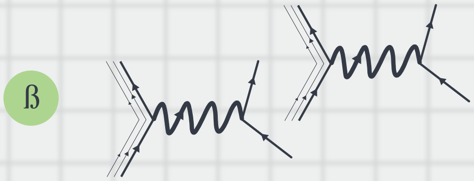
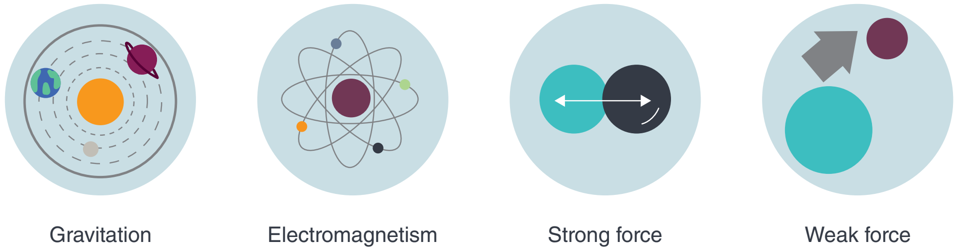


# SMALL THINGS CONSIDERED

FOUR FUNDAMENTAL FORCES OF PHYSICS



The fundamental forces of nature are gravitation, electromagnetic force, the strong force, and the weak force.

GRAVITY. Electromagnetism. The strong nuclear force. The weak nuclear force. Four fundamental forces of nature govern everything that happens in the universe. The first two are readily observed in everyday life. Detecting the latter two calls for a dive into subatomic realms. Whereas the strong nuclear force holds atomic nuclei together and operates at distances of about $10^{-15}$ meters (the diameter of a proton), the weak nuclear force operates at even shorter distances, approximately $10^{-18}$ meters, and can trigger radioactive decays that alter the proton and neutron content of a nucleus.

Of the four forces, the weak nuclear force is the least understood and most difficult to detect. A Lawrence Livermore team headed by physicist Nick Scielzo partnered with scientists from Argonne National Laboratory (ANL), Louisiana State University (LSU), and other universities to better characterize the weak force's foundations. Thanks to significant advances in experimental design and theoretical calculations, researchers are now on the road to a clearer understanding of the mysterious force.

In 1933, physicist Enrico Fermi proposed the weak nuclear force as a way to explain nuclear beta decay, the most common form of radioactivity. Today, this force forms a pillar of the "Standard Model," a set of mathematical equations that describe fundamental particles and forces of nature. The weak nuclear force acts through the short-distance exchange of heavy particles called W and Z bosons. During beta decay, a neutron spontaneously changes into a proton inside the nucleus, and the exchange of a W boson emits a beta particle (electron) and an antineutrino.

To explore the weak nuclear force, Scielzo's team required a beta-decaying nucleus that is accessible to experiments and that has properties well-predicted by the Standard Model. They chose the isotope lithium-8, with a half-life of 840 milliseconds. Lithium-8 decays to beryllium-8, which further breaks apart into two alpha particles. In the Standard Model prediction, the beta particle and antineutrino are emitted at a precise distribution of relative angles. Scielzo says, "The current Standard Model predicts that beta decays for lithium-8 are due solely to the W boson, but extensions to this model predict there could be contributions from other, as-of-yet-unseen particles. If these new particles exist, they would reveal themselves by altering the correlation between the directions of the emitted beta particle and antineutrino."

