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BEYOND THE STANDARD MODEL

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This conference emphasizes (in part) rare decays and symmetries. My talk examines possible ways to get at physics beyond the standard model from the perspective of rare decays, CP violation, and the collider frontier.

1. INTRODUCTION

As we are all aware, the Standard Model is continuing to describe very well — too well — all particle physics experiments. We need new clues to tell us how to clarify the foundations of the Standard Model, how to understand the parameters and structure of the Standard Model, and how to extend it.

To complete the formulation and experimental of the Standard Model several tasks remain:

- Most important, the scalar sector[1] must be dealt with. That means finding the spectrum of scalar bosons (none, one, or more), and understanding what it implies — a task that will mainly be accomplished at LEP and at the SSC.
- The mass of the t quark needs to be determined. Since the b quark has had its value of T_3 measured[2] to be $-\frac{1}{2}$, there is a t quark (with $T_3 = +\frac{1}{2}$). The mass is particularly important in a practical sense because several major experimental tests depend on the value of m_t.
- Confirm the existence of ν_τ. Since the τ is measured to have $T_3 = -\frac{1}{2}$, there is a ν_τ, and since the lifetime and decays of τ would not make sense unless $m_{\nu_\tau} \ll m_\tau$, the ν_τ is light or massless.
- The elements of the CKM mixing matrix, particularly V_{ub} and the phase δ_{CP}, need to be better determined.

Some of these may also be probes to physics "Beyond the Standard Model" (BTSM).

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In general, a number of possible areas where clues could come are

- ⊙ Does t have non-Standard Model decays such as

$$t \longrightarrow H^+ b?$$
$$t \longrightarrow \tilde{t}\tilde{\gamma}?$$

- ⊙ Rare and forbidden K decays.
- Solar ν.
- Intermediate range forces.
- $B^0 - \bar{B}^0$ mixing.
- ⊙ Neutron electric dipole moment, d_n.
- ⊙ CP violating decays.
- ⊙ The search for supersymmetric partners in the new windows opened by increased energy and luminosity available at CERN and FNAL now and in the next few years.

Many other topics could be mentioned, but given the subjects of this conference and the types of data expected in the next few years, I will concentrate on those in the above list marked with ⊙.

2. THE t QUARK

The theorem that describes the situation for the t quark is that either $m_t \lesssim 200$ GeV, and

$$BR(t \longrightarrow be\nu) = BR(t \longrightarrow b\mu\nu) \simeq 1/9,$$

or new physics must exist on the weak scale. The upper limit arises[3] because $SU(2)$ breaking effects exceed limits from measurements of $\sin^2\theta_W$ if m_t gets too large. The decays are important because these Standard Model branching ratios could be suppressed if any new decays occurred, and experimental signatures are very sensitive to the presence of these branching ratios.

Presently the Tristan limits on m_t are model-independent, $m_t \gtrsim 26$ GeV. As $\sqrt{s}$ rises at Tristan they will search for m_t up to about 30 GeV. The UA1 limit, $m_t \gtrsim 41$ GeV, holds if the semileptonic branching ratios discussed above are valid. If 26 GeV $\lesssim m_t \lesssim 41$ GeV, then some other decay (such as $t \rightarrow H^+ b$ or $t \rightarrow \tilde{t}\tilde{\gamma}$) is dominating, and searches should take that into account.

Searches will continue. At UA2 a t quark decaying with the Standard Model semileptonic branching ratios could be found up to about $m_t \sim 60$ GeV. CDF can search up to about 100 GeV, higher if there is increased luminosity.

3. WHAT IS V_{ub}?

The CKM matrix element that measures the $b \rightarrow u$ transition, V_{ub}, is not yet measured. If the Argus report of observation of the decays $B \rightarrow \bar{p}p\pi$, $\bar{p}\pi\pi$ is correct, V_{ub} must be relatively large, but CLEO has not been able to confirm these signals; new data in the next year or two will clarify this situation.[4]

It is very important to know if $V_{ub} \neq 0$. If $V_{ub} = 0$, the phase factor of the CKM matrix could be rotated onto that element, and then CP violation would not occur in the Standard Model. A number of Standard Model tests also depend on V_{ub}.

Some methods to measure it are:

(a). The usual approach is to attempt to see events with hard leptons in the inclusive lepton spectrum. Leptons with energy above $m_b - m_c$ could only arise from $b \rightarrow u$ transitions. So far no such signal has appeared.

(b). Exclusive modes, such as $B \rightarrow \bar{p}p$ + pions (mentioned above), $B \rightarrow \rho\ell\nu$, $B \rightarrow \pi\ell\nu$, or $B \rightarrow \tau\nu$ would show $V_{ub} \neq 0$, though extracting a value for V_{ub} is a model-dependent procedure.

