ORIGIN OF THE UNIVERSAL V-A THEORY

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§1. FERMI'S THEORY OF β DECAY (1934-47)

When David Cline invited one of us (R.E.M.) to give the first talk at this conference, it provided an opportunity to pay tribute again to one of the great physicists of the twenthieth century, Enrico Fermi. The "50 years" in the title of this conference refers, of course, to the first explicit formulation of a theory of weak interactions by Fermi in 1934[1]. In these seminal papers, Fermi applied the methods of second quantized field theory to the β decay process: $n \rightarrow p + e^- + \bar{\nu}$ (accepting Pauli's neutrino hypothesis) and worked out the consequences of his postulated vector interaction among the four spin 1/2 particles. With an eye for the physically relevant, Fermi used non-relativistic wave functions for the nucleons to exhibit the selection rules for β transitions in nuclei. He deduced the important features of forbidden transitions and calculated the effect of a non-vanishing neutrino mass on the β spectrum.

Fermi selected the vector (V) interaction out of five possible choices (the others being scalar (S), pseudoscalar (P), axial vector (A) and tensor (T)) in analogy to the electromagnetic interaction even though the analogous "current" in β decay was charged and not neutral. The analogy with the electromagnetic interaction was not pursued further - either in the direction of extending gauge invariance in some fashion or invoking boson mediation of the weak interaction (let us recall that a meson theory of nuclear forces was only put forward by Yukawa[2] a year later). Parity conservation, as well as baryon and lepton conservation, were implicitly assumed. Fermi's four-fermion vector theory of β decay was a splendid beginning and provided the basic framework for the chiral (V-A) interaction proposed by us in 1957. A decade later, the chiral (V-A) interaction was used as the starting point for the electroweak gauge theory that has passed its first major test recently with the detection of the W and Z weak bosons.

But let us return to the extensions and refinements that followed Fermi's initial papers. While Fermi's selection rule for an allowed transition ($\Delta J = 0$, <u>no</u> - <u>no</u> refers to parity change) was later confirmed, Gamow and Teller[3] pointed out quite early that the β interaction can depend on the spin of the nucleon and, in that case, the selection rule is $\Delta J = 0, \pm 1$ (no $0 \rightarrow 0$), <u>no</u> for an allowed transition. A prime example supporting the Gamow-Teller conjecture was He^6 ($J = 0^+$) $\rightarrow$ Li^6 ($J = 1^+$) + e^- + $\bar{\nu}$, which decay played such a crucial role in the quest for a universal β interaction in later years. Hence the distinction between Gamow-Teller selection rules (corresponding to the A or T interaction) and Fermi selection rules (corresponding to the V or S interaction).

The observation of Gamow-Teller β transitions implied that Fermi's V interaction could not be the sole β interaction and might even be absent. The precise structure of the β interaction became a burning question and a variety of methods was suggested to determine its form. Thus, Feriz[4] pointed out that the presence of A and V or T and A in the β interaction leads to an interference term in the allowed β spectrum which vanishes in the absence of an admixture of S and V or T and A. Möller[5] suggested that additional information could be obtained from K electron capture in nuclei and several authors[6] noted that a study of forbidden β spectra could reveal a great deal about the form of the interaction. Other possible experiments to shed light on the structure of the β interaction, e.g. electron-neutrino angular correlation and β-γ angular correlation experiments, were proposed. However, World War II interrupted the implementation of this program and, in 1947, the discovery of the second generation lepton, the muon, broadened the scope of beta interaction physics to weak interaction physics.

§2. BEGINNINGS OF A UNIVERSAL THEORY OF WEAK INTERACTIONS WITHOUT PARITY VIOLATION (1947-56)

It was known before 1947 that the cosmic ray meson underwent electron decay with a long lifetime but the decay products were unknown and no plausible connection had been established between this phenomenon and β decay. Indeed, Yukawa[2] had failed to establish this connection within the framework of his meson theory. But events beginning in 1957 altered the entire situation.

