WEAK DECAYS OF HEAVY MESONS

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Weak decays of hadrons which contain a heavy quark are characterized by a subtle interplay of strong and weak forces, and thus constitute a very interesting testing ground for the standard model. Asymptotically, that is, for sufficiently heavy quarks, the short-distance dynamics should dominate, allowing a rather straightforward study of some of the fundamental $SU(3)_c \times SU(2)_L \times U(1)$ interactions. Weak decays of not so heavy quark states, on the other hand, are sensitive to the internal nature of QCD bound states and to soft hadronic interactions. Hence, they probe long-distance aspects which play a crucial rôle also in other prominent weak phenomena, such as the $\Delta I = \frac{1}{2}$ rule in kaon and hyperon decays and CP violation. This talk presents a brief discussion[1] of the two main theoretical issues of the present understanding of weak decays of heavy flavours: the effective Hamiltonian and the problem of estimating hadronic matrix elements of the latter. By contrasting simple valence quark descriptions with data on inclusive and exclusive D and B meson decays, the critical physics aspects are brought to light.

In the minimal $SU(2)_L \times U(1)$ electroweak model, heavy flavour decays proceed exclusively via charged current interactions[2]. To lowest order in the weak coupling and for three families of leptons and quarks with masses lighter than the W-boson mass, these interactions are described by the local Hamiltonian

$$H_W = \frac{G_F}{\sqrt{2}} \left(J_+^{\mu}(0) J_{-\mu}(0) + h.c. \right) ; \qquad (1)$$

$$J_-^{\mu} = (\bar{u}\,\bar{c}\,\bar{t})\gamma^{\mu}(1-\gamma_5) V \begin{pmatrix} d \\ s \\ b \end{pmatrix} + (\bar{\nu}_e\,\bar{\nu}_\mu\,\bar{\nu}_\tau)\gamma^{\mu}(1-\gamma_5)\begin{pmatrix} e^- \\ \mu^- \\ \tau^- \end{pmatrix} . \qquad (2)$$

While the weak and mass eigenstates of leptons are identical if neutrinos are massless, the corresponding quark eigenstates are related by the Kobayashi-Maskawa[3),4] matrix V.

Short-distance gluon exchange, however, modifies the bare four-quark interactions detailed in Eqs. (1) and (2). The QCD corrected non-leptonic Hamiltonian H_{NL}^{eff} can be obtained by using operator product expansion and renormalization group techniques[5)-8]. In the limit of massless quarks, one finds

$$H_{NL}^{eff} = \frac{G_F}{\sqrt{2}} \left[c_+\!\left(\alpha_s, \frac{m_W}{\mu}\right) O_+ + c_-\!\left(\alpha_s, \frac{m_W}{\mu}\right) O_- \right] ;$$
$$O_{\pm} = \frac{1}{2}\left[(\bar{U} V D)_L (\bar{D} V^{\dagger} U)_L \pm (\bar{U} V U)_L (\bar{D} V^{\dagger} D)_L \right] , \qquad (3)$$

where U(D) denote the up (down)-type quark arrays of Eq. (2) and $(\bar{\phi}_1 \phi_2)_L \equiv \bar{\phi}_1 \gamma^{\mu}(1-\gamma_5)\phi_2$. The leading logarithmic approximation[5] of the scale-dependent coefficients $c_{\pm}(\alpha_s, m_W/\mu)$ reads

$$c_- = \left[\alpha_s(\mu^2)/\alpha_s(m_W^2) \right]^{\frac{12}{33-2f}} ; \quad c_+ = 1/\sqrt{c_-} . \qquad (4)$$

Also the next-to-leading corrections[6] have been calculated. They are found to be of ordinary size and to reinforce the leading logarithmic inequality $c_- > 1 > c_+$, known as 8(6)-enhancement in strangeness (charm)-decays.

The case of realistic quark masses can be treated similarly[7),8]. However, the procedure becomes more clumsy because of a proliferation of operators in the expansion of H_{NL}^{eff}, mixing of operators under renormalization and more complicated renormalization group equations. Most noteworthy is the appearance of penguin operators, which differ in their (V-A)·V Lorentz-structure from the usual (V-A)·(V-A) four-quark operators. These remnants of a partial deficiency of the generalized GIM mechanism play an essential rôle in the explanation of the $\Delta I = \frac{1}{2}$ rule in kaon and hyperon decays[7]. In charm and bottom decays, however, penguins are expected to be unimportant for several reasons: small coefficients with respect to $c_{\pm}$, small mixing[4] of t and b quarks into the udsc-sector, and no appreciable enhancement[1] of penguin matrix elements with respect to $\langle f | O_{\pm} | i \rangle$. The decay modes $B \to K + n\pi$ constitute a rather special exception[9], but are very rare. Furthermore, since in the case of massive quarks the number f of excited flavours varies with the scale μ, the coefficients $c_{\pm}$ given in Eq. (4) also change[1),8]. Numerically, these modifications turn out to be quite small. In short, the QCD corrected non-leptonic Hamiltonian for heavy flavour decays is well approximated by Eq. (3), with ($c_- = c_+^{-2}$)

$$\begin{aligned} & c_-(m_c = 1.7\ \text{GeV}) = 1.7\text{–}2.1 \\ & c_-(m_b = 5\ \text{GeV}) = 1.4\text{–}1.5; \quad \Lambda_{QCD} = 0.2\text{–}0.5\ \text{GeV} \\ & c_-(m_t = 40\ \text{GeV}) = 1.07\text{–}1.09 \end{aligned} \qquad (5)$$

Of course, the semi-leptonic Hamiltonian is not affected by short-distance gluon interactions and can thus be directly read off from Eq. (1).

The inclusive decay properties of sufficiently heavy quark states are essentially determined by weak decays of the "free" heavy quark with the light constituents merely acting as passive spectators[10]. In this asymptotic limit, all weakly-decaying hadrons with a given heavy flavour Q have roughly the same semi- and non-leptonic widths. The latter can readily be calculated[1] from the effective Hamiltonian given in Eqs. (1) and (3):

$$\Gamma_{SL} = \sum_{\ell,q} |V_{Qq}|^2 \, I\left(\frac{m_{q,\ell}}{m_Q}\right)\left[1 - \frac{2}{3}\frac{\alpha_s(m_Q^2)}{\pi} f\left(\frac{m_q}{m_Q}\right)\right]\frac{G_F^2 m_Q^5}{192\pi^3} \; ; \tag{6}$$

$$\Gamma_{NL} = \sum_{q_i} |V_{Qq_1}|^2 |V_{q_2 q_3}|^2 \, I\left(\frac{m_{q_1,q_2,q_3}}{m_Q}\right)\frac{2c_+^2 + c_-^2}{3} \cdot \left[1 + \frac{2}{3}\frac{\alpha_s(m_Q^2)}{\pi} h_Q\left(\frac{m_{q_1,q_2,q_3}}{m_Q}; c_\pm\right)\right]\frac{G_F^2 m_Q^5}{64\pi^3} \; . \tag{7}$$

The above estimates include quark mixing ($V_{q_i q_j}$), phase space effects[11] of final state quark masses (I), radiative gluon corrections[6),12),13)] [$f(0) = \pi^2 - 25/4$ and $h_{c,b}(0;c_\pm) \simeq 2.2,\ 0.6$] and the short-distance non-leptonic enhancement[10]. One can, furthermore, take into account the Fermi motion[13] inside the heavy hadron. Even though the spectator model makes unambiguous predictions for asymptotically heavy flavours, in the mass range of bottom and, particularly, of charm, the results are still quite sensitive to the choice of the effective quark masses and the normalization of the QCD running coupling constant.

Considering these uncertainties, the spectator model appears to be consistent with the present data on inclusive B decays:

(i) The semi-leptonic electron spectrum is well described[14] by the "free" b-quark decay $b \to e\nu_e c$. [Contributions from $b \to e\nu_e u$ are excluded at the level of $|V_{ub}/V_{cb}| < 0.116$ (90% c.l.)].

(ii) For the two sets of quark masses, m(u,d;s;c;b) = = 0; 0.15; 1.4; 4.8 GeV (I) and 0.35; 0.5; 1.8; 5.2 GeV (II), Eqs. (6) and (7) yield[1] the semi-leptonic branching ratio and lifetime,

$$BR_{e,\mu} \simeq \begin{cases} 12\% \\ 15\% \end{cases} ; \quad \tau_b |V_{cb}|^2 \simeq \begin{cases} 2.8 \cdot 10^{-15}\,s & (I) \\ 3.2 \cdot 10^{-15}\,s & (II) \end{cases} \tag{8}$$

Comparison of these expectations with the world averages[4] $BR_e = (13.0 \pm 1.3)\%$ and $BR_\mu = (12.4 \pm 3.5)\%$ reveals a respectable agreement and shows that current-type quark masses (I) are favoured and QCD corrections are absolutely needed to reconcile the spectator model with experiment: putting $\alpha_s = 0$ gives $BR_{e,\mu} \simeq (15\text{-}18)\%$. [From the observed[4] B lifetime, $\tau_B = (1.4 \pm 0.4) \cdot 10^{-12}$s, and Eq. (8I), one further derives $|V_{cb}| \simeq 0.0^{35}_{65}$.

(iii) To the extent that the average number of kaons per B decay reflects the average number of s-quarks, the prediction $\langle n_s \rangle \simeq 1.4$ is confirmed by the experimental result[15] $\langle n_K \rangle = 1.45 \pm 0.1$.

(iv) The inclusive D°-momentum distribution[16] bears great resemblance to the c-quark spectrum expected from $b \to ce\nu_e$, and thus supports the similarity of semi- and non-leptonic decay processes in the spectator model.

(v) The decay mode $b \to c\bar{c}s$ can lead to J/ψ resonances. Using the quark masses given in (ii) set I and including the probability factor 1/9 for the $(c\bar{c})$ pair to be produced in a colour-singlet state, one predicts[17] $BR(B \to J/\psi X) \simeq 1.3\%$ in agreement with the experimental upper limit[16] of 1.6% (90% c.l.).

It should, however, be kept in mind that the above data refer to an average of 60% $B^\pm$ and 40% $\overset{(-)}{B}{}^\circ$ decays[16] and may, therefore, hide non-spectator effects in the same way as the early data on D decays.

