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THE WEAK INTERACTION: PAST ANSWERS, PRESENT QUESTIONS

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by

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From β-ray to π-decay[1)]

It is with feelings of high appreciation and of warm affection that we have come here today to honor our colleague Robert Marshak's six decades and to discuss the five decades of the Weak Interaction. I have been asked to open with a historical sketch of the latter. However, the two topics are closely related: research-wise, Marshak's most important contributions have pertained to this field, even though he has made very important ones in astrophysics, nuclear physics, etc.; and it is impossible to discuss the history of the Weak Interaction without mentioning Marshak's name at every major step.

The Five Decades in the title of our Conference notwithstanding, it was almost exactly eighty years ago, in February 1896, that Henri Bequerel discovered radioactivity, and it was in 1899-1890 that he identified β-radiation as one component of radioactivity and then showed it to be composed of electrons.

Indeed, it was because of the bad weather on February 26 and 27, 1896 that Bequerel left his photo-plates in a drawer for two days, together with the crystal of potassium uranyl sulphate from his (physicist) father's collection. Lack of sunshine had made him postpone the continuation of his series of sunlight exposures, originally motivated by the belief that the effect on his plates was caused by phosphorescence of a salt which was known to be luminescent. Bequerel's scientific method made him develop the plates from the drawer as "controls"--and radioactivity and the nuclear interactions were ushered in.

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This was indeed the first laboratory observation of a nuclear effect and of a Weak Interaction process. However, it was generally interpreted in terms of nuclei with electrons as constituents. We have to wait for another 36 years, until 1932, when the experiments of Bothe and Baker, Irene and Frederic Joliot-Curie and of H. C. Webster, are reinterpreted by J. Chadwick as due to the existence of the neutron, an interpretation which is then given direct experimental proof in the 1934 photo disintegration of the deuteron by M. Goldhaber and Chadwick. Heisenberg's suggestion, that nuclei are made of nucleons and do not contain "nuclear electrons", then transforms β-radiation into β-decay, emphasizing for the first time the charge-changing transition occurring within the nucleon multiplet. With Pauli's neutrino conjecture providing for a similar lepton multiplet the stage was set for Fermi's 1933 conceptual great leap forward and for his laying the foundations of a β-decay current-current description (later generalized by Puppi, Klein, Lee Rosenbluth and Yang, Tiomno and Wheeler, and by Dallaporta to include all Weak Interactions). This is how the eight decades of dealing with Weak processes reduce to less than five decades of doing it consciously.

In the same year 1933, the Joliot-Curie's discover the next Weak process, positron emission, right after the discovery of the positron in cosmic rays by C. Anderson. In 1936, Yukawa and Sakata predict K-electron capture, which is indeed observed by L. Alvarez in 1938. The other processes connected with β-decay via crossing, came much later, since they required the development of high flux neutrino sources and of appropriate detection techniques: Reines and Cowan's $\bar{\nu} + p \rightarrow n + e^+$ (1953,1956), Davis' expt. proving $\nu \neq \bar{\nu}$ etc.

The discovery of the muon and the study of its decay mode and of its interaction with nucleons provided a second set of Weak processes, once the coupling was evaluated directly, (Pontecorvo, 1947). Bethe and Marshak (1947) then postulated[2)] the existence of another "meson", the π, with a Weak decay $\pi \rightarrow \mu + \bar{\nu}$, the first Weak decay of a meson. They estimated the lifetime of their hypothetical π and found a figure of 10^{-8} sec, even though they used wrong spin assignments in their model calculation. Sakata and Inoue, and T. Tanikawa had previously (1946) put forth a similar idea, with correct spins but without distinguishing between Strong and Weak couplings (just as Yukawa's theory did not contain the distinction) and thus getting very different lifetime estimates. With $\mu^{\mp} \rightarrow e^{\mp} + \bar{\nu} + \nu$, $\mu^- + p \rightarrow n + \nu$, $\mu^+ + n \rightarrow p + \bar{\nu}$ (and in 1962 $\nu_\mu + n \rightarrow p + \mu^-$) it became clear that one coupling and one general Hamiltonian were involved, and the suggestion of a "Universal" Fermi interaction started evolving. Some of the discussion referred to the choice of the more fundamental description: should $\pi^- \rightarrow \mu^- + \bar{\nu}$ be described as a Strong πNN vertex followed by a β-decay diagram, or should it be considered in terms of the more fundamental Weak vertex, and β decay or μ absorption be given by the Strong $NN\pi$ followed by π-decay? We now know that the latter description (advocated by Marshak in 1949) fits well the axial vector part, where the π is proportional to the divergence of that current (PCAC) but that the most general description is anyhow in terms of a quark-current coupled to an Intermediate Boson.

