The weak interactions from now on

Their spin structure, flavor dependence and their very weakness remain major puzzles, but these have now become subsumed into the general problems of elementary particles.

Steven Weinberg

We like to think of physics as moving toward unity, but at any one moment it is fragmented into specialties, which sometimes seem even to define different scientific personalities. This certainly appeared to be the case when I arrived in Palmer Lab at Princeton University as a new graduate student just 30 years ago. Physicists who worked on strong and weak interactions seemed to me to be very different sorts of animals, differentiated especially by the quantity and nutritional value of the data on which they fed.

For strong-interaction physicists there was a growing quantity of data on nucleon–nucleon and pion–nucleon interactions, which was soon after to reveal a huge forest of new mesonic and baryonic states. But the data didn't have much food value; the strong interactions were too strong to allow us to do much in the way of calculations that could be compared with the data.

On the other hand, the weak interactions were weak enough to allow us to do perturbative calculations (except where strong interactions got in the way) but their weakness meant that there wasn't too much information available, just some incomplete data about the form of the interaction in nuclear beta decay and a few precious bits of data about weak interactions of muons, pions and strange particles.

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I suppose the strong-interaction physicists could have been compared to elephants, who gobble up enormous quantities of un-nutritious vegetation, while the weak-interaction types were like leopards, who lie in trees for long periods, waiting for a nice juicy antelope to pass beneath, but mostly staying very hungry. Anyway, when I arrived in Princeton as a student I easily recognized that Sam Treiman was a pretty sharp leopard, and I attached myself to him, to learn how to hunt for good things among the weak interactions. Strong interactions seemed then to me to be just a nuisance that had to be taken into account in analyzing the weak interactions of hadrons but would never themselves reveal anything very interesting.

Changing the direction of research

As it happened, nothing did more to break down the barrier between strong- and weak-interaction physicists than a paper by Sam Treiman and a newcomer to Princeton, Murph Goldberger, in 1958. This is one of those mysterious works, like Max Planck's second paper on blackbody radiation in 1900 or Werner Heisenberg's first paper on quantum mechanics in 1925, that derive striking results whose success changes the direction of physics research, but that do not fully explain their own success.

The paper was perhaps written because Princeton could not afford separate offices for Treiman and Goldberger. Be that as it may, they set out to use dispersion relations to calculate the charged-pion decay rate, and with a number of tricky approximations obtained the result

$$F_\pi = 2m_N g_A / G$$

where F_π is the pion decay amplitude, m_N is the nucleon mass, g_A is the axial-vector coupling constant of beta decay and G is the pion–nucleon coupling constant. The agreement with experiment was striking.

The problem of understanding why this relation should work so well led to a great spurt of theoretical activity around 1959–60, followed by a second spurt around 1965, to which no one contributed more than a student of Treiman's, Steve Adler. It was in the course of this work that theorists realized that the strong interactions have an approximate symmetry, based on the group $SU(2) \times SU(2)$, the two SU(2)s acting just like ordinary isospin transformations but separately on the left- and right-handed nucleon (actually, quark) fields. Correspondingly, there exist approximately conserved vector and axial-vector currents, which can be identified with the hadronic currents of nuclear beta decay. The symmetry is spontaneously broken, which means that it is manifest not in the multiplet structure of hadrons but rather in the properties of the currents and in the interactions of low-energy pions. From this point of view, the Goldberger–Treiman relation should really be written

$$G = 2m_N g_A / F_\pi$$

That is, the amplitude G for emitting a soft pion from a nucleon is proportional to the amount ($2m_N g_A$) by which the one-nucleon state violates the conservation of the axial-vector current, with $1/F_\pi$ a factor that appears whenever a

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soft pion is emitted. With another student, Curt Callan, Treiman later derived another important relation of this sort, comparing the amplitude for $K \rightarrow \pi\mu\nu$ to that for $K \rightarrow \mu\nu$; again, a factor $1/F_\pi$ accompanies the pion emission.

This discovery of a spontaneously broken symmetry of the strong interactions woke us up to the possibilities of spontaneous symmetry breaking in other quarters, and this led in turn to our modern understanding of the weak interactions in terms of spontaneously broken gauge symmetries. One result is that we can now understand the previously mysterious relation between the currents of the broken chiral symmetry of the strong interactions and the vector and axial-vector currents of beta decay: It is just that the electroweak gauge group and the chiral symmetry group overlap in their action on quark doublets.

