RARE DECAY AND CP VIOLATION: THEORETICAL REMARKS

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Rare Decays of Strange Particles

The interest in pushing limits on these processes is (at least) three-fold: searches for deviations from superweak CP-violation, deviations from quark- and lepton-flavor conservation in neutral currents, and evidence scalar particles.

CP Violation

Optimistically 10^{11} useful K_L's could be collected in a Tevatron experiment. This may be just within reach of expected effects on rare decays ($K \to \gamma\gamma$, $\mu\mu$, πee, $\pi\nu\bar{\nu}$) in the KM model. One may also be able to obtain a relatively clean sample of $\sim 10^6$ K_S by exploiting the Primakoff effect (see below). This should allow observation of $K_S \to \gamma\gamma$, but not of CP violation at the level expected in the KM model (although the previous estimate, for CP violation in $K_{S,L} \to \gamma\gamma$ might be enhanced by Penguin diagrams). Estimates within the context of more general models, as well as an updated KM estimate, would provide a useful measure of whether searches for these modes could shed light on the origin of CP violation.

Flavor Violation[1,2]

One expects that an ultimate, truly unified theory will include heavy neutral flavor changing vector bosons. In a technicolor context such objects are expected to have masses in the 10 to 10^2 TeV region. The most sensitive probes of their exchange should be those processes where both quark and lepton flavors are changed. Making the plausible assumption that the semi-weak couplings of these vectors is of the same order as semi-weak W-couplings, we can parameterize branching ratios in terms of the heavy vector mass m_V, e.g.,

$$B(K_L \to \mu e) \sim 10^{-4}(\mathrm{TeV}/m_V)^4$$

$$B(K_L \to \pi^0 \mu e) \sim 10^{-5}(\mathrm{TeV}/m_V)^4$$

$$B(\Sigma^+ \to p \mu e) \sim 10^{-7}(\mathrm{TeV}/m_V)^4$$

Both decay modes of the kaon are required to probe both axial and vector couplings; the total flux of 10^{11} cited above allows a sensitivity to masses $m_V \lesssim$ 60 TeV and 30 TeV respectively.

The Σ^+ decay[1] is sensitive to both axial and vector exchange. A conventional positive hyperon beam[3] can be expected to provide 10^4 Σ^+'s per pulse or 10^7 in 1600 hours. One might be able to improve this number by two or three orders of magnitude by constructing a dedicated Σ^+ beam. Such an enterprise might be worthwhile in any case since precision measurements of $\Sigma^+ \to p\gamma$ and $\Sigma^+ \to \Lambda e^+ \nu$ are still lacking.

Light Scalars

While there is a strong theoretical prejudice against a very light neutral Higgs particle, the fact remains that the only firm experimental limit is $M_H \gtrsim 15$ MeV. Estimates[4] of the direct decay $K \to H\pi$ suggest

$$B(K_L \to H\pi) \lesssim 10^{-7}.$$

Another mechanism[5] is Higgs formation by two pions in the final state of the 3π decay mode. From the estimate[4]

$$\Gamma(H \to \pi\pi) \simeq 10^{-6}(m_H^3/\mathrm{GeV}^2)\beta_\pi$$

we might expect

$$B(K_L \to H\pi) \sim B(K_L \to 3\pi)\Gamma(H \to \pi\pi)/\beta_\pi m_K \sim 2 \times 10^{-8}$$

for $M_H \simeq 300$ MeV. There is an unpublished limit, obtained from $K^+ \to \pi^+ e^+ e^-$ data,

$$B(K^+ \to He^+e^-) \lesssim 4 \times 10^{-8}$$

which is relevant for $M_H < 2M_\mu$. Studies of $K_L \to \pi^0 e^+ e^-$, $\pi^0 \mu^+ \mu^-$ and $\pi^0 \gamma\gamma$ at the 10^{-11} level should certainly suffice to exclude a conventional Higgs boson with $M_H \lesssim 2M_\pi$. Light Higgs searches via heavy onia decay ($\Upsilon^* \to \Upsilon + H$,[4] $\tilde{\Upsilon} \to H + \gamma$[6]) will presumably be done more easily at PETRA and PEP.

CP Violation in Heavy Quark Decays

It is anticipated that B^0 decays will provide an observable source of CP violation. The standard approach is to look for "wrong" final states[7]: one "signs" a B^0 by observing that the decay products of the accompanying state are those of a $\bar{B}$ ($\bar{B} \to \ell^+ + X$, $D + X$) and conversely for a $\bar{B}^0$. Because B-decays, like K-decays, are Cabibbo-forbidden, one expects appreciable B^0-$\bar{B}^0$ mixing, although the mixing may be stronger for $b\bar{s}$ states than for $b\bar{d}$. CP violation can then manifest itself through a charge asymmetry

$$\frac{N(B^0 \to \ell^+ \text{ or } \bar{D} + X)}{N(\bar{B}^0 \to \ell^- \text{ or } D + X)} \neq 1$$

which is expected to be $\gtrsim O(10^{-3})$. The Tevatron may have an advantage over e^+e^- collisions for this type of measurement since the decay path of the D, and with luck also of the B, will be visible. This permits on the one hand an easy separation of primary leptons from the (opposite sign) secondary leptons from charm decay, and on the other hand a better possibility for using the charm as well as the lepton signature. If tens of thousands of B are produced, this measurement should be feasible.

