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THREE GENERATIONS OF QUARKS AND LEPTONS

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ABSTRACT

The spectroscopy of quarks and leptons is reviewed with emphasis on weak transitions, mass patterns, right-handed currents, Cabibbo-like angles and the connection between quarks and leptons.

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I. INTRODUCTION

Hadron spectroscopy has been with us for several decades, and will continue to stay with us for a long time. However, in reviewing the developments of the last three years one cannot escape the feeling that we have already moved into the next spectroscopy: the spectroscopy of quarks and leptons.

Hadron spectroscopy deals with the old hadrons (containing only u, d, s quarks) as well as with the new hadrons. The new hadrons include the $c\bar{c}$ "charmonium" family, the charmed D-mesons and the soon to be discovered F-meson and charmed baryons. Hadron spectroscopy is relevant to questions such as the possible existence of $qq\bar{q}\bar{q}$ states; the Zweig-Iizuka rule; the applications of the asymptotically free QCD to couplings of quarks and gluons; the nature of qq and $q\bar{q}$ potentials and most importantly—the questions of quark confinement.

The spectroscopy of quarks and leptons involves questions such as the number of quark and lepton flavors; the nature of their weak and electromagnetic transitions; the properties and classifications of the gauge vector particles and the Higgs scalar particles; the possible existence of right-handed weak currents in addition to the usual left-handed ones; the connection between quarks and leptons and the grand unification of strong, weak and electromagnetic interactions; the experimental measurement and theoretical calculation of the Cabibbo angle and several additional related angles; the incorporation of CP violation into the gauge theory; the experimental measurement and theoretical calculation of the Weinberg angle.

Most of these problems are still wide open. However, the striking experimental developments of the last three years have brought us to a point in which we can study various ideas, confront them with experiment, modify them, proceed to new predictions, etc. Who would have guessed at the last EMS conference (1974) that we would now have six leptons (possibly more) as well as suspicions about a fifth (and possibly sixth) quark? Indeed, the prophecy of the fourth quark was considered at that time to be somewhat outlandish!

In the present talk we would like to review the new emerging features of the spectroscopy of quarks and leptons. Throughout most of our discussion we shall assume the Weinberg-Salam[1] SU(2) × U(1) gauge theory of weak and electromagnetic interactions and the minimal set of Higgs particles. Only towards the end we will very briefly mention modifications (or, rather, extensions) of these two postulates.

Our approach will be to discuss "fundamental" processes involving only quarks and leptons. Needless to say, the discussion of any given such process (say: $s \rightarrow u + e^- + \bar{\nu}_e$) may reflect knowledge which was gathered by studying many hadronic processes ($\Lambda \rightarrow p + e^- + \bar{\nu}_e$, $\Sigma^- \rightarrow n + e^- + \bar{\nu}_e$, $K \rightarrow \pi + e^- + \bar{\nu}_e$, etc.). However, our attention will be focused on the quark and lepton level rather than on the hadronic level.

II. THE FIRST GENERATION OF QUARKS AND LEPTONS

The first generation of quarks and leptons includes the four "old" fermions: u, d, ν_e, e^-. Their left-handed states are assigned to SU(2) × U(1) doublets:

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \quad \begin{pmatrix} u \\ d \end{pmatrix}_L$$

Amazingly enough, we still do not know how to assign to right-handed u, d, e. All we know is that if these right-hand states are not in SU(2) × U(1) singlets, each one of them must be paired with particles of later generations.

At present, we have information concerning four types of weak processes involving only first generation fermions:

$$d \rightarrow u + e^- + \bar{\nu}_e \tag{II.1}$$

$$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^- \qquad (\text{and } \nu_e + e^- \rightarrow \nu_e + e^-) \tag{II.2}$$

$$e^- + (u, d) \rightarrow e^- + (u, d) \tag{II.3}$$

$$\nu + (u, d) \rightarrow \nu + (u, d) \qquad \text{and } \bar{\nu} + (u, d) \rightarrow \bar{\nu} + (u, d) \; . \tag{II.4}$$

The process (II.1) is none other than good old β-decay. The data on it tells us that all four fermions are coupled left-handedly to the charged weak current. There is some room for a right-handed (u, d) coupling, presumably at the 5%-10% level of the left-handed coupling. We must remember that the translation of data for $n \rightarrow p + e^- + \bar{\nu}_e$ into conclusions for $d \rightarrow u + e^- + \bar{\nu}_e$ involves theoretical assumptions which are not expected to hold to better than a few percent.

