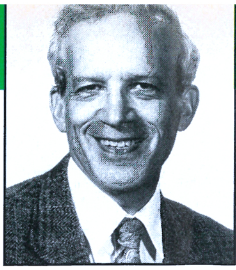

SOME SMALL BIG SCIENCE

Daniel Kleppner

Can one say kind words about small science without being classified as an enemy of big science? I hope so. The important issue is not which is better but how much of each we need. Unfortunately today's helter-skelter science policy climate makes tackling that problem almost impossible. Big science runs into trouble because it is attractive to politicians; small science runs into trouble because it is unattractive to politicians.

So much for ideology. What I really want to discuss are some atomic experiments that address issues in particle physics that normally require accelerators. Although bench-top experiments are not going to replace accelerators, the atomic experiments deserve to be taken seriously because they have joined in the central quest of high-energy physics—to find life beyond the standard model. To date, the atomic experiments have yielded precise values for several parity-violating electroweak coupling parameters, constrained others, put a dent in what is known as technicolor theory and helped set limits on possible new gauge bosons and other new electron–quark interactions.

The starting point is the observation that atoms are neither right- nor left-handed. To put it formally, the electromagnetic interaction conserves parity. Isolated atoms that are excited with linearly polarized light, for example, cannot radiate circularly polarized light, and the rates for absorbing right- and left-handed polarized light must be identical. In 1958 the polymath Yakov B. Zel'dovich pointed out that neutral currents could in principle generate a minuscule electron–nucleon interaction that would let atoms tell left from right, and in 1965 F. Curtis Michel proposed—while he was waiting to become an astronaut—that such a parity violation should occur in hydrogen. But Michel's effect was far too small to inspire experiments. With the advent of the Weinberg–Salam–Glashow electroweak theory, however, the search for neutral-current parity violations in atomic physics became serious.

The bible for the atomic experiments was written in Paris in the early 1970s by an experimental and theoretical team of two: Claude and Marie-Anne Bouchiat. The parity-violating transition amplitude for a light nucleus is forbiddingly small, but the Bouchiats discovered that it grew at least as rapidly as the cube of the atomic number Z. (The quarks add coherently, and the interaction is proportional to the electron density and momentum. Each factor scales with Z.) The Bouchiats' Z^3 scaling law pointed the way to all of today's experiments. Initially the goal was simply to detect the presence of neutral currents. Once the electroweak theory was confirmed by electron scattering experiments at SLAC, however, the goal shifted to measuring the coupling parameters accurately enough to reveal something new about the standard model.

To get some idea of the size of the effect, consider an atom with a single valence electron in a spherical ground state—an S state. The parity-violating interaction, which behaves like a contact interaction between an electron and a nucleon, mixes in some P-state character, distorting the sphere. On a scale in which the transition amplitude for a typical atomic interaction is unity, the parity-violating amplitude in a heavy element is only about 10^{-11}. Observing this by brute force—for instance, by driving an optical transition that is allowed solely by the parity-violating interaction—is out of the question: The rate, which depends on the square of the amplitude, would be 22 orders of magnitude smaller than for a normal transition.

What makes the parity-violating effects observable is a process that is as important to physics as compound interest is to banking: interference. If A is some known transition amplitude, and B is the small, unknown parity-violating amplitude, then the total transition rate is proportional to $|A \pm B|^2$, where the sign depends on the relative phase of the amplitudes, which ideally can be varied in an experiment. The fractional change in signal if the phase is reversed is approximately $4B/A$, which grows larger as A decreases. Unfortunately the total signal also decreases as A decreases; choosing the best value of A is one of the secrets of the experimental art.

Interference between the parity-violating amplitude and some other weak optical transition amplitude can transform an atomic gas into an optically active medium. The polarization plane of a laser beam passing through such a gas will rotate. One class of experiments exploits this effect—no easy task considering that the total rotation angle is only about 10^{-6} radian. In another class of experiments, descended from early research by the Bouchiats and by Eugene Commins at the University of California, Berkeley, the interfering amplitude is created by application of an electric field. The idea is to drive a highly forbidden transition, in particular the $6S \rightarrow 7S$ transition in cesium, by Stark-mixing in enough P state to produce the desired value of A. The absorption rate is measured by monitoring the fluorescence. The "handedness" of the experiment depends on the relative directions of the applied electric and magnetic fields, and the angular momentum of the photons. Reversing any of these changes the absorption rate slightly—typically by one part per million—as a result of the parity-violating effect.

