Ten Years of the Universal *V–A* Weak Interaction Theory and Some Remarks on a Universal Theory of Primary Interactions*

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1 Beta Decay Prior to 1957

Beta radioactivity has been known ever since the turn of the century but it was only about thirty years ago that some quantitative understanding of the phenomenon began to emerge. In 1932–33, B. W. Sargent[1] gave a compilation of the electron energy distribution for various beta emitters. He classified beta emitters by observing groupings of radioactive nuclides in a plot of the partial decay constants versus the upper energy limits of the beta particles for various components of complex beta spectra. In a log-log plot he identified several groups of nuclei clustering around what came to be called the Sargent curves, I, II, III, etc. We may also recall that W. Pauli had already proposed, in 1930, the hypothesis of the neutrino to account for the continuous energy distribution of electron energies from a quantum nucleus.

These clues were sufficient for E. Fermi[2] to propose a remarkably successful theory of beta decay. He assumed, by analogy with electromagnetism, that the beta interaction was a new interaction-by-contact and that its law could be expressed by considering an interaction energy density proportional to the product of the neutron, proton, electron and neutrino wave functions. Fermi chose the interaction density to be as similar as possible to electric interaction, and in the approximation of treating the nuclear particles to be at rest only the analogue of the electrostatic interaction survives. In view of the fact that the de Broglie wavelength of the

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electron and neutrino were large compared with nuclear dimensions, only the overall effect of the nucleus was felt: in other words only the analogue of the total electric charge was effective in causing the radioactive transmutation in this approximation. We now call this the 'allowed Fermi' transition. If we neglect the corrections due to the motion of the nuclear particles (velocity effects) and the variation of the electron and neutrino wave-functions over the nucleus (retardation effects) but include the Coulomb distortion (enhancement) of the electron wave-function, we can calculate the expected electron energy distribution. This (Coulomb-corrected) 'allowed shape' was the first quantitative verification of Fermi's theory. The proper measurement of the low energy end of the spectrum did not come about for another decade or so but it did eventually come. Fermi had attempted a calculation of the expected transition rate taking the nuclear matrix elements to be of the order of unity. The transition rate is then, for 'allowed' decays, the square of the postulated Fermi coupling constant G multiplied by a known function of the upper limit of the beta spectrum. Hence the product of this function and the lifetime must be a constant for allowed decays; any variation among the allowed decays must be attributed to variation of the nuclear matrix elements (the beta decay 'transition charges'). Fermi was thus able, on the basis of this ft-value classification to give a correspondence with Sargent's curves.*

Two important supplementary developments came about in the two succeeding years. H. Yukawa proposed his fundamental theory of meson fields[3], in which he wished to relate the meson field with the source of weak interactions. At that time Yukawa thought in terms of scalar meson fields but later on the Fermi interaction turned out to be vector and axial vector so that the detailed implementation of his ideas required modern developments. But his was the first idea of relating strongly interacting meson fields and weak interactions. The second development was the proposal of G. Gamow and E. Teller[4] that there are beta decay interactions which involved the spin of the nuclear particles. They were motivated by the radioactive thorium series for which one could not consistently assign spin values and understand their Sargent classification in terms of the degree of forbiddenness with Fermi selection rules. These new Gamow-Teller interactions were thus the analogues of the magnetic part of the electromagnetic interactions in their dependence on the spin of the nuclear particles (but were non-vanishing even for zero momentum transfer). It is now well known that pure Gamow-Teller transitions like

* Fermi's paper and many of the more important subsequent papers are reprinted in *The Development of Weak Interaction Theory*, edited by P. K. Kabir and published by Gordon and Breach, New York, 1963.

$Co^{60}(5^+ \rightarrow 4^+)$ and $He^6(0^+ \rightarrow 1^+)$ as well as pure Fermi transitions like $O^{14}(0^+ \rightarrow 0^+)$ and $C^{14}(0^+ \rightarrow 0^+)$ exist.

Using both the Fermi type and the Gamow-Teller type interactions one can calculate the electron energy distribution. The 'allowed shape' is equally valid for the Gamow-Teller allowed interactions. For forbidden interaction the shapes are more complicated, but for low energy release beta transitions in heavy nuclei the effect of relativity and Coulomb attraction is to restore the allowed shape to first forbidden (retarded) decays (like Ce^{141}, Au^{198}); for a class of unique Gamow-Teller forbidden transitions, again one can work out the unique forbidden shapes (as examples we have Be^{10}, Y^{91} unique first forbidden, Na^{22} unique second forbidden, K^{40} unique third forbidden). These shape predictions have been carefully verified in the succeeding years, particularly in the late forties and early fifties.

When relativity is taken into account the local non-derivative couplings in beta decay increase to five, called respectively scalar, vector, tensor, axial vector and pseudoscalar, depending upon the transformation property of the combination of the nuclear wave-functions. By studying the non-relativistic limit one classifies the scalar (S) and vector (V) terms as Fermi couplings, the tensor (T) and axial vector (A) as Gamow-Teller couplings and the pseudoscalar may be ignored in the non-relativistic limit. The question therefore arose as to which of these interactions did really enter nuclear beta decay. We already know that both Fermi and Gamow-Teller interactions were about equally important by a study of ft-values for various allowed transitions. The common coupling could be assigned a coupling constant of about $1{\cdot}5 \times 10^{-49}$ erg cm^3, which could equally well be given as 10^{-23} if the electron mass is chosen as the inverse unit of length (or 10^{-13} with the pion Compton wavelength as the unit of length).

