mass must be greater than or equal to 10 GeV (or possibly even much greater if the double-beta decay transition takes place among quarks in that part of the nuclear wave function in which nucleons have lost their identity). In discussing all the bits of evidence for nonvanishing neutrino mass, Primakoff told us "the exciting thing is that the various numbers for the electron neutrino mass—values and limits—obtained from different kinds of experiments are all in the range 10–50 eV."

Capture of orbital electrons. In the process of capturing an orbital electron, the transition $Z \rightarrow (Z-1) + \gamma + \nu_e$ occurs. By measuring the shape near the endpoint of the photon spectrum, one can hope to determine the neutrino mass. If the number of these photons in the x-ray range is sufficiently large, their energies can be measured very accurately by Bragg reflection from crystals. For typical nuclides, which capture electrons from the K shell, the photon emission rates are too low. However, Alvaro De Rújula (CERN) noted[9] that in electron-capturing isotopes in which capture from the K or L shell is forbidden, the fractional counting rate at the endpoint is enhanced by several orders of magnitude. The probability for emission of photons in bremsstrahlung capture from the angular-momentum-one orbital is very high when the photon energy is below or close to the energy of the subsequently emitted characteristic x ray. By a search of isotope tables, De Rújula found that Nature has provided six isotopes where the photon endpoint energy is below the x-ray energy. Two in particular, are very good: $Pt^{193} \rightarrow Os^{193}$ has an endpoint of about 45 keV. The optimal electron-capturing isotope, De Rújula found, was $Ho^{163} \rightarrow Dy^{163}$. In this case, both the lifetime and the photon energy end point are not well determined; the latter probably lies in the range 2–10 keV.

Now theorist De Rújula is participating in an experiment at the on-line isotope separator at CERN, which is known as ISOLDE. His collaborators are J. U. Andersen (University of Aarhus, Denmark), P. Gregers Hansen (Aarhus), Bjorn Johnsen (CERN), E. Laegsgaard (Aarhus) and Helge Ravn (Aarhus). In their first round of experiments, the group expects to use relatively low resolution photon detectors made of Ge–Li. They are doing coincidence measurements between bremsstrahlung and Auger electrons or x rays.

Experiments using photon emission in electron orbital capture (in other words, internal bremsstrahlung electron capture) have essentially no problems with atomic interplay. The high Z and the retained total charge in the inner region of the atom cooperate to produce negligible shake-up in the outer shells. The CERN–Aarhus collaboration believes its experiment will have a sensitivity to a neutrino mass in the region 10–200 eV.

At Princeton, a group is also working on Ho^{163}, but not looking at internal bremsstrahlung electron capture. Charles Bennett explained that he and his collaborators are measuring the decay rates for capture of 3s, 3p, 4s and higher electrons. Because the 3s electrons are bound with 2 keV, if the mass difference between Ho^{163} and Dy^{163} is 2.5 keV, only 0.5 keV is left for the neutrino, and as a result, the 3s capture rate is strongly suppressed by a neutrino mass. The 4s electrons, on the other hand, are bound by only 0.4 keV and are less strongly affected. The relative capture rates, 3p/3s and 4s/3s, can therefore be used in combination to determine both the neutrino mass and the Ho^{163}–Dy^{163} mass difference. Decay rates also depend on the details of atomic structure. But the atomic-physics effects are essentially identical in Ho^{162} and Ho^{161}, and similarly for Ho^{163}. The mass difference between Ho^{161} and Dy^{161} is 850 keV; so the neutrino mass is totally irrelevant and the atomic-physics effects can be extracted, he said.

Last fall the group, consisting of Aksel L. Hallin, Bennett, Robert A. Naumann, Paul Springer, Mike Witherell, Frank Calaprice (all at Princeton), Robert Chrien (Brookhaven), Patricia Baisden, and David Sisson (Livermore) sent an Er^{162} sample to the High-Flux Beam Reactor at Brookhaven and now has 3 mg of Ho^{163}; experiments are under way, and x rays from 3s capture have already been seen. Bennett notes that although the quoted value of its halflife is (33 ± 23) years, the halflife could easily be considerably longer, indicative of a higher sensitivity to neutrino mass effects. Also, as has been discussed above, there is a big uncertainty in the mass difference. If it is small and favorable, M_ν of 50 eV will introduce a 10% correction to the 3s capture rate. If the mass difference is larger, the sensitivity of the relative capture rates to neutrino mass effects rapidly decreases.

