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Strong Inference and Weak Interactions

An episode in nuclear physics offers an example of the complex interplay between theory and experiment.

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In a recent paper (*1*), J. R. Platt has attempted to explain why some scientific fields advance more rapidly than others. He concludes that a primary factor is the degree to which scientists in a particular discipline teach and use a systematic method which he calls "strong inference." This is a procedure for generating and pruning a logical tree of growth in a field of science. According to this metaphor, the trunk of the tree is the state of knowledge in the field at a given time. The branches are a set of alternative hypotheses. A "crucial experiment" (or several of them) can then be devised "with alternative possible outcomes, each of which would, as nearly as possible, exclude or disprove one or more of the hypotheses." So the crucial experiment leads to a decision as to which branches should be eliminated and which should be allowed to grow.

Strong inference is a methodology that places an especially heavy burden on the experimentalist. In deciding what to do next, he must give priority to a task whose outcome is crucial to a choice among current hypotheses. He must resist the temptation to stray from a central path following the hot scent of the present chase. An interesting investigation carried out in defiance or merely in ignorance of pressing questions is likely to be a waste of time. And so much is at stake that the experimenter must be completely sure of his results. Error can do more than delay progress; it can endanger the health of the entire logical tree.

We suggest that the notion of strong inference is an idealized scheme to which scientific developments seldom conform. A look at the real world of science reveals that its trees grow in many ways whose structure is evident only when growth is complete. The role ultimately to be played by "crucial" experiments is often not clear at the moment of their design, or even after they are performed. When an experiment disagrees with a theoretical prediction, the theory does not necessarily die. It may, instead, serve to question the correctness of the experimental result. Platt remarks that molecular biologists at Cambridge, when confronted with a puzzling new result from an outsider, allow themselves to ask "What did he do wrong?" This is the *only* question we ask about puzzling results from student laboratories, where laws of nature would otherwise be disproved every day.

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Weak Inference

Methodologies of science often tend to suggest that, whereas theories may be right or wrong, experiments are always right. The method of strong inference, with its emphasis on step-by-step experimental disproof, appears to sponsor this view. Perhaps such schemes are accurate pictures of how we teach finished products of science, but they are not accurate pictures of how these products really grew. Largely as a matter of habit, we prefer the story of a wrong hypothesis to the story of a faulty experiment. The art of speculation enjoys, even in retrospect, a policy of *laissez faire*; the art of experimentation emerges with an aura of infallibility.

There is no doubt that crucial experiments exist, nor can we question their decisive role in the evolution of theoretical ideas. But it may be realistic to broaden the meaning of cruciality. In the method of strong inference, the design of crucial experiments follows from explicit study of alternative hypotheses already formulated. In the broader sense, any experiment, regardless of motivation, is crucial to a choice among hypotheses if it is in principle capable of restricting the choice. The class can therefore include work done long before its crucial role becomes apparent. An observation that was so unbelievable as to be judged wrong, or that was simply mysterious in its time, can become crucial to the resolution of subsequent dilemmas.

The actual history of science, when viewed in this light, contains interesting examples of what might be called "weak inference," by which we mean a breakdown of the scheme of strong inference. A well-known case is the work of Becquerel (*2*) in the early months of 1896. His initial hypothesis was that x-rays are given off during visible fluorescence, an idea suggested by the appearance of fluorescence on the glass walls of x-ray tubes. Since his first test was to use uranium salts in his exposures to sunlight, he found immediate confirmation of the idea. Then, by accident, a "crucial" observation: the same salts radiate in the dark, long after their fluorescence has vanished. At this point in the usual abbreviated history, we say that Becquerel "discovered radioactivity." But what actually happened? In the scientific context of his discovery, Becquerel had nowhere to turn except to a slight modification of his original idea: he proposed that, whereas the visible fluorescence is short-lived, there is another invisible component of fluorescence with a very long lifetime.

Becquerel held fast to the idea of fluorescence throughout the sequence of his early experiments. Some observations, which turned out to be wrong, appeared to support the hypothesis. For instance, one of his experiments "demonstrates the small difference between emission from uranium salt kept in the dark, and the same brilliantly illuminated by magnesium," although it was admitted that "this study is made very difficult by the prodigious persistence of the emission when the substances are kept in darkness." Other experiments violated the hypothesis only to be explained away. Becquerel thus tried, and failed, to stimulate the activity by ultraviolet light and concluded "either that the characteristic emission of the substance masked the weak differences which might have been observed, or that the excitation did not take place in this region of the spectrum." It was only after another crucial experiment, revealing persistent radiation from pure uranium and from solutions, that the notion of fluorescence lost ground to a new conviction: the source of the radiation is the uranium atom itself.

Especially at the frontiers of science, where clear-cut alternative hypotheses do not easily appear, cases like this are likely to recur. Far from dealing harshly with a man like Becquerel (after all, he *did* discover radioactivity), we should draw what wisdom we can from his experience. It might be suspected that, after an interval of 70 years, during which physics has braved many new storms, our understanding of method has been significantly deepened. Perhaps we can now see that a growing science is not an idealized logical tree; that theory plays a crucial role in the evaluation of experiment; that we must expect to encounter an occasional mistake in observation; and that experimentalists deserve as much freedom as theorists. In order to give a recent and revealing illustration of these ideas, we devote the remainder of this paper to a review of major events in the history of the universal Fermi interaction. Our purpose is to show the points at which the method of strong inference applies, as well as those at which it breaks down.