The allowed spectrum shapes gave little information on the type of the interaction; at one time it was thought that if both S and V were present we would get a correction factor of the form $[1 + b(m_e/E_e)]$; and similarly for T and A. We know *now* that these so-called Fierz interference terms would vanish with the special kind of maximal parity violation. But before this was known people assumed that the absence of the Fierz terms was evidence of the absence of both S and V or both T and A. It turns out that the conclusion was in fact true though the argument supporting it was false!

More definitive evidence comes from the angular correlation of the electron and neutrino. In the decay of a particle (parent nucleus) into three particles (daughter nucleus, electron, neutrino) the non-trivial part of the decay momentum configuration is specified if we give either the energies of two particles or energy of the one particle and the angle made by another particle with this direction. It turns out that his correlation has a particularly simple form $\left(1 + a\frac{v_e}{c}\cos\theta_{e\nu}\right)$ where the correlation coefficient $a = -1, +1, +\frac{1}{3}, -\frac{1}{3}$ for *S*, *V*, *T*, *A* interactions respectively. The measurement of the mixed transitions of Ne^{19} and neutron gave a value near zero which suggested a mixture of *V-A* or *S-T*. The first measurement of the pure Gamow-Teller beta emitter He^6 gave a positive value favouring *T* and hence the *S*, *T* combination. But the nearly pure Fermi beta transition in A^{35} gave also a large positive value suggesting *V* and hence the *V-A* combination. Clearly there was some disagreement in the measurement of angular correlations; and *until this was resolved* we could not determine the relevant beta interactions.

2 The Discovery of the *V-A* Interaction

This brings us to the exciting year 1957. It was a fateful year for beta decay and for nuclear physics in general. The possibility of parity violation that was pointed out by T. D. Lee and C. N. Yang[5] was brilliantly confirmed by C. S. Wu and others[6] in their experiments on the correlation of electron emission direction with the spin direction of decaying Co^{60}. A new era was initiated in that many new quantities could be measured in nuclear beta decay, but along with this the possible number of beta decay interactions also increased since there could be parity-conserving or parity-violating interactions. The possibility was also raised that some or all of the various coupling constants could be complex signalling violating of time reversal invariance. A period of intense activity resulted in a number of significant indications on the nature of the beta interactions. Starting in the summer of 1956 I had followed these developments with great interest at the suggestion of my professor, R. E. Marshak. By the end of spring 1957, I was convinced that the available experimental information crystallized into the following items:

(1) The electron-neutrino angular correlation data favoured *V-A* if the A^{35} was correctly and He^6 was wrongly measured and *S-T* if the He^6 was rightly and A^{35} wrongly measured.

(2) The measurement of electron asymmetry for polarized nuclei or the longitudinal polarization of beta electrons from the Gamow-Teller decay of Co^{60} gave a number negative in sign and very near the maximum absolute value. This was consistent with *A* or *T* according as the antineutrino was right or left polarized.

(3) The corresponding measurement for the Fermi decay of Ga^{66} was

consistent with V or S according as the antineutrino was right or left polarized.

(4) The mixed transitions Sc^{46} and Au^{198} gave results consistent with both the above determinations. If the antineutrino was the same in both Fermi and Gamow-Teller transitions, we would get V-A or S-T according as the antineutrino was right or left polarized.

(5) By measuring the beta-polarized gamma correlations in the mixed transition Sc^{46} we get a nearly maximum effect which is consistent with approximately equal V and A or equal S and T (with approximately real phase factor) and the antineutrinos in both Fermi and Gamow-Teller transitions had to have the same handedness.

(6) If we thought of pion decay as the decay of a nucleus with atomic weight zero this would give additional information about nuclear beta decay. This could take place only via A or P interaction and any evidence for it would imply A or P should be present. The indications were that the electron mode was absent.

On the basis of these data, one had to choose either the V-A or the S-T combination. By appealing to the principle of universal Fermi interaction I was led to the choice of V-A and thus rejected the He^6 experiment and the experiment on pion decay into electron and neutrino. This result, that is the postulation of a maximal parity-violating V-A beta interaction, was first presented in a paper by E. C. G. Sudarshan and R. E. Marshak to the Padua-Venice Conference in early September of 1957. It is important to stress that *this was the deduction of a universal law from analysis of empirical evidence*; the use of symmetry principles came as an afterthought! Since that time increasing evidence has accumulated, adding remarkable *confirmation* to the conclusion that was made in this paper on the basis of my analysis of the experimental data. In particular, Goldhaber, Grodzins and Sunyar[7] made a direct determination of the neutrino helicity in Gamow-Teller transitions by measuring the helicity of gamma rays emerging in a direction opposite to that of the neutrino in the proceeding beta transition. This gave the helicity of the neutrino in the Gamow-Teller electron capture process in Eu^{152*} to be negative. This, together with the previous information that beta electrons from Gamow-Teller transitions are left-handed, tells us that the Gamow-Teller interaction must be A and hence beta decay must be via the V-A combination. The relative sign was determined to be negative from Sc^{46} and neutron decays. Since that time both the He^6 experiment and the electron-neutrino mode of the pion have been redone with new results which confirm the V-A prediction.

