problems exist: In situ sensors do not agree, and satellite instruments lack sufficient absolute agreement to provide consistent trends (4). Even if stratospheric trends are more determinable, it will not necessarily imply anything about the upper troposphere; if tropopause temperatures increase, more water vapor could get into the stratosphere without implying there is more water vapor below.

So given these difficulties, researchers are attacking pieces of the problem. Efforts have been made to assess whether vertically integrated water vapor changes have been occurring; the general conclusion is yes, but it is not unanimous (5). On shorter time scales, drying does occur in the upper troposphere immediately after convective events, but wetter conditions soon follow, presumably as the associated cloud cover dissipates (6). Considering annual cycle variations, water vapor and the global atmospheric greenhouse effect do increase with surface temperature, especially in the tropics (7). Nevertheless, it is still uncertain how such effects relate to what happens as climate itself changes.

Where does this leave us with respect to global climate change estimates? So far, there has been no evidence to indicate that a strong negative water vapor feedback in the upper troposphere will in fact arise as climate warms. However, without our being able to observe upper tropospheric and stratospheric water vapor with sufficient accuracy over a long enough time period to see ongoing trends, some uncertainty will remain in this most important of climate sensitivity feedbacks.

References

1. R. S. Lindzen, *Bull. Am. Meteorol. Soc.* **71**, 288 (1990).
2. W. P. Elliott and D. J. Gaffen, *ibid.* **72**, 1507 (1991).
3. S. J. Oltmans and D. J. Hofmann, *Nature* **374**, 146 (1995); S. Evans, R. Toumi, J. E. Harries, M. Chipperfield, J. M. Russell III, *J. Geophys. Res.* **103**, 8715 (1998).
4. M. P. McComrick and E. W. Chiou, paper presented at the American Geophysical Union Spring Meeting, Boston, MA, 26 to 29 May 1998; H. K. Rosenlof *et al.*, paper presented at the American Geophysical Union Spring Meeting, Boston, MA, 26 to 29 May, 1998.
5. IPCC, in *Climate Change 1995*, J. T. Houghton *et al.*, Eds. (Cambridge Univ. Press, Cambridge, 1995); S. R. Schroeder, and J. P. McGuirk, *Geophys. Res. Lett.* **25**, 1301 (1998).
6. X. Liao and D. Rind, *J. Geophys. Res.* **102**, 19543 (1997).
7. A. K. Inamdar and V. Ramanathan, in preparation.

PERSPECTIVES: PARTICLE PHYSICS

Electroweak Reconciliation

Michael E. Peskin

High energy physicists view themselves as intrepid explorers, searching for new concepts of space and time. So it is sometimes difficult for them to accept that the theories in their textbooks actually work well. Over the past few years, however, experiments have tested the structure of the weak interaction—the basic force that gives rise to radioactive decay—and, with remarkable precision, the results have converged on the standard textbook model. The experiments confirm the elementary couplings of this interaction to the basic constituents of matter, the leptons (such as the electron) and the quarks (from which the proton and other nuclear particles are made). The observed large mass of the heaviest quark, the top quark, plays a key role in this reconciliation. The results close a chapter in the history of particle physics and present some interesting clues to the content of the next chapter.

The heavy particles $W^{\pm}$ and Z^0, which mediate the weak interactions, were discovered in 1982 at CERN (1). The masses of these particles are 80 and 91 GeV, respectively (for comparison, the proton mass is about 1 GeV). In 1989, the inauguration of two new machines, the Stanford Linear Collider (SLC) and the Large Electron-Positron (LEP) collider at CERN, allowed precision studies of the properties of the Z^0. An important property of the weak interaction is that it violates parity (as reflected in the radioactive decay of nuclei, which produces electrons and neutrinos with left-handed, as opposed to right-handed, spin). This spin asymmetry leads to distinctive effects in Z^0 decays.

