'Ghostly' neutrinos provide new path to study protons

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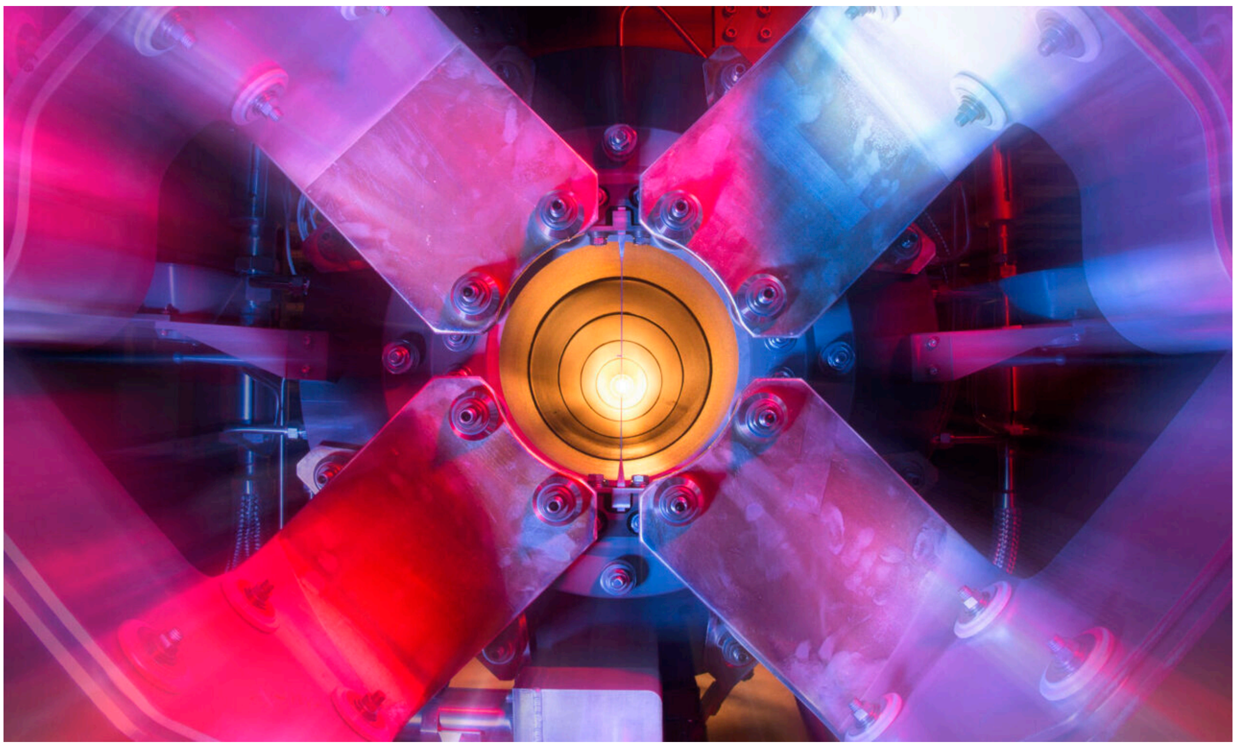

Members of the international collaboration MINERvA, including University of Rochester researchers, used a particle accelerator at Fermilab—a portion of which is shown in a stylized image above—to create a beam of neutrinos to investigate the structure of protons. The work was part of the MINERvA experiment, a particle physics experiment to study neutrinos. Credit: Reidar Hahn/Fermilab

Neutrinos are one of the most abundant particles in our universe, but they are notoriously difficult to detect and study: they don't have an electrical charge and have nearly no mass. They are often referred to as "ghost particles" because they rarely interact with atoms.

But because they are so abundant, they play a large role in helping scientists answer fundamental questions about the universe.

In groundbreaking research described in *Nature*—led by researchers from the University of Rochester—scientists from the international collaboration MINERvA have, for the first time, used a beam of neutrinos at the Fermi National Accelerator Laboratory, or Fermilab, to investigate the structure of protons.

MINERvA is an experiment to study neutrinos, and the researchers did not set out to study protons. But their feat, once thought impossible, offers scientists a new way of looking at the small components of an atom's nucleus.

"While we were studying neutrinos as part of the MINERvA experiment, I realized a technique I was using might be applied to investigate protons," says Tejin Cai, the paper's first author. Cai, who is now a postdoctoral research associate at York University, conducted the research as a Ph.D. student of Kevin McFarland, the Dr. Steven Chu Professor in Physics at Rochester and key member of the University's Neutrino Group.

"We weren't sure at first if it would work, but we ultimately discovered we could use neutrinos to measure the size and shape of the protons that make up the nuclei of atoms. It's like using a ghost ruler to make a measurement."

Using particle beams to measure protons

Atoms, and the protons and neutrons that make up an atom's nucleus, are so small that researchers have a difficult time measuring them directly. Instead, they build a picture of the shape and structure of an atom's components by bombarding atoms with a beam of high-energy particles. They then measure how far and at what angles the particles bounce off the atom's components.

Imagine, for example, throwing marbles at a box. The marbles would bounce off the box at certain angles, enabling you to determine where the box was—and to determine its size and shape—even if the box was not visible to you.

