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THEORY OF PRIMARY INTERACTIONS OF ELEMENTARY PARTICLES*+

E. C. G. Sudarshan

Physics Department
Syracuse University
Syracuse, New York

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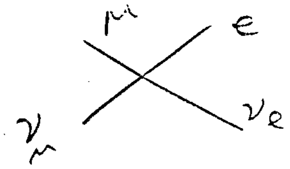
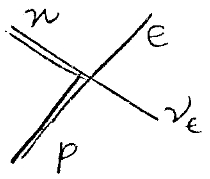
About ten years ago, we had the pleasure to discover a universal interaction for describing weak interactions between particles which was the logical completion of a theoretical framwork outlined in papers written in 1934 by Fermi and in 1936 by Gamow and Teller. This "phenomenological" interaction seems to violate some tenets of field theory that one normally expects things to obey but somehow our theory seems to have survived with modifications here and there. We also have another "phenomenological" interaction which is somewhat older: namely, the interaction of electrons with the electromagnetic field. However, in looking back on the period 1934 to 1936, one comes across another fundamental paper on β -decay which for some reason has been ignored for sometime. This is the paper written by Yukawa in 1935. In this paper it was pointe d out that the a particle associated with a new quantized field (called meson field) exists; it was supposed to serve as the agent for strong interactions between nuclear particles as well as carry the beta-decay of the nuclear particles. The beta-decay was the property of the meson, which was then induced onto the nuclear particles. I have recently reexamined this particular suggestion (which had fallen into disfavor in recent times) and it seems to me that then particle physics phenomenology finds a theoretical explanation in terms of three parameters, one for each interaction, provided we take the particle masses to be given. So given all the masses, and assuming one coupling constant for each kind of interaction it appears to be possible within the present theoretical framework to be able to explain most of the salient features provided you don't look beyond ten or fifteen percent "fits" to experimental numbers.

We begin with the familiar expressions that one has for weak interactions of leptons, weak interaction of baryons, effective electromagnetic interactions of protons and "phenomenological" interactions of electrons.

$$\frac{G}{\sqrt{2}}\left(\bar{e}\,\gamma^{\lambda}(1+\gamma_5)\,\nu_e\right)\left(\bar{\mu}\,\gamma_{\lambda}(1+\gamma_5)\,\nu_{\mu}\right)^{+}$$



$$\frac{G}{\sqrt{2}}\left(\bar{p}\,\gamma^{\lambda}(1+g_A\gamma_5)\,n\right)\left(\bar{e}\,\gamma_{\lambda}(1+\gamma_5)\,\nu_e\right)$$

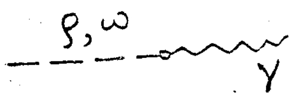


$$e\;\bar{p}\,\gamma^{\lambda}p\;a_{\lambda} \qquad (1)$$

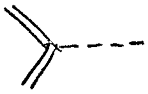
$$\bar{e}\;\bar{\psi}\,\gamma^{\lambda}\psi\;a_{\lambda}$$

In place of these interactions of hadrons, following Yukawa, we introduce two other interactions of nuclear particles to the mesons. (There are lots of mesons these days so I have to write so many of these expressions!)

$$-\frac{e}{g}\left(m_\rho^2 V^{\lambda}+m_\omega^2 W^{\lambda}\right)\cdot a_{\lambda}$$



$$g\,\bar{N}\left[\tfrac{1}{2}\,\underset{\sim}{\tau}\cdot\left(V^{\lambda}\gamma_{\lambda}+(g'/g)\,V^{\lambda\nu}\tfrac{1}{2}\sigma_{\lambda\nu}\right)\right]N \qquad (2)$$



$$+\,g_0\,\bar{N}\left[\tfrac{1}{2}\left(W^{\lambda}\gamma_{\lambda}+(g_0''/g_0)\,\Phi^{\lambda\nu}\tfrac{1}{2}\sigma_{\lambda\nu}\right)\right]N$$