The discovery of the V-A interaction for nuclear beta decay was very satisfying from another point. As early as 1948, O. Klein[8] and G. Puppi[9] had noticed the marked similarity between the beta decay, muon decay and muon capture processes and proposed a universal Fermi interaction based on the approximately equal strength for these couplings. The discovery of parity violation gave new direction to this work and one could conclude, from the negative correlation between the direction of emission of the electrons from stopped muons of pion decay with the original muon momentum direction, that the muon decay coupling should be of the *V-A* type with maximal parity violation. The charged pion decays almost all the time into a two-body state involving the muon but an electron-neutrino mode with a branching ratio $1{\cdot}2 \times 10^{-4}$ was subsequently found experimentally. An *A* interaction with equal coupling of muon-neutrino and electron-neutrino would give precisely this ratio if the weak interaction involving muons or electrons was universal. These facts, together with other fragmentary data, again suggest *V-A* as a universal interaction. Sudarshan and Marshak therefore deduced that if the weak interactions were universal they had to be *V-A*; this proposal was also contained in their original paper.

Once the coupling was determined to be V-A many new elegant symmetry features could be discerned for this form of coupling. The best determination showed that the *A* interaction was 1·2 times the *V* interaction in nuclear beta decay but they were equally strong in muon decay. Assuming this feature was a renormalization effect due to strong interactions, we may think of vector and axial vector couplings of equal strength in their primary form. Such an interaction may be written in the form

$$g\bar{A}\gamma_\lambda(1 + \gamma_5)B, \quad \bar{C}\gamma^\lambda(1 + \gamma_5)D$$

where *A*, *B*, *C*, *D* are the four spinor fields which are coupled together. It then appears that only the positive 'chiral' projections

$$A' = \tfrac{1}{2}(1 + \gamma_5)A, \quad B' = \tfrac{1}{2}(1 + \gamma_5)B$$

etc., appear in the coupling; moreover the coupling above, which may be rewritten in the form

$$4g\bar{A}'\gamma_\lambda B', \quad \bar{C}'\gamma^\lambda D'$$

is the only invariant coupling. We therefore referred to this property of the coupling as 'chirality invariance'.

Previous attempts at using general invariance properties to deduce the general form for the beta interaction have had little success. The difference here is that here we 'admire' the structure of the interaction *after* it has been deduced from an analysis of the experimental data.

Other people found different ways of displaying the remarkable symmetry properties of the universal chiral coupling. R. P. Feynman and M. Gell-Mann, in a paper which followed almost immediately[10], showed that by a suitable form of restriction to non-derivative coupling of the chiral *V-A* interaction could be deduced. J. J. Sakurai[11] showed how chirality invariance could be related to the mass reversal transformation. Several people discovered that the *V-A* form was invariant under recoupling of the spinor fields. Altogether the *V-A* chiral coupling is a most remarkable interaction. But these symmetry properties were incidental. As was stated in the original paper of Sudarshan and Marshak, 'The analysis of the decay of pions and kaons thus seems to point unequivocally to a dominant *A* interaction among those operative in the decay process. The muon decay data is consistent with *V-T*, *A-T* or *A-V*. Among these three possible assignments the only one involving the *A* interaction is *A-V*. Since this is the only assignment consistent with beta decay data . . . the only possibility for a universal Fermi interaction is to choose a vector and axial vector coupling . . .'

3 The Present Status of the *V-A* Interaction

In the ten years since the original *V-A* interaction was proposed, considerable refinement of the experimental results has taken place, and it is of interest to examine the experimental confirmation of our four-fermion interaction structure. In the case of the purely leptonic process of muon decay, no strong interaction effects enter the discussion and we could hope to make a direct comparison of the experimental results with the theoretical prediction. The general four-fermion interaction (which is invariant under *CP*) yields the following differential spectrum:

$$P(\varepsilon, \cos\theta)\, d\varepsilon\, d\Omega = \frac{m_\mu{}^5}{3\pi^4 2^9}\,\varepsilon^2 \left\{\left[1 + 4\left(\frac{m_e}{m_\mu}\right)\eta\right]^{-1}\left[3(1-\varepsilon) + 2\rho(\tfrac{4}{3}\varepsilon - 1) + 6\left(\frac{m_e}{m_\mu}\right)\frac{1-\varepsilon}{\varepsilon}\eta\right] - \xi\cos\theta[1 - \varepsilon + 2\delta(\tfrac{4}{3}\varepsilon - 1)]\right\} d\varepsilon\, d\Omega$$

for the *V-A* interaction, where ε is the ratio of the electron energy to its maximum value $\frac{1}{2}m_\mu$, $\cos\theta$ the cosine of the angle between the muon spin and electron momentum, ξ the asymmetry parameter, δ the energy dependence of the asymmetry parameter, ρ the spectrum shape (Michel) parameter, and η a low energy correction to the spectrum shape. For the *V-A* interaction the predicted values of ρ and δ are both 0·750 while the experimental values are 0·747 ± 0·005 and 0·78 ± 0·05 respectively, and

