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I. Introduction

CURRENT PROBLEMS IN THE WEAK INTERACTIONS*

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Well, Bob, we have seen a thing or two happen to weak interactions, haven't we, since we first met in 1947 at the Shelter Island Conference^{*}? I recall a particular session during that meeting. Oppenheimer was officiating, in his inimitable priestly style. There was a discussion on what was then known in the trade as the Pinocchio effect (with apologies to Conversi, Pancini and Piccioni¹). You remarked at that time that the high production rate of cosmic ray mesons could be reconciled with their subsequent weak interaction with matter by the assumption that a strongly interacting mother meson decays into a non-strongly interacting daughter meson.² The first meson, our present pion, is now the lightest member of the large meson family to which, last year, we welcomed the D's, the charmed $S=0$ isodoublets. This year we anticipate the arrival of a newborn, the charmed F isosinglet ($S=\pm 1$). The second meson of which you spoke, the present muon, has for nearly thirty years appeared to be a member of a very small clan, the leptons, the μ and e , each with its attendant neutrino. However, of late there are signs that the lepton class is larger than we thought. The growing evidence³ for charged heavy leptons, $L^\pm$, is one of the most startling developments of the nineteen seventies. The existence of these particles strongly indicates - and there are more such clear signals - that the recent advance in

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* This meeting was held at the Rams Head Inn, Shelter Island, New York, June 2-4, 1947. It was followed by similar topical meetings at the Pocono Manor Inn (March 30-April 1, 1948) and at Old Stone on the Hudson (April 11-14, 1949). Out of these meetings grew the International Conferences on High Energy Physics, largely due to the initiative of Marshak who was then at the University of Rochester. For years these meetings were known as the Rochester Conferences, regardless of where they were held.

MASTER

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in the theory of weak interactions, impressive as it is, only constitutes one further step on the road toward the goal that still eludes us: a dynamical theory of weak interactions interwoven, no doubt, with electrodynamics and possibly also with the dynamics of strong interactions.

The advance to which I just referred is the $SU(2) \times U(1)$ gauge theory of the weak and electromagnetic interactions, with the following particle content (modulo color):

$$\left. \begin{array}{l} \text{left} \\ \text{doublets} \end{array} \right\} \left(\begin{array}{c} \chi_L \\ e_L \end{array} \right), \left(\begin{array}{c} \nu_L \\ \mu_L \end{array} \right), \left(n \cos \theta + \lambda \sin \theta \right)_L, \left(-n \sin \theta + \lambda \cos \theta \right)_L \\ \text{right} \\ \text{singlets} \end{array} \right\} e_R, \mu_R, \tau_R, \nu_R, \lambda_R, \tau_R \\ \text{one Higgs} \\ \text{doublet} \end{array} \left\{ \begin{array}{c} \phi^+ \\ \phi^0 \end{array} \right\} \text{ and its h.c.} \quad (1)$$

I shall call this the standard model (SM). There is promise that this model is part of the truth. There are good reasons to believe that it is not the whole truth. One of the aims of this paper is to spell out some of these reasons, (but not all of them. For example, I shall not discuss the early results on the atomic bismuth experiments which, if substantiated, would indicate that the neutral current of the SM needs modification⁴).

A first reason is already obvious. The SM does not contain $L^\pm$. Of course $L^\pm$ can be incorporated in $SU(2) \times U(1)$ without much pain. Later on we shall see that also the quark content of the SM may be incomplete. Again it may be that this can be remedied by enlarging the particle content of the standard $SU(2) \times U(1)$ model. However, there is a second question of enlargement which is often discussed: is it sufficient

to increase the particle content in $SU(2) \times U(1)$ or is it (also) necessary to enlarge the group? I would not be surprised if group enlargement were necessary. In this paper I shall refrain from pursuing this question further, however.