Not until one discovered substantially differing lifetimes for the $D^\pm$ and $\overset{(-)}{D}{}^\circ$ mesons, to wit[4]

$$\tau^\pm = \left(5.2^{+1.7}_{-1.2}\right)\cdot 10^{-13}\,s \;; \quad \tau^\circ = \left(4.4^{+0.8}_{-0.6}\right)\cdot 10^{-13}\,s \; , \tag{9}$$

did it become clear that the spectator model is insufficient for charm decays. While the "free" c-quark decay $c \to e\nu_e s$ provides a good description of the semi-leptonic electron spectrum[14] measured in $D \to e\nu_e X$, the non-leptonic D decays are apparently influenced by non-asymptotic effects involving the light constituents. The same is indicated by the D semi-leptonic branching ratios: $BR_e(D^+) = (17 \pm 3 \pm 3)\%$ and $BR_e(D^\circ) = (6 \pm 2 \pm 2)\%$ reported by the MARK III collaboration at this Conference[18]. Since the partial widths of the $\Delta I = 0$ Cabibbo-allowed semi-leptonic decays must be identical for the D^+ and D°, these data imply that

$$\frac{\tau^+}{\tau^\circ} \simeq \frac{BR_e(D^+)}{BR_e(D^\circ)} = 2.8^{+0.9\,+0.3}_{-0.6\,-0.4} \; . \tag{10}$$

In order to find out which, if any, of the charmed mesons is "normal" from the point of view of the spectator model, one may recall the predictions[1] obtained from Eqs. (6) and (7):

$$BR_{e,\mu} \simeq \begin{cases} 13\% \\ 19\% \end{cases} ; \quad \tau_c \simeq \begin{cases} 6.0 \cdot 10^{-13}\,s & (I) \\ 7.5 \cdot 10^{-13}\,s & (II) \end{cases} \; , \tag{11}$$

where (I) and (II) refer to the quark masses, m(u,d; s;c) = 0.15; 0.3; 1.6 GeV and 0.3; 0.4; 1.7 GeV respectively. Although the theoretical and experimental uncertainties do not allow a firm conclusion, it seems that the non-leptonic D° decays deviate most significantly from the spectator picture.

Two effects have been put forward which can give rise to lifetime differences and other modifications of the asymptotic decay pattern: the interference[19] of a light constituent with an identical quark produced in the heavy quark decay and weak annihilation of, or W-exchange[20] between, the heavy and a light constituent. Both effects depend strongly on QCD bound state properties and are, therefore, difficult to quantify. However, the qualitative aspects are quite clear. Whereas the D° final state produced by the Cabibbo-allowed c-quark decay $c \to s\bar{d}u$ consists of different quark flavours, the D^+ final state contains two $\bar{d}$ quarks. These interfere according to the Pauli exclusion principle[21]. As a consequence of the short-distance QCD corrections, the interference turns out to be destructive and, hence, increases the lifetime and semi-leptonic branching ratio of the D^+ relative to the D°. Numerical estimates[1] in a variety of bound state models indicate that the overall effect is probably not larger than 20%. It is obvious from the structure of the weak Hamiltonian given in Eq. (1) that the D° can also decay via W-exchange ($c\bar{u} \to s\bar{d}$), while weak annihilation ($c\bar{d} \to u\bar{d}$) of the D^+ is Cabibbo-suppressed. Thus, non-specator processes tend to shorten the lifetime of the D° and to lower its semi-leptonic branching ratio relative to the D^+, in qualitative agreement with experiment. However, this effect was thought to be negligible for two reasons: (a) the small value of the decay constant $f_D \sim O(f_{\pi,K}) << m_D$ expected theoretically, and (b) the suppression of $D \to q_1\bar{q}_2$ by helicity conservation, at least in the usual valence quark picture. On the other hand, it has been argued[20] that as gluons carry spin, helicity suppression may be abolished by the presence of gluons in the D bound state or by gluon radiation from the initial valence quark state. In order to explain the observed lifetime ratio $\tau(D^+)/\tau(D^\circ) \sim 2\text{-}3$, W-exchange must obviously be at least as "strong" as the c-quark decay mechanism. While model estimates[1] show that this is not impossible, one still lacks a clear-cut quantitative proof. It is, therefore, important to test further qualitative predictions of the above hypotheses on D and F meson decays and to search for non-spectator effects also in B-decays[1]. Although one can argue on quite general grounds that the latter should not exceed O(10%), at the present stage only experiment can decide.

Exclusive non-leptonic decays are conceptually more difficult than inclusive decays since no simple "free" quark limit exists, an almost trivial statement. The original suggestion[10),21),22] to calculate the two-body matrix elements of the effective Hamiltonian Eq. (3) in a valence quark approximation was found[1] to fail for certain D-decay modes. Now that the MARK III collaboration has remeasured the prominent D-decays into two pseudoscalar mesons or into a pseudoscalar and a vector meson with better accuracy[18], one can clarify the problematic issues.

In the valence quark approximation, the matrix element of a four-quark operator is factorized in a product of matrix elements of quark currents with the vacuum as an intermediate state. This has the consequence that weak annihilation and W-exchange amplitudes vanish in the SU(3)-limit because of conservation of vector currents and, therefore, contribute at most at the level of SU(3)-breaking effects. In the cases considered later on, these contributions can safely be neglected. The c-quark decay mechanism, on the other hand, gives rise to two types of amplitude: a "colour-unmixed" amplitude describing the formation of the final state mesons directly out of the two colour-singlet quark-antiquark pairs produced in the c-decay [e.g., $D^\circ \to (\bar{u}s)(\bar{d}u) \to K^-\pi^+$] and a "colour-mixed" amplitude corresponding to the formation of mesons by exchanging the quarks (or antiquarks) of these pairs [e.g., $D^\circ \to (\bar{u}s)(\bar{d}u) \to (\bar{d}s)(\bar{u}u) \to \bar{K}^\circ\pi^\circ$]. The latter is suppressed by the colour-singlet projection factor 1/3 relative to the former. Short-distance QCD corrections decrease "colour-mixed" amplitudes further by the factor $2c_+-c_-$, whereas "colour-unmixed" amplitudes are enhanced by the factor $(2c_++c_-)/3$. In general, both amplitudes add coherently. SU(3) [and SU(6)] breaking effects enter via the matrix elements of quark currents (form factors) and via phase space. Consideration must also be given to the quark mixing parameters.

The various aspects addressed above can be studied by choosing suitable ratios of partial $D \to PP$ and $D \to PV$ widths. In the following analysis, I shall use the valence quark predictions of Fakirov and Stech[21]. Whenever theoretical ratios depend on QCD corrections, results are given for $c_- = c_+^{-2} = 1.7$ and 2.1 to cover the uncertainty in Λ_{QCD} expressed in Eq. (5). The experimental ratios calculated from the MARK III data[18] are quoted in brackets. I find:

(i) ratios sensitive to SU(6) breaking:

$$K^-\rho^+/K^-\pi^+ \simeq 1.3 \ (1.5\pm0.75)$$
$$K^{*-}\pi^+/K^-\pi^+ \simeq 0.6 \ (0.85\pm0.30) \qquad (12)$$
$$\bar{K}^\circ\rho^\circ/\bar{K}^\circ\pi^\circ \simeq 0.4 \ (0.7\pm0.35)$$

(ii) ratios sensitive to SU(6) breaking weighted by QCD corrections:

$$\bar{K}^\circ\rho^+/\bar{K}^\circ\pi^+ \simeq 1.5\text{-}2.0 \ (2.2\pm1.2)$$
$$\bar{K}^{*\circ}\pi^+/\bar{K}^\circ\pi^+ \simeq 0.5\text{-}0.4 \ (0.4\pm0.35)$$

QCD corrections improve the agreement with the data: putting $c_+ = c_- = 1$ would yield the ratios 1.0 and 0.7 respectively.

(iii) ratios testing colour suppression:

$$\bar{K}^\circ\pi^\circ/K^-\pi^+ \simeq 0.002\text{-}0.05 \ (0.35\pm0.14)$$
$$\bar{K}^\circ\rho^\circ/\bar{K}^{*-}\pi^+ \simeq 0.002\text{-}0.05 \ (0.28\pm0.11) \qquad (14)$$

These predictions are clearly at variance with the data. I should emphasize, however, that for $c_+ = c_- = 1$, one obtains 0.1 for the above ratios, which disagrees with the data "only" by a factor of 3. Thus, QCD corrections worsen the situation! On the other hand, one notices from Eq. (14) that the leading logarithmic factor $(2c_+-c_-)^2$ is extremely sensitive to the values of c_+ or, equivalently, of

Λ_{QCD}. This puts strong doubts on its reliability.

(iv) ratio sensitive to SU(3) breaking and the interference of "colour-mixed" and "unmixed" amplitudes:

$$\bar{K}^\circ\pi^+/K^-\pi^+ \simeq 0.9\text{–}0.5 \ (0.25\pm0.17) \qquad (15)$$

Here QCD corrections again improve the theoretical result.

(v) ratios testing quark mixing distorted by SU(3) breaking:

$$K^-K^+/K^-\pi^+ \simeq 0.09 \ (0.125\pm0.028)$$

$$\pi^-\pi^+/K^-\pi^+ \simeq 0.0^{57}_{76} \ (0.038\pm0.015) \qquad (16)$$

The uncertainty in $\pi^+\pi^-/K^-\pi^+$ reflects the present uncertainty[4] of $|V_{cd}/V_{cs}|^2$.

(vi) ratio involving SU(3) breaking, interference of "colour-mixed" and "unmixed" amplitudes and quark mixing:

$$\bar{K}^\circ K^+/\bar{K}^\circ\pi^+ = 0.14\text{–}0.23 \ (0.29\pm0.13) \qquad (17)$$

Again, large QCD corrections are favoured.

One can conclude that the valence quark approximation agrees with the data on 11 two-body channels within the experimental uncertainties or, in the case of the ratios (15) and (16), within 1.5 standard deviations if the short-distance QCD corrections with $c_- = c_+^{-2} = 2.1$ (corresponding to $\Lambda_{QCD} \simeq 500$ MeV) and SU(3) [SU(6)] breaking are taken into account. The only exceptions are the purely "colour-mixed" channels $\bar{K}^\circ\pi^\circ$ and $\bar{K}^\circ\rho^\circ$ on which model and data disagree by more than two standard deviations. This failure has been attributed to soft gluon interactions[23], W-exchange contributions[20], and final state resonance effects[24], to mention some of the suggestions. It is very important to identify the correct physics reason. In this context, I should note that MARK III has also measured the mode $D^+ \to \phi\pi^+$, which is both colour- and Cabibbo-suppressed and, thus, should be very rare. The experimental ratio $\phi\pi^+/\bar{K}^\circ\rho^+ = 0.11\pm\pm0.06$, on the other hand, is barely consistent with Cabibbo-suppression, but does certainly not show any sign of colour-suppression. Further interesting information can be expected from two-body B decays.

After one decade of quite intensive experimental and theoretical efforts, it seems that the standard model can well account for the observed features of heavy flavour decays. Yet two important pieces of the puzzle are still missing: a quantitative basis for dealing with pre-asymptotic (non-spectator) effects and a clear understanding of the rôle of the colour degrees of freedom in exclusive decays.

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WEAK DECAYS OF CHARMED BARYONS

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1. Introduction

The physics of heavy flavours is very young and to a large part still unexplored. In particular, heavy hadrons with open flavour represent an interesting system whose weak decays are determined by an interplay of strong and weak interactions.

In this talk I want to give a brief survey of inclusive as well as exclusive weak decays of charmed baryons. Particular emphasis will be put on the discussion of explicit model estimates of weak matrix elements and their comparision with experiments.