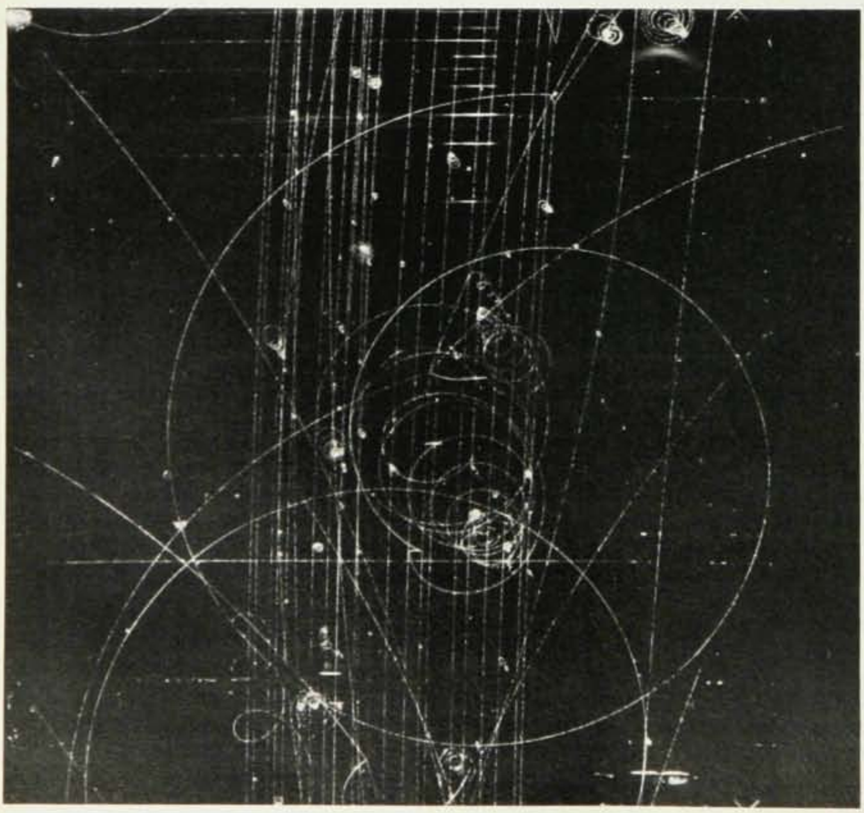
I have given just one example of how everything has come together in the last several years. It would be difficult to imagine a young graduate student arriving in Princeton today announcing that he or she wanted to work on the weak interactions. Elementary-particle phenomenology, yes, or gauge-field theories, or something newer like supersymmetry or string theory, but not weak interactions—it would be like a doctor specializing in diseases of the left hand. It is not that every one of the problems of weak-interaction theory that we used to worry about has now been solved—the old problems are in fact still with us, but they have merged with the general problems of elementary-particle physics. To illustrate this, I want to take up three of the old problems we used to worry about and look at how these problems appear today.

Three old problems

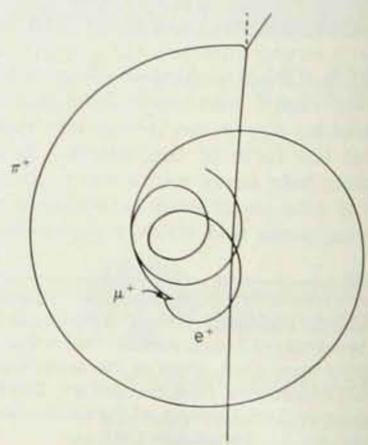
First, the spin structure of weak interactions. As you all know, after a quarter-century of studying the form of the Fermi interaction in nuclear beta decay, people finally realized in 1956–57 that the weak interaction violates parity maximally, and has the form $V - A$, vector minus axial vector. All this can be summarized in the statement that the charged-current weak interaction involves only the left-handed parts of the fields of the elementary fermions, the leptons and (as later realized) the quarks. We understand this today in the context of modern gauge theories as due to the fact that it is the left-handed parts of the quark and lepton fields that form gauge doublets; the right-handed parts are gauge singlets. This is usually abbreviated by saying that the fermions are *chiral*. But why should this be the case? Oddly enough, this fundamental fact about the weak interactions has today the character of both a tautology and a mystery.

It has become a tautology because we have in the last ten years gotten used to the idea that the really fundamental energy scales of physics, whether we think of them as the Planck scale, the grand-unification scale, the compactification scale or the string-tension scale, are vastly larger than the scales accessible to us in the laboratory, perhaps as large as 10^{19} GeV. According to this viewpoint, the only particles that we *should* have been able to discover are those that are protected by symmetries from getting masses at the very high energy scale. And the only known cases are gravitons, gauge bosons and chiral fermions (and perhaps their partners in supersymmetry theories). So the observed fermions have to be chiral, because otherwise they would be too heavy to have been observed.

But the existence of chiral fermions also is a mystery. Most Lie groups that might be candidates for a grand unified



Pion decay. Much of our understanding of weak interactions began with the Goldberger–Treiman relationship that gave the amplitude for the decay of charged pions in terms of fundamental coupling constants. This bubble-chamber photograph taken at Brookhaven National Laboratory in 1966 shows a pion decaying into a muon (and a muon neutrino, which left no track); the muon in turn quickly decayed into a positron and a neutrino–antineutrino pair.



gauge group have only real representations, which means no chiral fermions. Also, purely gravitational theories in higher dimensions, when compactified down to four space–time dimensions, always turn out to have only nonchiral fermions. One of the reasons for all the recent excitement about $E_8 \times E_8$ string theories, such as the heterotic superstring, is that these theories naturally lead to E_6 in the compactification from ten to four space–time dimensions, and this is one of the few candidate grand unified groups that do allow chiral fermions. We don't as yet know how all this will turn out, but the existence of chiral fermions is one of the crucial clues that for the past decade has allowed us to discriminate among theories of fundamental physics at very high energy.

