Neutrino, parity violaton, V-A: a historical survey

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Abstract

This is a concise story of the rise of the four fermion theory of the universal weak interaction and its experimental confirmation, with a special emphasis on the problems related to parity violation.
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Foreword

This article emerged initially as a part of a bigger project (joint with Ivan Todorov, still under construction) on the foundations of the Standard Model of particle physics and the algebraic structures behind its symmetries, based in turn on a lecture course presented by Ivan Todorov at the Physics Department of the University of Sofia in the fall of 2015.

The first controversies found in beta decay properties were successfully resolved in the early 30-ies by Pauli and Fermi. The bold prediction of Lee and Yang from 1956 that parity might not be conserved in weak interactions has been confirmed in the beginning of 1957 by the teams of Mme Wu and Lederman and nailed by the end of the same year by Goldhaber, Grodzins and Sunyar who showed in a fine experiment that the neutrino was indeed left-handed. The present survey covers the development in this field till 1958 when the universal chiral invariant (V-A) four fermion interaction proposed by Sudarshan and Marshak, Feynman and Gell-Mann was widely accepted.

Certainly, these glorious days for particle physics have attracted attention from many researchers and historians. The author has learned a lot, in particular, from the beautiful narrative of Jagdish Mehra [Me] as well from [Fr79, M, Fo, J00, L09], among others. The written memories of some of the main participants in these events like Yang (e.g. in [Y82]), Feynman [FL], Sudarshan and Marshak [SM3, SM4] and also of S. Weinberg [W09] and S. Glashow [G09] provide both first hand expert evidence and evaluation of the discoveries from the position of the elapsed time.

For everyone honestly interested in understanding how this precious cornerstone of the present day Standard Model was put in its place, finding and reading the sources is a thrilling experience. It is astonishing, for example, to learn that parity violation could have been discovered already in 1928-1930 by Cox and Chase, see Remark 2 below, or to follow Feynman on his way toward V-A, and it is very impressive to see how theoreticians and experimenters from particle and nuclear physics collaborated to reach the solutions of some of the most difficult puzzles provided by nature.
1 The beta decay and the neutrino

Soon after radioactivity was discovered by Antoine Henri Becquerel in 1896 and studied further by Pierre and Marie Curie, Ernest Rutherford, Becquerel and Paul Villard identified the three types of observed emissions, $\alpha, \beta$ and $\gamma$, as ions of helium, J.J. Thompson’s electrons and high energy electromagnetic radiation, respectively. The nuclear beta decay, in particular, is a manifestation of the weak interactions whose understanding required several unexpected, quite radical changes in our assumptions about the basic laws of nature.

In 1913 Niels Bohr suggested correctly that it was the nucleus discovered by E. Rutherford in 1911 that was ”the seat of the expulsion of high speed beta particles” (rather than the electronic distribution round it)\(^1\). It was found that the kinetic energy of the emitted electrons varied from almost zero to ultra relativistic levels and moreover (James Chadwick 1914), had a continuous spectrum\(^2\). In 1922 Lise Meitner noticed that, if the energy levels of an atomic nucleus are quantized, such a continuous distribution would pose a real puzzle\(^3\). After the discovery of the spin, another confusion arose from examples of beta decays in which initial and final nuclei both had integer angular momentum, thus contradicting the statistics rules provided that the electron, of spin $1/2$, was the only emitted particle detected in experiments. To resolve all this mess, ideas as reckless as that of energy non-conservation were proposed (by N. Bohr \(^{[B30]}\), and later by W. Heisenberg \(^{[H32]}\)). One should have in mind that by 1930, the only known ”elementary particles” were the electron and the proton (the nucleus of hydrogen, E. Rutherford 1920), and that Dirac’s theory had not been yet confirmed and widely accepted.

A possible solution of the puzzle, at once explaining the continuous energy spectrum and correcting the energy balance and the seemingly wrong

\(^{1}\)N. Bohr, On the constitution of atoms and molecules, Part II. Systems Containing Only a Single Nucleus, *Phil. Mag.* 26 (1913) 476-502.

\(^{2}\)J. Chadwick, Intensitätsverteilung im magnetischen Spektrum von $\beta$-Strahlen von Radium B+C, *Verhandl. Dtsch. Phys. Ges.* 16 (1914) 383-391.

\(^{3}\)L. Meitner, Über die Entstehung der $\beta$-Strahl-Spektren radioaktiver Substanzen, *Z. Physik*, 9:1 (1922) 131-144.

\(^{4}\)Note that the BKS theory of radiation, see N. Bohr, H.A. Kramers, J.C. Slater, The quantum theory of radiation, *Phil. Mag.* 47 (1924) 785-802 (Über die Quantentheorie der Strahlung, *Z. Physik*, 24 (1924) 69-87, in German) reduced conservation of energy to a statistical law, but these were still the times of the ”old quantum theory”.

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statistics, was submitted in the famous one-page "Open letter to the group of radioactive people", sent by Wolfgang Pauli to the participants at the meeting in Tübingen on 4 December 1930. In it Pauli proposed that "in the nuclei there could exist electrically neutral particles, which I will call neutrons, that have spin 1/2 and obey the exclusion principle and that further differ from light quanta in that they do not travel with the velocity of light." [P30]. Pauli thus assumed that in beta decay, in addition to the electron, this yet unknown, light neutral particle of half integer spin was emitted so that the sum of energies of this particle and the electron was constant (equal to the upper limit of the $\beta$ energy spectrum). Experimental evidence required that the new particle should have a very large ability to get through matter. In June 1931 Pauli announced his idea at the Pasadena American Physical Society meeting where it was met with scepticism, and discussed it later in October at the Rome Nuclear Physics conference with Enrico Fermi who, by contrast, was immediately attracted by it.

In December that same year Carl Anderson discovered the positron, and in February 1932 J. Chadwick announced the possible existence of "particles of mass 1 and charge 0, or neutrons" [Ch32]. Neutrons were actually observed (but erroneously interpreted as high energy $\gamma$ quanta) earlier, when a radiation emitted from beryllium bombarded by $\alpha$-particles of polonium was registered by Walther Bothe and Herbert Becker in Berlin and then by Irène Curie and Frédéric Joliot in Paris. Similar studies were carried out simultaneously at the Institute of Radium Studies in Vienna by a group including, in particular, the Austrian Marietta Blau and Elisaveta (Elisabeth) Karamichailova, born in 1897 in Vienna in the family of the Bulgarian Ivan Mikhaylov and the English Mary Slade. For a recent account of the contribution of the young Italian genius Ettore Majorana to both the theory and the interpretation of these experiments, see [Re] and references therein.

In his contribution to the 7th Solvay Conference in Brussels (October 1933) Pauli already used the name "neutrino" to distinguish the light particle

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5W. Bothe, H. Becker, Künstliche Erregungen von Kern $\gamma$-Strahlen, Z. Phys. 66 (1930) 289-306.

6I. Curie, F. Joliot, Émission de protons de grande vitesse par les substances hydrogénées sous l’influence des rayons $\alpha$ très pénétrants, C. R. Acad. Sci. Paris 194 (1932) 273-275.

7See e.g. M. Rentetzi, Gender, Politics, and Radioactivity Research in Vienna, 1910-1938, PhD Thesis, Virginia Tech, Blacksburg (2003), available at https://vtechworks.lib.vt.edu/handle/10919/27084.
from the heavy neutron. The decisive step to a theory of the beta decay has been taken soon after that by Enrico Fermi himself [F33] who proposed his famous four fermion interaction Hamiltonian

$$
\frac{G_F}{\sqrt{2}} (\bar{p}(x)\gamma_\mu n(x)) (\bar{e}(x)\gamma^\mu \nu(x)) + h.c. , \tag{1.1}
$$

$p, n, e$ and $\nu$ standing for the proton, neutron, electron and neutrino, respectively. The structure of (1.1) imitated the newly discovered second quantization approach to the theory of photon radiation: a vector coupling involving a (charged) current of heavy particles, analogous to the EM one (with no derivatives of any of the fields), creating an electron-neutrino pair (instead of a photon) in such a way that charge conservation is guaranteed. In contrast to Pauli who assumed that the light particles are also residing in the nucleus, Fermi followed Heisenberg [H32] in admitting that all nuclei only consist of protons and neutrons (considered as two different quantum states of a heavy particle), and further supposed that an electron and a neutrino are created in every transition from a neutron into a proton – or destroyed, in the opposite process.

Remark 1. The story of the name ”neutrino” The name ”neutrino” with its Italian flavor is usually attributed to E. Fermi. In fact it has been pronounced for the first time by Edoardo Amaldi (1908 – 1989) see the remark under [277] in the list of references of [A84]: ”The name ‘neutrino’ (a funny and grammatically incorrect contraction of ‘little neutron’ in Italian: neutronino) entered the international terminology through Fermi, who started to use it sometime between the conference in Paris in July 1932 and the Solvay conference in October 1933 where Pauli used it. The word came out in a humorous conversation at the Istituto di Via Panisperna. Fermi, Amaldi and a few others were present and Fermi was explaining Pauli’s hypothesis about his ‘light neutron’. For distinguishing this particle from the Chadwick neutron Amaldi jokingly used this funny name, – says Occhialini, who recalls of having shortly later told around this little story in Cambridge.”

