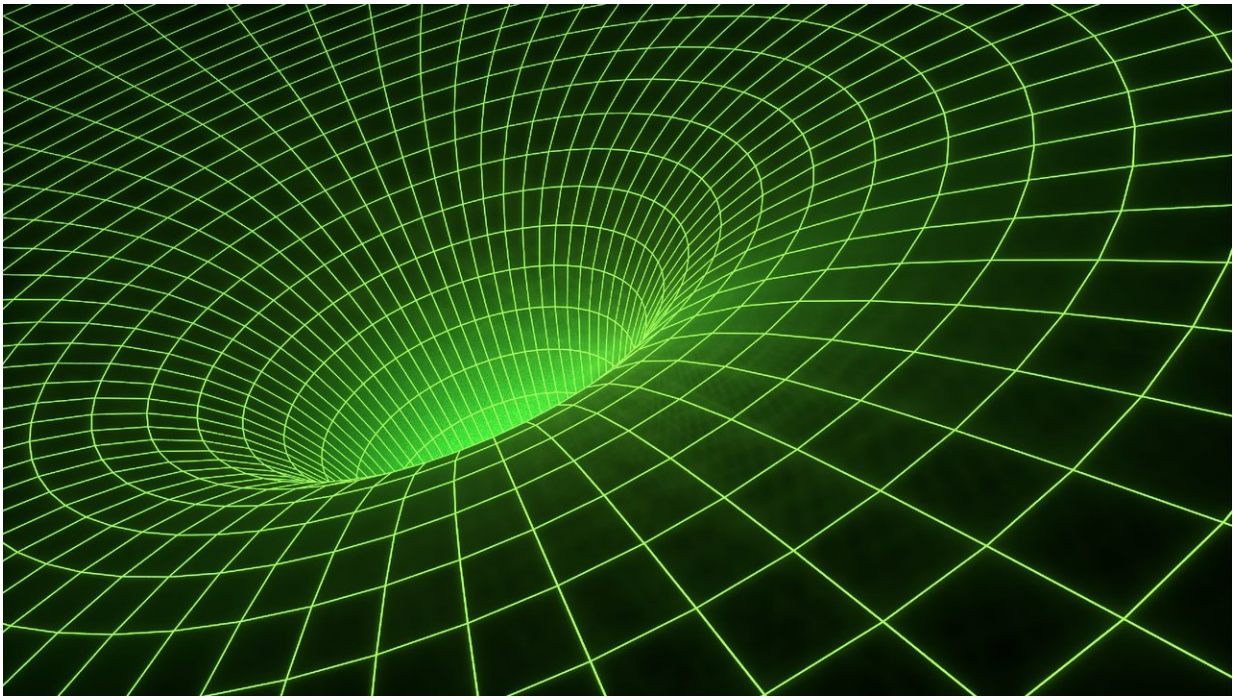
The weak force—life couldn't exist without it

November 15 2018, by Joseph Mcclain



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David Armstrong studies a phenomenon that is ubiquitous in nature, yet only a few non-scientists know what it is.

It's called the weak force, or the weak interaction. Armstrong was recently named a 2018 Fellow of the American Physical Society. His citation reads that the honor is based on "his leadership role in a career-long program of research centered on characterizing and understanding

the role of the weak force and parity-violating phenomena in nuclear physics."

"This is a significant professional honor. The number of fellows elected each year is limited to no more than one half of one percent of the APS membership," said Christopher D. Carone, chair of the William & Mary Department of Physics.

"At present, roughly 30 percent of the regular physics faculty at William & Mary are APS Fellows. I look forward to seeing this percentage grow significantly in future years!" Carone added.

Armstrong came to William & Mary in 1994. Now, as Chancellor Professor of Physics, divides his time between Small Hall and the Jefferson Lab, where he collaborates on a number of particle-physics experiments, most of which involve the weak force. When Armstrong talks about his work to people who don't speak physics, he starts by explaining that the weak force is one of the four fundamental interactions that keep the universe running.

"Two of them are familiar to most of us," Armstrong said. "Gravity: it keeps the planets in orbit around the sun and keeps us affixed to the Earth. Electricity and magnetism: We've learned since Maxwell that they're two aspects of the same force. We're familiar with those, and electromagnetism is what's responsible for the electrons staying in orbit around the nucleus. Basically, all of chemistry arises from electricity and magnetism."