The process (II.2) was measured using the antineutrino flux from nuclear reactors.[2] The process involves direct channel charged current interactions as well as crossed channel neutral currents. Assuming that the charged current interaction is of the V-A type, and that $\bar{\nu}_e$ is always right-handed, we can deduce the vector and axial vector components of the electron contribution to the neutral current. Assuming an effective interaction of the form:

$$\bar{\nu}_e \gamma_\mu (1+\gamma_5) \nu_e \; \bar{e} \, \gamma_\mu (g_V + g_A \gamma_5) e$$

we obtain the limits shown in Fig. 1. We see that there are possible solutions with $g_V=0$ and/or $g_A=0$. At present, there are no data on the companion reaction $\nu_e + e^- \to \nu_e + e^-$.

The weak process (II.3) is probed by the search for parity violating effects in atomic physics. The observed rotation angle in the Bismuth experiments measures the product of the axial vector neutral coupling of the electron (denoted above by g_A) and the vector neutral coupling of the appropriate combination of u and d quarks. The present results of the experiments[3] indicate an upper limit which is substantially smaller than the prediction of the "standard" SU(2) × U(1) theory, and is consistent with zero. Should the result turn out to be zero to a very high accuracy, the most likely conclusion would be $g_A=0$ (as marked on Fig. 1). That would be perfectly consistent with the process (II.2).

The processes (II.4) are measured in the inclusive neutral current experiments involving ν and $\bar{\nu}$ beams. The available beams are, of course, ν_μ and $\bar{\nu}_\mu$ beams. However, for the sake of our discussion of first generation fermions, we shall assume that the ν_e and $\bar{\nu}_e$ inclusive cross sections on nuclei are, respectively, identical to those of ν_μ and $\bar{\nu}_\mu$. The measured quantities are:

$$R_\nu = \frac{\sigma(\nu + N \to \nu + \text{any})}{\sigma(\nu + N \to \mu^- + \text{any})} = \begin{cases} 0.25 \pm 0.04 & \text{GGM}^4 \\ 0.31 \pm 0.06 & \text{HPWF}^5 \\ 0.24 \pm 0.02 & \text{CTF}^6 \end{cases}$$

$$R_{\bar{\nu}} = \frac{\sigma(\bar{\nu} + N \to \bar{\nu} + \text{any})}{\sigma(\bar{\nu} + N \to \mu^+ + \text{any})} = \begin{cases} 0.39 \pm 0.06 & \text{GGM}^4 \\ 0.39 \pm 0.10 & \text{HPWF}^5 \\ 0.39 \pm 0.06 & \text{CTF}^6 \end{cases}$$

These numbers are perfectly consistent with a Salam-Weinberg neutral current, with $\sin^2\theta_W \sim 0.35 \pm 0.07$. This particular value of θ_W is consistent with the experimental results of (II.2) (as shown in Fig. 1). However, they cannot be reconciled with $g_A=0$, as implied (?) by the atomic physics experiment.

We conclude that already at the level of the first generation fermions, we face a problem. The SU(2) × U(1) model can accommodate the data for reactions (II.1), (II.2) and (II.3) or (II.1), (II.2) and (II.4), but not all four reactions.

At the moment it seems that we have only two possible resolutions of this conflict: (i) one of the experiments is incorrect; (ii) the gauge group for weak and electromagnetic interactions is larger than SU(2) × U(1).

What are the theoretical questions which can be asked about the first generation fermions?

Firstly, we would like to understand the mass spectrum of the first generation quarks and leptons. This seems to be surprisingly easy. The neutrino and the electron have the same strong and weak interactions. They differ only by their response to the electromagnetic current. It is entirely reasonable to assume that the ν_e - e mass difference is of electromagnetic origin. The u and d quarks differ from ν_e and e by the fact that

