CHIRALITY INVARIANCE AND THE UNIVERSAL $V-A$ THEORY OF WEAK INTERACTIONS

E. C. G. Sudarshan
University of Texas at Austin
Austin, Texas

R. E. Marshak
Virginia Polytechnic Institute and State University
Blacksburg, Virginia

1 Cartan Spinors and Weyl Neutrino

This celebration of the scientific work of Jayme Tiomno provides us with an opportunity to pay tribute to the many people who contributed to the discovery of the universal chiral $V - A$ weak interaction theory and, particularly, to relate it to several of the contributions made by Professor Tiomno.

P. A. M. Dirac invented the relativistic equation for the electron; but decades before his discovery, Elie Cartan had introduced the geometrical notion of spinors in three and four dimensions. Cartan introduced a spinor in three dimensions by its behavior under reflection in a plane defined by its normal[1]:

$$\zeta \to \boldsymbol{\sigma} \cdot \boldsymbol{n} \zeta$$

where $\boldsymbol{\sigma}$ is the triplet of Pauli matrices. The spinor in $\mathbb{R}^3$ is necessarily complex. Since two reflections generate a rotation, the behavior of the spinor under rotation is derivable and is unique:

$$\zeta \to \exp(\tfrac{1}{2}\boldsymbol{\sigma} \cdot \boldsymbol{\theta})\,\zeta. \tag{1}$$

The complex conjugate of a spinor is, apart from a fixed transformation, a spinor. For a four-dimensional Euclidian space, there are two kinds of spinors: spinors of the first kind transform as two-component spinors under the triplet of self-dual components:

$$A_j = \tfrac{1}{2}(J_{j4} + \tfrac{1}{2}\varepsilon_{jkl}J_{kl}) \tag{2}$$

and as a scalar under the anti-self-dual components:

$$B_j = \tfrac{1}{2}(J_{j4} - \tfrac{1}{2}\varepsilon_{jkl}J_{kl})$$

of the angular momentum in four dimensions. For Minkowski space, the combinations A_j and B_j are hermitian conjugates; therefore the complex conjugate of a spinor of the first kind is a spinor of the second kind. The spinor of the second kind is a spinor with respect to B_j but a scalar with respect to A_j.

When Dirac invented his relativistic equation for the electron, he introduced the spinor wave functions from a different point of view, as the carrier space[2] of the $\boldsymbol{\alpha}$, β matrices:

$$\begin{aligned} \nabla^2 - \tfrac{\partial^2}{\partial t^2} - m^2 &= \left(i\,\tfrac{\partial}{\partial t}\right)^2 - D^2, \\ D &= -i\boldsymbol{\alpha} \cdot \boldsymbol{\nabla} + \beta m, \end{aligned} \tag{3}$$

with

$$\begin{gathered} \alpha_j\alpha_k + \alpha_k\alpha_J = 2\delta_{jk}\mathbb{1}; \\ \alpha_j\beta + \beta\alpha_j = 0; \qquad \beta^2 = \mathbb{1}. \end{gathered}$$

There is only one irreducible representation of the Dirac matrices $(\boldsymbol{\alpha}, \beta)$ apart from unitary equivalence. This is by two +1 diagonal elements (upper block) and two −1 diagonal elements (lower block). This representation, so eminently suited for slow electrons and electrons in atomic bound states, became so common that Cartan's spinor calculation was not used by physicists.

The distinction between the two versions is very analogous to the equations of motion of the electromagnetic field in a vacuum. Usually we write the equations in the form of two four-vector equations:

$$\begin{gathered}\partial^\mu F^{\nu\lambda} + \partial^\nu F^{\lambda\mu} + \partial^\lambda F^{\mu\nu} = 0 \\ \partial_\mu F^{\mu\nu} = 0\end{gathered} \tag{4}$$

or its noncovariant versions in terms of the electric E and magnetic B fields. However, in terms of the self-dual and anti-self-dual components:

$$\begin{aligned}\partial_j \mathcal{A}_j &= 0; \qquad & \partial_j \mathcal{B}_j &= 0; \\ \mathcal{A}_j &= E_j + iB_j; \qquad & \mathcal{B}_j &= E_j - iB_j.\end{aligned} \tag{5}$$

Recall that under homogeneous Lorentz transformations, A_j and B_j transform independently. The A_j and B_j fields are associated with circular polarizations and are therefore chiral ("handed").

The notion of handedness in relation to polarization and thus of chirality goes back to Sir Joseph Larmor[3], from whom Sir Arthur Eddington[4] borrowed it. Satosi Watanabe was the first to suggest the use of chirality in relation to circular polarization in the context of particle physics[5]. Cartan's two kinds of spinors were put to use in physics by Herman Weyl[6], who observed that for a zero mass particle ("neutrino"), Dirac's equation could be written in terms of two-component (complex) spinors. This Weyl equation was not considered suitable for describing a particle, since it would not allow for parity conservation. (If we took the equations of motion for a circularly polarized light wave, we would have a similar problem.) There are two distinct Weyl equations, one for spinors of the first kind and one for spinors of the second kind. It is important to note that the possibility of separating the kinematic modes of a Fermi field in a Lorentz-invariant way into the chiral components (Cartan's spinors of the first and second kind) stems from the structure of the kinematic part of the Lagrangian and is independent of the dynamical interactions including mass. The chiral fields are themselves autonomous field degrees of freedom and may be arranged in patterns of internal symmetry. The chiral transformation will change the sign of the mass as well as the coupling with a pseudoscalar (or scalar) meson. Moreover, the independent chiral components get mixed up by S, P, T couplings.