which is the hadron strong interaction. The V_λ, V_λ are components of the vector meson field; there are the four-vector components V_λ, there are six tensor components V^λ ; these quantities V^λ and W^λ are all vector fields; V^λ is an isotopic vector, W^λ is an isotopic scalar: these are the kinds of particles that we happen to have. In addition, for the hadron electromagnetic interaction I introduce a new kind of interaction following the suggestion for β-decay: we assign the electromagnetic property of the hadron, entirely and exclusively to the vector field. The vector fields are directly coupled to the electromagnetic vector potential. [I do not have a term quadratic in e but probably if I find trouble along the way I might add it on.] As a consequence of this, the electromagnetic interactions of the nucleon is now a "derived property", it is exclusively obtained by means of the intermediary of the ρ, ω fields. The gauge invariance of this interaction, or at least charge conservation, now requires that the vector field be absolutely conserved. There are two vector fields; therefore both of them must be conserved.

$$\partial_\lambda V^\lambda = 0 \; ; \; \partial_\lambda W^\lambda = 0 \; ;$$

$$g_0 = g \quad . \tag{3}$$

It also follows that to the extent that the coupling constants are the same, as I have written, it follows that the coupling of these two mesons to the nucleons must equal so that the neutron charge should be zero and the proton charge is precisely equal to the electron charge; and experiment says that the neutron charge seems to be very very small. Assuming this kind of coupling, we might now ask: is it possible to calculate other electromagnetic properties? We have already used the charges to normalize the vector meson-photon coupling.

I have tried to make a computation of the magnetic moments. The results are

$$K_1 = \frac{2m}{m_\rho}\frac{g'}{g} = \frac{10}{3}\frac{m}{m_\rho} = 4.1 \qquad (3.7 \text{ expt})$$

$$K_o = \frac{2m}{m_\omega}\frac{g_o'}{g_o} = 0 \qquad (0.1 \text{ expt}) \qquad (4)$$

$$-\mu_p/\mu_n = 1 + \left(\frac{g}{g'}\right)\frac{m_\rho}{m} = 1.49 \qquad (1.48 \text{ expt})$$

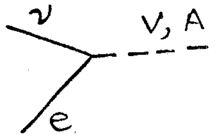
These are the truly anomalous moments which do not contain the contribution of the Dirac moment. In (4), g' is the tensor coupling of vector mesons, g is the vector coupling of the vector meson. This g comes in the denominator because of the fact that we have used it to normalize the electric charge. Within a certain framework of strong interactions g'/g can be taken to be 5/3. [The SU(4) scheme is so familiar that I dare not mention it in detail!] In that case, of course, you get a numerical value for the isovector magnetic moment of 4.1 units; the experimental number is 3.7. Under the same conditions one could also arrange to have the isoscalar magnetic moment equal to zero: it is not absolutely dictated but it seems to be a fair approximation to choose this quantity equal to zero. The ratio of the two proton magnetic moments can be computed but of course this is a reexpression of the above predictions; the numerical value that appears here depends upon the choice of g'/g; and the g'/g that I have chosen is 5/3. The result appears as the third member of (4).

We have now two universal interactions which are related to each other: the vector universal interaction of all baryons and the electromagnetic interaction of all baryons; they are universal because of the fact that the photon coupling is mediated by the vector mesons and the vector mesons are coupled in the universal fashion. Well, if you have this and these are both universal interactions and of course it would be nice to have the β -decay interaction also, at least the vector part of it, as a universal interaction; and this of course is now a familiar idea. The only thing is that since the time of Yukawa we have many more mesons and therefore we have our choice of which mesons are to be used for mediating the weak interactions. Of course, it was necessary to discover these mesons because it was known since 1936 that there was a Gamow-Teller part of the interaction and if you had only pi-mesons mediating the interaction then of course you could not get either Fermi or Gamow-Teller, you would only get an effective pseudoscalar interaction. We now consider our axial vector (isovector) meson field:

$$\partial_\lambda A^\lambda \longrightarrow \xi m_\pi \phi_\pi \quad (\mathrm{PCAC})$$
$$A^\lambda = B^\lambda + (\xi / m_\pi)\, \partial^\lambda \phi_\pi \,. \qquad (5)$$