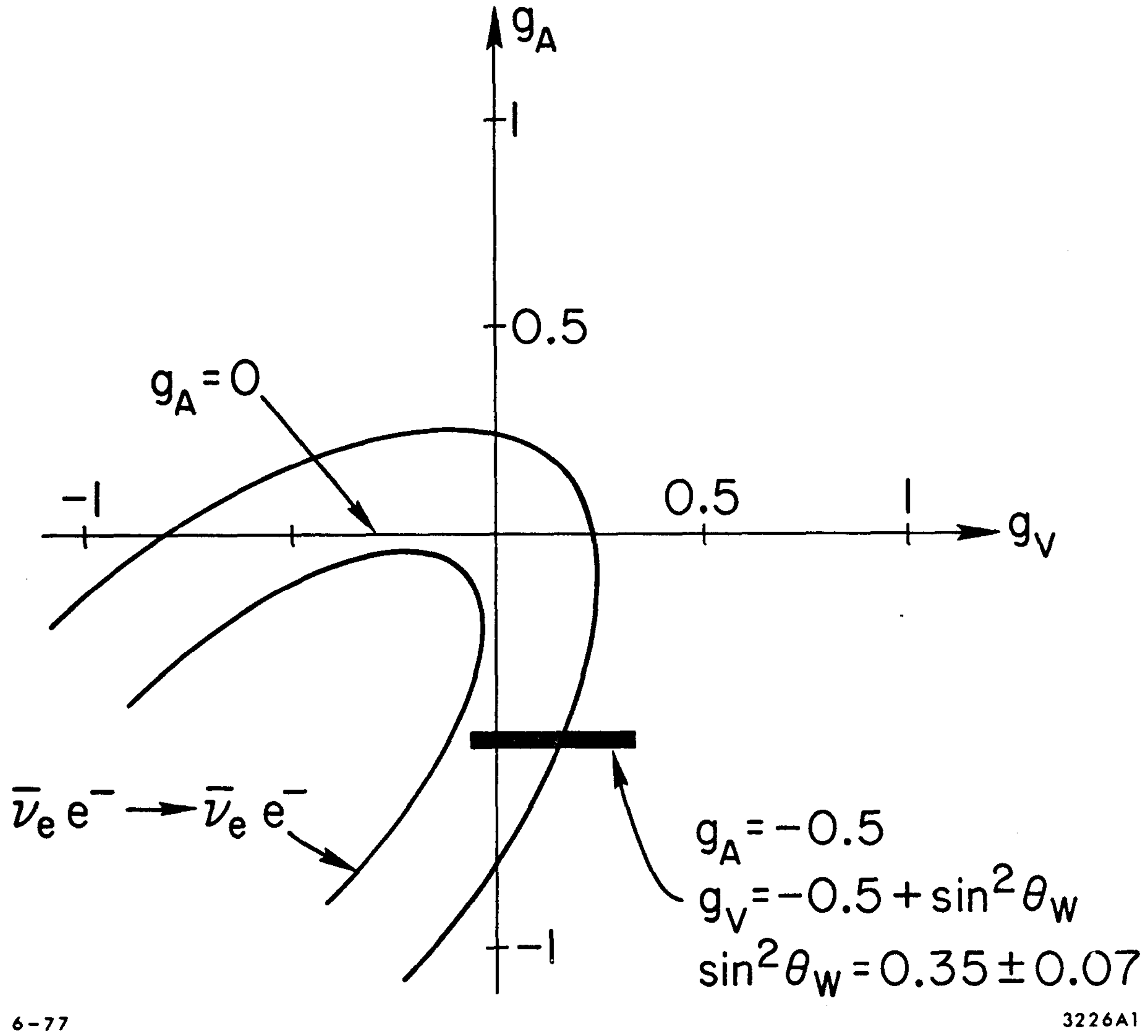

Fig. 1. We assume an effective Lagrangian of the form $\bar{\nu}_e\gamma_\mu(1+\gamma_5)\nu_e\,\bar{e}\,\gamma_\mu(g_V+\gamma_5\,g_A)e$. The figure shows the allowed region for g_A, g_V as determined by the $\bar{\nu}_e e^-$ elastic scattering experiment of Ref. 2. Also shown are the predictions of a left-handed SU(2) × U(1) model and the $g_A=0$ region implied by the atomic physics experiments (Ref. 3).

they respond to the strong interactions. Consequently, it makes perfect sense to find that u and d are heavier than ν_e and e. Finally, we note that u and d have identical strong and weak interactions and differ in their electromagnetic properties. Indeed, their mass difference is of the same order of magnitude and the same sign as the ν_e-e mass difference. We therefore conclude that the entire mass pattern of the first generation fermions can be qualitatively explained without any difficulty. The only unexplained fact is the masslessness of the neutrino, which probably follows from some fundamental principle which we do not yet understand.

The second interesting problem which is already raised at the level of the first generation fermions, is the possible connection between quarks and leptons. All motivations for establishing such a connection already exist: The first generation quarks and leptons are both pointlike J=1/2 fermions; their electric charges are quantized in a related way; the sum of electric charges of all first generation fermions vanishes (as required by the absence of triangle anomalies in a pure left-handed model, and as required if all of these fermions form a representation of a unifying gauge algebra). Models such as the SU(5) scheme of Georgi and Glashow[7] or the SO(10) scheme,[8] actually relate first generation quarks and lepton, without reference to the second generation fermions.