2 Chirality

When we consider second-quantized fermion field theory, the primary kinematic characterization is the commutation relation between the fields;

$$\{\psi_r(\boldsymbol{x},t), \psi_s^\dagger(\boldsymbol{y},t)\} = \delta(x-y)\,\delta_{rs} \tag{6}$$

which has the property that spinors of one chirality (first kind or second kind) do not mix with those of the other. This remarkable property flows from the splitting of the kinematic terms:

$$\psi^\dagger\left(i\beta\gamma^\mu\frac{\partial}{\partial x^\mu}\right)\psi = \psi_L^\dagger\, i\beta\gamma^\mu\frac{\partial}{\partial x^\mu}\,\psi_L + \psi_R^\dagger\, i\beta\gamma^\mu\frac{\partial\psi_R}{\partial x^\mu} \tag{7}$$

and is invariant under the proper Lorentz group. Here we have defined the chiral components [5]:

$$\begin{gathered} \psi_L = \tfrac{1}{2}(1+\gamma_5)\psi; \qquad \psi_R = \tfrac{1}{2}(1-\gamma_5)\psi \\ \gamma_5 = i\gamma_0\gamma_1\gamma_2\gamma_3 = i\alpha_1\alpha_2\alpha_3. \end{gathered} \tag{8}$$

The four-vector charge current for a complex Dirac field also splits into separate chiral flows:

$$j^\mu = \bar{\psi}\gamma^\mu\psi = j_L^\mu + j_R^\mu. \tag{9}$$

Hence, the chiral fields can sustain a gauge-invariant electromagnetic interaction and this is the reason chiral fermions play such an important role in the present-day gauge theory of strong and electroweak interactions. However, a scalar mass term would mix them and this is the reason fermion mass generation requires the breaking of chiral symmetry.

In this background of the work of Cartan, Dirac, and Weyl, the only objection to using chiral fields was that their quanta would be particles that would not have any way of being reflected in space. A more subtle objection was that they would have antiparticles that were of the opposite chirality. But with the discovery of maximal parity violation in weak interactions in 1956[7], this objection was no longer relevant. Indeed, the existence of maximal parity violation in the weak interactions made it appropriate to consider each chiral field by itself, though there was no *a priori* reason to do so.

We now summarize the sequence of events that led from Fermi's theory of beta decay to chiral invariance and the universal V-A theory of weak interactions. In 1934, Enrico Fermi[8] gave the first explicit formulation of a theory of β decay when he constructed a theory of direct coupling of four spinor fields with a point interaction. Much as Dirac[9] had used the direct vector interaction of the electron with the electromagnetic (gauge) field as the starting point for dealing with spontaneous emission of a light quantum by an excited atomic electron, Fermi used the (four-fermion) vector (V) interaction to compute the spectrum and rate for the spontaneous decay: $n \rightarrow p+e+\bar{\nu}$. In analogy with electromagnetism, Fermi computed the beta processes in the limit of slowly moving nucleons. His work included a nonperturbative treatment of the Coulomb field of the nucleus and a possible non-zero neutrino mass. While the current in electromagnetism is neutral, the current in beta decay is charged! Despite this difference, Fermi chose the vector interaction. But beyond this, neither the possibility of vector meson mediation nor of gauge invariance was pursued, despite Yukawa's own attempt to use his meson hypothesis[10] to do so. Doubtless, the need for the spin-dependent Gamow–Teller interaction, which had to be added to Fermi's theory to account for β decays like that of He^6, would have made it difficult to establish a formal connection with electromagnetism. The decomposition of the electric current of electrons into its chiral components was not recognized at this point in time.

The Fermi theory, as augmented by Gamow and Teller[11], still was not sufficiently specific. For a fully relativistic theory with parity conservation, there are scalar (S) and vector (V) interactions to choose from as possibilities for the Fermi interaction and, similarly, for the tensor (T) and axial vector (A) as regards the Gamow–Teller interaction; the fifth pseudoscalar (P) interaction has a vanishing limit for slow nucleons. So the choice had to be made from among these five Fermi theories! The electron energy spectrum for allowed beta decays is the same for each of these interactions, although there is the possibility of an additional (Fierz interference[12]) term in case S and V or T and A are present. Careful experiments showed no evidence for Fierz interference. There was some evidence from "mixed" β transitions (involving a combination of Fermi and Gamow-Teller nuclear matrix elements) for an S, T combination of β interactions but the false step in determining the Lorentz structure of the β interaction came from a measurement of the electron-neutrino angular correlation in He^6. It can be shown that such an experiment distinguishes among the various allowed transitions and gives an angular distribution proportioned to:

$$\left\{1 + \lambda \left(\frac{v_e}{c}\right) \cos\theta_{e\nu}\right\} \tag{10}$$

with $\lambda = -1, +1, +\frac{1}{3}, -\frac{1}{3}$ for S, V, T, A interactions. The first serious experiment to find λ in a pure Gamow-Teller transition was performed on He^6 and gave $\lambda = 0.33 \pm 0.08$[13], which implied that the Gamow-Teller part of the β interaction is T; taken together with the mixed transition data, the combination S, T appeared to be nature's choice for the Lorentz structure of the parity-conserving β interaction.