The coupling of the Z^0 to each species of quark and lepton is predicted by the weak-interaction theory of Glashow, Salam, and Weinberg (1). This theory contains four fundamental particles—two electrically charged and two neutral—which are responsible for the weak and the electromagnetic (collectively, "electroweak") interactions. At the basic, symmetrical level of the theory, all four particles are massless. To give mass to these particles, it is necessary to assume an additional field, existing throughout space. This is known as the "Higgs boson field," and it gives mass to the weak-interaction bosons according to a specific pattern. The charged particles acquire mass and can be identified with the $W^{\pm}$. The two neutral particles mix with one another by a small amount, and one of these particles remains massless. This massless state is precisely the photon. The remaining state is the Z^0, which obtains a mass slightly larger than that of the $W^{\pm}$. The mixing angle is a single parameter that determines the coupling strengths and spin asymmetries of all of the individual quark and lepton species. The predicted spin asymmetries differ greatly, from about 14% for the electron to 94% for the b or bottom quark. Through systematic measurements, at LEP and SLC, of the angular distributions and decay patterns of particles produced from the Z^0 (2) and through an experiment at SLC that directly measures the rate of Z^0 production separately from left- and right-handed electrons (3), these various values for the spin asymmetries are confirmed experimentally.

The most accurate way to determine the mixing parameter is to combine a precise absolute measurement of the Z^0 mass with two quantities that are already known to part-per-million accuracy, the rate of muon beta decay and the electromagnetic fine-structure constant. In the past 2 years, the LEP collider at CERN has been calibrated to five-decimal-place accuracy (a level at which influences of the tides, the water level in Lake Geneva, and local railroad operation must be identified and subtracted) to give a very precise determination of the Z^0 resonance position (4). The decay rate and spin asymmetry measurements for the various species give additional measurements of the mixing to four decimal places, which provide detailed tests of the model.

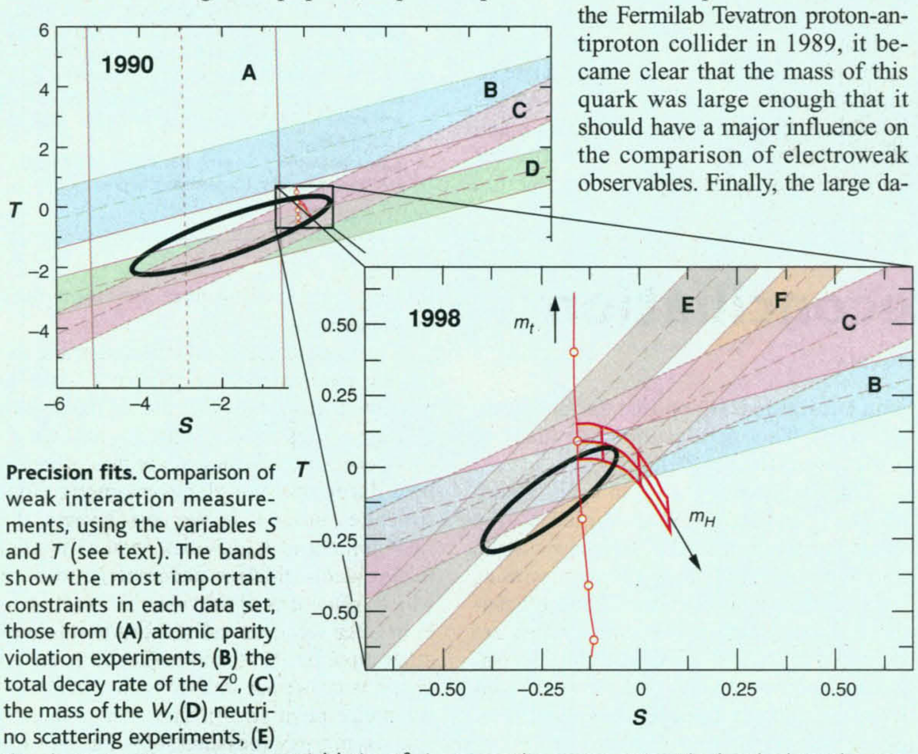
The accuracy of these experiments is such that they cannot be compared without taking into account the higher order quantum mechanical corrections. Exotic quantum processes involving the weak interactions play an equal role with high-order quantum electrodynamics processes in the computation of these corrections. Both types of effects influence the predictions for weak-interaction rates and asymmetries at the 1% level of accuracy. Thus, the detailed comparison of different experiments that measure the mixing parameter can determine whether these quantum processes are actually present to the extent predicted by the theory. Although the full structure of the corrections is rather complicated, the most important effects come from the "vacuum polarization" process, in which a Z^0 converts for a short time, by a quantum fluctuation, into a pair of electrons, quarks, or W bosons. In principle, the Z^0 could also fluctuate to a pair of heavier particles, indeed, to any particle that couples to the weak in-

The author is at the Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309, USA. E-mail: mpeskin@slac.stanford.edu

teractions. In comparing the precision measurements, it is possible that new sources of vacuum polarization might be required to bring the data into agreement. The comparison could then give evidence for or against new particles that are not included in the textbook model.

