V-A theory: a view from the outside

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Abstract

In this talk I will review the V-A theory within the context of the prevalent experimental results at the time.

It is a great pleasure for me to be able to participate in this celebration in honor of Professor George Sudarshan. Let me say right away that unlike the other speakers in this session, I haven't had the opportunity to collaborate with George yet. On the other hand, George is still young and who knows!

Much of what is being discussed in this session happened many, many years ago. I am, of course, not going to tell you how old I am. Let me simply say that all of this happened long before my time, which is the reason for the title of my talk. The only reason I agreed to speak in this session is because George is a dear friend, a former student of Rochester and I felt that I had access to all the resources of Rochester. This was before I knew who else were going to be speaking in this session and that the organizers had kindly deprived me of part of my resources, thank you very much!

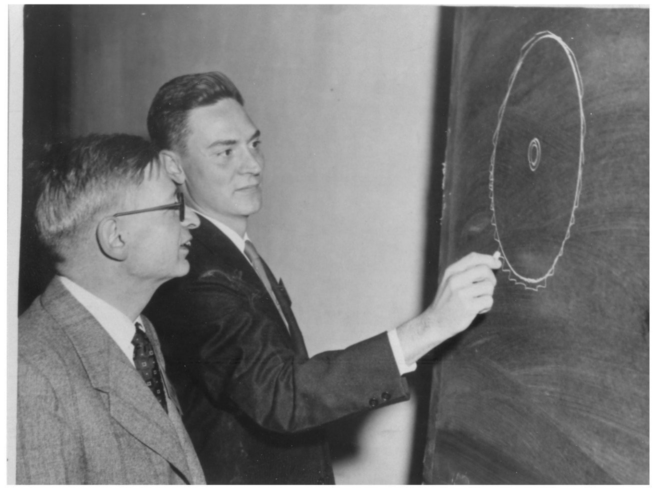
So, I had to work very hard, go back to the old papers and the archives and reconstruct events. What I learnt is that the story of V-A theory is a fascinating one. You can even think of this as one of the stories of *Sheherazade* in the *Arabian Nights*. As we all know these are very intricately woven stories that naturally lead from one story to the next. In fact, if only *Sheherazade* were aware of the story of V-A, you can hear her starting the story as, "A long time ago, there was....". The difference is that the "long time" in this case can be quantified. You have already heard that it all happened 50 years ago, but let me simply say that "it all happened that many years ago".

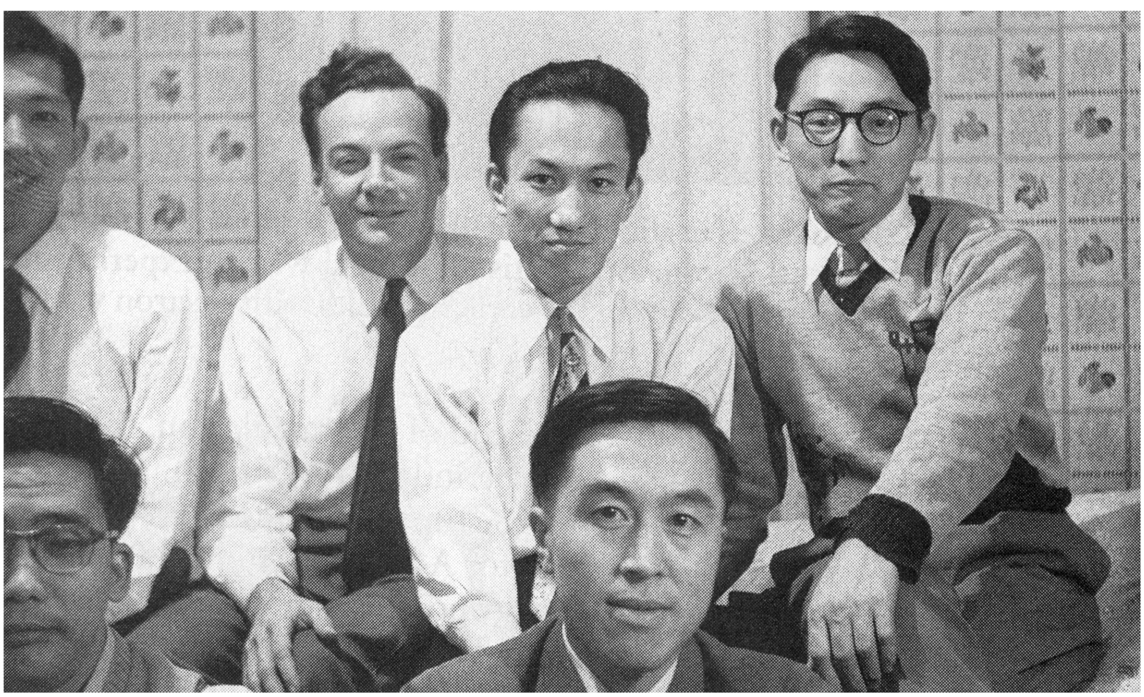
The story of V-A has two aspects to it. There is, of course, the physics aspect that I will come to. But, more important is the sociological aspect. Many younger people in the audience may not know that the Rochester conference which started in Rochester in 1951 was one of the first successful international conferences in high energy physics in this country. Over the years, the character of this conference has, of course, changed enormously. The first Rochester conference, for example, had only 50 participants and lasted for just one day.