Table 1. Key to the history of the "universal Fermi interactions."

Theory	
T1	Two-component neutrino theory
T2	Fermi theory
T3	Hypothesis of universal interaction
T4	Hypothesis of parity nonconservation
T5	V—A theory
Experiment	
E1	Nuclear β-decay spectra and lifetimes
E2	Meson decay
E3	Electron-neutrino correlations in nuclear β-decay
E4	Electron angular distributions: β-decay of polarized nuclei
E5	Electron polarization in nuclear β-decay
E6	Decay of polarized muons and kaons
E7	Polarization of e^{+} from μ^{+}
E8	Electron angular distribution: β-decay of polarized neutrons
E9	Neutrino helicity

Beta Decay

In his earliest studies of the mysterious and spontaneous radiation discovered by Becquerel, Rutherford observed a component with low penetrating power, and another, long-range component. He called them "alpha rays" and "beta rays," respectively, without at first knowing that both components are identical with atomic constituents of ordinary matter. The alpha rays are helium nuclei; the negative beta rays are electrons. Rutherford's terminology is still in use: "alpha particles" are nuclei of He^4, and "beta decay" is the process in which a nucleus emits an electron (or positron) and an antineutrino (or neutrino). It is the description of this process which we wish to review. Nuclear beta decay has turned out to be one manifestation of the class of physical forces now generally known as "weak interactions." It is currently believed that the same interaction—the "universal Fermi interaction"—accounts both for nuclear beta decay and for certain slow decays of the elementary particles. Physicists became aware that this might be so in 1949, but the idea did not receive its present precise formulation until 1957, when the so-called "V—A" theory of weak interactions was proposed. The growth of this theory, in the context of an expanding body of experimental knowledge, is the principal subject of our review.

Major contributions to the history of theory and experiment can be grouped according to the general scheme of Table 1, which establishes a key for our discussion. A chronological summary of the history, referring to the same scheme, is shown in Table 2. Entries in this table mark the significant steps leading to acceptance of the V—A theory and provide reference to the research literature. The table is intended to show lines of development for *groups* of ideas. Thus, for example, E3 is not a single experiment; it denotes *all* experiments on electron-neutrino correlation in nuclear beta decay.

Most of the early work on beta decay consisted of measurements of lifetimes and electron energy spectra over a wide range of nuclear species. In order to account for the continuous electron spectra, it was necessary to postulate the existence of the neutrino (zero mass, zero charge, spin ½). In 1929, H. Weyl (*3*) pointed out that this particle lends itself to an especially simple description (T1 in Tables 1 and 2) which we now recognize as the "two-component" theory. But the idea was immediately rejected: it implied a breakdown of the parity principle, which at the time, and for almost three subsequent decades, was regarded as inviolable.

The most fruitful theoretical description (T2) of beta decay was formulated by Fermi (*4*) in 1934. In its subsequent more general form (*5*), the theory postulates that the interaction Hamiltonian (a quantum-mechanical operator for the energy of the system) describing beta decay is, in schematic form,

$$H = \mathrm{V} + \mathrm{A} + \mathrm{S} + \mathrm{T} + \mathrm{P} \qquad (1)$$

Each term exhibits a certain behavior (vector, axial vector, scalar, tensor, or pseudoscalar) under Lorentz transformations. It is an essential feature of the Hamiltonian, as originally proposed, that it does not violate conservation of parity.

Following the acceptance of a Hamiltonian of this form, the central question in beta decay was the experimental determination of relative magnitudes for the five terms. It was a question about which the early theory had nothing to say. Thus began a tree of inference: the prediction of five possible branches, leaving to experiment the task of discovering which one, or which combination, describes actual beta decay.

Selection Rules: Kurie Plots (E1)

The first evidence on this question came from identification of nuclear spins. It is characteristic of beta decay that it involves four fermions (particles of spin ½), the essential process being either the transformation of a proton into neutron, positive electron, and neutrino:

$$p \rightarrow n + e^{+} + \nu$$

or the transformation of a neutron:

$$n \rightarrow p + e^{-} + \bar{\nu}$$

The free neutron decays to the stable free proton; when nucleons are bound into radioactive nuclei, both types of transition are possible.

Let I_i be the spin of the decaying nucleus and I_f the spin of the daughter. According to the rules of addition of angular momentum in quantum mechanics, the spins of electron and neutrino may combine to form a singlet state (total spin zero) or a triplet state (total spin unity). Now angular momentum must be conserved during the decay, and the so-called "allowed" transitions conserve spin and orbital angular momentums separately. Thus an allowed transition to a singlet state involves a spin selection rule

$$I_i = I_f$$

(the Fermi transition). An allowed transition to a triplet state requires

$$I_i = I_f \neq 0$$

or

$$I_i = I_f \pm 1.$$

(the Gamow-Teller transition). A given transition can be a pure example of one type, or a mixture of both.

The interest in these two kinds of beta decay arises from the realization that Fermi transitions are generated only by the V or S terms in the Hamiltonian of Eq. 1, whereas Gamow-Teller transitions are generated only by A or T. By 1937, pure examples of both types were known to exist. It was therefore understood that the Hamiltonian must contain at least two terms, one to generate each type of transition.