It is worth mentioning that in [F33] Fermi also proposed the direct method of measuring the neutrino mass by examining the energy spectrum of electrons emitted in $\beta$ decay near its kinematic end point which was subsequently

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8The author thanks Serguey Petcov for providing evidence on this point.
used in a number of experiments.\footnote{The last experiment of this type, the Karlsruhe Tritium Neutrino Experiment KA-TRIN \cite{K2018} (with the unprecedented sensitivity of 0.2 eV) has been inaugurated on June 11, 2018.}

The vector interaction implies that the nuclear angular momentum doesn’t change and hence, the spins of the emitted leptons are antiparallel. Introducing an axial vector interaction term, G. Gamow and E. Teller \cite{GT36} incorporated also observed decays with $\Delta J = 1$ change in the total angular momentum of the nucleus. In this dual form the model was able to serve in the next years as the theory of weak interactions.

Meanwhile, in 1935 Hideki Yukawa \cite{Y35} predicted the existence, and also the mass, of the ”meson” carrying the force needed to hold the particles forming the atomic nuclei together. In the same next year 1936 when Carl Anderson received the Nobel prize for the positron, during his studies of cosmic rays by cloud chambers he discovered, together with Seth Neddermeyer, a new particle of nearly the ”proper” meson mass. This gave rise to a great confusion since it was actually the muon $\mu$, a heavier analog of the electron. The correct Yukawa particle, the pion $\pi$, was identified after World War II, in 1947, by the Bristol group led by C.F. Powell in traces of cosmic rays left on photographic emulsions exposed for several months on mountain tops in the Alps and in the Andes. Yukawa and Powell received the Nobel Prizes in Physics in 1949 and 1950, respectively.

By the end of the 1940’s measurements of the energy spectrum of electrons produced in muon decay favoured the assumption (suggested by B. Pontecorvo\footnote{B. Pontecorvo was the first to understand that the muon was a ”heavy electron”, see \cite{P27} where he also formulated the idea of $\mu - e$ universality of the Fermi interaction (cf. Section 4 of \cite{P94}).}, O. Klein, G. Puppi, L. Michel) that the latter, like the beta decay, is actually a three-particle process. Moreover, the $\mu$ lifetime was found to be ”consistent with the hypothesis that $\mu$-decay and $\beta$-decay are separate instances of the same phenomenon, with the same coupling constant ” (see \cite{TW49} and references therein). These developments brought to life the notion of ”universal Fermi interaction” (UFI).

In 1949 T.D. Lee, M. Rosenbluth and C.N. Yang \cite{LRY49} noted that, in order to explain why three independent experiments\footnote{The mentioned three independent experiments were the $\beta$-decays of nucleons and muons, and the capture of $\mu^-$ by (a proton in) nuclei.} lead to coupling constants in Fermi type interactions of the same order of magnitude, it would
be reasonable to assume that the latter are "transmitted through an intermediate field with respect to which all particles have the same 'charge'. The 'quanta' of such a field would have a very short lifetime and would have escaped detection." (their idea is known under the name of "Intermediate Vector Boson", or IVB hypothesis). In such a case the original Fermi form of the interaction Lagrangian would be obtained in the limit of infinite mass of the (charged) intermediate field $W_{\mu}$. (The actual lifetime of the weak bosons $W^{\pm}$ and $Z$ discovered at CERN in 1983 is $\sim 3.10^{-25}$ s. The mass of $W^{\pm}$ is $\sim 80$ GeV, and that of $Z \sim 91$ GeV.)

In 1947 two new, heavier mesons produced by cosmic rays in a cloud chamber have been observed in Manchester by G.D. Rochester and C.C. Butler. Both having nearly half of the proton mass, one of these decayed into two, and the other – into three pions. The number of newly discovered particles increased quickly in the following years. The observed selection rules required additional quantum numbers. For example, the notion of *strangeness* $S$ was introduced to explain the enormous disproportion (of 13-15 orders in time) between the fast production (in pairs, in pion-nucleon collisions) and the slow decay of some of them. It was assumed that $S$ is conserved in strong and electromagnetic interactions but could be violated in the weak decays of "strange" particles. Another, quite unexpected peculiarity of the weak interactions was however almost impossible to grasp.

2 The notion of parity and the $\theta - \tau$ puzzle

Despite the increasing precision of measurements, it turned out that two species of mesons share the same masses and lifetimes. The problem dubbed in the middle of the fifties ”the $\theta - \tau$ puzzle” arose from the intrinsic parity $P$ mismatch in decays of the type

$$\theta^+ \rightarrow \pi^+ + \pi^0, \quad \tau^+ \rightarrow \pi^+ + \pi^+ + \pi^-,$$

respectively. Anticipating the breakthrough that followed, we may reveal that eventually $\theta^+$ and $\tau^+$ were identified with each other and called (in this case, positively charged) $K$-mesons, or kaons.

\footnote{More precisely, in the IVB interaction Hamiltonian the point Fermi current-current interaction (1.1) is replaced by current-IVB couplings with a common *dimensionless* coupling constant $g$ obeying $\frac{g^2}{M_W^2} = \frac{G_F}{\sqrt{2}}$ where $M_W$ is the IVB mass.}

\footnote{Actually, of the same type as those observed by Rochester and Butler in 1947!}
Generally speaking, (space) parity could be described as the relation between an object and its mirror reflection. (This is seemingly different from the definition based on reflection in all three space coordinates,

\[ I_s (x^0, x) = (x^0, -x) , \]

but reduces to it by rotating the mirror at angle \( \pi \).) Developments in optics, crystallography, and chemistry led by the beginning of the 19th century to the discovery that certain crystals or liquids were optically active, rotating the polarization plane of linearly polarized light in a specific way, clockwise (in (+)-isomers, in modern notation) or counter-clockwise (in (-)-isomers). In 1848 Louis Pasteur sorted manually two different, non-superimposable mirror-image crystal types of the sodium ammonium salt of tartaric acid produced by chemical synthesis and found that in solution their optical rotations were equal in magnitude but opposite in direction. (This fact came as a surprise since natural tartaric acid extracted from wine lees only contained the (+)-isomer.) Pasteur correctly attributed these macroscopic properties to the existence of two mirror-image molecule types of tartaric acid, using the term "dissymmetry" to express the fact that they could not be transformed one into another in a continuous way. The present day notion of chirality, first used by Lord Kelvin in 1893 (see [Th1894]), originates from the Greek word χειρ for "hand"; indeed, left or right handedness is a common manifestation of this property.

The first application of the notion of parity to quantum systems was made in 1924 by the German-born American physicist Otto Laporte, then doctoral student of the great Arnold Sommerfeld at LMU Munich [L24]. His studies of iron spectra led to the discovery that atomic states fell into two separate groups so that, after a single photon emission or absorption, the initial and the final states always belonged to different groups.

Anticipating later developments, this finding can be interpreted in the following way. As the quantum mechanical reflection operator \( P \) generates a multiplicative \( \mathbb{Z}_2 \), it has eigenvalues \( \pm 1 \). Grouping the atomic orbitals into subsets of even \( (P = 1) \) and odd \( (P = -1) \) parity and assigning negative parity to the photon, Laporte’s rule is equivalent to parity conservation in single photon atomic transitions. A complete theoretical understanding has been obtained soon after that by E.P. Wigner [W27].

\[ ^{14}\text{M. Arago (1811), J.-B. Biot (1812-1818); see J.F.W. Herschel’s [H1820].} \]
The following excerpt from C.N. Yang’s 1957 Nobel lecture sheds light on the next about 30 years: "In 1927 E. Wigner took the critical and profound step to prove that the empirical rule of Laporte is a consequence of the reflection invariance, or right-left symmetry, of the electromagnetic forces in the atom. This fundamental idea was rapidly absorbed into the language of physics. Since right-left symmetry was unquestioned also in other interactions, the idea was further taken over into new domains as the subject matter of physics extended into nuclear reactions, β-decay, meson interactions, and strange-particle physics. One became accustomed to the idea of nuclear parities as well as atomic parities, and one discusses and measures the intrinsic parities of the mesons. Throughout these developments the concept of parity and the law of parity conservation proved to be extremely fruitful, and the success had in turn been taken as a support for the validity of right-left symmetry."

This common belief also leaned on the observation (made by J. Schwinger, G. Lüders, W. Pauli, ...) that the combined CPT symmetry, i.e. the conservation of the product of $P$ with the operators of charge conjugation (particle-antiparticle exchange) $C$ and time reversal $T$, follows from the basic principles of QFT. (In Wightman’s axiomatic setting $CPT$ conservation is a theorem following from locality, Lorentz invariance and energy positivity, see [SW, BLT]; its rigorous proof was first given by R. Jost in 1957.)

