a fly Tcf family member, *dTcf* (also called *pangolin*), plays a key role in transduction of Wingless signal in vivo (*6*). Loss-of-function mutations in *dTcf* disrupt normal anterior-posterior patterning, and epistasis analysis places *dTcf* downstream of *armadillo* in the Wingless signal transduction pathway. Mutations in *dTcf* block expression of Wingless-responsive genes, and analysis of a Wingless-response element revealed an essential dTcf binding site. dTcf alone is inactive, even though it binds DNA. The active transcription factor is a bipartite complex, with dTcf contributing the DNA binding domain and Armadillo a potential transactivation domain.

This brings us back to the scene of the crime, suggesting that β-catenin cooperates with Tcf family proteins to alter gene expression in human colon. This thesis was tested and extended in the three reports in this issue. In colon cancer cell lines (*1*), and surprisingly also in many melanoma cell lines (*2*), high levels of free β-catenin drive formation of complexes with Tcf-4 or Lef-1, activating gene expression. The genes activated may include those stimulating cell proliferation or inhibiting apoptosis. There are at least two ways to increase levels of free β-catenin. The first is due to the previously described mutations in *APC*. The second is to mutate β-catenin itself, altering an NH_2-terminal domain that down-regulates β-catenin stability in cell lines (*7*) and up-regulates Wg-Wnt signaling ability in vivo (*6, 8*). Thus β-catenin itself is an oncogene.

These data firmly establish APC as a negative regulator of β-catenin signaling. However, APC likely has additional abilities. It localizes in vivo to the end of cell processes, clustering at the tips of microtubule bundles (*9*). This suggests that APC regulates migration by regulation of the cytoskeleton. This model was tested by manipulating APC activity in cultured epithelial cells. APC promotes cell migration and regulates cell adhesion both of individual cells and of cells cooperating to form epithelial tubules (*10*). This is consistent with the behavior of normal colon epithelial cells, which migrate from crypt to villus, where they die and are sloughed off. These data also suggest that free β-catenin prevents APC from stimulating migration. The APC–β-catenin complex appears to be a binary switch. In the absence of outside input, APC mediates β-catenin degradation and promotes cell migration. In contrast, in the presence of Wg-Wnt signal, β-catenin is stabilized (perhaps by inactivation of GSK kinase). This inactivates APC, down-regulating migration and promoting formation of β-catenin–Tcf complexes, thereby altering gene expression. Mutations in either APC or β-catenin mimic Wg-Wnt signaling, stimulating proliferation or antagonizing apoptosis.

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PHYSICS

Atomic Parity Violation and the Nuclear Anapole Moment

W. C. Haxton

Until 40 years ago, physicists had assumed that the fundamental forces of nature did not distinguish between left and right. That is, it was believed that the laws of physics in a mirror-symmetric universe would be the same as in ours. Then in 1957, following a suggestion by Lee and Yang (*1*), experimenters discovered that the weak nuclear force, which is responsible for beta decay, violated this conservation of parity (*2*). Shortly thereafter, Vaks and Zeldovich (*3*) independently noted that particles could therefore have parity-violating couplings to the electromagnetic field. Such "anapole moments"—in the more modern language of today's standard model—would arise from very small effects associated with weak forces among, for example, the quarks within a nucleon or nucleus. On page 1759 of this issue, the first definitive measurement of an anapole moment is reported by Wood *et al.* (*4*).

Some nuclear interactions with the electromagnetic field are quite familiar. As a charged object, the nucleus accelerates when an electric field is applied. If the nucleus has a nonzero spin **I**, it also has an interaction with an applied magnetic field **B** of the form $\mu\mathbf{B}\cdot\mathbf{I}$, where μ is the magnetic moment. More exotic interactions can arise when symmetries preserved by electromagnetism are violated by other, weaker forces. Perhaps the best known of these interactions is that of the electric dipole moment d (which can be visualized as an asymmetric distribution of charge along a particle's spin axis) with an electromagnetic field. A particle with an intrinsic dipole moment will experience an interaction $d\mathbf{E}\cdot\mathbf{I}$ when placed in an electric field **E**. Electric dipole moments arise only if the laws of physics are asymmetric under both parity inversion and time reversal. Studies of the decays of the long-lived neutral K meson have shown that this combination of symmetries is violated, although only weakly. Consequently, despite considerable effort, no one has succeeded in detecting a nonzero nuclear electric dipole moment.