The second old problem is the flavor dependence of the weak interactions. The weak interactions were successfully described years ago by a picture in which the u quark does not make independent transitions to either d or s quarks, but rather to a specific linear combination, the mixture $d \cos\theta_C + s \sin\theta_C$, with θ_C the Cabibbo angle, empirically determined to be about 13°. Later it was proposed that the orthogonal linear combination, $-d \sin\theta_C + s \cos\theta_C$, should also appear, but in conjunction with a new quark, the c. But no one knew where the mysterious angle θ_C came from.

Of course, now we have two more quarks (one yet to be pinned down). This has provided us with two more mixing angles, plus a phase that can account for the observed CP violations.

Today the problem of the mixing angles is still with us, but has been somewhat stood on its head. From the standpoint of modern gauge theories, it is the quark fields defined by their transformation under the electroweak gauge group that are really fundamental, and we think of the quarks of definite mass (which get their mass through the same symmetry breaking that splits the W and Z from the photon) as mixtures of the fundamental quarks. So there is no mystery as to why there should be a Cabibbo angle, and the mystery of why it has the value it has has merged into the general problem of understanding the values of the quark and lepton masses.

But that remains quite a problem. We see mass ratios of 3000 between the lightest and heaviest charged leptons, the e and τ, and at least 10 000 between the lightest and heaviest quarks, the u and the t. And while there is nothing very surprising about the value of the Cabibbo angle, the two new mixing angles are surprisingly small. Many of us have tried to find some sort of pattern in these masses and angles, but so far the secret has eluded us.

The last of the old problems I want to talk about is the weakness of the weak interactions. We all know that you can vividly describe the weakness of the weak interactions and frighten small children by telling how many light years of lead can be penetrated by a beta-decay neutrino. But from the point of view of the electroweak gauge theories, there is nothing particularly weak about the weak interactions. The only dimensionless parameters are the SU(2) and U(1) coupling constants, which are of the same order as the electronic charge e. The electroweak theory has built into it a fundamental energy scale, roughly 247 GeV, that characterizes the spontaneous breakdown of the electroweak gauge symmetry; the W and Z masses are predicted to be of order e times this scale, and as you know they come out right. The old mystery of why the weak interactions are so weak appears here instead as the mystery of why some quarks and leptons—the e, u and d—are so much lighter than the W and Z, but this is just part of the general mystery of the quark and lepton masses. In fact, from this point of view, the *least* mysterious fermion is the t quark, which can't be much lighter than the W, and the most mysterious one is the one first discovered, the electron.

Really, though, the great mystery is not why the weak interactions are so weak, but why they are so strong. That is, why is the electroweak breaking scale of 300 GeV so small compared with the really fundamental Planck or GUT or Kaluza–Klein or string scale of around 10^{17} GeV? This mystery, sometimes known as the hierarchy problem, has driven a good deal of the adventurous theorizing of the last decade.

The end of weak interactions

So the problems of weak-interaction physics are still with us, but I think it fair to say that weak-interaction theory is finished as a separate discipline. Now, in closing, I would like to ask whether history may repeat itself, whether experiment may present us with weaker weak interactions of some new sort.

One way to approach this question is to imagine what physics would be like today if we knew all about the strong and electromagnetic interactions, and

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were very sophisticated mathematically, but knew nothing about any weak interactions. We would know about a large number of apparently exact symmetries: Lorentz invariance, color and charge gauge invariance, C, P and T invariance, and separate conservation of each quark and lepton flavor—strangeness, charm, mu-ness and so on. It would be tempting to accept all these symmetries as fundamental facts of nature. However, a skeptic might notice that in the context of color and charge gauge theories, there is simply no way that one could introduce any violation of the other symmetries—strangeness, charge-conjugation invariance, and so on—without introducing complicated interactions among the known quarks and leptons, involving at least four fermion fields. Such nonrenormalizable interactions necessarily have coupling constants given by negative powers of some new mass scale, and if this scale were very large (say 247 GeV) then these couplings that violate strangeness, parity and so on could have escaped detection. In this way a very skeptical physicist might have been led at least to consider the possibility of weak interactions that violate known symmetries.

The moral of this fable is clear. History *may* repeat itself: We may discover new, superweak interactions associated with new energy scales larger than 247 GeV, and these interactions may violate currently accepted symmetries—perhaps mu-ness, or baryon or lepton number, or who knows what. If this happens we will all of us—theorists and experimenters—be in for another period of great fun.

Obviously, I don't know if this will happen. However, I do have one word of advice for any aspiring young student who would like to participate in this sort of excitement. It is to get Sam Treiman to be your thesis adviser. □