Goerge Sudarshan and V-A Interactions

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β Decays

- Some nuclei undergo β decays. For example,

$$Bo_{12} \rightarrow C_{12} + e^{-} + \bar{\nu}^{e}$$
$$N_{12} \rightarrow C_{12} + e^{+} + \nu^{e}$$

- In a seminal paper (duely rejected by Nature) in 1933 Fermi proposed that all β decays are caused by one of two elementary reactions within the nucleus

$$n \rightarrow p^{+} + e^{-} + \bar{\nu}^{e}$$
$$p^{+} \rightarrow n + e^{+} + \nu^{e}$$

- He proposed that both these reactions find their explanation in a single term in the Hamiltonian of the very schematic form

$$(\bar{\psi}_n \psi_p)\,(\bar{\psi}_{\nu^e} \psi_e) + \mathrm{cc}$$

β and π Decays

- Pions also decay

$$\pi^+ \to \mu^+ + \nu^\mu$$

- Though pion decays appear qualitatively differnt from β decays, they actually reflect the same underlying physics.
- We now know that none of the proton, neutron or pion are really 'elementary'. In some very rough sense

$$P = uud, \quad N = udd \quad \pi^+ = u\bar{d}$$

- The decay of the p^+ and the π^+ are respectively a consequence of the reaction

$$u \to d + e^+ + \nu^e \tag{1}$$

$$u \to d + \mu^+ + \nu^\mu \tag{2}$$

We now know that the 4 Fermi Hamiltionians for (1) and (2) are essentially identical. Already suspected in 1950s.

Precise nature of interaction

- Simple 4 Fermi interaction contains great deal of physics. Exact form of the 4 Fermi Lagrangian?
- 4 given scalar fields have a unique contact interaction $\phi_1\phi_2\phi_3\phi_4$. Because of their spinor indices, the same is not true for 4 fermions. There are as many 4 Fermi Lagrangians as there are ways of building scalars out the product of 4 fermions.
- Warm up problem. Consider 4 different distinguishable $SU(2)$ representations j_1, j_1, j_2, j_2 with $j_2 < j_1$. How many $SU(2)$ singlets does the product of these 4 reps contain?
- Product equals $(j_1 \otimes j_2) \otimes (j_1 \otimes j_2)$. But

$$(j_1 \otimes j_2) = (j_1 - j_2) \oplus (j_1 - j_2 + 1) \oplus \ldots (j_1 + j_2) \qquad (3)$$

Fusing two of (3) gives one singlet for every term on RHS of (3)

Counting Singlets

- Euclidean Lorentz group $SO(4) \sim SU(2) \times SU(2)$. Fermion is in $(\frac{1}{2}, 0) + (0, \frac{1}{2})$. Need just apply above result for each $SU(2)$.
- $$\left((\frac{1}{2}, 0) + (0, \frac{1}{2})\right) \otimes \left((\frac{1}{2}, 0) + (0, \frac{1}{2})\right) \\ = (0,0) + (1,0) + (\frac{1}{2}, \frac{1}{2}) + (\frac{1}{2}, \frac{1}{2}) + (0,1) + (0,0) \tag{4}$$

  In $SO(4)$ language the two $(0,0)$ are one scalar and one pseudoscalar. The two $(\frac{1}{2}, \frac{1}{2})$ are a vector and a pseudo vector. $(1,0) + (0,1)$ is an antisymmetric rank 2 tensor. There are 4 singlets associated with the scalars (SS', SP', PS', PP'), similarly four singlets associated with vectors VV', VA', AV', AA' and two with tensors. Total 10.

Lagrangians

- The corresponding Lagrangians are given by combinations above with

$$S = \bar{\psi}_n \psi_p, \; P = \bar{\psi}_n \gamma_5 \psi_p, \; V = \bar{\psi}_n \gamma^\mu \psi_p, \; A = \bar{\psi}_n \gamma^\mu \gamma^5 \psi_p, T = \bar{\psi}_n \gamma^\mu \gamma^\nu \psi_p$$

$$S' = \bar{\psi}_{\nu^e} \psi_e, \; P' = \bar{\psi}_{\nu^e} \gamma_5 \psi_p, \; V' = \bar{\psi}_{\nu^e} \gamma^\mu \psi_e, \; A' = \bar{\psi}_{\nu^e} \gamma^\mu \gamma^5 \psi_e, T' = \bar{\psi}_{\nu^e} \gamma^{\mu}$$

- So there are a 10 parameter set of possible Fermi type Lagrangians (fewer with more conditions). What values of the parameters does nature choose?
- 1940s and 1950s, many experiments. β decay of many nuclei. Also meson decays. What is the proton neutron part of Hamiltonian? Interpretation of experimental results confusing. Rough consensus. β decays best explained by combination of S and T and maybe P.