There was first the Italian experiment[7], published in February 1947, which discolosed that a substantial fraction of negative sea level mesons decayed in a carbon plate, but were absorbed in an iron plate. Analysis of this experiment by Fermi, Teller and Weisskopf[8] led to the startling conclusion that there was a factor of 10^{12} discrepancy between the meson's production and absorption cross sections. At the Shelter Island Conference in early June of 1947, Marshak and Bethe put forward the two-meson hypothesis[9] to explain the factor of 10^{12} by having the strongly interacting (Yukawa) meson produced in the upper atmosphere decay into the lighter weakly interacting meson at sea level. By mid-June, Nature had arrived in the U.S. with the beautiful photographs of $\pi \to \mu$ decay discovered by the Bristol group[10]. And by the end of June, Pontecorvo[11] made the brilliant observation: "We notice that the probability ($\sim 10^6$ sec^{-1}) of capture of a bound negative meson [in carbon] is of the order of the probability of ordinary K capture processes, when allowance is made for the difference in the disintegration energy and the difference in the volumes of the K shell and of the meson orbit. We assume that this is significant and wish to discuss the possibility of a fundamental analogy between β processes and processes of emission or absorption or charged mesons...". Pontecorvo did not know about the two-meson theory nor the $\pi \to \mu$ decays but he was really asserting that the muon was a "heavy electron" ("second generation lepton" in modern parlance) - an identification that has withstood the test of time. 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.

By the beginning of 1948, the production of pions in the Berkeley synchrocyclotron and further work on muon decay and muon capture had made it clear that theory was called upon to explain the interrelationship of the various processes shown diagramatically in Fig. 1. It is true that by mid-1947, Pontecorvo[11] had already noted the rough equality $g_3 \sim g_1$ (see Fig. 1), and that Marshak and Bethe[9] had related $g_{\pi\mu\nu}$ to g_3 and $g_{\pi NN}$; but muon decay had not been brought into the discussion and serious calculations of muon capture still had to be made. Through 1948 and the early part of 1949, a number of authors[12] examined the relationship of the various weak processes implied by Fig. 1 with or without the mediation of the strong pion-nucleon interaction. The record shows that the first and most comprehensive attempt to relate g_1, g_2 and g_3 (the legs of the large triangle in Fig. 1) was made by Tiomno and Wheeler[12] who found $g_1 \sim g_2 \sim g_3$ as long as the β interaction was not predominantly P. This work and that of the others in Ref. 12 gave great impetus to the concept of a universal Fermi interaction (UFI) even though the structures of the three weak interactions were as yet undetermined. Ruderman and Finkelstein[13] immediately latched on the UFI and pointed out that if UFI is accepted, the ratio of the decay rates of the pseudo-scalar π into (e, ν) and (μ, ν) is independent of the strong pion-nucleon interaction and depends only on the form of the weak coupling, in the following fashion: $\pi_{e2}/\pi_{\mu 2} \sim 10^{-4}$ for the A weak interaction, ~ 1 for the P weak interaction and =0 for the S, V or T weak interaction. The measurement of the $\pi_{e2}/\pi_{\mu 2}$ ratio was important in checking the universal V-A theory, as we shall see below.

The period 1947-56 also saw considerable progress in the unraveling of the structure of the β interaction although it ended on an inconclusive note. During this period, further experiments on muon decay fixed the decay products and value of the Michel parameter for the electron spectrum[14], and new muon capture experiments were consistent with UFI. However, the greatest effort went into β spectra (requiring A or T), and the occurrence of $J = 0 \to 0$, no transitions (requiring the presence of S or V). The measurement of the electron-neutrino angular correlation coefficient $\lambda = 0.33 \pm 0.08$ in the decay of He^6 favored T as the Gamow-Teller contribution to the β interaction by a rather wide margin[16]. Since the P interaction is very elusive in β decay measurements (because it does not contribute in the non-relativistic limit), one entered the crucial year 1956 with only two allowable combinations of the β interaction, namely S, T <u>or</u> V, T, except for a possible admixture of P[17]. Whether either preferred choice of the β interaction could be reconciled with the as-yet-undetermined forms of the muon decay and muon capture interactions remained to be seen. It was also unclear whether UFI could be extended to the strange particle decay processes that were coming under close scrutiny.