It is not the only purpose of this paper to raise questions on the level of the structure of gauge theories. Also on the mundane^{*} level of instrumentation, experimentation and theoretical analysis the new particles present new problems and I should like to mention some of these. A main issue which arises is how to determine the properties of particles whose life times are in the awkward range of 10^{12} - 10^{14} secs. Questions once asked for the muon must be asked again for heavy leptons. Questions once asked for strange particles must now be asked for charmed particles. CP studies once made for the K^0 - $\bar{K}^0$ system must now be done also for the D^0 - $\bar{D}^0$ system. It may seem as if these are instances of history repeating itself. It should be a matter of concern to experimentalists and theorists alike that in important ways this is not quite true.

Having stated my two main themes, let me turn next to some specific questions concerning leptons.

^{*} The word mundane has several usages. The one I have in mind here is "Belonging to the 'world' as distinguished from the church"⁵.

II Action on the lepton front

(a) $\mu \rightarrow e \gamma$?! $\mu \rightarrow 3e$??!

Once upon a time there came from a far country, known for its great natural beauties, the steadfastness of its citizens and the power of its banks, a rumor that $\mu \rightarrow e \gamma$ had been observed. The time was a few weeks ago.

Particle physics is breathless enough as it is without discussion of rumors in lectures. Yet it is impossible to discuss the current problems in weak interactions without mentioning that the $\mu \rightarrow e \gamma$ question is on the minds of all concerned. In the absence of hard information, let me address the question, an honest one in any event: Can $\mu \rightarrow e \gamma$ be incorporated in the gauge theory strategy without doing violence to the published bounds⁶ on the rate for this process?

The answer is: yes, in a variety of ways, all of which evidently necessitate a departure from the SM. Let me mention here only one example, the first of its kind to be proposed.⁷ The group is $SU(2) \times U(1)$, the lepton sector is enriched* with two neutral heavy leptons, N_1 and N_2 :

$$\left. \begin{array}{l} \text{Left} \\ \text{doublets} \end{array} \right\} \left(\begin{array}{c} \nu_e' \\ e \end{array} \right)_L, \left(\begin{array}{c} \nu_\mu' \\ \mu \end{array} \right)_L; \quad \left. \begin{array}{l} \text{Left} \\ \text{singlets} \end{array} \right\} N_{1L}, N_{2L}$$

$$\left. \begin{array}{l} \text{Right} \\ \text{doublets} \end{array} \right\} \left(\begin{array}{c} N_1 \cos \alpha + N_2 \sin \alpha \\ e \end{array} \right)_R; \left(\begin{array}{c} -N_1 \sin \alpha + N_2 \cos \alpha \\ \mu \end{array} \right)_R \quad \left. \vphantom{\begin{array}{l} \text{Left} \\ \text{doublets} \end{array}} \right\} \quad (2)$$

Right singlets: e_R, μ_R .

* ν_e' and ν_μ' differ from ν_e and ν_μ by small N_1, N_2 admixtures, the magnitude of which depend on details of the Higgs system.

The $\mu \rightarrow e \gamma$ transition is generated, in essence, by the chain $\mu \rightarrow (N_1 \text{ or } N_2) + W + e$; the W shakes off the γ . Adequate suppression of the rate is brought about by a GIM type mechanism. Thus the leading effect is itself a "radiative correction", (closed loops are involved). This feature will probably be inherent in any gauge theory description of the effect.

If $\mu \rightarrow e \gamma$ occurs then so will $\mu \rightarrow 3e$ (i.e. $u^+ e^+ e^- e^+$), for example by the Dalitz conversion of the γ , suppressed (in rate) relative to $e \gamma$ by a further factor $\sim \alpha$. However, in this model the rate for $\mu \rightarrow 3e$ is most probably much larger than that⁸. Indeed $\mu \rightarrow 3e$ can also occur without intervention of an intermediate photon, namely by purely weak mechanisms involving $2W$ exchange and the lepton- Z couplings. Topologically, the set of graphs involved is identical with that in the SM for $\bar{n} \lambda \rightarrow \bar{\mu} \mu$ (arising for $K_L \rightarrow \bar{\mu} \mu$) and one finds

$$\frac{R(\mu \rightarrow 3e)}{R(\mu \rightarrow e \gamma)} \sim \text{const.} \frac{\alpha}{\sin^4 \theta_W} \left[\ln \frac{m^2}{m_W^2} \right]^2. \quad (3)$$

m is the mean N -mass. It is not unfair to guess that the logarithm is ~ 5 . The const. is of general order unity. It would appear quite possible that $\mu \rightarrow 3e$ is competitive with $\mu \rightarrow e \gamma$!