The V-A Theory of Marshak and Sudarshan[3)]

The development of physical theories may follow extremely intricate paths. The only obvious example of almost a single jump to the complete theory is Einstein's discovery of General Relativity, and even that took ten years of gradually overcoming the various difficulties. Still, that theory has stood up to every challenge for sixty years of active twentieth century physics, cosmology and astronomy. However, it was a theory in which a large amount of experimental data had been known for centuries and had already been beautifully synthetized by Newton, and where the problem consisted in finding the correct relativistic general theory.

For the Weak interaction, we are still in the age of Tycho-Brahe Kepler and Galilei, with Newtonian flashes once in a while. In Lakatos' approach to the History of Science, growth is described as going by "programs". Here, Fermi had indeed defined a program, which it took 25 years to complete. Theoretical preconceptions had to be removed, e.g. notions such as the Conservation of Parity as a natural must. Further partial clarification was supplied by Lee and Yang, by Salam and by Landau, with the understanding of the role of the massless two-component neutrino and of chirality. Notice incidentally, that the role of chiral transformations in space-time was only understood very recently, when it turned out that the supersymmetric graded extension SU(2,2/1) of conformal transformations in space-time actually requires chiral transformations as a sixteenth generator E of the ordinary Lie subalgebra; i.e. the conformal $SU(2.2)_C$ is connected to E in $SU(2,2)_C \times U(1)_E$

as a group extension within SU(2,2/1).

It seems that more than in any other case, the synthesis was obstructed by wrong experimental results. When in the summer of 1957, Sudarshan and Marshak accomplished their synthesis and settled for a V-A effective Hamiltonian, they had to assume that one published and three unpublished experiments had reached erroneous conclusions and should be repeated.[30)]

Symmetry-wise, the V-A Hamiltonian implied CP invariance, replacing the lost laws of C and P conservation. It also meant that the weak current was left-handed, and that chiral invariance was preserved. This also explained the zero-mass neutrino. The recovery of a new (discrete) fundamental symmetry principle (CP) explained the quantitative aspect of P-violation; in fact it predicted a maximal violation. This happy state of affairs should be compared with the situation that we have been facing since 1964, with respect to the CP violation (and T violation) discovered by Fitch and collaborators[9)] in K_2^o decay. After 13 years, we still have no understanding of this "small" violation, no principle providing an explanation for $\varepsilon = .002$ (among others, Marshak and Okubo have put forth a theory of the Milliweak type). Indeed, now that various unified theories are suggested with "spontaneously" broken symmetries, we encounter models (such as in some of the "vector-like" theories) in which the CP invariance of the effective "low-energy" Weak Hamiltonian becomes somewhat accidental.

CVC - a Principle of Equivalence[3)]

The Feynman-Gell Mann version of the V-A synthesis emphasized the Conserved Vector Current (CVC) idea, originally suggested by Gershtein and Zeldovich. This was the extension of a principle encountered in QED, the equality of renormalized electric charges for hadrons and leptons, assuming they share the same bare charges (in magnitude). The Strong interactions contributing to the hadrons' renormalized charges must somehow cancel, since the result is the same as for the leptons, where there are no such Feynman diagrams. This is explained by the fact that the electric current happens to be the density of the charge algebraic generator, a symmetry of the Strong (and other) interactions.