§3. PARITY VIOLATION AND THE DILEMMA FOR UFI (1956-57)

In one of those fortunate circumstances that leads to a quantum jump in scientific understanding, the θ-τ puzzle triggered a series of rapid-fire developments (both theoretical and experimental) that first created an impasse for UFI but which was soon resolved by the universal V-A theory. By 1956, the θ-τ puzzle (wherein two strange mesons, θ and τ, decaying respectively into two and three π's, were observed to have the same masses and lifetimes) was becoming increasingly troublesome. The subject came under intense discussion at the Sixth Rochester Conference (April 1956) and parity violation was one of the possible explanations suggested[18]. It devolved upon Lee and Yang[19] to delineate with great care other weak decay processes in which parity violation would manifest itself other than through the 2π and 3π decay modes of strange mesons. The parity violation hypothesis was spectacularly confirmed within months of the publication of the Lee-Yang paper by Wu and collaborators[20] who looked for an electron asymmetry from polarized CO^{60}. The backward asymmetry which was found gave unequivocal evidence for parity violation and could be explained (since the decay of Co^{60} was a Gamow-Teller transition) by a T interaction with a right-handed neutrino (ν_R) or an A interaction with a left-handed neutrino (ν_L). Consequently, the combination of the Co^{60} parity-violation experiment, the Fierz interference experiments and the (e-ν) correlation experiment in He^6 mandated the choice S, T for the β interaction (with Fermi's V interaction lost in the shuffle!).

During the hectic year from the Spring of 1956 to the 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[21]. If one assumed the two-component neutrino[22] and the conservation of leptons - which was consistent with all other experiments - this results required the V, A interaction for muon decay. Apparently, UFI was in deep trouble. At the Seventh Rochester Conference in April 1957, T. D. Lee acknowledged (in his introductory talk at the session on weak interactions[23]) that: "Beta decay information tells us that the interaction between (p, n) 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...". The T contribution to the β interaction was still not being questioned because of He^6!

The dilemma became more acute after C. S. Wu's talk at the 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 term between S and T produced disagreement with the experimental result. This discrepancy led Wu to remark[24] that: "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 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[17]), 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[25] had obtained a similar result to that of Wu in measuring the β-γ (circularly polarized) correlation in Co^{58}. The second rumor was that an Illinois group[26] 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[27] 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 ECGS was a graduate student at the time and since REM was making a major 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 specter 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.

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[28] where we presented our arguments for the universal V-A theory and asked for an updating on the β-γ (circulary polarized) correlation program in which he was engaged. Boehm informed us that his latest experiment on Sc^{46} [25] 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 (see §4), 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.

§4. 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 theory. Thus, we were able to discuss not only the electron asymmetry experiment in Co^{60}, the "Fierz interference" experiments, and the electron-neutrino angular correlation experiment in He^6, but also the electron polarization experiment on the Fermi decay of Ga^{66} [29] and the electron-neutrino angular correlation experiment in A^{35} [26], in addition to the β-γ correlation experiment in Sc^{46} [25].

This comprehensive analysis of β processes led us to conclude in our Padua-Venice paper (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 right-handed (or left-handed) both for the Fermi and the G-T interactions [the neutral particle emitted in electron days 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. As regards the electron-neutrino angular correlations, this implies a choice between the A^{35} and He^6 experiments...". [The term "spirality" was used interchangeably with "helicity" in the early days of parity violation.]

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 $\pi_{e2}/\pi_{\mu 2}$ and $K_{e2}/K_{\mu 2}$ 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, Λ°p, 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: $g\,\bar{P}\,\gamma_\mu\,(1+\gamma_5)\,N\,\bar{e}\,\gamma_\mu\,(1+\gamma_5)\,\nu$ + 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 field A, B, C, D, in the form:

$$g\,\bar{A}\,\gamma_\mu\,(1+\gamma_5)\,B\,\bar{C}\,\gamma_\mu\,(1+\gamma_5)\,D = g\,\bar{A}'\gamma_\mu\,B'\,\bar{C}'\,\gamma_\mu\,D' \qquad \text{(I)}$$

where A', B', C', D' are the "two component" fields:

$$A' = (1/\sqrt{2})\,(1+\gamma_5)A,\ \bar{A}' = (1/\sqrt{2})\,\bar{A}\,(1-\gamma_5),\ \text{etc.}$$

Now the "two-component" field $(1/\sqrt{2})\,(1\pm\gamma_5)$ A is an eigenstate of the chirality operator[30] with eigenvalue $\pm$ 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 neutral 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[31] and reprinted in P. K. Kabir's book on "History of Weak Interaction Theory"[32]. 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"[33] 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[34], the polarized neutron experiment has come down to a value consistent with the V-A theory[35] and the helicity of the positron from μ^+ decay has turned out[36] 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[37].

