References

1. Various gauge models are reviewed by H. Fritzsch, in these Proceedings.
2. S. Weinberg: Phys. Rev. Letters **19** (1967) 1264; A. Salam: in *Elementary Particle Theory*, ed. N. Svartholm (Stockholm, 1968).
3. T. Appelquist *et al.*: Phys. Rev. **D7** (1973) 2998. See also, A. Sirlin, paper 185 submitted to this Conference.
4. Experimental results of τ are reviewed by G. Feldman and G. Flügge, in these Proceedings.
5. Some of the early discussions of the heavy lepton are A. K. Mann, Letters Nuovo Cimento **1** (1971) 486; J. J. Sakurai: *ibid.*, **1** (1971) 624; E. W. Beier: *ibid.*, (1971) 1118; H. B. Thacker and J. J. Sakurai: Phys. Letters **36B** (1971) 103; Y. S. Tsai: Phys. Rev. **D4** (1971) 2821; J. D. Bjorken and C. H. Llewellyn Smith: Phys. Rev. **D7** (1973) 889 and references therein. A nice review of heavy leptons up to the summer of 1977 is found in T. Walsh, in Proceedings of the Hamburg Conference (1977).
6. As for radiative corrections, A. Ali and Z. Z. Aydin, Nuovo Cimento **43** (1978) 270.
7. A. I. Sanda and S-Y. Pi: Phys. Rev. Letters **40** (1978) 286.
8. K. Fujikawa and N. Kawamoto: Phys. Rev. **D14** (1976) 59.
2. A. M. Cnops *et al.*: Phys. Rev. Letters **40** (1978) 144.
10. A. Benvenuti *et al.*: Phys. Rev. Letters **35** (1975) 1486; H. Faissner *et al.*: Phys. Letters **60B** (1976) 401; D. Bechis *et al.*: Phys. Rev. Letters **40** (1978) 602.
11. A. De Rujula *et al.*: Phys. Rev. Letters **35** (1975) 628.
12. G. Steigman *et al.*: Phys. Letters **66B** (1977) 202; B. W. Lee and S. Weinberg: Phys. Rev. Letters **39** (1977) 165; P. Hut: Phys. Letters **69B** (1977) 86; M. Kobayashi and K. Sato: Progr. theor. Phys. **58** (1977) 1775 and references therein.
13. M. Nakagawa *et al.*: Progr. theor. Phys. **30** (1963) 727; B. Pontecorvo: Sov. Phys. -JETP **26** (1968) 984.
14. S. Weinberg: Phys. Rev. Letters **36** (1976) 294; A. D. Linde, JETP Letters **23** (1976) 64.
15. M. Veltman: Acta Phys. Polon. **B8** (1977) 475; Phys. Letters **70B** (1977) 253; B. W. Lee, C. Quigg and H. B. Thacker: Phys. Rev. Letters **38** (1977) 883; Phys. Rev. **D16** (1977) 1519. Cf. Y. Nambu: Nucl. Phys. **B130** (1977) 505.
16. M. Biyajima and O. Terazawa, paper 556 submitted to this Conference.
17. J. L. Basdevant and E. L. Berger, paper 577 submitted to this Conference; D. A. Geffen and W. J. Wilson, paper 327. Cf., N. Kawamoto and A. I. Sanda, Phys. Letters **76B** (1978) 327; F. J. Gilman, and D. H. Milman, Miller, Phys. Rev. **D17** (1978) 1846.
18. T. N. Pham, C. Roiesnel and T. N. Truon, papers 718 and 719 submitted to this Conference, and Phys. Rev. Letters **41** (1978) 371.
19. Y. Achiman and B. Stech, paper 697 submitted to this Conference.

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C 10

Quark Masses and Cabibbo Angles

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The calculation of quark masses and Cabibbo angles is one of the most important open problems of the physics of quarks and their interactions. This is a progress report on an attempt to calculate Cabibbo angles, relating them to ratios of quark masses. A preliminary report will soon appear in Physics Letters¹ and we hope to present a more complete report in the near future.

Our starting point is an $SU(2)_L \times SU(2)_R \times U(1)$ gauge theory of weak and electromagnetic

interactions. As usual, the left-handed quarks are in the $(1/2, 0)$ representation while the right-handed quarks are in $(0, 1/2)$. The W and Z boson masses are generated by a set of Higgs mesons, which are not necessarily relevant to our discussion of quark masses. The only Higgs particles which interest us are associated with the $(1/2, 1/2)$ multiplet of $SU(2)_L \times SU(2)_R \times U(1)$ and couple directly to the quarks.

We first consider a six-quark scheme. The

sassignments of the “bare” left-handed quarks to doublets are:

$$\begin{pmatrix} u_0 \\ d_0 \end{pmatrix}_L \quad \begin{pmatrix} c_0 \\ s_0 \end{pmatrix}_L \quad \begin{pmatrix} t_0 \\ b_0 \end{pmatrix}_L$$

The right-handed quarks are assigned to the following doublets:

$$\begin{pmatrix} u_0 \\ q_1 \end{pmatrix}_R \quad \begin{pmatrix} c_0 \\ q_2 \end{pmatrix}_R \quad \begin{pmatrix} t_0 \\ q_3 \end{pmatrix}_R$$

where q_1, q_2, q_3 are a certain permutation or combination of d_0, s_0, b_0 , defined by the matrix:

$$\begin{pmatrix} q_1 \\ q_2 \\ q_3 \end{pmatrix} = O \begin{pmatrix} d_0 \\ s_0 \\ b_0 \end{pmatrix}$$

We will separately discuss results which hold for a general choice of q_1, q_2, q_3 (or the matrix O), and results which follow from a specific choice of the O -matrix.