The S, T form of the β interaction was widely accepted just prior to the parity-violation breakthrough in 1956, and misled a number of theoretical speculations until the advent of the universal V-A theory. In particular, Tiomno[14] and, independently, Stech and Jensen[15] applied the principle of chirality invariance (*with parity conservation*) in an attempt to identify some type of symmetry principle that would fix the Lorentz structure of the β interaction consistent with the experimental data, and recognized the capability of chirality invariance to distinguish between the S, T interactions on the one hand and the V, A interactions on the other. But they accepted the conventional wisdom of S, T at that time and were pleased that chirality invariance provided an additional argument for the S, T choice. We shall shortly come back to this work of Tiomno (and Stech and Jensen) but, before doing so, we trace the progress on the concept of the universal Fermi interaction (UFI) up to the crucial year of 1956—to which Tiomno made a major contribution.

3 Universal Fermi Interaction

The UFI idea required a broader range of weak interaction phenomena—in addition to β decay—to be interesting and this interest was supplied by the muon (the "second-generation" lepton) in the late 1940s. The Yukawa meson was around since 1935 and its expected strong nuclear interaction was beginning to create problems for its identification with the observed cosmic ray meson (e.g. the long lifetime for β decay of the cosmic ray meson, the weak scattering cross section of the cosmic ray meson, etc.). But the shattering blow came with the experiment of Conversi, Pancini, and Piccioni[16] in 1947, which found a majority of negative sea level cosmic ray mesons to decay in a carbon plate but to be absorbed in an iron plate. Fermi, Teller, and Weisskopf[17] showed that this result implied a factor of 10^{12} discrepancy between the production and interaction coupling strengths. Later the same year, Marshak and Bethe[18] put forward the two-meson hypothesis, in which a strongly interacting Yukawa meson produced in the upper atmosphere is supposed to decay into a weakly interacting meson at sea level; the Bristol group, in the meantime, had obtained photographic emulsion evidence for just such a decay[19]. B. Pontecorvo[20] pointed out that the capture probability of a bound negative cosmic ray muon in carbon is the analog of a K capture when the altered radius of the K-shell orbit and the energy release are properly taken into account. Thus, by the end of 1947, one was poised for the extension of Fermi's theory of β decay to other weak processes like muon decay and muon capture. This quickly led to UFI, in the hands of Tiomno and Wheeler and others[21], culminating after parity violation in Sudarshan and Marshak's universal chiral $V-A$ theory of weak interactions[22].

In the search for the possibility of having a universal weak interaction, the decay of the muon into an electron and two neutrinos had to be computed. In 1948 and early 1949, several authors computed the rate of this decay. The first comprehensive calculation was performed by Tiomno and Wheeler,[21], who found approximate equality for muon decay, muon capture, and nuclear beta decay constants provided that nuclear beta decay is not predominantly P. The complete muon decay spectrum was calculated by L. Michel[23] with the most general muon decay interaction. In the meantime, Ruderman and Finkelstein[24] showed that if the muon and electron are coupled to the nucleon in the same manner, the decay rates of the pseudoscalar pion into (e,ν) and (μ,ν), namely $\mathbb{R}=\Gamma(\pi\rightarrow e\nu)/\Gamma(\pi\rightarrow\mu\nu)$ is independent of the strong pion interaction. If one assumes $e-\mu$ universality, $\mathbb{R}$ depends on the form of the weak interaction in the following fashion: $\mathbb{R}=1.2\times10^{-4}$ for A, $\mathbb{R}=5.4$ for P, and $\mathbb{R}=0$ for the S,V or T interaction. So the branching ratio in charged pion decay could be decisive in pinning down the Lorentz structure of UFI.

During the period 1947–56, nuclear beta decay and muon decay were studied more systematically. The experiments on muon decay fixed the decay products and the value of the Michel parameter for the electron spectrum, while new muon capture experiments were consistent with UFI. In β decay, a critical new measurement of the electron-neutrino correlation in He^6—already alluded to[13]—gave strong preference to the S,T or V,T combination. The electron-neutrino correlation experiment for the mixed transition in Ne^{19}[25] (and for the neutron) gave $\lambda\simeq0$, implying that the β interaction should be a combination of S,T or V,A. The "parity-conserving" experimental period ended on an inconclusive note.