Astrophysicists are continuing to investigate enthusiastically the ramifications of neutrinos with mass. It is widely believed now that neutrinos with masses in the range of a few eV would provide most of the mass of the universe. Massive neutrinos might be responsible for the invisible mass in galactic halos and for the missing mass of the universe. Clearly the study of neutrino mass continues to be a weighty subject. —GBL

References

1. F. Reines, H. N. Sobel, E. Pasierb, Phys. Rev. Lett. **45**, 1307 (1980).
2. D. Silverman, A. Soni, Phys. Rev. Lett. **46**, 467 (1981).
3. K. Bergkvist, Nucl. Phys. **B39**, 317 (1972).
4. V. A. Lyubimov, E. G. Novikov, V. Z. Nozik, E. F. Tretyakov, V. S. Kosik, Phys. Lett. **94B**, 266 (1980).
5. J. J. Simpson, Phys. Rev. **D23**, 649 (1981).
6. B. Cleveland, W. Leo, C. S. Wu, L. Kasday, A. Rushton, P. Gollon, J. Ullman, Phys. Rev. Lett. **35**, 737 (1975).
7. M. K. Moe, D. D. Lowenthal, Phys. Rev. **C22**, 2186 (1980).
8. A. Halprin, P. Minkowski, H. Primakoff, S. P. Rosen, Phys. Rev. **D13**, 2567 (1976) and references therein.
9. A. De Rújula, TH 3045-CERN, 1 April 1981.

Fractionally charged solitons

Move over, quarks. Make room for solitons with fractional charges. These newcomers have surfaced in theories from two distinct branches of physics—relativistic field theory and condensed-matter physics. The appearance of solitons (solitary wave solutions to nonlinear problems) in a wide range of physics problems is increasingly common, but their association with non-integer quantum numbers is a new feature. The analogous mathematical structure of the theories that show this feature is especially appealing to particle theorists because the predictions of the condensed-matter model are more amenable to experimental verification than are those of the more abstract field theories.

The emergence of fractional fermion numbers in relativistic field theory was noted[1] several years ago by Roman Jackiw (MIT) and Claudio Rebbi (now at Brookhaven) in their mathematical investigations of various relativistic field theories. Independently several condensed-matter physicists were working on a soliton theory of the linear organic polymeric chain, polyacetylene. Recently J. Robert Schrieffer (Institute for Theoretical Physics, Santa Barbara) has carried this model far enough to show the emergence of fractional quantum numbers. Jackiw and Schrieffer realized[2] the convergence of their two approaches when Jackiw visited the Institute for Theoretical Physics, whose purpose is to promote just such interactions across physics disciplines. In one of the field theories investigated by Jackiw and in the condensed-matter model, the presence of a soliton produces degenerate, zero-energy solutions for the fermion field, each with a quantum number of $\pm\frac{1}{2}$.

Schrieffer's recent work is based on a model he developed[3] at the University of Pennsylvania with Wu-Pei Su (now at the Institute for Theoretical Physics) and Alan J. Heeger. Almost concurrently Michael J. Rice (Xerox Webster Research Center) proposed[4] a similar theory. Hajime Takayama (Hokkaido University, Sapporo, Japan), Y. R. Lin-Liu (now at the University of California in San Diego) and Kazumi Maki (University of Southern California) then constructed[5] a continuum version of the same model that is exactly solvable. Although the seeds are there, none of the earlier models explicitly yields the prediction of fractional quantum numbers.

Su and Schrieffer recently extended[6] their work to one-dimensional systems, where the charges associated with the soliton would be $\pm\frac{1}{3}$ and $\pm\frac{2}{3}$. Jeffrey Goldstone (MIT), when accepting his Heineman prize at the January APS meeting in New York, described similar investigations he had undertaken with Frank Wilczek (Institute for Theoretical Physics) to show how fractional quantum numbers emerge in various quantum field theories.

Solitons in linear molecules. A generic feature of any problem in which solitons arise is the presence of some strong nonlinearity. In certain systems these nonlinearities lead to several distinct ground states of equal energy. Regions having different ground-state configurations are separated by localized interfaces of infinite energy called "solitons." One might picture solitons variously as domain walls in ferromagnetics, as phase boundaries in metal alloys, or as vortices in fluids.

In the model of a single polymeric chain of the isomer trans-polyacetylene proposed by Su, Schrieffer and Heeger, by Rice and by Takayama, Lin-Liu and Maki, the soliton becomes a kink in the bond alternation pattern of a linear molecule, interpolating between one end where the odd-numbered bonds are double and the other end, where the odd-numbered bonds are single. Thus the soliton in the phonon field arises because of the broken symmetry. The electronic states are modified by the soliton: The number of states per spin in the valence band and in the conduction band is reduced by $\frac{1}{2}$ and a singlet state appears in the gap between the two bonds. The double degrees of freedom introduced by the electron spin obscure the fractional charge. Still, unusual spin-charge relationships result. The charged (+e) soliton has no spin. (The valence band is full, and all spins are paired.) The neutral soliton has spin of $\pm\frac{1}{2}$. (The isolated state is occupied by a single electron.)