Other early information came from Kurie plots of beta spectra. The Kurie plots relate an electron momentum distribution $I(p)$ to the electron energy E. It was found that, for all allowed transitions, the plot of $[I(p)/p^2]^{1/2}$ against E is linear. This fact, added to the previous observations, implies that the Hamiltonian contains two and only two terms: either V or S alone generates the Fermi transitions, and either A or T alone generates Gamow-Teller transitions. Thus we have arrived at step 7 of Table 2. Of the 31 interactions formed from five terms taken singly or in combination, only four possibilities remain. They are VA, VT, SA, or ST. No further restriction can be made from measurements on beta spectra alone. It is necessary to devise new experiments that are both more subtle and more difficult.

Table 2. Development of understanding of the universal Fermi interaction.

Step	Date	Theory	Exp. group	Status	Ref.
1	–1929		E1	Early accumulation of β-decay data	
2	1929	T1		Considers and rejects T1	*(3)*
3	1934	T2		Predicts V form of Hamiltonian	*(4)*
4	1936	T2		Predicts general form V + A + S + T + P	*(5)*
5	–1937		E1	Pure Fermi → V or S ≠ 0	
6	–1937		E1	Pure GT → A or T ≠ 0	
7	–1937		E1	Kurie plots → VA, VT, SA, or ST	
8	1949	T3	E2	Universal interaction proposed, confirmed	*(15)*
9	1955		E3	Favors VA or ST	*(6)*
10	1955		E3	Favors VA or ST	*(7)*
11	1955		E3	Favors ST	*(8)*
12	1956	T4		Extends general Hamiltonian to ten terms	*(9)*
13	1/57	T1		T1 revived; sets V = V′, A = A′, . . .	*(10)*
14	2/57		E4	Confirms T4	*(11)*
15	4/57		E5	Confirms T1: restores favored status of ST	*(12)*
16	5/57		E3	Favors VA	*(13)*
17	6/57		E5	Favors VA or ST	*(21)*
18	9/57		E6	Favors VA	*(17)*
19	9/57		E2	R (μ/e) contradicts both VA and ST	*(20)*
20	9/57		E8	Contradicts T5	*(23)*
21	9/57		E7	Favors VA	*(19)*
22	9/57	T5		Proposes V − A form of interaction	*(22)*
23	12/57		E9	Favors VA; confirms T5	*(24)*
24	12/57		E3	Removes evidence for 11	*(25)*
25	4/58		E8	Supersedes 20; confirms T5	*(26)*
26	9/58		E2	Supersedes 19; confirms T5	*(27)*
27	10/58		E3	Supersedes 11; confirms T5	*(28)*
28	1958–			T5 generally accepted	

Electron-Neutrino Correlation (E3)

In discussing the next set of experiments, we consider for definiteness an allowed decay to positrons. In a pure Fermi transition, the spins of e^+ and ν form a singlet state, and the interaction, under the assumption of a Hamiltonian given by Eq. 1, is either V or S. If it is V, theory predicts that the positron and neutrino are most likely to be emitted in the same direction. If the interaction is S, they are most likely to appear in opposite directions. The two cases are shown in Fig. 1. We expect the form of the distribution in angle θ between positron and neutrino to be

$$1 + \alpha\beta \cos \theta$$

where $\alpha = +1$ for V and $\alpha = -1$ for S, and β is the velocity of the positron.

In a pure Gamow-Teller transition, the form of the distribution is the same, and the expected correlation coefficient is either $\alpha = -1/3$ (if the interaction is A) or $\alpha = +1/3$ (if the interaction is T). In a transition allowed by both types of selection rules, α is expected to fall between -1 and $+1$, with a value that is approximately predictable for each of the four choices of interaction.

The earliest experiments of this kind were performed on the neutron *(6)*, Ne^{19} *(7)*, and He^6 *(8)*. Only for He^6, a case of pure Gamow-Teller beta decay, did the results appear to be completely unambiguous. Measurement of the correlation coefficient gave the value $\alpha = +0.33 \pm 0.09$, implying strongly that T is to be preferred to A as the source of Gamow-Teller transitions. Combined with the other measurements, the result also implied that S is to be preferred to V as the source of Fermi transitions. The situation at this point (step 11 of Table 2) is shown by the first three entries in Fig. 2.

If the history of theory and experiment in beta decay had ended in 1955, it would have constituted a striking monument to the methodology of strong inference. Fermi's theory of the process had generated a fruitful tree of hypotheses which, in a long sequence of beautiful experiments, had been brought down to a single conclusion: the Hamiltonian of the interaction is a combination of scalar and tensor terms. But