2. Inclusive charmed baryon decays

The simplest picture of inclusive weak decays of charmed hadrons is the decay of the charmed quark inside the hadrons, $c \to s u \bar{d}$ with the light quarks acting as inert spectators (spectator model).[1] One then integrates over the phase space of the final state quarks, on the assumption that the initial mass is large enough for this to represent the sum of all hadronic final states ("quark-hadron duality"). Clearly this spectator model predicts equal lifetimes and semileptonic branching ratios for both charmed mesons D^0, D^+, F^+ and charmed baryons $\Lambda_c^+ = c[u, d]$, $A^0 = c[s, d]$, $A^+ = c[s,u]$ or $T^0 = css$, respectively.+)
The total width $\Gamma(h \to \text{all})$ for Cabibbo-favoured inclusive hadron decays $h \to$ all may be scaled from the rate $\Gamma(\mu \to \nu_\mu e \bar{\nu}_e)$ as (we set here $\cos\theta_c \approx 1$, θ_c-Cabibbo angle)

$$\Gamma(h \to all) \equiv \Gamma_{sp}(c \to all) = \left\{(2f_+^2 + f_-^2) + 2\right\} \times \\ \times \left(\frac{m_c}{m_\mu}\right)^5 0.7\, \Gamma(\mu \to \nu_\mu e \bar{\nu}_e) \qquad (1)$$

+) The bracket $[q_1, q_2]$ denotes antisymmetric flavour combinations. Experimental knowledge of the charmed baryons A^+ and T^0 was recently obtained at the CERN hyperon beam.[2], [3]

where the coefficients f_+ and f_- (both equal to unity in the absence of strong interactions) are the usual short-distance enhancement factors of the nonleptonic weak Hamiltonian Hw[4], $f_- = [\alpha_s(m_c^2)/\alpha_s(m_W^2)]^{0.48} \sim 2$, $f_+ = f_-^{-1/2} \sim 0.7$, and the 2 in the curly bracket comes from the semileptonic decays. The factor 0.7 is a phase space correction factor due to the strange quark mass and $\Gamma(\mu \to \nu_\mu e \bar{\nu}_e) = G_F^2 m_\mu^5 / 192\pi^3$.
Using $m_c = 1.5$ GeV one obtains $\tau_c = [\Gamma_{sp}(c \to all)]^{-1} \sim 7 \cdot 10^{-13}$ sec. For comparision let us quote the 1983 "best estimates" for charmed particle lifetimes[5]. The corresponding quantities are $\tau(D^+) = (8.8^{+1.3}_{-1.0}) \cdot 10^{-13}$ sec which is close to τ_c, and $\tau(D^0) = (4.4^{+0.6}_{-0.5}) \cdot 10^{-13}$ sec, $\tau(F^+) = (2.1^{+1.3}_{-0.6}) \cdot 10^{-13}$ sec and $\tau(\Lambda_c^+) = (2.2^{+0.8}_{-0.5}) \cdot 10^{-13}$ sec. There is also a recent measurement of the A^+ lifetime, $\tau(A^+) = (4.8^{+4.0}_{-1.8}) \cdot 10^{-13}$ sec.[2] Notice that the evident discrepancies in the lifetime pattern can be solved by taking into account non-spectator ("annihilation") processes $c\bar{u} \to s\bar{d}$, $c\bar{s} \to u\bar{d}$ or $cd \to su$ which contribute in D^0, F^+ or Λ_c^+, A^0 decays but not in D^+ or A^+ and T^0 decays. Because there are no helicity constraints for the process $cd \to su$ in baryon decays, gluons play here a minor role and can, at least in a first approximation, be neglected.
For illustration let us consider the $\Lambda_c^+(c[u, d])$ decay processes shown in Fig. 1

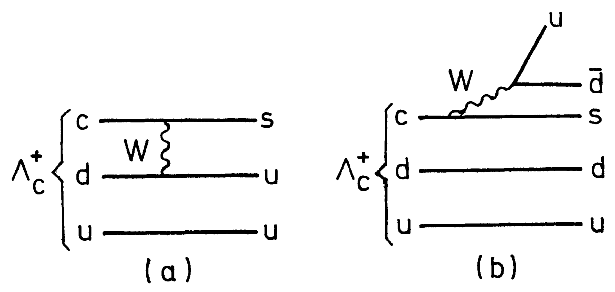

Fig.1

The decay rate for the non-spectator process $\Lambda_c^+ \rightarrow suu$ of Fig. 1a has been calculated by Barger et al. in the nonrelativistic quark model[6], $\Gamma_{ns}(\Lambda_c^+) = \frac{G_F^2}{2\pi}\cos^4\theta_c f_-^2 |\psi(0)|^2 m_c^2$. Here $\psi(o)$ denotes the Λ_c^+ wave function at the origin, and light quark mass effects were neglected. The major source of uncertainty in Γ_{ns} is $|\psi(0)|^2$. Using $|\psi(0)|^2 = 7.4 \cdot 10^{-3}$ GeV^3 as derived in ref. /6/ on the basis of the $\Sigma_c^+ - \Lambda_c^+$ hyperfine mass splitting one obtains $\Gamma_{ns}(\Lambda_c^+) \approx 0.3 \cdot 10^{13}$ sec^{-1}. The total rate then follows by adding the non-spectator and spectator contributions associated to Fig.1a, b (for Fig. 1b use Γ_{sp}(c $\rightarrow$ all)). This yields the lifetime relation $\tau(\Lambda_c^+) = \tau_c [1 + \Gamma_{ns}(\Lambda_c^+)\tau_c]^{-1}$. Taking the above estimates for τ_c and $\Gamma_{ns}(\Lambda_c^+)$ one predicts $\tau(\Lambda_c^+) \sim 2.1 \cdot 10^{-13}$ sec in agreement with the data. In principle, one must take into account also Pauli interference contributions due to identical quarks in the final state[7]. Their effect is simply to reduce the value of $\Gamma_{ns}(\Lambda_c^+)$ by $\Gamma_{ns}(\Lambda_c^+) \rightarrow \sim 0.7\, \Gamma_{ns}(\Lambda_c^+)$ which leads to a somewhat larger value $\tau(\Lambda_c^+) \sim 2.7 \cdot 10^{-13}$ sec. Finally, we mention that non-spectator (annihilation) diagrams of the type shown in Fig. 1a contribute to nonleptonic weak decays of the A^o baryon but not to A^+ or T^o decays. One expects therefore the following inequalities for total rates and semileptonic branching ratios: i) $\Gamma(\Lambda_c^+, A^o) > \Gamma(T^o, A^+)$ (compare, for example, the estimates obtained from nonrelativistic quark models[8] or by summing up partial widths of two-body and quasi-two-body processes[9]) and ii) $B(\Lambda_c^+ \rightarrow e^+\nu_e X) \approx B(A^o \rightarrow e^+\nu_e X) < B(A^+ \rightarrow e^+\nu_e X) \approx B(T^o \rightarrow e^+\nu_e X) \approx \frac{1}{5} = 20\ \%$. Note the experimental result $B(\Lambda_c^+ \rightarrow e^+\nu_e X) = (4.5 \pm 1.7)\%$[10]. Finally, for a recent discussion of inclusive Λ_c^+ decays within the framework of a $1/N_c$-expansion we refer the reader to ref./11/.

3. Exclusive two-body decays+)

The estimate of the baryonic matrix elements of the effective weak Hamiltonian H_W (as given in ref. /4 /) for exclusive charmed baryon decays is more involved than for inclusive decays. A particularly convenient framework for evaluating matrix elements is the MIT bag model which manifestly allows the confinement of relativistic quarks inside hadrons. This model has been successfully applied to a study of nonleptonic hyperon decays[14] and later on to a study of charmed baryon decays[12], /13/, /15/. Let us briefly review some recent bag-model calculations for Cabibbo favoured nonleptonic charmed baryon decays $B_\alpha^c \rightarrow B'_\beta + \mathcal{M}_k$. For definiteness, we consider the processes $\Lambda_c^+ \rightarrow (\Lambda\pi^+, p\bar{K}^o, \Xi^o K^+, \Sigma^o\pi^+)$, $A^+ \rightarrow \Xi^o\pi^+$, $A^o \rightarrow \Xi^-\pi^+$ and $T^o \rightarrow \Xi^o \bar{K}^o$/13/. The experimental mass values are $M_{\Lambda_c^+} = 2282$ MeV, $M_{A^+} = 2460$ MeV and $M_{T^o} = 2740$ MeV. (For another approach to these processes using the chiral SU(4) meson-baryon Lagrangian of ref./16/ see also ref./17/). The corresponding matrix element of H_W takes the form

$$\langle \mathcal{M}_k(q)\beta | H_W | \alpha \rangle = i\bar{u}_\beta(p')[A + B\gamma_5]u_\alpha(p)\varphi_k(q) \qquad (2)$$

where A and B are the (parity-violating) s-wave and (parity-conserving) p-wave amplitudes, respectively. For later use we also introduce baryon-baryon matrix elements of the parity-conserving (PC) and parity-violating (PV) parts of H_W by $\langle\beta|H_W^{PC}|\alpha\rangle = a_{\beta\alpha}\bar{u}_\beta u_\alpha$ and $\langle\beta|H_W^{PV}|\alpha\rangle = b_{\beta\alpha}\bar{u}_\beta\gamma_5 u_\alpha$. It is convenient to reduce the three-hadron matrix element in (2) by applying standard soft-meson current algebra techniques. The A and B amplitudes may then be expressed as a sum of so-called commutator terms, baryon pole terms (meson pole terms give a 10 % contribution and will be neglected) and factorizable contributions. One gets, for example,

$$A = -\frac{1}{\sqrt{2}F_k}\left(I^k_{\beta\gamma}a_{\gamma\alpha} - I^k_{\varrho\alpha}a_{\beta\varrho}\right) - \frac{1}{\sqrt{2}F_k}(M_\alpha - M_\beta)\left[\frac{g^A_{k\beta\delta}b_{\delta\alpha}}{M_\alpha + M_\delta} - \frac{g^A_{k\gamma\alpha}b_{\beta\gamma}}{M_\beta + M_\gamma}\right] + A^{fac} \qquad (3)$$

where F_k is the meson decay constant ($F_\pi = 93$ MeV, $F_K = 1.27\, F_\pi$), M_α etc. are baryon masses, $I^k_{\beta\gamma}$ are unitary-spin matrix elements and g^A are axial vector coupling constants defined by baryon matrix elements of the weak current. The factorizable con-

+) Based on work done in collaboration with W. Kallies (ref./12/, /13/)

tribution A^{fac} corresponds to the usual quark decay (spectator) diagrams and is given by
$A^{fac} = -\frac{1}{3} G_F F_k \cos^2\theta_c [2f_+ \pm f_-](M_\alpha - M_\beta) g^V_{k\beta\alpha}$
where the +(-) sign in the bracket refers to π^+ ($\bar{K}^0$) emission.

