Chapter 9

Broken Symmetries and the Higgs Mechanism

9.1 Introduction

Not every symmetry observed in the mathematical laws of physics is visible in nature. A symmetry may exist in the equations while the lowest-energy state, or vacuum, does not exhibit that symmetry. This phenomenon is called spontaneous symmetry breaking.

9.2 Exact and Broken Symmetries

An exact symmetry is preserved under all conditions. A broken symmetry occurs when the equations remain symmetric but the physical state selects one of many equivalent possibilities.

9.3 Spontaneous Symmetry Breaking

A common analogy is a pencil balanced on its tip. The laws governing the pencil are rotationally symmetric, but once it falls, a particular direction is chosen. The symmetry of the laws remains even though the observed state is no longer symmetric.

9.4 The Higgs Field

The Higgs field permeates all of space. Unlike most quantum fields, its lowest-energy state has a nonzero vacuum expectation value. This property is responsible for electroweak symmetry breaking.

9.5 The Higgs Mechanism

When the Higgs field acquires a vacuum expectation value, the electroweak symmetry $SU(2)_L \times U(1)_Y$ is broken to the electromagnetic symmetry $U(1)_{EM}$. The W and Z bosons acquire mass while the photon remains massless.

9.6 Mass Generation

The Higgs mechanism also allows quarks and charged leptons to acquire mass through Yukawa interactions with the Higgs field. Different coupling strengths produce different particle masses.

9.7 Goldstone Bosons

Spontaneous breaking of a continuous symmetry normally produces massless Goldstone bosons. In gauge theories these degrees of freedom are absorbed by the W and Z bosons, providing their longitudinal polarization states.

9.8 Broken Symmetries in Nature

Examples include electroweak symmetry breaking, chiral symmetry breaking in quantum chromodynamics, and the small but important violation of CP symmetry observed in weak interactions.

9.9 Why Broken Symmetry Matters

Broken symmetry explains why the weak force has a short range, why elementary particles have mass, and why the electromagnetic interaction remains long ranged.

9.10 Open Questions

The Standard Model successfully describes electroweak symmetry breaking, but questions remain concerning the origin of the Higgs potential, the hierarchy problem, and whether additional Higgs particles exist.

Chapter Summary

Broken symmetry is one of the central concepts of modern particle physics. The Higgs mechanism demonstrates how an underlying symmetry can remain present in the laws of nature while giving rise to massive particles and the distinct forces observed in everyday experience.