One counterintuitive property of these quantum corrections is that heavy quarks can have an especially important effect. The corrections involving the top quark, in particular, are enhanced by the factor m_t^2/m_W^2 (where m_t is the mass of the top quark and m_W is the mass of the W particle) relative to the general 1% level of quantum corrections (*5*, *6*). The large size of these effects comes from the fact that the masses of quarks are also due to the Higgs boson field. The top quark, being the most massive quark known, couples most strongly to the Higgs field and, through this mediator, has an especially large influence on the properties of the Z^0. The top-Higgs interaction is not so strong that it creates bound states or other new dynamical features (*7*); it is only large enough to leave its imprint on precisely measured observables.

When the enhanced influence of a heavy top quark was discovered in the 1970s, few physicists thought that this might be an important effect. In the first systematic accounting of the top quark contributions to weak-interaction reaction rates in 1980 (*8*), Marciano and Sirlin guessed a value of 18 GeV for the top quark mass and wrote, "for nonexotic values of ... m_t, the corrections ... turn out to be small" (p. 2695). They did not know that high-energy experimenters would be unsuccessfully searching for the top quark for the next 15 years. When the top quark failed to show up in the first data of the Fermilab Tevatron proton-antiproton collider in 1989, it became clear that the mass of this quark was large enough that it should have a major influence on the comparison of electroweak observables. Finally, the large data samples available at the Tevatron collider in 1995 allowed the CDF and D0 experiments there to collect definite evidence for this particle and determine its mass to be about 175 GeV.



Precision fits. Comparison of weak interaction measurements, using the variables S and T (see text). The bands show the most important constraints in each data set, those from **(A)** atomic parity violation experiments, **(B)** the total decay rate of the Z^0, **(C)** the mass of the W, **(D)** neutrino scattering experiments, **(E)** the electron spin asymmetry, and **(F)** the Z^0 decay angular asymmetries. The bands show the constraints from each measurement at $\pm 1\sigma$; the ellipse shows the 68% confidence contour for the full analysis. For comparison, the flag-shaped figure in red shows the prediction of the textbook weak-interaction model. The vertical line shows the dependence on the top quark mass, with circles at 25-GeV intervals. The flag shows the 1σ error band on m_t from the Tevatron and the dependence on the assumed mass of the Higgs boson. The vertical lines in the flag correspond to Higgs boson masses of 60, 100, 300, and 1000 GeV, from left to right. [Analysis by Swartz (*19*).]

Very recently, the CDF and D0 experiments at the Tevatron collider have announced new and more precise measurements of the mass of the top quark (*9, 10*), yielding a value $m_t = 173.9 \pm 5.2$ GeV. The identification of top quark production is a feat in itself, because top quarks are produced in only one out of every 10^7 proton-antiproton collisions. It is a delicate balancing act to select for top quark events in a way that does not unduly bias the mass measurement. Fortunately, one can make use of the fact that a heavy top quark has a very simple decay scheme, $t \rightarrow b + W^+$, in which the b or bottom quark has a mass that is quite small ($m_b = 5$ GeV) and the mass of the W is known precisely.

With these experimental results in hand, we can explore whether the particles already known suffice to give the correct contribution to the vacuum polarization effect. The possible contribution of new heavy particles can be described by two parameters S and T (*11*, *12*). The parameter S measures the total size of the new set of particles; the parameter T measures the extent to which these particles violate the symmetry among the weak bosons. The top and bottom quarks, for example, provide only one weak-interaction multiplet, but their masses are very asymmetrical; thus, this multiplet gives a small contribution to S and a large contribution to T. The two variables are defined in such a way that a contribution of 1 unit to S or T produces a 1% correction to weak interaction observables, a typical size for vacuum polarization effects. Each precision measurement is sensitive to one linear combination of S and T, and so it picks out a band in the S-T plane. The overlap of the various bands tells us the extent to which the size of the vacuum polarization effect is well determined. In the figure, I show the situation as it was in the summer of 1990, when only the first data from SLC, LEP, and the Tevatron were available, and as it is today. The new measurements focus in on a tiny region in the S, T plane.

