ZOMBIES: Measuring strong-force induced modifications of electroweak interactions

Team members

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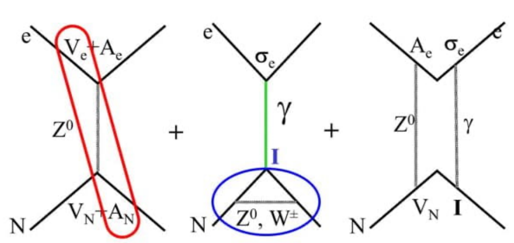
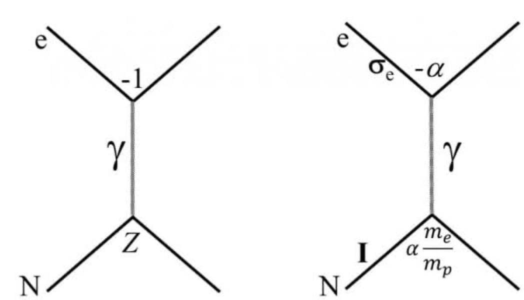
Background & context

Atoms and molecules are composed of electrons, protons and neutrons. The protons and neutrons are bound together tightly into nuclei by one of Nature's four fundamental forces, the strong force. The negatively charged electrons are bound to the positively charged nuclei by another fundamental force, the electromagnetic force. Within both the nuclei and the atoms, the other two fundamental forces—gravity and the weak force—also affect how they are bound (though gravity is *so* weak that we ignore it for the rest of this discussion). In the language of quantum field theory, each fundamental force is related to the exchange of certain particles. For example, the Coulomb force between an electron and a nucleus in an atom or molecule can be described as due to the exchange of photons. The strong force is associated with exchange of gluons, and the weak force with exchange of W and Z bosons. In a stable atom or molecule, each electron-nucleus pair is exchanging not only photons, but also Z0 bosons.

The strength of the Coulomb interaction is determined by the product of the electric charges of the two interacting particles. The charges can be written as dimensionless numbers (for an electron, -1; Z for a nucleus with that atomic number) times a fundamental constant that characterizes the particular type of force (here, the square *e*^2 of the unit of electric charge, *e*) but independent of the particle type. Similarly, the magnetic interaction between the spins of particles at rest is proportional to their magnetic *g*-factors (see Figure 1). In an analogous way, the strength of other fundamental forces between two particles can be characterized by dimensionless numbers, referred to here as “generalized charges”, carried by each particle (again, times a fundamental constant characteristic of that type of force, constant for all particles).



Feynman diagrams showing different contributions to nuclear spin-dependent parity violation in atoms. Left: tree-level Z boson exchange, vector electron-axial nucleon coupling. Center: Weak interactions inside nucleus deform nuclear structure to induce an “anapole



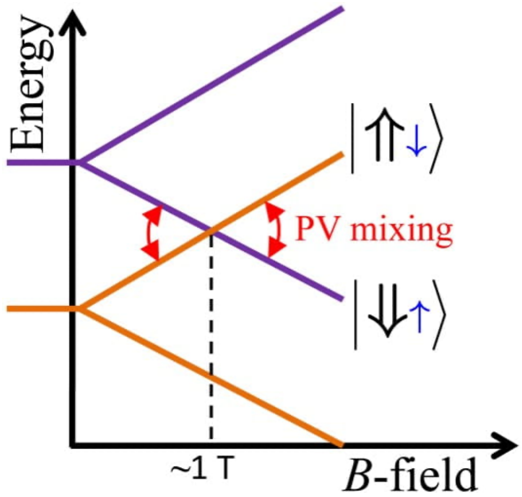
Feynman diagrams depicting the Coulomb (left) and hyperfine (right) interactions. The strength of the Coulomb interaction is determined by the charges in units of e. The strength of the hyperfine interaction is determined moment", which couples magnetically to the electron. Right: coherent effect of combined tree-level Z boson exchange (axial electron-vector nucleon) with ordinary hyperfine interaction.

by the magnetic moments, which depend on the fine structure constant α and the electron and proton masses.

