V-A: Universal Theory of Weak Interaction

The story of the discovery of the Chiral V-A interaction in the classic weak processes of beta decay, muon capture by nuclei, and muon decay has been told many times. Sudarshan was a student working under the supervision of Robert Marshak. Marshak suggested in early 1956 that he should study weak interactions. Sudarshan studied every paper on weak interactions beginning with Sargent, Fermi, Yukawa, Gamow and Teller, Konopinski, Wu, and a multitude of others. He had also read the paper by Tiomno and Wheeler on the possibility of a Universal Fermi Interaction. Fermi had postulated a scalar, formed out of four Fermi fields, for the form of the weak interactions, in analogy with electromagnetic interactions. Soon it was found that the form of the interaction had to be generalized to include spin-dependent interactions as pointed out by Gamow and Teller. However, when special relativity had to be taken into account, the most general form for the interaction Lagrangian turned out to be

$$\mathcal{L}_i = \sum_{i=1}^{5} g_i \left\{\bar{\psi}_1 \mathcal{O}^i \psi_2\right\} \left\{\bar{\psi}_3 \mathcal{O}_i \psi_4\right\} \tag{1}$$

where the operator $\mathcal{O}_i$=($\mathbf{1}$, γ_μ, $\sigma_{\mu\nu}$, $i\gamma_5\gamma_\mu$, or γ_5), and ψ_i are the four spinor fields involved in the decay. These covariant forms were called scalar (S), vector (V), tensor (T), axial vector (A), and pseudoscalar (P), respectively. In the non-relativistic limit, S and V reduce to the Fermi interaction, while T and A reduce to Gamow-Teller.

The consensus at that time, based on many experiments, was that the beta decay weak interaction was scalar and tensor. After the discovery of parity violation in 1956, papers on this subject appeared in torrents. Having studied all of them, by the end of 1956, Sudarshan was convinced that if there was a Universal Fermi Interaction it had to include the axial vector interaction since the charged pion decay may be viewed as if it were beta decay of a "nucleus with zero atomic weight". He then systematically studied all the work up to that time, both theoretical and experimental, with this criterion in mind.

By December 1956 - January 1957, Sudarshan had discovered that the results of angular correlation experiments on "classical" (non parity violating) beta decays were internally inconsistent! The electron-neutrino angular correlation in the neutron and in the Ne^{19} decays were indicative of S, T or V, A. But the available data on He^6 showed it to be tensor T. On this basis, the preferred combination was S, T. But the Ar^{35} decay, which is dominantly

of the Fermi type, showed that it is V. Not all these could be true at the same time. In muon decay, since the neutrino and antineutrino were taken to be massless and chiral, the only interaction was vector or axial vector, or a combination of both [in the charge retention order $(\mu e)(\nu\nu)$].

At the time of the Rochester conference in spring 1957, Sudarshan had essentially all the arguments in place for Chiral V-A interaction, but there were four experiments which stood in the way. He wanted to present it at the Rochester High Energy Conference, but it was ruled out since he was still only a graduate student! Marshak himself was very preoccupied with the nucleon-nucleon strong interactions. He had chosen to present a phenomenological nucleon-nucleon potential at the conference. P.T. Matthews, a visiting professor at Rochester, was entrusted with reporting the V-A theory in a few lines, but he forgot to do so. There was much inconclusive discussion between experts about the form of the weak interactions which Sudarshan could have resolved had he been given a few minutes to present his theory.

Marshak was going to be at the RAND Corporation in Los Angeles and offered Sudarshan and Bryan (another student of his) one-month summer salary if they could be in Los Angeles. As an alien, Sudarshan could not enter RAND, so it was arranged that they meet outside off and on. At that time Gell-Mann was also a consultant to RAND. Marshak told him briefly about their work on weak interactions and Gell-Mann was appreciative of it. So, ten days later Marshak had arranged lunch at a nearby restaurant. The lunch group included Marshak, Gell-Mann, Bryan, Leona Marshall, Felix Boehm, A.H. Wapstra, Berthold Stech, and Sudarshan. Sudarshan was asked to give a presentation which he did in full detail. (This was the only time he was invited to give a talk on V-A!) He made the observation that the data was internally inconsistent. He also singled out the experiments which were most likely to be mistaken. He suggested that the weak decay interaction was of the universal form V-A with maximal parity violation, in which every field was multiplied by the chiral projection operator. Incidentally, if this is so, both the charge exchange and the charge retention ordering give the same unique interaction. As presented, Sudarshan's work was a critical examination of all the existing data on all weak interactions, and it showed that the only possibility was Chiral V-A. Gell-Mann was enthusiastic about Sudarshan and Marshak's discovery.

Marshak asked Sudarshan to write up the work, which he did, and gave it to Marshak

that weekend. Marshak decided to present this fundamental discovery at the Padua-Venice conference on Mesons and Newly Discovered Particles in September 1957 [1], rather than to have it published immediately (which probably cost him and Sudarshan a Nobel prize). Later, Marshak decided that a sequel to the presentation at the Padua-Venice conference (which, incidentally, was published two years later) should be published in the Physical Review [2].

In the meantime, Feynman and Gell-Mann published a paper in the Physical Review *asserting* the V-A structure of the weak interactions, merely thanking Sudarshan for "important discussions". Their paper, which most people quote in precedence over the Sudarshan-Marshak paper, does not contain any analysis of the data, including those of the experiments that Sudarshan and Marshak had singled out to be most likely in error. These experiments were eventually redone and gave the results predicted by Sudarshan and Marshak.

Many fables and some actual accounts about this have been presented by various people. Notably, Feynman made a public statement in 1963 [3]: "The V-A theory that was discovered by Sudarshan and Marshak, publicized by Feynman and Gell-Mann —". Marshak has also spoken and written about this history ([4–8]).

Weak interaction theory (V-A) could be extended to the leptonic decays of baryons and mesons. The question arises as to the isotopic spin transformation properties of these. THe simplest is to assume that the interaction current in leptonic decays transforms as I=$\frac{1}{2}$. This leads to sum rules [9]. The non-leptonic decays of hyperons have also been studied and shown to involve near-maximal parity violation and consequent baryon polarization [10, 11].

In quantum electrodynamics the conservation of the electric current led to the Ward-Takahashi identities. This was generalized to cases where the divergence of the interaction current does not vanish but is a multiple of the pion field, resulting in generalized Ward-Takahashi identities [12].

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