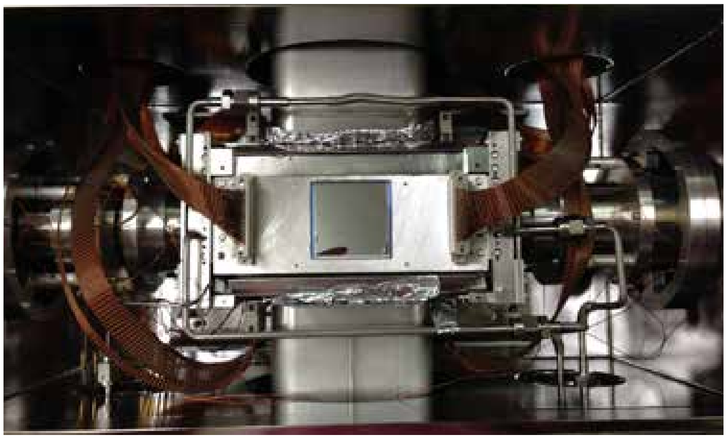
## Experimental Precision

The lithium-8 experiments were conducted at ANL's ATLAS accelerator over a two-week period. Lithium ions produced in the accelerator are guided into the vacuum chamber of the Beta-decay Paul Trap (BPT). (See *S&TR*, September 2013, pp. 16–18.) An oscillating electric field created by electrodes confines the ions to a small area, floating in vacuum, where they decay. Numerous radiation detectors consisting of double-sided silicon strip detectors and plastic scintillators surrounding the trap measure the energies and directions of all emitted particles except the virtually undetectable antineutrino. However, the two emitted alpha particles carry information on the size and direction of nuclear recoil, which, together with the detection of the beta particle, allowed the team to reconstruct the antineutrino's heading and determine its angular correlation with the beta particle.

The team resolved the angular correlation between the beta particle and the neutrino to higher precision than ever before, sensitively probing the mechanisms driving the weak nuclear force. "Precision in these experiments was critical," Scielzo notes. Higher precision increases the likelihood of detecting subtle distortions caused by the hypothesized heavy, exotic bosons that may briefly pop into existence before decaying. Achieving such precision was no easy task.

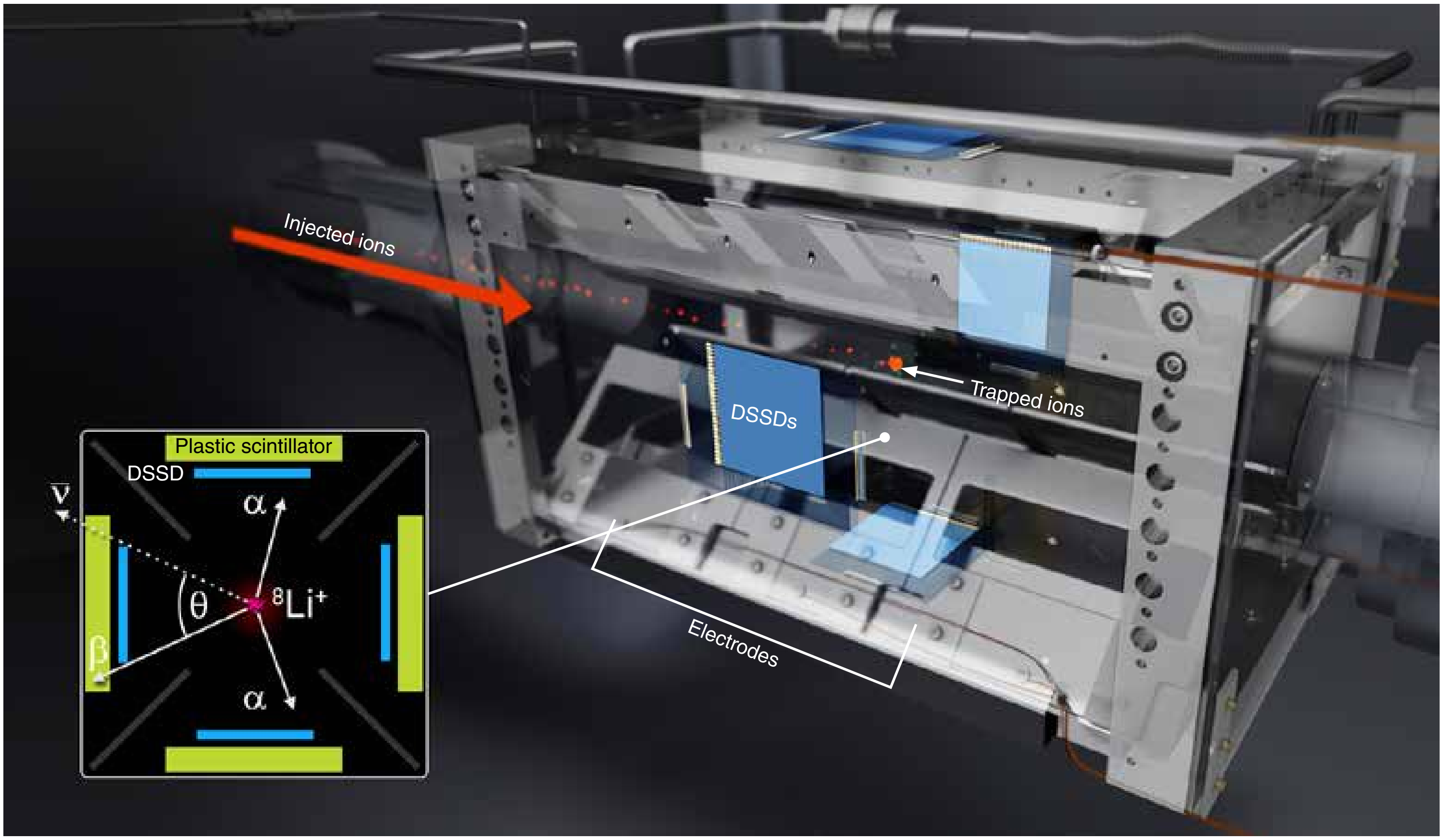
To that end, Lawrence Livermore staff scientist Mary Burkey, then a University of Chicago graduate student, worked with the Laboratory's Scielzo, Aaron Gallant, and others to upgrade the BPT. She found a way to manage the impact of the electrodes' oscillating high voltages that were being picked up by the radiation detectors and corrupting the incoming decay signals, worsening the energy resolution, and blurring out the angular correlation. Burkey's solution was to install hundreds