In contrast to earlier bag model calculations[12], [15] we included the PV-matrix elements $b_{\beta\alpha}$ in (3) which are expected to give a contribution comparable with $a_{\beta\alpha}$ due to large SU(4) braking. Straight-forward calculations yield explicit representations of $g^{A(V)}$, $a_{\beta\alpha}$ and $b_{\beta\alpha}$ in terms of two-quark or four-quark overlap integrals of the MIT-bag, respectively. As we find the ratio $|b/a|$ is indeed larger than the value 0.1 found for hyperon decays but smaller than the value 1 anticipated in ref./18/. The partial rates for the different decay modes calculated from the A and B amplitudes are (in units of 10^{11} sec^{-1}):

$\Gamma(\Lambda_c^+ \to \Lambda\pi^+) = 3.8$, $\Gamma(\Lambda_c^+ \to p\bar{K}^0) = 1.7$,
$\Gamma(\Lambda_c^+ \to \Xi^0 K^+) = 0.1$, $\Gamma(\Lambda_c^+ \to \Sigma^0\pi^+) = 1.2$,
$\Gamma(A^+ \to \Xi^0\pi^+) = 1.4$, $\Gamma(A^0 \to \Xi^-\pi^+) = 10.1$
and $\Gamma(T^0 \to \Xi^0\bar{K}^0) = 3.7$. The PV-matrix elements yield generally corrections at the 20 % level in Γ. The changes are, however, more manifest if one considers the asymmetry parameter α. One gets e.g. $\alpha(\Lambda_c^+ \to \Xi^0 K^+) = -0.9$ (b included) instead of -0.1 (without b). Our estimate for $\Gamma(\Lambda_c^+ \to p\bar{K}^0)$ is compatible with the experimental value $\Gamma(\Lambda_c^+ \to p\bar{K}^0) = (1.00^{+0.86}_{-0.78}) \cdot 10^{11}$ sec^{-1} /19/. Similarly the ratio $\Gamma(\Lambda_c^+ \to \Sigma^0\pi^+)/\Gamma(\Lambda_c^+ \to p\bar{K}^0) = 0.71$ is consistent with the data of the Fermilab bubble chamber[20]. Unfortunately, the rate $\Gamma(\Lambda_c^+ \to \Lambda\pi^+)$ comes, however, out too large by a factor of 3-5 when compared with experiment. Finally, notice that the large difference between the A^+ and A^0 partial rates is caused by non-spectator contributions.

We have reviewed some models and ideas in the field of weak decays of charmed baryons. Presumably in the near future more precise data will be accumulated which will help to sort out the relevant models for describing weak decays of charm and heavier beauty hadrons.

I wish to thank U. Gensch, W. Kallies, T. Naumann and R. Rückl for helpful conversations. I have also profited from discussions with B. Stech.

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FORWARD BACKWARD ASYMMETRIES IN HEAVY GAUGE BOSON DECAYS

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Summary

R. Robinett, J. Rosner and I have studied[1,2] the prospects for producing and detecting massive (e.g. 1 TeV) new gauge bosons at pp and $p\bar{p}$ colliders, including charged W bosons with right-handed couplings and several types of neutral bosons. We especially emphasize that forward-back asymmetries of decay leptons, which can occur in both pp and $p\bar{p}$ collisions, may be a very useful probe of the gauge boson couplings.

Conclusions

(a) At a $\sqrt{s}$ = 40 TeV pp collider with an integral luminosity L of $10^{40}cm^{-2}$ it should be possible to detect a right-handed charged W_R by its leptonic decays if $M_{W_R} \lesssim 8$ TeV. We assume that detections of a W_R^+ is possible if there are at least 10 events each of $pp \to W_R^+ \to e^+N$ and $pp \to W_R^+ \to \mu^+N$.

(b) Under similar assumptions the Z_χ (the additional neutral boson in SO_{10}) can be detected by its e^+e^- or $\mu^+\mu^-$ decays if $M_{Z_\chi} \lesssim 6$ TeV.

(c) For the purposes considered here a pp collider with L = $10^{40}cm^{-2}$ is slightly better than a $p\bar{p}$ collider with the same energy and L = $10^{39}cm^{-2}$.

(d) For a boson mass $M_B \lesssim 1$ TeV a useful diagnostic signature for both pp and $p\bar{p}$ collisions is the forward-backward asymmetry of the emitted lepton:

$$A_{FB}(y) = \left[\left(\frac{d\sigma}{dy}\right)_{z^*>0} - \left(\frac{d\sigma}{dy}\right)_{z^*<0}\right] \Bigg/ \frac{d\sigma}{dy} \quad ,$$

where z^* is the cosine of the lepton angle with respect to the beam direction in the gauge boson rest frame and y is the gauge boson rapidity. As an example, A_{FB} is shown for the ordinary Z and the Z_χ in Figures (1) and (2), respectively, for both pp and $p\bar{p}$.

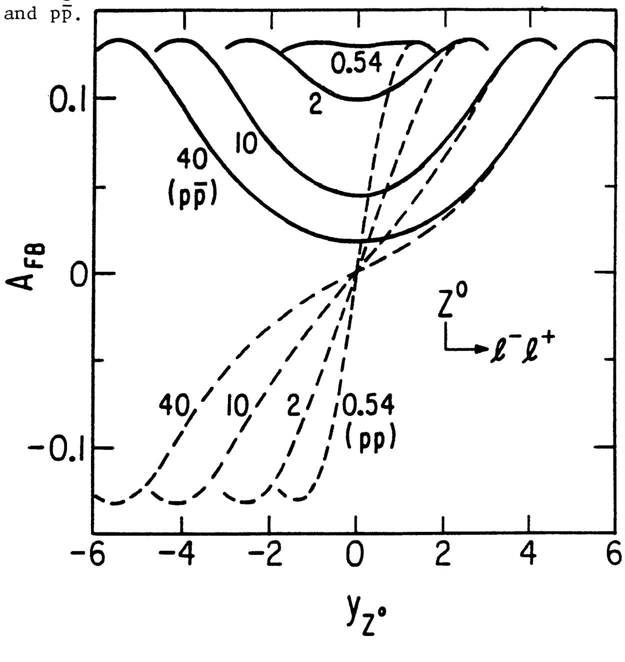

Figure 1. A_{FB} of ℓ^- vs. y_{Z^0} in pp (dashed line) and $p\bar{p}$ (solid lines) $\to Z^0 \to \ell^-\ell^+$. Curves are labeled by total c.m. energy in TeV.

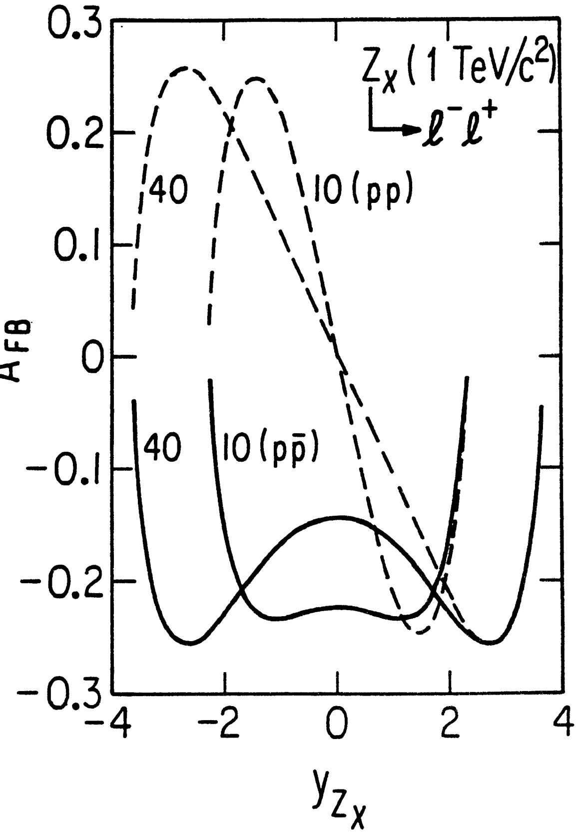

Figure 2. A_{FB} of ℓ^- vs. y_{Z_χ} for M_{Z_χ} = 1 TeV/c^2. (Other labels as in Figure 1).

(e) For $M_B \lesssim$ 1-5 TeV global asymmetry variables are useful. For pp a promising variable is $\langle E_{\ell^-}\rangle/\langle E_{\ell^+}\rangle$, where $\langle E_\ell\rangle$ are the average lepton energies in $W'^{\pm} \to \ell^\pm X$ or $Z' \to \ell^+\ell^-$.

(f) The secondary decays $N \to e^\pm + X$, where N (the SU_{2R} partner of e^-_R) is produced in $W_R^\pm \to e^\pm \overset{(-)}{N}$ or $Z_\chi \to N\bar{N}$, may occur essentially instantaneously, a finite distance from the production vertex, or even outside the detector (depending on the model). Observation of such decays could be very useful both for reconstructing the W_R and for determining the nature (eg. Majorana or Dirac) of the N (see ref. 1).

(g) Lepton sign identification is extremely important.

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RECENT MEASUREMENTS OF ε'/ε IN KAON SYSTEM

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INTRODUCTION

This paper summarizes the results obtained by Chicago-Saclay collaboration[1] at Fermilab and Yale-BNL collaboration[2] at BNL. Due to the experimantal discoveries of c,b and possibly t quark in recent years,Kobayashi-Maskawa model[3] (KM model) become a attractive model of CP violation. Unlike the superweak hypothesis where CP violation occurrs only in the mass matrix,in KM model $\Delta S=1$ decay can also violates CP through complex phase of quarks.As a result, η_{00} can be different from η_{+-} where $\eta_{00}(\eta_{+-})$ is the ratio between the $K_L \to \pi^0\pi^0(\pi^+\pi^-)$ and the $K_S \to \pi^0\pi^0(\pi^+\pi^-)$ decay amplitudes. With isospin decompositi tion $\eta_{+-} \simeq \varepsilon+\varepsilon'$, $\eta_{00} \simeq \varepsilon-2\varepsilon'$, $\varepsilon' = \frac{i}{\sqrt{2}} \mathrm{Im}(a2/a0) e^{i(\delta 2-\delta 0)}$ where a0(2) is the amplitude for $K^0 \to 2\pi$ in the I=0(2) final state and $\delta 0(2)$ is the $\pi-\pi$ phase shift in the I=0(2) state. Since the phase of ε and $\delta 2-\delta 0$ are nearly equal,we have

$$\left|\eta_{00}/\eta_{+-}\right|^2 \simeq 1-6\varepsilon'/\varepsilon \,. \quad (4)$$

In KM model, the prediction for ε'/ε depends directly upon the top quark mass,the bottom quark life time, the ratio Γ(b- u)/Γ(b- c) and the hadronic parameter B which relate K^0 and quark diagram. In spite of these ambiquities, calcurations indicate that ε'/ε likely to be greater than 0.005.(5)

THE CHICAGO-SACLAY EXPERIMENT

This experiment was performed at M3 neutral beam line at Fermilab. K_L was produced at 5 mrad ,using 400GEV/C proton. The K_L beam was divided into two parallel,seperated beams. In one of the beam a regenerator,consisting of 1m Carbon and 1/2" lead was placed to produce K_S. The regenerator was moved back and forth between two beams for each pulse so that not only beam flux but also any asymmetries of detector calcell out in the ratio of K_L and K_S decay.

