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JEFF LAB SHINES LIGHT ON UNIVERSE'S WEAK FORCE

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The weak force is one of four fundamental forces of nature that, together, prevent all matter in the universe from breaking up and floating away.

Three of those forces — electromagnetism, the strong force and the weak force — are accounted for in the Standard Model of particle physics, or the grand mathematical theory that scientists came up with in the 1970s to try to explain how the quantum world works. The fourth force is gravity.

But particle physicists around the globe are forever poking and prodding at the sub-atomic level to test the

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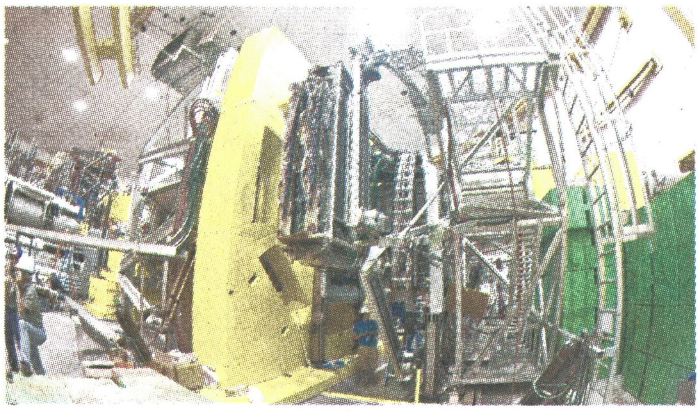

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Shown is the detector system for measuring scattered electrons in the Q-weak experiment. The electromagnet is to the left of the yellow concrete shielding, and several of the eight sets of precision detectors for identifying the electrons are seen at center.

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limits of that model, and to fill in where it falls short. It doesn't account, for instance, for gravity, dark energy or dark matter.

By design, the Standard Model doesn't only account for particles and forces that are already known — it also predicted particles yet to be discovered, like the elusive Higgs boson, dubbed the "God particle," that was finally found in 2012.

"We have reasons to believe that the Standard Model — which has been tremendously, frustratingly successful — that it's not the whole story. That there are other forces or other particles out there in nature," said David Armstrong, chancellor professor of physics at the College of William and Mary in Williamsburg.

"The holy grail of particle and nuclear physics is to look for forces or particles that are beyond the Standard Model of particle physics."

One way to suss out new particles or forces is by using the most powerful, most energetic accelerators in the world — such as the Large Hadron Collider (LHC) in Switzerland — to smash subatomic particles together and see what happens.

Yet another is to make super-precise measurements using accelerator beams that are less energetic, but just as intense, just as bright — like the one at Thomas Jefferson National Accelerator Facility in Newport News.

In fact, that's just what a collaboration of some 100 physicists and graduate students from this country and Canada spent years doing: Using Jefferson Lab's world-class Continuous Electron Beam Accelerator Facility (CEBAF) to make the most precise measurement ever of the weak force's grip on a proton.

Their finding has "significantly refined our understanding of the weak force," said Armstrong, as well as verified for the first time and "to a high degree of precision" what the Standard Model predicts for this property of the proton.

While the so-called Q-weak Collaboration didn't discover an anomaly in the Standard Model, its precise measurement of the weak charge of the proton, compared to the model's prediction, will help physicists going forward.

"Because we were able to

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measure it so precisely, we're able to use that comparison, the difference between what we measured and what was predicted, to place limits on possible new physics beyond the Standard Model," said Greg Smith, nuclear physicist at Jefferson Lab and Q-weak project manager.

Smith, along with Armstrong, are founding members and leaders of the Q-weak Collaboration, which launched in the year 2000.

Exception to the rule

The term "weak force" is a bit of a misnomer.

Because it's responsible for radioactive decay, the weak force is literally the reason the sun shines, by helping to transmute hydrogen to helium. Without the sun, life on Earth wouldn't exist.

Radioactive decay is also important in human health care, enabling various radioisotope imaging diagnostics and nuclear medicine.

The weak force gets its name, said Armstrong, from the fact that it is rather feeble and only manifests itself over very short distances.

"For two objects to have a weak force between them," he said, "they have to be very, very close together — on the scale of the size of atomic nuclei."

The weak force also holds a unique position among the four fundamentals.

"What holds atoms together, what holds the electrons to the nucleus of an atom, is the electromagnetic force," said Armstrong. "What holds the protons and neutrons together in the nucleus is the strong force. What holds the atoms and molecules together into the planets and stars is largely the gravitational force.

"The weak force is the exception to the rule in the sense that it's not so much responsible for holding things together, but allowing things to change."

'We tickled it'

Jefferson Lab was particularly well-suited for the Q-weak experiment.

For one, the measurement didn't call for an "atom-smasher" like the Large Hadron Collider, but for an accelerator that could deliver in other, more subtle ways.

"We're not at the highest energies, but we are at the intensity frontier, which we can use, if you will, to reach the precision frontier," said Smith.

"In many ways, this is the perfect place to do it: We have this very bright beam, and we needed a liquid hydrogen target that's only 20 degrees above absolute zero."

Jefferson Lab's two cryogenic refrigeration plants are the largest single plants in the world, enabling CEBAF to work as a superconducting accelerator. It's that super-cryogenic capability that allowed researchers to keep a liquid hydrogen target cold and stable even as an electron beam with more than 2,000 watts of heat plowed into it.

"To me, it was an amazing accomplishment," Smith said. "It was the highest-power liquid hydrogen target ever built, and we have the most restrictive conditions for its boiling that have ever been accomplished."

Because lower energy was called for, it was important that the experiment run before CEBAF was upgraded to double the energy of its beam, a $338 million renovation completed just last year.

CEBAF can also polarize the beam's electrons, or keep them all spinning in the same direction — a critical factor for this experiment.

"Because the measurement at some level," Armstrong said, "is nothing more than asking this question: How many electrons bounce off the proton when their spin is pointing in the direction they're moving compared to how many bounce off the proton when their spin is pointing opposite to the direction they're moving — what's that difference?

"And it's a tiny, tiny difference. It's a few hundred parts-per-billion difference in the scattering probabilities.

"To measure the weak charge, we didn't smash the atom, we tickled it," Armstrong said.

Moving forward

And so for two years, said Smith, they ran the experiment in 24-hour shifts on the floor, seven days a week, performing measurements millions of billions of times.

"We just gave it our all," Smith said.

After that came five years of painstaking analysis, double- and triple-checking their work.

"We had to chase down every ghost," said Smith. "And to make sure we wouldn't be influenced by unconscious bias, we blinded our result, so that none of us knew until a year ago what our result was.

"That day was really exciting, because we've invested so much in the experiment at that point. We don't know if we're a mile off — it would be exciting, but nobody would believe us — or if we're right on the Standard Model.

"We were kind of hoping to be the ones to find a big deviation, which we didn't find. But, at the same time, because the experiment's so precise, we can put all these really interesting limits on extensions in new physics to the Standard Model that I think will be with us for some time to come."

Their work was just published in the journal "Nature."

"After more than a decade of careful work," said Anne Kinney of the National Science Foundation in a statement, "Q-weak not only informed the Standard Model, it showed that extreme precision can enable moderate-energy experiments to achieve results on par with the largest accelerators available to science. Such precision will be important in the hunt for physics beyond the Standard Model, where new particle effects would likely appear as extremely tiny deviations."

The NSF funded the collaboration at nearly $1 million. Other support came from the U.S. Department of Energy's Office of Science, the Natural Sciences and Engineering Research Council of Canada and the Canadian Foundation for Innovation.

Next up, the physicists hope to get funding to pursue a similar Q-weak measurement of the electron.

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