In 1953, R. Dalitz and E. Fabri noticed that one can obtain information about the spins and the parities of the $\theta$ and $\tau$ particles (2.2), as the intrinsic parity of the pions has been already determined as odd, i.e. $-1$. Indeed, if one neglects the relative motion of the $\pi$-mesons, parity conservation would imply that the parity of $\theta$ is $(-1)^2 = 1$ and that of $\tau$, $(-1)^3 = -1$.

To quote C.N. Yang again, "By the spring of 1956 the accumulated exper-

\footnote{As put by A. Franklin [Fr79] (citing H. Frauenfelder and E.M. Henley’s ”Nuclear and Particle Physics” (1975)), the concept of parity conservation has become a sacred cow – in a sense, literally: "A very amusing early reference to this occurs in a paper by P. Jordan and R. de L. Kronig, [Movements of the lower jaw of cattle during mastication.] Nature \textbf{120} (1927) 807. In this paper Jordan and Kronig note that the chewing motion of cows is not straight up and down, but is rather either a left-circular or a right-circular motion. They report on a survey of cows in Sjælland, Denmark, and observe that 55\% are right-circular and 45\% left-circular, a ratio they regard as consistent with unity." The original conclusion of Jordan and Kronig was actually the following: "As one sees, the ratio of the two kinds is approximately unity. The number of observations was, however, scarcely sufficient to make sure if the deviation from unity is real. Naturally these determinations allow no generalisation with regard to cows of different nationality."}
imental data seemed to unambiguously indicate, along the lines of reasoning discussed above, that $\theta$ and $\tau$ do not have the same parity, and consequently are not the same particle. ... the inference would certainly have been regarded as conclusive, and in fact more well-founded than many inferences in physics, had it not been for the anomaly of mass and lifetime degeneracies.” (The masses were found to be equal within a fraction of a percent.) So some thirty years after the missing neutrino energy, the theory of weak interactions met another challenge of a similar magnitude in the $\theta - \tau$ puzzle.

3 Parity violation

As a way out T.D. Lee and C.N. Yang [LY2] suggested that strange particles – like $\theta$ and $\tau$, in particular – appear in doublets of opposite parity. A few days after their work has been published, Yang presented it at the Sixth Annual Conference on High Energy Nuclear Physics held at the University of Rochester on April 3-7, 1956. In the discussion that followed Richard Feynman asked the bold question what would be the consequences if the parity rule was wrong. (Feynman actually posed it on behalf of Martin Block, a fellow experimentalist and his roommate at the conference, who was afraid that the audience wouldn’t listen to him.) Although Yang answered that he and Lee had considered the idea without reaching any conclusion, they both apparently felt "the beginnings of doubt” [M].

Most of the experts (with the important exception of E. Wigner, the founder of the quantum reflection symmetry notion [17]) met the possibility of parity violation with reservation, see e.g. the recollections in the Discussion chapter at the end of [Y82]. Feynman himself thought of it as possible but unlikely and even proposed later a 50:1 bet against it.

T.D. Lee and C.N. Yang however decided to reconsider the problem performing a thorough examination of the experimental evidence. Their analysis in [LY] (the paper was received by the editors on June 22 and appeared on October 1, 1956) showed that $P$-invariance of strong and electromagnetic

\[16\] If correct, such an idea (named "parity doubling") would provide a solution of the equal mass problem. Unfortunately, it neither worked for other (pairs of) particles nor did it explain the equal lifetimes.

\[17\] The possible violation of discrete symmetries was actually admitted by Wigner before, cf. footnote 9 in the famous paper [WWW52] where the notion of superselection sectors was introduced.
interactions was confirmed to a high degree of precision but experiments involving weak interactions “had actually no bearing on the question of parity conservation”. The argument of Lee and Yang was simple: to verify $P$, one needed a pseudoscalar (like the projection of spin along a momentum, or the mixed product of three momenta) formed out of the measured quantities, and no such information could be extracted from the data available to that moment (see however Remark 2 below). To fill this gap, Lee and Yang proposed feasible experimental tests of parity conservation in $\beta$ decays and, separately, in meson and hyperon decays.

In particular, they argued that a simple possibility to detect $P$-violation would be the asymmetry $\alpha \neq 0$ in the angular distribution

$$I(\theta) d\theta \sim (1 + \alpha \cos \theta) \sin \theta d\theta$$

(3.4)

of the $\beta$ radiation emitted by a polarized nucleus, say $\text{Co}^{60}$. (Here $\theta$ is the angle between the orientation of the nucleus and the electron momentum.) Obviously, finding that $I(\theta) \neq I(\pi - \theta)$ (i.e., $\alpha \neq 0$) would constitute “an unequivocal proof that parity is not conserved in $\beta$ decay”.

Noting that without the parity invariance constraint the most general form of the $\beta$ decay interaction would involve 10 arbitrary complex constants,

$$\sum_{i=S,V,T,A,P} (\bar{p}(x) O_i n(x)) \bar{e}(x) O^i (C_i + C'_i \gamma_5) \nu(x) + \text{h.c.},$$

$$O_S = 1, \quad O_V = \gamma_\mu, \quad O_T = \sigma_{\mu\nu}, \quad O_A = \gamma_\mu \gamma_5, \quad O_P = \gamma_5,$$

(3.5)

Lee and Yang expressed the anisotropy parameter $\alpha$ (3.4) in terms of these.

T.D. Lee discussed the cobalt experiment\textsuperscript{18} with Mme C.S. Wu from Columbia University, a renowned expert in $\beta$ decay, even before their paper with Yang was submitted to Physical Review in June 1956 \textsuperscript{19}. Overcoming a series of problems with cryogenics, Wu and her team from the National Bureau of Standards at Washington obtained the first result confirming the anisotropy (with $\alpha \sim -0.4$, i.e. more electrons in the direction opposite to the spin of the nucleus) on December 27, 1956 \textsuperscript{19}. When the news pointing at parity violation reached the next day Columbia, Leon Lederman who worked with the cyclotron there decided to perform, together his graduate

\textsuperscript{18}The $\beta$ decay of $\text{Co}^{60}$ (into an excited state of $\text{Ni}^{60}$) is of Gamow-Teller type, i.e. with a spin difference of 1 \textsuperscript{Wu57}.

\textsuperscript{19}A detailed description of the experiment is contained e.g. in the beautiful exposition by P. Forman \textsuperscript{Fo}.
students M. Weinrich and R. Garwin, an independent test involving pion
and muon decays (another one of those proposed by Lee and Yang). In the
first half of January 1957 the preliminary results of Wu were confirmed, and
those of Lederman also showed a distinct parity violation \( \alpha \sim -\frac{1}{3} \). The
articles [Wu57] and [GLW57] (both received on January 15, 1957) appeared
in Physical Review on February 15.

The clear experimental evidence of parity non-conservation in weak de-
cays shocked the physical community. T.D. Lee and C.N. Yang won the 1957
Nobel prize; this had sad effect on their friendship (see [G99]). Mme Wu was
honored much later: in 1978 she became the first winner of the Wolf prize
in Physics. L. Lederman shared the Nobel Prize in 1988 with M. Schwartz
and J. Steinberger "for the neutrino beam method and the demonstration
of the doublet structure of the leptons through the discovery of the muon
neutrino”.

Remark 2. The Cox (1928) and Chase (1930) experiments As it
turned out, Lee and Yang’s claim that no experiment prior to 1956 had pro-
vided a test of parity conservation in weak interactions was not correct. In
1928, a team led by R.T. Cox from the New York University carried out
an investigation of double scattering of beta rays [Cox28], and Cox’es stu-
dent C.T. Chase continued the experiments with much improved and more
definitive techniques [Chase30]. Their results showing clear evidence for the
negative helicity of the beta rays (implying parity violation in weak interac-
tions) are commented in detail by Lee Grodzins [Gr59]. The very interesting
comments on this subject of E. Wigner in [Y82] also confirm their prior-
ity; see as well [Fr79]. Most probably, Lee and Yang have overlooked these
(too) early papers due to the practical impossibility for their authors to use
the appropriate ”keywords”: e.g. the purpose announced in R.T. Cox et al.
[Cox28] was that ”... it might be of interest to carry out with a beam of
electrons experiments analogous to optical experiments in polarization.”.