ξ should be 1·00 while experiment yields 0·978 ± 0·030. These quantities are in principle to be corrected for electromagnetic effects. The latter turn out to be finite in lowest order. We could compute the muon transition rate in the form:

$$\tau_\mu^{-1} = \frac{G^2 m_\mu^5}{192\pi^3}\left[1 - \frac{\alpha}{\pi}\left(\pi^2 - \frac{25}{4}\right)\right]$$

where α is the fine structure constant. For the lifetime the radiative correction is less than a percent. From the observed muon lifetime of $(2{\cdot}198 \pm {\cdot}001) \times 10^{-6}$s we can deduce the numerical value for the weak coupling constant

$$G = (1{\cdot}435 \pm 0{\cdot}001) \times 10^{-49} \text{ erg cm}^3$$

Most of the weak processes involve strongly interacting particles; hence the comparison of the experimental results with the predictions of the *V-A* theory becomes entangled with the difficulties of making reliable strong interaction calculations. The one exception is the comparison of processes involving muon and its neutrino and the corresponding processes involving electron and its neutrino. We have already remarked about the significance of the $(\pi \rightarrow e\nu)/(\pi \rightarrow \mu\nu)$ branching ratio for the *V-A* theory. For the strange particle decays we have to make sure that the comparison be made at the same total lepton momentum. Such a comparison is given in the accompanying table. We can see that the electron and muon are coupled in the same manner in all weak interaction processes.

TABLE 1

Test of electron-muon universality[a]

Decay Process	Theory	Experiment
$\frac{\Gamma(\pi^+ \rightarrow e^+ + \nu_e)}{\Gamma(\pi^+ \rightarrow \mu^+ + \nu_\mu)}$	$1{\cdot}23 \times 10^{-4}$	$(1{\cdot}24 \pm 0{\cdot}03) \times 10^{-4}$
$\frac{\Gamma(K^+ \rightarrow e^+ + \nu_e)}{\Gamma(K^+ \rightarrow \mu^+ + \nu_\mu)}$	$2{\cdot}47 \times 10^{-5}$	$(3 \pm 1{\cdot}89) \times 10^{-5}$
$\frac{\Gamma(K^+ \rightarrow \pi^0 + \mu^+ + \nu_\mu)}{\Gamma(K^+ \rightarrow \pi^0 + e^+ + \nu_e)}$	0·69	0·703 ± 0·056
$\frac{\Gamma(\Lambda \rightarrow p + e^- + \bar{\nu}_e)}{\Gamma(\Lambda \rightarrow p + \mu^- + \bar{\nu}_\mu)}$	5·88	5·87 ± 0·75
$\frac{\Gamma(\Sigma^- \rightarrow n + \mu^- + \bar{\nu}_\mu)}{\Gamma(\Sigma^- \rightarrow n + e^- + \nu_e)}$	0·45	0·496 ± 0·26

[a] R. E. Marshak: University of Rochester Report UR–875–187

The general order of magnitude of the coupling strength, the violation of parity and charge conjugation in these processes and the electron-muon universality demonstrated above all point to the leptonic weak interactions of strange particles to be due to the same interaction. We could then ask whether the baryonic currents which are responsible for strangeness conserving and strangeness violating decays are the 'same'. To give a sense to this question we must have a method of considering an object which has both strangeness conserving and strangeness violating components. We shall see that such a scheme for assignment of the low lying baryons and mesons exist and we shall discuss this question within this context. Before doing this, however, let us return to the nuclear beta decay phenomenon and review it from the point of view of strong interactions.

The V-A structure of the nuclear beta decay interaction, if it is to be understood in terms of the primary neutron and proton fields, does not automatically predict the same $(G/\sqrt{2})\gamma_\lambda(1+\gamma_5)$ structure for the effective nuclear beta decay matrix element. This is just as well, since it is more properly of the form $(G/\sqrt{2})\gamma_\lambda(1+g_A\gamma_5)$, with $g_A \simeq 1{\cdot}2$. We have already remarked how we could understand the numerical equality of the vector coupling coefficients of the neutron beta decay and the muon beta decay in terms of the conservation of the vector current of nucleons. But there is still the embarrassment of the axial vector coupling constant being different by about 20%. The problem here is not so much to understand why there is a change of the effective coupling constant but to be able to compute this correction in a quantitative manner. Such a calculation has been made only very recently and the success of this calculation *removes the last significant obstacle to the form of the four-fermion interaction that we had proposed for nuclear beta decay*. The principle of this calculation is related to Yukawa's suggestion that the *weak and strong* interactions are related. Quantitatively we may take Yukawa's hypothesis as stating that the meson field is proportional to the nuclear source of beta decay. At the time of Yukawa's hypothesis of the meson field and the connection between the strong and weak interactions, neither vector mesons nor pseudoscalar mesons were known and no precise analytic formulation of the hypothesis could be made. But at the present time we may take the axial vector current A_λ and the pseudoscalar field ϕ to be proportional. We may implement this either by taking A_λ to be proportional to $\partial_\lambda\phi$ or by taking $\partial^\lambda A_\lambda$ to be proportional to ϕ. The first alternative is incompatible with the existence of Gamow-Teller interactions and we may therefore put:

$$\partial^\lambda A_\lambda = c\phi$$

Using this partial conservation of axial vector current we could relate g_A to the ratio of the pion and muon lifetimes; this relation is in reasonable agreement with experiment.