A possibility of observing "direct" CP violation in decay channels is offered by the observation[8] that B^0 and $\bar{B}^0$ have common final states through the decay chains

$$B^0 \to D^0 + X \to K_S + Y + X$$

$$\bar{B}^0 \to \bar{D}^0 + X \to K_S + Y + X$$

The time dependent partial decay widths for initially signed B^0 and $\bar{B}^0$ are, respectively

$$\begin{aligned} \Gamma(t) &= |f_+(t)a|^2 + |\lambda f_-(t)\bar{a}|^2 \pm 2\mathrm{Re}\,[f_+^* f_- \lambda \bar{a}^2] \\ \bar{\Gamma}(t) &= |f_+(t)\bar{a}|^2 + |\lambda^{-1} f_-(t)a|^2 \pm 2\mathrm{Re}\,[f_+^* f_- \lambda^{-1} a^2], \end{aligned} \qquad (1)$$

where the $\pm$ depends on the overall CP of the final state,

$$\bar{a} = e^{-2i\phi} a, \quad \phi = \mathrm{Arg}\ U_{sc} U_{cb}^*$$

with U_{ij} the appropriate matrix elements of the Cabibbo KM matrix,

$$|f_\pm(t)|^2 = 1/4(e^{-\Gamma_1 t} + e^{-\Gamma_2 t} \pm 2 \cos(\Delta m t) e^{-\Gamma t})$$

$$f_+^*(t)f_-(t) = 1/4(e^{-\Gamma_1 t} - e^{-\Gamma_2 t} - 2i\,\sin\,(\Delta m t)e^{-\Gamma t})$$

$$\int dt\,|f_\pm(t)|^2 = 1/4(1/\Gamma_1 + 1/\Gamma_2 \pm 2\Gamma/(\Gamma^2 + \Delta m^2))$$

$$\int dt\; f_+^* f_- = 1/4(1/\Gamma_1 - 1/\Gamma_2 - 2i\,\Delta m/(\Gamma^2 + \Delta m^2))$$

with $\Gamma = \frac{1}{2}(\Gamma_1 + \Gamma_2)$, $\Delta m = M_1 - M_2$ if $\Gamma_{1,2}$ and $M_{1,2}$ characterize the mass and decay eigenstates of the neutral B system, and

$$\lambda^2 = \frac{\Gamma_{12}^*/2 + m_{12}^*}{\Gamma_{12}/2 + m_{12}}$$

with $m_{12} \approx e^{i\delta}\Delta m$ if δ is the conventional KM phase, and Γ_{12} is the overlap in the B_1 and B_2 decay final states. CP violation will appear through an asymmetry in the (time-dependent or integrated) decay rates

$$A = \frac{\Gamma - \overline{\Gamma}}{\Gamma + \overline{\Gamma}}.$$

The contribution to A from the second term in Eqs. (1) is just another measure of the "super-weak" type CP violation through mixing and depends, as does the charge asymmetry measurement discussed above, on a value $|\lambda| \neq 1$, which in turn depends on M_{12} and Γ_{12} being comparable in magnitude and out of phase. One estimates Δm to be appreciable[9]

$$\Delta m/\Gamma \approx (m_t/\text{GeV})^2$$

whereas the most optimistic[7,9] guess is

$$\Gamma_{12} \approx \Gamma/10 \approx \text{real}$$

giving

$$1-|\lambda|^2 \approx \sin\delta(16/m_t)^2$$

with probably $\delta \lesssim 10^{-2}$. However a larger effect is expected[10] in a model where CP violation arises through a multi-Higgs system.

The more interesting and expectedly larger contributions to A from the third term alternates in sign with the CP of the final state (which is changed by simply adding an S-wave π^0), so it tends to be washed out in an inclusive experiment. Knowledge of the final state CP is therefore crucial; this requires states which are either totally neutral -- and seem not to be feasible for event identification -- or final states which are quasi two-body in both decays of the B-D-K chain, i.e., via resonances with well-defined CP. It may nevertheless be possible -- with sufficient improvement in vertex detector technology (see below) -- to obtain 10^3 useful events. It appears that such analyses can be done only at the Tevatron if at all.

There may also be partial width differences in $B^{\pm}$ decay through the interference of two Cabibbo forbidden amplitudes[8,11] or of one favored and one doubly suppressed amplitude. The absolute width difference is the same in both cases; the first has a larger relative effect, while the second has larger statistics and may have the advantage of being more inclusive, i.e., one can ask for a single K_S instead of two as in Ref. 8. Again one must be careful to avoid a washout in the sum over final states (which is complete by CPT if all states are summed -- see the more explicit analysis below), and an observable effect depends on the interplay of strong interaction effects rendering interpretation of a result more problematic.

Finally, we should remember that the Tevatron will provide a D-factory. In the KM model D^0-mixing is expected to be negligible due to the fast Cabibbo allowed decay channels, and CP violation in decay amplitudes is expected[12] to be generally $O(10^{-3})$, although the effect may be enhanced for certain final states such as $D \to K^0\bar{K}^0$ with zero U-spin. With the large numbers of D's expected, it may turn out be easier to pinpoint these effects than the relatively larger ones expected in B-decay. Any observation of a non-superweak type CP violation would be most welcome and should be looked for.

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