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Neutrinos offer a new way to investigate the building blocks of matter

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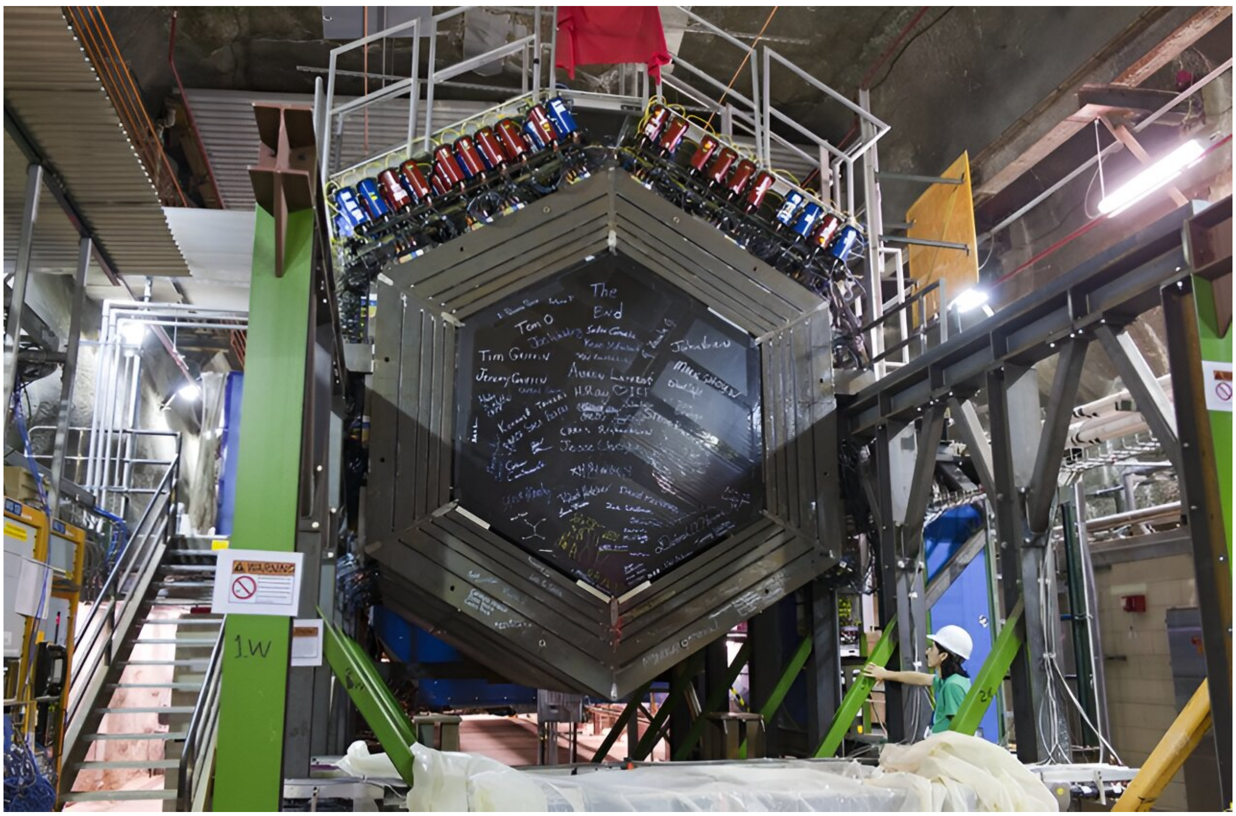

The particle detector used in the MINERvA experiment enabled scientists at DOE’s Fermilab to use neutrinos to measure the size and structure of protons. Credit: Fermilab

Depictions of the Roman goddess of wisdom Minerva show her in flowing robes, wearing a noble war helmet and holding an owl. In contrast, the MINERvA experiment features a huge particle detector with the names of collaborating scientists scrawled on the front of it.

While quite different in appearance, this neutrino experiment provides deep wisdom to scientists just like its namesake represented. Among its many insights, scientists have used MINERvA to better understand the size and structure of protons, one of the building blocks of atoms.

MINERvA is a neutrino scattering experiment at the Department of Energy's Fermilab. Neutrinos are tiny, electrically neutral particles that are incredibly abundant. The sun, other stars, and many different objects produce them as a result of atomic reactions. In fact, there are more neutrinos in the universe than any other particle that has mass.

Despite being ubiquitous, we never notice neutrinos because they hardly ever react with anything. Studying neutrinos is essential to understanding how our universe formed in the past and functions now.