This had also been the case for the anapole moment, which can be generated by parity violation in the weak interaction but does not require time reversal violation. This moment has a number of curious properties. It vanishes when probed by real photons (that is, photons satisfying the usual energy-momentum relation). Thus, the anapole moment of a nucleus, for example, can be measured only in processes where virtual photons are exchanged with some interacting particle, such as an atomic electron. The resulting electron-nucleus interaction is point-like: The atomic cloud feels the nuclear anapole moment only to the extent that the wave functions of the orbiting electrons penetrate the nucleus. Although the exchanged photon is electric dipole in nature, its absorption by the nucleus takes place through parity-violating components of the nuclear wave function. The combination of the usual nuclear current and the parity violation produces a current configuration similar to a winding about a torus.

Exquisitely precise (1%) measurements of atomic parity violation have been made in recent years. It is now widely recognized that these efforts are important not only as tests of the standard electroweak model, determining parameters, such as the weak mixing angle θ_W, but also as crucial searches for new physics beyond the standard model, complementing the efforts at high-energy colliders. The dominant contribution to atomic parity violation comes from direct Z_0 exchange between electrons and a nucleus, with the elec-

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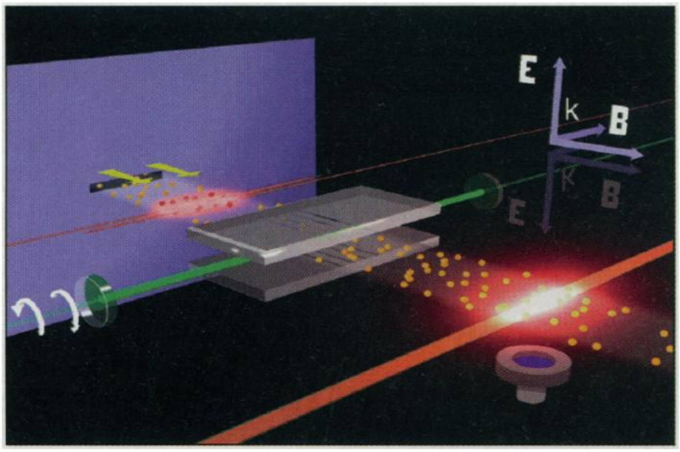
tron coupling being axial (or spin-dependent) and the nuclear coupling being vector (independent of spin). The interaction with the nucleus is thus coherent, proportional to the total weak charge, a quantity that scales approximately as the neutron number.



Cesium atoms interacting with lasers for measurement of parity nonconservation and the nuclear anapole moment. The atoms are prepared by sending them through two red laser beams. The intense green laser beam exites the atoms to a higher energy level, and this excitation rate is detected with another red laser. The applied magnetic and electric fields can be reversed to create a mirror-reversed environment for the atoms, causing a tiny but measurable change in the excitation rate. [Figure drawn by T. Andrews, University of Colorado]

Almost two decades ago it was realized that the electromagnetic interaction of atomic electrons with the nuclear anapole moment might generate a measurable nuclear-spin dependence in atomic parity violation experiments (*5*). The associated effects, which are considerably weaker than those of the coherent Z_0 interaction, involve a vector coupling to the atomic electrons and an axial coupling to the nucleus. Such an interaction can also be generated by direct Z_0 exchange similar to that described above, but with the electron coupling being vector and the nuclear coupling being axial. At first it seems very surprising that the anapole moment could then compete with this direct contribution: The anapole interaction requires photon exchange between an electron and the nucleus in addition to the weak interaction within the nucleus. Such a "weak radiative correction" would seem to be suppressed by a relative factor of the fine structure constant, 1/137. However, this direct Z_0 exchange is inhibited: The axial coupling to the nucleus is no longer coherent (only the last unpaired nucleon contributes), and the vector coupling to the electron is suppressed by the factor $(4 \sin^2\theta_W - 1)/2 \sim -0.05$. Furthermore, the nuclear anapole moment has the remarkable property that it grows as $A^{2/3}$, where A is the atomic number, thus increasing in proportion to the nuclear surface area. The net result is the expectation that this weak radiative "correction" will exceed the direct nuclear-spin–dependent parity violation for nuclei heavier than $A \sim 20$.