The partial conservation law related weak axial vector coupling to pseudoscalar pion coupling. To use this to deduce the axial vector renormalization constant g_A we have to make use of a non-linear relation involving the axial vector current A_λ. If the axial vector currents have the form

$$A_\lambda{}^\alpha(x) = \bar{\psi}(x)\gamma_\lambda\gamma_5\tau^\alpha\psi(x)$$

where $\psi(x)$ is the spinor-isospinor nucleon field which satisfies standard equal-time anticommutation relations, they would satisfy the equal-time commutation relations

$$[A_0{}^\alpha(\mathbf{x}, t), A_0{}^\beta(\mathbf{y}, t] = 2\mathrm{i}\, \varepsilon^{\alpha\beta\gamma}\delta(\mathbf{x} - \mathbf{y})V_0{}^\gamma(\mathbf{x}, t)$$

where

$$V_\lambda{}^\gamma(x) = \bar{\psi}(x)\gamma_\lambda\tau^\gamma\psi(x)$$

is the corresponding vector density. This non-linear relation is clearly for the primary ('unrenormalized') fermion fields and can be taken to include the contribution of pions, etc. Using this equal-time commutation relation along with the partial conservation law we can show that the axial vector renormalization constant g_A satisfies the sum rule

$$g_A{}^{-2} = 1 - \frac{c^2}{2\pi m_\pi{}^4}\int \frac{\mathrm{d}\nu}{\nu}\,[\sigma^+(\nu) - \sigma^-(\nu)]$$

where $\sigma^\pm(\nu)$ is the scattering cross-section for pions on nucleons (extrapolated to pions with zero momenta). This was derived by W. I. Weisberger[12] and S. L. Adler[13]. The technique of derivation is to compute the scattering amplitude for zero 4-momentum pions on nucleons which could be expressed as the contribution from the equal-time commutator plus the contribution from the double divergence of the axial vector-nucleon scattering amplitude, and then expressing this zero energy scattering amplitude as an integral over the nucleon-pion scattering over all energies. The numerical evaluation making a careful estimate of the extrapolation of the physical amplitudes gives a remarkably close value for the quantity g_A. The general theory of such relations have been developed by K. Raman and E. C. G. Sudarshan[14]. Y. Tomozawa[15] and several others showed that instead of this we could equally well relate the axial vector coupling constant in terms of the S-wave pion-nucleon scattering length which again gives a remarkably good prediction for g_A.

We have thus ample reason to justify our hypothesis that the beta decay interaction is chiral *V-A* and has the same strength as in muon decay and muon capture.

If the basic beta decay interaction is the four-fermion coupling in terms of the primary nucleon fields, the vector and axial vector currents of beta decay are both the charge changing components of isotopic vectors. We have

$$\frac{G}{\sqrt{2}} j_\lambda^{+}(x) = \frac{G}{\sqrt{2}} \bar{\psi}\gamma_\lambda\tau^{+}\psi = \frac{G}{\sqrt{2}} \bar{P}\gamma_\lambda N$$

$$\frac{G}{\sqrt{2}} j_\lambda^{5+}(x) = \frac{G}{\sqrt{2}} \bar{\psi}\gamma_\lambda\gamma_5\tau^{+}\psi = \frac{G}{\sqrt{2}} \bar{P}\gamma_\lambda\gamma_5 N$$

On the other hand the corresponding electric current is a pure vector of the form

$$\frac{e}{2}[j_\lambda^{0}(x) + j_\lambda^{00}(x)] = \frac{e}{2}(\bar{\psi}\gamma_\lambda\tau_3\psi + \bar{\psi}\gamma_\lambda\psi)$$
$$= e\bar{P}\gamma_\lambda P$$

Consequently, apart from a scale factor, the isotopic vector part of the electric current and the vector part of the beta decay current are components of the same isotopic vector operator. Hence the matrix elements of both these currents must have the same momentum dependence (apart from purely electromagnetic corrections). In particular, there should be a term in vector beta decay matrix element that is the analogue of the anomalous magnetic moment. What is more, we can compute this weak magnetism term in terms of the difference of the proton and neutron anomalous magnetic moments. The effective Fermi matrix element can be written

$$\frac{G_v}{\sqrt{2}} \bar{u}_p \left[\gamma_\lambda F_1(t) + \frac{\kappa}{2m_n}\sigma_{\lambda\nu}q^\nu F_2(t)\right] u_n$$

where $F_1(t)$ and $F_2(t)$ are the isovector charge and magnetic form factors, t is the invariant momentum transfer squared and

$$\kappa = \mu_p - \mu_n$$

From experiments on the shape of the electron and position spectra of B^{12} and N^{12} this weak magnetism term has been quantitatively verified.

In summary then, the universal chiral *V-A* four-fermion interaction for non-strange particles is completely confirmed by the continuing experimental work of the last ten years. The weak magnetism and the departure of the axial vector effective coupling constant are now quantitatively understood. The chirality invariant theory that we had formulated a decade ago has been accepted as *the* theory of universal Fermi interaction.