20 Analogous to Lederman’s results were announced also by J.I. Friedman and V.L.
Telegdi [FT57]. Another experiment, similar to Wu’s but with positrons obtained from
the \( \beta^+ \) decay of polarized Co\(^{58} \), carried out in the Kamerlingh Onnes Laboratory in Leiden,
Netherlands showed that ”positon emission occurs preferably in the direction of the nuclear
spin” [P57].
4 The two-component neutrino

Alongside with experimentalists, Lee and Yang’s paper \[LY\] of course inspired theorists to look for models that could incorporate the breaking of parity. Abdus Salam was the first to notice that parity violation may be related to the vanishing of the neutrino mass (a common belief at that time). His argument started as follows: the Lagrangian of the free massless neutrino field $\psi^{(\nu)} (\equiv \nu(x))$, given by (A.7) for $m^{(\nu)} = 0$, is chiral invariant, i.e. invariant for the substitution

$$
\psi^{(\nu)} \rightarrow \gamma_5 \psi^{(\nu)}, \quad \bar{\psi}^{(\nu)} \rightarrow -\bar{\psi}^{(\nu)} \gamma_5, \quad \bar{\psi}^{(\nu)} \psi^{(\nu)} \rightarrow -\bar{\psi}^{(\nu)} \psi^{(\nu)}. \tag{4.6}
$$

One way to secure that no mass term would be produced in neutrino interactions is to require invariance of the total Lagrangian for (4.6) while the other fields remain unchanged \[Salam57\]. Similar arguments, exploited further by L.D. Landau \[L57\] (who predicted exact CP-invariance) and by T.D. Lee and C.N. Yang \[LY3\] (who already had information about the progress of C.S. Wu’s experiment), revived H. Weyl’s 2-component theory of 1929 \[W29\] which we will briefly recall.

The Lagrangian (A.7) of a free massless Dirac field splits into chiral parts,

$$
\mathcal{L}_{m=0}^{\gamma} = - \psi^* \beta \partial \psi = i \left[ \psi_L^* (\partial_0 + \sigma \partial) \psi_L + \psi_R^* (\partial_0 - \sigma \partial) \psi_R \right], \tag{4.7}
$$

(cf. (A.6), (A.12)) implying the Weyl equations for the two-component fields:

$$
(\partial_0 + \sigma \partial) \psi_L = 0 = (\partial_0 - \sigma \partial) \psi_R. \tag{4.8}
$$

In contrast with the massive case (A.11), the positive and negative frequency Fourier modes (for each chirality) obey identical homogeneous equations,

$$
(|p| + \sigma p) u^+_L(p) = 0, \quad (|p| - \sigma p) u^+_R(p) = 0. \tag{4.9}
$$

The matrices $|p| \pm \sigma p$ being degenerate, Eqs.(4.9) only have one dimensional spaces of solutions, implying negative/positive helicity\[21\] for the corresponding left/right chiral one-particle states of definite momentum, respectively:

$$
J = 1/2 \sigma. \tag{4.10}
$$

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\[21\]Helicity is the appropriate invariant counterpart of spin in the massless case, see e.g. \[BLOT\]. By analogy with the screw rule for circularly polarized electromagnetic waves, negative or positive helicity is equivalent to “left or right handedness”, respectively.
In a sense, chiral invariance implies maximal parity violation, as the space inversion transformation of Dirac fields

$$U(I_s) \psi(x) U(I_s)^* = \gamma^0 \psi(I_s x), \quad U(I_s) \tilde{\psi}(x) U(I_s)^* = \tilde{\psi}(I_s x) \gamma_0$$

($\gamma^0 \gamma^0 = \mathbb{1}$) exchanges left and right handed Weyl components:

$$U(I_s) \psi_L(x) U(I_s)^* = -i \psi_R(I_s x), \quad U(I_s) \psi_R(x) U(I_s)^* = -i \psi_L(I_s x).$$

The same is valid for the charge conjugation (cf. (A.12)),

$$U(C) \psi_L(x) U(C)^* = \psi_R^*(x) c^{-1}, \quad U(C) \psi_R(x) U(C)^* = \psi_L^*(x) c, \quad c = i \sigma_2$$

which implies, in particular, that the two component (left-handed) neutrino and the corresponding (right-handed) antineutrino are different particles.

The assumption of chiral invariance (4.6) (with respect to transformations of the massless neutrino field only) has important consequences. In their "second" paper Lee and Yang pointed out that it reduces the number of arbitrary constants in the general parity non-conserving Hamiltonian (3.5) to five, since

$$\tilde{e}(x) O^i (C_i + C_i' \gamma_5) \frac{1}{2} (1 + \gamma_5) \nu(x) = (C_i + C_i') \tilde{e}(x) O^i \nu_L(x).$$

They also proposed several new tests of the two component neutrino theory as e.g. the measurement of momentum and polarization of electrons emitted in the beta decay of an unoriented nuclei which provides another observable pseudoscalar. Such experiments were promptly executed\(^{22}\) and the results agreed with these of Wu et al.

The overall success of the two component neutrino theory, based on the assumption of an "accidental" (not following from any gauge principle) vanishing of the neutrino mass, was limited. It could not explain parity violating effects in weak interactions not involving neutrino which contradicted the idea of universality – and in particular, it did not help to resolve the $\theta - \tau$ puzzle.

**Remark 3. The reaction of Pauli**

In 1933 Wolfgang Pauli, the inventor of the neutrino, had made the following comment on the two component Weyl equations (4.8): "Indessen sind diese Wellengleichungen, wie ja aus ihrer Herleitung hervorgeht, nicht

\(^{22}\)See for example [F57].
invariant gegenüber Spiegelungen (Vertauschung von links und rechts) und infolgedessen sind sie auf die physikalische Wirklichkeit nicht anwendbar.”

[However, as the derivation shows, these wave equations are not invariant under reflections (interchanging left and right) and thus are not applicable to physical reality.]

An excerpt from [Fr79] reads: "Even as late as January 17, 1957, Pauli still had not given up his belief. In a letter to Victor Weisskopf he wrote, ‘I do not believe that the Lord is a weak left-hander, and I am ready to bet a very large sum that the experiments will give symmetric results.’ In a letter to C. S. Wu on January 19, 1957, after hearing word of the results of her experiment he noted, ‘I did not believe in it (parity non-conservation) when I read the paper of Lee and Yang.’ ” And further: "In another letter to Weisskopf he wrote: 'Now, after the first shock is over, I begin to collect myself. Yes, it was very dramatic. On Monday, the twenty-first, at 8 p.m. I was to give a lecture on the neutrino theory. At 5 p.m. I received three experimental papers (those of Wu, Lederman, and Telegdi)... I am shocked not so much by the fact that the Lord prefers the left hand as by the fact that He still appears to be left-right symmetric when He expresses Himself strongly.’”

A few months before that (and two and a half years before Pauli’s death on 15 December 1958) the great man’s prediction from 1930 of the mere existence of the (anti)neutrino had been finally confirmed by Frederick Reines and Clyde L. Cowan, Jr. [CR56]. In their experiment based on inverse beta decay,

\[ \bar{\nu}_e + p \rightarrow e^+ + n \quad (4.15) \]

carried near the 700 MW Savannah River nuclear plant, Cowan and Reines detected both the positron and the neutron which produced \(\gamma\)-quanta of specific energies after annihilation and delayed capture in cadmium, respectively. On 14 June 1956 they sent Pauli the following telegram from Los Alamos: "We are happy to inform you that we have definitely detected neutrinos from fission fragments by observing inverse beta decay of protons. Observed cross-section agrees well with expected six times ten to minus forty-four square centimeters.\[24\] Frederick Reines, Clyde Cowan.”

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23 Page 226 in W. Pauli, Die allgemeinen Prinzipien der Wellenmechanik [P33], translated as in [Fr79], p. 215.

24 The order \(10^{-44}\) cm\(^{2}\) of the cross-section was estimated correctly by H. Bethe and R. Peierls already in 1934, in the first paper on the subject [BP34]. The result was commented pessimistically by the authors who concluded that "there is no practically possible way of observing the neutrino".
"Thanks for message. Everything comes to him who knows how to wait.\textsuperscript{[Enz]},
answered on the next day Pauli [Enz].

A year and a half later M. Goldhaber, L. Grodzins and A.W. Sunyar [GGS] confirmed the left-handedness of the (electron) neutrino in an ingenious experiment using electron capture by the nucleus Eu\textsuperscript{152}:

\[ \text{Eu}^{152m} + e^- \rightarrow \text{Sm}^{152*} + \nu_e \rightarrow \text{Sm}^{152} + \gamma + \nu_e . \] (4.16)

5 The V-A hypothesis

By the time of the Seventh Rochester Conference (April 15-19, 1957) the fast growing amount of experimental data from weak decays (including the $\beta$-decay and also the decays of $\mu, \pi$ and strange particles) started to raise strong concern about the validity of the Universal Fermi Interaction (UFI) hypothesis. Various decays seemed to favor different combinations of the Lorentz invariants in (3.5) so that, to save UFI, one had to refute some experimental evidence. It was widely believed, in particular, that the $\beta$-decay coupling was S (for Fermi type transitions in nuclei) and T (for Gamow-Teller, i.e. spin changing, transitions) and the $\mu$-decay coupling, V and A.