Less familiar to the lay public, he said, are the two nuclear forces. The strong force holds together the protons and neutrons (and their constituent quarks) in the nucleus. The last, and least familiar, of the fundamental interactions is the weak force, responsible for certain kinds of radioactive decay.

"Unlike those other interactions, I can't give you an example of something that's held together by the weak force," Armstrong said. "But the weak force is incredibly important, because life wouldn't exist without it."

He pointed out that the fusion process in the sun, whereby hydrogen atoms glom onto one another to become helium, is an example of the weak force in action. A critical step in that reaction chain takes place through the weak force, so in fact the weak force drives the sun's nuclear furnace.

"If the weak interaction were significantly stronger than it is, then the sun would have burned out years ago," he said. "If the weak interaction were weaker, then the sun wouldn't have ignited."

"Certain kinds of radioactive decay, which are often useful in things like medical imaging, take place through the weak interaction," he explained.

His early research involved a particle called the muon, which he called "the electron's short-lived, heavier sister." ("I don't know why, but the muon seems female to me," he said.)

The muon is 200 times more massive than the electron, but can do everything that an electron does. For example, Armstrong said physicists can make an atom in which muons replace electrons. This ability to switch roles stems from a characteristic unique to the weak interaction.

"It allows particles to transmute —to change their nature," Armstrong said. "The muon will decay through the weak interaction into other particles. The muon typically decays into an electron and a couple of neutrinos."

The muon's weak force-driven superpower of transmogrification allows

it to interact with the nucleus, as well, converting protons into neutrons, with some neutrinos as change.

"So a lot of my research initially was based on understanding the weak interactions of protons and neutrons in nuclei," he said.

Shortly after he came to JLab and William & Mary, 25 years ago, he realized that there was an opportunity to use his investigation of the weak force of muons and apply it to the weak force of the muon's more svelte sibling, the electron.

Armstrong is part of Qweak Collaboration, a collection of scientists who recorded the first-ever direct measurement of the weak charge of the proton at the Department of Energy's JLab facility. In his most recent work, Armstrong is using another property unique to the weak force in his experiments.

"It violates a symmetry of nature called parity," he explained. "Symmetries are extremely important in physics; they tell us something fundamental is going on."

Parity exists when a "mirror image" of a system (one in which all the pluses and minuses are changed) is identical to the original system. Parity is a property of gravity, electromagnetism, the strong force—and for a long while, parity was believed to be a universal property of the universe.

"In the 1950s, we found that wasn't the case, solely due to the weak interaction," Armstrong said. If your reflection in a mirror revealed, say, an extra finger, that would be pretty weird, especially when you look down at your hand and see no new digits. It's an analogue of parity violation, but not a complete one: Unlike an extra pinkie in the mirror, parity violation in the weak force is completely natural.

And, for scientists, the odd-one-out parity status of the weak force gives Armstrong and other physicists an entry point into the pursuit of new physics, beyond the Standard Model. This pursuit involves investigation into the weak force and other areas beyond everyday perception, such as gravitational waves, neutrinos and quarks.

In addition to the Q-Weak experiment at JLab, Armstrong also studies the quarks that make up protons and neutrons. There are six quarks, elementary particles within the Standard Model that carry a set of unusual names: top, bottom, up, down, strange and charm.

"I can identify the different kinds of quarks through their weak interactions," he said. Up and down quarks are the elementary building blocks of matter, as they assemble into protons and neutrons, and Armstrong and his collaborators were able to use the weak force to learn about the contribution of the strange quark to the size and magnetic moment of the proton.

He's involved in an upcoming JLab experiment that uses parity violation to examine a very heavy nucleus: lead.

"Lead has more neutrons than protons," Armstrong said. "Therefore, one might expect that the distribution of neutrons in a lead nucleus would cause them to 'stick out'—making a neutron skin on the outside of the nucleus.

"It turns out that the weak interaction is a great way to look for that," he added. "Because the neutrons interact differently than the protons."

The neutron skin, he said, remains theoretical. But he hopes his experiment will be the first to confirm it observationally. It would be an important observation with cosmological implications.

"Not only does it tell us about nuclei, but it also connects with things of interest to astronomers and astrophysicists," Armstrong explained. "Because a neutron star is nothing more than the universe's biggest nucleus—and one that is dominated by neutrons."

Provided by The College of William & Mary

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