Once upon a time there was .....

Second Rochester Conference, January 11–12, 1952

The discussions in these conferences were friendly but intense and this was the venue for announcing new results. So, it was an exciting place to be in. If you think arranging visas for foreign visitors is difficult now, you should think again. Things were not at all easy at that time.





The other sociological aspect is that it is around this time that Bob Marshak started recruiting smart foreign graduate students into the university. Even the university was not fully supportive, but in his characteristic way, Marshak prevailed. It is in this way that both George Sudarshan and Susumu Okubo arrived into the middle of all the exciting things that were happening in Rochester around the Rochester conferences.

Young graduate students in the middle of all the excitement.

The physics aspect can be summarized by saying that it was a very exciting period, I guess because everything was so confusing. To me the most impressive thing about the V-A theory is that it was formulated in the face of experimental results that did not support its predictions. In physics experiments are expected to give guidance to theorists. Sometimes an experiment may itself be wrong, but then it is the responsibility of other experiments to "weed out" the wrong experiment. On the other hand, when repeated experiments stand by a result, it is generally foolish to propose a theory that contradicts the accepted experimental results. However, this is exactly what Sudarshan and Marshak did in proposing the V-A theory simply because they had a desire to have a universal theory of weak interactions and the predictions of their theory were subsequently vindicated by more careful experiments. Basically, there was a combination of wrong experiments that had completely dominated the physics scene before the V-A theory. Let me explain this in some detail.

The story of weak interactions started with the observations of nuclear β decays and the developments in the field can be divided into two phases: a phase prior to the discovery of parity violation and a phase after this discovery. In the earlier phase, with more and more studies on nuclear decays, it was established that there are three kinds of nuclear beta decays [1, 2]:

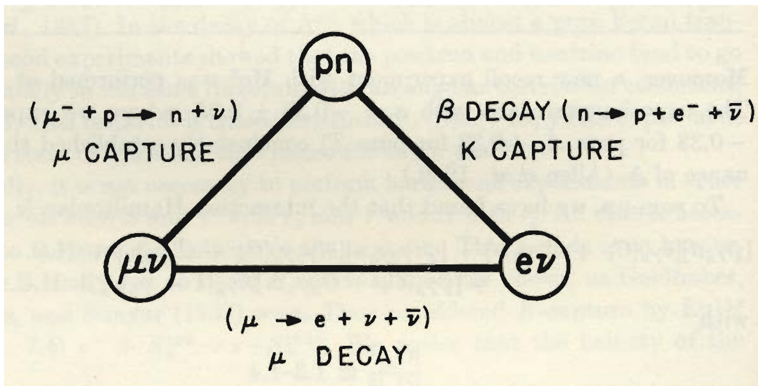
1. Fermi transitions: $\Delta J = 0, \quad 0 \to 0. \quad (\mathrm{O}^{14} \to \mathrm{N}^{14} + e^+ + \nu)$
2. Gammow-Teller transitions: $\Delta J = 1. \quad (\mathrm{He}^6 \to \mathrm{Li}^6 + e + \bar{\nu})$

3. Mixed transitions: $\Delta J = 0, \quad 0 \not\to 0. \quad (n \to p + e + \bar{\nu})$

In addition to the nuclear β decays, it was also observed (1948) that the *muon* decays through weak interactions as

$$\mu^- \to e + \nu + \bar{\nu}.$$

Tiomno and Wheeler [3] were the first to carry out a systematic study of the strengths of all these decays which suggested a universal nature of the weak force governing all of these decays (Puppi's triangle):