Each particle is characterized by two primary electroweak "charges": a "vector" charge and an "axial" charge. (There are also electroweak analogues of magnetic moments, but these cause such tiny effects that we ignore them here.) The vector electroweak charge is entirely analogous to the electric charge in electromagnetism. However, the axial electroweak charge has no analogue in electromagnetism. This unique type of weak-force charge is linked to the spin angular momentum of each particle. The existence of *both* axial and vector charges is precisely what gives rise to violation of parity in the electroweak interaction. Consider an electron, with vector and axial charges V_e and A_e, respectively, interacting with a nucleus with charges V_N and A_N (Figure 2, left panel). The strength of their electroweak interaction is proportional to the product of these charges, $(V_e + A_e)\times(V_N + A_N) = V_eV_N + A_eA_N + A_eV_N + V_eA_N$. The first and second terms act like minor corrections to the electromagnetic force. However, the third and fourth terms are associated with parity-violating interactions. (The terms "vector" and "axial" are shorthand for "polar vector" and "axial vector", respectively; the dot product of one polar vector with one axial vector is a number that changes sign under a parity transformation.)

The strength of the weak force must be measured in parts.

The effect of gravity within these systems is far too small to detect. The effect of the weak force is, in some cases, large enough to measure. However, because of their tiny effect, certain aspects of the weak force have been poorly measured, to date. The primary goal of this project is to more accurately measure these particular aspects of the weak force.



Simplified depiction of the mechanism used to enhance NSD-PV signals using molecules. A magnetic field B interacts with the electron spin (black arrows) to Zeeman-shift states with opposite parity (orange and purple lines) to near degeneracy. Here, the presence of the nuclear spin (blue arrows) allows the states to be mixed by NSD-PV.

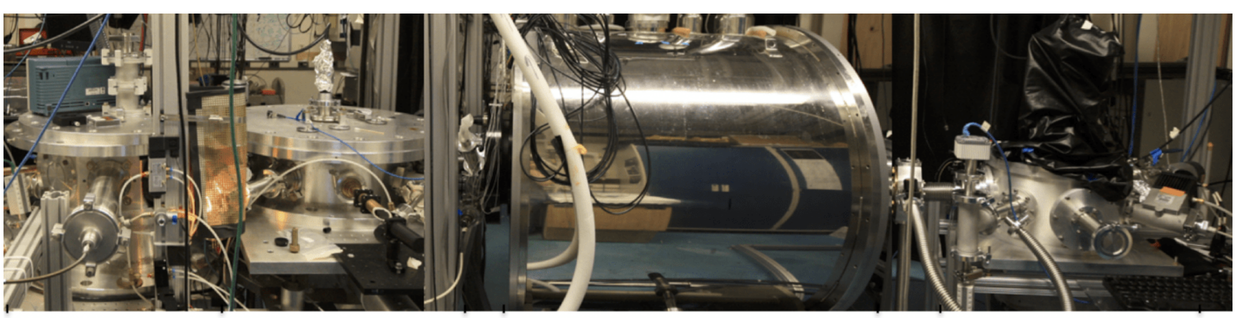
Once measured, we will compare our results to the theoretically expected size of these effects. Discrepancies between measured and predicted outcomes could signal the existence of a new, previously undiscovered force. In addition, we will test whether the weak force we measure is constant over the duration of our experiment, or instead oscillates or drifts over time. Such a time variation could be caused by certain types of a cosmological "background field" that permeates all of space. Fields of this type have been proposed as a possible constituent of "dark matter", the substance of unknown composition that causes galaxies to be bound together more strongly than if only the gravitational attraction between visible stars were at play.

The weak force has a critical difference from all other known forces: its strength depends on the handedness of the configuration of particles on which it acts. Put differently, the weak force breaks the symmetry between mirror-image configurations; in the language of quantum physics, this is known as violation of parity symmetry. In our experiment, we use this feature of parity violation to distinguish the tiny effect of the weak force from the much larger effects of electromagnetic and strong forces. In particular, we measure changes in the energy difference between two quantized states in a diatomic molecule, when we put the molecules in configurations of electric and magnetic fields of different handedness. Our experimental approach uses the properties of diatomic molecules, together with a very precisely controlled magnetic field, to greatly amplify the measurable effect of this parity-violating energy change. Compared to prior experiments studying the weak force using atoms instead of molecules, this amplification makes it possible to measure particular aspects of the weak force that were previously difficult to observe.

