search & discovery

New theory of weak and electromagnetic interactions

A new paper by Steven Weinberg (MIT) is causing great excitement among high-energy physicists. One leading theorist calls it "the most important development in weak-interaction theory in the last 15 years." Weinberg explained to us that his new work is a possible solution of two outstanding problems. One is how, in a natural way, to unify the weak and electromagnetic interactions. The second is how to make a theory of weak and electromagnetic interactions in which the infinities can be dealt with in as simple a way as they are in quantum electrodynamics.

Weinberg's theory is very close in spirit to theories proposed much earlier by Julian Schwinger (Harvard), Sheldon Glashow (Harvard), Abdus Salam (then at Imperial College, London), John Ward (then at Johns Hopkins University) and many others. Their idea is that the weak interactions are carried by some kind of intermediate vector meson in the same way that electromagnetism is carried by the photon. The weak interactions might arise from some kind of gauge invariance of the theory. (A gauge invariance is a symmetry in which not only does the theory have a symmetry with respect to some kind of internal rotation performed everywhere all at once, but it also is invariant even if you perform independent internal transformations at every point in space-time.)

If the Lagrangian were gauge invariant, this would explain why the vector and axial vector currents used to describe the weak interactions are conserved or partly conserved. In addition, you might be able to unify the electromagnetic and weak interactions in some way. Furthermore, the weak interactions might be renormalizable in the way they are in quantum electrodynamics. In the usual weak-interaction picture, you imagine a contact interaction between currents, which interact at the same point, producing very badly divergent integrals at high energy. But if an intermediate vector meson were transmitted in the interaction, one would expect somehow that the high-energy behavior would be better.

The difficulty with the usual formulations of weak-interaction theory is that there is not an exact gauge invariance because the intermediate vector meson does not have zero mass like the photon, but is in fact very heavy. So if there is a gauge invariance, it's very badly broken. Because of this breaking of the gauge invariance, the high-energy behavior is no better than the usual contact interaction between currents.

In 1967 Weinberg suggested[1] a way to make the gauge invariance an exact invariance of the Lagrangian; it would not be broken by any mass term in the Lagrangian. Because the invariance of his theory is exact and it is only the vacuum that breaks the symmetry (that is, there are physical states that do not respect the symmetry), the theory might be renormalizable, Weinberg said. He also showed that this proposal would very naturally lead to a unification of the electromagnetic and weak interactions in which the photon had zero mass and the other particles were much more massive. His model

continued on page 20

Absolute laser frequency measurements

If we knew a precise value for the frequency of the length standard, or, alternatively, for the wavelength of the frequency standard, we would have a good way to define the velocity of light *c*. But until now the hitch has been that wavelength measurements, although fairly easily done in the visible through the near infrared (to three microns or so), are difficult at longer wavelengths, whereas frequency measurements have until recently been limited to the microwave region. Now a group at the National Bureau of Standards in Boulder, Colorado, mixing their oscillators by means of a metal-metal diode originally used at the Massachusetts Institute of Technology,[1] reports the highest "absolute" frequency measurement to date.[2]

Mixing of signals from 10-micron CO_2 laser (right) and 3.39-micron He–Ne laser (upper left) occurs in a metal–metal point contact diode (lower left). Diode response time is fast enough to measure the 88-THz He–Ne signal.

The series of experiments by the Boulder group (Kenneth Evenson, Gordon Day, Joseph Wells and Lewis Mullen) completes a chain of frequency measurements linking the NBS cesium frequency standard with a 3.39-micron, 88-THz (1 THz = 10^{12} Hz) helium–neon laser. (A chain of experiments is needed because two frequencies differing by more than a factor of 12 cannot be compared directly). The laser wavelength is already well known from independent studies.

The present result, 88.376245 ± 55 THz, is good to six parts in 10^7 and does not itself improve our knowledge of *c*; Evenson and his coworkers plan to repeat the chain of experiments with stabilized lasers, and they expect a frequency measurement good to about half a part in 10^8. Getting a better value for *c* will help astronomy, for example; some studies are even now limited by uncertainties in *c*. And precise high-frequency techniques are useful in atomic physics to determine the exact center of absorption resonances.

Much of the work in absolute high-frequency measurements has been done either by the Boulder group or by Ali

Transitions between the ground electronic state of hydrogen ($X^1\Sigma_g^+$) and excited electronic states ($C^1\pi_u$ and $B^1\Sigma_u^+$, see figure) can be induced in either of the two new lasers. The pulse is of such high power and short duration that a large inversion density builds up in the upper level before spontaneous-emission transitions can populate the upper vibrational levels of the ground state. When the inversion density is great enough, stimulated emission, that is, lasing, occurs without the need for the mirrors customary in conventional lasers.

Proof that stimulated emission is occuring can be obtained from an examination of the Werner-band spectrum, obtained with an ultraviolet spectrograph at 0.25-Å resolution. The relative intensities of the lines in the band are in agreement with what is calculated for stimulated emission, and are completely different from the normal spontaneous-emission intensities. Waynant has an extra (and, he maintains, a better) check for stimulated emission with his travelling-wave discharge. The propagation velocity of the excitation wave down the laser channel can be varied, and maximum laser output (for earlier nitrogen and Lyman-band hydrogen lasers) is obtained when the excitation wave velocity is less than c. The Werner-band lines only appear when the phase velocity of the wave is less than c; this effect is taken as evidence that stimulated-emission gain is occurring.