Because of the uncertain and sometimes contradictory implications of the experimental data during the decade or so before 1956, theorists tried a variety of symmetry principles to determine the form of the β interaction, but no one symmetry principle could quite keep up with the experimental situation. The Wigner-Critchfield $S-A-P$ interaction—based on complete antisymmetrization of the four fermion spinors in the Fermi theory[26] was considered a candidate by Tiomno and Yang[27]; Schwinger[28] had his version (based on a "gauge" argument) in which he obtained a combination of V and T. The closest approach to the correct interaction was proposed by Tiomno[14], in which he invoked (following Peaslee[29]) the chirality invariance of the weak current (thereby conserving parity) and ended up with two distinct classes of interactions: the S, T combination or the V, A combination, and followed the experimentalist in preferring the S, T combination; Jensen and Stech[15] added the interesting fillip that the "chirality invariance" argument of Tiomno should be augmented by the additional "symmetry" condition that the correct Lorentz structure of the β interaction should have a built-in invariance under "Fierz rearrangement", but still expressed preference for the $S - T$ (for allowed transitions) rather than the $V - A$ combination (it should be stressed that here $V - A$ is a parity-conserving combination).

4 Conserved Currents. The V Interaction

We have already noted Ruderman and Finkelstein's very useful observation[30] during the early UFI discussion that the branching ratio for the decay of the pseudoscalar pion is extremely sensitive to the form of the weak interaction, independently of the strong pion-nucleon interaction. Five years later, Finkelstein and Moszkowski[30] returned to the related questions of UFI and the Fermi and Gamow–Teller-type coupling constants, g_{F} and g_{GT}, respectively, with an analysis of the available ft values for mirror-nuclei transitions such as $n - p$, $H^3 - He^3$, $O^{15} - N^{15}$ and $F^{17} - O^{17}$, which led them to the ratio $g_{\mathrm{GT}}^2/g_{\mathrm{F}}^2 \simeq 1.6 \pm 0.2$. They attributed this effect to the vertex modification brought about by virtual neutral pions and deduced the correct sign of the effect and that the magnitude was consistent with the parameters of the Chew static cut-off theory[30]; they concluded that:

> "the existence of this mesonic perturbation of the correct sign and approximately right magnitude makes it possible to assume that the unperturbed Gamow–Teller and Fermi constants are exactly equal in accordance with various hypotheses about the Universal Fermi Interaction. We note also that this correction is present to the *same* extent in muon capture but absent in muon decay; the effective Fermi constant for the μ decay should, for this reason, be slightly different from its value for μ capture and n decay..."

The last statement is rather surprising, since earlier they observe: "One ought to add contributions from diagrams corresponding to wave function renormalization ."

This brings us to the prescient observation of Gershtein and Zeldovich concerning the strong interaction effects on a V hadron current in the weak interaction. Yakov Zeldovich, who had been working on many fronts, was also concerning himself with the possible β decay of the charged pion [31]:

$$\pi^- \rightarrow \pi^0 + e^- + \nu.$$

This was followed by the paper of Gershtein and Zeldovich [32], in which they critically reexamined the problems posed by Finkelstein and Moszkowski on the basis of covariant perturbation theory, including the effect of nuclear wave function renormalization. They basically agreed with Finkelstein and Moszkowski, acknowledging that the covariant method is not really superior to the static calculation. But the most important contribution in this paper [32] was a cursory remark that was hastily and wistfully dismissed! We quote the authors:

> "It is of no practical significance but only of theoretical interest that in the case of the vector interaction type V, we should expect the equality [g' refers to bare coupling constant]:
>
> $$g_{\mathrm{F}(V)} \equiv g'_{\mathrm{F}(V)}$$
>
> to any order of the meson-nucleon coupling constant, taking nucleon recoil into account and allowing also for interaction of the nucleon with the electromagnetic field, etc. This result might be foreseen by analogy with Ward's identity for the interaction of a charged particle with the electromagnetic field; in this case, virtual processes involving particles (self-energy and vertex parts) do not lead to charge renormalization of the particle..."

Gershtein and Zeldovich considered their idea of a conserved vector current (CVC) of "no practical significance" because they accepted the conclusion in a 1954 paper [25], stemming from a measurement of the (e, ν) correlation in Ne^{19}, that the β interaction is a combination of S and T. This conclusion only followed if one believed in the He^6 result [13], an error that Gershtein and Zeldovich shared with many others.

5 Parity Violation and Universal Fermi Interaction

We now come to the hectic year from Sixth Rochester Conference (in the Spring of 1956) to the Seventh Rochester Conference (in the Spring of 1957). The full magnitude of the $\theta - \tau$ dilemma in strange particle physics (i.e. the existence of $\theta \rightarrow 2\pi$ and $\tau \rightarrow 3\pi$ meson decay modes with equal masses and lifetimes for θ and τ) became apparent, and the parity violation explanation was first mentioned and discussed[33]. It devolved upon Lee and Yang[34]—after the conference—to delineate with great care the weak decay processes in which parity violation would manifest itself other than through the 2π and 3π decay modes of the K meson. The parity-violation hypothesis was spectacularly confirmed within months of the publication of the Lee-Yang paper by Wu and collaborators[7], who looked for an electron asymmetry from polarized Co^{60}; a backward asymmetry was found, giving unequivocal evidence for parity violation that could be explained (since the decay of Co^{60} is a Gamow-Teller transition) by a T interaction with a righthanded neutrino (ν_R) or an A interaction with a lefthanded neutrino (ν_L). General acceptance of the results of the 1955 He^6 $(e - \nu)$ correlation experiment led Wu, Lee and Yang in particular, to accept T as the Gamow-Teller contribution to the β interaction.