In addition to violating parity, the weak force has another important difference from the other forces: each type of particle has two independent types of "charge" that determines the strength with which the weak force acts on it. One of these weak-force charges, known as the vector weak charge, is exactly analogous to the electromagnetic charge. The other, however has no analogue in the other forces. This unique type of weak-force charge, known as the axial charge, is linked to the angular momentum of each particle—the property known in quantum mechanics as "spin".

Our experiment will specifically measure the product of two weak force charges: the electron's vector charge and the axial charge of nuclei. This particular combination is predicted to be accidentally small in the Standard Model of particle physics. This small effect has been measured in only one nucleus, in one experiment, to date—and the results of that measurement disagree with theoretical predictions. In addition, the axial charges of protons and neutrons are significantly modified by the presence of the strong force. These modifications are difficult to measure or to predict with very high accuracy. Our experiment will shed important new light on the interplay between weak and strong forces.

Our specific initial goal is to measure the axial weak charge of the ^{137}Ba and ^{135}Ba nuclei, in the molecule BaF. These will be the first measurements of the axial weak charge of nuclei whose spin comes mostly from neutrons. Once measurements of Ba nuclei are complete, we will apply our method to other nuclei, where the energy shifts are smaller but theoretical predictions for the size of the axial charge are more reliable. This will enhance the possibility to detect the effect of new forces.



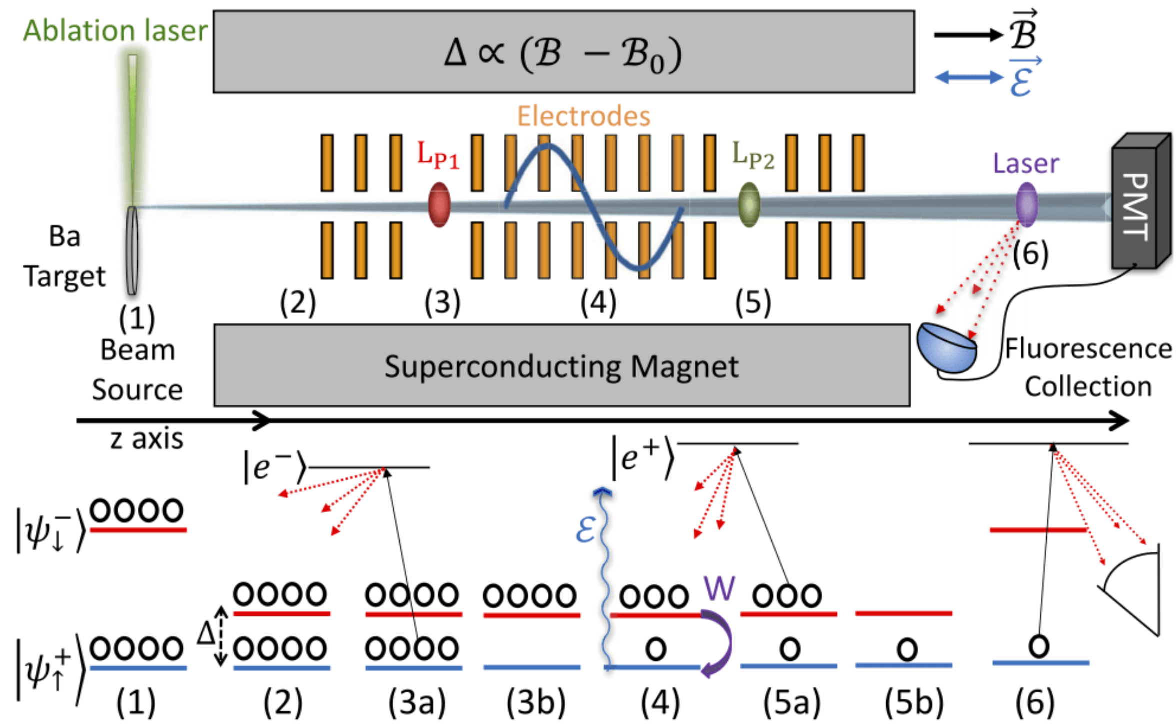
Beam source (Chamber 1) | Chamber 2 | Superconducting Magnet | State detection (Chamber 3)

More details for physicists

How strongly do electrons interact with the atomic nucleus via the weak force? For electromagnetism the answer is easy: the electron and nuclear charges determine the strength. However, the weak force is more complicated, having two effective types of charge for each particle. The strength of the weak force must be measured in parts.