The "V-A hypothesis", i.e. the assumption that in fact only the left components $\psi_L$ of all four fermion fields (and not only those of the neutrino -- and implicitly, of the electron, what concerns the $\beta$-decay) take part in the weak interaction, was made by E.C.G. Sudarshan and R.E. Marshak [SM1, SM2] and independently, by R. Feynman and M. Gell-Mann [FG-M]. As the Dirac conjugate of $\Pi_L\psi$ is $\bar{\psi}\Pi_R$ where $\Pi_L = \frac{1}{2}(1 \pm \gamma_5)$, and due to the equalities

\begin{align*}
\left[\gamma_5, O_i\right] &= 0 \quad \Rightarrow \quad \Pi_R O_i \Pi_L = O_i \Pi_R \Pi_L = 0 \quad \text{for} \quad i = S, T, P , \\
\left[\gamma_5, \gamma_\mu\right]_+ &= 0 \quad \Rightarrow \quad \Pi_R O_i \Pi_L = O_i \Pi_L^2 = O_i \Pi_L \quad \text{for} \quad i = V, A , \\
\gamma_\mu \Pi_L \otimes \gamma^\mu (C_V + C_V'\gamma_5) \Pi_L + \gamma_\mu \gamma_5 \Pi_L \otimes \gamma^\mu \gamma_5 (C_A + C_A'\gamma_5) \Pi_L = \\
&= (C_V + C_V' + C_A + C_A') \gamma_\mu \Pi_L \otimes \gamma^\mu \Pi_L , \quad \text{(5.17)}
\end{align*}

see (3.5), the V-A hypothesis amounts to setting

\[ C_i = C_i' = 0 , \quad i = S, T, P , \quad C_V = C_V' = C_A = C_A' \equiv \frac{G}{4\sqrt{2}} . \] (5.18)
The number of the coupling constants is thus reduced to one and the UFI Hamiltonian takes the following simple and elegant form:

$$\frac{G}{\sqrt{2}}(\bar{\psi}_4(x) \gamma_\mu \Pi_L \psi_3(x))(\bar{\psi}_2(x) \gamma^\mu \Pi_L \psi_1(x)) + h.c. \quad (5.19)$$

V-A was in a very good agreement with most of the experiments but its authors had to make the bold assumption that the predictions of the rest were actually erroneous; needless to say, this required a thorough work. Sudarshan and Marshak [SM1] concluded: "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 [RR53]25 and several unpublished experiments cannot be reconciled with this hypothesis... All of these experiments should be redone... If any of the above four experiments stands, it will be necessary to abandon the hypothesis of a universal V+A four-fermion interaction..."26.

In their review [G-MR] published in December 1957 (the survey of literature pertaining to the review being completed in July, 1957) Gell-Mann and Rosenfeld made the following comment: "... there has been speculation that the form of the interaction might also be 'universal'. Such a situation seems to be ruled out if the $\beta$-decay coupling is primarily S and T and the $\mu$ decay coupling V and A... Since the $\beta$-decay picture is somewhat confused at the moment, let us discuss briefly the possibility that we may have V and A there too, instead of S and T with a possible admixture of V. We may call this V, A hypothesis the 'last stand' of the UFI... We must first of all disregard much of the evidence on $e-\nu$ angular correlation in $\beta$-decay, especially the result of Rustad & Ruby27 on He$^6$, which clearly indicates T rather than A. This is already a very serious objection to the UFI."

Discussing the universality of the weak interaction with V-A in [FG-M], Feynman and Gell-Mann also stressed that "... At the present time several $\beta$-decay experiments seem to be in disagreement with one another. Limiting ourselves to those that are well established, we find that the most serious disagreement with our theory is the recoil experiment in He$^6$ of Rustad and

25Sudarshan and Marshak cited also the later paper [RR55].
26Sheldon Glashow commented on this in [G09]: "This is theoretical physics at its zenith! The experiments were redone with results that now confirmed their hypothesis. It was a stunning accomplishment, yet one which has never been recognized with a prize."
27In [RR55].
Ruby indicating that the T interaction is more likely than the A. Further check on this is obviously very desirable.” Feynman’s picturesque story in [FL Me] about experimental points at the edge of the data range reflects his personal battle with this problem.

Feynman’s line of thought actually started with the following intriguing observation, documented first in the Proceedings of the Seventh Rochester Conference [F-VII], and then in [FG-M]. The electron wave function in the presence of electromagnetic interaction obeys the Dirac equation

\[(\not{D} + m)\psi = 0 \quad (\not{D} = \gamma^\mu D_\mu \ , \ D_\mu = \partial_\mu + ie A_\mu \ , \ F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu) \ . \tag{5.20}\]

Multiplying it by \(\not{D} - m\), one obtains

\[\not{D}^2 \psi = m^2 \psi \quad (\not{D}^2 = D^\mu D_\mu + e \frac{i}{2} \sigma^{\mu\nu} F_{\mu\nu} \ , \ \sigma^{\mu\nu} = \frac{i}{2} [\gamma^\mu, \gamma^\nu]) \ . \tag{5.21}\]

The key point here is that \([\gamma_5, \sigma^{\mu\nu}] = 0\) so that any solution of (5.21) can be presented as a sum \(\psi = \psi_+ + \psi_-\) where \(\psi_\pm\) also solve (5.21) and

\[\gamma_5 \psi_\pm = \pm \psi_\pm \quad \Leftrightarrow \quad \frac{1}{2} (1 \pm \gamma_5) \psi_\pm = \psi_\pm = \frac{1}{2} (1 \pm \gamma_5) \psi \ . \tag{5.22}\]

Clearly, both \(\psi_+\) and \(\psi_-\) only have two independent components. It is most appropriate to use the chiral basis (A.6) in which \(\psi_+ = \begin{pmatrix} \psi_L \\ 0 \end{pmatrix}\), \(\psi_- = \begin{pmatrix} 0 \\ \psi_R \end{pmatrix}\) and the matrix part of (5.21) is block diagonal:

\[\frac{i}{2} \sigma^{\mu\nu} F_{\mu\nu} = F_{0k} \begin{pmatrix} -\sigma_k & 0 \\ 0 & \sigma_k \end{pmatrix} - \frac{i}{2} \varepsilon_{ijk} F_{ij} \begin{pmatrix} \sigma_k & 0 \\ 0 & \sigma_k \end{pmatrix} = \frac{i}{2} \sigma_0 \begin{pmatrix} E_k + iB_k \\ 0 \end{pmatrix} \sigma \begin{pmatrix} 0 \\ -E_k + iB_k \end{pmatrix} \ , \quad E_k = F_{0k} \ , \quad B_k = \frac{1}{2} \varepsilon_{ijk} F_{ij} \ . \tag{5.23}\]

As a result, the two-component spinors \(\psi_L\) and \(\psi_R\) satisfy separate Klein-Gordon type equations only involving Pauli matrices; choosing the first one we obtain

\[[(\partial^\mu + ie A^\mu)(\partial_\mu + ie A_\mu) - e (\not{E} + i\not{B}).\sigma] \psi_L = m^2 \psi_L \ . \tag{5.24}\]

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28 Again, [RR55].

29 See the Appendix for the free case conventions adopted here.
Feynman "has always had a predilection" for Eq. (5.24) because "if one tries to represent relativistic quantum mechanics by the method of path integrals, the Klein-Gordon equation is easily handled, but the Dirac equation is very hard to represent directly" [FG-M]. He had checked that the rules of calculation for electrodynamics worked out on the basis of (5.24) give exactly the same results as those calculated with Dirac matrices. Moreover, he argued, to describe the spin 1/2 of the electron and the positron one only needs two component (Pauli) spinors, if one uses a second order equation. (Similarly, for a spin 0 particle the single component Klein-Gordon equation automatically takes into account the positive and negative energy solutions, the latter being specified by initial conditions for both the function and its time derivative.) Now having secured the point that the chiral projection makes sense even in the massive case, Feynman suggested that in the $\beta$-decay Hamiltonian the electron (instead of the massless neutrino!) field $\psi^{(e)}$ should be replaced by $\frac{1}{2} (1 + \gamma_5) \psi^{(e)}$. So the final steps in [FG-M] towards V-A – putting forward the hypothesis that "the same rule applies to the wave functions of all the particles entering the interaction" (cf. (5.17)) and then assuming universality of the coupling, looked already quite natural for him.

Sudarshan and Marshak [SM1, SM2] derived (5.19) instead by directly requiring the invariance of the weak interaction Hamiltonian with respect to chiral transformations of any of the four fermion fields separately. Clearly, this is a universal condition, stronger than the invariance (4.6) which is only applicable when one of the fields is a (massless) neutrino. The explicit calculation was provided actually soon after in [S57] by J.J. Sakurai who included chiral invariance into a more general framework, generalizing the earlier observation of J. Tiomno [T55] that the Dirac equation (5.20) is invariant under simultaneous chiral and mass reversal transformations:

$$\psi \rightarrow \eta \gamma_5 \psi, \quad \bar{\psi} \rightarrow -\eta^* \bar{\psi} \gamma_5 \quad (|\eta|^2 = 1), \quad m \rightarrow -m, \quad A_\mu \rightarrow A_\mu. \quad (5.25)$$

(It is worth mentioning that, in the free case, inverting the sign of the mass is equivalent to exchanging $u_\zeta(p) \leftrightarrow v_\zeta(p)$, see (A.9) and (A.11). Clearly, (5.25) is also a symmetry of Feynman’s second order formulation of QED based on (5.21) and (5.24) since it only contains the square of $m$. In effect, both the electromagnetic and the weak Lagrangians (including the mass terms) are left invariant with respect to the combined chiral transformation and mass inversion.