The problem of separating the anapole moment contribution from the much larger coherent Z_0 exchange remains. Because the former is dependent on the nuclear spin whereas the latter is independent of spin, this separation can, in principle, be done by studying the dependence of the parity-violation signal on the choice of hyperfine level. In practice, the hyperfine differences are very small, and their extraction requires heroic efforts to control experimental systematics. An earlier effort by the Colorado group (*6*), where parity violation in ^{133}Cs was measured to 2.2%, provided a tentative identification of the anapole moment, but the Seattle group's (*7*) 1.2% measurement in ^{205}Tl found a null result, despite reaching a sensitivity where theorists had predicted an effect. The unprecedented precision of the measurements reported in this issue by Wood *et al.* (*4*), a sevenfold improvement to 0.35% in the ^{133}Cs results, has produced the first definitive isolation of nuclear-spin–dependent atomic parity violation. The resulting value for κ, the parameter indicating the size of the anapole moment, is 0.127 ± 0.019, a result differing from zero by 7σ. [The atomic matrix elements of Blundell *et al.* (*8*) were used in this determination.] One can write $\kappa = \kappa(Z_0)[1 + \kappa(A)/\kappa(Z_0)]$, where $\kappa(Z_0)$ is the nuclear-spin–dependent Z_0 exchange contribution and the quantity in square brackets is the expected enhancement due to the anapole weak radiative correction. The standard model gives a value of ~0.013, using $\sin^2\theta_W \sim 0.223$ and taking the nuclear axial matrix element from (*9, 10*). Clearly, the ^{133}Cs result demands an additional source of spin-dependent atomic parity violation, namely the anapole moment.

As the calculations of (*9, 10*) show that the largest contribution to the nuclear anapole moment arises from parity mixing in the nuclear wave function, the efforts of Wood *et al.* have produced a new technique for studying the hadronic weak interaction. This interaction has proven more elusive than the weak interactions involving leptons. Whereas the charged-current hadronic weak interactions can be studied in strangeness- or charm-changing decays, the standard model predicts that neutral-current interactions do not change flavor. Thus, the only opportunity for studying the hadronic interactions of Z_0 is provided by nucleon-nucleon interactions, where parity violation must be exploited to separate the weak interaction from the much stronger strong and electromagnetic interactions. But this is a tough game: Only a few experiments have been done with the precision required to see such an effect, and only some of the nuclear systems are sufficiently well understood to allow a quantitative interpretation of the results (*11*). Thus, new atomic physics techniques, applicable to a variety of nuclei, could have substantial impact on this field.

When the effects of the ^{133}Cs anapole moment are included, the calculations of (*9, 10*) yield values of κ of 0.074 and 0.074 to 0.095, respectively. At a qualitative level, these results are quite pleasing: Theory predicts that radiative corrections will strongly enhance nuclear-spin–dependent atomic parity violation, and the magnitude of the predicted enhancement is in reasonable accord with the measurements of Wood *et al.* However, these calculations employed the "best value" hadronic weak meson-nucleon couplings of (*12*); experimental evidence has mounted (*11*) that suggests these estimates are somewhat too high. The ^{133}Cs anapole moment depends (*9*) primarily on the coupling combination $(f_\pi + 0.52 f_\rho^0)$, where f_π and f_ρ^0 are the pion and isoscalar weak meson-nucleon couplings in units of the best values (*12*). Hadronic parity violation experiments suggest that f_π may be substantially less than one, a puzzling and important result, as this coupling is generated almost entirely by the neutral current. But the ^{133}Cs anapole results do not appear consistent with this conclusion. This is a conflict that will clearly draw some attention.

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