Feynman's diagram (represented in the illustration) provides researchers with an explanation of beta decay in quantum field theory.



The Beta-decay Paul Trap (BPT, pictured at right) captures the energy and direction of travel of all the particles except antineutrinos, which have no charge and essentially no mass.

Lithium-8 ions ($^8$Li+) are produced with an accelerator and injected into the BPT. The ions are confined in the BPT's center by strong electromagnetic fields produced by thin, segmented, planar electrodes. Decay products—two alpha ($\alpha$) particles, one beta ($\beta$) particle—and an antineutrino ($\bar{\nu}$) are collected by double-sided silicon strip detectors (DSSDs) and plastic scintillators (not shown in larger diagram) surrounding the trap. The correlation angle ($\Theta$) between $\beta$ and $\bar{\nu}$ is recorded by researchers. (Image by Ryan Chen.)



of tiny notch filters—simple electrical components to filter out electrical signals at the same frequency as the BPT voltages. Data analysis revealed more challenges. She explains, "I spent most of my time comparing the data to extremely detailed simulations in which we try to take into account everything we possibly could—the nuclear physics, of course, but also the interactions of decay products with the detectors and the rest of the apparatus."

These groundbreaking experiments yielded extremely precise results, but certain aspects of the data seemed to conflict with the Standard Model. Were these differences due to something in the apparatus, or the data-gathering, or a bug in the data analysis? Or was it new physics, something happening at such a small scale it had been undetectable with earlier experiments?

## Theorists and Experimentalists Unite

Interpreting the results required an in-depth consideration of theory. Livermore nuclear theorist Grigor Sargsyan was still a doctoral student at LSU when he examined the experiments' theoretical aspects. "My role was to calculate the higher-order effects that become a significant source of uncertainty for this kind of precise measurement," he explains. "Imagine trying to measure the height of a 20-story building by throwing stones from the top and measuring the time it takes the stones to hit the ground. Only a stopwatch is needed to determine the height within a meter. But to know the height within millimeters, precise devices are required to exactly measure the start and end of the stone's journey. Higher-order effects such as air resistance and wind that are otherwise negligible would also be considered."