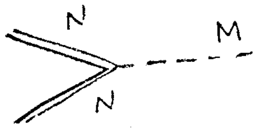
These expressions are nowadays very familiar; for the axial vector field the divergence is proportional to the pion field. The axial vector field therefore contains two parts. B^λ must be divergence free. The weak interactions are now written in essentially the same form as the electromagnetic interactions.

$$-\frac{G}{g}\,(m_A^{\,2} A^\lambda + m_\rho^{\,2} V^\lambda)\,(\bar{e}\gamma_\lambda (1+{}_5)\nu_e\,). \qquad (6)$$



The vector and axial vector fields come along with their masses so that the quantities in the brackets have the dimensions of a density, so that we could choose the G that appears here to be a universal coupling constant both in purely leptonic interactions and in semileptonic interactions. And this normalization of $(-m_\rho^2/g)V$ is exactly the same as we had used for electromagnetism; therefore the fact that the same field is coupled now immediately says that the magnitude of the weak charge must be exactly the same for leptons and baryons. As a consequence of this interaction together with the fact that the mesons are coupled to the lepton covariants we now have an effective interaction which is written down below:

$$\bar{N}\ M\ N$$



$$M = f\,\tfrac{1}{2}\,\underset{\sim}{\tau}\left\{\gamma^{\lambda}\gamma_5\,\underset{\sim}{A_{\lambda}} + (f'/f)\,\sigma^{\lambda\nu}\gamma_5\,\tfrac{1}{2}\,A_{\lambda\nu}\right\}$$

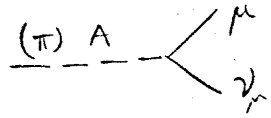
$$+\ g\,\tfrac{1}{2}\,\underset{\sim}{\tau}\left\{\gamma^{\lambda}\,\underset{\sim}{V_{\lambda}} + (g'/g)\,\sigma^{\lambda\nu}\,\tfrac{1}{2}\,\underset{\sim}{V_{\lambda\nu}}\right\} \qquad (7)$$

$$+\ g_o\,\tfrac{1}{2}\left\{\gamma^{\lambda}\,W_{\lambda} + (g'_{oo}/g_o)\,\sigma^{\lambda\nu}\tfrac{1}{2}\,\Phi_{\lambda\nu}\right\}\ ;$$

$$g' = \tfrac{5}{3}\,g \quad , \qquad g'_{oo} = g\ .$$

It produces an effective interaction; I have to go beyond the previous interaction (2) for the strongly interacting particles to include the axial vector field couplings. Previously I wrote down only vector meson tensor- and vector-coupled to the nucleon, now I have to consider the couplings of the axial vector meson; so I write down two corresponding terms for the axial vector mesons. Again, depending upon the numerical values for these ratios, one would be able to make predictions but apart from the details of the numerical values of the coupling constants there is still a direct connection between the strong coupling constants of the vector and axial vector fields (and by implication, of the pseudoscalar field) with the strong and the weak interaction of the strongly interacting particles. Associated with these fields there are three particles: the ρ meson which was discovered around 1960, the pi meson which was discovered around 1945 and A_1 which has not yet been discovered but will probably be discovered next year. It has been found that the ratio of axial vector to vector coupling constants have the numerical expression which is very well represented by $\sqrt{25/18}$, and in this theory, this particular number is equal to the ratio of the two coupling constants because of the fact that (the vector meson propagator essentially balances the squares of the masses which are appearing in the coupling term and therefore) this is a direct measure of the ratio of the strong coupling constants. One would like to arrange for a strong coupling interaction which would produce f/g to be equal to $\sqrt{25/18}$. Now we have the 5/3 from SU(4), so if we want an additional factor of $\sqrt{2}$ we may look for a mechanism of producing such. We know for example that in the Kemmer coupling of pions with nucleons the charged mesons are coupling by a stronger factor of $\sqrt{2}$ than the neutral mesons; and it comes in essentially from the normalization of the charged meson field in terms of the two components. So I make use of a corresponding scheme in which I assign the scalar-isovector, pseudovector-isoscalar, and pseudovector-isovector meson states to form a meson matrix. If you'll do this, since the pseudovector-isovector has two different kinds of components, the vector and the tensor components of the axial vector field. Both the space components and the time-space components are large in the nonrelativistic limit; they are both Gamow-Teller interactions. Consequently I keep both of them. When you have two of a good thing you take both of them, but then you have to remember to introduce the normalization factor ($1/\sqrt{2}$). This yields f/g = $\sqrt{25/18}$.