In any event, those who will report the existence of $\mu \rightarrow e \gamma$ should be advised to look immediately for $\mu \rightarrow 3e$ as a direct process. If $\mu \rightarrow e \gamma$ indeed occurs, then it is strongly indicated that the $e \gamma / 3e$ ratio will become a key issue.

(b) The heavy lepton and its neutrino

The main evidence for the existence of $L^\pm$ (mass ≈ 2 Gev) comes from the μe events seen in e^+e^- annihilation.³ The least far fetched explanation of the bulk of these events (at this time there are⁹ about 170) is the sequence

$$e^+ + e^- \rightarrow L^+ + L^- \quad \begin{array}{l} \xrightarrow{\quad} e^- + \bar{\nu}_e + \nu_L \\ \xrightarrow{\quad} \mu^+ + \nu_\mu + \bar{\nu}_L \end{array} \quad (4)$$

(for $e^- \mu^+$ events, and similarly for $e^+ \mu^-$). I shall not discuss the detailed reasons for this interpretation. Rather, I will concentrate on new problems raised by this discovery.

Even simple questions concerning the $L^\pm$ lead at once to technical complications. Here is an elementary example: are the $L^\pm$ really leptons, particles whose strongest interaction is the point coupling to the electromagnetic field? If we only had time to observe $e^+e^- \rightarrow L^+ + L^-$, the answer would be trivial. One would measure, just as for muons, the quantity $ds(s, \theta)/d \cos \theta$, $s = (\text{lab energy})^2$, $\theta = (L^+, \text{beam})$ angle. But one cannot do that, the life time is too small ($\sim 10^{-12}$ sec. is a reasonable guess): because of the awkward life time one must find new style methods to answer old style questions.

In the present case, a possible method is the following¹⁰. Consider the cross section σ_x for the inclusive reaction $e^+e^- \rightarrow x + \text{all}$ via

$$e^+ + e^- \rightarrow L^+ + L^- \quad \begin{array}{l} \xrightarrow{\quad} \text{all} \\ \xrightarrow{\quad} x + \text{all} \end{array} \quad (5)$$

where x is any particle whose mass we may neglect (an e , or a μ , or a π). Let θ be the (x, beam) angle. Then from the two structure functions in $d\sigma_x(s, \theta)/d \cos \theta$ one can extract (for $m_x=0$) the corresponding two structure functions for $e^+e^- \rightarrow L^+L^-$, and compare the result with the standard electromagnetic answer for point particles¹¹. In any event $d\sigma_x(s, \theta)/d \cos \theta$ should be the same (up to an overall scale factor) for $x=e$, $x=\mu$, $x=\pi$.

And here is a second old timers' question: what is the V_A, S, P, T , structure of leptonic L -decay? We cannot apply in practice the classical Michel parameter analysis for an L at rest - since we won't find an L at rest. Rather, one must start from the reaction (4), integrate at least over all neutrino variables and, where possible without total loss of information on the question at hand, over more variables as well. This problem has been analyzed in its generality. For the purpose of obtaining ρ -parameter information, the distribution in the final μ (or e) energy turns out to be the most useful one. Further information can be obtained from the distribution in the final state (μ, e) angle, from the dependence on beam polarization, etc.¹¹ These two examples should suffice to indicate how different the ways of obtaining information are going to be for heavy leptons as compared to muons.

There are many more old style questions: what is the overall strength of the L -leptonic weak interaction, is it "normal" or not? There are isospin (and even second class current) questions, one may inquire about semi hadronic channels etc. These problems have already been the subject of much study.¹² To conclude these cursory

¹¹The implementation of the method may be hampered by the circumstance that one should observe all possible energies of the particle x , or given s and θ . However, this method for finding out whether L is a lepton is independent of any weak decay information.

remarks on heavy leptons I shall select two questions which seem particularly challenging to me.