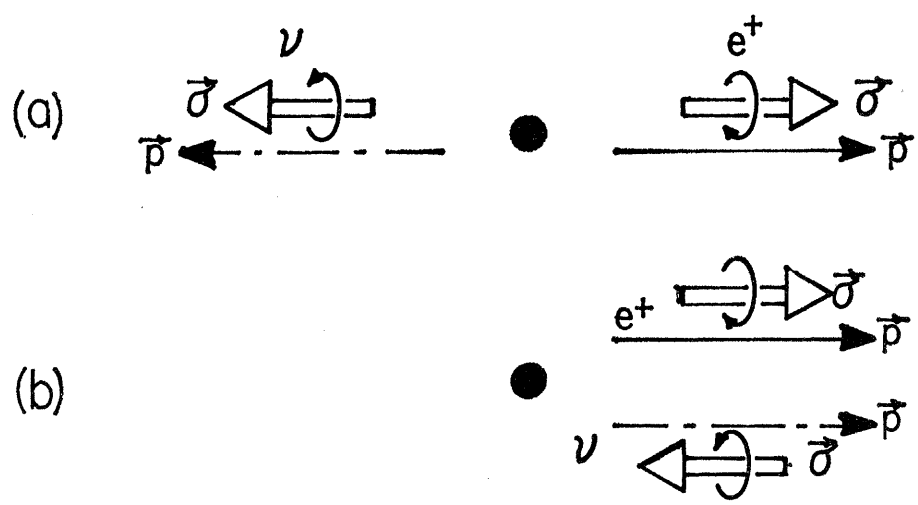

Fig. 1. Most probable positron-neutrino emissions in a Fermi transition. Case *a* follows from a scalar interaction; case *b* from vector interaction. The longitudinal polarizations shown here are predictions from two-component neutrino theory.

subsequent events have shown that the entire structure was untenable. A revolution in the laws of physics removed a principal pillar of the theory, and an extension and review of the measurements led to a reversal of judgment.

Parity Nonconservation (T4)

In 1956, the Fermi theory underwent a radical change. Attempting to resolve a new and puzzling problem in the physics of elementary particles, Lee and Yang (*9*) proposed that the Hamiltonian of Eq. 1 be extended to include terms which, in combination with the original terms, fail to conserve parity. Under this hypothesis, the initial Hamiltonian would have the schematic form

$$H = \mathrm{V} + \mathrm{A} + \mathrm{S} + \mathrm{T} + \mathrm{P} + \mathrm{V}' + \mathrm{A}' + \mathrm{S}' + \mathrm{T}' + \mathrm{P}' \qquad (2)$$

with more than a thousand possible combinations to be narrowed down by experiment. The suggestion took cognizance of the fact that, despite its strong appeal to the intuition of physicists, the notion of reflection symmetry had never been consciously tested by any experiment in the long history of beta decay. If the new Hamiltonian were allowed, conclusions drawn from old experiments would have to be reviewed. For example, it would no longer be possible, from the existence of pure transitions and linear Kurie plots alone, to restrict the combinations to VA, VT, SA, or ST. In the absence of further theoretical guidance, the status of weak interactions would return to chaos.

Almost immediately after the proposal of the new Hamiltonian, the two-component neutrino theory (T1) was revived (*10*). The neutrino had conventionally been described by a four-component theory in which, for a given momentum, there are two possible spin states for the neutrino and two for the antineutrino. In other words, each of the two particles would be both "right-handed" and "left-handed" (Fig. 3) with equal probability. Under the two-component theory, only one such spin state or "helicity" for the neutrino is allowed, the opposite helicity being assigned to the antineutrino. Thus only the combination ν_R, $\bar{\nu}_L$ or the combination ν_L, $\bar{\nu}_R$ can occur; it is the task of experiment to discover the choice that nature has made.

The two-component theory has several attractive features. It gives theoretical meaning to parity nonconservation; when combined with a law of conservation of leptons (the class of light particles including neutrinos, and muons), it accounts for the zero mass of the neutrino; and it brings the number of independent terms in the Hamiltonian back to five by relating them in pairs. The strength of the V term is equal to the strength of the V′ term, and so on.

In February 1957, C. S. Wu and her collaborators (*11*) exhibited an experimental violation of parity conservation in beta decay (E4) by a very direct method. They polarized nuclei of radioactive Co^{60}, measured the angular dependence of the electron intensity, and observed that the emission is predominantly in the direction opposite to the direction of nuclear spin (Fig. 4). This observation, which confirmed the idea of a parity-nonconserving Hamiltonian, was astonishing in several respects. The experiment was conceptually very simple, the effect was large, and the result destroyed a principle that had been accepted by generations of physicists without question. It was the first of many experiments that demonstrate parity nonconservation in weak interactions.