As a result, the Fermi theory of β decay [1] involving a current-current interaction of vector currents (in analogy with QED) was generalized to an interaction of the form

$$H_{\rm int} = \sum_i C_i J_i J^{i\,\dagger}, \quad J_i = J_i^{\rm hadron} + J_i^{\rm lepton},$$

where the generalized "current" had the generic form

$$J_i = \bar{\psi}_1 \Gamma_i \psi_2, \quad i = S, V, T, A, P.$$

Namely, the generalized "current" involved all the five bilinear covariants of Dirac matrices. On the other hand, since the nucleons inside the nucleus were nonrelativistic, one could immediately deduce:

1. Only S, V terms contribute to Fermi transitions (since they do not change spin).
2. Only T, A terms can contribute to Gamow-Teller transitions (since these can change spin).

The pseudoscalar term vanishes in the nonrelativistic limit and, therefore, nothing could be deduced about this coupling. Furthermore, since Fermi and Gammow-Teller transitions were observed, it meant that one cannot have vanishing couplings for both S, V or both T, A terms in the interaction. The form of the interaction Hamiltonian can, of course, be constrained further by experimental studies.

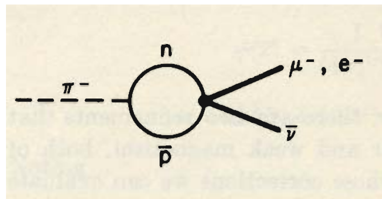
However, before I describe the experimental results, let me point out a theoretical result that will play a crucial role in the later developments. It was already known from cosmic ray studies that the *pion* decays through weak interactions through the channel

$$\pi^- \to \mu^- + \bar{\nu}.$$

However, the decay involving the electron

$$\pi^- \rightarrow e^- + \bar{\nu},$$

had never been seen. That was a bit puzzling at the time since e, μ had similar properties except for their mass difference. Based on the universal interaction hypothesis of Tiomno and Wheeler, a theoretical calculation was carried out by Ruderman and Finkelstein [4] for the ratio of the decay rates for the two modes



and their results are expressed in the table (f denotes forbidden)

TABLE I. Ratio of $\pi \rightarrow (e, \nu)$ to $\pi \rightarrow (\mu, \nu)$-decay for couplings (1) and (7).

Meson	Type of β-decay: Scalar	P-scalar[a]	Vector	P-vector	Tensor
Scalar	5.1	f	f	f	f
P-scalar	f	5.1	f	1.0×10^{-4}	f
Vector	f	f	4.0	f	2.4
P-vector	f	f	f	4.0	f

I have highlighted the relevant numbers for the appropriate couplings. Since the only allowed channels through which the *pion* can decay to electrons are the P and the A channels and since this decay is so rare, theoretically, the P (P-scalar) channel was ruled out (This is the channel on which we had no information in the nonrelativistic limit). Therefore, experimentally one had to look at only the S, V, T, A channels.

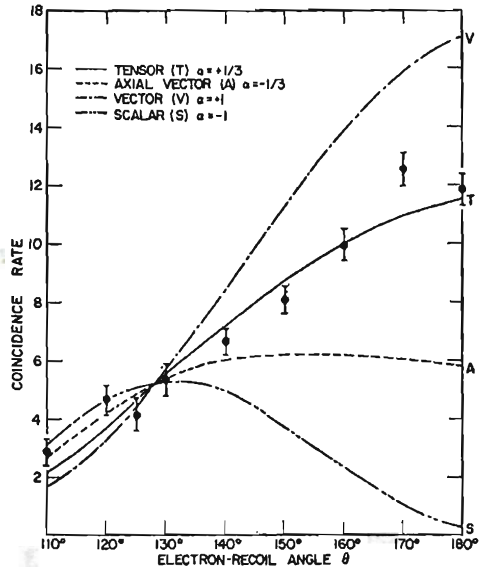
The way experiments looked for these terms in the decay process is by looking at the end spectrum of the electron energy in the decay or by looking at the angular correlation between the electron and the neutrino which can be determined from the recoil of the nucleus. For example, the angular correlation can be parameterized as

$$f(\theta) \sim 1 + \lambda\, \frac{v}{c} \cos\theta,$$

where v denotes the speed of the electron. (In writing this I have neglected a term known as the *Fierz interference* term which was not observed experimentally.) Theoretically, the parameter λ can be calculated for the different channels and takes the values

	S	V	T	A
λ	-1	$+1$	$+1/3$	$-1/3$

So, for example in the decay of He^6 (which is a Gammow-Teller decay), λ was determined to have the value $\lambda = \frac{1}{3}$ so that one would conclude the coupling for Gamow-Teller transitions to be primarily of T type [5].



