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HIGH ENERGY & PARTICLE PHYSICS
An EPS Review

In the following articles devoted to high energy and particle physics, an impression is given of the important progress that has been made over the past decade in our understanding of the fundamental structure of matter. An introduction is also given to the basically new — and difficult — concepts that are being formulated in order to resolve the problems that are still outstanding and at the same time allow us to include gravity in our thinking. A brief review is given of the technological advances that have been made in the experimental domain and of the efforts made to accelerate particles to ever higher energies — at a cost that is still acceptable — and improve the precision and completeness of data recording.

Since it became clear in the early seventies that quarks were not just mathematical entities but were real constituents of matter, we have come to accept that of the many hundreds of particles known, the elementary constituents comprise 18 quarks (six flavours each with three colours) and 18 antiquarks as well as six leptons and six antileptons.

The Interactions and their Mediators

Because of the huge success of Quantum Electrodynamics (QED), the quantum theory of the electromagnetic interactions, we have taken it as a model on which to base the quantum theory of the other interactions. The forces between electrical charges are transmitted by photons and by analogy we started thinking long ago that the other interactions should also occur *via* the exchange of some particles. Today there is strong experimental evidence that the mediators of the interactions are bosons.

The mediator of the strong interactions between quarks is the gluon, those of the weak interactions are the intermediate weak vector bosons, W^+, W^- and Z^0, and of the gravitational interactions a hypothetical boson called the graviton. The first experimental evidence for gluons was obtained at DESY in 1979, in the study of hadron production in e^+e^- annihilations. The W^+, W^- and Z^0 were discovered at CERN in 1983, with the now famous proton-antiproton collider. There is not yet experimental evidence for the graviton.

QCD, Electroweak Interactions; Standard Theory

The quantum theory of the strong interactions of quarks, is called Quantum Chromodynamics (QCD), by analogy with Quantum Electrodynamics. There is, however, a fundamental difference between QED and QCD. In QED, the source of the electromagnetic field is the electrical charge and the quantum of the field, the mediator, is the photon. A field of this type, in which the source and the quantum are different entities is called Abelian. In QCD the source of the field and its mediator are the same entity, the gluon and a field of this type is called non-Abelian. QCD has proved to have great power and whenever experiments have been possible the results have agreed with predictions.

A great step towards the old dream of unifying the four interactions was made by Glashow, Salam and Weinberg who succeeded in unifying two of them, the electromagnetic and the weak, leading to the so-called electroweak. The photon, the $W^{\pm}$ and the Z^0 are treated on an equal footing.

The two theories: QCD for the strong interactions and the electroweak theory for the electroweak interactions are together called the Standard Theory. This does not mean there has been a unification of the three interactions and we must recognize that gravitational interactions are not covered as, so far, it has not been possible to formulate a quantum theory of gravity.

Symmetries and Symmetry Breaking

Symmetry is a fundamental concept in particle theory. The first example was the symmetry between protons and neutrons arising from the charge independence of nuclear forces. The proton and the neutron form a doublet; the symmetry there consists in transforming a proton into a neutron, or *vice-versa*, by a rotation in the isotopic spin space. This is done by the SU(2) group. The group is unitary (has a unit matrix), unimodular (determinant = 1) and the S stands for special. Special is for being unimodular; the 2 indicates that the generators (operators) of the group are 2×2 matrices — the famous Pauli matrices. Gell-Mann introduced the SU(3) group to make the operations of symmetry among the triplet comprising the three initial quarks u, d and s, and among the triplet of the three antiquarks $\bar{u}$, $\bar{d}$ and $\bar{s}$. The generators of this group are the Gell-Mann eight 3×3 matrices, which are a generalization of the Pauli matrices. The SU(3) group transforms the members of the quark triplet amongst themselves.

The SU(2) and SU(3) symmetries are not exact; they are broken. SU(2) is broken because the proton and the neutron have different masses, but as this difference is small the breaking of the symmetry is also small. The SU(3) symmetry is broken because the masses of the u, d and s quarks are different and the masses of the hadrons of the same multiplet are different. In the electroweak theory, the symmetry of the intermediate vector bosons is very badly broken, because their masses are very different: the mass of the proton is zero, that of the $W^{\pm}$ is 81 GeV and that of the Z^0 is 93 GeV. We need then a mechanism to create the masses of the $W^{\pm}$ and Z^0, but this is not all, as we shall see.

The above is a summary of an introduction to the subject prepared by

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