Chapter 1

Root Concepts of the Standard Model

The standard model of particle physics accurately describes a vast range of phenomena using a small number of parameters. Much of the power of the standard model arises from the fact that it embodies a few deep physical and mathematical concepts which are difficult, but not quite impossible, to make consistent with one another. These principles include, first of all, the general principles of special relativity and quantum mechanics. Those lead us to local quantum field theory. To these general principles, the standard model adds one more specific ingredient: local, or gauge, symmetry. Gauge symmetry is a vast generalization of the principle of electric charge conservation.

Formulating equations that embody these concepts is only half the job, because it is not at all straightforward to see that the resulting equations describe Nature. Specially, apart from the special case of quantum electrodynamics, which forms only a small sub-theory of the standard model, local gauge symmetry is not manifest in the superficial appearance of phenomena. In applying the basic highly symmetrical equations to describe observed reality, which appears much less symmetric, two profound dynamical effects must be taken into considerations.

The first of these dynamical effects is the spontaneous breaking of local gauge symmetry. It is a form of super-conductivity, but operating in (what we perceive as) empty space. In conventional super-conductivity, roughly speaking, the electrons in a metal, which normally behave as a gas of independent particles, condense into a liquid of overlapping Cooper pairs. The dynamical response of this liquid screens the electromagnetic interactions, and renders magnetic fields short-ranged. That is the essence of the Meissner effect. In the context of the standard model, the role of Cooper pairs is played by a new form of matter, the so-called Higgs field, or more accurately the Higgs multiplet of fields. The Higgs multiplet is a theoretical construct that was invented specially to fulfill this mission. According to the theory, a condensate of Higgs particles fills empty space, and its dynamical response screens the weak interactions, rendering them short-ranged.

There is weighty indirect evidence for the existence of the Higgs multiplet, but at present direct observation of its quanta, the Higgs particles, remains a major unmet challenge, as we shall discuss in detail later.

The second of these dynamical effects is confinement of quarks. Confinement should be considered together with the closely related property of asymptotic freedom, which is in a sense its inverse. Confinement and asymptotic freedom occur in the sector of the standard model dealing with the strong interaction, quantum chromodynamics or QCD. In this context, local gauge symmetry takes a most peculiar form. The fundamental building-blocks of the theory – quarks and gluons – transform non-trivially under an $SU(3)$ local gauge symmetry. Indeed, the so-called color charges of these particles, which specify their transformation properties, are entirely responsible for their QCD interactions. But the physical particles in QCD are all singlets, which do not transform under the gauge symmetry. They are formed out of combinations of quarks, anti-quarks, and gluons in which the color charges all cancel.

Although the colored building blocks are real and tangible, and reveal their existence quite directly to suitable probes, they cannot be separated out and examined individually. Attempts to pull them apart call ever-growing forces into play, and are inevitably frustrated. This is confinement. Yet when the color charges are close together, or when we consider processes that involve large changes in energy and momentum, the forces are feeble an d the radiation is rare. This is asymptotic freedom. These unusual behaviors – fundamental forces that grow with distance, radiators that become quiescent as they are shaken violently – were once thought to be paradoxical or even problematic. They are now understood to be a general feature of many model theories with local gauge symmetry. They are deeply related, respectively, to the most basic formulation of local gauge symmetry, and to the ultimate consistency of quantum field theory.

In QCD itself, asymptotic freedom is born out of a interplay among our three basic concepts of relativity, quantum mechanics, and gauge symmetry. All three play crucial roles, as we shall see in detail later.