The model for such a principle was in fact Einstein's Principle of Equivalence. Einstein explained the equality between the gravitational mass (i.e. the coupling) and the inertial mass (a conserved quantum number of the Poincare' group) by postulating that the gravitational field be coupled to the energy-momentum tensor, i.e. to the density of the conserved generator of momentum. Since P^{μ} is conserved by all interactions stronger than gravitation, $\theta^{\mu\nu}$ is not renormalized, and the Principle of Equivalence holds for all matter. Okubo, Ioffe and Takahashi showed[5)] how the same thing occurs for the $\mathcal{J}$-spin current (provided it includes all fields as derived from the Lagrangian following Noether's theorem), just as the QED case had been understood in great detail through the Ward identity. In the 1960 Rochester conference (and Rochester conferences are another of Marshak's initiatives), Gell-Mann showed how the principle should hold for a "rotated" Weak $\mathcal{J}$-spin, in the

in the event that $\nu_{\mu} \neq \nu_{e}$. This was later realized within SU(3) by Cabibbo[6)] with great success. CVC was first vindicated by the observation by Fassini et al. of $\pi \rightarrow e+\bar{\nu}$ at the rate predicted by the theory, again in contradiction to previous experimental results.

<u>Universality - an Algebraic Condition</u>

For the Weak Interactions to be "Universal", as suggested in a general way by Puppi and others, several elements were required: (1) the above mentioned non-renormalization by stronger interactions (explaining the near-equality of μ and β decay <u>vector</u> couplings), (2) a similar principle for the axial vector current, and (3) equal bare couplings (or rather couplings whose values obey some fixed ratios) for either the vector and axial vector currents separately, or for the entire left-handed current. The provision that the current coincide in its hadron vector part with the density of a strong interaction symmetry generator provided for requirement (1) only. The Goldberger-Treiman (1958) relation and its more refined "PCAC" versions provided for (2). Requirement (3) could be construed at two different levels of rigor in the interpretation of universality. One could rest satisfied with the existence of a symmetry algebra obeyed by the Strong Interactions and under which the Weak Hamiltonian has a well-defined behavior. Fields and particle-states are then assigned to its representations. Even if all fundamental fields were put in one irreducible representation (say quarks, in 1977 parlance), the coupling for particle states might have a free scale parameter (which could still be fixed thanks to electric charge universality, i.e. by identifying the electric charge component, provided it is entirely contained in that "flavor" algebra). It might also have additional freedom, such as an F/D parameter for octet states, etc.

If however the Weak charge is identified with the algebra directly, the commutation relations of the Lie algebra provide a non-linear relation which fixes the couplings completely. They are then identical with the amount of "charge" carried, whatever the multiplet. This fixes for octets a pure F-type coupling, for the SU(3) vector current or in chiral $SU(3)_L$ for the entire Weak current. The mathematical formulation of universality had been studied by Gell-Mann and by Glashow. The issue was reconsidered in the definition of "current algebra". Identifying the coupling with a "charge" means that the zero momentum--transfer matrix element (i.e. the Coulomb-like part, the low-energy limit of the coupling) is given by a number, which is the matrix element of the abstract matrix representing the algebra for this particular representation, and between these particular components.

One of the earliest versions of such an algebraic system was the Gamba-Marshak-Okubo ("GMO") $SU(3)_L$ hypothesis,[7] also independently suggested in Japan by the Nagoya group and by Thirring in Europe. This incorporated the $(pn\Lambda)_L$ Sakata triplet, adjoining the lepton $(\nu e^- \mu^-)_L$ triplet. The model had many advantages; the $(pn)_L$, $(\nu_e e^-)_L$ subset has almost survived and is incorporated in the Weinberg-Salam model for the symmetric fundamental (as against the "effective" 4-Fermion V-A) Yang-Mills type Hamiltonian