Hodgson and Dreyfus reported the energy in their Werner-band output as 5 erg/cm^2, but Hodgson tells us that he has now revised the figure upwards to 100 erg/cm^2; he discovered that the lithium-fluoride window he was using had become absorbent, apparently because color centers were formed during the intense ultraviolet exposure. —JTS

References

1. R. W. Waynant, J. D. Shipman Jr, R. C. Elton, A. W. Ali, Appl. Phys. Lett. **17**, 383 (1970).
2. R. T. Hodgson, Phys. Rev. Lett. **25**, 494 (1970); R. T. Hodgson, R. W. Dreyfus, Phys. Lett. **38A**, 213 (1972).

Weak-interaction theory

continued from page 17

specifically predicts a charged intermediate vector meson with a mass greater than 37.3 GeV and a neutral intermediate vector meson with a mass greater than 74.6 GeV as well as a photon of zero mass.

Normally, as in recent work on chiral symmetry, the spontaneous breaking of symmetries is accompanied by massless Goldstone bosons. Peter Higgs (University of Edinburgh) had pointed out in 1964 that the spontaneous breaking of an exact gauge invariance was an exception and did not necessarily entail Goldstone bosons. Therefore in Weinberg's theory there are no massless scalar mesons.

Weinberg's paper was allowed to sink into obscurity for the next four years while he struggled to prove that the theory was renormalizable, that the infinities could be reabsorbed like they are in quantum electrodynamics into redefinitions of the fundamental parameters such as electric charge.

Last summer a graduate student at the University of Utrecht, Gerhard 't Hooft, studying the kind of theory in which gauge invariance is exact but broken spontaneously, developed a method[2] of dealing with the theory that indicated the theory was probably renormalizable. Then Benjamin W. Lee (State University of New York at Stony Brook) offered a proof[3] that theories of this class, in particular Weinberg's weak-interaction theory, are indeed renormalizable.

Now Weinberg has published a new paper[4] that shows how his theory escapes some of the divergence difficulties present in conventional models. In the usual weak-interaction theory, with or without the presence of an intermediate vector meson, you find that the cross section for certain processes grows without bound and you get a violation of unitarity. It was generally believed that there would have to be some modification of the theory that would set in at about 300 GeV that would bring everything into agreement with unitarity. Weinberg has shown that in his model the cross sections behave quite well and that the theory heals itself considerably before you reach the 300-GeV limit. This self-healing may explain why the theory is renormalizable, if indeed it is. In the process of a neutrino and an antineutrino producing a pair of intermediate vector mesons, one obtained a scattering amplitude that increased proportionally to energy, whereas unitarity predicts a proportionality to the reciprocal of energy. The Weinberg theory gives an amplitude that is indeed proportional to reciprocal energy.

Since then Thomas Appelquist and Helen Quinn (Harvard) have done some calculations[5] that verify that in a particularly simple version of Weinberg's theory, the conjectured higher-order renormalizations are in fact possible, that is, the theory gives finite results for physical processes.

Weinberg told us that two things remain to be done: to find the right model and then to find experimental evidence for the validity of the model. He emphasized that although his 1967 model has so far received most attention, it is only one of a much larger class of renormalizable models based on various gauge groups. One is looking for a model that incorporates the weak and electromagnetic interactions not only with the leptons but also with the hadrons, he said. This problem is exceedingly difficult, he went on, because there are so many constraints. One of the constraints is that you must not allow the gauge invariance to be broken at all by any term in the Lagrangian. This is difficult to reconcile with accepted belief, which was that some of the effects seen in the strong interactions, such as the finite mass of the pion, arise from an actual breaking of the symmetry in the equations of motion.

Although the 1967 Weinberg model predicts lower bounds for the mass of the intermediate vector meson, the meson is not likely to be found soon, he notes. But there is some indirect experimental evidence that can be examined. Frederick Reines (University of California at Irvine) has done a reactor experiment on scattering of antineutrinos by electrons. If its accuracy can be improved by an order of magnitude it could serve as a test between the Weinberg theory and that of Richard Feynman and Murray Gell-Mann (Cal Tech). An improved experiment on the scattering of muon neutrinos on electrons could also test both theories. Calculations by Weinberg and Roman Jackiw (MIT) show that if the measurement of the anomalous magnetic moment of the muon can be improved by two orders of magnitude, this could also serve as a check on the theories.

"Right now there's not a grain of experimental evidence that this general idea is right. But it solves so many theoretical problems all at once, that it smells right," Weinberg says. —GBL

References

1. S. Weinberg, Phys. Rev. Lett. **19**, 1264 (1967).
2. G. 't Hooft, Nucl. Phys. **B33**, 173 (1971); Nucl. Phys. **B35**, 167 (1971).
3. B. W. Lee, Phys. Rev., to be published; B. W. Lee, J. Zinn-Justin, to be published.
4. S. Weinberg, Phys. Rev. Lett. **27**, 1688 (1971).
5. T. W. Appelquist, H. Quinn, Phys. Lett., to be published. □