During the same hectic year—Spring of 1956 to Spring of 1957—the parity-violation hypothesis was also tested in muon decay through a measurement of the backward electron asymmetry with respect to the muon momentum[35,36]. If one assumes the two-component neutrino and the conservation of leptons—which was consistent with all other experiments—these results required the V, A interaction for muon decay. Apparently, UFI was in deep trouble. Indeed, at the Seventh Rochester Conference, T. D. Lee, in his introductory talk at the session on weak interactions[37], said that:

> "Beta decay information tells us that the interaction between (p, ν) and (e, ν) is scalar and tensor, while the two-component neutrino theory plus the law of conservation of leptons implies that the coupling between (e, ν) and (μ, ν) is vector. This means that the Universal Fermi Interaction cannot be realized in the way we have expressed it... at

> this moment it is very desirable to recheck even the old beta interactions to see whether the coupling is really *scalar*...."

It is interesting that T. D. Lee does not question the T interaction (presumably, because of He^6) but is open-minded on S or V for the Fermi selection rule part of the interaction.

The dilemma became more acute after C. S. Wu's talk at the same conference wherein she reported on her unpublished measurement of the e^+ asymmetry from Co^{58} (undergoing a mixed-Fermi plus Gamow–Teller transition), which was giving a smaller value than the e^- asymmetry from Co^{60} and of opposite sign. This result could be explained if Co^{58} decay was primarily Gamow–Teller; however, if one inserted the accepted ratio of Fermi to Gamow–Teller matrix elements, the interference between S and T produced disagreement with the experimental result. This discrepancy led Wu to remark that[38]:

> "The evidence on the relative strengths of scalar and vector components in the Fermi interaction is no longer so convincing as we previously had thought.... The decay of A^{35} would furnish a much more sensitive test...."

The implication was that an appreciable amount of V in the β interaction would help to explain the small measured positron asymmetry in Co^{58}. However, if the β interaction was predominantly V, T (despite the evidence of some old parity-conserving β experiments), one would be forced to assign opposite helicities to the neutrinos emitted in Fermi- and Gamow–Teller-type β transitions, a very displeasing prospect indeed. To add to the confusion, the possibility of a V, T beta interaction was reinforced by two rumors circulating at the Seventh Rochester Conference (β experiments were being performed at an incredible rate!): one rumor was that Boehm and Wapstra[39] had obtained a similar result to that of Wu in measuring the $\beta - \gamma$ (circularly polarized) correlation in Co^{58}. The second rumor was that an Illinois group[40] had measured the electron-neutrino angular correlation coefficient from A^{35} (a dominantly Fermi transition) and was finding $\lambda = -1$ (as required by the V interaction) instead of $\lambda = +1$ (as required by the S interaction). Could the beta interaction be V, T after all[28] and UFI have to be abandoned?

It was our original intention to make a brief report at the Seventh Rochester Conference on the universal $V-A$ theory. We had identified the problems with reconciling all the known β decay experiments with a unique β interaction and had recognized that some experiments must be wrong. But since one of us (ECGS) was a graduate student at the time and since the other (REM) was making a lengthy presentation on nuclear forces (the Signell–Marshak potential), it was decided that P. T. Matthews, then a Visiting Professor at Rochester (who was conversant with our work) would report on the $V-A$ theory in place of ECGS. For reasons unconnected with the $V-A$ theory, Matthews never made the presentation. During the conference, REM would have stepped into the fray but for the spector of a V, T interaction in β decay (requiring opposite helicities for the neutrino); he was reluctant to argue for $V-A$ as the UFI option as long as a consistent picture did not emerge from the *parity-violating* experiments in weak interactions.

After the Seventh Rochester conference, it was essential to clarify as soon as possible whether the V, T combination was a mirage insofar as the parity-violating β decay experiments were concerned. This clarification came during the first week of July (1957), as the result of a meeting with F. Boehm,[41], where we presented our arguments for the universal $V-A$ theory and asked for an updating on the $\beta-\gamma$ (circularly polarized) correlation program in which he was engaged. Boehm informed us that his latest experiment on Sc^{46} gave a much larger correlation coefficient than Co^{58}, implying that the choice V, T (or S, A) for the β interaction was excluded; presumably, the estimate for the ratio of Fermi to Gamow–Teller matrix elements was in error for Co^{58}. With this assurance, and the benefit of several additional experimental numbers (available by the time of the Boehm meeting), we were able to complete our paper within a matter of days and to send off an abstract to the organizers of the Padua-Venice conference, where we expected to present our work in September (1957).

