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Abstract

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PHYSICS AT THE SUPERCONDUCTING SUPERCOLLIDER

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Elementary particle, or high energy, physics seeks to identify the most elementary constituents of nature and to study the forces that govern their interactions. Increasing the energy of a probe in a laboratory experiment increases its power as an effective microscope for discerning increasingly smaller structures of matter. Thus we have learned that matter is composed of molecules that are in turn composed of atoms, that the atom consists of a nucleus surrounded by a cloud of electrons, and that the atomic nucleus is a collection of protons and neutrons. The more powerful probes provided by high energy particle accelerators have taught us that a nucleon (proton or neutron) is itself made of three objects called quarks. Different quarks are distinguished by attributes known as "flavor" and "color". The interactions of quarks and electrons are understood within the framework of the "standard model". Probing for deeper structures in quarks and electrons defines the present frontier of particle physics.

THE STANDARD MODEL

Electrons are bound to the nucleus in an atom by the exchange of photons between the negatively charged electrons and the positively charged protons in the atomic nucleus. Photons are quantum excitations of the electromagnetic field: a ray of light or a radio wave is a beam of photons. The exchange of photons creates an attractive force between particles of opposite electric charge. This is the electromagnetic force.

Protons and neutrons are in turn bound together within a nucleus by the exchange of particles called π-mesons, or pions. Pions are not elementary particles, but are themselves quark-antiquark bound states; that is, while the "atomic glue" (the photon) is elementary (as far as we know today), the nuclear glue is not. Pion exchange is one manifestation of the strong nuclear force.

In a similar way, quarks are bound together in nucleons by the emission and absorption of elementary quanta called gluons, believed to be the fundamental mediators of the strong force. Gluons differ from the photon in that they are themselves carriers of the strong "color charge" to which they couple; the photon, which couples to electromagnetic charge, is itself electrically neutral. A consequence of this gluon self-coupling is that the color force between two colored particles increases in strength with increasing distance between the particles. As a result, quarks and gluons do not appear as free particles in nature. They exist only inside composite particles like nucleons and pions, generically known as "hadrons".

When one tries to use a very high energy probe to split a hadron into its constituents, one finds instead that quark-antiquark pairs (as well as gluons) are created in the strong color field and rearrange themselves together with the original constituents to form more hadrons. Nevertheless, elementary interactions among quarks and gluons can be studied in high energy laboratory experiments, because the hadronic debris of a hard collision involving quarks or gluons forms into collimated jets of particles that leave visible tracks or electronic signals in detectors. The energy and direction of a high energy jet reflects that of the elementary quark or gluon from which it emanated.

The third elementary force of the standard model is the weak force, responsible for the radioactive β-decay of unstable nuclei. This decay occurs when, for example, one of the "down" quarks in a nucleus converts into an "up" quark ("up" and "down" are the names for the two quark flavors found in ordinary matter; up and down quarks differ in their electric charge by one unit of electron charge) emitting an electrically charged quantum known as a W-particle. The W rapidly converts into an electron and a neutrino, which is an electrically neutral, apparently massless particle. Together with the electrically neutral Z-particles, the W's are the mediators of the weak force. Like gluons, they couple to one another – that is, they are carriers of the "weak charge", but unlike either the gluons or the photon, they are massive: the W and Z weigh, respectively, about 80 and 95 times the proton mass. They were discovered in 1983 in experiments using proton-antiproton ($p\bar{p}$) colliding beams at the European Center for Particle Physics, CERN, in Geneva, Switzerland. Their properties will be studied further at the higher energy $p\bar{p}$ collider at Fermilab, near Chicago, and the properties of the Z will be studied in great detail at facilities where electrons collide with their antiparticles, positrons: a linear collider, SLC, now coming into operation at Stanford University, and a higher energy circular collider, LEP, under construction at CERN.

All of ordinary matter is composed of electrons (e) and of up and down quarks (u and d). Quarks of each flavor carry one of three possible color charges. Together with the electron-neutrino (ν_e), the neutral massless particle emitted in radioactive β-decay, these particles are the members of what is referred to as the first family of matter particles. Two other families of matter particles are known to exist. Their members have properties identical to those of the first family, except that they are more massive (aside, possibly, from neutrinos, which have all been found to be massless within the experimental errors). The quark flavors analogous to (u, d) for the second and third families, respectively, are called "charm" and "strangeness" (c, s) and "top" and "bottom" (t, b). (The top quark is in fact so heavy that it has not yet been established experimentally, but few particle physicists doubt its existence.) These heavy quarks live only briefly, decaying rapidly to lighter quarks by a mechanism similar to the $d \rightarrow u$ transition that induces β-decay. Each family also includes two types of leptons, that is, particles that carry no color charge and thus do not interact with gluons, like (e, ν_e) of the first family. The electrically charged counterparts of the electron for the second and third families are called the muon (μ) and the τ-lepton, respectively. Like the heavy quarks, they are short-lived and decay to lighter leptons. Their companion neutrinos (ν_μ and ν_τ) may be stable.