Problems with Pions

- Coming back to pion decay. Can check pion decays mediated by either P or A. P leads to decay mainly into e^+. Experimentally about $(210)^2$ times more likely to decay into μ^+. Suggests no P, only A type coupling (this guess actually gets the factor of $(210)^2$ right). But then why dont we see A couplings in β decay. Was 'universality' wrong?
- In 1956 George Sudarshan was a young graduate student at Rockerfeller enters the story. In the next few slides I will describe his journey in his own words, using, as far as possible, direct quotes from Ananya Dasgupta's 2009 oral history interview of G Sudarshan for TIFR Archives.
- 1956: 'Then Marshak said, "You like weak interactions. Why dont you look into them?.. The textbooks at that time said it was scalar or tensor. But if it was scalar or tensor, the decay of the pi-meson into muon and neutrino should not take place anywhere near the rate at which it did."

Sudarshan and Weak Interactions

- "And there was some consideration at that time about universal Fermi interaction. I got the idea that they (all weak interactions) must be the same ... Then I looked at all the papers written on this. One of the things to do was to look at electron-neutrino angular correlation.... Eventually Madame Wu and others started using gaseous targets so that everything was out in the open and one could determine it very well. So the question was 'What was the interaction?"
- "I found all the claims of scalar and tensor were based on one experiment .... on the angular correlation Helium 6 decay.... (they) concluded that it was a tensor interaction because they found a positive angular correlation of a small magnitude...So when I told Marshak that this could be wrong, he said, "Don't ever say it aloud. People will laugh at you if you say Madame Wu is wrong." But she was wrong!"

- “I said as far as pi-decay was concerned it was very clear that it had to be axial vector or pseudo-scalar. Nothing else would work. So I went on the hunt to see why it should be axial vector. I found that there was very little reason why it shouldn’t be axial vector. I told Marshak that axial vector-vector seemed to be the universal one.”
- “This was just before the 1957 Rochester High Energy conference. He said, ” Look, you better be careful. If you say something like this and you are wrong, people will never again look at your work.” I said, ” That did not matter because I would be right.” He replied, ” You have no reputation to lose but I have a standing in the field.” So the net result was that I didn’t get the chance to present this. Five minutes would have made all the difference.”

Complications

- Marshak felt unsure of his students results and wanted them to be validated by an expert before going public. Returning to Sudarshan's words.
- “Marshak suggested that I have lunch with Murray Gell-Mann. Actually he wanted me to be examined by Gell-Mann. I told him that in this matter I knew better than Gell-Mann. But Marshak was insistent. So I presented every possible argument in great detail - almost like a legal brief. Gell-Mann was very impressed. Marshak asked, ”So what do you think of George?s work?” Gell-Mann said, ”First class! I think this is finally the solution.”

Delays

- “Then I was told by Marshak to write the thing up. I did it and gave him the write-up the next morning. He didn?t do a thing with it for two months! That was his mistake, his error in judgement... He simply thought that this was not very important!... He was busy with other things. So it never got sent to the journal. ”
- Marshak presented this paper in a conference a few months later. Before the conference proceedings were published Feynman and Gell Mann published a competing paper with the same results. For quite a while Sudarshan and Marshak’s ‘unpublished’ work was relatively unknown. It took decades for the actual sequence of publications to seep into the community’s consciousness.

Significance of $V - A$

- This talk is officially titled 'ECG Through the eyes of the younger generation'. This title emboldens me to give you my personal assessment of the importance of Sudarshan's work"
- For a while in the early 1950s, the problem of weak interactions must have seemed a matter of grungy detail. It must have appeared that the principles - Fermi's 4 fermion theory - were already in place. All that remained was to find the actual values of parameters. Some people might reasonably have felt that the precise values of the parameters - while important to get straight - were unlikely to teach you anything of deep conceptual significance. I suspect Marshak took this view.
- A modern analogy for such a scenario might be the determination of the precise values of all Yukawa parameters of the Standard Model.

Significance of V-A

- Sudarshan, on the other hand, appears to have been driven by the hope that the precise form of the four Fermi interactions would turn out to be simple, universal and beautiful. And he was correct.
- Sudarshan, on the other hand, appears to have been driven by the conviction that the precise form of the four Fermi interactions would turn out to be simple, universal and beautiful. And he was correct.
- This is what Feynman had to say about the beauty and thrill of his own discovery of the same effect. “As I thought about it, as I beheld it in my mind’s eye, the god damn thing was shining...Now it was not as beautiful as Dirac’s or Maxwell’s, but my equation for beta decay was a bit like that”
- The answer was so simple and beautiful that it must have seemed likely that this result would be the key to progress. It was.

- In my opinion the discovery of V-A made the subsequent developments in the Standard Model almost inevitable. It made it clear there was something beautiful to uncover.
- So it proved. The vectorial nature - and universality- of the 4 Fermi interaction was the the key to uncovering the $SU(2)$ gauge structure of weak interactions.
- The $V - A$ (rather than V) nature of interactions was the key to uncovering its chiral nature: the fact only positive chirality fermions are charged under the weak $SU(2)$.
- In my mind $V - A$ was one of the great scientific accomplishments of the previous century.
- We can all be very proud that this discovery was made in large part by a young Indian, who grew up in a small town in Kerala, a student of Madras Christian College and then TIFR, just a couple of years out of India.