6 Universal $V-A$ Theory and its Rapid Confirmation (1957–59)

The several months' delay—from April to July 1957—in putting the finishing touches on our paper was most useful, since it allowed time for certain key β experiments to pass from the rumor to completion stage and thereby to consolidate the experimental underpinning of our V-A theory. Thus, we were able to discuss not only the electron asymmetry experiment in Co^{60}, the "Fierz interference" experiments, and the (e,ν) angular correlation experiment in He^6, but also the electron polarization experiment on the Fermi decay of Ga^{66}[42] and the (e,ν) angular correlation experiment in A^{35},[40] in addition to the $\beta-\gamma$ correlation experiment in Sc^{46}[39]. This comprehensive analysis of β processes led us to conclude in our Padua-Venice paper[22] (entitled "Nature of the Four-Fermion Interaction") that:

> "The present β decay data, while still somewhat contradictory from an experimental point of view, seem to suggest some definite choices for the coupling types... the simplest inference would be that the β decay coupling is either AV or ST.... The AV (or ST) combination has the added merit that the neutral particle emitted in electron decays is then righthanded (or lefthanded) both for the Fermi and the $G-T$ interactions [the neutral particle emitted in electron decays is the antineutrino].... In the case of both AV and ST, the Fierz interference terms in allowed spectra and first forbidden spectra vanish identically. The choice between AV and ST thus hinges essentially on the electron-neutrino angular correlations or, equivalently, on the determination of the spirality of the neutral particle emitted in β decay. [The term "spirality" was used interchangeably with "helicity" in the early days of parity violation[43]]. As regards the electron-neutrino angular correlations, this implies a choice between the A^{35} and He^6 experiments.... "

We then proceeded to consider the evidence from other weak interactions. Our analysis of muon decay was, of course, in accord with T. D. Lee's, and we stated that

> "the muon decay data thus suggest A, V interaction irrespective of the spirality of the neutrino field. The latter can be unambiguously determined if one measures the longitudinal polarization of the positron from μ^+ decay. The positron would be expected to be right- or left-polarized, according as the Co^{60} transition proceeds via axial vector or tensor interactions, provided the Law of Conservation of Leptons is valid.... "

We continued with an analysis of the evidence from the $\pi_{e2}/\pi_{\mu 2}$ and $K_{e2}/K_{\mu 2}$ branching ratios and finally concluded that:

> "the only possibility for a Universal Fermi Interaction is to choose a vector + axial vector coupling [the nomenclature $V - A$ was adopted later] between every two of the pairs of fields $\mu\nu$, $e\nu$, np, $\Lambda^{\circ}p$, with $\Lambda^{\circ}p$ and np leading to the τ and θ modes of the K meson. In the framework of our hypothesis, the β decay interaction is defined uniquely by the sign of the electron asymmetry in the decay of oriented Co^{60}. This unique form is:
>
> $$g\bar{P}\gamma_\mu(1+\gamma_5)N\bar{e}\gamma_\mu(1+\gamma_5)\nu + \text{h.c.}$$
>
> The hypothesis of Universal Interaction generalizes this β coupling to a coupling of four Dirac fields A, B, C, D in the form: $g\bar{A}\gamma_\mu(1+\gamma_5)B\bar{C}\gamma_\mu(1+\gamma_5)D$. Since γ_5 and γ_μ anticommute, one can rewrite the interaction of the four fields A, B, C, D in the form:
>
> $$g\bar{A}\gamma_\mu(1+\gamma_5)B\bar{C}\gamma_\mu(1+\gamma_5)D = g\bar{A}'\gamma_\mu B'\bar{C}'\gamma_\mu D',$$
>
> where A', B', C', D' are the "two-component" fields:
>
> $$A' = (1/\sqrt{2})(1+\gamma_5)A, \quad \bar{A}' = (1/\sqrt{2})\bar{A}(1-\gamma_5), \quad \text{etc.}$$
>
> Now the "two-component" fields $(1/\sqrt{2})(1 \pm \gamma_5)A$ are eigenstates of the chirality operator[30] with eigenvalue ±1.
>
> Thus the Universal Fermi Interaction, while not preserving parity, preserves chirality, and the maximal violation of parity is brought about by the requirement of chirality invariance. This is an elegant formal principle, which can now replace the Lee–Yang requirement of a two-component neutrino field coupling (or equivalently the Salam postulate of vanishing bare mass and self-mass for the neutrino).... Thus our scheme of Fermi interactions is such that if one switches off all mesonic interactions, the gauge-invariant electromagnetic interactions (with Pauli couplings omitted) and Fermi couplings retain chirality as a good quantum number...."

We ended our paper with:

> "While it is clear that a mixture of vector and axial vector is the only universal four-fermion interaction which is possible and possesses many elegant features, it appears that one published and several unpublished experiments cannot be reconciled with this hypothesis. These experiments are:
>
> (a) The electron-neutrino angular correlation in He^6....
>
> (b) The sign of the electron polarization from muon decay....
>
> (c) The frequency of the electron mode in pion decay....
>
> (d) The asymmetry from polarized neutron decay...."

> All of these experiments should be redone, particularly since some of them contradict the results of other recent experiments on the weak interactions. If any of the above four experiments stands, it will be necessary to abandon the hypothesis of a universal $V+A$ four-fermion interaction or either or both of the assumptions of a two-component neutrino and/or the law of conservation of leptons."

