EXTENSIONS OF THE STANDARD MODEL*

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Some generic extensions of the standard model of weak, electromagnetic, and strong interactions among quarks and leptons are considered, emphasizing the constraints imposed by experimental data.

1. The Standard Model

We now have a very successful theory of the weak, electromagnetic, and strong interactions: the so-called standard model¹ in which the elementary fermions are the quarks and leptons with interactions determined by the gauge group $SU(3) \times SU(2) \times U(1)$. The intermediate vector bosons are the photon, γ , the charged and neutral weak bosons, $W^\pm$ and Z^0 , and the gluons, g . In addition, in its most naive form, there is a Higgs boson, H , which accounts for the spontaneous symmetry breaking that results in masses for the $W^\pm$ and Z^0 , as well as the fermions. This standard model has enjoyed a great deal of success and no failure in a variety of experimental tests. There is good reason to be very pleased with this striking achievement in the field. Yet there remains a sense that the standard model is incomplete, is not aesthetically pleasing, and does not provide answers to a number of issues of great interest. Bob Marshak devoted much of his restless intellect and boundless energy to exploring possible extensions and modifications of the standard model. In this tribute to his memory I will discuss some of the possible directions that extensions of the standard model could take, emphasizing the limits current experiments place on the various possibilities, with the hope that experimental guidance may provide some insight as to which directions are likely to prove most fertile to explore.

2. Composite Models

Simply the large number of fermions, occurring in triplication, in the standard model naturally leads one to wonder if they are actually composites of more elementary objects, generically referred to as preons. Certainly there is historical precedent for this scenario provided by the chemical elements, the atomic nucleus, and the hadrons. One approach to searching for compositeness is to look for new, non-standard model, interactions among the quarks and leptons. Presumably such interactions would appear at an energy scale comparable to the scale of the binding energies of the quarks and leptons. At low energies these can be characterized by effective point interactions of the four-fermion type; either four leptons, or four quarks, or two leptons and two quarks. Experimental searches² now put a lower limit of about a TeV, or about 10^{-4} F, on such manifestations of compositeness. Clearly, the quarks and leptons do not appear to be bound states of constituent preons at the scale of energies available to present experiments.

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3. Extensions of the Gauge Group

3.1 Grand Unification

There are not only a very large number of elementary particles in the standard model, but it also does not really unify their interactions: there are three independent gauge coupling strengths. It is natural to speculate that this distinction among the weak, electromagnetic, and strong interactions is an artifact of the low energies, or large sizes, at which we now view these interactions. That is, perhaps the standard model $SU(3) \times SU(2) \times U(1)$ gauge group is the low energy remnant of a larger gauge symmetry, broken at some high energy scale. The extrapolation of the running coupling constants indeed suggests that there is a grand unification mass around 10^{15} GeV or larger³. It should be stressed that the coefficient functions in the evolution of these coupling constants is determined by the low energy structure of the standard model and it is further assumed that no new physics is encountered in the extrapolation. The prototypical example of such a grand unified theory is the $SU(5)$ theory.⁴ Characteristically in these models quarks and leptons appear in the same multiplets and there are gauge interactions which do not separately conserve quarks and leptons. Consequently, the nucleon is not stable and this provides a striking low energy test of a large class of grand unification schemes. The current experimental limit on the nucleon lifetime, about 10^{32} years², seems to rule out any such straightforward grand unification.

Another unattractive feature of the grand unification approach to improving the standard model is the issue of the very large number of fermions. Grand unification of the gauge group, while merging the three coupling constants, still leaves the quarks and leptons in three families of multiplets.

3.2 Left-Right Symmetric Weak Interactions

A less ambitious direction in which the standard model has been extended is based on the possibility that the nonconservation of parity may be only a low energy phenomena. From the outset, the electroweak sector of the standard model does not respect parity. The left-handed fermions are assigned to doublets, while the right-handed fermions are singlets. In the left-right symmetric extension of the standard model⁵ the gauge group is $SU(3) \times SU(2)_R \times SU(2)_L \times U(1)$ with the transformation properties of right- and left-handed fermions being interchanged under the additional $SU(2)_R$. There are, consequently, new right-handed charged-current weak interactions mediated by another charged weak boson $W_R^\pm$. The mass of such a boson is severely restricted by the smallness of the $K^0 - \bar{K}^0$ mixing. From the box diagram contribution to Δm_K one finds⁶ $M(W_R) > 1.6 \text{ TeV}/c^2$ or $M(W_R) > 4 \text{ TeV}/c^2$ when strong interaction effects are included.⁷ Clearly, this is beyond the present range of direct experimental investigation.

3.3 Horizontal Interactions

A very puzzling aspect of the standard model is the replication of the fermions in three families. Why are there only three? Or, why are three required? Perhaps this is a hint that there is another interaction between fermion families. Such a horizontal gauge interaction based on a family $SU(3)$ gauge symmetry can easily be written down. One might even imagine a grand unification of the resulting extension of the standard model into a larger gauge group; for example, $SU(8)$. But this leads to severe problems rather

quickly if the interactions are very strong. From the constraints on flavor-changing transitions any gauge boson mediating interactions between quarks from different families is limited to be in the several TeV regime², well beyond direct investigation with present accelerators.

4. Summary

We have discussed a few selected types of extensions of the standard model which fall into categories: compositeness of particles that we now regard as elementary, complete unification of the gauge interactions, and intermediate enlargements of the gauge group to include specific new interactions, either weak or strong. In each case there are severe limits provided by existing data.² The energies required to directly explore the regimes where new phenomena might occur are beyond present accelerators.⁸ Although, one cannot confidently predict where something new is going to show up, it would appear that the better strategy for the moment is in the direction of precision experiments at the low energies now available.

Certainly the future of the field is challenging, inviting the kind of energetic imagination that was so characteristic of Bob Marshak's distinguished career.

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6. References

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