All of the above matter particles are "fermions", which means that they are tiny spinning tops, carrying a half a unit (in units of Planck's constant $h/2\pi$) of "spin" or intrinsic angular momentum. The elementary glue, that is, the quanta of the electromagnetic, color and weak fields (generically called gauge fields) carry one unit of spin. These particles, called "vector bosons", are, respectively, the photon (γ), eight colored gluons (g), and the weak bosons W and Z.

The strong color interactions are characterized by a high degree of symmetry. Particles with the same spin and flavor, but different color charges, have identical masses; in fact there is no way to distinguish experimentally among particles that differ only in their color charge. The weak and electromagnetic interactions are understood in the context of an "electroweak" theory according to which the laws of nature are such that members of a fermion family with the same color charge, but different electric charge (e.g., a red up quark and a red down quark, or the electron and its neutrino) should be similarly indistinguishable. Clearly this is not what we observe: the symmetry of the elementary laws of nature is not reflected in the world around us.

SYMMETRY BREAKING

To understand symmetry and symmetry breaking, imagine that the earth is a perfect sphere with no magnetic field. An ant crawling over the earth's surface would be completely lost; it could not distinguish one place from another. Now turn on the earth's magnetic field and give the ant a compass. The ant now can distinguish the north pole from the south pole, but it doesn't know its position along the equator: the presence of the magnetic field reduces the original spherical symmetry of the earth to a cylindrical symmetry.

Next consider a sphere in an abstract space, such that the north pole represents green color charge and the south pole red; the symmetry of the strong color interactions means that no position on this sphere is distinguishable from any other.

Finally, consider a sphere in another abstract space where the north and south poles correspond to electric charges differing by one unit. The observed spectrum of particles and their interactions can be understood if we assume the existence of a field – known as the Higgs field – which distinguishes the north and south poles of this sphere, leaving a residual "cylindrical" symmetry.

Just as a photon passing through matter moves at a velocity less than the speed of light due to its interactions with atomic electrons, the W and Z interact with the Higgs field that permeates all space, and they cannot propagate with the speed of light; they acquire an "index of refraction", or equivalently, a rest mass. The photon does not interact with the Higgs field (corresponding to the residual cylindrical symmetry of the imagined sphere), and hence remain massless.

The mass m_W acquired by the heavy gauge bosons is proportional to the strength g_W of their coupling to the Higgs field and to the strength v of that field. The field strength $v = m_W/g_W$ is known from the measurement of the free neutron lifetime. (The probability amplitude for neutron β-decay is proportional to the coupling strength g_W, and suppressed by a factor proportional to the range of the weak interaction divided by the size of the nucleon. The interaction range is determined by the Heisenberg uncertainty principal as $r_{int} = h/2\pi m_W c$, where c is the velocity of light and $m_W c$ is the minimum momentum uncertainty required for the emission of a particle of mass m_W from a much lighter particle.) The coupling g_W has been independently determined by a series of measurements of weak transitions, including neutrino-induced interactions, and it was thus possible to predict accurately the masses of the W and Z particles before they were discovered.

Electrically charged quarks and leptons also couple to the Higgs field, and acquire masses in a similar way. However their coupling strengths cannot be independently determined (this is one of the weaknesses of the standard model) and therefore the mass of the top quark, for example, cannot be predicted.

While the standard model successfully accounts for a very large body of experimental data, the origin of electroweak symmetry breaking and the nature of the Higgs field are not understood. Another puzzle is the replication of fermion families. Why are there three families? Are there more? There is no understanding of the pattern of fermion masses, nor of flavor mixing parameters that determine how fast heavy quarks and leptons decay to lighter ones. All of these parameters are determined by the couplings of fermions to the Higgs field: put another way, we do not understand why these couplings take the values that are observed. In particular, these seem to be the only couplings in nature that are not invariant under the CP (charge conjugation times parity) operation which turns a fermion spinning parallel to its direction of motion into an antifermion spinning antiparallel. If CP were an exact symmetry of nature we would have no way of understanding the predominance of matter over antimatter in our universe, which made possible the formation of galaxies, planets, DNA, ... and life.