4 Further Developments in Weak Interactions

Several new experimental developments, however, suggest that it is profitable to reexamine the fundamental hypothesis of a four-fermion interaction. Within the realm of weak interactions it has been found that the leptonic decays of kaons and hyperons are slower by a factor of about ten as compared with the predictions of the universal four-fermion interaction extended to include the strangeness violating decays of hyperons. In the decay of the neutral long lived kaon there is unmistakable evidence for a small violation of *CP*. Among strong interactions a whole collection of vector mesons have been identified and the coupling of the rho meson seems to be essential for an understanding of low energy pion-nucleon scattering and nucleon electromagnetic properties. It is very suggestive to consider that the conserved vector currents of electromagnetism, Fermi-type beta decay and strong interactions are all related. In such a theory the four-fermion coupling in beta decay is no longer primary; we are led to resurrect Yukawa's hypothesis of a beta interaction mediated by meson fields.

Before outlining such a theory let us examine the transformation property of the leptonic weak interaction current in strangeness changing decays. Since the kaon decays into leptons and the Λ hyperon decays into proton there must be an $I = 1/2$, $\Delta S = \pm 1$ component to the current with $\Delta Q = \Delta S$. It is tempting to assume that this must hold generally. This $I = 1/2$ current rule is in good agreement with experiment both for vector and for axial vector currents. But one could go beyond this and ask if the various strangeness violating transitions in hyperon decay can themselves be related. For this purpose we have to consider a higher symmetry group which contains both strange and non-strange particles. Following Sakata, the simplest such group is the SU(3) group, which has eight-dimensional representations to accommodate the eight baryons or eight pseudoscalar mesons. It then appears that the baryon currents of leptonic weak interaction can be taken to transform like the pseudoscalar mesons, namely as octets. The $\Delta Q = \Delta S$ property is then an automatic consequence. Since we could have two different ways of coupling octets to octets via an octet operator (the D and F type couplings) we must specify the D/F ratio also. The generators of SU(3) themselves transform as pure F type; and the present view is that the pseudoscalar couplings have $D/F = 3/2$. The choices of pure F type for vector and a mixture of D and F types with $D/F = 3/2$ for the axial vector seem to be in agreement with experiment. But on comparing the strangeness conserving and strangeness violating decays we find that the strangeness violating decay amplitudes are suppressed by factors of tan θ_V and tan θ_A where

$$\theta_V = \tan^{-1} 0{\cdot}22$$

$$\theta_A = \tan^{-1} 0{\cdot}28$$

are called the Cabibbo angles. It is quite interesting to note that these suppression factors are very close to the ratio m_π/m_K of the pseudoscalar masses. If only we could include the inverse pseudoscalar meson mass as a factor in the interaction we could restore universality of weak interactions. *Within a purely four-fermion theory such a factor cannot enter; but if we could take a theory in which the interactions are mediated by meson exchange such a possibility may obtain.* We shall see that the theory of primary interactions does precisely this.

There are also non-leptonic weak decays. In this case the strong interaction effects make it difficult to identify the current-current structure, but if we assume that these decays result from a four-fermion coupling of the primary baryon fields through the same octet type current-current coupling we would expect an octet and 27-type contribution to strangeness violating decays. These imply contributions with the isospin transformation properties of $\Delta I = 1/2$ and $\Delta I = 3/2$, but not $\Delta I = 5/2$. For kaon decay into two pions these imply a sum rule which is satisfied reasonably well. Similar relations also obtain for the SU(3) transformation property with only the 8-type and 27-type contributions. To a fair accuracy it appears also than an 8-type contribution alone can account for all the non-leptonic transition amplitudes.

5 Universal Primary Interactions

We now propose a theory of primary interactions which retains much of the successes of our chiral V-A interaction but extends it in a universal fashion to strange particle decays and related strong, electromagnetic and weak interactions. The basic idea of the theory is that weak interactions and electromagnetism of strongly interacting particles are not primary interactions but are induced by the direct coupling of vector and axial vector fields. The primary interactions are the direct couplings of the vector and axial vector meson fields with leptons and the photon.

The electrons and muons are directly coupled to the Maxwell field a^λ according to the standard interaction

$$-e(\bar{\mu}\gamma_\lambda\mu + \bar{e}\gamma_\lambda e)a^\lambda$$

This is a primary interaction; so is the electric interaction

$$-e'\left(\frac{m_\rho{}^2}{g}\rho_\lambda + \frac{m_\omega{}^2}{g}\omega_\lambda\right)a^\lambda$$

where g is the (strong) coupling constant for the vector mesons. The fact that electric charge must be absolutely conserved in the beta decay of neutrons demands the equality of the two coupling parameters e and e'. The vector fields ρ_λ and ω_λ are both the divergence-free neutral vector meson fields. As a consequence the electric current

$$ej_\lambda = -e\left(\bar{\mu}\gamma_\lambda\mu + \bar{e}\gamma_\lambda e + \frac{m_\rho}{g}\rho_\lambda + \frac{m_\omega{}^2}{g}\omega_\lambda\right)$$

is conserved.