The parity-violating parts of the weak force in an atom or molecule can be split into two groups: nuclear spin dependent effects (NSD-PV) and nuclear spin independent effects. The spin independent effects are much easier to measure since they grow proportionally with the number of nucleons, while NSD-PV effects arise only from the unpaired spins in a nucleus—of which there is typically only one. Consequently, nuclear spin independent parity violation is stronger and has been measured well while NSD-PV effects are weaker and largely unmeasured.

The two NSD-PV effects that we are principally interested in are Z boson exchange between electrons and nucleons, and the nuclear anapole moment. Z boson exchange is a fundamentally simpler process (it corresponds to a tree level Feynman diagram) and directly addresses the question of how strong the electron-nucleon weak force is. However, the strengths of these two effects (Z exchange and nuclear anapole) are roughly the same order of magnitude, and the contribution of the nuclear anapole moment cannot be distinguished from Z boson exchange in a measurement with a single isotope.



Although the nuclear anapole moment complicates the measurement of the strength of the weak force, it is interesting in its own right. Inside the nucleus, the weak force causes the spin of the unpaired nucleon to point in its direction of motion as it orbits the nuclear core. The magnetic moment associated with the nuclear spin is equivalent to a current loop; its orbit around the nuclear core results in an effectively toroidal current. This toroidal current gives rise to an **anapole moment**, analogous to how a current loop gives rise to a dipole moment. Atomic electrons then interact magnetically with the anapole moment. Measuring nuclear anapole moments will give valuable insight into the strength of the nucleon-nucleon weak force. In addition, the magnitude of the nuclear anapole moment is unique to each nucleus, so having a table of these values may be useful in a way analogous to how nuclear magnetic moment measurements have been useful to NMR.

Our novel approach to measuring these small effects uses diatomic molecules. The NSD-PV effects cause levels of opposite parity to be mixed, and it is this mixing that we directly measure in order to deduce the NSD-PV strengths. The mixing is very small, but is amplified if the levels are closely spaced in energy. Due to their large moment of inertia, diatomic molecules have rotational levels that are very closely spaced and are thus an ideal system for measuring NSD- PV. The levels are brought even closer together using a magnetic field and associated Zeeman shifts of the levels. Finally, the mixing is amplified through interference with an oscillating electric field, and detected using laser-induced fluorescence from the molecules. The NSD-PV signal is found by taking the difference between the measured interference terms when the handedness of the applied configuration of electric and magnetic fields is reversed.

Recently, we used this apparatus to make a proof-of-principle measurement of NSD-PV, using ^{138}BaF (See the Publications page for details.) Here, because 138Ba has spin zero, the only nuclear spin in the system is from ^{19}F, where the resulting NSD-PV signal is calculated to be orders of magnitude smaller than in ^{137}Ba or ^{135}Ba. The goal of this test measurement was to demonstrate the sensitivity of the method, and to check for possible systematic errors (since here we know in advance that the NSD-PV signal should be effectively zero). As expected, we achieved a sensitivity roughly 7 times better than any prior measurement of NSD-PV in an atomic system, and sufficient to measure the anticipated nonzero NSD-PV effect in ^{137}Ba or ^{135}Ba at the 10% level of accuracy.

Unfortunately, the raw signal sizes from which we deduce the NSD-PV signal are much smaller in ^{137}BaF than in ^{138}BaF, because the isotopic abundance of ^{137}Ba is about 7 times smaller, and because we can use only one of the 4 nuclear spin states of ^{137}Ba in any given measurement. This means our purely statistical noise would be more than 5 times worse using ^{137}BaF, using the exact same system. To improve the signal size, we have recently installed a new cryogenic buffer gas beam source (CBGB) that delivers more molecules per pulse. The velocity of molecules in this beam is also 3 times slower than in our old room-temperature source, which increases the measurement sensitivity by a factor of 3. Once the new source is fully operational, we will be well on the way to a measurement of the "weak axial charge" of ^{137}Ba and ^{135}Ba!