except that $(pn)_L$ have been replaced by the relevant valence quarks $(ud)_L$ active in the (pn) transition. The triplet structure had to be discarded when ν_μ was proved to be different from ν_e; but the GMO approach has now been vindicated with the discovery of Charm and the parallelism of the Weak quartets: $(u,d';c,s')_L$ and $(\nu_e,e^-;\nu_\mu\mu^-)_L$ where c is the charmed quark, $d' = \cos\theta d + \sin\theta s$, $s' = -\sin\theta d + \cos\theta s$. This does not reflect recent experiments at SIN (by the Engfer group, a Un. of Zurich - ETH-S/N collaboration[9] who have found 6 events looking like $\mu^- \rightarrow e^- + \gamma$, which they feel cannot be explained by their background. This, if confirmed, is around the previous bound of 10^{-8} of all μ decays. The two neutrinos would mix, (perhaps through some other "heavy" neutrinos, as in one model[10]) so that the lepton quartet becomes $(\nu_1',e^-;\nu_2' \mu^-)$ with $\nu_e = \nu_1' = \nu_1 \cos\alpha + \nu_2 \sin\alpha$ $\nu_\mu = \nu_2' = -\nu_1 \sin\alpha + \nu_2 \cos\alpha$

In various models, the $\nu_e - \nu_\mu$ "direct" transition (i.e.α) is of order G_F or even $G_F^{1/2}$. The first suspicion regarding such a violation of muon-number was raised by Gribov and Pontecorvo [11] in an attempt to explain the missing solar neutrinos[11] (where it could provide a factor of 2).

Local gauge couplings (a la Yang-Mills) are automatically universal and unrenormalized. However, in the decade of the sixties, when field theory was held somewhat in disrepute, the emphasis was put on the algebraic relations and the system of currents, which were easier to define in terms of measurable matrix-elements.[12]

Throughout the sixties--and to this day--the question of the complete isospin (and SU(3)) behavior of the non-leptonic $\mathcal{H}_W^{NL}$

remained open. The $|\Delta I = 1/2$ preponderance over $|\Delta I| = 3/2$ could be either an exact mathematical and physical statement or an effective renormalization effect.

PCAC

The fact that the axial vector coupling differed by only 20% in β-decay from the μ-decay value, encouraged searchers for an "approximate" CVC-like condition. Indeed Goldberger and Treiman[3)] found in 1958, using dispersion relations, a connection between the Strong π-N coupling and the μ-lifetime, a Weak process. This was reformulated in various attempts as just that missing condition: the Strong Interaction is invariant under a Chiral Symmetry such as $SU(3)_L \times SU(3)_R$ generated by scalar and pseudo-scalar charges whose densities coincide with the Weak vector and axial vector currents. However, the pseudoscalar charges are conserved through a Goldstone-Nambu mechanism,[13)] i.e. the Hamiltonian is invariant under these transformations even though the vacuum isn't. This is made possible through the existence of a "compensating" massless meson with the same Quantum Numbers as these charges, with a non-zero vacuum expectation value. The limit of a massless π corresponds to this exact conservation law. Another way of rephrasing this "conservation through compensation" statement was to state that the phenomenological π field is proportional to the divergence of the axial vector current, and since this is an exact compensation only for a massless π, it comes under the name of Partial Conservation of the Axial Vector Current (PCAC).

The vindication of this approach came when it was used in conjunction with the 1962-64 Gell-Mann reformulation of Universality, in terms of the Algebra of Charges--better known as "Current Algebra" because of the emphasis on the observability of the current densities through a first-order treatment of Weak and Electromagnetic transitions.[12)] Adler and Weissberger[13)] applied both postulates and came up with a good value of $\left|\frac{G_A}{G_V}\right| = 1.2$. An extensive series of interesting results relating to processes where a soft π is emitted or absorbed then ensued, and Nambu's soft-π theorems produced results in both Strong and Weak Interactions (such as the $K\to 2\pi$ to $K\to 3\pi$ relations etc.).