The lines in red superimposed on the plot show the prediction of the minimal textbook model for various values of the masses of the top quark and the Higgs boson. We see that the value of the top quark found at Fermilab is just what is needed to reconcile the electroweak data. The vacuum polarization effect of the Higgs boson also enters this comparison. Remarkably, large values of the Higgs boson mass are excluded, and values below 200 GeV are highly favored. There is no evidence that additional new heavy particles are needed.

Is this a depressing or a hopeful sign for high energy physics? The low value of the Higgs boson mass is certainly encouraging; it indicates that this particle might even be found in the next few years at LEP or at the Tevatron. Thinking more broadly, the pattern displayed in the figure chooses sides in the most important current controversy in high energy physics, the debate over the nature of the Higgs field. Models in which the Higgs boson is composite prefer a very heavy Higgs boson mass. Typically, they also include new particles that induce extra large positive contributions to S and T (*11*, *14–16*). Such effects are excluded by the data. Models in which the Higgs boson is a new elementary constituent of matter allow the low values of the mass that are preferred by the fit, and certain of these models even require it. The most ambitious models of this type, "supersymmetric grand unified theories," require that the Higgs boson is light (*17*). These models contain a huge number of new particles—a heavy partner for every particle in the standard theory. Surprisingly, though, the particular species predicted by these models give very small additional contributions to the vacuum polarization (*18*).

The new measurements, then, put the structure of the weak interactions into focus in a way that brings the story of elementary particle physics to a state of high tension. The possibilities for what we might find around the next corner are increasingly limited. The alternatives include the simple possibility of one light Higgs boson. But they also include models whose new symmetries lead to a parade of exotic particles and even to promised new visions of space and time. In the next decade, at the next step in accelerator energy, we will learn which of these alternatives nature chooses.

References and Notes

1. For a review, see R. N. Cahn and G. Goldhaber, *The Experimental Foundation of Particle Physics* (Cambridge University Press, Cambridge, UK, 1989), chap. 12.
2. For a summary and extensive bibliography, see LEP Electroweak Working Group, CERN-PPE/97-154 (1997). Available at: www.cern.ch/LEPEWWG/stanmod/
3. K. Abe *et al., Phys. Rev. Lett.* **73**, 25 (1994); *ibid.* **78**, 17 (1997).
4. R. Assmann *et al., Eur. Phys. J. C*, in press. [CERN-EP-98-040 (1998)]
5. M. Veltman, *Nucl. Phys. B* **123**, 89 (1977).
6. M. S. Chanowitz *et al., Phys. Lett. B* **78**, 285 (1978); *Nucl. Phys. B* **153**, 402 (1979).
7. This is a controversial statement. For another viewpoint, see C. T. Hill, *Phys. Lett. B* **345**, 483 (1995).
8. W. J. Marciano and A. Sirlin, *Phys. Rev. D* **22**, 2695 (1980).
9. F. Abe *et al., Phys. Rev. Lett.* **80**, 2767 (1998).
10. B. Abbott *et al.*, xxx.lanl.gov/abs/hep-ex/9801025.
11. M. E. Peskin and T. Takeuchi, *Phys. Rev. Lett.* **65**, 964 (1990); *Phys. Rev. D* **46**, 381 (1992).
12. Similar parametrizations have been proposed by P. Langacker and D. Kennedy [*Phys. Rev. Lett.* **65**, 2967 (1990)] and by G. Altarelli and R. Barbieri [*Phys. Lett. B* **153**, 161 (1991)] and G. Altarelli, R. Barbieri, and S. Jadach [*Nucl. Phys. B* **369**, 3 (1992)].
13. Some further improvements are expected in the next year, because of improved analyses of the *b* quark Z^0 asymmetries from LEP with a higher purity *b* sample, a higher statistics determination of the electron asymmetry at SLC, and improved measurements of the *W* boson mass from LEP.
14. B. Holdom, *Phys. Lett. B* **247**, 88 (1990).
15. M. Golden and L. Randall, *Nucl. Phys. B* **361**, 3 (1991).
16. For a counterexample to this rule, see T. Appelquist and J. Terning, *Phys. Rev. D* **47**, 3075 (1993).
17. G. Kane *et al., Phys. Rev. Lett.* **70**, 2686 (1993). J. R. Espinosa and M. Quiros, *Phys. Lett. B* **302**, 51 (1993).
18. For reviews, see A. Dobado, M. J. Herrero, S. Penarandra, xxx.lanl.gov/abs/hep-ph/9710313; D. M. Pierce, xxx.lanl.gov/abs/hep-ph/9805479.
19. For a full discussion of the fitting procedure, see M. Swartz, in *Proceedings of the International Symposium on Lepton and Photon Interactions*, P. S. Drell and D. L. Rubin, Eds. (American Institute of Physics, New York, 1994), pp. 381–424.