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 had the electron asymmetry from polarized neutrons come down and the polarization of e from μ decay acquired the correct sign and magnitude but also the electron-neutrino angular correlation coefficient in He^6 had become -0.39 ± 0.02[38] and the $\pi_{e2}/\pi_{\mu 2}$ ratio had changed to $0.93 \pm 0.37 \times 10^{-4}$[39]. 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[40]. Experimental support for the universal V-A theory (for charged currents, of course, and with the Cabibbo or, shall we say, Kobayashi-Maskawa modification) has continued to pile up ever since 1959 - with one experimental success following another. Indeed, within the past year, the measurement of the angular distribution of decay leptons from the very massive charge W boson has confirmed the V-A theory up to 80 GeV!

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 - at the midpoint in time between the date when Fermi's β decay theory was formulated and the present - there was 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[41], and, of course, no electroweak model. The past quarter of a century has seen enormous progress in the theory of weak interactions but it is fair to say that the form of UFI that we wrote down in our Padua-Venice paper (Eq. (I) above) recognized for the first time the importance of chiral fields, irrespective of the fermion mass[42]. Chiral fermion fields are not only crucial for the electroweak theory but appear to be essential to progress with grand unification and composite models as well.

§5. CONCLUDING HISTORICAL REMARKS

In a perfect world we could have ended our story at this point but, in the imperfect world which we inhabit, it is incumbent upon us to make some historical comments. The very success of the universal V-A theory has led to claims that other work either anticipated our work or was conceived independently of it. In order to contribute to the historical record on the origin of the universal V-A theory, we shall briefly evaluate these claims as objectively as we can.

In the early 1950's - after UFI was proposed and before parity violation was confirmed in weak interactions - a number of authors attempted to deduce the form of UFI from some type of symmetry principle. The papers that were closest in spirit to the chirality invariance underlying the V-A theory were written by Tiomno and by Stech and Jensen. Tiomno[43] invented the idea of "mass reversal invariance" (the idea that the Dirac equation is invariant under the transformation $\psi\to\gamma_5\psi$, $m\to -m$) and postulated the invariance of the weak current $\bar{\psi}_1 O_\mu \psi_2$ (where O_μ is the S, V, P, A or T operator) under the simultaneous transformation (to conserve parity): $\psi_1 \to \pm\gamma_5\psi_1$, $\psi_2 \to \pm\gamma_5\psi_2$. Tiomno found that if the signs in the γ_5 transformations are the same, O_μ has to be a combination of V and A whereas if the signs are different, the combination has to be S, P, T. This clearcut separation into two classes of Fermi interactions was interesting but still quite different from the idea of applying separate chirality invariance to each Dirac field which led to parity violation and the V-A interaction. Stech and Jensen[44] proposed to consider the limiting case $m\to 0$ for the Dirac particles (since $m \to -m$ has no field-theoretic meaning), applied simultaneous chirality transformation to the Dirac spinors and therefore arrived at the same bifurcation of interactions into (S,P,T) or (V,A). They did go a step further and argued that the four-fermion interaction should be invariant under Fierz rearrangement and ended up with the two combinations: (S+P-T) or V-A. They favored the S+P-T beta interaction for the usual reasons. We were aware of these papers at the time that we wrote ours but we chose not to refer to them because of their limitation to the parity conservation case. In hindsight, we consider these papers as valuable contributions to the chirality invariance approach and wish to correct the record on this score.