To better understand this fundamental particle, scientists study how neutrinos interact with materials on the rare occasions that they actually do. MINERvA's mission is to capture these interactions.

It uses a high-intensity neutrino beam to study how they interact with the nuclei of five different elements. By having the neutrinos hit targets made of different materials—water, helium, carbon, iron, lead, and plastic—scientists can compare the reactions. Charting out the different interactions will help scientists analyze the results of other experiments like the upcoming Deep Underground Neutrino Experiment.

In addition to this goal, scientists from the MINERvA collaboration figured out another clever use for their data—to investigate the proton's size and structure.

Along with neutrons, protons make up the nuclei of the atoms that make up us and everything around us. They're one of the building blocks of matter we interact with every day.

But studying subatomic particles is a lot trickier than studying larger objects. Subatomic particles are far too small to study with ordinary tools like microscopes. In addition, the "size" of a subatomic particle doesn't quite have the same meaning as the size of an object you can measure with a ruler. Instead, scientists study the forces that hold the proton together.

In the past, scientists have studied the proton's size using the electromagnetic force. Electromagnetism is one of the four fundamental forces of the universe. Magnetic fields, electrical fields, and even light fall under the electromagnetic force. It binds electrons to the nucleus (made of protons and neutrons) in the atom. It's also partly responsible for the structure of the nucleus.

To represent the proton's size, scientists have typically used the electric charge radius. That's the average radius of the electric charge distributed in the proton. To measure this characteristic, scientists aim a beam of electrons at a single energy at a target. The electrons fly away from the protons in many different directions and energies, which gives scientists information about the internal structure of the protons.

Using this technique, scientists have been able to make a very precise measurement of the size of the average electric charge radius of the proton, and therefore the quarks that provide the electric charge.

Led by Tejin Cai (then a Ph.D. student at the University of Rochester), the MINERvA collaboration had a different approach. The idea was to use antineutrinos—the antimatter twin of neutrinos—to study protons.

Because neutrinos (and antineutrinos) don't have a charge, they wouldn't interact via the electromagnetic force. Instead, the neutrinos would interact via the weak force in the protons. The weak force and gravity are the only two ways neutrinos interact with anything.

Despite its name, the weak force is powerful. Another one of those four fundamental forces, it enables the process by which protons turn into neutrons or vice versa. These processes are what drive the sun and other stars' nuclear reactions. Neutrinos offer a unique tool to study the weak force.

But the weak force only comes into play when particles are very, very close together. As neutrinos are soaring through space, they're usually moving through the (comparatively) vast spaces between an atom's electrons and nucleus.

Most of the time, neutrinos simply aren't close enough to protons for them to interact via the weak force. To possibly get enough measurements, scientists need to shoot staggering numbers of neutrinos or antineutrinos at a target.

MINERvA's powerful neutrino beam and diverse targets made that goal possible. In an ideal world, scientists would aim neutrinos at a target made of pure neutrons, or antineutrinos at a target made of pure protons. In this way, scientists could get the most specific measurements. Unfortunately, that's not a very realistic experimental setup.

But MINERvA already had the next best thing—a lot of antineutrinos and a target made of polystyrene. The material that makes up Styrofoam, polystyrene is made of hydrogen bonded to carbon. Using this target, scientists would get measurements of how antineutrinos interact with both hydrogen and carbon.

To separate hydrogen from carbon, the scientists took an approach similar to taking a photo and then deleting the background to allow you to focus on just a few items. To determine those "background" neutrino-carbon interactions, the scientists looked at neutrons.

When antineutrinos interact with protons in carbon or protons by themselves in hydrogen, they produce neutrons. By tracking the neutrons, scientists could work backwards to identify and remove the carbon-antineutrino interactions from the hydrogen-antineutrino interactions.

Getting the needed number of interactions truly tested MINERvA's capabilities. Over the course of three years, scientists recorded more than a million interactions of antineutrinos with other particles. A mere 5,000 of those were with hydrogen.

That data finally allowed the scientists to calculate the proton's size using neutrinos. Instead of the electric charge radius, they calculated the proton's weak charge radius. It was the first time that scientists have used neutrinos to make a statistically significant measurement of this characteristic.

Considering uncertainties, the result was very close to the previous measurements of the proton's electric charge radius. Since it is fundamentally measuring the spatial distribution of quarks and gluons that make up the proton, the value was expected to be similar.

This new technique gives scientists another tool in their toolkit to study the proton's structure. It's a testament to the wisdom we can gain when scientists think creatively about using existing experiments to explore new areas of research.

Provided by US Department of Energy

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