The full symmetric lagrangian of the theory (before the spontaneous symmetry breaking) is invariant under the discrete group $S_{3L} \times S_{3R}$, where S_3 is the permutation group of three elements. When we generate fermion masses by introducing Higgs fields transforming according to the $(1/2, 1/2)$ representation of $SU(2)_L \times SU(2)_R \times U(1)$, we must also specify their transformation properties under $S_{3L} \times S_{3R}$.

We break the symmetry in two stages:

Step I: We introduce a Higgs field ϕ , with a vacuum expectation value λ_1 , transforming according to the symmetric representation of both S_{3L} and S_{3R} . The resulting mass matrix is:

$$(\bar{u}_0 \bar{c}_0 \bar{t}_0)_L \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix} \begin{pmatrix} u_0 \\ c_0 \\ t_0 \end{pmatrix}_R + \text{h.c.}$$

One quark acquires mass (let us define it to be the physical t -quark), and two quarks remain massless. At this stage the “upper” and “lower” quarks undergo the same treatment.

Step II: We introduce additional Higgs fields (to be specified later, below) which remove the mass degeneracy of the remaining two quarks. If the symmetric massive quark of Step I is denoted by S , and the two massless quarks of Step I are M_1, M_2 , the mass matrix of Step II is given by:

$$(SM_1M_2)_L \begin{pmatrix} K & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix} \begin{pmatrix} S \\ M_1 \\ M_2 \end{pmatrix}_R + \text{h.c.}$$

where K is an arbitrary constant. At this stage, the possible mismatch between the assignments of left-handed quarks and right-handed quarks will, in general, lead to the generation of Cabibbo angles.

The results which we obtain for any q_1, q_2, q_3 (arbitrary O -matrix) are²:

$$m_u = 0$$

$$\tan^2 \theta_c = m_d/m_s$$

However, if we identify: $q_1 \equiv b_0; q_2 \equiv s_0; q_3 \equiv d_0$ we can explicitly calculate the Cabibbo angle. We find:

$$\theta_c = 15^\circ$$

$$m_d/m_s = (2 - \sqrt{3})/(2 + \sqrt{3}) \sim 1/14$$

These results are, clearly, very encouraging (experimentally, $\theta_c \sim 13^\circ$).

We have also considered an eight-quark scheme, in which we add a left-handed doublet:

$$\begin{pmatrix} g_0 \\ h_0 \end{pmatrix}_L$$

and a right-handed doublet:

$$\begin{pmatrix} g_0 \\ q_4 \end{pmatrix}_R$$

Following the same two steps of mass generation, we find that for any assignment of q_1, q_2, q_3, q_4 :

$$m_u = m_d = m_s = 0$$

$$\tan^2 \theta_2 = m_c/m_t$$

where θ_2 is the second Cabibbo-like angle.³ For the specific choice $q_1 \equiv h_0; q_2 \equiv b_0; q_3 \equiv s_0; q_4 \equiv d_0$, we get:

$$\theta_1 = 13^\circ; \quad \theta_2 = 18^\circ; \quad \theta_3 = 0$$

$$\frac{m_c}{m_t} = \left| \frac{\sqrt{3} - \sqrt{6} - \sqrt{2} + 3}{\sqrt{3} - \sqrt{6} - \sqrt{2} - 6} \right| = 0.107$$

Phenomenologically, we know that³:

$$\theta_1 = 13^\circ; \quad \theta_2 < 30^\circ; \quad \theta_3 < 16^\circ$$

For $m_c \sim 1.5$ GeV, we predict $m_t \sim 14$ GeV.

What is the Higgs structure which leads to our mass matrix of steps I and II?

We have constructed two models. The first¹ involve only two Higgs fields:

Field	$S_{3L} \times S_{3R}$ properties	VEV	$SU(2)_L \times SU(2)_R \times U(1)$ properties
ϕ_1	(S_L, S_R)	λ_1	$(1/2, 1/2)$
ϕ_2	(M_L, M_R)	λ_2	$(1/2, 1/2)$

Here S , M refer to the symmetric and the mixed-symmetry representations of S_3 , respectively. This simple Higgs model is “minimal.” It gives the mass matrices mentioned above. However, it is not “natural”⁴ and it suffers

from unpleasant γ_5 -terms.⁵ We have also constructed a more complicated model which is “natural” and avoids the problem of γ_5 -terms. It involves the following fields:

Field	Coupling	$S_{3L} \times S_{3R}$ properties	VEV	$SU(2)_L \times SU(2)_R \times U(1)$ properties
ϕ_1	Scalar	(S_L, S_R)	λ_1	$(1/2, 1/2)$
ϕ_2, ϕ_3	Scalar and pseudoscalar	$(S_L, M_R), (M_L, S_R)$	0	$(1/2, 1/2)$
ϕ_4	Scalar	(M_L, M_R)	λ_2	$(0, 0)$

This model also gives the simple mass matrices mentioned in our discussion above. The details of our “natural” Higgs model as well as further discussion of other open problems will be reported in a future publication.

References

1. H. Harari, H. Haut and J. Weyers: Phys. Letters, to be published.
2. The relation between θ_c and m_d/m_s was earlier obtained from different assumptions by F. Wilczek and A. Zee: Phys. Letters **70B** (1977) 418 and by H. Fritzsch: Phys. Letters **70B** (1977) 436.
3. See e.g., J. Ellis *et al.*: Nucl. Phys. **B131** (1977) 285; H. Harari: Phys. Reports **42** (1978) 235.
4. S. Weinberg: Rev. mod. Phys. **46** (1974) 255.
5. J. M. Frore: Brussels preprint, 1978.

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