GENERAL FEATURES OF 1-TeV PHYSICS*

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Both the energies of the new machines being discussed at this workshop and the details of the theoretical proposals under study look toward new interactions at an energy of roughly 1 TeV. This energy certainly expresses the frontier of our ignorance: it represents the limits of the ability of proposed accelerators to view new physics, and it represents as well the boundary of applicability of the theoretical synthesis represented by the standard model. But the energy region of 1 TeV is also the place where our current understanding of physics compels us to look for new phenomena, the place where something should happen that will shape the next development of fundamental physics. In this short contribution, I would like to summarize the most important predictions for physics in this energy region, and to stress their relative model independence.

At this workshop, I have been impressed by the diversity of theoretical proposals for new physics at this scale; but perhaps even more strongly, I have been impressed that these diverse proposals lead to observable phenomena accessible to the new accelerators which are, at a qualitative level, remarkably similar. I intend here to indicate why this is so, and to argue that the effects these theories hold in common should be searched for diligently, since they are more likely than any specific theories to be true aspects of nature.

Why do we focus on energies of 1 TeV? The answer comes from examining the standard model. The standard model has had great experimental success, and, for the purpose of this discussion, we will assume it is correct in its domain. We note, however, that this model is essentially a theory of symmetries, a theory of gauge bosons and gauge couplings. All of the successful predictions of the theory are connected directly to its constraints of symmetry in identifying testable relations between coupling constants. However, there is, in any dynamical theory, a second aspect complementary to that of symmetry: the aspect of mass scales, of overall magnitudes.[1] In the theory of the strong interactions represented by QCD, the origin of the mass scale is a calculationally difficult question, but one which is not problematical in principle; one can understand intuitively that a scale is determined by the point where the scale-dependent coupling α_s becomes of order 1. In the SU(2) × U(1) theory of the weak interactions, the question of the origin of the mass scale is addressed by a parameterization rather than a piece of physics: one writes for the W boson mass

$$m_W = \frac{g}{2} \langle \phi \rangle$$

where g is a gauge coupling but $\langle \phi \rangle = 250$ GeV is a number which comes from outside the sector of the model which is determined by symmetries. In the standard model $\langle \phi \rangle$ is interpreted as the vacuum expectation value of a scalar field, the Higgs fields. That statement, however, does not satisfy our intuition that this mass scale has a mechanical origin, that it is determined by physics. The current diversity of theoretical speculations reflects, essentially, the attempt to guess what that physics might be. What these guesses have in common is their starting point, the need to explain $\langle \phi \rangle = 1/4$ TeV.

In some models the magnitude of $\langle \phi \rangle$ is set by invoking new strong interactions which produce this quantity directly. (Technicolor models are of this type.) Such new interactions are forced to have as their basis mass scale at roughly 1 TeV. In other models $\langle \phi \rangle$ appears as a radiative correction induced by a new sector of particles relatively weakly coupled to the gauge bosons of the standard model. (This situation occurs in many models of supersymmetry.) In such models, however, the influence of this new sector on the other particles to which quark and lepton couple directly can be no more strong than the influence which creates $\langle \phi \rangle$. The fundamental scale of such models is much higher, but its effects are just those of a direct interaction from a scale of 1 TeV.

If 1 TeV is the scale of these new interactions, however, that certainly does not mean that one needs center-of-mass energies of 1 TeV to see new physics. A remarkably universal property of models which explain the scale of $\langle \phi \rangle$ is that they predict new physics at center-of-mass energies of order 100 GeV. In the remainder of this section, we will explain why this happens and point out the basic phenomena which are predicted. We should note that the center-of-mass energy we refer to is that of a reaction between quarks or leptons; in hadron-hadron collisions, the required machine energies are an order of magnitude higher.

It is possible to construct a model in which the new physics creates the W and Z masses and, essentially, does nothing else. The standard model is a construct of this type. But if the new physics which creates $\langle \phi \rangle$ has any non-trivial structure — if, for example, it can account for the quark and lepton mass spectrum — that physics will manifest itself in other ways. In particular, if the new physics reflects, as the physics of quarks and leptons does, an internal symmetry, the constraints of this symmetry lead naturally to new observable phenomena. These phenomena fall into two classes: new particles with masses below 300 GeV, and new interactions among quarks and leptons. Let us discuss each of these in turn.

There are two arguments for the occurrence of new particles. The first is tied most directly to the realization of the internal symmetry. The internal symmetry may be spontaneously broken or it may not be. If it is spontaneously broken, Goldstone's theorem requires that there be new bosons, one for each spontaneously broken symmetry directions, which are much lighter than the characteristic scale of the new interactions. These bosons, called pseudo-Goldstone bosons, typically acquire mass from the electromagnetic, weak, or QCD perturbations on the new interactions; these masses are typically

$$m^2 \sim (\alpha \text{ or } \alpha_s) \cdot (1 \text{ TeV})^2 \quad .$$

If the symmetry is not spontaneously broken, there is no completely general complementary principle, but if the new interactions are, like the familiar ones, gauge interactions of fermions, a theorem of 't Hooft[2] assures us that there must be light composite fermions bound by the new interactions. (Some of these may be the familiar quarks and leptons.)