As an immediate consequence of this form of the coupling it would follow that the electric form-factor of the nucleon (or any other strong interaction) is given by the form-factor of the vector meson vertex multiplied by an additional pole term to take account of the vector meson propagator. This is in qualitative accord with the two-pole structure observed in the nucleon electromagnetic form factors. In addition to this, the nucleon would exhibit anomalous magnetic properties which would be a direct reflection of the effective magnetic coupling of the vector meson with the nucleon. If we denote the vector meson-nucleon coupling by

$$\tfrac{1}{2}g\bar{N}[\gamma^\lambda \boldsymbol{\tau}\boldsymbol{\rho}_\lambda + (g'/g)\sigma^{\lambda\nu}\tfrac{1}{2}(\boldsymbol{\tau}\boldsymbol{\rho}_{\lambda\nu})]N$$

the nucleon isovector magnetic moment is given by

$$\mu_1 = \frac{2m_N}{m_\rho}\cdot\frac{g'}{g}$$

If we take $g'/g = 5/3$ as suggested by the SU(4) symmetry scheme we predict an isovector magnetic moment of

$$\mu_1 = 4{\cdot}1$$

which is to be compared with the experimental value

$$\mu_1 = 3{\cdot}7$$

An extension of this method leads to a calculation of the ratio of proton and neutron total magnetic moments of

$$-\mu_p/\mu_n = 1 + (g/g')(m_\rho/m_N) = 1{\cdot}49$$

which is to be compared with the experimental value 1·46. It is now appropriate to see how we could use a similar scheme for weak interactions.

The primary weak interactions of the leptons is of the chiral *V-A* form:

$$\frac{G}{\sqrt{2}}[\bar{\mu}\gamma_\lambda(1+\gamma_5)\nu_\mu]^\dagger[\bar{e}\gamma^\lambda(1+\gamma_5)\nu_e]$$

with a *possible self-coupling* of the electron covariant or muon covariant. But as far as the nucleons are concerned they have no primary weak interactions; but the charged vector and axial vector mesons couple according to

$$-G\left(\frac{m_\rho^{\ 2}}{g}\rho^\lambda + \frac{m_A^{\ 2}}{g}A^\lambda\right)[\bar{\mu}\gamma_\lambda(1+\gamma_5)\nu_\mu + \bar{e}\gamma_\lambda(1+\gamma_5)\nu_e]$$

By virtue of the strong interaction of the ρ meson we get the effective Fermi interaction:

$$\frac{G}{\sqrt{2}}(\bar{P}\gamma_\lambda N)[\bar{e}\gamma^\lambda(1+\gamma_5)\nu_e]$$

The effective Gamow-Teller interaction is of the form

$$\left(\frac{f}{g}\right)\cdot\frac{G}{\sqrt{2}}\cdot(\bar{P}\gamma_\lambda\gamma_5 N)[\bar{e}\gamma^\lambda(1+\gamma_5)\nu_e]$$

with the axial vector field coupling to nucleons being given by:

$$\tfrac{1}{2}f\bar{N}[\gamma^\lambda\gamma_5\boldsymbol{\tau}\mathbf{A}_\lambda + (f'/f)\sigma^{\lambda\nu}\gamma_5\tfrac{1}{2}\partial\mathbf{A}_{\lambda\nu}]\cdot N$$

Comparison with beta decay experiment suggest that

$$f/g = g_A \simeq 1{\cdot}2$$

We also find a small *CP*-violating interaction from the coupling of $A_{\lambda\nu}$. Its contribution to effective nuclear beta decay interaction seems to be beyond the present experimental limit. It is interesting to note that the weak magnetism term is predicted in this theory with the correct numerical magnitude.

The values of (g'/g), (f/g), (f'/g) can all be derived from the following line of reasoning. As emphasized in connection with the symmetries of the beta interaction, the important question is not whether the symmetry is elegant but whether it is in accordance with experiment. We come back to this question later. We note that the vector and axial vector meson interactions in the low energy limit consist of both Fermi and Gamow-Teller type couplings. The coupling of the vector meson through ρ_λ is Fermi type; but the coupling of the vector meson through $\rho_{\lambda\nu}$ and the axial vector meson through A_λ or through $A_{\lambda\nu}$ are Gamow-Teller type. For vector meson couplings by identifying the two types with the respective generators of SU(4) we arrive at the ratio

$$g'/g = \tfrac{5}{3}$$

As far as the axial vector fields are concerned, since both of them are Gamow-Teller type we should require by a similar identification:

$$\sqrt{(f^2 + f'^2)}/g = \tfrac{5}{3}$$

If in addition we take

$$f'/f = 1$$

we get

$$g_A = f/g = f'/g = \frac{5}{3\sqrt{2}} \simeq 1{\cdot}2$$

in reasonable agreement with experiment.

If these arguments are to be trusted, we should be able to explain low-energy meson-nucleon scattering in terms of a single coupling constant for strong interactions. We should of course associate the vector meson field with the observed vector mesons. Since the neutral fields ρ_λ, ω_λ must be divergence-free to assure the conservation of electric current, this implies, in turn, that no neutral currents are expected to be present; none are, of course, found. On the other hand, as far as the axial vector meson fields are concerned no such conservation law is required; we could then associate the pseudoscalar mesons with the divergence of the axial vector field. Such an assignment is closely related to the partial conservation law for the axial current that we had discussed earlier. We write:

$$\partial^\lambda V_\lambda = 0$$
$$\partial^\lambda B_\lambda = 0;\; A_\lambda = B_\lambda + (\xi/m_\pi)\partial_\lambda\phi_\pi$$

Here V_λ stands for the divergence-free vector fields and B_λ for the divergence-free part of the axial vector field. We have introduced a dimensionless parameter ξ to indicate the relative strength of the pion field. We now get a pseudovector coupling of the pion to the nucleon:

$$(f_1/m_\pi)\bar{N}\gamma^\lambda\gamma_5\boldsymbol{\tau}\cdot\partial_\lambda\boldsymbol{\phi}_\pi N;\quad f_1 = \tfrac{1}{2}gg_A\xi$$

We may determine f_1 from purely strong interaction data and consider f_1 and g to be the relevant strong interaction parameters.