III. THE SECOND GENERATION OF QUARKS AND LEPTONS

The second generation of quarks and leptons includes the next four fermions: c, s, ν_μ, μ. Their left-handed states are, again, assigned to SU(2) × U(1) doublets:

$$\begin{pmatrix}\nu_\mu \\ \mu^-\end{pmatrix}_L \qquad \begin{pmatrix}c \\ s\end{pmatrix}_L$$

The right-handed components are, again, not fully understood. This is, of course, not surprising. If we cannot classify the right-handed electron, eighty years after its discovery, we should not be unnerved by our inability to classify the right-handed charmed quark!

At the level of the second generation fermions we have a large number of experimentally observed fundamental processes:

$$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu \qquad \text{(III.1)}$$

$$s \to u + e^- + \bar{\nu}_e \qquad \text{(III.2)}$$

$$c \to s + e^+ + \nu_e \qquad \text{(III.3)}$$

$$\nu_\mu + d \to \mu^- + c \qquad \text{(III.4)}$$

$$\bar{\nu}_\mu + e^- \to \bar{\nu}_\mu + e^- \qquad \text{(III.5)}$$

$$\nu_\mu + e^- \to \nu_\mu + e^- \qquad \text{(III.6)}$$

$$\bar{s} + d \to \bar{d} + s \qquad \text{(III.7)}$$

$$\bar{c} + u \rightarrow \bar{u} + c \qquad \text{(III.8)}$$

$$\nu_\mu + u \rightarrow \nu_\mu + c \qquad \text{(III.9)}$$

$$\mu^- \rightarrow e^- + \gamma \qquad \text{(III.10)}$$

The process (III.1) is, of course, well studied. It teaches us about the relation between the vector coupling of μ-decay and β-decay; it dictates the left-handed classification of (ν_μ, μ^-) and it provides an upper limit on the ν_μ mass.

The reaction (III.2) is studied in many hadronic weak decays. We learn from it that the s→u transition is largely left-handed and that there cannot be a significant right-handed s→u coupling. The rate of this process determines the value of the Cabibbo angle, which represents the mixing between quarks of the first two generations.

The first process which is not fully understood is (III.3): the semileptonic decay of the charmed quark. We do not know yet whether this decay proceeds via a V-A interaction or whether it has a V+A component. The semileptonic c-decay has now been seen both in the neutrino experiments[9] (where it provides for the two-muon events) and in e^+e^- collisions at Doris.[10] The best way of determining the V, A structure of this process is, probably, to study the decay:

$$D \rightarrow \bar{K}^* + e^+ + \nu_e$$

where K* is the vector particle at 890 MeV. Note that the decay $D \rightarrow \bar{K} + e^+ + \nu_e$ must be a pure vector transition. The semileptonic decay into K* is, therefore, the simplest process which allows both vector and axial vector transitions. These can be determined, for instance, by studying the momentum spectrum of the emitted electron. Preliminary indications from DESY show[10] consistency with a pure V-A transition, but a certain amount of V+A cannot be excluded.

It is important to note that among the eight fermions of the first two generations, the only two that could be paired in a right-handed doublet are (c, s). No other combination is allowed by the data, and any right-handed current involving one of the fermions u, d, e, μ, ν_e or ν_μ must connect it to fermions beyond the second generation. A right-handed (c, s) doublet is favored by some "explanations" of the $\Delta I = 1/2$ enhancement in nonleptonic strange particle decays.[11] If that is the case, the transition (III.3) $c \rightarrow s + e^+ + \nu_e$ would be a parity conserving pure vector transition. It would therefore be extremely interesting to analyze the decay $D \rightarrow K^* + e^+ + \nu_e$ and to determine the nature of the c→s weak transition.

The reaction (III.4) is observed in neutrino experiments and is largely responsible for the production of the charmed mesons whose decays yield the two-muon events.[9] We do not have a full space-time analysis of (III.4) but we have good reasons to exclude a substantial c→d right-handed transition.[12]

So far we have discussed charged current processes. We now move on to the neutral current reactions involving second generation fermions. The leptonic reactions (III.5) and (III.6) are pure neutral current processes (unlike elastic $\bar{\nu}_e + e$ scattering). Assuming that ν_μ is left-handed, the reactions (III.5) and (III.6) provide us with further information on the neutral current of the electron and on the parameters g_V and g_A defined in the previous section.

The data for these two processes[13] can be added to our Fig. 1 in order to narrow down the allowed regions for g_V and g_A. We end up with two allowed regions (Fig. 2). One of them is consistent with $g_A=0$ and with the results of the atomic physics parity violation experiment. The other region is consistent with a pure left-handed Salam-Weinberg model with $\sin^2\theta_W \sim 0.35$, but is inconsistent with the atomic parity experiment. While the $\nu_\mu e$ and $\bar{\nu}_\mu e$ data provide us with some new restrictions, they shed no light on the conflict that we faced at the level of first generation fermions (Fig. 1, Section II).

