FLAVOR PROSPECTS

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Beauty 2003
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October 14, 2003

The quarks and leptons as we see them have first of all an odd-looking set of standard model quantum numbers:

$$\begin{pmatrix} u \\ d \end{pmatrix}_{1/3} \oplus \overline{u}_{-4/3} \oplus \overline{d}_{2/3} \oplus \begin{pmatrix} \nu \\ e^{-} \end{pmatrix}_{-1} \oplus e^{+}_{2}$$

When one first sees this structure, it looks like a bizarre hodge-podge – the fractional charges and parity violation in the gauge charges are perhaps the biggest surprises.

The quantum numbers are however at least partly demystified by

- *naturalness* – the chiral structure explains why the quarks and leptons that we see are "light" compared to the scale of gravity or GUT's. We see the stragglers; vector-like fermions have huge bare masses

- *anomaly cancellation* – the strange fractional charges cannot be changed at random or the theory would be inconsistent because of “triangle anomalies”

- most ambitious of all – *Grand Unified Theories* – SU(5) and its refinements – potentially explain the structure of a generation of quarks and leptons by unifying the pieces in a (relatively) simple representation of a simple gauge group

To whatever extent we do or do not understand the structure of a single generation, we also have to face the fact that nature has presented us with three of them, which we could call the electron, muon, and tau families.

Why did nature repeat structure in this way? “Who ordered that?” as Rabi asked about the muon.

Apart from understanding why there are three flavors, we also want to understand the “flavor structure’’ of the masses and interactions.

In fact, most measured particle physics parameters -- both Standard Model parameters and beyond -- are flavor parameters.

Standard Model parameters – quark and lepton masses and CKM mixing matrix.

Most striking thing to explain about these parameters: extreme smallness of some quark and lepton masses

Non-Standard Model parameters – neutrino mass differences and the PMNS neutrino mixing matrix.

Neutrino masses are about right for GUT’s!

Tentatively assuming that that is on the right track, the most striking thing to explain about neutrino parameters: large neutrino mixing angles in contrast to small quark mixing….

Most attempts to explain flavor begin by asking why nature has repeated herself, why there are three flavors. One then tries to understand the mass and mixing parameters.

Approaches include

- symmetries
- compositeness
- unification
- extra dimensions

- Symmetries

Place the three families in a representation of a “horizontal” flavor symmetry group such as SO(3) or possibly a finite group

Use symmetry structure to explain why there must be several generations
In many attempts (Froggatt-Nielsen,…), in some unbroken-symmetry limit, the CKM

matrix is diagonal – its off-diagonal terms are related to small symmetry-breaking effects.

* Compositeness – get known fermions as bound states from some more elementary constituents – with three generations because of different internal wave functions. I'd say that the *chirality* has made this unworkable, at least until now.

- Another approach to flavor involves *gauge unification* . Grand Unified Theories explained a single family in terms of the gauge structure of a GUT representation such as the $\bar{5} + 10$ of SU(5), or 16 of SO(10)

This elegant structure is one of the prime achievements of GUT's

So try to find a larger gauge group with a larger irreducible representation that contains several families of the Standard Model.

This is an interesting program, and several Lie groups such as SO(16) and E_8 have some of the right properties.

The program goes wrong again because of *chirality* -- the families come with antifamilies of the opposite handedness.

This is another important lesson in how fundamental the handedness of the fermions is. This handedness ….

- Is odd at first sight
- explains "lightness" of the fermions
- helps separate the sheep from the goats in terms of theories beyond Standard Model

* may mean that flavor is even more fundamental than it appears

In this problem, ideally, we'd like to find a "beyond GUT" group G with an anomaly-free simple representation R leading in terms of the Standard Model to n families and m anti-families where

$$n - m = 3$$

Then the Higgs mechanism could reduce us to the real world, $n = 3$, $m = 0$ as families and anti-families can pair up with large bare masses.

But this doesn’t work.

When we try to explain flavor this way, we get $n - m = 0$.

For example, we could use the spinor of SO(18) and then we find $n = m = 8$.

Or we could use the group E_8. This group is worthy of describing nature as it is the biggest and most splendid of the exceptional simple Lie groups. But we find in four dimensions $n = m = 4$.

* Another idea about flavor is to use extra dimensions.

For example, the (heterotic) string models of the mid-1980's are rather similar to the GUT models that I just mentioned, except that the unification occurs in ten dimensions, and the starting point is more constrained – the starting gauge group has to be SO(32) or E_8 . When one tries to count generations and antigenerations, one starts in a sense with n=m = infinity, because of the Kaluza-Klein harmonics. The infinity is regularized by the bare masses, and one is left with a finite remainder that depends on the topology of the extra dimensions.

In the original model, the number of light generations – 3 in the real world – comes out to be $\chi/2$, where χ is the most elementary topological invariant, the "Euler characteristic" of the extra dimensions.

