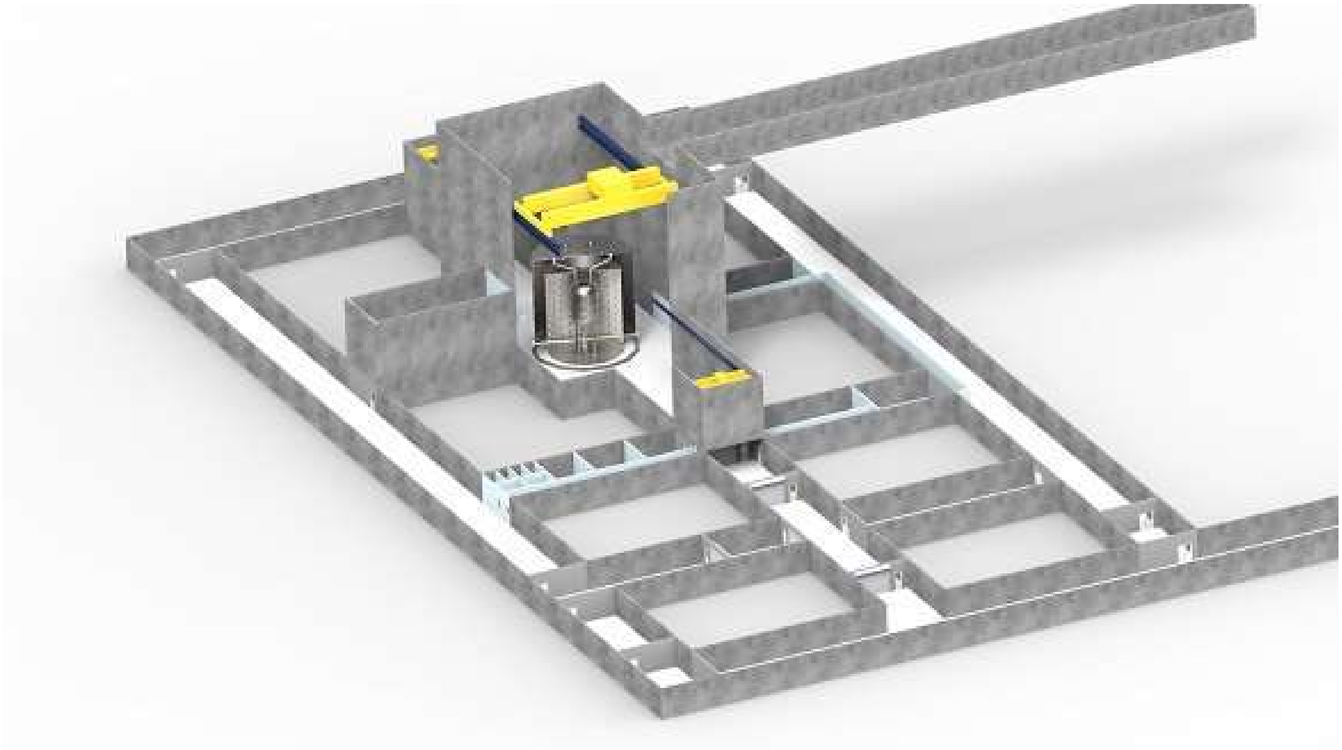
“We are now closer than ever to achieving this and as long as we can come together as an international community, invest in the right instruments, and remain focussed on our search, there are potential big breakthroughs just around the corner.

“The XLZD experiment is the clear next step for dark matter research and will also be an important instrument for understanding wider fundamental questions about the content of our universe. I’m delighted that Boulby, Imperial, and all contributing UK institutions are playing this key role in making it a reality.”

Professor Sergey Burdin, from the Department of Physics at the University of Liverpool, said: “This award, as well as the LZ results announced in August, demonstrates our strength and engagement in the highest quality science. A major opportunity to have a large-scale international experiment in the north of England certainly adds more excitement to this proposal.

“Here at Liverpool, we will lead the work on the Outer Detector which is based on our LZ expertise and strong synergy with the BUTTON@Boulby project led by Professor Jon Coleman.

“The XLZD@Boulby project represents a huge challenge including clean manufacturing underground and environmental sustainability of the experiment. This is also a great opportunity to expand the work on Dark Matter searches in Liverpool and create stronger links with theorists and engineers.”



Concept for the underground lab layout. Image Credit: Liam Cooper, STFC Technology Department

Laying the groundwork

The preliminary funding from the UKRI Infrastructure Fund will be instrumental in devising initial plans for how best to host and run the experiment in the near future and developing essential components required for constructing the detector.

UK project leader Professor Henrique Araújo, from Imperial College London, added: "Several underground laboratories around the world are bidding to host our experiment; this is fantastic "discovery science", using the leading technology which we helped pioneer in the UK – and this development project is critical to position the UK to host. We must now show that this is viable!"

Although it remains to be decided exactly where the experiment will be located, this foundational work by UK universities and Boulby Underground Laboratory will be crucial in deciding how best to build the experiment for success. If the project is hosted at Boulby, this will be amongst the largest and most significant UK-based science projects in over 50 years, attracting international scientists to the North East region.

The project team comprises researchers from the institutions Birmingham University, Bristol University, Edinburgh University, Imperial College London, King's College London, the University of Liverpool, Oxford University, Queen Mary, Royal Holloway, University of London, Sheffield University, Sussex University and teams from STFC’s Daresbury and Rutherford Appleton Laboratories.

This internationally collaborative effort highlights the UK’s strong commitment to advancing scientific research and its capability to contribute significantly to common worldwide scientific endeavours.

END OF NEWS LETTER

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