The K_L,K_S decays were recorded simultaneously so that possible bias,due to dead time,efficiencies, resolution and background tracks ,does not affect the result. The detector is shown in Fig.1.

The data were collected in two phases,the neutral mode($\pi^0\pi^0$) and the charged mode($\pi^+\pi^-$). For the charged mode,the trigger required a two charged particles.The events were reconstructed by drift chamber spectrometer to give invariant mass,pt^2 relative to incident K_L and decay vertex which is essential to decide wether the event belong to K_L or K_S decay. For the neutral mode running, a thin anti-counter and 0.1 rl. lead converter were added immediatly before"HV"hodo scope that defined the end of the decay region. The trigger required one and only one photon to be converted..The resultant e^+e^- pairs was detected with the spectrometer.Both position and energy of the pair and remaining thr. e photond were measured in 804 lead glass block array

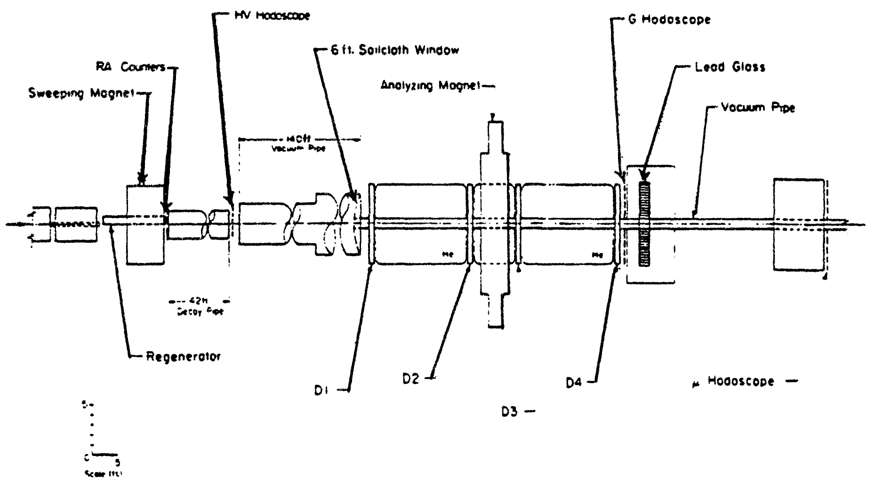

Figure 1

The lead glass array yield about 3mm position resolution and an energy resolution of $_E/E$=2%+6%/ E.

The resulting mass distribution are shown in Fig.2 for $K_L \to 2\pi^0$ for each momentum bins. The background fits are superimposed in the figure. For the charged mode and K_S decays, invariant mass distributions were essentially free from background.

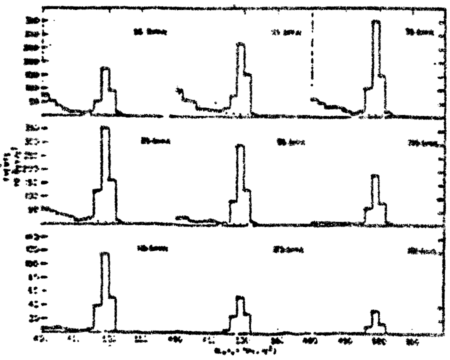

Figure 2
$M_{\pi^0\pi^0}$ distributions
vs. momentum

For K_S decay, events due to inelastic regeneration were subtracted based on pt^2 distributions.

In order to correct for the acceptance differences of K_L and K_S, come from life time difference, a Monte Carlo was used. Fig.3 indicates the agreement of data and Monte Carlo simulation.

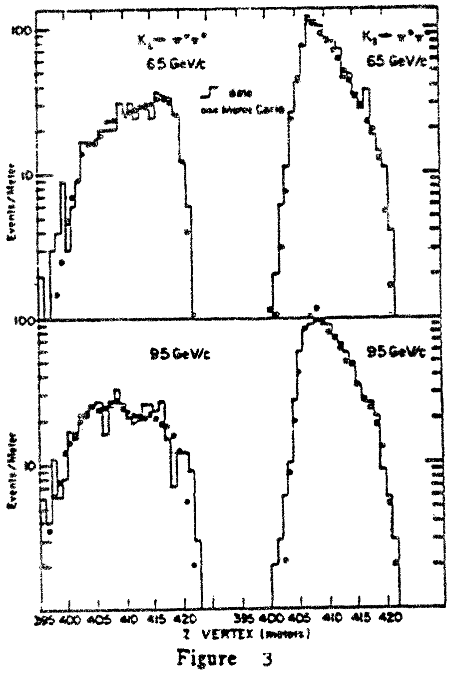

Figure 3
Reconstructed $\pi^0\pi^0$ data and
Monte Carlo (the open circles)
vertex distributions

After the acceptance correction, the number of event will be proportional to an integral over the decay region of

$N^V_{+-} = |\varepsilon + \varepsilon'|^2$, $N^V 00 = |\varepsilon - 2\varepsilon'|^2$ for vacuum beam and
$N^r{+-} = |\rho e^{i\Delta mt - t/2} + (\varepsilon + \varepsilon')|^2$, $N^r 00 = |\rho e^{i\Delta mt - t/2} + (\varepsilon - 2\varepsilon')|^2$
for regenerated beam. (ρ is the regeneration amplitude and $\rho \propto (\frac{f-f}{k})_c$; the difference in forward scattering amplitudes of K^0 and $\bar{K}^0$ on Carbon. From either the ratio $N^r{+-}/N^v{+-}$ or the ratio $N^r 00/N^v 00$, one can determine $\frac{f-f}{k}$, given the value of and . Assuming ε'=0, the charged mode data yields the amplitude consistent with power law p^a behavior as shown in fig.4. with a a=-0.610 ± 0.023, to be compared with previous measurements a=-0.614 ± 0.009.

Similaly, using neutral mode data as shown in Fig.5 a=-0.572 ± 0.072. If ε'=0, the effect would show up in the normalization difference between Fig.4 and Fig.5

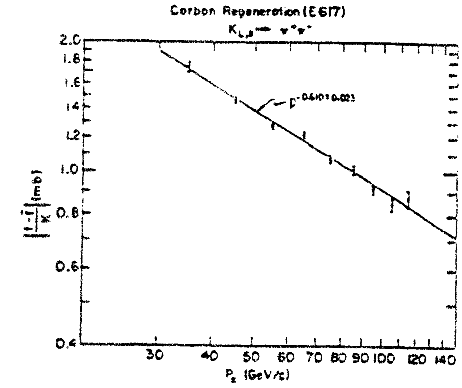

Figure 4

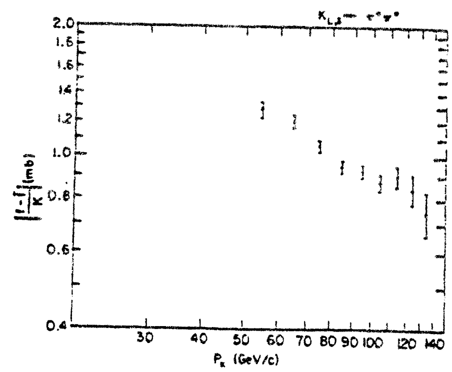

Figure 5

The value of ε'/ε has been detemined by a simultaneous fit of 18 ratios(the ratio of regenerated to vacuum events in nine momentum bins, each data set) searching for the best value of the magnitude of ε' and $\left|\frac{f-f}{k}\right|_c$ at 1 Gev/c, while fixing the power law. The result is

$\varepsilon'/\varepsilon = -0.0046 \pm 0.0053$(statistical error)

This result is consistent with zerro and not in a good agreement with naive expectation of Kobayashi-Maskawa model which predicts $\gtrsim 0.005$.

This result was chaecked in variety of ways.

(1)The charged and neutral mode data were divided into momentum and z vertex bins. ε'/ε was determined from the bin-by-bin ratio of ratio. Although this method is statistically weak, free from Monte Carlo corrections and yield a consistent result.

(2)Using the neutral vacuum events which decayed in the same region as regenerated evnts so that Monte Carlo corrections are relatively small,one get consistent ε'/ε value.

(3)By entirely depend on Monte Carlo,one can calculate $(K_L - 2\pi^0)/(K_L - 3\pi^0)$. ε'/ε can be determined, using the branching ratio for the $K_L - 3\pi^0$, $K_S - 2\pi^0$, $K_L \to \pi^+\pi^-$ and $K_S - \pi^+\pi^-$ from Particle Data. Although one expects a large systematic error,this method yields

$$\varepsilon'/\varepsilon = -0.0082 \pm 0.0098$$

which gives some confidence in the Monte Carlo.

The systematic error estimates from various source together with the event totals is summarized in Table 1.

The final result of this experiment is

$$\varepsilon'/\varepsilon = -0.0046 \pm 0.0053(\text{statistical}) \pm 0.0024(\text{systematic})$$

This result(with errors added in quadrature) is shown in Fig.12 with previous measurements. Yet a better experiment,together with better theoretical prediction ,are needed.

Table 1

Summary of results

Number of events		
	$K_S \to \pi^0\pi^0$	5663
	$K_L \to \pi^0\pi^0$	3152
	$K_S \to \pi^+\pi^-$	25751
	$K_L - \pi^+\pi^-$	10676
Errors on ε'/ε		
Statistics	$K_S \to \pi^0\pi^0$	0.003
	$K_L - \pi^0\pi^0$	0.004
	$K_S - \pi^+\pi^-$	0.001
	$K_L - \pi^+\pi^-$	0.002
Background		0.002
Monte Carlo corrections		0.001
Power law of $\left\lvert\frac{f-f}{k}\right\rvert_C$		0.0008
τ_S		0.0001
K_L-K_S mass difference		0.00004

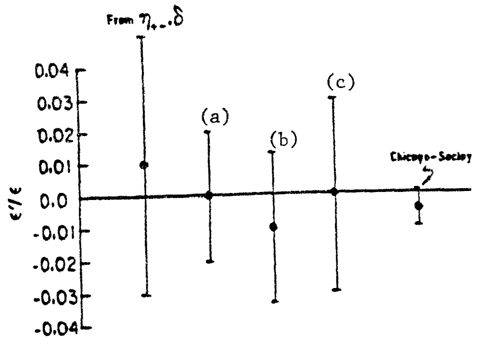

Figure 6
The Chicago-Saclay result in comparison to previous determinations of ε'/ε

A Measurement of ε'/ε by a BNL-Yale Group

Another measurement of ε'/ε was conducted at Brookhaven National Laboratory by the BNL-Yale group of Adair, Black, Kasha, Larsen, Leipuner, Mannelli, Morse, Schmidt, and Schwarz by simultaneously observing the intensity of charged and neutral two-pion decays from a K_L beam and then from a K_s beam produced by introducing a regenerator in the K_L beam. About 300 alternations during the 600 hours of experimental data-taking, concluded in April, 1984, gave about 1200 $K_L \to \pi^0 + \pi^0$ events used in the analysis as well as 10,000 $K_L \to \pi^+ + \pi^-$ events, 3500 $K_s \to \pi^0 + \pi^0$ events, and 23,000 $K_s \to \pi^+ + \pi^-$ events.