The unusual spin-charge relationships predicted by the soliton model of polyacetylene provide the basis on which it can be experimentally tested. Researchers have been looking either for spin structures in undoped polyacetylene, which could correspond to neutral solitons, or for the absence of spin in doped polyacetylene. Additionally, spectroscopic measurements might detect a mid-gap energy level expected to be associated with soliton solutions, or infrared spectral studies might sense changes in lattice dynamics associated with soliton formation. Several experiments have certainly provided evidence for such signatures, while others have yielded opposite results. Comparison of experimental results with one another and with the theoretical predictions is complicated by differences of sample preparation, by uncertainties over the morphology, and by the many possibilities for inhomogeneities. Furthermore, polyacetylene can exist in either of two isomeric forms, one of which cannot support solitons.

In an extension of their work on polyacetylene, Su and Schrieffer have studied one-dimensional systems with commensurability of three, that is, ones where the wavelength of a charge density wave equals three lattice spacings (one-third of an electron charge per site). A precursor to their work but in a different context was the analysis by Rice, Alan R. Bishop (Los Alamos), James A. Krumhansl (Cornell) and Steven E. Trullinger (USC), who pointed out that solitons might be current-carrying excitations in this class of one-dimensional systems. Because the solitons proposed by Su and Schrieffer would be associated with charges of $\pm\frac{1}{3}$, $\pm\frac{2}{3}$ or even $\pm\frac{4}{3}$, they would not be masked by the effect of the electron spin. Thus these systems may offer the possibility for the direct observation of fractional charges. The one-dimensional system TTF–TCNQ under pressure is one candidate for such experimentation.

Solitons in particle theory. Jackiw and Rebbi undertook their study as a formal mathematical investigation of various relativistic quantum field theories rather than as a vehicle to understand a particular physical phenomenon such as molecular structure. The one theory they studied that is analogous to the condensed-matter model involved a continuum rather than a lattice, and their fermions were spinless. Nevertheless, other features of their approach are very similar to that of the condensed-matter models. They both involved a fermion field coupled to a scalar field (the Bose field or the phonon field) with broken symmetry. The results in the particle theory were similar to those in the case of the linear molecule, except for the effect of the electron spin.

Jackiw commented to us that in relativistic field theory, one must postulate a broken symmetry; theorists don't yet understand how the symmetry in particle theories can be broken dynamically, as they are in the condensed-matter examples. The connection of solitons with broken symmetries is especially important because many current theories, most notably the unified field theories, postulate broken symmetries. These[1] broken symmetries then imply the presence of a soliton. Gerard 't Hooft (University of Utrecht) and Alexander Polyakov (Landau Institute in Moscow) have shown that solitons in three dimensions can be interpreted as magnetic monopoles. The possibility thus arises that magnetic monopoles may both exist and have fractional charges.

't Hooft warned against associating the fractionally charged solitons directly with quarks. The quark interacts too weakly and is too pointlike to be identified as a soliton. Nevertheless, the existence of solitons is important in theories of quark confinement.

Jackiw mentioned one other reason for excitement about the appearance of fractionally charged solitons. Whereas the fractional charges of quarks are now built into a theory in an *ad-hoc* manner, the solitons with their fractional quantum numbers emerge quite naturally in the soliton theories. In fact, several unconventional combinations of quantum numbers associated with solitons have already surfaced in other particle field theories. Other "unphysical" or unexpected quantum numbers may yet be encountered. —BGL

References

1. R. Jackiw, C. Rebbi, Phys. Rev. **D13**, 3398 (1976).
2. R. Jackiw, J. R. Schrieffer, to be published in Nuclear Physics B.
3. W. P. Su, J. R. Schrieffer, A. J. Heeger, Phys. Rev. **B22**, 2099 (1980).
4. M. J. Rice, Phys. Lett. **71A**, 152 (1979).
5. H. Takayama, Y. R. Lin-Liu, K. Maki, Phys. Rev. **B21**, 2388 (1980).
6. W. P. Su, J. R. Schrieffer, Phys. Rev. Lett. **46**, 738 (1981).

Have glueballs been seen?

There is general optimism among elementary-particle physicists that quantum chromodynamics will prove to be the correct theory of the strong interactions. Although QCD is constructed in close analogy to quantum electrodynamics, the uniquely successful gauge theory of the electromagnetic interactions, the multiplicity of QCD "color charges" make it considerably more elaborate than QED. Unlike the uncharged photon of QED, "gluons," the field quanta that mediate the strong interaction between quarks in QCD, are themselves bearers of the color charges.

Thus, in addition to the quark bound states that appear to account for all the well-known mesons and baryons, QCD leads us to expect a new class of elementary particles—quarkless bound states of the gluons themselves. Finding such "glueballs" (some prefer the name "gluonium") would constitute an important verification of QCD. Specific model calculations within the framework of QCD have in fact predicted a number of two-