In 1957, both R.P. Feynman (May 11, 1918 – February 15, 1988) and
the younger M. Gell-Mann (born September 15, 1929) were already well established at Caltech, while E.C.G. Sudarshan was finishing his PhD thesis under the supervision of R.E. Marshak (October 11, 1916 – December 23, 1992), then chairman of the Physics Department at Rochester. In Marshak’s recollections from 1991, “It was therefore completely natural – after the Wu et al. announcement – to suggest to Sudarshan that he might take a fresh look at to whether a common Lorentz structure and strength could be assigned to all weak interactions. ... Sudarshan plunged into this problem with alacrity and exceeding good taste... By the time of the Seventh Rochester Conference in April 1957, it was clear to both Sudarshan and myself that the only possible UFI for weak processes was V-A (with a left-handed neutrino) and not a combination of S and T (with a righthanded neutrino), as was widely believed.”. The first official announcement on the way to V-A was made however by Feynman (who borrowed a few minutes from Kenneth Case’s talk time for a quick outline of his ideas at Rochester VII) while Marshak did not opt to talk on theirs. Informally, this has been done at a luncheon meeting in the first week of July at Caltech (attended by Sudarshan, Marshak, Gell-Mann as well by the experimentalists F. Boehm and A.H. Wapstra, the theoretician B. Stech and some others from Caltech); a few days later the abstract of [SM1] has been sent to Prof. N. Dallaporta, chairman of the Padua-Venice Conference on Mesons and Newly Discovered Particles, 22-27 September 1957. The preprints of [SM1] and [FG-M] both appeared on September 16, 1957. However, while [SM1], after having been reported at the meeting in Italy, had to await publication till May 2018 (only to be practically buried in the proceedings), Feynman and Gell-Mann’s paper was sent immediately to Physical Review where it appeared on the first day of 1958. On January 10, 1958 Sudarshan and Marshak sent a short letter to the same journal which appeared in the March 1 issue. Their intention was "to take stock of experimental developments favoring the V-A theory since the Padua-Venice Conference" in Marshak’s own words, “Our short note ... was not intended as a substitute for our detailed 1957 Padua-Venice paper but, unfortunately, it was treated by all too many physicists in later years as the sole publication of our V-A theory.”.

The personal viewpoint of E.C.G. Sudarshan and R.E. Marshak on the

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30Ennackal Chandy George Sudarshan (16 September 1931 – 14 May 2018) was born in Pallom, a small village in the Kerala state, south India.
31Exactly on the 26-th birthday of E.C.G. Sudarshan.
emergence and the public reception of the V-A theory is presented e.g. in [SM3, SM4] as well as in the aforementioned Marshak's 1991 talk "The pain and joy of a major scientific discovery" [M91] on the occasion of E.C.G. Sudarshan's 60th birthday. R.P. Feynman's feelings about his own participation in these events are reflected in "The 7 percent solution" article in [FL] and, even stronger, in the interview given to Jagdish Mehra in January 1988, shortly before his death [Me]: "As I thought about it, as I beheld it in my mind’s eye, the goddamn thing was sparkling, it was shining brightly! As I looked at it, I felt that it was the first time, and the only time in my scientific career, that I knew a law of nature that no one else know. Now, it wasn’t as beautiful a law as Dirac’s or Maxwell’s but my new equation for beta decay was a bit like that. It was the first time that I discovered a new law, rather than finding a more efficient method of calculating from someone else’s theory ... I learned later that others had thought of it at about the same time or a little before, but that didn’t make any difference. At the time I was doing it, I felt all the thrill of a new discovery! ... I thought, 'Now I have completed myself!'. Yet, after years have passed, according to Mehra Feynman was ”perfectly happy to share the credit for the discovery with Gell-Mann, Sudarshan, and Marshak.”. The role of M. Gell-Mann in V-A is justly described by G. Johnson in Chapter 7 "A Lopsided Universe" of the biographical book [J00].

The incontestable experimental confirmation, by the end of 1957, of the neutrino left-handedness [GGS] and the careful re-examination and correction, in the following couple of years, of all the data pointed in [SM1, SM2] and [FG-M] as contradicting the V-A theory, gave the latter a triumphant status. It is quite impressive to read the retrospective judgment of two of the greatest living particle theorists, the Nobel laureates S. Glashow [G09] and S. Weinberg [W09] presented more than a half a century later at the Sudarshan Symposium in 2009. For one, it is for the priority issues commented by them from the standpoint of direct participants, both as young scientists just beginning their career in most glorious days of V-A and then, as true leaders in the following developments. Not less important is the value assigned by both of them to the achievement; in Weinberg’s words, ”V-A was the key” to the future.

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32 In [M91], one year before his death in an accidental drowning in Cancun, Mexico, Marshak admitted "three cardinal blunders" of his that prevented Sudarshan to receive the due share of fame for the V-A discovery.
6 The end of the beginning

In a sense, establishing the V-A structure of the weak Hamiltonian marked the end of the beginning. The following is well known: in a nutshell, it included the idea of electroweak unification as a $U(1) \times SU(2)$ gauge theory, the Brout-Englert-Higgs mechanism and the proof of the renormalizability of the ensuing theory; the latter was backed by the discovery of its main ingredients, the neutral currents, the massive intermediate bosons and finally, the Higgs boson, in a series of spectacular experiments, most of which have been carried at CERN. Several Nobel prizes have been awarded in recognition of the progress, both theoretical and experimental.

Some of the properties of neutrinos remain still elusive, and the quest for clarification is at the forefront of contemporary particle physics. B. Pontecorvo’s idea from 1957-1958 of neutrino oscillations turned out to be correct, showing in particular that neutrinos, after all, are massive.

The parity violation and the resulting V-A theory taught us that the basic players in QFT are irreducible representations of the simply connected quantum mechanical Lorentz group $SL(2, \mathbb{C})$. The only surviving discrete symmetry, Pauli’s $CPT$ theorem, is a consequence of continuous space-time symmetries combined with the basic principles of local QFT.

Weak interactions are unique among all known (four, including gravity) in two respects – they violate parity and are mediated by massive bosons. From its emergence to its ultimate success, their story added lots of examples verifying T.D. Lee’s two laws of physicists: “Without experimentalists, theorists tend to drift. Without theorists, experimentalists tend to falter.”

Acknowledgments

The author thanks Ivan Todorov and Serguey Petcov for their precious suggestions and critical reading of the manuscript. Without their help and encouragement this survey simply wouldn’t exist. This work was supported in part by the Bulgarian National Science Fund under research grant DN-18/3.

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33T.D. Lee, History of the weak interactions, Talk at the ”Jackfest” marking the 65th birthday of Jack Steinberger, see e.g. CERN Courier, January/February 1987.
References

[A84] E. Amaldi, From the discovery of the neutron to the discovery of nuclear fission, Phys. Rep. 111:1-4 (1984) 1-332 (see Ref. [277] for the origin of the name ”neutrino”).

[BP34] H. Bethe, R. Peierls, The ”Neutrino”, Nature 133 (1934) 532.

[BLOT] N.N. Bogolubov, A.A. Logunov, A.I. Oksak, I.T. Todorov, General Principles of Quantum Field Theory, Kluwer, Dordrecht et al. 1990.

[BLT] N.N. Bogolubov, A.A. Logunov, I.T. Todorov, Axiomatic Quantum Field Theory, authorized translation from the Russian manuscript, Ed. by Stephen A. Fulling, Addison-Wesley/W.A. Benjamin, 1975, 708 p.

[B30] N. Bohr, Faraday Lecture delivered on May 8th, 1930: Chemistry and the quantum theory of atomic constitution, J. Chem. Soc. (1932) 349-384.

[Ch32] J. Chadwick, Possible existence of a neutron, Nature 192 (Feb 27, 1932) 312;
       J. Chadwick, The Existence of a Neutron, Proc. Roy. Soc. London Ser. A 136 No. 830 (June 1, 1932) 692-708.

[Chase30] C.T. Chase, The scattering of fast electrons by metals. II. Polarization by double scattering at right angles, Phys. Rev. 36 (1930) 1060-1065.

[Cox28] R.T. Cox, C.G. McIlwraith, B.Kurrelmeyer, Apparent evidence of polarization in a beam of $\beta$-rays, Proc. Natl. Acad. Sci. USA 14 (1928) 544-549.

[CR56] C.L. Cowan, Jr., F. Reines, F.B. Harrison, H.W. Kruse, A.D. McGuire, Detection of the free neutrino: a confirmation, Science 124 (1956) 103-104.