The value of ε'/ε was found from the relation,

$$R = \frac{|\eta_{-+}|^2}{|\eta_{00}|^2} = 1 + 6\cdot(\varepsilon'/\varepsilon) = \frac{L{+}{-}/L00}{S{+}{-}/S00}$$

Here L00 and L+- are transition rates for $K_L \to \pi^0 + \pi^0$ and $K_L \to \pi^- + \pi^+$ and S00 and S+- are similar transition rates for K_s decays.

Since charged and neutral decays were determined simultaneously by a spectrometer designed to serve both functions, the acceptances of the apparatus cancels out in the ratio if the energy and decay position of the K_L and K_s particles were the same. This was true to an adequate degree over small energy regions and small decay sectors. Values of R(i,j) were determined for i=7 values of K-energy (ranging from 7 GeV to 14 GeV) and j=6 sectors of 20 cm for the decay position. An appropriately weighted average of the R(i,j), subject to a correction of about 14% for backgrounds, led to a preliminary value,

$$R = 1.027 \pm 0.036 \pm 0.035 \to \varepsilon'/\varepsilon = 0.0045 \pm 0.0087$$

where the first error in R is statistical and the second systematic.

We note that this result is quite consistent with the Fermilab result (though with a 60% larger error) although the measurements were made using different techniques on much lower energy K-mesons.

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ON THE SIGN AND MAGNITUDE OF ε'/ε

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In this conference two new experimental results on ε'/ε have been presented[1].

$$\varepsilon'/\varepsilon=-.0046\pm.0053\pm.0027 \quad \text{Chicago-Saclay,} \quad (1)$$

$$\varepsilon'/\varepsilon=.0045\pm.008 \quad \text{Yale-BNL,} \quad (2)$$

where the error for Yale-BNL result is the sum in quadrature of both systematic and statistical errors. Also presented were: (a) A very suggestive evidence[2] for t quark with the mass between 30 and 50GeV. (b) Updated numbers on B meson lifetime[3]

$1.16^{+.37}_{-.34}$ psec (DELCO); $1.78^{+.62}_{-.42}$ psec (JADE);

$1.6\pm.5$ psec (MAC); $1.2^{+.54}_{-.47}$ psec (MARK II);

$1.9\pm.72$ (TASSO). (c) An updated bound

$$R=\frac{\Gamma(b\to u)}{\Gamma(b\to c)}<.04$$

My task in this talk is to review theoretical studies which related these experimental results. In particular, I shall focus on the sign and magnitude of ε'/ε for: (a) The standard model, where CP violation is mediated by the complex phase of the Kobagashi-Maskawa (KM) matrix and (b) The Higgs model of CP violation, where CP violation is mediated by scalar particles.

In general, we can write[4]

$$\varepsilon'=\frac{i}{\sqrt{2}}\frac{\mathrm{Re}a_2}{\mathrm{Re}a_0}e^{i(\delta_2-\delta_0)}\left(\frac{\mathrm{Im}a_2}{\mathrm{Re}a_2}-\frac{\mathrm{Im}a_0}{\mathrm{Re}a_0}\right), \quad (3)$$

$$\varepsilon=e^{i\pi/4}\frac{1}{\sqrt{2}}\left(\frac{\mathrm{Im}M_{12}}{2\mathrm{Re}M_{12}}+\frac{\mathrm{Im}a_0}{\mathrm{Re}a_0}\right), \quad (4)$$

where $a_I e^{i\delta_I}$ denotes $K^0\to(\pi\pi)_I$ amplitude with the final state pion in the isotopic spin I; δ_I is the $\pi\pi$ scattering phase shift; M_{12} is the K^0-$\bar{K}^0$ transition amplitude. We shall evaluate these quantities in the two model mentioned above.

Standard Model

In the standard model for electro-weak interaction with three quark flavors, where weak eigenstates are defined by the KM matrix, the imaginary parts of a_I and M_{12} arise from the contributions of c,t,b quarks. It is, therefore, believed that the imaginary parts of amplitudes a_I and M_{12} are free of long distance ambiguities. In this phase convention, where the phases of quark Feynman diagrams are kept, components of eqs. (3) and (4) can be written as follows[5].

$$\mathrm{Im}a_0=\sqrt{2}s_1s_2s_3s_\delta G_F\eta\langle(\pi\pi)_0|O_5|K^0\rangle \quad (5)$$

$$\mathrm{Im}a_2=0 \quad (6)$$

$$2m_K\mathrm{Im}M_{12}=\frac{G_F^2}{4\pi^2}\,m_c^2\,s_1^2\,s_2s_3s_\delta$$
$$\times\left\{-\eta_1+\eta_3\ln\frac{m_t^2}{m_c^2}+s_2(s_2+s_3c\delta)\eta_2\frac{m_t^2}{m_c^2}\right\}$$
$$\times\langle K^0|O_{LL}|\bar{K}^0\rangle \quad (7)$$

where $\eta_1=.68\sim1.06$; $\eta_2=.60\sim.62$; $\eta_3=.39\sim.38$; $\eta=-.07\sim-.15$ are QCD correction factors evaluated for Λ_{QCD} ranging between $.1\sim.3$GeV; $m_t\sim30\sim50$GeV; $m_c=1.3\sim1.7$GeV; $m_b=4.5\sim5.2$GeV. Evaluation of the matrix element $\langle\pi^0|O_5|K^0\rangle$ using the bag model or vacuum saturation approximation and current algebra leads to[6]

$$\sqrt{2}G_Fs_1\langle(\pi\pi)_0|O_5|K^0\rangle=+(2\sim9)|a_0| \quad (8)$$

where the range of value is due to theoretical uncertainties. The matrix element in Eq. 7 can be parametrized as[7]

$$\langle K^0|O_{LL}|\bar{K}^0\rangle=\frac{4}{3}Bf_K^2m_K^2 \quad (9)$$

$$=\frac{\sqrt{2}8f_\pi^2m_K^2}{G_Fs_2\eta_K}a_2 \quad (10)$$

where B is the bag constant, f_K and f_π are K meson and π meson decay constants, respectively, and η_K is the QCD correction to $K^+\to\pi^+\pi^0$ hamiltonian. The second relation is obtained by using SU(3) symmetry and current algebra. In the region where $\varepsilon'/\varepsilon\ll|\mathrm{Re}a_2/\mathrm{Re}a_0|\sim1/20$, $\mathrm{Im}a_0/\mathrm{Re}a_0$ in Eq. 4 does not play a major role in ε. In the region where this term can be ignored Eq. (3), (4), (6) lead to

$$\varepsilon'/\varepsilon=-e^{i(\frac{\pi}{4}+\delta_2-\delta_0)}\frac{\mathrm{Re}a_2\mathrm{Im}a_0}{\mathrm{Re}a_0\mathrm{Re}a_0}\frac{\Delta m_{K_L-K_S}}{\mathrm{Im}M_{12}} \quad (11)$$

where we have written $2\mathrm{Re}M_{12}=\Delta m_{K_L-K_S}$, the K_L-K_S mass difference. From Eqs. (7) and (10), $\mathrm{Re}a_2/\mathrm{Im}M_{12}>0$ and from Eqs. (5) and (8), $\mathrm{Im}a_0<0$ so that[8]

$$\varepsilon'/\varepsilon e^{-i(\frac{\pi}{4}+\delta_2-\delta_0)}>0 \tag{12}$$

Putting in the experimental value $|Re a_2/Re a_0|\sim 1/20$, $\Delta m_{K_L-K_S}/m_K = .71\times10^{-14}$, $G_F=1.18\times10^{-5}GeV^{-2}$, $f_K = .16GeV$ we obtain

$$\frac{\varepsilon'}{\varepsilon}=\frac{.11\ \eta(2-9)}{B\{m_c^2(-\eta_1+\eta_3\ell n\frac{m_t^2}{m_c^2})+s_2(s_2+s_3c_\delta)\eta_2 m_t^2\}} \tag{13}$$

where masses are to be evaluated in GeV. Knowledge of τ_B, R, ε, m_t, B,.... are not sufficient to fix s_2, s_3, s_δ uniquely. Here we shall be satisfied with a lower bound of ε'/ε. To this end, upper bound on $s_2(s_2+s_3c_\delta)$ is needed. Consider

$$\frac{1}{\tau_B}=\frac{1}{28.2}\ m_b^5\gamma_1[s_2^2+s_3^2+2s_2s_3c_\delta] \tag{14}$$

where m_b, and τ_B are in unites of GeV, and psec, respectively, $\gamma_1=3.2$ is the phase space factor with QCD corrections, and we have set $c^2{}_1=1$. For $\tau_B=.7$psec, we have

$$(s_2+s_3c_\delta)<(s_2^2+s_3^2+2s_2s_3c_\delta)^{1/2}=.078 \tag{15}$$

and thus $s_2<.078$. For the values of $\eta=-.07$ $m_t=50$GeV, $m_c=1.3$GeV, $\eta_1=.68$, $\eta_2=.62$, $\eta_3=.39$, B=1 we obtain

$$\frac{\varepsilon'}{\varepsilon}\ e^{-i(\frac{\pi}{4}+\delta_2-\delta_0)}\geq 1.2\times10^{-3} \tag{16}$$

All parameters were adjusted, within limites of uncertainties, to minimize the right hand side, thus the bound is very conservative one.[9] At this time the bound is not in conflict with experiments. If future experiments prove to violate above bound, it implies that the standard model is ruled out or that there is a serious flow in evaluating the matrix element in Eqs. (8) and (9).

Higgs Model of CP Violation

An elegant model which explains CP violation through scalar particle interactions has been described by Weinberg[10]. Such a model with natural flavor conservation predicts that[11]

$$\left|\frac{ImM_{12}}{2ReM_{12}}\right|_{SD} << \left|\frac{Ima_o}{Rea_o}\right| \tag{17}$$

where SD denotes the short distance contribution. This inequality least to a result

$$\left|\frac{\varepsilon'}{\varepsilon}\right|=\frac{1}{20}\ \frac{1}{1-D} \tag{18}$$

where D is the parameter for the long range contribution to Δm defined[12] by $(\Delta m)_{long\ range}=D\Delta m$. In the standard model $B\approx1.4(1-D)$, but this result can not be used in the present consideration. D has been estimated to be[13]

$$-.7<D<3 \tag{19}$$

using $\pi\pi$ phase shift data, current algebra and SU(3) symmetries. The prediction for ε'/ε given in Eq. (18) together with the value of D given in Eq. (19) is in conflict with experiments Eqs. (1) and (2). Recently it has been pointed out[14] that the SU(3) singlet combination of η and η' contributes to $(\Delta m)_{long\ distance}$ in a way which has been over looked by all investigators. It has been varified that such new contribution has to be unusually large in order to modify above prediction on ε'/ε.