Let me just add that one of the more puzzling features of the recent successes of Gauge Field theories with spontaneous breakdown is that these beautiful results now appear fortuitious and that the π has now become a "pseudo-Goldstone" particle instead of a full fledged Goldstone-Nambu meson.

Field Theory Rehabilitated: a Renormalizable Weak Hamiltonian

Sometime in the mid-fifties, Relativistic Quantum Field Theory RQFT), which had been so successful in QED (though still not mathematically rigorous) had to be rejected as a tool for the study of either Weak or Strong Interactions. Weak--because the 4-Fermion Interaction Lagrangian was clearly unrenormalizable, and its conjectured "square-root", the current-intermediate boson Lagrangian appeared to have renormalization difficulties. The Strong interaction might or might not be renormalizable (the γ_5 Lagrangian of the fifties was OK, but the Lagrangian corresponding to Current Algebra π couplings of the late sixties wasn't) but in any case what was the meaning of a perturbative approach for $\frac{g^2}{4\pi} \sim 15$? Field theory went underground, Dispersion Relations flourished and Current Algebra served as a better-based field theory wherever it could be used.

For a decade and a half, one of the efforts pursued in that underground centered on the Yang Mills[15] Universal interaction. The sequence of contributions by Feynman, De Witt, Faddeev and Popov, and then very successfully[16] t'Hooft, managed to overcome this problem, with further additions by Veltmann, B. Lee and Zinn-Justin and by Slavnov. The end result included the case of a massive gauge boson, provided the mass is due to a Higgs-Kibble-Englert-Brout, etc. mechanism.[17] Field theory was back as far as the Weak interaction was concerned. Another application of that same Lagrangian structure led in 1973 to Asymptotic Freedom and the rehabilitation of Field Theory was complete since it could now be tried for the Strong Interaction as well. This is why in the QCD approach (but not in the Pati-Salam alternative) the true Strong Interaction is believed to involve the color gauge, whereas "flavor" Strong Interactions including SU(3) symmetric ones and PCAC become somewhat phenomenological (depending on the model).

It had always been accepted that the V-A Hamiltonian was probably a contracted second order term involving a more fundamental and hopefully renormalizable current-intermediate boson Lagrangian.

One indication of renormalizability had been pointed out by Okun and Pontecorvo[3] in 1957 when they noted that the K_L^o/K_S^o mass difference fitted a second order term in the Fermi interaction. A "factorized" $G^{1/2}$ renormalizable theory could now be treated meaningfully, and the Weinberg-Salam model[18] became testable. Its first prediction involved neutral currents, and they were indeed found[19] in 1973-74. Other predictions of the model have involved the mixing angle giving the two physical neutral currents (electromagnetic and Weak neutral) in terms of the $I_3^{(w)}$ and $Y^{(w)}$ of the Weak Isospin-Hypercharge SU(2) X U(1) set. Other parameters of the theory involve the Higgs fields, a subject of some uncertainty. Of course, a very important test would consist in the direct observation of the $W^{\pm}$ and Z^o when the necessary energies become available.

The existence of $\Delta S = 0$ neutral Weak currents at the usual intensity level implied the existence of "charm" and a fourth quark "C", as predicted by Glashow Iliopoulos and Maiani.[20] This would explain the inappearance of $\Delta S = 1$ strangeness-changing neutral currents at that intensity level. We have seen this prediction vindicated first by the discovery of the ψ-J states[21] in 1974 and then more directly by the discovery of "charmed" mesons by the G. Goldhaber group[22] in 1976.

Current Issues

As noted previously, some of the unanswered questions have been with us for a long time: the $|\Delta I| = 1/2$ rule or octet dominance, the CP violation, direct evidence for the existence of

$W^{\pm}$ and Z^{o}, the Higgs mesons. However, we also have new issues. Going from experiment to theory, we have:

1) the ratio[23] $R = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$ appears to have a value $5 \sim 5\frac{1}{2}$ in the region of 7-8 GeV. This serves to imply that in that region we have reached the threshold for the production of new quarks; another pair $(t_{2/31}\ b_{-1/3})$ would make R=5. Alternatively, it could imply the production of new leptons, or both a quark and a lepton.