It was with such questions in mind that the construction of the superconducting supercollider was proposed.

THE SUPERCONDUCTING SUPERCOLLIDER

The proposed supercollider, the SSC, would have a circumference of 52 miles; to visualize its size, it could fit roughly around the periphery of Washington D.C. or straddle the Hudson River over an area encompassing Manhattan and large chunks of the Greater New York City and New Jersey. A tunnel ten feet in diameter would contain counter-rotating proton beams guided by two rings of superconducting magnets. The beams would be injected after being accelerated to an energy of a trillion electron volts (1 *TeV*) in a circular "booster" accelerator similar to the physics facility now operating at Fermilab near Chicago. The proton beams would then be accelerated in the main ring to an energy of 20 *TeV*, and made to collide at points around the ring where detectors would be placed to record the passage of particles produced by proton collisions. The size of the proposed Supercollider was determined by technological feasibility and by scientific requirements.

Quite generally, charged particles like protons and electrons can be accelerated in an electric field (or, often in practice, a radiofrequency cavity), as for example in the linear electron accelerator, SLAC, at Stanford University. However, given a fixed field strength and a finite geographical area, continued acceleration requires that the beam be bent around curves; this can be done using a magnetic field. This bending process results in a beam energy loss due to synchrotron radiation which increases with energy for a fixed radius of curvature, and is far more important for electrons than for the more massive protons.

In a conventional proton accelerator, a single rotating beam is extracted from the accelerator and guided by magnets to a "target" where the energetic protons collide with nuclei in the stationary target. As with the linear electron accelerator at Stanford, much of the initial energy of the projectile is converted into kinetic energy of the exited struck nucleon, which, by momentum conservation, must move in the direction of the incident beam. On the other hand, when two fast projectiles with equal energy collide head-on, all of their energy is available for conversion into mass, and heavier new forms of matter can be created.

With a fixed magnetic field, the radius of a proton accelerator, and therefore the cost of building the tunnel, increases in proportion to the beam energy required. Superconducting magnets provide much higher fields than conventional magnets, resulting in reduced construction cost as well as less energy consumption during operation. The magnets proposed for the SSC are similar to those already operating successfully at the Fermilab facility.

The two important SSC parameters, as set by physics goals, are the beam energy of 20 *TeV* and the "luminosity" of 10^{33} proton crossings per second per squared centimeter of area. In fact, when two protons collide, most of the time their elementary constituents do not themselves collide head-on; instead their interactions result in excited nucleon states that rapidly decay into collimated beams of hadrons emitted in the directions of the incident beams. In searches for new physical phenomena at high mass scales, the interesting events are those in which two elementary constituents undergo a hard collision resulting in the creation of a massive state that decays quasi-instantly to two jets of hadrons emitted at large angles relative to the incident beam directions. According to the Heisenberg uncertainty principle, the effective area over which such a hard collision can take place is inversely proportional to the squared mass of the state created. Thus the required luminosity increases with the mass scale one wishes to probe.

The energy requirement for the SSC takes into account the fact that a fast moving proton is an ensemble of quarks, antiquarks, and gluons. The energy of the proton is shared among its constituents, each of which carries on average a tenth of the proton momentum. Thus colliding protons, each with an energy of 20 TeV, will allow the study of new phenomena up to energy scales of about 4 TeV. This scale could also be probed by electron-positron collisions with an energy of 2 TeV per beam, but at present the technology to achieve this does not exist; an avenue being explored is to collide linearly accelerated electron and positron beams. The SLC collider at Stanford, where each beam has half the Z rest energy, is a prototype for such a possible future collider.

A signpost for the requisite hard collision energy is provided by the scale of electroweak symmetry breaking which is fixed by the value of the Higgs field strength, $v = g_W/m_W$, corresponding to an energy of a fourth of a TeV. Since, among the known particles, the massive W and Z couple most strongly to this field, their collisions are expected to provide the most efficient probe of its nature and origin. W's and Z's are present in the colliding protons because, like photons, they can be radiated from energetic quarks and leptons – but with a further loss of energy. W and Z collisions with up to one or two TeV of total energy can be probed at the SSC.