We now move on to <u>flavor changing</u> neutral currents. The most famous among these is the process (III.7). Its main claim to fame is, of course, its absence. The GIM mechanism[14] provides us with a beautiful and natural explanation for the absence of the reaction $\bar{s} + d \rightarrow \bar{d} + s$ to the first two orders in the coupling constant.

But what about other flavor changing neutral transitions? Is there a $\bar{c}u$ neutral current? If there is, it would manifest itself in two relatively simple reactions: (III.8) and (III.9). The reaction (III.8) $\bar{c} + u \rightarrow \bar{u} + c$ would lead to D^0-$\bar{D}^0$ mixing. The smallness of such mixing would indicate that the $\bar{c}u$ neutral current is small (or absent) and that it is analogous to the $\bar{d}s$ current. A significant D^0-$\bar{D}^0$ mixing would imply substantial flavor changing neutral weak transitions.

The SLAC-LBL collaboration have recently come up with an upper limit on D^0-$\bar{D}^0$ mixing.[15] They are observing events of the type:

$$e^+ + e^- \rightarrow \underset{\hookrightarrow K^\pm \pi^\mp}{D^0} (\text{or } \bar{D}^0) + \text{anything}$$

The $K^\pm\pi^\mp$ system has the invariant mass of a D^0 (or a $\bar{D}^0$). Having observed one charged K which emerges from a D^0 (or $\bar{D}^0$) decay, they then look for another charged K in the same event. In the absence of any D^0-$\bar{D}^0$ mixing the second charged K should always be of the opposite charge. They therefore measure the quantity:

$$\mathscr{E} = \frac{N(K_{\text{opposite}}) - N(K_{\text{same}})}{N(K_{\text{opposite}}) + N(K_{\text{same}})}$$

The case of no D^0-$\bar{D}^0$ mixing clearly corresponds to $\mathscr{E}=1$, while complete mixing would imply $\mathscr{E}=0$. Experimentally, they observe[15]:

$$\mathscr{E} = 0.76 \pm 0.17$$

Hence, complete mixing is ruled out by 4.5 standard deviations. The data is essentially consistent with no mixing.