1) Is ν_L (as defined in Eq. (4)) an old neutrino (ν_e or ν_μ) or a new one? The matter is not settled as yet, but indications are¹³ that ν_L is "new", in which case we would be dealing with a new * lepton pair (L, ν_L), sequential to (e, ν_e) , (μ, ν_μ) . (However, analyses of this question do depend on the explicit assumption of normal strength of the (L , neutrino) term in the charged current.)

If ν_L indeed is new then what is the value m_0 of its mass? The question cannot be taken lightly, especially in view of the current uproar in the lepton sector. Recall that neutrino mass determinations are the harder the heavier the charged partner is - after 30 years, the best bound on $m(\nu_\mu)$ is still¹⁴ ≈ 0.8 MeV, while $m(\nu_e) < 0$ eV! Let us ask: what does it take to show that $m_0 < 100$ MeV, a seemingly modest demand?

Consider again the reaction (4). The upper limit $E_{\max}(m_0)$ of the final muon depends on m_0 but only weakly:

$$E_{\max}(m_0) = E_{\max}(0) \left[1 + O\left\{\left(\frac{m_0}{m_L}\right)^2\right\}\right]. \quad (6)$$

Alternatively, consider $e^+e^- \rightarrow L^+L^-$, $L^+\pi^+ + \nu_L$, $L^-e^- + \dots$ and ask for the maximal pion energy, (the L 's are in flight). Again one finds the relation (6). It takes a 1% accuracy experiment to determine whether or not ν_L is lighter than a muon!

Are there other ways? In principle, yes. Events of the type $L^- \rightarrow D^- + \nu_L$ (or $F^+ \rightarrow L^+ + \nu_L$) would be most illuminating in regard to m_0 . Low rates¹⁵ would not be the

* If ν_L is indeed "new" then e^+e^- rings are the prime source for L^+ . The extraction of L pair events from hadron collisions would appear to be ferociously difficult.

only difficulty, however. One readily sees that severe background problems arise when one asks for event identification.¹⁶

2) Let us return to the V-A-S-T-P question. Surely all of us share the strong presumption that the (L, ν_L) vertex actually is of V,A type. Imagine $m_0=0$. Then many of us would venture to guess that the vertex is $V \pm A$. But is it plus or minus?

Here intuition fails. Nice teleological arguments for either case do not help much. The issue is of cardinal importance for the theory of weak interactions, even on a qualitative level. Theorists would love to know if they should introduce a new left handed or a new right handed doublet.

The corresponding experimental question is: can one at least exclude either $\rho=0$ or $\rho=3/4$? Theoretical analyses show¹¹ that this is not trivial, yet not too demanding. We may know about this distinction in a year or so.

One sees: the existence of heavy leptons raises qualitative questions of a fundamental nature which pose many new challenges, some of which are of considerable magnitude.

III Mundane aspects of charm

During the last two years, the existence of at least one new hadronic quantum number, "charm", has been established beyond doubt. The idea of charm (C) in its precise sense¹⁷ looks most appealing but has not yet been completely established. What do we know? What do we want to know?

From the first charmed baryon event¹⁸ at BNL, from the results on charmed mesons obtained with e^+e^- rings¹⁹ and from subsequent results on charmed baryons²⁰ at FNAL we know that the weak interactions of these particles satisfy (S=,strangeness)

$$\frac{\Delta S}{\Delta C} = 1. \quad (7)$$

It has also been shown that the nonleptonic decays of the charmed mesons violate parity²¹. Mass formulae for these new particles²², as naive as they are successful, further corroborate the charm picture.

The charm of the idea is that it provided (even prior²³ to the recent developments in gauge theories) a theoretical explanation for an important weak interaction feature, the suppression of the strangeness changing neutral currents. For a full fledged verification of charm properties, the weak decays of charmed particles will continue to be of paramount importance. One requires that they satisfy the following set of selection rules.