Immediately after this discovery, interest grew in testing the predictions

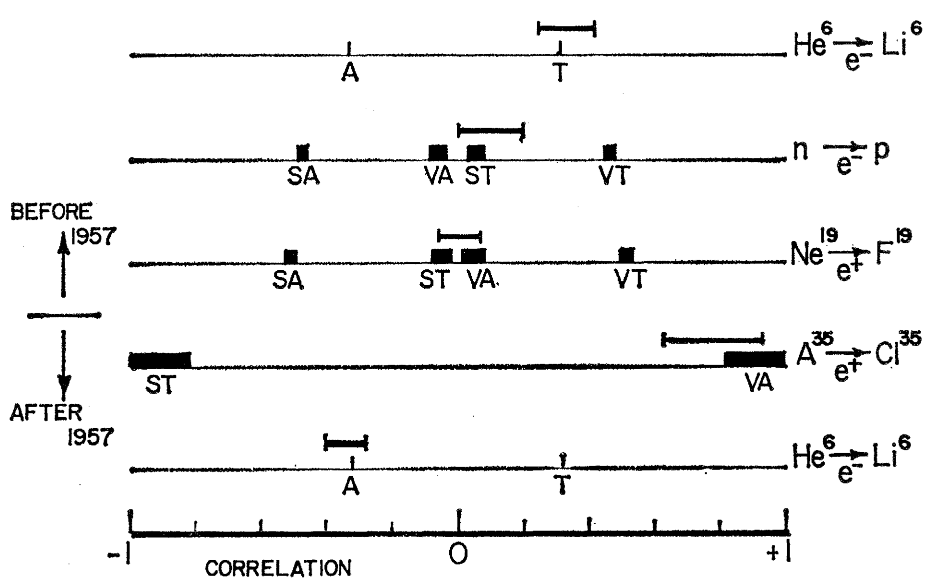

Fig. 2. Comparison of election-neutrino correlation measurements with theoretical predictions. The first three entries, showing the situation in 1955, are taken from Goldhaber (*32*). The subsequent A^{35} result (*13*) and the He^6 remeasurement (*28*) replaced ST with VA as the favored form of the Fermi interaction

of the two-component theory. A crucial experiment was the measurement of electron polarization in beta decay (E5). Let us look again at the case of Co^{60} with this question in mind. The transition to Ni^{60} is accompanied by a change of nuclear spin from 5 to 4, as indicated in Fig. 4. In order to conserve angular momentum, downward electrons have left-handed spin while upward electrons have right-handed spin. If parity conservation were not violated, both cases would be equally likely, and the net polarization observed for randomly oriented nuclei would be zero. But since the downward emission predominates, a net polarization arises from the fact that more electrons are left-handed than right-handed. Frauenfelder and his collaborators (*12*) were the first to observe this effect. The two-component theory gives a simple prediction for the strength of the net polarization in any beta decay: it should be equal to β, the velocity of electrons (or positrons) that one chooses to analyze. Although Frauenfelder's original experiment was not accurate enough to confirm this prediction, subsequent work quickly showed close agreement.

By early 1957 (step 15 of Table 2), the two-component theory was well established, and the number of independent terms in the most general Hamiltonian was reduced to the original five. The old evidence from beta decay once again restricted the acceptable combinations to VA, VT, SA, or ST. And of these, as we have seen, ST was highly favored by electron-neutrino correlation experiments. At this point, therefore, it appeared that the upsetting effects of parity violation had been only temporary. While giving greater insight to an understanding of weak interactions, the theoretical advance had not altered prior conclusions about the terms in the Hamiltonian.

Crisis

The first sign of a new confusion, which was to persist for more than a year, appeared in May of 1957, when Herrmannfeldt and his collaborators (*13*) reported the results of a positron-neutrino correlation measurement on A^{35}. This is a pure Fermi transition; if the interaction were ST, the expected correlation coefficient would be $\alpha = -1$. The surprising result (Fig. 2) was a coefficient close to $+1$, implying that

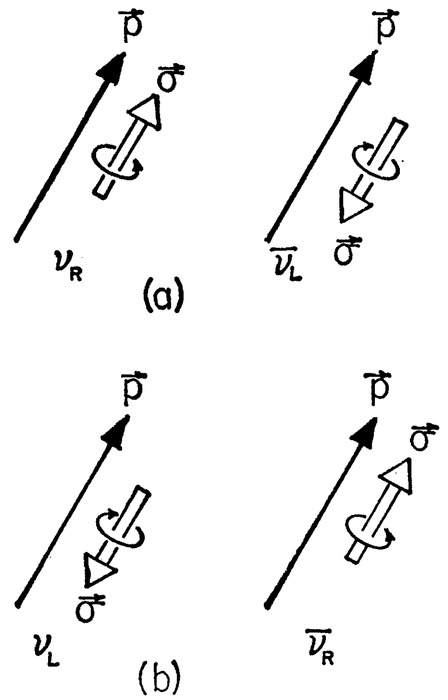

Fig. 3. The four components of the neutrino. On the two-component theory, only one pair can occur in nature.

the transition is generated by a vector rather than a scalar interaction. It could only be said at this point (Table 2, step 16) that positron decays were consistent with VA, while the electron decays were consistent with ST. Accounting for an ambiguity of this kind, in which the form of the interaction depended on the sign of the charge, would have required a complicated theory appealing to no one.

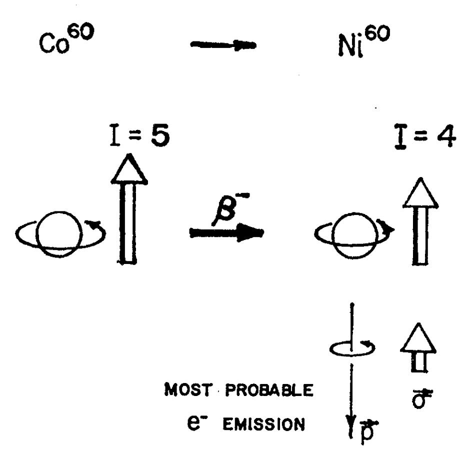

Fig. 4. Decay of Co^{60}, showing preferred direction of electron emission relative to nuclear spin. Parity is not conserved because the mirror image of this situation does not occur in nature. The longitudinal polarization of electrons is required to conserve angular momentum: the nuclear spin changes from 5 to 4 in the transition. An antineutrino provides the remainder of the momentum balance.