[Enz] Ch.P. Enz, No Time to be Brief. A scientific biography of Wolfgang Pauli, Oxford University Press 2002.
[F33] E. Fermi, Versuch einer Theorie der $\beta$-Strahlen. I, La Ricerca scientifica 2, Heft 12 (1933); Z. Phys. 88:3 (1934) 161-177 [for a complete translation in English, see F.L. Wilson, Fermi’s theory of beta decay, Amer. J. Phys. 36:12 (1968) 1150-1160]; An attempt to a $\beta$ rays theory, Il Nuovo Cimento Nuova Serie N. 1 (1934) 1-20.

[F-VII] R. Feynman, Alternative to the 2-component neutrino theory, in: Proceedings of the Seventh Rochester Conference on High Energy Nuclear Physics, 15-19 April 1957, Interscience, New York, Session IX, pp. 42-44.

[FL] R.P. Feynman, "Surely You’re Joking, Mr. Feynman!", Adventures of a Curious Character as told to Ralph Leighton, E. Hutchings (ed.), W.W. Norton, 1985 (available electronically); see, in particular, "The 7 percent solution" in Part 5 "The World of One Physicist", pp. 161-166.

[FG-M] R. Feynman, M. Gell-Mann, Theory of the Fermi interaction, Phys. Rev. 109:1 (1958) 193-198.

[Fo] P. Forman, The Fall of Parity, https://www.nist.gov/pml/fall-parity.

[Fr79] A. Franklin, The discovery and nondiscovery of parity nonconservation, Stud. Hist. Phil. Sci. 10:3 (1979) 201-257.

[F57] H. Frauenfelder et al., Parity and the polarization of electrons from Co$^{60}$, Phys. Rev. 106:2 (1957) 386-387, received on March 1, 1957.

[FT57] J.I. Friedman, V.L. Telegdi, Nuclear emulsion evidence for parity nonconservation in the decay chain $\pi^+ - \mu^+ - e^+$, Phys. Rev. 105:5 (1957) 1681-1682, received on January 17, 1957.

[GT36] G. Gamov, E. Teller, Selection rules for the $\beta$-disintegration, Phys. Rev. 49:12 (1936) 895-899.

[GLW57] R.L. Garwin, L.M. Lederman, M. Weinrich, Observations of the failure of conservation of parity and charge conjugation in meson decays: the magnetic moment of the free muon, Phys. Rev. 105:4 (1957) 1415-1417.
[G-MR] M. Gell-Mann, A.H. Rosenfeld, Hyperons and heavy mesons (systematics and decay), *Annual Review of Nuclear Science*, vol. 7 (1957) 407-478 (Volume publication date December 1957; the survey of literature pertaining to the review completed in July, 1957).

[G99] J. Glanz, What fuels progress in Science? Sometimes, a feud, *The New York Times*, Science, September 14, 1999.

[G09] S. Glashow, Message for Sudarshan Symposium, *J. Physics: Conf. Ser.* 196 (2009) 011003.

[GGS] M. Goldhaber, L. Grodzins, A.W. Sunyar, Helicity of neutrinos, *Phys. Rev.* 109 (1958) 1015-1017, received on December 11, 1957.

[Gr59] L. Grodzins, The history of double scattering of electrons and evidence for the polarization of beta rays, *Proc. Natl. Acad. Sci. USA.* 45:3 (1959) 399-405.

[H32] W. Heisenberg, Über den Bau der Atomekerne. I, *Z. Phys.* 77:1-2 (1932) 1-11; II, *Z. Phys.* 78:3-4 (1932) 156-164.

[H1820] J.F.W. Herschel, On the rotation impressed by plates of rock crystal on the planes of polarization of the rays of light, as connected with certain peculiarities in its crystallization, *Transactions of the Cambridge Philosophical Society* 1 (1820) 43-51.

[J00] G. Johnson, *Strange Beauty (Murray Gell-Mann and the Revolution in Twentieth-Century Physics)*, Vintage Books, New York 2000.

[K2018] KATRIN experiment home page: [https://www.katrin.kit.edu/](https://www.katrin.kit.edu/).

[L57] L.D. Landau, On the conservation laws for weak interactions, *Nucl. Phys.* 3 (1957) 127-131, received on January 9, 1957.

[L24] O. Laporte, Die Struktur des Eisenspektrums, *Z. Physik* 23 (1924) 135-175.

[LRY49] T.D. Lee, M. Rosenbluth, C.N. Yang, Interaction of mesons with nucleons and light particles, *Phys. Rev.* 75 (1949) 905.
[LY2] T.D. Lee, C.N. Yang, Mass degeneracy of the heavy mesons, *Phys. Rev.* **102**:1 (1956), 290-291, received on 29 December 1955, published on 1 April 1956.

[LY] T.D. Lee, C.N. Yang, Question of parity conservation in weak interactions, *Phys. Rev.* **104**:1 (1956) 254-258, received on June 22, 1956, published on October 1, 1956.

[LY3] T.D. Lee, C.N. Yang, Parity nonconservation and a two-component theory of the neutrino, *Phys. Rev.* **105**:5 (1957) 1671-1675, received on January 10, 1957; revised manuscript received on January 17, 1957.

[L09] A. Lesov, The weak force: from Fermi to Feynman, arXiv:0911.0058 [physics.hist-ph].

[Ma] J. Magueijo, *A Brilliant Darkness. The Extraordinary Life and Disappearance of Ettore Majorana, the Troubled Genius of the Nuclear Age*, Perseus, Basic Books, N.Y. 2009.

[M91] R.E. Marshak, The pain and joy of a major scientific discovery, Banquet talk on the occasion of E.C.G. Sudarshan’s 60th birthday celebration, *Z. Naturforsch.* **52a** (1997) 3-8.

[Me] J. Mehra, *The Beat of a Different Drum: The Life and Science of Richard Feynman*, Oxford Univ. Press, 1994, 630 p.; see, in particular, Section 21 ”’The only law of nature I could lay a claim to’: the theory of weak interactions”, pp. 453-481.

[M] Krishna Myneni, Symmetry destroyed: the failure of parity (1984), https://www.hep.ucl.ac.uk/~nk/teaching/PH4442/parity-violation.html.

[P30] W. Pauli, Open letter to the group of radioactive people at the Gauverein meeting in Tübingen (Zürich, December 4, 1930); the original text in German and the translation (by Kurt Riesselmann) are available at http://microboone-docdb.fnal.gov/cgi-bin/RetrieveFile?docid=953; filename=pauli%20letter1930.pdf.

[P33] W. Pauli, Die allgemeinen Prinzipien der Wellenmechanik, in: *Quantentheorie, Handbuch der Physik* **24** (1933) 83-272, H. Bethe et al. (eds.), Springer Berlin, Heidelberg.
[P94] S.T. Petcov, On B. Pontecorvo contributions to weak interaction and neutrino physics, in: Proceedings of the 6th International Symposium on Neutrino Telescopes, Istituto Veneto di Scienze, Lettere ed Arti, Venice, 22-24 February, 1994, M. Baldo-Ceolin (ed.), pp. 17-26; available at https://cds.cern.ch/record/265610/files/P00024340.pdf.

[P47] B. Pontecorvo, Nuclear capture of mesons and the meson decay, Phys. Rev. 72:3 (1947) 246-247.

[P57] H. Postma et al., Asymmetry of the positon emission by polarized $^{58}$Co-nuclei, Physica 23 (1957) 159-160, received on February 25, 1957.

[Re] E. Recami, Majorana, the Neutron, and the Neutrino: Some elementary historical remarks, Hadronic J. 40 (2017) 149-185, arXiv:1712.02209[physics.gen-ph].

[RR53] B.M. Rustad, S.L. Ruby, Correlation between electron and recoil nucleus in He$^6$ decay, Phys. Rev. 89:4 (1953) 880-881.

[RR55] B.M. Rustad, S.L. Ruby, Gamow-Teller interaction in the decay of He$^6$, Phys. Rev. 97:4 (1955) 991-1002.

[S57] J.J. Sakurai, Mass reversal and weak interactions, Nuovo Cimento 7:5 (1958) 649-660, received on October 31, 1957.

[Salam57] A. Salam, On parity conservation and neutrino mass, Il Nuovo Cimento Ser. X 5 (1957) 299-301, received on November 15, 1956.

[SW] R.F. Streater, A.S. Wightman, PCT, Spin and Statistics, and All That, Princeton Univ. Press, 2000.

[SM1] E.C.G. Sudarshan, R.E. Marshak, The nature of the four-fermion interaction, in: Proceedings of the Padua-Venice Conference on Mesons and Newly Discovered Particles, 22-27 September 1957, N. Zanichelli (ed.), Bologna 1958, p. V-14, available e.g. at https://web2.ph.utexas.edu/~gsudama/pub/1958_005.pdf; reprinted in: P.K. Kabir, The Development of Weak Interaction Theory, Gordon and Breach, New York 1963, pp. 118-128.