$\Delta S/\Delta C$	$ \Delta I $	Cabibbo suppression for rate *	Sample decay mode
<u>Nonleptonic</u> :			
1	1		$D^+ \rightarrow K^+ \pi^+ \pi^+$
0	$\frac{1}{2}, \frac{3}{2}$	$\sin^2 \theta$	$D^+ \rightarrow \pi^+ \pi^+ \pi^+$
-1	0, 1	$\sin^4 \theta$	$D^+ \rightarrow K^+ \pi^+ \pi^-$
<u>Semileptonic</u>			
1	0		$D^+ \rightarrow K^0 e^+ \nu_e$
0	$\frac{1}{2}$	$\sin^2 \theta$	$D^+ \rightarrow \pi^0 e^+ \nu_e$

* The suppression factors are relative to the dominant modes for the nonleptonic and semileptonic categories separately. The semileptonic/nonleptonic overall ratio appears to be ~ 10-20%.

We should be grateful for the fact that the relation (7) for the dominant decay modes has already been established. Evidently it is going to be a tall order to verify all of (8). The task is not made easier by the following circumstances.

- 1) D^* states play an important role in charm production. These states decay non-weakly into D 's, but the decay modes strongly violate isospin because the D^*-D mass differences are quite close to the pion mass. This causes complications for the verification of the weak isospin decay rules in the presence of D^* 's.
- 2) We must be prepared for complex many body decay channels (as observations on charmed baryon decays have already illustrated so well^{18,20}). This is one of several important reasons why one must look forward to the completion of new detector systems suitable for dealing with neutral pions. Theoretically, it may perhaps pay to pursue inclusive predictions²⁴ for charm decay following from (8). But beware of D^* !
- 3) I know of no simple isospin relations for charm change which are analogs of the $\Lambda+\pi$ nucleon ratio or the $K^0+2\pi$ ratio for strangeness change.
- 4) Once again we are dealing with particles that have awkward life times (10^{-12} sec. presumably). This complicates the decay analysis, especially when charmed particles are created in company with other hadrons.

It would of course be of much interest to measure the life times themselves of these particles. One way of doing this is to use emulsions.²⁵ However, it was recently noted²⁶ that the life time ratio of the D^+ , D^0 can be obtained also

from e^+e^- annihilation data under the single assumption (see (8)) that semi-leptonic decays of these particles dominantly conserve isospin. From this it follows, in obvious notation, that*

$$\frac{\tau(D^+)}{\tau(D^0)} = \frac{\sigma(e^+e^- \rightarrow D^+ + \bar{D}^- \xrightarrow{\text{all}} e^+ \pi^- \pi^-)}{\sigma(e^+e^- \rightarrow D^+ + \bar{D}^- \xrightarrow{\text{all}} K^+ \pi^- \pi^-)} \times \frac{\sigma(e^+e^- \rightarrow D^0 + \bar{D}^0 \xrightarrow{\text{all}} K^+ \pi^-)}{\sigma(e^+e^- \rightarrow D^0 + \bar{D}^0 \xrightarrow{\text{all}} e^+ \pi^-)} \quad (9)$$

Since the verification of the full set (8) of selection rules will take some time, one is led to ask the following interim theoretical question. Does the validity of (7) not imply that the charm scheme is correct at least insofar as the placement of the p, n, λ, c quarks in the standard model is concerned, see (1)? The answer is probably in the affirmative but not certainly so. One can conceive of gauge models²⁷ which coincide with the charm scheme in that (7) holds for the dominant modes but in which the nonleptonic modes with $\Delta S/\Delta C=0$ are absent and the rates for those with $\Delta S/\Delta C=-1$ are $\sim \sin^2\theta$ rather than $\sin^4\theta$. The verification of the properties of the subdominant modes is therefore of some interest.

* The argument can be extended to the D^+/F^+ life time ratio by a simple $SU(3)$ argument.²⁶

However, even if we accept that these four quarks are correctly placed within the SM, there are early indications from neutrino reactions that this quark scheme may need enlargement. Let us recall that these reactions gave the first firm evidence (after the single BNL event) for the existence of some new hadronic quantum number. I refer to the prompt dimuon events observed at FNAL in ν and in $\bar{\nu}$ reactions.²⁸ At higher energies there are indications of further novelty. I can be brief on this. The pertinent material has been presented by Rubbia in the preceding talk. There have ^{also} been several recent reviews on this subject.²⁹ Let me make only one remark about the total cross section ratio for the charged current processes induced by $\bar{\nu}$ and ν .