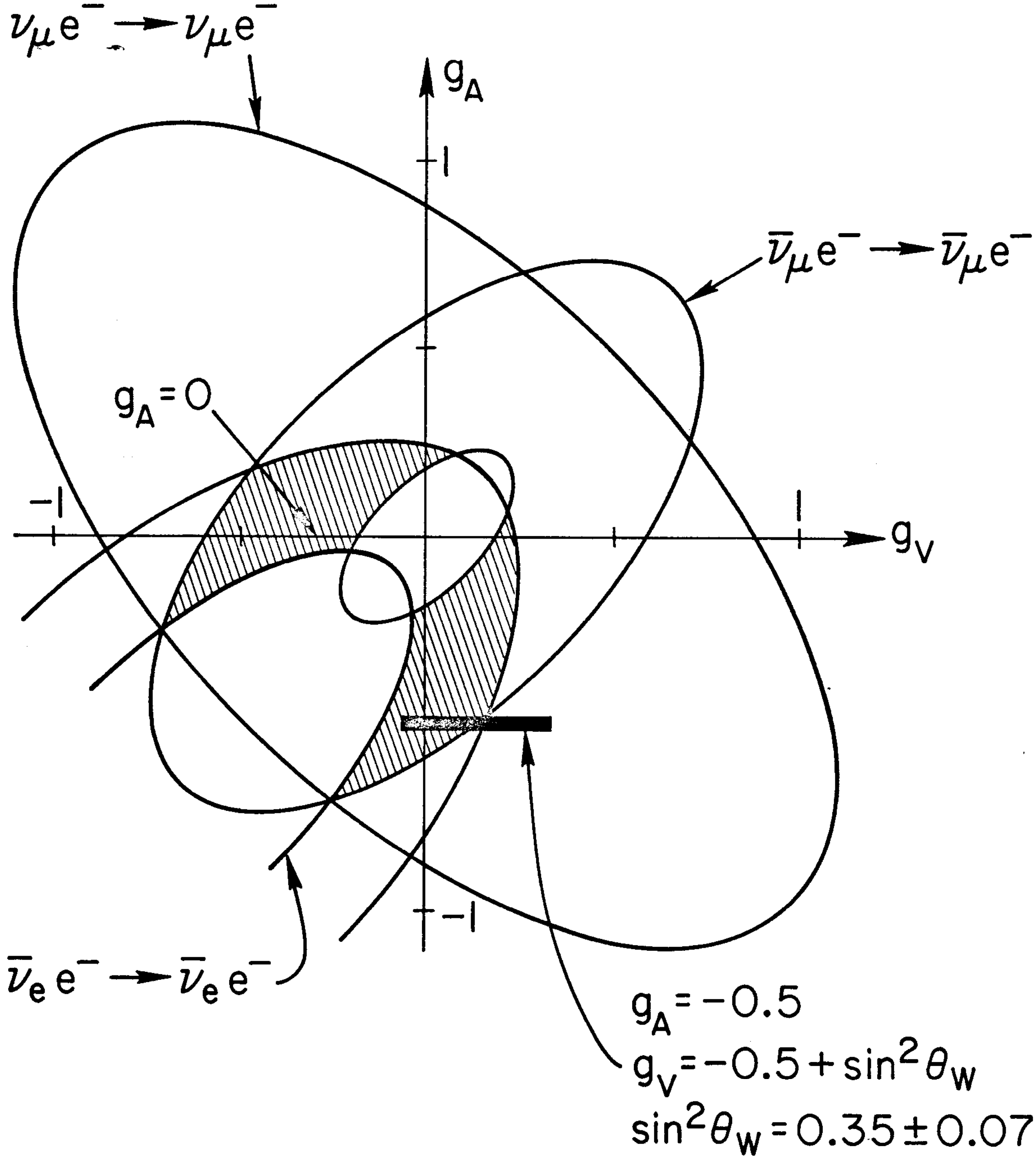

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Fig. 2. Data from $\bar{\nu}_\mu e^-$ and $\nu_\mu e^-$ elastic scattering (Ref. 4) further restrict the allowed values of g_A, g_V, as defined in Fig. 1. The two shaded regions are the two possible solutions. However, one of them is consistent with the pure left-handed SU(2) × U(1) model and the other with the atomic physics experiments.

The second experimental search for a flavor changing $\bar{c}u$ neutral current involves the reaction (III.9) $\nu_\mu + u \rightarrow \nu_\mu + c$. Experimentally, the Columbia-Brookhaven Bubble Chamber experiment at Fermilab have observed[16] 23 events of the type:

$$\nu_\mu + N \rightarrow e^+ + \text{anything (no additional charged leptons)}$$

Such events could come from the $\bar{\nu}_e$ contamination in the ν_μ beam (estimated as 0.1%) or from events of the type:

$$\nu_\mu + u \rightarrow \nu_\mu + c$$

followed by:

$$c \rightarrow s + e^+ + \nu_e$$

Consequently, the observed rate for $\nu_\mu + N \rightarrow e^+ + \text{anything}$ leads to an upper limit for the $u \rightarrow c$ neutral current reaction. The limit obtained is[16]:

$$\frac{\sigma(\nu_\mu + u \rightarrow \nu_\mu + c)\cdot B(c \rightarrow e^+ + \text{any})}{\sigma(\nu_\mu + N \rightarrow \mu^- + \text{any})} < 5 \times 10^{-4}$$

We may therefore conclude that the $\bar{u}c$ neutral current is either absent or is very small. It would, of course, be very elegant if all flavor changing neutral currents would be absent, as a result of a generalized GIM mechanism. The conditions for such a situation were recently studied.[17] Any model in which the different generations of quarks follow the same pattern of $SU(2) \times U(1)$ representations for both left-handed and right-handed states, would provide for a "natural" mechanism for flavor conservation by neutral currents.

Another flavor changing neutral transition which could exist in higher orders is the transition $\mu^- \rightarrow e^- + \gamma$. It could proceed via neutrino mixing or via other mechanisms involving Higgs particles. We only have an upper limit for this transition, contrary to preliminary rumors that were spreading earlier this year.

What are the new theoretical problems posed by the second generation of quarks and leptons?

First, we return to the question of the mass spectrum. Here, the situation is extremely embarrassing. The weak, electromagnetic <u>and</u> strong interactions of the second generation fermions are apparently completely identical to those of the first generation, and yet, the mass pattern is totally different. While discussing the first generation fermions, we claimed that we could qualitatively explain all features of the mass spectrum (except for the masslessness of the neutrino). If our explanation was any good, it should have equally applied to the second generation. But here we find complete chaos.