[SM2] E.C.G. Sudarshan, R.E. Marshak, Chirality invariance and the universal Fermi interaction, Phys. Rev. 109:5 (1958) 1860-1862.
[SM3] E.C.G. Sudarshan, R.E. Marshak, Origin of the Universal V-A Theory, in: Proceedings of the Wingspread Conference ”50 Years of Weak Interactions”, University of Wisconsin, Madison (1984), pp. 1-15; and in: AIP Conference Proceedings 300 ”Discovery of Weak Neutral Currents: the Weak Interaction Before and After”, A.K. Mann, D.B. Cline (eds.), AIP, New York (1994), pp. 110-124.

[SM4] E.C.G. Sudarshan, R.E. Marshak, Conserved Currents in Weak Interactions, Frontiers of Physics (Proc. of The Landau Memorial Conference, Tel Aviv, Israel, 6-10 June 1988), E. Gotsman, Y. Ne’eman, A. Voronel (eds.), Pergamon Press, Oxford (1990), pp. 169-182.

[Th1894] Sir William Thomson Lord Kelvin, The Molecular Tactics of a Crystal, Clarendon Press (1894).

[T55] J. Tiomno, Mass reversal and the universal interaction, Nuovo Cimento 1 (1955) 226-232.

[TW49] J. Tiomno, J.A. Wheeler, Energy spectrum of electrons from meson decay, Rev. Mod. Phys. 21:1 (1949) 144-152.

[T11] I. Todorov, Clifford algebras and spinors, Bulg. J. Phys. 38:1 (2011) 3-28; arXiv:1106.3197 [math-ph].

[W09] S. Weinberg, V-A was the key, J. Phys.: Conf. Ser. 196 (2009) 012002.

[W29] H. Weyl, Gravitation and the electron, Proc. Natl. Acad. Sci. USA 15:4 (1929) 323-334; H. Weyl, Elektron und Gravitation. I. (in German), Z. Physik 56 (1929) 330-352.

[WWW52] G.C. Wick, A.S. Wightman, E.P. Wigner, The intrinsic parity of elementary particles, Phys. Rev. 88 (1952) 101-105.

[W27] E.P. Wigner, Einige Folgerungen aus der Schrödinger-schen Theorie für die Termstrukturen, Z. Physik 43 (1927) 624-652.

[Wu57] C.S. Wu, E. Ambler, R.W. Hayward, D.D. Hoppes, R.P. Hudson, Experimental test of parity conservation in beta decay, Phys. Rev. 105:4 (1957) 1413-1415.
[Y82] C.N. Yang, The discrete symmetries P, T and C, *J. de Physique Colloques* 43 (C8) (1982) 439-451.

[Y35] H. Yukawa, On the Interaction of Elementary Particles, *Proc. Phys. Math. Soc. Jap.* 17 (48) (1935) 48-57; *Prog. Theor. Phys. Suppl.* 1 (1955) 1-10.
Appendix.

Gamma matrices and the free spin $1/2$ field

We will use the *space-like* metric $\eta_{\mu \nu}$ in Minkowski space so that e.g.

$$p^2 = p^\mu \eta_{\mu \nu} p^\nu = p^2 - p_0^2, \quad p^2 = p_1^2 + p_2^2 + p_3^2.$$  \hfill (A.1)

The Clifford algebra $C\ell(3,1)$ generated by the $\gamma$ matrices satisfying

$$[\gamma_\mu, \gamma_\nu] := \gamma_\mu \gamma_\nu + \gamma_\nu \gamma_\mu = 2 \eta_{\mu \nu}, \quad (\eta_{\mu \nu}) = \text{diag}(-, +, +, +)$$  \hfill (A.2)

is isomorphic to the algebra of $4 \times 4$ real matrices, see e.g. [T11]. The Dirac conjugate of a 4-component spinor $\psi$ is defined as

$$\tilde{\psi} = \psi^* \beta, \quad \gamma_\mu^\ast \beta = -\beta \gamma_\mu$$  \hfill (A.3)

(the star * standing for hermitean conjugation) and the charge conjugate, as

$$\psi^C = \tilde{\psi} C^{-1}, \quad \gamma_\mu^t C = -C \gamma_\mu$$  \hfill (A.4)

where $C$ is the charge conjugation matrix and $^t$ stands for transposition.\footnote{The matrix $\beta$ defines a hermitean form, and $C = (C_{\alpha \beta})$ a skew-symmetric bilinear form on the spinors $\psi = (\psi^\alpha)$.}

It is convenient to define $\gamma_5$ as a hermitean matrix:

$$\gamma_5 = i \gamma_0 \gamma_1 \gamma_2 \gamma_3; \quad \text{tr} \gamma_5 \gamma_\mu \gamma_\nu \gamma_\rho \gamma_\sigma = 4 \epsilon^{\mu \nu \rho \sigma} \quad (\epsilon^{0123} = 1 = -\epsilon_{0123}).$$  \hfill (A.5)

The chiral ($\gamma_5$-diagonal) basis of $\gamma$ matrices can be realized as

$$i \gamma_0 = \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix} = \beta, \quad i \gamma = \begin{pmatrix} 0 & \sigma \\ -\sigma & 0 \end{pmatrix}, \quad \gamma_5 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$C = \begin{pmatrix} c & 0 \\ 0 & c^{-1} \end{pmatrix}, \quad c = i \sigma_2 = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} = -c^t = -c^{-1}.$$  \hfill (A.6)

The Lagrangian of a free (complex) Dirac field is

$$\mathcal{L} = \frac{1}{2} \left( \partial_\mu \tilde{\psi} \gamma^\mu - \tilde{\psi} \gamma^\mu \partial_\mu \psi - m \tilde{\psi} \psi \right) = \mathcal{L}_c + \frac{1}{2} \partial_\mu (\tilde{\psi} \gamma^\mu \psi) ,$$
$$\mathcal{L}_c = -\tilde{\psi} (m + \dot{\theta}) \psi , \quad \dot{\theta} = \gamma^\mu \partial_\mu \equiv \partial^\mu \gamma^\mu ,$$  \hfill (A.7)

\footnote{A real (Majorana) representation is given e.g. by $\gamma_0^M = \sigma_3 \otimes c$, $\gamma_1^M = I \otimes \sigma_3$, $\gamma_2^M = I \otimes \sigma_1$, $\gamma_3^M = -c \otimes c$ \quad ($c = i \sigma_2$); $\gamma_0^M \gamma_1^M \gamma_2^M \gamma_3^M = \sigma_1 \otimes c = - (\sigma_1 \otimes c)^t$.}
so that the Dirac equation for $\psi(x)$ and the conjugate equation for $\bar{\psi}(x)$ read

$$(\slashed{D} + m) \psi(x) = 0, \quad \partial_\mu \bar{\psi}(x)\gamma^\mu - m \bar{\psi}(x) = 0.$$  \hspace{1cm} (A.8)

The solution of the Dirac equation (A.8) is presented in the form

$$\psi(x) = \sum_\zeta \int [b_\zeta(p, +) e^{ipx} u_\zeta(p) + b^*_\zeta(p, -) e^{-ipx} v_\zeta(p)] (dp)_m,$$

$$\bar{\psi}(x) = \sum_\zeta \int [b^*_\zeta(p, +) e^{-ipx} \bar{u}_\zeta(p) + b_\zeta(p, -) e^{ipx} \bar{v}_\zeta(p)] (dp)_m, \hspace{1cm} (A.9)$$

where the invariant measure on the future mass hyperboloid $(dp)_m$ is

$$(2\pi)^3 (dp)_m = \int_0^\infty \delta(p^2 + m^2) dp_0 d^3p = \frac{d^3p}{2\omega_p}, \quad \omega_p (= |p_0|) = \sqrt{m^2 + p^2}.$$  \hspace{1cm} (A.10)

Here $u_\zeta$ and $v_\zeta$ are classical ("c-number") spinors satisfying the linear algebraic equations

$$(m + i\not{p}) u_\zeta(p) = 0 = \bar{u}_\zeta(p)(m + i\not{p}),$$

$$(m - i\not{p}) v_\zeta(p) = 0 = \bar{v}_\zeta(p)(m - i\not{p}) \quad \text{for} \quad p^0 = \omega_p \hspace{1cm} (A.11)$$

and $\zeta = \pm \frac{1}{2}$ is the spin projection index. In the $\gamma_5$-diagonal basis the field $\psi(x)$ (as well as $u_\zeta(p)$ and $v_\zeta(p)$) splits into chiral components:

$$\psi(x) = \begin{pmatrix} \psi_L(x) \\ \psi_R(x) \end{pmatrix}, \quad \bar{\psi}(x) = (\psi_R^*(x), \psi_L^*(x)),$$

$$\psi^C(x) = \bar{\psi}(x) C^{-1} = \begin{pmatrix} \psi_R^*(x) c^{-1} \\ \psi_L^*(x) c \end{pmatrix}. \hspace{1cm} (A.12)$$

A Majorana field is equal to its charge conjugate, $\psi(x) = \psi^C(x)$ (which amounts in the chiral basis to $\psi_R(x) = \psi_L^*(x) c$). It is a special case of (A.9) with $b_\zeta(p, +) = b_\zeta(p, -)$ and $v_\zeta(p) = u_\zeta^C(p)$. 

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