2) there are about a hundred events[21)]

$$e^+ + e^- \to e^{\pm} + \mu^{\mp}$$

at SPEAR. They could be due to the production of a new lepton $U^{\pm}$, $e^+ + e^- \to U^+ + U^-$, $U^+ \to e^+ + \nu_e + \bar{\nu}_u$, $U^- \to \mu^- + \bar{\nu}_\mu + \nu_u$ with M(U) ~2 GeV. There is now corroborating evidence from DESY.

3) the ratio[25)] $S = \frac{\sigma(\bar{\nu}_\mu N \to \mu^+ + x)}{\sigma(\nu_\mu N \to \mu^- + x)}$ changes from $\frac{1}{3}$ at low energy (fitting theory) to $\frac{2}{3}$ at 150 GeV. This could be due to the appearance of V+A currents.

4) the $\bar{\nu}$ N events[26)] are also said to display at that energy an anomalously high y-distribution, which doesn't fit the $(1-y)^2$ predicted by V-A theory. It could be explained[27)] by V+A terms. Assuming for both (3) and (4) that the original quark is a $u_{2/3}$ quark, it cannot be connected by V+A to d', a well-known V-A transition (if the struck quark comes from an anomalously enriched $q\bar{q}$ sea, this conclusion doesn't hold). The V+A current thus involves a new (heavy) $b_{-1/3}$ quark. Note that the experimental status of the "high y anomaly" is still unclear.

5) Parity violation has been inferred for the hadron neutral

current from S in 3). Rumor has it that it is not seen in the leptons. This is either wrong or requires new theorizing.

6) It has been pointed out[28)] that the existence of charm-changing neutral currents would induce in order G "$\Delta C = 2$" effects, would make for a much more marked CP violation in the D^o-$\bar{D}^o$ complex etc. Do they exist?

7) can the new[9)] $\mu \to e + \gamma$ Weak interaction explain the μ-e mass-difference in some clever model? and what is then the general picture in the lepton set? And how well founded is the $\mu \to e + \gamma$?

8) is the CP violation due to additional quarks?[29)] It would be due to the existence of weaker V+A currents in the (udsc) set, or to new quarks and ordinary V-A currents.

9) the removal of triangle anomalies can be achieved by adopting a "vector-like" theory in which the P-violating terms appear only as a result of the diagonalization of the quark mass-matrix, i.e. they are a symmetry-breaking effect. However, such a theory generally implies pure vector neutral currents, which is contradicted by (5).

10) anomalies can also be removed by a proper balance between quarks and leptons. The number of L-quark doublets should be equal to the number of L-lepton doublets. This seems to represent an argument for Unified descriptions in which leptons and quarks appear in the same multiplet of a unifying group.

11) the introduction of the Higgs mechanism to explain the masses of $(W^{\pm}, Z^o)$ involves an entire set of theoretical issues connected with the $h\bar{q}\phi q$ coupling of the Higgs fields to the quarks. Presumably, $h \ll 1$. If, however, $h \sim 1$ the picture is much more complicated because the Higgs fields themselves play a role in mediating the

Weak Interactions. If doubled in number, they could also produce the observed CP violation.

As you see, with all our progress, we seem to have found more new issues than ever faced us before. That mark on Bequercl's film was really the tip of an iceberg, and who knows how much deeper it still goes!

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30. It is a pity that the ethical principles enunciated by Z. H. Koidonover (the second Marshak) in his treatise of good conduct "Kav Ha-yashar" ("the Straight Line") in 1700, were insufficient in distinguishing between Right or Wrong experiments. Z.H. Koidonover also edited the writings of his father, Morenu Rabbi SHmuel Koidonover ("our teacher Rabbi Samuel of Koidonovo") 1614-1676, the MaRSHaK (sometime MaHaRSHaK--from HaRav instead of Rabbi) the founder of this dynasty of scholars).