The ν_μ-μ mass difference and the c-s mass difference are both much larger than the corresponding first generation mass differences, and are both unlikely to be due to electromagnetism alone. The μ is heavier than

ν_μ but s is lighter than c, namely, the order is reversed! The situation is baffling and appears to be very difficult to explain on the basis of the usual interactions.

We might speculate that there is some new interaction to which first generation fermions are indifferent, and which distinguishes between the generations and provides most of the mass of any second generation fermion. Such a speculation would meet its hardest test in the measured (g-2) value for the muon. One would have to concoct a new interaction which would be strong enough to produce the large mass of the c-quark and yet weak enough so as to preserve the first ten significant figures in $(g-2)_\mu$!

The mass pattern of the second generation fermions remains a major puzzle, especially in view of the simple and logical mass pattern of the first generation.

A new feature which appears for the first time in the second generation of fermions is the Cabibbo angle. This is the only link between the two generations, and it should be calculable or at least related to fermion masses. No one has yet produced even a semiconvincing calculation of the Cabibbo angle.

If <u>at least</u> one neutrino (ν_e or ν_μ) has a nonvanishing mass, we might have a Cabibbo-like angle in the leptonic sector. The weak interaction eigenstates would then be:

$$\begin{pmatrix} \nu'_e \\ e^- \end{pmatrix} \quad \begin{pmatrix} \nu'_\mu \\ \mu^- \end{pmatrix}$$

where

$$\nu'_e = \nu_e \cos\theta_\ell + \nu_\mu \sin\theta_\ell$$

$$\nu'_\mu = -\nu_e \sin\theta_\ell + \nu_\mu \cos\theta_\ell$$

Here, ν_e and ν_μ are the physical (mass eigenstates) neutrinos and θ_ℓ is the leptonic Cabibbo angle. A nonvanishing θ_ℓ could lead to interesting (but extremely hard to measure) effects such as neutrino oscillations, $\mu^- \to e^-\gamma$ transitions, etc.

The computation of these and all other Cabibbo-like angles remains one of the most profound unsolved questions of the physics of quarks and leptons.

IV. THE THIRD GENERATION OF QUARKS AND LEPTONS

In our discussion of the first two generations we have emphasized that if any of the quarks and leptons (except perhaps, c and s) participate in right-handed charged weak currents, they could do so only by transforming into fermions beyond the first two generations. The only indications that we have for the possible existence of right-handed currents are the atomic physics parity violation experiment, and the controversial data in $\bar{\nu}N$ scattering (y-anomaly and $\bar{\nu}/\nu$ cross section ratio).

We do have, however, a clear indication for the existence of third generation leptons. We therefore proceed by guessing that the structure of the third generation is similar to that of the first two:

$$\begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

What is the evidence for each of these fermions?

(i) The τ^--lepton has now been seen in several e^+e^- experiments.[18, 19] Its decay modes presumably include:

$$\tau^- \to e^- + \bar{\nu}_e + \nu \qquad \text{(IV. 1)}$$

$$\tau^- \to \mu^- + \bar{\nu}_\mu + \nu \qquad \text{(IV. 2)}$$

$$\tau^- \to \nu + \text{hadrons} \quad . \qquad \text{(IV. 3)}$$

Its mass is around 1.9 GeV. We do not know yet whether it decays by a pure V-A interaction. The τ^- appears to be a sequential lepton, and it is presumably not associated with the electron or the muon.

(ii) The associated neutral lepton ν_τ has not been seen. However, there are convincing indirect arguments for its existence. A way to avoid the existence of ν_τ would be to assign τ^- to an SU(2) × U(1) singlet, allowing some τ-μ and/or τ-e mixing. The τ would then decay through this mixing into, say, $e + \bar{\nu}_e + \nu_e$. It has been shown,[20] however, that in such a case, the process:

$$\tau^- \to \ell^- + \ell^+ + \ell^-$$

where ℓ^- is e^- or μ^-, would have a branching fraction of 5% or more. Experimentally[21]:

$$\frac{\Gamma(\tau^- \to \ell^- + \ell^+ + \ell^-)}{\Gamma(\tau^- \to \text{anything})} < 0.6\%$$

We therefore conclude that ν_τ exists.

There is no evidence, whatsoever, for the masslessness of ν_τ. It could easily have a mass of a few hundred MeV. In principle, it could even be heavier than τ itself.[22] The τ would then decay by the emission of an "old" neutrino (ν_e or ν_μ) as a result of ν_τ-ν_e or ν_τ-ν_μ mixing.