We could now calculate the pi-meson decay.



$$\frac{G\, m_A^2\, \xi}{g}\; \frac{1}{m_\pi}\, \partial^\lambda \phi_\pi\, \bar{\mu}\, \gamma_\lambda (1+\gamma_5)\, \nu_\mu$$

$$= h\, \frac{1}{m_\pi}\, \partial^\lambda \phi_\pi\, \bar{\mu}\, \gamma_\lambda (1+\gamma_5)\, \nu_\mu \qquad (8)$$

$$\tau(\pi) = 2{\cdot}551 \times 10^{-8}\ \mathrm{sec} \quad ; \quad G = 2{\cdot}43 \times 10^{-7}\, m_\pi^{-2}\, ,$$

$$h(\pi) = 1{\cdot}48 \times 10^{-7} \quad ; \quad (\xi/g) = 1{\cdot}02 \times 10^{-2}\, ,$$

The pi-meson decay contains only known constants; the quantity m_A^2 is the square of the axial vector meson mass, it is now well known that it is approximately 2 times the square of the meson mass. One can calculate the ratio (ξ/g) of two parameters. [They may appear unfamiliar, but during this ten minutes that I have I would not have a chance to explain it fully!] In terms of this value of $\xi/g = 10^{-2}$ and the value of the weak coupling constant, making use of the divergnece condition (PCAC) we can compute both ξ and g. The vector coupling constant g comes out to be nine.

I have also tried to calculate the magnitude fo CP violation implied by (7), since we introduced a tensor coupling of the axial vector meson. This coupling is CP violating unless you very specially arrange the coupling constant to be pure imaginary. I don't choose it to be imaginary and therefore there is a CP violation. If you have one Mev energy release in the β-interaction, the corresponding CP violation is of the order 10^{-3}. This morning we heard from Cronin that this degree of CP violating is too small to be tested experimentally (even though experiments are improving rapidly!). I have also tried to calculate the strange particle axial vector and vector decay. I calculate the ratio of the π meson and K meson decay. This follows in spirit a scheme of calculating weak interaction due to Pradhan and Patnaik, who observed that if you make use of a certain scheme of calculation in which you said that the axial vector currents had equal matrix elements, then you find that the observed suppression of the K^+ seems to be produced phenomenologically. In our theory this scheme is recovered and the Cabibbo suppression factor is the familiar number $\tan\Theta = m_\pi/m_K$. We have

$$
\begin{aligned}
M(\pi^+ \to \mu^+\nu) &= h'_\pi \cos\Theta_M\, \partial^\lambda \phi_\pi\, \bar{\mu}\, \gamma_\lambda q_\pi^\lambda (1+\gamma_5)\nu \\
M(K^+ \to \mu^+\nu) &= h' \sin\Theta_M\, \partial^\lambda \phi_K\, \bar{\mu}\, \gamma_\lambda q_K^\lambda (1+\gamma_5)\nu \qquad (9) \\
\tan\Theta_M &= (m_\pi/m_K) = 0.28
\end{aligned}
$$