One can summarize the results of many of these experiments at the time as [6]

Nuclear decay	Method	λ	Conclusion
Prior to parity non-conservation			
^{6}He	Recoil Spectrum		T (not A)
n	Recoil Spectrum	$+0{\cdot}09 \pm 0{\cdot}11$	S and T or V and A
^{19}Ne	Recoil Spectrum	$-0{\cdot}21 \pm 0{\cdot}08$ $+0{\cdot}14 \pm 0{\cdot}2$ $-0{\cdot}15 \pm 0{\cdot}2$	S and T or V and A
^{6}He	Angular Correlation	$+0{\cdot}34 \pm 0{\cdot}12$	T (not A)

This suggested that the β decays were governed by S, T couplings. On top of that the leading search for the $\pi \to e + \nu$ led to the result [7]

$$\frac{\Gamma(\pi \to e + \nu)}{\Gamma(\pi \to \mu + \nu)} = (-3 \pm 9) \times 10^{-5}.$$

This further ruled against an interaction of A type and supported the S, T couplings. Thus, the dominant sentiment in the theoretical physics community at the time was that the generalized Fermi theory with S, T couplings was responsible for the weak decays.

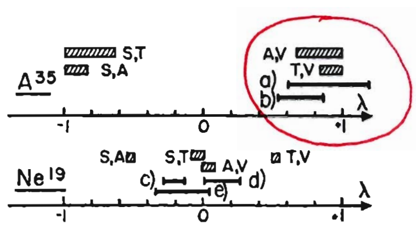
Then came the proposal by Lee and Yang [8] that parity is violated in weak interactions which was soon [9] established in the Gamow-Teller decay of Co^{60} which also showed that parity is violated maximally in these decays. Violation of parity necessitated that the interaction Hamiltonian should be further generalized to

$$H_{\text{int}} = \sum_i \bar{\psi}_1 \Gamma_i \psi_2 \; \bar{\psi}_3 \Gamma^i \left(C_i + C_i' \gamma_5\right) \psi_4 + \text{hermitian conjugate}, \quad i = S, V, T, A.$$

As a result, experiments needed to be analyzed afresh. Surprisingly, however, the large volume of experimental data in β decays were unaffected by violation of parity since they involved measuring parity invariant quantities. However, there were two new experiments that are worth talking about. First, there was the experiment [10] which studied the transitions:

$$\mathrm{Ar}^{35} \rightarrow \mathrm{Cl}^{35} + e^{+} + \nu, \quad \text{(Fermi)}, \quad \mathrm{Ne}^{19} \rightarrow \mathrm{F}^{19} + e^{+} + \nu \quad \text{(Mixed)}.$$

The angular correlation measurements in these decays gave a value of $\lambda \approx 0.9$ supporting a strong V coupling in the interactions.



However, these results were in contradiction with most other results including one of their own earlier experiments. (Let me remark here parenthetically that IUPAC changed the symbol for Argon from A^{35} to Ar^{35} in 1957.) The second was a better experiment [11] designed to search for $\pi \rightarrow e + \nu$ decays and it gave even a lower limit on the ratio to be

$$\frac{\Gamma(\pi \rightarrow e + \nu)}{\Gamma(\pi \rightarrow \mu + \nu)} = (-0.4 \pm 9) \times 10^{-6},$$

and, therefore, in spite of the new component of parity violation in the theory, the general sentiment continued to be that the interactions were of S, T type.