Two papers which bear on chirality invariance in relation to parity violation, of which we were not aware when we wrote our paper, are those by Salam and Tiomno. Salam brought his unpublished paper (dated February 1957)[46] 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[46]. In his Nobel address[47], 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[45], 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[48,49] in early July 1957 and published in October. He 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 now come to the Feynman-Gell-Mann and Sakurai papers. 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[50]. 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 this Racine conference that the Feynman-Gell-Mann paper was written during the Summer of 1957 (with the help of amateur radio between Rio de Janiero and Pasadena!) with the result that the paper was dispatched to the *Physical Review* by September 16, precisely the date on which our preprint was circulated. The first public presentation of our work was made during the Padua-Venice Conference September 22-28, 1957 and several months later, the Feynman-Gell-Mann paper was published in the *Physical Review* (January 1, 1958)[51]. Our followup note on the universal V-A theory was published in the March 1, 1958 issue of the Physical Review while the publication of our first paper in the Padua-Venice conference proceedings was unexpectedly delayed[52] to May 1958. 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[53], who said a decade ago: "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."

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. Their "derivation" is no more perspicuous than our "derivation" based on chirality invariance and has been less successful in withstanding the test of time[54]. Feynman and Gell-Mann then proceed to confront 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 a 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[55] on the subject but, in any case, examined the consequences in greater depth. All in all, the Feynman-Gell-Mann paper was a most valuable contribution to the theory of weak interactions.

We conclude with a brief comment concerning Sakurai's work on the universal V-A theory. In the acknowledgement to his paper[56], 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). 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 non-leptonic decays of the strange particles. Sakurai's paper was sent to Nuovo Cimento on October 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 intearction.

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Conf. (1956), p. VIII-27) there is the following exchange: "Feynman brought up a question of [Martin] Block's: Could it be that the θ and τ are different parity states of the same particle which has no definite parity, i.e., that parity is not conserved. That is, does nature have a way of defining right or left-handedness uniquely? Yang stated that he and Lee looked into this matter without arriving at any definite conclusions...".

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28. The meeting with Boehm was attended by Murray Gell-Mann, who actually arranged it, by B. Stech, one of Boehm's collaborators at that time, and by R. A. Bryan, a Rochester graduate student who had driven ECGS to California to see the sights. One of us (REM) had encountered Gell-Mann in late June at the Rand Corporation in Santa Monica, California (where we both happened to be consultants) and, after a briefing concerning V-A the the Co^{58} problem, Gell-Mann graciously consented to set up a luncheon meeting with his Cal Tech colleague, Felix Boehm.
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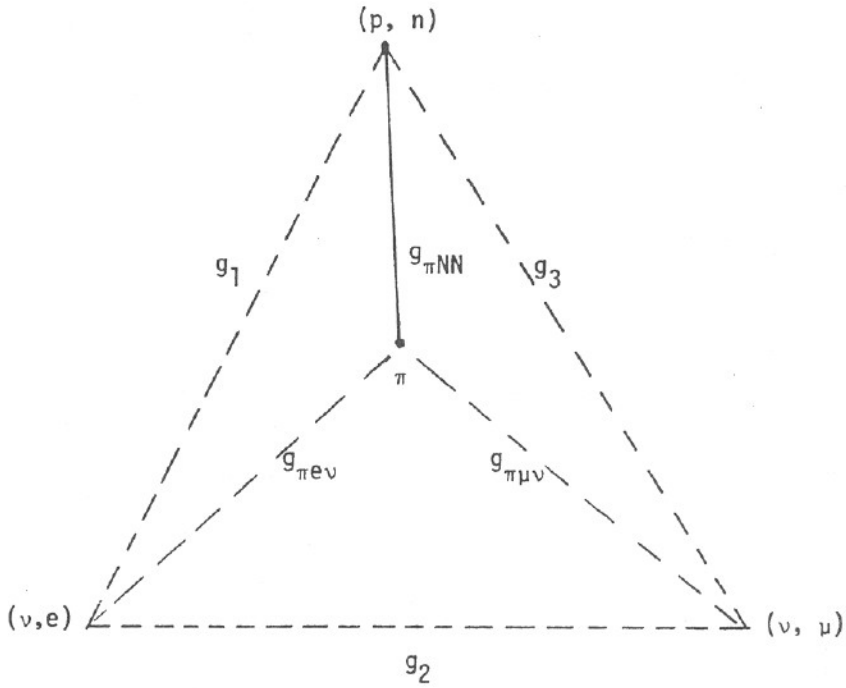

Fig. 1. Diagrammatic sketch showing the weak interactions (dotted lines) and the strong interaction (solid line).

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DISCOVERY OF WEAK NEUTRAL CURRENTS: THE WEAK INTERACTION BEFORE AND AFTER

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