"This is a very indirect way of measuring something, but it allows us to relate the structure of an object—in this case, a proton—to how many deflections we see in different angles," McFarland says.

What can neutrino beams tell us?

Researchers first measured the size of protons in the 1950s, using an accelerator with beams of electrons at Stanford University's linear accelerator facility. But instead of using beams of accelerated electrons, the new technique developed by Cai, McFarland, and their colleagues, uses beams of neutrinos.

While the new technique does not produce a sharper image than the old technique, McFarland says, it may give scientists new information about how neutrinos and protons interact—information they can currently only infer using theoretical calculations or a combination of theory and other measurements.

In comparing the new technique with the old, McFarland likens the process to seeing a flower in normal, visible light and then looking at the flower under ultraviolet light.

"You are looking at the same flower, but you can see different structures under the different kinds of light," McFarland says. "Our image isn't more precise, but the neutrino measurement provides us with a different view."

Specifically, they are hoping to use the technique to separate the effects related to neutrino scattering on protons from the effects related to neutrino scattering on atomic nuclei, which are bound collections of protons and neutrons.

"Our previous methods for predicting neutrino scattering from protons all used theoretical calculations, but this result directly measures that scattering," Cai says.

McFarland adds, "By using our new measurement to improve our understanding of these nuclear effects, we will better be able to carry out future measurements of neutrino properties."

The technical challenge of experimenting with neutrinos

Neutrinos are created when atomic nuclei either come together or break apart. The sun is a large source of neutrinos, which are a byproduct of the sun's nuclear fusion. If you stand in the sunlight, for example, trillions of neutrinos will harmlessly pass through your body every second.

Even though neutrinos are more abundant in the universe than electrons, it is harder for scientists to experimentally harness them in large numbers: neutrinos pass through matter like ghosts, while electrons interact with matter far more frequently.

"Over the course of a year, on average, there would only be interactions between one or two neutrinos out of the trillions that go through your body every second," Cai says. "There's a huge technical challenge in our experiments in that we have to get enough protons to look at, and we have to figure out how to get enough neutrinos through that big assembly of protons."

Using a neutrino detector

The researchers solved this problem in part by using a neutrino detector containing a target of both hydrogen and carbon atoms. Typically researchers use only hydrogen atoms in experiments to measure protons. Not only is hydrogen the most abundant element in the universe, it's also the simplest, as a hydrogen atom contains only a single proton and electron. But a target of pure hydrogen wouldn't be sufficiently dense for enough neutrinos to interact with the atoms.

"We're performing a 'chemical trick', so to speak, by binding the hydrogen up into hydrocarbon molecules that make it able to detect sub-atomic particles," McFarland says.

The MINERvA group conducted their experiments using a high-power, high-energy particle accelerator, located at Fermilab. The accelerator produces the strongest source of high-energy neutrinos on the planet.

The researchers struck their detector made of hydrogen and carbon atoms with the beam of neutrinos and recorded data for nearly nine years of operation.

To isolate only the information from the hydrogen atoms, the researchers then had to subtract the background "noise" from the carbon atoms.

"The hydrogen and carbon are chemically bonded together, so the detector sees interactions on both at once," Cai says. "I realized that a technique I was using to study interactions on carbon could also be used to see hydrogen all by itself once you subtract the carbon interactions. A big part of our job was subtracting the very large background from neutrinos scattering on the protons in the carbon nucleus."

Says Deborah Harris, a professor at York University and a co-spokesperson for MINERvA, "When we proposed MINERvA, we never thought we'd be able to extract measurements from the hydrogen in the detector. Making this work required great performance from the detector, creative analysis from scientists, and years of running" the accelerator at Fermilab.

The impossible becomes possible

McFarland, too, initially thought it would be close to impossible to use neutrinos to precisely measure the signal from the protons.

"When Tejin and our colleague Arie Bodek (the George E. Pake Professor of Physics at Rochester) first suggested trying this analysis, I thought it would be too difficult," McFarland says. "But the old view of protons has been very thoroughly explored, so we decided to try this technique to get a new view—and it worked."

The collective expertise of MINERvA's scientists and the collaboration within the group was essential in accomplishing the research, Cai says.

"The result of the analysis and the new techniques developed highlight the importance of being creative and collaborative in understanding data," he says. "While a lot of the components for the analysis already existed, putting them together in the right way really made a difference, and this cannot be done without experts with different technical backgrounds sharing their knowledge to make the experiment a success."

In addition to providing more information about the common matter that comprises the universe, the research is important for predicting neutrino interactions for other experiments that are trying to measure the properties of neutrinos. These experiments include the Deep Underground Neutrino Experiment (DUNE), the Imaging Cosmic And Rare Underground Signals (ICARUS) neutrino detector, and T2K neutrino experiments in which McFarland and his group are involved.

"We need detailed information about protons to answer questions like which neutrinos have more mass than others and whether or not there are differences between neutrinos and their anti-matter partners," Cai says. "Our work is one step forward in answering the fundamental questions about neutrino physics that are the goal of these big science projects in the near future."

More information: Tejin Cai, Measurement of the axial vector form factor from antineutrino-proton scattering, *Nature* (2023). DOI: 10.1038/s41586-022-05478-3.
www.nature.com/articles/s41586-022-05478-3

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