The quotations are all from the paper presented to the Padua-Venice Conference on "Mesons and Recently Discovered Particles" held September 22–28, 1957. Our paper was published in the proceedings of this conference in late Spring 1958 [22] and reprinted in P. K. Kabir's book on *Development of Weak Interaction Theory.* [22] In those halcyon days of collegiality, it never occurred to us to republish the Padua-Venice paper in a journal; we did send out a preprint dated September 16, 1957 (a date we remember because it happened to be ECGS's 26th birthday!). Several months later, we decided to publish a short note on "Chirality Invariance and the Universal Fermi Interaction" [44] to make some new points and to take stock of experimental developments following the Padua-Venice Conference. Thus, we remarked in that note:

> "Since the conference, the validity of the He^6 experiment has been questioned, the polarized neutron experiment has come down to a value consistent with the $V-A$ theory, and the helicity of the positron from μ^+ decay has turned out to be $+1$, as it should...There has been no change in the experimental situation with regard to the electron decay of the pion, but it is clear that this very difficult experiment should be redone. . . . "

Our note (sent to the Phys. Rev. on Jan. 10, 1958) was not intended as a substitute for our 1957 Padua-Venice paper, but, unfortunately, it was treated by all too many physicists in later years as the sole publication of our universal $V-A$ theory [45].

Apart from the priority question (which will be discussed in the next section), the fact is that within a year and a half of the Padua-Venice Conference, the four experiments, whose demise was required by the universal $V-A$ theory, had all been redone and the new results were in complete accord with the theory. Not only did the electron asymmetry from polarized neutrons come down and the polarization of e from μ decay acquire the correct sign and magnitude, but also the electron-neutrino angular correlation coefficient in He^6 became $-0.39 + 0.02$[46] and the $\pi_{e2}/\pi_{\mu 2}$ branching ratio changed to $0.93 \pm 0.37 \times 10^{-4}$[47]. The most striking confirmation of the $V - A$ theory was the direct measurement of the neutrino helicity as -1 in an ingenious experiment on K capture in Eu^{152} performed by Goldhaber and collaborators[48]. And so it came to pass—only three years after parity violation in weak interactions was hypothesized—that the pieces fell into place and that we not only had confirmation of the UFI concept but we also knew the basic $V - A$ structure of the charged currents in the weak interactions for both baryons and leptons. Let us remind ourselves that, in 1959, there were only one neutrino, only two charged leptons, no quarks, no Cabibbo mixing, no neutral currents, no CP violation, no role for Yang–Mills fields (proposed five years earlier[49]), and, of course, no electroweak group. Within fifteen years, there were two neutrinos, four quarks, the Kobayashi-Maskawa mass mixing matrix, neutral currents, CP violation, and, to cap it all, the triumphant non-Abelian $SU(2)_L \times U(1)_Y$ gauge theory of the electroweak interaction. It is gratifying that the justification given in our Padua-Venice paper for the universal V-A interaction on the basis of chirality invariance has had many far-reaching ramifications in the development of the present-day gauge theory of particle interactions: chirality invariance is basic to combining the chiral charged weak current and the non-chiral neutral electromagnetic current under the rubric of the chiral $SU(2)_L \times U(1)_Y$ electroweak group; chiral gauge anomalies fix the chiral quark and lepton representations in the standard model[50]; and the need for chiral fermions places strong restrictions on all theories attempting to "go beyond the standard model".

7 Historical Remarks

Much has been written about the origin of the universal V-A theory and a variety of views have been offered concerning the rapid-fire developments during the 1957–59 years. While we do not intend—in this historical piece for the Festschrift honoring Professor Tiomno—to give a complete account of that controversial period in particle physics, it is incumbent upon us to comment on a few of the claims and counter-claims. We first note two papers bearing on chirality invariance in relation to parity violation by Salam and Tiomno, of which we were not aware when we wrote our Padua-Venice paper. Salam brought his unpublished paper (dated February 1957) to the attention of one of us (REM) in 1968, with the consequence that it was acknowledged in the book by Marshak, Riazuddin, and Ryan of that year [51]. In his Nobel address, Salam mentions his contribution to the development of the $V-A$ theory as follows:

> "*The idea of chiral symmetry leading to a $V-A$ theory.* In those early days my suggestion of this was limited to neutrinos, electrons, and muons; shortly after that, Sudarshan and Marshak, Gell-Mann and Feynman, and Sakurai had the courage to postulate γ_5 symmetry for baryons as well as leptons, making it into a universal principle of physics...."

In his unpublished paper [51], Salam examined muon decay, wrote down the four-fermion interaction in charge *retention* order, adopted the two-component neutrino hypothesis, and applied Tiomno's mass reversal invariance to the e and μ spinors; he thereby deduced a combination of V and A interaction (not necessarily $V-A$) for muon decay. As Salam implies in his Nobel address, he did not question the conventional wisdom at that time that the β interaction was a combination of S and T. Unbeknown to us, Tiomno's paper on "Nonconservation of Parity and the Universal Fermi Interaction" was sent to Nuovo Cimento in early July 1957 and published in October [52]. Tiomno went beyond Salam in trying to reconcile the accepted (S, T, P) combination for the β interaction with the (V, A) muon interaction by postulating opposite helicities for the neutrino and thus ended up with a somewhat inelegant and incorrect UFI.