We have shown that the standard model predicts $\varepsilon'/\varepsilon>.001$. Better determination of τ_B, R, m_t, m_b can increase the bound considerably. If experiments prove to be inconsistent with this bound, either the standard model is ruled out or there is a serious flaw in our understanding of hadronic matrix elements. We have also shown that CP violation mediated by scalar particles with natural flavor conservation has been ruled out unless matrix element for certain operators is unusually large.

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SEARCH FOR CP - VIOLATION IN $K^0 \to 3\pi$

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The 180 liter xenon bubble chamber /1/ without magnetic field was used in the joint Moscow-Padova experiments /2,3/ on the 3π-decays of K^0-mesons to obtain the new estimation of possible violation of CP-invariance in such processes. The charge exchange reaction $K^+ + Xe \to K^0 +$ all at 0.85 GeV/c /4/ momentum was as a source of K^0-meson sample. In total $1.8\cdot10^6$ photograms $6.3\cdot10^5$ K^0-mesons were obtained. All the events which had a V^0 inside the fiducial volume of the chamber with two γ-rays pointing to the apex of the V^0 and satisfying the same conditions as the candidates for $K^0 \to \pi^+\pi^-\pi^0$ decay were considered. The total number of such events was 1588. The procedure of scanning for events with six γ-rays appeared to come from a single point inside the fiducial volume of the chamber was used for selection of the candidates for $K^0 \to 3\pi^0$ decays. 1455 events such type were found. In the both cases we assume as candidate origins for each event all visible interaction in which any track leaving the interaction point is compatible with the proton hypothesis and stops in the chamber with range smaller than 20 cm. The background conditions were considered. With the following selection criteria: $0.8 < R_{K^0} < 40$ cm, $50 < P_{K^0} < 850$ MeV/c and $|M_{3\pi} - M_{K^0}| < 3\sigma_{M3\pi}$ we obtain the final samples of 409 events for $K^0 \to \pi^+\pi^-\pi^0$ decay mode and 632 events for $K^0 \to 3\pi^0$ decay mode.

The procedure of a maximum likelihood calculation was used for the estimations of the parameters of CP-violation in the $K^0 \to 3\pi$ decay modes

$$\eta_{+-0} = \frac{A(K_S^0 \to \pi^+\pi^-\pi^0)}{A(K_L^0 \to \pi^+\pi^-\pi^0)} \quad \text{and} \quad \eta_{000} = \frac{A(K_S^0 \to 3\pi^0)}{A(K_L^0 \to 3\pi^0)}.$$

Known data of K^0-meson properties and numerical characteristics of the experimental conditions of the K^0-meson detection in the xenon bubble chamber were used for the calculations of the likelihood functions.

The results of the maximum likelihood calculation for the parameter η_{+-0} are shown in Fig.1a where the one and two standard deviation contours are represented by solid lines. The most probable value is

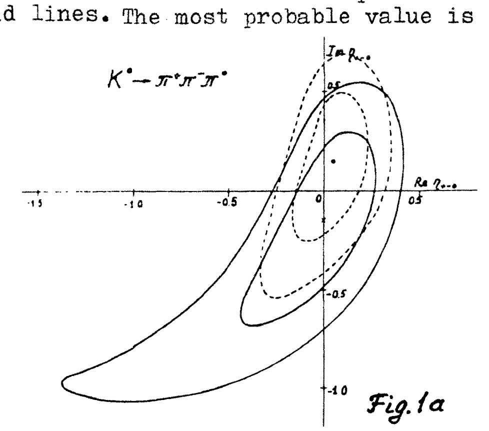

Fig.1a

$\eta_{+-0} = (-0.002 \pm 0.23) + i(-0.14 \pm 0.35)$. Assuming CPT-invariance, the parameter η_{+-0} is pure imaginary when terms of the order of ε are neglected. In this hypothesis the results are:

$$\eta_{+-0} = -0.14 \pm 0.24, \qquad |\eta_{+-0}|^2 < 0.26 \quad \text{and}$$
$$\Gamma(K_S^0 \to \pi^+\pi^-\pi^0)/\Gamma(K_S^0 \to \text{all}) < 5.5\cdot10^{-3}$$

at 90% confidence level. Furthermore we combined our results with those obtained in a previous experiment /5/ performed in similar conditions and analysed with the same procedure. The likelihood functions of both experiments on the base 601 events have been added, and results are shown in Fig.1a (dotted lines). The most likely value is now $\eta_{+-0} = (0.05 \pm 0.17) + i(0.15 \pm 0.33)$. Now the upper limits at 90% confidence level are:

$$|\eta_{+-0}|^2 < 0.23 \quad \text{and}$$
$$\Gamma(K_S^0 \to \pi^+\pi^-\pi^0)/\Gamma(K_S^0 \to \text{all}) < 4.9\cdot10^{-5}.$$

Analogous results for $K^0 \to 3\pi^0$ decay mode /3/ are shown in Fig.1b, where the one, two and three standard deviation contours are represented. The most probable value is

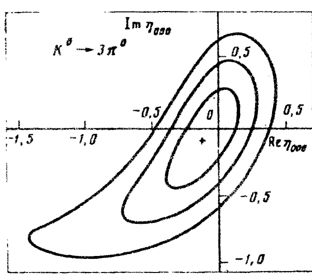

Fig. I B

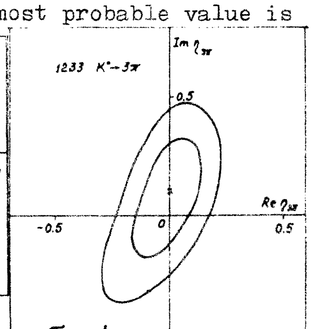

Fig. 1c

found equal to $\eta_{000} = (-0.08 \pm 0.18) + i(-0.05 \pm 0.27)$. Under the same assumptions one obtains

$$|\eta_{000}|^2 < 0.1 \quad \text{and}$$
$$\Gamma(K_S^0 \to 3\pi^0)/\Gamma(K_S^0 \to \text{all}) < 3.7\cdot10^{-5}.$$

Finally, since under hypothesis of CPT-invariance and neglecting I=3 contributions to $3\pi^0$ and I=2 contributions to $\pi^+\pi^-\pi^0$ channels η_{+-0} and η_{000} are the same, the total $K^0 \to \pi^+\pi^-\pi^0$ sample has been added to the $K^0 \to \pi^0\pi^0\pi^0$ one. The likelihood contours for $\eta_{3\pi}$, evaluated from total sample of 1233 $K^0 \to 3\pi$ events are shown in Fig.1c. The branching ratio $\Gamma(K_S^0 \to 3\pi)/\Gamma(K_S^0 \to \text{all})$ turns out to be smaller than $6.5\cdot10^{-5}$ at 90% C.L.

Using new estimations of the upper limits of the η_{+-0} and η_{000} parameters it is possible to consider on the new level of the accuracy the problem of the discrete CPT and T-symmetries in the description of the CP-violating decay properties of the neutral K-mesons and the internal consistence known experimental data on K^0-decay properties /6/. For these purposes we used the Bell-Steinberger relation /7/, writting down in the following form /8/:

$$(1+i\,\mathrm{tg}\,\varphi_{SW})\,(\mathrm{Re}\,\varepsilon+i\,\mathrm{Im}\,\tilde{\Delta}) = \varepsilon'-\tilde{\Delta}+\alpha$$

with

$$\varepsilon_0 = \varepsilon - \tilde{\Delta},$$

where CPT-conserving, T-violating part ε and T-conserving, CPT-violating part $\tilde{\Delta}$ describe amplitude ε_0. We solved this system of equations using experimental values /9/ for parameters

$$\mathrm{tg}\,\varphi_{SW} = 0.953 \pm 0.005$$
$$\varepsilon_0 = [(1.535 \pm 0.065)+i(1.686 \pm 0.052)]\cdot 10^{-3}$$
$$\alpha = [(-0.006 \pm 0.068)+i(-0.026 \pm 0.120)]\cdot 10^{-3}$$

and obtain the following results:

$$\varepsilon = [(1.62 \pm 0.05)+i(1.58 \pm 0.09)]\cdot 10^{-3}$$
$$\tilde{\Delta} = [(0.10 \pm 0.07)+i(-0.11 \pm 0.10)]\cdot 10^{-3}$$

This means that the K°-decay processes are appearing to be CPT-conserving and T-violating. The same conclusion was made by Cronin /10/ but he had more rough estimations of the contributions of 3π decays of K°-mesons and as a result

$$\alpha = [(0.14 \pm 0.19)+i(0.19 \pm 0.25)]\cdot 10^{-3}$$

which may be compared with one used in our calculations. This means that our statement is grounded on the higher level of the accuracy.

Let us consider /11/ the parameter $\tilde{\Delta}$. It is easy to show, that

$$\alpha_{2\pi,I=2} = (0.007 \pm 0.003)+i(0.002 \pm 0.003)\cdot 10^{-3}$$
$$\alpha_{3\pi} = (-0.02 \pm 0.07)+i(-0.04 \pm 0.10)\cdot 10^{-3}$$
$$\alpha_{e3} = (0.004 \pm 0.0002)+i(0.01 \pm 0.06)\cdot 10^{-3}$$

and we have value of the parameter α used above in the calculations of the values of the parameters ε and $\tilde{\Delta}$. It is quite naturally to believe that CP-violation in the 3π-decays of K°-meson not larger than in the 2π-decays. Then we may to ignore the contributions of all decay modes of K°-meson except $K^{\circ}\to 2\pi\,(I=0)$, i.e. to put $\alpha = 0$ and one obtain the result

$$\tilde{\Delta}\,(\alpha=0) = [(0.11 \pm 0.05)+i(-0.12 \pm 0.05)]\cdot 10^{-3}$$

which differs from zero (if the CPT-conservation takes plase) by two standard deviations.

Let us consider the situation with the parameters of the phenomenological description of the properties of the CP-violating 2π-decay of the K_L°-mesons. It is known that $\varphi_{+-} = \arg \rho_{+-} = (44.6 \pm 1.2)^{\circ}$ and this value is rather close to one existing in the model of the superweak interaction $\varphi_{SW} = (43.72 \pm 0.14)^{\circ}$. In the same time there is badly known value of the $\varphi_{00} = \arg \rho_{00} = (54 \pm 5)^{\circ}$.