However, at this point, there was a new twist from the theoretical side. Observing that all the parity violating experiments involved a neutrino, it was argued that it is the neutrino that is responsible for the violation of parity and this resurrected the two component theory of neutrinos. Salam [12] was the one who introduced the concept of γ_5 invariance into the neutrino equations. "Chirality" or handedness crept into this discussion through the works of Watanabe [13] and it was clear that unlike other particles, neutrinos were either left-handed or right-handed. Various β asymmetry measurements showed that if the neutrino was left-handed, the interaction will have a (V, A) form while if it was right-handed (S, T) form would be favored. (Handedness of neutrino will be measured only a year later in a beautiful experiment by Goldhaber et al. [14]) The *muon* decay experiments, on the other hand, seemed to support a (V, A) form of the interactions. The idea of a universal Fermi theory was, therefore, in jeopardy and the confusion that prevailed is best summarized by the remarks of T. D. Lee in the seventh Rochester conference (1957)

"$\cdots$ *We turn to the universal Fermi interaction, which is an attempt to gain a more unified understanding of certain of the weak interactions. We draw the famous triangle representing the interactions of interest. Beta decay information tells us that the interaction between* (p, n) *and* (e, ν) *is scalar and tensor, while the two component 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* $\cdots$"

This basically summarizes the climate in which Sudarshan and Marshak proposed the universal V-A theory [15]. Their desire was to have a universal Fermi theory and was not based primarily on symmetry principles which came only after the fact. Let me try to reconstruct here their reasoning for proposing such a structure for the theory. First, since neutrinos have a definite handedness, they satisfy

$$(1 \pm \gamma_5)\, \psi^{(\mathrm{R,L})} = 0 = \bar{\psi}^{\,(\mathrm{R,L})}\, (1 \mp \gamma_5)\,,$$

depending on their handedness. Since the longitudinal polarization of the electron in the Co^{60} decay is negative (predominantly left-handed), this then determined that the current in the lepton sector would involve (S,T) couplings if the neutrino is right handed and (V,A) couplings if the neutrino is left handed. From the β decay experiments, therefore, it would correspond to choosing between the He^6 or the Ar^{35} results respectively. I want to emphasize here that the He^6 results were the commonly accepted ones at the time and the Ar^{35} results were not generally in favor. The muon decay, on the other hand, favored the (V,A) coupling which can be seen in the following way. The current involving the neutrino and the antineutrino (with well defined handedness)

$$\bar{\psi}_\nu\, (1 \mp \gamma_5)\, \Gamma_i\, (1 \pm \gamma_5)\, \psi_\nu = 0, \quad \text{for } i = S, T, P,$$

and is nontrivial only for $i = V, A$. Therefore, if one wants a universal theory for all the interactions, one must choose the results of the Ar^{35} experiment over the commonly accepted He^6 results. That is exactly what Sudarshan and Marshak did. Such a choice then leads to the universal V-A theory of the form

$$H_{\rm int} = G\bar{\psi}_1\gamma_\mu(1+\gamma_5)\psi_2\bar{\psi}_3\gamma^\mu(1+\gamma_5)\psi_4 + \text{hermitian conjugate}, \quad \begin{array}{l} C_i = C_i',\ i = V, A;\ C_V = C_A, \\ C_i = C_i' = 0,\ i = S, T. \end{array}$$

On the other hand, such an interaction would predict the *pion* to decay into an electron. Subsequently, several new experiments measured the ratio for this decay leading to the value [16]

$$\frac{\Gamma(\pi \to e + \nu)}{\Gamma(\pi \to \mu + \nu)} = (1.03 \pm 0.20) \times 10^{-4},$$

which vindicated the V-A hypothesis. Many of the β decay experiments were soon redone and corrected for the errors in the older results.

Once a V-A structure for the interaction was proposed, its symmetry properties, which are important for later developments, followed. For example, it was realized that the interaction Hamiltonian is invariant under a γ_5 transformation. It was also observed that the V-A structure is invariant under the *Fierz rearrangement*. In fact, the combination S-$T+P$ is also invariant, but as I have tried to emphasize, the P interactions do not enter the weak interaction Hamiltonian. However, I do not have time to get into these.

You can almost hear it now. At the conclusion of this triumphant story, the curious emperor, *Sheheriyar*, asks *Sheherazade*, "What happened next?" Like a good story teller, politely and respectfully, *Sheherazade* reminds the emperor that it is almost dawn and that it may be better to rest a little and continue the next day, to which the emperor agrees. After a sumptuous dinner the following evening, *Sheherazade* meets the emperor at the appointed hour and resumes her story. "You see, your excellency, ...", she continues and as we have learnt from Professor Weinberg's talk this morning, the story of V-A leads naturally to the story of the Standard Model. The story (of *Sheherazade* and of scientific discoveries), of course, continues. However, unlike *Sheherazade*, I have only half an hour and, therefore, let me thank you all for your attention and stop here.

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