(c). The process $B_u^+ \rightarrow D_s^+ +$ pions (or + an even number of kaons) is proportional to V_{ub}. Perhaps, with luck, its branching ratio would be large.

4. RARE AND FORBIDDEN DECAYS

Since a great deal has been written about most of these, and there are several talks on the experimental aspects and motivation at this meeting, I will just highlight a few modes, and briefly comment.

- $K_L \rightarrow \mu e$, $\pi\mu e$

These decays are forbidden in the Standard Model, where a conserved lepton number can be defined for each family. If they were found to occur it would have an extraordinary impact on the future of particle physics, as large an impact as would the discovery of proton decay. No general argument has ever been given as to why these decays should not occur. The experiments underway at Brookhaven are described in separate talks at this meeting.

- $K_L \rightarrow \pi^o e^+ e^-$

The expected Standard Model branching ratio for this decay is about 10^{-11}, making it very difficult to detect in the near future. The Yale-BNL proposal (discussed by H Kasha elsewhere in these proceedings) is thus really probing a large region down to a branching ratio of order 10^{-10} (or eventually maybe 10^{-11}) in search of a non-Standard Model mechanism.

If they indeed do not detect this mode, future experiments at the Standard Model predicted level will aim to study it. It is particularly interesting because the CP-violating and CP-conserving contributions are of the same order. Considerable useful work has been done recently[5] to understand the details of this situation, and it should be well understood in a year or so

- $K^+ \longrightarrow \pi^+ \nu\bar{\nu}$

This decay, which will appear as $K^+ \rightarrow \pi^+ +$ nothing with an appropriate spectrum for the π^+, is also predicted to occur at a certain small level in the Standard Model. Once the elements of the CKM matrix and m_t are known, a precise prediction will be available (or, if this decay is measured first, it will strongly constrain the allowed values for m_t, etc., unless new physics contributions are important). At the present time the Standard Model requires

$$BR\left(K^+ \longrightarrow \pi^+ \nu\bar{\nu}\right) \leq \left[\frac{m_t(\mathrm{GeV})}{15} - 2.3\right] \times 10^{-10}.$$

A branching ratio larger than this can only occur if there is new physics beyond the Standard Model.

- $K^+ \longrightarrow \pi^+ \gamma$

It is interesting to consider $K^+ \rightarrow \pi^+ + \gamma$ as a rare decay. It is not listed in the particle data tables! By usual criteria it will not occur, since it violates angular momentum conservation (it is a "zero-to-zero transition"), and requires a photon to couple to a non-conserved current, which implies charge conservation is violated (theorists say gauge invariance is violated). Nevertheless, we do not test basic symmetry principles quantitatively enough or often enough, and this is a good opportunity for a significant test.

One can write down a mechanism by which this decay could occur. The basic transition $K \rightarrow \pi\gamma V$, where V is a hypothetical new vector field, is not forbidden. If V gets a vacuum expectation value then $K \rightarrow \pi\gamma$ results. For the Higgs mechanism spin zero fields get vacuum expectation values, and consideration has been given[6] to spontaneous violation of P and CP by giving a vacuum expectation value to a pseudoscalar. Violating lepton number conservation by giving vacuum expectation values to sneutrinos has also been considered in supersymmetric theories. There is no reason not to consider giving a vacuum expectation value to a spin one field. Such a transition can also violate CPT invariance.[7]

However, such a vacuum expectation value violates Lorentz invariance, and angular momentum conservation in particular. Consequently, there are strong constraints from tests of Lorentz invariance and rotational invariance. Work is in progress to evaluate these constraints. Whatever the situation, it is certainly worthwhile to put the best possible limits on such a decay as a by product of some other kaon decay experiment; whether it is worthwhile to extend limits further by a dedicated search depends on how strong the limits from other tests of Lorentz invariance are.

5. CP VIOLATION

CP violation[8] is almost 25 years old, and there have been a number of remarkable experiments to learn more about its properties. Nevertheless, the mechanism is not yet known. In the Standard Model, CP violation is described by a phase factor in the CKM matrix. There is no known reason for the phase angle, δ_{CP}, to be zero, so presumably the Standard Model mechanism contributes to CP violation.

Other kinds of physics may contribute as well. Phases can enter through the Higgs sector, or if the underlying theory is left-right symmetric, or if heavy fermions are mixed with the three "light" families, or from the supersymmetric sector (if there is one), and possibly from more sources. In addition, CP violation is allowed in the strong interaction sector because a CP violating term is allowed in the QCD Lagrangian; it's strength is described by a parameter θ. This source of CP violation is of phenomenological interest mainly for the neutron electric dipole moment.[9] Detection of d_n at about the present experimental limits would correspond to $\theta \simeq 2 \times 10^{-9}$; several complicated effects enter into computing d_n from quark level effects, so the value of θ corresponding to a given d_n is very uncertain, perhaps by an order of magnitude. Since θ is very small, it does not affect other CP measurements.