The second argument is a matter of our experience with quantum-mechanical perturbation theory. It may seem accidental in any given case, but, nevertheless, it happens more often than not, that the first-order perturbation to the energy of some state in the theory will vanish by virtue of a symmetry constraint. In a

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*Work supported in part by the Department of Energy, contract number DE-AC03-76SF00515.

theory in which this first-order influence sets the scale of masses, this means that some particles are left light. If one insists that a theory has supersymmetry but that the usual quarks and leptons not be involved directly in supersymmetry breaking, the bosonic partners of the quarks and leptons are also insulated from supersymmetry breaking, which would have provided their masses, up to effects of order α or α_s. In detailed studies of technicolor theories, one can almost always find a set of bosons (or fermions) forbidden by chiral symmetries of the theory from acquiring mass in leading order.[3] In models in which quarks and leptons are composites of preons, the restriction on mass generation comes from the familiar SU(2) × U(1) quantum numbers: one can create new fermions by rearranging the preon spin or flavor orientation from those of the light quarks and leptons; these new fermions, like the familiar ones, cannot acquire mass until SU(2) × U(1) is broken. Any of these constraints lead to particle masses well below 300 GeV. If the structure of the new interactions results from another symmetry, this symmetry almost invariably implies an analogous constraint.

It should be emphasized that new particles in the mass range 5-300 GeV may display unusual patterns of quantum numbers. Above 300 GeV, QCD is a weak interaction, and color SU(3) becomes another global flavor symmetry. One might, then, expect colored bosons, or fermions in more unusual color representations. Any complexity in the mechanism of SU(2) × U(1) breaking leads to the requirement of charged scalar mesons: technicolor and supersymmetry both require charged scalars and light (mass << 50 GeV) neutral scalars, as the result of very different constraints which add structure to the mechanism of SU(2) × U(1) breaking. Of this plethora of new particles, some should be accessible, and therefore copiously produced, at the Z^0; more will be accessible in proton-proton collisions. New particles with thresholds above Z^0 will cause a shift in the Z^0 mass, perhaps by as much as 1 GeV. An e^+e^- collider in the energy range of several hundred GeV will find much of the total cross section made up by the production of such exotic particles.

The second class of phenomena one finds almost universally in such models is the appearance of new interactions. In some models, the quarks and leptons couple directly to the new force at 1 TeV, or are formed as composite states by that force. In this case, they will acquire new interactions beyond those described by the standard model. Such interactions will provide weak couplings that correct the interactions of SU(2) × U(1) (in some models,[4] they even replace the weak interactions) and drastically enhance weak cross sections as $(s)^{\frac{1}{2}}$ approaches 1 TeV.

In addition to these strong interactions at 1 TeV, one also finds couplings of another sort, weaker, but still very interesting. These couplings stem from disparate attempts to resolve a secondary paradox of the mass scale of the weak interactions: why are quark and lepton masses so much smaller than the W and Z masses? The interactions which couple the quarks and leptons to the mechanism of SU(2) × U(1) breaking must be somehow suppressed, either by a small coupling constant or by the invocation of some higher mass scale. Taken in second order, these interactions can couple the quarks and leptons to themselves, with no necessary regard for the conservation of flavor. Such interactions would then be expected to mediate flavor-changing neutral transitions, which should then appear in rare K, μ, and D decays and in neutrino masses. Whatever one guesses makes the quark lighter than the W can explain why these processes are so rare; the theoretical expectations for the rates of the processes, however, press the experimental bounds.

I expect, then, in the coming decade of experimental particle physics, the appearance of a variety of new phenomena at accessible mass scales (up to 300 GeV) associated with new physics at the mass scale of 1 TeV. The specifics of the phenomena depend on the details of one's expectations; however, I have abstracted a few phenomena which follow from diverse models set at this common mass scale:

1. A rich particle spectroscopy in the mass range 5-300 GeV,
2. Relatively light charged and neutral scalars,
3. Colored bosons or exotically colored fermions,
4. New interactions among quarks and leptons; a dramatic increase in large Q^2 cross sections in conventional channels,
5. Flavor-changing neutral transitions: rare K, μ, and heavy quark decays; ν masses.

All of these phenomena occur in specific models, but we have argued that they occur for reasons more general than the validity of any particular model. I find the existence of 1 TeV physics — of some kind — compelling; whatever the details of this physics, its signatures will be striking. The recognition of these signatures and the clarification of this physics will be a major task of the coming generation of accelerators.

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