For some years this ratio hovered near the value 1/3 (for isoscalar targets) and this gave much support to the so called naive parton model according to which these reactions are dominantly due to neutrino interactions with the three valence quarks in the nucleon. More recently, and at higher energies, it appears that

- 1) the linear rise of $\sigma_{\text{total}}^{\nu\mu}$ continues without any significant breaks³⁰ (<15%);
- 2) $\sigma_{\text{total}}^{\bar{\nu}\mu}$ does show an upward break so that the $\bar{\nu}/\nu$ ratio increases significantly.^{*}

Why?

Perhaps there is something amiss with the usual assumptions of the parton model^{30a} (even if one includes in some reasonable way the inevitable threshold effects due to charm excitation). Since the rise occurs in the anti neutrino cross section (for which charm production can only occur off the sea quarks and is therefore rather suppressed, except perhaps for small x) it is perhaps more plausible, however, that the explanation will come from the existence of still another hadronic quantum number.

Theorists are already quite busy tooling up for such an eventuality. One simple way of looking at the $\bar{\nu}$ -rise is to assume the existence of a fifth quark $\bar{b}$ which

^{*} For interesting new features of the x and y distribution see ref.30 and also Rubbia's report to this symposium.

forms a right doublet with p . A new quantum number (call it F) would appear, associated with this new quark. A table of corresponding selection rules, analogous to (8), is easily written down. The first intimation of such a new set of rules would most probably come from the analog of (7):

$$\frac{\Delta S}{\Delta F} = 0, \text{ effectively } ^*.$$

Since the alleged rise of $\sigma_{\text{total}}^{\bar{\nu}\mu}$ does not appear to be accompanied by a similar rise in dilepton production, the semileptonic/nonleptonic branching ratio for this new breed of particles would presumably be smaller than for charm, which is perhaps not surprising²⁹. In any event, prompt dileptons produced in $\bar{\nu}$ reactions should again play an important role in the verification of the possible existence of these newer particles. Especially the question whether or not K particles accompany the dileptons would be of great interest: in the reactions

$$\bar{\nu} + \text{target} \rightarrow \mu^+ + \text{charm} + X, \\ L_{\mu^+} \rightarrow Y$$

both X and Y should contain one K particle (or X should contain a Λ or Σ), while in

$$\bar{\nu} + \text{target} \rightarrow \mu^+ + (\text{hadron containing } b) + X \\ L_{\mu^+} \rightarrow Y$$

the number of K particles in X and Y should be zero^{**}.

It is quite probable that neutrino reactions will again bring us exciting new physics, in the near future. Meanwhile there is other and present evidence that the SM may be incomplete. This comes from theoretical arguments concerning CP violation.

^{*} This rule would hold for semileptonic decay, for the nonleptonic quark transition $b \rightarrow p\bar{p}n$ and for the chain $b \rightarrow c\bar{c}\lambda$, $\bar{c} \rightarrow \bar{s}\bar{p}$. For implications of such new quantum numbers see also Ref.31.

^{**} Here "one" and "zero" hold modulo 2.

IV The CP Problem

The standard model sheds no light on the origin of CP violation. Rather, the opposite is true. The known existence of CP violating effects in the $K-\bar{K}$ system is the surest signal for the incompleteness of the SM for the description of weak (and weaker than weak) effects. The situation is this.

Consider the SM, Eq. (1), and write it in its most general hermitian form. Do not assume CP invariance from the outset. Then it is true nevertheless that this theory is necessarily CP invariant. In other words, the structure of the SM is so tight that, where one might legitimately introduce certain complex coupling constants ab initio in order to pave the way for a possible incorporation of CP violation, these constants can all be made real by the golden rule that for each complex wave field one may once and only once define its phase by convention.

What to do?

It may be that CP violation is an effect so subtle that gauge theories, of one form or another, are inadequate for its ultimate description. I cannot argue as to whether this view is true or false. (I conjecture it is false.) In any event, two major questions are now before us.

The first one is theoretical. Can one construct gauge theories which incorporate the attractive features of the SM and which violate CP? (Recall that CPT is good in any gauge theory.) The answer is: easily, almost too easily. In order of appearance, the following approaches have been envisaged.