The confused atmosphere of the time was reflected during the international conference on particle physics held at Padua and Venice in September of 1957. Discussing the status of weak interactions, Lee (*14*) and Marshak and Sudarshan (*15*) dealt with several connected aspects of the problem. Their first and most important consideration was that the weak interactions are presumed to account not only for nuclear beta decay, but also for meson and muon decays. This idea, which is suggested by measurements of the particle lifetimes (E2), is contained in the hypothesis of a "universal Fermi interaction" (T3) which had been under scrutiny for almost a decade (*16*). According to the hypothesis, an interaction of fixed strength and fixed form accounts for all weak decays.

By 1957, there was an accumulation of evidence suggesting that the interaction operating in pion and muon decay is a combination of vector and axial vector couplings—the same as the VA choice that seemed to be preferred by some, but not all, of the beta decays. Most of the data came from studies of the $\pi \rightarrow \mu \rightarrow e$ sequence. Charged pions decay mainly to muons and neutrinos; muons decay to electrons (or positrons) and pairs of neutrinos. An important piece of evidence comes from the decay of polarized muons (E6). One can show, for example, that if the VA combination dominates the interaction, the correlation coefficient between positron direction and the spin of the μ^+ is $+1/3$; the corresponding coefficient for electrons from polarized μ^- is $-1/3$. This prediction was verified (*17*) in 1957; similar measurements (*18*) on the analogous kaon decays also confirmed predictions based on VA dominance of a universal Hamiltonian.

A choice of VA makes a very definite prediction about the polarization of electrons in muon decay (E7): the positron from μ^+ should, for example, be polarized in the direction parallel to its momentum. Preliminary observation suggested that the polarization was opposite to this prediction. But a subsequent and more detailed investigation (*19*), announced for the first time at the Padua conference, gave results in agreement with the VA combination.

As we have already seen, the electron-neutrino correlation measurement (*8*) of 1955 on He^6 was in conflict with a VA form of interaction. Another crucial observation appeared to be in conflict with the entire universal inter-

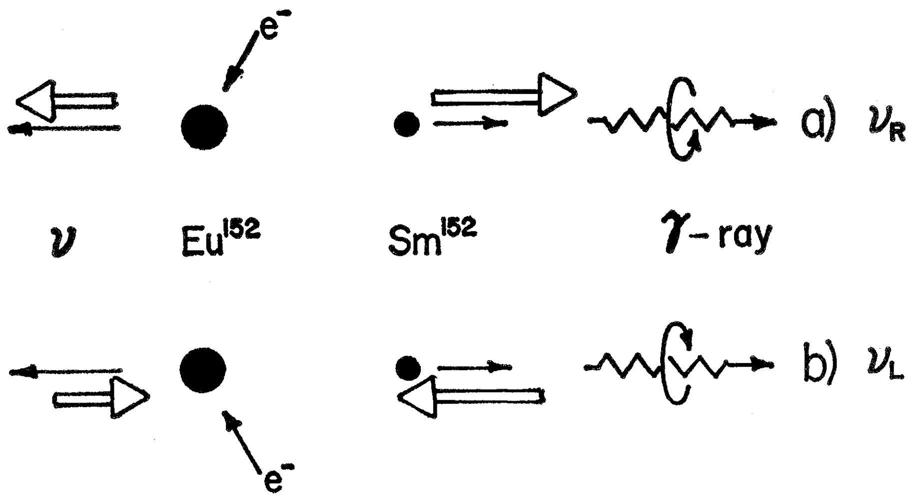

Fig. 5. A measurement of neutrino helicity (*24*). Following electron capture by a spinless nucleus (Eu^{m152}), a recoiling excited nucleus of spin 1 (Sm^{*152}) has a sense of spin which depends on the neutrino helicity. This means, in turn, that the gamma ray in the forward direction has right or left circular polarization, the determination of which decides the issue.

action hypothesis. The problem arose in the branching ratio for two possible modes of pion decay (E2). Competing with the familiar mode $\pi \rightarrow \mu + \nu$, there is an electronic mode $\pi \rightarrow e + \nu$. Let $R(\mu/e)$ denote the branching ratio. On the assumption of a universal interaction with VA dominance, it is possible to predict $R(\mu/e) = 7.8 \times 10^3$; that is, we should see on the average one electron in 7800 decays. If V and A are absent, we predict $R(\mu/e) = 0.18$; the electrons outnumber the muons by 5 to 1. At the time of the Padua conference, a search (*20*) for the electron mode had been carried out with a null result. A lower limit to $R(\mu/e)$ had been set at 10^5, in disagreement with both predictions.

Thus, by September of 1957, a strong crisis had emerged. Many observations in nuclear beta decay had lent support to the two-component neutrino theory and had indicated that VA, VT, SA, or ST were the only possible combinations of interactions in the Hamiltonian. Some of the experiments, including recent work (*21*) on electron polarization in Sc^{46} and Au^{149}, had favored the choice of VA or ST. But the electron-neutrino correlation data were not consistent with a single choice: the He^6 result favored ST, whereas the A^{35} result favored VA with as little ambiguity.