The results that have had the greater impact so far have come from an experiment by Carl Wieman's group at the Joint Institute for Labo-

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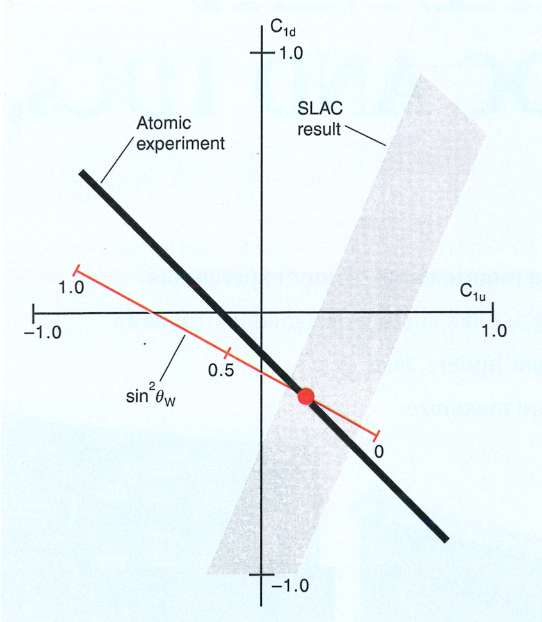

Electron–quark coupling parameters C_{1u} and C_{1d} (for the up and down quark, respectively) for the parity-violating electroweak interactions. In the Weinberg–Salam–Glashow theory these parameters are uniquely related by the Weinberg angle θ_W, as shown by the thin red line. The dot indicates the value of θ_W determined from measurements of the Z^0 mass at CERN. The heavy black line is the locus of values determined from the cesium parity-violation experiment of Carl Wieman's group at the Joint Institute for Laboratory Astrophysics; the line's width indicates the total uncertainty. Failure of this line to pass through the point would have indicated physics beyond the standard model. The gray region indicates the results from high-energy polarized electron–deuterium scattering experiments at SLAC. (Data courtesy of Wieman.)

ratory Astrophysics, in Boulder, Colorado.[1] The experiment uses an atomic beam, which makes for an extremely clean experimental geometry though at a considerable loss in intensity. Wieman makes up the loss by enhancing the laser power in a resonant cavity. The laser produces a mere 300 milliwatts, but the atoms "see" more than 4 kilowatts. The last version of the experiment measured the parity-violating amplitude to 2%, and a new version is well advanced. (Norval Fortson, at the University of Washington, has achieved an experimental precision of 1% by measuring optical rotation in lead vapor,[2] though the atomic theory has not yet reached that level of accuracy.)

Determining the electroweak coupling parameters from the measured parity violation requires understanding atomic structure in great detail, a challenge to relativistic many-body theory that is every bit as formidable as the experimental challenge. A number of groups have worked on the theory of cesium, with the most accurate results coming from groups at Notre Dame University[3] and the Institute of Nuclear Physics at Novosibirsk.[4] The two groups independently extended relativistic many-body theory and obtained values for the important atomic structure factors that agreed with each other within their estimated accuracy, 1%.

The largest part of the parity-violating amplitude is generated by the weak charge of the nucleus. This is roughly analogous to the electric charge, with the up quarks and down quarks contributing different amounts. The strength of each of these sources is described by the parameters C_{1u} and C_{1d}, respectively. The experimental values of the weak charge define a line—actually a thin strip—on a plot of C_{1u} vs C_{1d}, as shown in the figure above. According to the standard electroweak theory, however, the coupling parameters are uniquely determined by the Weinberg angle θ_W. Their relation—$C_{1u} = \frac{1}{2} - \frac{4}{3}\sin^2\theta_W$ and $C_{1d} = \frac{1}{2} + \frac{2}{3}\sin^2\theta_W$—is also shown in the figure. The Weinberg angle is now known precisely from measurements of the Z^0 mass. The two lines intersect at that value. Failure to agree would be evidence of physics beyond the standard model. The broad gray band in the figure shows the limits on C_{1u} and C_{1d} from polarized electron–deuteron scattering experiments at SLAC. The two experiments are almost orthogonal in their sensitivity to the two parameters. Our understanding of the up-quark parity-violating coupling parameter C_{1u} comes almost entirely from the atomic measurement.

Though pinning down the standard model with respect to some particular parameter is about as easy as putting a straitjacket on an octopus, the atomic experiment has lots of things to say about the standard model. The possibility of extra neutral gauge bosons has been reduced, and the prospects for technicolor theory have been dimmed. One proposed class of isospin-conserving corrections has been constrained. On the positive side, Wieman's group has found a glimmer of evidence for the anapole moment, a toroidal-like magnetization within the nucleus that, unlike all other nuclear moments, generates no external field.

Atomic physics has recently acquired a new experimental bag of tricks: laser cooling, atom trapping and single-ion spectroscopy. Its theoretical bag of tricks has also grown, and a new generation of atomic studies of electroweak physics is in the offing.

The National Science Foundation has been generous in its support of the atomic parity-violation research—at least by NSF standards—justifying it on traditional criteria of scientific excellence. Those criteria are being demoted in favor of strategic goals, and the future of this research, along with the future of fundamental research in all of the physical sciences at the NSF, is clouded. Laser atomic research may fare relatively well in the new climate, because of its connections with optical technology. (Wieman's buildup cavity, for instance, represented a major advance in optical coatings.) But if for some reason the research stops needing lasers it will have a rough time.

The future of high-energy research at DOE is also clouded, because of money problems and the political difficulties of large projects. Nevertheless there is general agreement about the scientific goals for particle physics, and the atomic experiments rank high on any list of cost-effectiveness for achieving those goals.

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