(a) $SU(2) \times U(1)$ with four quarks, some right handed quarks are in doublets rather than singlets.³²

(b) Enlarge $SU(2) \times U(1)$ in such a way that CP violation is due to a phase between the quark and the lepton sector.²⁷ Several other group enlargements have been proposed more recently.³³

(c) $SU(2) \times U(1)$, more left doublets (and right singlets).³⁴ (Types (a) and (c) have recently been discussed further in a survey of CP violating $SU(2) \times U(1)$ type theories subject to naturalness constraints.³⁵)

(d) $SU(2) \times U(1)$, same fermion content as the SM, but the Higgs system contains more than one doublet.³⁶

(e) In all these cases CP violation already appears in the tree approximation. It has been shown³⁷ that there are other types of gauge theories in which CP violation appears as a quantum effect. (The inclusion of loops is necessary before one can even establish whether the theory violates CP.)

A more detailed discussion of such models makes for interesting theory seminars but is not well suited for a symposium. Suffice it to say that in all the mentioned models one can implement the constraints imposed by the CP effects in the $K\bar{K}$ system and by the existing experimental bounds³⁸ on electric dipole moments of fermions.

In summary, the model which served as such a good guide for neutral currents and charm deserts us on the CP issue. At the present stage it is hard to choose between the numerous options designed to incorporate CP by enlarging the SM: The few experimental criteria we have are not constraining enough. More information on CP is badly needed.

This makes the experimental study of the CP question for charmed particle decays all the more urgent and important. Here, indeed, are welcome new avenues for the pursuit of CP violation. Since there is no certified model for CP violation, there is no firm guess what such experiments will yield. It may be that CP effects for charmed particles will differ from those for strange particles in that they will already show up as on shell effects. It may also be that charmed

and strange particles behave similarly in the sense that the only effect will be CP impurity in the D^0 - $\bar{D}^0$ system, with an impurity parameter ϵ_C analogous to (but not as yet related to) the ϵ parameter of the neutral K system; ϵ_C may turn out to be quite small, as is ϵ ; or it may not be small. We may conjecture about all this, but we just do not know.

This brings me to the second question concerning CP: what are the general phenomenological signatures of CP violation for $\Delta C \neq 0$ processes? For $\Delta C = 0$ these have been analyzed in detail.³⁹ For $\Delta C \neq 0$ the general principles are the same, of course, but their implications are different in practice. Some of these differences are good news, some are bad news.

First the good news. Since the low lying charmed states are rather massive they have many decay channels. This gives more possibilities for studying CP questions for D's as compared to K's. For example for $K^\pm$ one has^{*} (B-branching ratio)

$$CPT \rightarrow B(K^+ \rightarrow \pi^+ \pi^0) = B(K^- \rightarrow \pi^- \pi^0), \quad (10)$$

if one neglects photon channels (and higher order weak effects). However, under the same conditions one has⁴⁰

$$CP \rightarrow \begin{cases} B(D^+ \rightarrow \bar{K}^0 \pi^+) = B(D^- \rightarrow K^0 \pi^-), & (11) \\ B(D^+ \rightarrow \pi^0 \pi^+) = B(D^- \rightarrow \pi^0 \pi^-), & (12) \\ B(D^+ \rightarrow \pi^+ X) = B(D^- \rightarrow \pi^- X), & (13) \\ \frac{B(D^+ \rightarrow \pi^+ X)}{B(D^+ \rightarrow K^+ X)} = \frac{B(D^- \rightarrow \pi^- X)}{B(D^- \rightarrow K^- X)}, \text{ etc.} & (14) \end{cases}$$

Thus, both exclusively and inclusively (as in the last two relations), there exist simple on shell CP comparisons which have no analog for K particles. CP is also

* In the subsequent relations the lifetime equality of K^+ and K^- and of D^+ and D^- has been used, (CPT invariance is assumed).

tested by

$$B(D^+ \rightarrow K^- \pi^+ \pi^+) = B(D^- \rightarrow K^+ \pi^- \pi^-) \quad (15)$$

as well as by the identity of certain distributions^{*} (for example the K^- and the K^+ spectra). It is clear that these simplest tests for CP can already be applied to existing data. (For other tests I refer to the literature.⁴¹). Let me stress that charm production in e^+e^- annihilation offers the unique advantage that D^+ and D^- are produced with the same energy distribution. (Likewise for other conjugate pairs.). Hence all mentioned tests may immediately be applied to the "raw" data!