Approximately the same method was used for lambda decay and one finds a difference angle there but it has practically the same numerical value:

$$\Gamma_A^{\lambda} = F_1 \gamma^{\lambda}\gamma_5 + F_2 \gamma_5 q^{\lambda}$$

$$\partial^{\lambda} A'_{\lambda} = \xi m_K \phi_K$$

$$(m_A + m) F_1 = \frac{3-2d}{\sqrt{6}} 2m m_{\pi} g_A \tag{10}$$

$$\tan \theta_B = \left[1+\tfrac{1}{2}(m_{\Lambda}-m_N)\right]^{-1} \cdot \frac{m_{\pi}}{m_K} = 0{\cdot}26$$

$$F_1 = \frac{3-2d}{\sqrt{6}} \tan\theta_B \; g_A .$$

For the strange vector interaction, I continue to require that the divergence of this quantity be equal to zero and my excuse for this is that we do not seem to find any scalar strange particles, unlike in the axial vector case; and therefore I would like the divergence of the strange vector field to be equal to zero. If I demand this, then I find that the corresponding coupling seems to be very small. We have:

$$\Gamma_V^{\lambda} = G_1 \gamma^{\lambda} + G_2 \sigma^{\lambda\nu} q_{\nu} \; ;$$

$$\partial_{\lambda} V^{\lambda} = 0 \Rightarrow 0 = (m_A - m) G_1 \; ; \qquad G_1 = 0 . \tag{11}$$

This of course does not mean that there is no vector coupling, it simply means that the dominant term in the vector coupling disappears; it becomes something like the neutron electromagnetic interaction. There is always the possibility of a charge radius kind of effect that is coming.

For the nonleptonic weak interaction one could try to make use of this kind of mediation by vector and axial vector fields by considering the interactions.

$$G \sqrt{2} \, (m_A^2 A^{\lambda} + m_V^2 V^{\lambda}) \; (m_A^2 A'^{\lambda} + m_V^2 V'^{\lambda}) \qquad \text{"charged"} \tag{12}$$

In this theory since the strange vector mesons refuse to couple directly to the baryons in a reasonable fashion, the K* exchange mechanism is no longer valid and one would have to do something else. I have estimated these numbers and it seems that it produces a refined version of the pole model of Salam, Feldman and Mathews both for the parity violating and parity conserving things and the numbers seem to be of the right order of magnitude.

The right place to test the theory of strong interactions is in the phenomenology of the nuclear force. There is an old problem with regard to the singularity of the tensor force; even though one does not believe in a simple perturbation calculation it is still nice to be able to cancel out the singularity. If you look at this, following some old work of Møller and Rosenfeld and of Schwinger, one finds that there are terms of the kind

$$e^{-m_\pi r} \cdot r^{-3} ,$$

but if you have the various meson fields there are lots of such singular terms and they have to cancel each other. This yields

$$\left(\frac{f\xi}{m_\pi}\right)^2 + \left(\frac{f}{m_A}\right)^2 - \left(\frac{f'}{m_A}\right)^2 - \left(\frac{g}{m_\rho}\right)^2 = 0 . \qquad (13)$$

In my theory since f and f' are equal, the second and third terms cancel each other, therefore the 1st and 4th have to cancel each other. This implies

$$(m_\pi / m_\rho) = (f\xi / g) = 0.13 \qquad (14)$$

The "observed" ratio is 0.18. The agreement is not too good but it is interesting that it is of the right order of magnitude.

One could also make use of this kind of machinery for making other predictions. I indicate another sum rule which is very familiar from symmetry groups, which seems to be obeyed very well; it also follows automatically from the present theory. It is

$$M(\pi^{+} p \rightarrow \pi^{+} N^{*+}) = M(\pi^{-} p \rightarrow \pi^{-} N^{*+})$$

$$A_1/A_3 = + \sqrt{10} \qquad (+3.34 \text{ expt}) . \qquad (15)$$

Pradhan, Saxena and I have calculated scattering lengths; this calculation shows that if you use the large vector and axial vector coupling constants you seem to be able to reproduce the s- and p- wave pion-nucleon scattering lengths.

I would like to end with a comment. It may be pointed out that these are "effective", "phenomenological" interactions. But then who would want ineffective interactions, or interactions at variance with phenomena?

Thank you.