(iii) There is no direct evidence for the existence of the b-quark. Such a quark must exist if the right-handed u-quark belongs to an SU(2) × U(1) doublet. The HPWF data on $\bar{\nu}$N scattering indicates[23] that such an assignment for u_R may be necessary, thus implying the existence of b. However, other antineutrino experiments do not observe this effect, and we will have to be patient until the experimental conflict is resolved. If the b-quark is produced in $\bar{\nu}$-reactions, the relevant process would be:

$$\bar{\nu}_\mu + u \to \mu^+ + b$$

(iv) There is no direct or indirect experimental evidence for the existence of a t-quark. The only arguments for the (t, b) doublet are based on the apparent existence of the (ν_τ, τ) doublet and the hope that the third generation follows the pattern of the first two. If all weak currents are left-handed, the cancellation of anomalies would require that the (ν_τ, τ^-) doublet be supplemented by a (t, b) doublet.

What are the new theoretical questions raised by the third generation of fermions?

The mass pattern is as puzzling as ever. The new added ingredient provided by the third generation is the following: If we had only two generations, we might speculate that the second generation masses are determined by some intrinsic mass scale for fundamental fermions while the first generation fermions are approximately massless, and their relatively small masses are generated through higher order effects. This argument disappears when we observe yet another mass scale for the third generation.

As the number of generations increases, the number of Cabibbo-like angles increases (quadratically). In fact, in the case of six quarks we are allowed, for the first time, to have complex Cabibbo-like angles, leading to CP-violation effects.[24] This is an extremely attractive possibility, since it enables us to incorporate the CP-violating weak interactions into our "standard" gauge theory of weak and electromagnetic interactions, without spoiling any of the attractive features of the theory.

As we have already remarked, the possibility of right-handed currents requires at least three generations of fermions. The only possible assignment of right-handed quarks to SU(2) × U(1) doublets would be:

$$\begin{pmatrix} u \\ b \end{pmatrix}_R \quad \begin{pmatrix} c \\ s \end{pmatrix}_R \quad \begin{pmatrix} t \\ d \end{pmatrix}_R$$

Not all of these doublets must exist. Any one or two of them may exist, while the other right-handed quarks are in SU(2) × U(1) singlets. However, the only pairings allowed by the data are the ones listed here.

Finally, it is evident that the first two generations do not tell the full story, but it is not at all clear that the third generation is indeed similar to the first two. In addition to the lack of concrete information on the t and b quarks, we have the tantalizing trimuon events[25] at Fermilab which defy any simple explanation. These events are still subject to experimental confirmation by other groups, but if they are genuine trimuons, they may force us into more leptons, possibly of a different nature than the first three generations of leptons.

V. SUMMARY

As a prelude to my summary, let me emphasize the amazing progress which was made in the field of quark and lepton physics in the last few years. We have listed here 19 fundamental quark and lepton processes about which we have some information at the present time: (II. 1)-(II. 4); (III. 1)-(III. 10);

(IV.1)-(IV.5). Of these nineteen processes, only four [(II.1), (III.1), (III.2), (III.7)] were known four years ago, in April 1973!!

The open experimental problems in quark and lepton spectroscopy are the following:

(a) What is the V, A structure of neutral current processes, charmed particle decays and τ-decays?

(b) Are there additional quarks such as b and t? These could be found in neutrino reactions or by discovering additional ψ-like bumps in e^+e^- collisions.

(c) Are there more leptons, as implied, perhaps, by the trimuon events? Are there additional leptons which are not of the sequential type?

(d) Are the neutrinos massless? Are some neutrinos massless and others not? Are there neutrino oscillations?

The fundamental theoretical problems are:

(A) What is the correct gauge group for the weak and electromagnetic interactions? Is it SU(2) × U(1) or do we need a larger group as implied by the neutral current data, and especially by the atomic physics experiments? Is SU(2) × SU(2) × U(1) the correct extension?[26] Is it SU(3) × U(1)?[27] Is it some other group?

(B) What is the structure of the Higgs particle spectrum? This must be crucial to any model which extends SU(2) × U(1), but is also possibly important for an SU(2) × U(1) theory.

(C) What is the connection between quarks and leptons? We believe that such a connection exists (see Section II) but we do not yet know how to pursue it. Is the grand unification approach correct? If so, which is the correct group? SU(5)?[7] E(7)?[28] SU(4) × SU(4)?[29] SO(10)?[8]

(D) How can we explain the observed mass spectrum of fundamental fermions, and the observed value of the Cabibbo angle? Can we compute them from some basic theory, or at least relate them by methods similar to those which led to hadronic mass formulae?

It is clear that all of us, experimentalists as well as theorists, have a lot to do in the coming years. Quark and lepton spectroscopy is a fascinating subject, and will remain so for a long time.

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