We next turn to the Feynman–Gell-Mann papers [53]. It is clear from the record that Feynman was toying with the idea of using the 2-component Klein–Gordon equation in place of the 4-component Dirac equation to express parity violation in weak interactions as early as April 1957. [54] It is a fact that Gell-Mann was informed of our work on the universal $V-A$

theory not later than the first week of July, at which time our paper was completed and an abstract sent off to Padua. It also seems clear from Tiomno's paper at the 1984 Racine conference[55] that the Feynman–Gell-Mann paper was written during the Summer of 1957 and dispatched to the Physical Review by Sept. 16, precisely the date on which our Padua-Venice preprint was sent out. The first public presentation of our work occurred during the Padua-Venice Conference, Sept. 22–28, 1957 and, several months later, the Feynman–Gell-Mann paper was published in Phys. Rev. (January 1, 1958)[53]. Our followup note on the universal $V - A$ theory was published in the March 1, 1958 issue of Phys. Rev. while the publication date of our Padua-Venice paper was unexpectedly delayed, until May 1958[22]. With this complicated set of facts, how does one settle the priority question in which historians of science are interested? In this instance, perhaps the simplest solution is to quote Feynman, who said in 1962[56]: "The same proposal [of the V-A theory] was also made, possibly somewhat earlier, by Marshak and Sudarshan...", and again, in 1974[57]: "So I would like to say where we stand in our theories of weak interactions. We have a conventional theory of weak interactions invented by Marshak and Sudarshan, published by Feynman and Gell-Mann, and completed by Cabibbo—I call it the conventional theory of weak interactions—the one which is described as the $V - A$ theory." This last remark by Feynman gives recognition to our work, but implies, it seems to us, that unfortunately he never read the original Padua-Venice paper but only our short note in the March 1958 Phys. Rev.

For purposes of the historical record, it may also be worthwhile to compare the approaches of the $V - A$ papers by ourselves and Feynman and Gell-Mann. Our paper adopted the "inductive" approach—after a thoroughgoing analysis of all key parity-violating and parity-conserving weak interaction experiments then extant, we reached the unequivocal conclusion that the only possible UFI was the $V - A$ interaction, at the expense of a certain number of explicitly identified contradictory experiments. We noted that the $V - A$

interaction possessed a number of interesting properties; chief among them was the invariance of the $V-A$ interaction under *separate* chirality transformations of the Dirac spinors. The Feynman–Gell-Mann paper adopted the "deductive" approach, purporting to derive the $V-A$ interaction by using half of the solutions of the 2-component Klein–Gordon equation without gradient coupling. This "derivation" did not withstand the test of time—in constrast with the chirality invariance approach—because the 2-component Klein-Gordon approach implicitly introduces the inadmissable indefinite metric. The Feynman–Gell-Mann paper confronts the $V-A$ theory with experiment, using pretty much the same empirical findings as we do, and, of course, come to similar conclusions. The novel feature of the Feynman–Gell-Mann paper is the rather extensive discussion of the conserved vector current hypothesis as a further argument for the universality of $V-A$; apparently, the authors were not aware of the earlier work of Gershtein and Zeldovich [32] on the subject but, in any case, examined the consequences in greater depth. Overall, the Feynman–Gell-Mann paper was a most valuable contribution to the theory of weak interactions.

We conclude our historical sketch with a brief comment concerning Sakurai's work on the universal $V-A$ theory. In the acknowledgement to his paper [58], Sakurai states: "The present investigation is directly stimulated by conversations the author had with Professor R. E. Marshak, to whom he wishes to extend his sincere thanks. . . ." It is true that Sakurai did meet with one of us (REM) in Rochester at the beginning of October 1959 to be briefed concerning the status of the universal $V-A$ theory; *he also received copies of the preprints of our paper* and that of Feynman and Gell-Mann. He prepared a paper, upon his return to Cornell, in which he pointed out that *separate* chirality invariance of the four-fermion interaction could be restated in terms of *separate* mass reversal invariance with the same resulting $V-A$ interaction. He then argued that the use of mass reversal invariance to "derive" the $V-A$ interaction was justified by the fact that the relationship between momentum and energy for a particle, as well as the 2-component Klein–Gordon equation used by Feynman and Gell-Mann, depend on m^2 (not on m). [The second Sakurai argument for m^2 misses the point because the real problem is not the sign of m but the difficulty of generating a massive (Dirac) fermion from a massless (Weyl) fermion, a problem of great current interest.] Sakurai then repeats some of the experimental discussion contained in our paper and that of Feynman and Gell-Mann, paying somewhat greater attention to the compatibility of the $V - A$ interaction with the experimental results on the nonleptonic decays of the strange particles. Sakurai's paper was sent to Nuovo Cimento on Oct. 31, 1957, and was published March 1, 1958, several months before the publication of our Padua-Venice paper. Apart from the priority question—which seems easy to resolve—it is difficult to see how the mass reversal invariance argument improves upon chirality invariance in "deriving" the universal $V - A$ interaction.

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Jayme Tiomno's life, enthusiasm and dedication are sources of inspiration to us and to future generations of physicists and it gives us great pleasure to participate in this celebration. We wish him many happy returns.

S. MacDowell
H. M. Nussenzveig
R. A. Salmeron

Essays in Honour of Jayme Tiomno

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