In the Standard Model CP violation enters[10] through charged current vertices,

$$H_{ch} = \frac{g_2}{\sqrt{2}} W^{\mu} \left(\bar{U}_L \gamma_\mu V D_L \right)$$

where

$$\bar{U} = (\bar{u}\bar{c}\bar{t}),$$

$$D = \begin{pmatrix} d \\ s \\ b \end{pmatrix},$$

and

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}.$$

Since one phase, δ_{CP}, is allowed to occur in the elements of V, the couplings for some processes will be complex, so they will not give matrix elements that are invariant under CP, since a complex conjugation is involved.

However, unitary transformations of V do not change anything, so the elements of V that contain the phase can be specified. In particular, if any process is considered for which only one or two families enter, that process will not show CP violation in the Standard Model because the phase can be rotated into the third family.

The Standard Model description of CP violation is very successful. It automatically predicts about the right size for the CP violation effect since products of off-diagonal elements of V are required, and it is consistent with ϵ and ϵ' (see H. Wahl's talk at this conference for a description of the data). Nevertheless, as described above, it would almost be surprising if some other CP violating effects did not enter.

How can we learn to distinguish the various CP violating mechanisms?[11] Considerable progress will come from having accurate measurements of ϵ', combined with determinations of m_t and V_{ub}. The Standard Model may not give a good description, which would imply another mechanism was operating. Or the Standard Model might continue to explain the data, which would argue against other sizable mechanisms.

If d_n is observed at the $10^{-25} - 10^{-26}$ level[12] it will require another mechanism. The Standard Model electroweak prediction for d_n is of order 10^{-32}. This occurs because of the need to get all three families involved so the phase cannot be rotated away. Since only u, d occur in the neutron in any quantity, the other families enter in loops, and at least two loops are required. Powers of couplings and mixing angles then guarantee the above numbers.

Other electroweak mechanisms can produce d_n at the 10^{-26} level, but so can QCD CP violation. Thus a measurement of d_n alone will not give us further immediate insight into sources of electroweak CP violation.

Another observable is the electron electric dipole moment, d_e. That receives no contribution from QCD CP violation, of course, and the Standard Model electroweak contribution is again very small, so an observable result at the 10^{-27} level or above would require another source of CP violation. Experiments are now underway[13] in Berkeley and Seattle that hope to achieve the 10^{-27} level, perhaps within two years.

Considerable discussion[14] has been given to using b quark mesons to study CP violation. Unfortunately, almost all methods to do so seem to require of order 10^8 B's to have a chance to reach the level of CP violation predicted by the Standard Model, and it is likely to be many years before facilities exist that achieve that quantity.

Fortunately, some "new" processes exist in the kaon system that will allow progress.[11] The essential point is that any kaon semileptonic decay occurs at the tree level, with $s \to u\ell\nu$, so only two quark families enter. Thus, CP violation does not occur for the leading contributions, and the loop corrections are very small. Any observable CP violating effects in $K \to \pi\ell\nu$ or $K \to \pi\pi\ell\nu$ are a guarantee of electroweak CP violation in addition to the Standard Model mechanism.

The situation is even better. Simple calculations[11] quickly show that left-right symmetric theories do not contribute to the transverse polarization of the μ in $K \to \pi\mu\nu$, while scalar theories do.[15] [Leurer[16] has generalized this to show that for any combination of vector and axial vector currents, and for massless or massive, Dirac or Majorana, neutrinos, no transverse polarization is generated for the muon.] Scalar interactions could give results of order 10^{-3} or even larger, though calculations are very model dependent. Thus, if a transverse polarization of the muon is observed in $K_{\mu 3}$ decays, it can only be due to electroweak interactions that give scalar effective Lagrangians. Higgs sector or leptoquark or supersymmetric physics could provide such interactions. If no polarization is observed it limits these contributions in a useful way.

$K_{\ell 4}$ decays[11] receive contributions from the scalar interactions discussed above, plus the vector and axial vector currents as well, since now these can both occur in the hadronic matrix elements and interfere. Possible observables include some that compare K^+ and K^- decays, or K^0 and $\bar{K}^0$ decays, but CP violating contributions in a single decay can also occur. In particular, observation of a $\sin 2\phi$ term in the distribution for any decay, where ϕ is the azimuthal angle between the pion pair plane and the lepton pair plane, signals CP violation from a V, A effective interaction; scalar interactions will not contribute to this term! Because of final state interactions, apparent CP violating effects can occur, but at a low level which should cause no difficulty, and such contributions can in principle be distinguished by a different dependence on another angular variable.