Some of the observations on meson and muon decay supported the hypothesis of a universal Fermi interaction, with VA favored. But the scarcity of electrons in pion decay stood in direct contradiction to this idea. It was a group of theorists, working along three independent lines, who suggested a common resolution. Facing the possibility that some of the experiments were in error, they proposed a specific universal interaction whose acceptance would have to depend on a drastic change in the experimental situation.

The V−A Theory (T5)

In spite of the chaotic experimental picture just described, the theoretical outlook of the time was rapidly clarifying. Three important papers (*22*) were written in 1957, one (*15*) of which was given at the Padua conference. Independently and on different grounds, the several authors proposed a simple and universal Hamiltonian for the description of all weak interactions. This Hamiltonian has several attractive features: it generates two-component neutrinos, violates parity maximally, preserves time-reversal invariance, and conserves a new quantity called "chirality." The only terms in this interaction are V and A, and, since the strengths of the two terms are taken to be equal and opposite, the idea has become known as the V−A theory.

In addition to its disagreement with experiments already mentioned, the V−A theory was in grave difficulty with the results of a measurement (*23*) on the decay of polarized neutrons (E8). In this experiment, neutrons were polarized by reflection from magnetized cobalt mirrors and the angular distribution of decay electrons relative to the neutron spin was measured. The V−A theory predicts an isotropic distribution of electrons; the experimental result was in strong disagreement.

Thus, at the time of its conception, the V−A theory was already in sharp disagreement with three crucial experiments. Anisotropy of the electrons from polarized neutron decay contradicted the specific V−A form of the theory; electron-neutrino correlation measurements on He^6 forbade all mixtures of VA; and the scarcity of electrons in pion decay threw doubt on the whole central idea of a universal interaction. But the arguments leading to the theory seemed strong enough to suggest that these experiments might be wrong. The theorists therefore urged that they be reviewed and repeated, on the long chance that disproof might thereby turn into confirmation.

Dénouement

A new and very encouraging sign appeared in December of 1957, taking the form of an ingenious experiment (*24*) which was the first to reveal the helicity of the neutrino (E9). The experimenters chose to study the pure Gamow-Teller transition from a metastable state of Eu^{152}. This state has zero spin. It can decay to an excited state of Sm^{152} (spin 1) by capturing an orbital electron:

$$Eu^{m152} + e^- \rightarrow Sm^{*152} + \nu.$$

As we have already mentioned, only the T and A interactions give rise to Gamow-Teller transitions, and, since the T interaction generates right-handed neutrinos while the A interaction generates left-handed neutrinos, the measurement of helicity provides a clear-cut way of choosing between the two interactions.

Following the electron capture, Sm^{*152} decays to its zero-spin ground state by emission of a gamma ray, which must carry off all the angular momentum in the form of circular polarization (Fig. 5). Therefore, gamma rays traveling in the direction of the recoiling Sm^{*152} nucleus have the same helicity as the nucleus. But the Eu^{152} metastable state has decayed from rest with zero spin. In order that linear and angular momentums be conserved, the neutrino and the recoiling nucleus must travel in opposite directions with opposite spins. Thus they have the same helicity, and a polarization measurement on the gamma ray reveals the helicity of the neutrino. The important experimental result was the detection of negative helicity; neutrinos are left-handed, and the interaction must be A instead of T.

During 1958, further investigations lent convincing support to the V—A theory. A critical analysis (*25*) of the original He^6 experiment revealed a large systematic error which had not been accounted for. In April, new experiments (*26*) on the decay of polarized neutrons gave a much smaller electron asymmetry, consistent with the V—A prediction.

In September, the elusive electron decay mode of the pion was found (*27*) and the branching ratio came down to a value consistent with the V—A prediction. Finally, in October, a remeasurement (*28*) of the electron-neutrino correlation in He^6 gave a coefficient $\alpha = -0.39 \pm 0.05$, in agreement with the expectation from a VA mixture. When this result was announced, all evidence for ST dominance had been superseded and the V—A theory was in accord with all newly accepted observations. Since then, many other experiments have added strength to the theory, which is now generally regarded as correct.

Conclusion

We have reviewed a period of the history of physics during which the principle of strong inference failed. Only in retrospect is it possible to discern some logical chain with a reasonable degree of clarity. Thus, an imaginary and idealized history of beta decay might begin with the general Hamiltonian of Eq. 2, required by crucial experiments which exhibit the nonconservation of parity. The first reduction of the general form follows from the two-component neutrino hypothesis, subject to such a crucial test as the measurement of electron polarization in the decay of Co^{60}. Further reduction, leading to the preference of certain pairs (VA, VT, SA, or ST), occurs when nuclear spins and Kurie plots are measured. The restriction to VA is required by an observation of neutrino helicity. Finally, the isotropy of electrons from decay of polarized neutrons determines the V—A form of the interaction. At the same time, the universality of this interaction passes such crucial tests as the μ/e ratio in pion decay and the measured lifetime of the muon.

The actual search was far more tortuous, obscured in the first place by theoretical preconceptions. The pattern of Becquerel's struggle with fluorescence is apparent once again, in a more highly ramified and sophisticated form. In the absence of a viable theory, experimental results (even when they are correct) can be misleading. They may appear to support an idea which is, in fact, a misconception. For example, beta-decay data were interpreted before 1956 in the context of a parity conserving Hamiltonian. When the theoretical viewpoint shifted, old experiments acquired a new significance.