PHYSICS AT THE TEV SCALE

The simplest possibility for understanding electroweak symmetry breaking is the existence of an elementary field that has a potential energy with a local maximum for vanishing field strength, and a global minimum at constant a value v of field strength. If this field is a vector on the imaginary "electroweak sphere" described earlier and if it is nonvanishing, it must be oriented. The direction of its orientation defines the "north" and "south" poles on the sphere, that is, it distinguishes between particles of different charges and thus breaks the electroweak symmetry. If such a field exists, it has quantum excitations, that is, particles. In this case the quantum excitation is a spinless particle called the "Higgs boson". A Higgs particle with a rest energy as high as a TeV could be discovered at the SSC. If it were more massive than that, W and Z collisions would grow rapidly in rate when their total collision energy exceeds a TeV; the study of these interactions would provide an alternative probe of the physics associated with electroweak symmetry breaking. They could be observable at the SSC if it operates at its maximum design energy and luminosity.

The existence of an elementary Higgs particle is problematic because the rest energy of a spinless particle gets large contributions from quantum fluctuations. It is difficult to understand how the Higgs mass can be as small as a TeV or so, as is required by the data and by the consistency of the theory. An alternative possibility is that the Higgs field is a composite field induced by fermion-antifermion pairs. To get a field value as large as the observed one in this case requires the introduction of new fermions, called "technifermions" that interact very strongly via a new force, "technicolor", transmitted by "technigluons". These new techniparticles, like quarks and gluons, would exist in bound states that could be produced only at collision energies as high as those to be made available at the SSC.

Alternatively, the large quantum corrections to the Higgs rest energy would be damped if the theory possessed a larger symmetry, called supersymmetry, which relates fermions (particles with half integral spin) to bosons (particles with integral spin). According to this conjecture, every known particle has a "superpartner" or companion "sparticle" with identical properties (mass, electric charge,...) but differing in spin by one half unit. This symmetry is also broken in nature by particle-sparticle mass splittings, but a Higgs mass of a TeV or less could be understood if sparticles have masses of the same order of magnitude. Some of these sparticles would be abundantly produced at the SSC.

Yet another possibility is that quarks and leptons are themselves composite and that some substructure would by revealed by analysing data from SSC experiments. A more fashionable idea at present is that elementary "particles" are not particles at all, but rather the lowest vibrational modes of tiny strings with an extension of the order of the Planck length, about $10^{-33}cm$. When supersymmetry is included, this "superstring" theory provides the only known possibility for a consistent quantum theory of gravity. It suggests that space-time is actually ten dimensional, but with six dimensions curled up with a radius comparable to the Planck length. In the context of superstring theory, many new exotic particles (in addition to the superpartners of ordinary particles) are predicted. Some of these could be produced at the SSC. Others would interact with ordinary matter only with couplings of gravitational strength, that is, too weakly to be produced in laboratory experiments. They could, however, have implications for the nonluminous matter that seems to exist in galactic haloes. Other candidates for this "dark matter" include massive neutrinos, stable sparticles, black holes...

THE EARLY UNIVERSE

According to the Big Bang theory, the universe began with an explosion yielding a hot dense gas of elementary particles that subsequently expanded and cooled. It's evolution to the presently observed universe was determined by the total number of particle species and their interactions at very high energies. It might also have involved phase transitions analogous to the condensation of a gas or the freezing of a liquid. The Higgs field is similar to a ferromagnetic material, in which the lowest energy state is one with all electron spins aligned. Spin alignment implies a direction; the choice this of direction breaks the rotational symmetry of the laws of nature, just as the choice of a Higgs field orientation breaks the electroweak symmetry. Rotational symmetry can be restored by heating: the hot, energetic electrons become randomly oriented and there is no longer a special preferred direction. Similarly, the electroweak symmetry should have been restored in the hot early universe. If the universe supercooled in the false, symmetric vacuum, this would have created a constant energy density that would have caused the universe to expand exponentially until the transition to the lower energy, asymmetric phase occurred. Such a period of exponential expansion could explain cosmological puzzles like the homogeneity, isotropy and flatness of the present universe. In fact, it is known that the specific phase transition associated with electroweak symmetry breaking cannot solve these problems. However if the underlying theory possesses a higher degree of symmetry, there could have been many other, earlier phase transitions. Understanding the origin of one such transition, with an energy scale that is accessible for study at the SSC, would have profound implications for cosmology as well as for particle physics.

It is conjectured that higher symmetries entail couplings among quarks and leptons that can induce the proton to decay into leptons and pions or other mesons. Together with CP violation, proton instability could account for the existence of matter in today's universe. Evidence for proton decay has been sought unsuccessfully in deep mine experiments. If they exist, the interactions responsible for proton decay are probably far too weak to be detected in accelerator experiments. However new particles discovered at the SSC could give clues to the underlying theory, which in turn could shed light on questions such as proton instability, the density of matter in the universe and the origin of galaxy formation, among many others.