Now the bad news. It concerns the D^0 - $\bar{D}^0$ system. Recall that the mass difference $m_S - m_L$ of K_S , K_L could be determined from the time dependence of the decay reactions, and that time dependent interferences between K_S and K_L played an important role in the determination of ϵ . For the $D\bar{D}$ system, on the other hand, there will be particle mixtures D_1 , D_2 with life times which are too short (presumably both of rough order 10^{-12} sec) to make use of time dependence! Unless new technologies are invented we shall be able to use only decay information integrated over time.

Detailed tests for CP in the $D\bar{D}$ system have been described in which only time integrated quantities are used.⁴⁰ These tests are very hard. Here I only note that if the CP violation were to be effectively superweak for charmed states as well, then $m_1 - m_2$, $\lambda_1 - \lambda_2$ the mass and decay rate differences for D_1 , D_2 are related to ϵ_C by⁴²

$$-\frac{2(m_1 - m_2)}{\lambda_1 - \lambda_2} = \frac{1 + |\epsilon_C|^2}{1 - |\epsilon_C|^2} \cdot \frac{\text{Im } \epsilon_C}{\text{Re } \epsilon_C}. \quad (16)$$

* For CP purposes one must of course compare a K^+ with momentum $\vec{p}$ with a K^- with momentum $-\vec{p}$.

Finally, it may be remarked that new CP information may also come from the comparison of the charged heavy leptons L^+ and L^- discussed earlier.¹⁰ From this point of view the reaction $e^+e^- \rightarrow L^+L^-$ offers the advantage (similar to the one noted earlier for charm) that the $L^\pm$ are produced with the same energy. Thus the pion spectra for $L^+ \rightarrow \nu_L + \pi^+$... and for $L^- \rightarrow \nu_L + \pi^-$... in the laboratory system for e^+e^- -annihilation ought to be identical if CP is good; likewise for $L^+ \rightarrow \nu_L + \pi^0$... versus $L^- \rightarrow \nu_L + \pi^0$... , etc.

In conclusion, it is evident that CP violation is posing very important new challenges, to experiment and theory alike.

V A Final Comment

How can a 1977 Symposium be called "Five Decades of Weak Interactions"? There were no weak interactions in 1927, nor had the neutrino even been postulated. The Symposium title is most fitting, nevertheless. For it was in 1927 that Ellis and Wooster published their paper⁴³ on calorimetric measurements in which they showed that the average energy of disintegration in the β decay of RaE equals the mean energy of the continuous spectrum, rather than its upper limit. I should like to conclude by making two comments on this classic work by Ellis and Wooster, which marks a milestone in the developments of weak interactions.

First, I would like to recall for you the authors' own reactions, fifty years ago, to their startling result: "The disintegration electrons must be emitted from the nucleus with varying energies, however contrary at first sight this might appear to the general principles of quantum theory."⁴³

My second comment concerns the experimental aspect of this work. You should know that in the 1927 experiment measurements of temperature differences were made by means of a system of thermocouples attached to a sensitive galvanometer. Just two weeks ago I received a letter⁴⁴ from Dr. Wooster in which he wrote about those days: " ... In spite of magnetic shielding provided by an enveloping core of iron 1 1/2" thick, the galvanometer was so sensitive to external changes in the magnetic field that we had to work between 12 midnight and 3 a.m. for a fortnight. Even so when the policeman walked by in the street, the nails in his boots disturbed the galvanometer ... " .

As you see, the two themes of the present paper: current theoretical schemes and current mundane problems are hardly new. Theoretical concepts and prejudices

as well as experimental techniques have been stretched to their limits if not beyond by the weak interactions ever since the inception of the subject. This talk ought to have made it clear that this will continue to be true for some time to come.

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