To calculate the higher-order effects in the lithium-8 beta decay, Sargsyan used the symmetry-adapted, no-core shell model—a modern ab initio model based on accepted physics principles. Implemented on supercomputers, such ab initio models consider all the complicated proton–neutron interactions in a nucleus. In a scientific first, Sargsyan and his doctoral advisor implemented calculations of the beta-decay higher-order effects into the symmetry-adapted model. "We found no previous theoretical calculations of these effects in the literature," says Sargsyan, "so we had to double and triple check each step to make sure our implementation was correct." Advancements in the nuclear theory that relates these calculations to measured nuclear moments allowed the researchers to calculate terms magnitudes smaller than the dominant decay effects. Scielzo notes, "This type of correction typically only contributes a 1 percent distortion in the decay, but when you are looking for 0.1 percent distortions, this is a big deal."

Theorists and experimentalists soon accepted that the discrepancies from the Standard Model they saw in the data arose from the physics that Sargsyan included in his calculations. In earlier experiments, the effects had been too small to acknowledge, but these ultraprecise experiments accounted for miniscule effects. Sargsyan says, "The experimentalists would show us how each of our calculations changed their interpretation of the results. We were happy to see that our predictions helped decrease the uncertainty on the final experimental values." Burkey adds, "Finally, we knew we weren't encountering a weird experimental issue, but 'missing' physics that hadn't been considered before." Scielzo adds, "This major advancement in our tests confirmed that the W boson is solely responsible for this type of decay. Our results, while consistent with the Standard Model, placed the strongest limit on a possible source of new physics and elevated the state of the art for precision measurements of this kind."

## Enduring Research Benefits

The benefits of addressing cutting-edge, fundamental science questions are many. Scielzo notes that such efforts draw early career researchers into the Laboratory hiring pipeline. Both Burkey and Sargsyan began the project as graduate students, based their dissertations on this work, and joined the Laboratory as postdoctoral researchers. Both published back-to-back papers on their research in *Physical Review Letters*, with Burkey's paper on the weak interaction in lithium-8 beta decay receiving a 2022 Laboratory Director's Excellence in Publication Award. The skill sets and approaches developed in the project stand to benefit other Laboratory endeavors. "For instance, we can apply these types of high-precision methods to improve studies of the beta decay of fission products that serve as key diagnostics and signatures for the Laboratory's Stockpile Stewardship Program and nuclear forensics efforts," says Scielzo.

Meanwhile, fundamental research continues. In mid-2022, the team performed similar experiments using boron-8 (5 protons and 3 neutrons), a mirror nucleus to lithium-8 (3 protons and 5 neutrons) that also decays to beryllium-8. When switching from studying lithium-8 to boron-8, some of the higher-order corrections switch signs, allowing the team to isolate their impact and gain a better understanding of these small but important effects. Since boron-8 is responsible for most high-energy neutrinos emanating from the Sun, this research will also aid Earth-bound experiments studying solar neutrino oscillations.

"We're a small and nimble experimental effort and can switch directions easily and follow the most compelling science," says Scielzo. "We're pushing the precision on all sorts of beta decays. The finer we can measure, the more we learn, and the greater the opportunities to address different topics—from probing the nature of the weak force and looking for physics that may lie beyond the Standard Model to improving the nuclear data that underpins our national security efforts. Theorists and experimentalists working together make these kinds of advances happen."

*– Ann Parker*

**Key Words:** Ab initio model, alpha particle, Argonne National Laboratory (ANL), ATLAS, beryllium-8, beta decay, Beta-decay Paul Trap (BPT), beta particle, boron-8, lithium-8, neutrino, particle physics, Standard Model, W boson, weak nuclear force.

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