In the $K_{\mu 3}$ case the best process to consider is $K^+ \to \pi^0 \mu^+ \nu$, since not even a Coulomb phase enters to provide a final state interaction. $K_L \to \pi^\pm \mu^\mp \nu$ can also be used without contamination from the opposite CP admixture in the K_L wave function, since the K^0 and $\bar{K}^0$ pieces give muons of opposite sign and thus do not interfere. Then the Coulomb phase does enter, but its effect is calculable.

These arguments can be extended in the future to semileptonic decays of D's and B's. In these systems any contributions from vector and axial vector currents are unchanged, while scalar contributions generally have mass factors so their size would increase in heavier mesons.

The basic idea can be extended[11] to other systems as well CP violation in the $u\bar{d} \to W^+$ vertex occurs only at two loops in the Standard Model, and is therefore too small to observe, while it may not be negligible in other models. It is observable by comparing $\bar{p}p \to W^+$ and $\bar{p}p \to W^-$, for example. At pp colliders the initial state is not CP invariant, but because the W polarization can be observed through its decays, some CP violating observables may be detectable.

Similarly, in the lepton sector no observable CP violating effects should occur in decays in the Standard Model, but could occur in other approaches. Very little study has been done here.

In general, by utilizing a number of processes as described above, it should be possible to systematically untangle the mechanism(s) of CP violation.

6. SUPERSYMMETRY

Supersymmetry is a natural and well-motivated extension of gauge theories. As in the Standard Model, the masses of the particles are not determined by the theory, but must be measured (at our present level of understanding). Nature may or may not be supersymmetric of course. If it is, we might expect the particle masses to be of order M_W if supersymmetry were relevant to understanding the weak scale. Since all but the most recent limits are well below M_W, we would have been very lucky if any superpartners had been detected so far.

New windows will be opened in the near future, at SLC, LEP, and at the Tevatron collider. As searches for superpartners go to larger masses, some effects enter that change the character of the search.[17] For gluinos, previously the dominant model considered was

$$\begin{tikzcd}
\widetilde{g} \arrow[r] & \overline{q}\widetilde{q} \arrow[dr] & \\
& & q\widetilde{\gamma}
\end{tikzcd}$$

where $\widetilde{\gamma}$ was assumed to be the lightest superpartner (LSP); the LSP will interact weakly and will escape collider detectors. For heavier states, the last stage can in fact give any gaugino, e.g.

$$\widetilde{q} \longrightarrow q\widetilde{\gamma},\ q\widetilde{Z},\ q\widetilde{W}.$$

Thus for $M_{\widetilde{g}} > M_W,\ M_z$ it could happen that unexpected W's and Z's were the signature of supersymmetry. The new signatures may well make detection easier. One example studied at Snowmass '88 gave branching ratios for a gluino of 150 GeV:

$$\begin{tikzcd}
\widetilde{g} \arrow[r] & q\overline{q}\,\widetilde{W}^{\pm} \arrow[dr] \arrow[ddr] & & & \\
& & q\overline{q} + \text{LSP} & & 32\% \\
& & \ell^{\pm}\nu + \text{LSP} & & 15\% \\
{} \arrow[r] & q\overline{q}\,\widetilde{Z} \arrow[dr] & & & \\
& & h^0 + \text{LSP} \arrow[dr] & & 18\% \\
& & & b\bar{b} & \\
{} \arrow[r] & q\overline{q} + \text{LSP} & & & 34\%.
\end{tikzcd}$$

The old signature occurs only 34% of the time, or 12% for a pair of gluinos. For a 750 GeV gluino, about 35% of the decays have a $W^{\pm}$ or Z^0. These effects have to be taken into account in searching and in setting limits.

A clever analysis was done[17] by Barnett, Gunion, and Haber. Gluinos are Majorana particles. They must be, since each gluino is the partner of a gluon; the gluon has only two transverse polarization states, so the gluino can only have two spin states, rather than four as a Dirac particle would have. Then a $\tilde{g}$ is equivalent to its antiparticle, so it can decay as either particle or antiparticle. That is, the two modes

$$\begin{tikzcd}
\widetilde{g} \arrow[r] & u\bar{d}\,\widetilde{W}^{-} \arrow[dr] & \\
& & \ell^{-} + X
\end{tikzcd}$$

and

$$\begin{array}{l}\tilde{g} \longrightarrow \bar{u}d\widetilde{W}^{+} \\ \qquad\quad \hookrightarrow \ell^{+} + X\end{array}$$

are equally likely. Then a pair of $\tilde{g}\tilde{g}$ can give $\ell^+\ell^+$, $\ell^+\ell^-$, $\ell^-\ell^+$, $\ell^-\ell^-$. Half the time gluino pairs give like sign dilepton pairs, always a sign of new physics since the Standard Model never gives prompt like sign dileptons. This approach will be a good way to look for supersymmetry, and/or to confirm a different signature.

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