Using the values $f_1 = 0{\cdot}85$, $g = 9{\cdot}0$ we can get excellent agreement for the low energy pion-nucleon scattering lengths for all S-waves and P-waves (with the exception of the resonant channel). We have for the S-wave scattering lengths:

$$a_1 = +0{\cdot}20 \quad (+0{\cdot}183)$$
$$a_3 = -0{\cdot}10 \quad (-0{\cdot}109)$$

and for P-waves:

$$a_{11} = -0{\cdot}091 \quad (-0{\cdot}101)$$
$$a_{13} = -0{\cdot}022 \quad (-0{\cdot}029)$$
$$a_{31} = -0{\cdot}022 \quad (-0{\cdot}039)$$
$$a_{33} = +0{\cdot}133 \quad (+0{\cdot}215)$$

(where the figures in parentheses are the experimental values).

This scheme gives qualitative accord with the main features of the nuclear force. In particular, the pion strength parameter

$$\xi = 2f_1/f = 0{\cdot}16$$

together with the absence of unacceptable singularities in the two-nucleon force imply the relation:

$$(f\xi/m_\pi)^2 - (g/m_\rho)^2 = 0$$

This leads to the prediction

$$(m_\pi/m_\rho) = 0{\cdot}188$$

which is to be compared with the observed value

$$(m_\pi/m_\rho) = 0{\cdot}182$$

We see that the theory of primary interactions is able to relate strong, electromagnetic and weak interaction phenomena involving the non-strange particles.

In the extension to strange particles we have to consider strange vector and axial vector mesons. We would like to incorporate the absence of strange scalar mesons by demanding that

$$\partial^\lambda V_\lambda' = 0$$

This implies that there can be no coupling of strange vector mesons to baryons through V_λ' because of the inequality of the strange and non-strange baryon masses. Instead the entire coupling should proceed through the coupling via $V_{\lambda\nu}'$. This would tend to suppress the vector decays. For the axial vector fields we write:

$$\partial^{\lambda}B_{\lambda}' = 0;\ A_{\lambda}' = B_{\lambda}' + (\xi/m_K)\partial_{\lambda}\phi_K$$

We choose the *same* value of the dimensionless parameter ξ because we can now demand that the coupling of the strange and non-strange axial vector fields are *universal*. We can immediately deduce for the ratio of the π and K decay widths:

$$\frac{\Gamma(K \to \mu\nu)}{\Gamma(\pi \to \mu\nu)} = \frac{m_\pi}{m_K}\left[\frac{1 - (m_\mu/m_K)^2}{1 - (m_\mu/m_\pi)^2}\right]^2$$

which yields an excellent value for the lifetime of the kaon. For the axial vector decays of the hyperons we could show that making use of the partial conservation law we could deduce an effective Cabibbo angle

$$\theta_B = \tan^{-1}\left\{\frac{m_\pi}{m_K}\frac{M + m}{2m}\right\}$$

which is in excellent agreement with experiment. Thus the choice of a universal value for the pseudoscalar meson strength parameter enables us to restore universality of the weak interactions. Needless to say, as long as the mesons form an octet coupled with the baryons, the octet property of the leptonic decays is assumed.

For the non-leptonic decays we could consider weak coupling of the vector and/or axial vector mesons with baryons and mesons. Independent of the details of this coupling we get the transformation properties of a current-current interaction with an octet current coupled to a suitable baryonic current. It will take us too far afield to discuss the question of non-leptonic decays in detail.

We have outlined here a theory of universal primary interactions of particles including strong, electromagnetic and weak interactions. The most important idea is that the primary interactions of the baryon consist of the strong coupling to vector and axial vector fields only. Both electromagnetic and weak interactions are acquired characteristics. Thus our theory may be viewed as the logical completion of the hypothesis that the beta decay of the nucleon arose only by virtue of its coupling to the meson. The theory has the ability to correlate such diverse aspects as nucleon magnetic moments, weak magnetism, ratio of Gamow-Teller and Fermi coupling constants, absence of neutral lepton currents, apparent suppression of strange particle leptonic decays and pion-nucleon scattering.

The hypothesis of chiral V-A interaction may thus be considered to be fully verified within the realm of non-strange particle decays for which it was formulated. The continuing work of the last decade has established this scheme. But it appears that its extension to strange particles and the desire to relate strong and weak interactions suggest that we modify the theory. The theory of primary interactions shows that the theoretical scheme acquires a much simpler form if we postulate that electromagnetism and weak interactions are not primary interactions of the nucleons but are acquired by virtue of their interaction with vector and axial vector fields. The next decade will tell as to what extent this theory is a step towards understanding nature.

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