PERSPECTIVES: CONDENSED MATTER PHYSICS

Electronic Confinement in Organic Metals

Claude Bourbonnais and Denis Jérome

In the last two decades, the synthesis of new low-dimensional materials such as the organic and high–transition-temperature superconductors has shattered our traditional views about the properties of electrons in metals. This has been especially true since the 1980s with the coming of the Bechgaard salts, the so-called $(TMTSF)_2X$ organic superconductors and their sulfur analogs $(TMTTF)_2X$. These systems consist of a vast series of isostructural organic metals for which the donor constituents TMTSF (tetramethyltetraselenafulvalene) or TMTTF (tetramethyltetrathiafulvalene) are planar molecules and the acceptor X is an inorganic radical. On page 1181 of this issue, Vescoli *et al.* report new evidence for the unusual electronic properties of these materials (*1*).

Because TMTSF and TMTTF interact only weakly in the solid state, the cation retains its planar conformation. The result is a plane-to-plane stacking and an electronic delocalization along a particular direction, which turns these materials into a close realization of a one-dimensional metal. The Coulomb interaction between electrons is found to have special consequences in low-dimensional systems. The concept of "quasi-particles"—so successful in the Fermi liquid description of ordinary metals as a collection of effectively noninteracting electrons—turns out to be inapplicable in one spatial dimension, where the spin and charge degrees of freedom separately merge into collective low-energy excitations (*2*). These collective modes completely replace the quasi-particles, giving rise to a quite different electronic state called a Luttinger liquid.

Although real organic metals like the Bechgaard salts exhibit a small but finite coupling between chains, making them not purely one dimensional but rather quasi–one dimensional, these materials are among the best candidates for detecting signs of a Luttinger liquid state (*3*, *4*) as well as its possible instabilities, namely the recovery by the interchain coupling of a Fermi liquid state and the stabilization of various ordered phases (*5*). Working on this wide-ranging series of isostructural quasi–one-dimensional materials offers great advantages, including the possibility of following almost continuously the evolution of physical properties of the normal state as a function of anion (X = PF_6, AsF_6, Br, ClO_4, and so forth) and cation (TMTTF or TMTSF) substitutions, the application of hydrostatic pressure (*3*, *4*), or even working in nonzero magnetic field (*6*, *7*).

In a effort to seek concrete evidence of a Luttinger liquid in these systems, Vescoli *et al.* (*1*) have performed a nice set of optical reflectivity measurements that display the evolution of the optical transport in the presence of a correlation gap Δ_ρ. The results allow analysis of an important reduction of the amplitude of the gap when the optical probe goes from members of the insulating sulfur series to the metallic selenides (from left to the right in the figure). Moreover, they corroborate and complete previous optical studies by the groups of Timusk (*8*) and Elridge (*9*), who pointed out from the start the existence of a gap in the normal state of the selenide compounds $(TMTSF)_2AsF_6$ and $(TMTSF)_2ClO_4$.

For typical sulfur compounds like $(TMTTF)_2PF_6$ and $(TMTTF)_2Br$, located on the left side of the figure, the experiments show that the correlation gap is associated with an insulating behavior below the temperature $T_\rho = \Delta_\rho/3$. The temperature variation of magnetic spin susceptibility is well known to remain unaffected by the gap (*3*), indicating that the spins are apparently decoupled from the charge degrees of freedom. A spin-charge decoupling of this sort is predicted to occur when electrons in a half-filled or quarter-filled one-dimensional energy band interact to form a Luttinger liquid state that is severed of its charge component (LL_σ), also known as a one-dimensional Mott-Hubbard insulator. Electronic correlations then become so strong that charge carriers remain confined along the organic stacks. In the experiments of Vescoli *et al.* (*1*),

C. Bourbonnais is at the Centre de Recherche en Physique du Solide, Département de Physique, Université de Sherbrooke, Québec J1K 2R1, Canada. E-mail: cbourbon@pauli.physique.usherb.ca. D. Jérome is in the Laboratoire de Physique des Solides (CNRS), Université de Paris-sud, Orsay 91405, France.