In the process, E_8 is revived.
Four-dimensional E_8 doesn’t work because of the fermion chirality, but ten-dimensional E_8 is (almost) forced on us by string theory, and leads in a simple way to the right Standard Model gauge group and chiral fermions.

From this point of view, topology (of the extra dimensions) plays the role for flavor that we might have assigned to symmetries.

The number of generations comes from topology (the Euler characteristic) and more subtle aspects of topology control the fermion masses and CKM matrix.

Nowadays, a much wider range of models of flavor are derived from extra dimensions. In string theory, there are many new types of models, frequently “dual” to the original ones in different regions of their parameter space, but possibly giving important new insights or more relevant to nature. There are also numerous “bottom-up” models, often incorporating aspects of the string models.

One lesson we might learn from this little survey of models is that while there may be a “theory of flavor” at accelerator energies, it may also be that the origin of flavor is at much higher energies and that understanding flavor is inseparable from understanding a larger unification of particle forces, possibly including gravity.

Indeed, fermion chirality is an important hint in this direction.

We might draw a contrast between flavor and another notorious problem in particle physics – the “gauge hierarchy” problem, which is the question of why the mass scale of observed particle physics is so tiny compared to the mass scale of gravity and, possibly, of Grand Unification.

Technically, the problem arises because the Higgs boson φ can have a bare mass $m^2\varphi^2$ and loop corrections will naturally renormalize m^2

up to an amount of order $\alpha = e^2/hc$ times the scale at which the ultraviolet divergences are somehow cut off.

There are numerous proposals for what this cutoff may be – among them supersymmetry, technicolor, models with large extra dimensions or low-scale unification with gravity, and “little Higgs” models. But all models that give any sort of rational explanation for the lightness of the elementary particle scale do this with a mechanism that can be probed at accelerator energies.

For example, in the case of Supersymmetry, the cutoff involves a cancellation between the known particles and their superpartners, and is only sufficiently effective if the superpartners weigh no more than a few hundred GeV.

So we expect that the LHC, or possibly Fermilab, can reveal a mechanism, or at least some of the ingredients of a mechanism, that stabilizes the scale of electroweak symmetry breaking and hence the particle bare masses.

If instead the LHC would discover only a Standard Model Higgs boson and no further mechanism accounting for the stability of the elementary particle mass scale, this would sharply contradict our way of thinking.

I don’t think we have the same expectation that the origin of flavor is accessible in an equally direct way in accelerator experiments. In some models it is, but in some perfectly plausible models (like the string models I mentioned) flavor originates at much higher energies, and then penetrates down to the energies at which we make our observations.

The difference arises because of chirality, which can keep fermions light compared to the mass scale at which their structure emerges. Fermion masses are “protected.”

By contrast, the Higgs boson is highly non-chiral, and “anything” can contribute is mass. The Higgs boson is in need of protection.

Part of the fascination of flavor is precisely that the chiral and CKM and PMNS structure may thus originate from the GUT or string scale.

But how can we learn more? More clues about flavor are emerging from current experiments, including those reported at this meeting, on CKM physics, CP violation, neutrino masses and mixing, and studies of rare or forbidden K and charm and B decays.

We may have the chance to learn many more clues about flavor physics when we can probe the mechanism of electroweak symmetry breaking at accelerators. Many of the models lead to dozens of new flavor observables, and not just the few additional flavor observables that we hope to measure in the neutrino sector, for instance.

For example, with supersymmetry, there would be dozens of new flavor observables involving the superpartners. And not only is the number of new observables large, but there is quite a bit of mystery about them – when it comes to flavor (and CP, and baryon number), the supersymmetric models, despite their other virtues, definitely have the potential to spoil some of the merits of the Standard Model. Why don't the superpartners mediate flavor changing neutral current processes at a level that would contradict what we see? It is a conundrum, with some possible solutions none of which appears perfect, yet many clues (involving SUSY-GUT's and gauge coupling unification as well as the hierarchy problem) suggest that supersymmetry may well be there at TeV energies. If so, our limited supply of clues about the flavor problem would get considerably longer, when we are able to study the superpartners in detail.

The whole story of the superpartners would be extremely rich and elaborate, almost surely requiring lepton colliders as well as hadron colliders for its elucidation.

Most other attempts at the gauge hierarchy problem lead to some of the same issues: many new flavor-dependent processes, potential for unwanted flavor-changing (or baryon-number changing) processes, lots of new flavor-dependent observables to study at accelerators.

Another place where we may get new information about flavor will be if we are lucky enough to discover proton decay, as suggested by SUSY-GUT's and related models.

Does the proton decay to e or μ? Left or right handed? To strange or non-strange particles?

There is another mixing matrix here analogous to the CKM matrix, but involving GUT interactions instead of weak interactions.

In short, we might find a theory of flavor at accelerator energies, but flavor might be even more fundamental if – as fermion chirality suggests – it originates at the GUT scale.

In this case, we can hope to obtain numerous new clues about *how* flavor emerges, especially if we have the good fortune to discover supersymmetry or another mechanism accounting for the scale of particle bare masses.