It is possible to reconsider the parameters of K°-decays by using of the Bell-Steinberger relation in the frame of validity of the CPT-invariance, i.e. $\tilde{\Delta} = 0$. Then one obtains /6/ $\varphi_{00} = (48.7 \pm 3.7)^{\circ}$ and $\varphi_{+-} = (44.0 \pm 1.1)^{\circ}$, if initially $\varphi_{00}-\varphi_{+-} = (9.4 \pm 5.1)^{\circ}$. Under additional condition $\tilde{\Delta}(\alpha=0)=0$ we get $\varphi_{00} = (44.1 \pm 2.2)^{\circ}$ and $\varphi_{+-} = (43.4 \pm 1.1)^{\circ}$, i.e. $\varphi_{00}-\varphi_{+-} = (0.7 \pm 2.5)^{\circ}$ in accordance with the theoretical estimations.

Returning to the problem of the validity of the CPT-symmetry in the K°-decays we should like to show where and why this problem appears in the analyses of the decay properties of K°-mesons. The result of the computation of the parameter $\tilde{\Delta}$ and one and two standard deviation contours by Monte Carlo method are shown in Fig.2 for α_{exp}. It is seen that the agreement with CPT-symmetry obtained with α_{exp} looks nearly perfect, but for the case $\alpha = 0$ we have noticed above the vanishing of $\tilde{\Delta}$ is unfavoured by two standard deviations. Let us also represent the projections of the parameters ε and $\tilde{\Delta}$ in the complex plane on the direction of the angle φ_{SW} without the contributions of 3π and $\pi\ell\nu$-decays of K°-mesons. It is easy to obtain /11/

$$\tilde{\Delta}_{\parallel} \ll \tilde{\Delta}_{\perp} = -\varepsilon_{0\perp} = -(0.16 \pm 0.07)\cdot 10^{-3}$$
$$\varepsilon_{\perp} \ll \varepsilon_{\parallel} = \varepsilon_{0\parallel} = (2.27 \pm 0.06)\cdot 10^{-3}$$

Fig.3 shows the situation creating the noncompletion of the conclusion on the validity of the CPT-invariance of K°-meson decay properties caused by nonvanishing value of the parameter $\tilde{\Delta}_{\perp}$ because of the existing difference of the $\varphi_{00}-\varphi_{+-}$ phases.

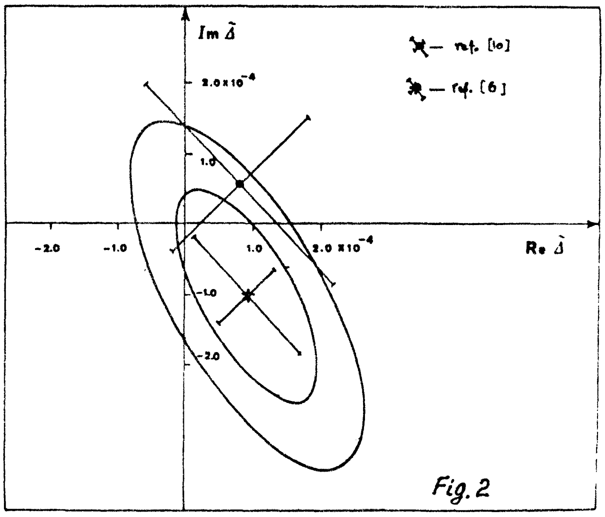

Fig. 2

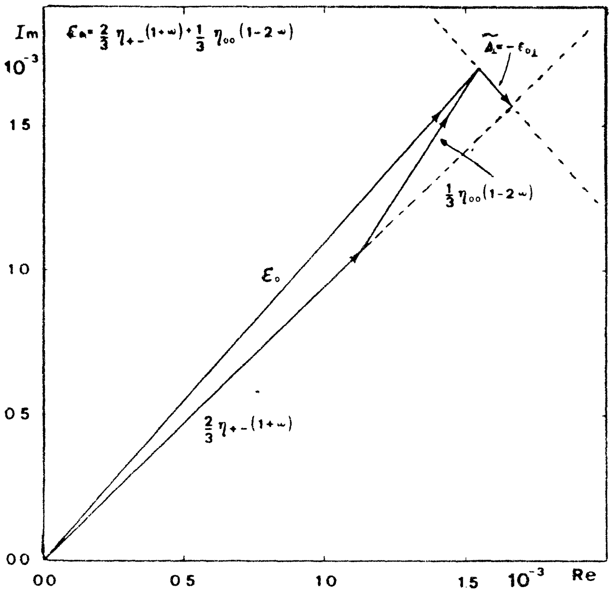

fig.3

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QUARK MIXING MATRIX FROM HEAVY QUARK SEMILEPTONIC DECAYS

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In the "standard Model" the b-quark contained within the B meson is assumed to be the charge −1/3 member of the third weak isospin doublet (t,b'). The three states (d',s',b') are mixtures of the mass eigenstates (d,s,b) defined by the unitary mass mixing matrix V as :

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

We show in the following that from the experimentally measured properties of the B meson weak decays: (i)lepton spectra from semileptonic decays, (ii)semileptonic branching ratios (BR), and (iii) lifetime (τ_B) we can extract the b→Wu(or c) coupling strengths (i.e. $|V_{ub}|$ and $|V_{cb}|$'s) accurately with the help of a model of the bound state decay, the "spectator model" [1], in a completely self consistent way without assumption about quark masses.

This simple model where the original light quark companion of the b in the B meson is assumed not to partake in the b decay process proper (b→Wu,c; $W\to q\bar{q}, \ell\bar{\nu}$) but combines with the flavored changed quark (u or c) in the final hadronization process, is ideally suited for describing B semileptonic decay since the leptonic final states of the color neutral W are isolated from the hadronic end products. In the model, the decaying b is assumed to be moving within the B meson with momentum p_F, and the spectator $\bar{u}$ or $\bar{d}$ to recoil with opposite momentum and definite mass M_{sp}, ultimately combining with the final quark (u or c) to form the recoiling system X_u (or X_c) with mass M_X. M_b is determined by 4-momentum conservation. The Fermi motion distribution $\Phi(|p|)$ is folded into the free quark decay spectrum to obtain the lepton spectrum from the decay of the B meson.

The semileptonic width is given by:

$$\Gamma(B\to e\bar{\nu}X_q)=BR(B\to e\bar{\nu}X_q)/\tau_B =$$

$$\sum|V_{q_i b}|(G_F^2/192\pi^3)\langle M_b^5\rangle I(\langle\varepsilon_i\rangle)f(\langle\varepsilon_i\rangle)$$

where i is to be summed over u and c, $\varepsilon=M_q/M_b$, the <>'s indicate that we must use the appropriate averages of M_b and M_q obtained from fitting the measured electron spectra. $I(\varepsilon)=[1-8\varepsilon^2+8\varepsilon^6-\varepsilon^8-24\varepsilon^4\ln\varepsilon]$ and $f(\varepsilon)$ are the tabulated small QCD radiative corrections [2]. We further define

$R_B=\Gamma(B\to X_u\ell\nu)/\Gamma(B\to X_c\ell\nu)$. Then the mixing matrix elements can be expressed as

$$|V_{cb}|= \{[BR(B\to Xe\nu)/\tau_B]\times[K_{cb}/(1+R_B)]\}^{1/2}$$

$$K_{cb} = 2.88\times10^{-11}\text{sec}/[\langle M_b\rangle^5 I(\langle\varepsilon_c\rangle)f(\langle\varepsilon_c\rangle)]$$

$$|V_{ub}|= \{R_B|V_{cb}|^2[I(\varepsilon_c)f(\varepsilon_c)/I(\varepsilon_u)f(\varepsilon_u)]\}^{1/2} .$$

Limits on the ratio R_B have been were obtained at CESR by examining the decay lepton spectra [3,4]. To obtain the limit given by all the CESR results, I combined the likelihood functions and found $R_B < 0.03$ at 90% c.l. or $R_B < 0.038$ at 95% c.l. [5].

The $\langle M_b\rangle$ and effective M_c which are used in the following for the evaluation of $|V_{ub}|^2$ and $|V_{cb}|^2$ were obtained by fitting the CUSB spectrum to various combinations of M_{sp} and p_F and minimizing χ^2. Two representative cases are presented below.

M_{sp} (MeV)	150	≈0
p_F (MeV)	150	300
χ^2 (for 18 d.o.f.)	11.6	9.8
$\langle M_b\rangle$ (GeV)	5.04	4.93
$\langle M_c\rangle$ (GeV)	1.74 ± 0.06	1.61 ± 0.05
End Point (GeV)	2.219 ± 0.020	2.202 ± 0.016
M_X, variance (GeV)	1.98, 0.089	1.90, 0.227
K_{cb} (10^{-14}sec)	2.353 ± 0.134	2.412 ± 0.113

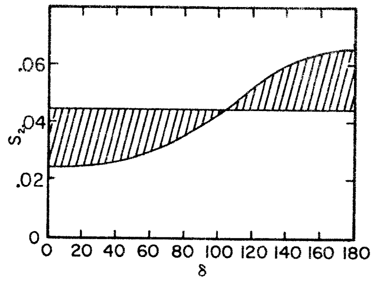
We note that the K_{cb} value is very well defined and is independent of assumptions on M_{sp} and p_F.

The world average of the semileptonic BR is (11.8±0.35±0.7)% [6]. The B meson lifetime has been recently measured by four groups [7], the average being τ_B=1.4±0.3±0.3 psec. Using the numerical values for R_B, K_{cb}, BR and τ_B we obtain:

$|V_{cb}|$ = 0.0439 ± 0.0049; $|V_{ub}|$ < 0.0051 at 90% c.l.
$|V_{ub}|/|V_{cb}|$ < 0.116 at 90% c.l.
$|V_{cb}|^2 = (2.777\pm0.179)\times10^{-15}\text{sec}/[(1+R_B)\tau_B]$
$|V_{ub}|^2 = R_B(1.228\pm0.086)\times10^{-15}\text{sec}/[(1+R_B)\tau_B]$

Using the original parametrization of Kobayashi and Maskawa [8] with s_1=0.231±0.003 [9] and $|V_{ub}|$<0.0051, we obtain s_3<0.022 at 90% c.l. We also obtain $s_2 = |V_{cb}|[\sqrt{(1-8.06R_B s_\delta^2)} - 2.84\sqrt{R_B}c_\delta]$, using c_1=0.9737±0.0025 . In figure 1 we show this relation evaluated for δ=0 to π, the curve is for R_B=0.03 and the line for R_B=0.

S_2 vs δ (the allowed area is shaded)



Using the above determined bounds we can determine or constrain the absolute values of all the elements of the mixing matrix (in this way one automatically satisfies unitarity).

$$|V| = \begin{matrix} 0.9737 \pm 0.0025 & 0.231 \pm 0.003 & <0.0051 \\ 0.231 \pm 0.003 & 0.972 \pm 0.002 & 0.044 \pm 0.005 \\ <0.015 & 0.043 \pm 0.001 & >0.999 \end{matrix}$$

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