Additional confusion, introduced by erroneous experiments, is also evident in the full account. Only after the growth of an insistent theoretical idea, with which these experiments were in conflict, did a clearer picture begin to emerge. Thus the interplay of hypothesis and observation in the real history is far more complex than might seem to be the case in an abbreviated account.

Some of the experiments in the history of weak interactions were crucial, but in a way that was not immediately visible. For example, measurement of the muon lifetime is a critical test of the universal weak interaction, but data were available long before this idea emerged as something to be tested. Our next observation, then, is that the design and performance of crucial experiments do not always follow the statement of a hypothesis to be tested. The experiments may have been performed for different reasons, or for no particular reason at all.

We have mentioned several crucial experiments whose results, at first attempt, were wrong and therefore misleading. One can also find examples of correct experiments that were not believed because they did not fit into the theoretical context of their time. In a paper (*29*) with the title "Apparent evidence of polarization in a beam of beta rays," published almost 30 years before the work of Lee and Yang, one finds the first experimental violation of parity conservation. By 1942, more data on electron scattering had been gathered (*30*). Many of the data do not agree with the predictions of Dirac theory, subject to the assumption that electron beams are necessarily unpolarized.

The authors of a definitive review (*31*) passed the following judgment on the experiments: "The internal consistency of all the experimental results using beta rays is not good, and it is likely that the discrepancies will largely disappear when radioactive sources are replaced by artificial ones of controlled energy." This remark is especially interesting because artificially accelerated electrons are unpolarized, so that the "discrepancies" do indeed "disappear." Thus observations with accelerated beams strengthen the mistaken conclusion that the results with beta rays were wrong. We realize now that the scattering experiments were misunderstood because the possibility of there being something special about beta rays was simply not open. And the experimenters themselves were occupied with the task of testing Dirac theory, not with a study of the beam itself. Nature's generous hint was therefore wasted.

Finally, we are led to examine the role of exclusion that experiment is supposed to play in a strongly inferential scheme of science. There are, of course, many problems where alternative hypotheses are well formulated, experiments are straightforward, and conclusions are unambiguous. The experiment on neutrino helicity (*24*) is perhaps the best example in the preceding account. Although the measurement involved many subtleties that we have not mentioned in our brief description, its outcome made a clear choice between two alternatives. But the story of V—A suggests that many experiments do not lead to such a clear reduction of alternatives. Especially at points where very little is known, the hypotheses may be only dimly visible and the experiments may be so difficult that their results are in doubt.

Thus we suggest that the procedure of strong inference is an idealization. It is only an excellent model which, in complex circumstances, frequently breaks down. In particular, it requires the existence of an already developed tree of hypotheses. When a problem has not yet reached this stage, the procedure may be difficult to apply. Or, in extension of the metaphor, one might say that many new trees are likely to grow in freshly broken ground. The progress of science depends on our ability to keep the soil fertile for freedom of growth, to nourish whole sets of contending theoretical ideas, to design and evaluate experiments with the greatest care, and to see a single observation as more than a discrete and local step: its effects can propagate in all directions.

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Networks of Scientific Papers

The pattern of bibliographic references indicates the nature of the scientific research front.

Derek J. de Solla Price

This article is an attempt to describe in the broadest outline the nature of the total world network of scientific papers. We shall try to picture the network which is obtained by linking each published paper to the other papers directly associated with it. To do this, let us consider that special relationship which is given by the citation of one paper by another in its footnotes or bibliography. I should make it clear, however, that this broad picture tells us something about the papers themselves as well as something about the practice of citation. It seems likely that many of the conclusions we shall reach about the network of papers would still be essentially true even if citation became much more or much less frequent, and even if we considered links obtained by subject indexing rather than by citation. It happens, however, that we now have available machine-handled citation studies, of large and representative portions of literature, which are much more tractable for such analysis than any topical indexing known to me. It is from such studies, by Garfield (*1, 2*), Kessler (*3*), Tukey (*4*), Osgood (*5*), and others, that I have taken the source data of this study.

Incidence of References

First, let me say something of the incidence of references in papers in serial publications. On the average, there are about 15 references per paper and, of these, about 12 are to other serial publications rather than to books, theses, reports, and unpublished work. The average, of course, gives us only part of the picture. The distribution (see Fig. 1) is such that about 10 percent of the papers contain no references at all; this notwithstanding, 50 percent of the references come from the 85 percent of the papers that are of the "normal" research type and contain 25 or fewer references apiece. The distribution here is fairly flat; indeed about 5 percent of the papers fall in each of the categories of 3, 4, 5, 6, 7, 8, 9, and 10 references each. At the other end of the scale, there are review-type papers with many references each. About 25 percent of all references come from the 5 percent (of all papers) that contain 45 or more references each and average 75 to a paper, while 12 percent of the references come from the "fattest" category—the 1 percent (of all papers) that have 84 or more references each and average about 170 to a paper. It is interesting to note that the number of papers with n references falls off in this "fattest" category as $1/n^2$, up to many hundreds per paper.

These references, of course, cover the entire previous body of literature. We can calculate roughly that, since the body of world literature has been growing exponentially for a few centuries (*6*), and probably will continue at its present rate of growth of about 7 percent per annum, there will be about 7 new papers each year for every 100 previously published papers in a given

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