GRESHAM COLLEGE

28 February 2018

Elementary Particles and Their Interactions

Professor Joseph Silk

Matter consists of a mêlée of elementary particles. There are protons and neutrons, made up of quarks, and many other short-lived massive particles. All atoms consist of protons, neutrons and an accompanying cloud of electrons - then there are electrons, muons and neutrinos - the lightest particles of all. And there are mass-less particles, the photons. The very early universe is a unique laboratory for studying the rarest of particles when the 'particle zoo' was once in equilibrium. We see the faded brilliance of the fiery past, and can assemble clues that enable us to trace out the particle content of the beginning of the universe. One of the greatest hopes is that we may discover particles of dark matter, but so far this has eluded our best efforts.

Protons

All atoms contain a nucleus of protons, along with occasional neutrons, surrounded by a neutralizing cloud of electrons. Let us begin with the protons. Hydrogen is the dominant element in the universe, its nucleus is the proton.

Physicists study the nature of the proton by colliding them at high energy. This is a brute force approach but it works because the debris seems to be fundamental particles, the three types of quarks, and the gluons that hold the quarks together. The upper limit on the size of a quark is 1/2000 of the proton radius. This is about 10^{-13} cm, whereas the atom has size of about 10^{-8} cm.

Protons cannot be stable. This is what unification of the fundamental forces implies. Particle physics tells us that at sufficiently high energy, the electromagnetic and the strong and weak nuclear forces are unified. Chemistry is controlled by electrons whose properties are determined by electromagnetism, with photons controlling electron and proton interactions. Neutrons and unstable isotopes radioactively decay via emission of electrons, positrons and neutrinos by the weak nuclear force, and the nuclei of atoms, combining protons and neutrons, are held together by the strong force, in which gluons play the binding role. Of these forces, the electromagnetic force is the weakest, but increases towards very high energies. Early enough in the universe, all three forces are united. This happens at an energy of about 10^{16} GeV. We call this the epoch of Grand Unification, some 10^{-36} second after the Big Bang. Unification means that the constituents of protons, the quarks, convert into electrons and positrons, and vice versa. At very low energies there must be an infinitesimal probability that protons decay. Measurement of proton decay is a fundamental prediction of unification.

The predicted lifetime of a proton is very long. The way to test this is to monitor a huge number of protons. Every now and then one must decay into gamma rays and muons. Decay of even a few hundred protons per year in the human body would trigger cancer. Hence the fact that we are not all dropping dead of cancer sets a lower bound on the proton lifetime of about 10^{14} years. The SuperKamiokande experiment in a disused Japanese zinc mine, monitors 50000 tons of ultra-purified water to look for proton decay and currently sets a lower bound on the proton decay lifetime that is longer, by some 10 billion times, than the human cancer limit. This is still within the range predicted by the theory.

Baryogenesis

Why is the universe almost entirely made of matter and not antimatter? We can be quite sure of this otherwise the universe would be glowing in gamma rays. Andrei Sakharov, who among other accomplishments was father of the Soviet H-bomb and later received the Nobel peace prize for his work on nuclear disarmament, made a fundamental contribution to cosmology in 1976. The context was that in the development of the modern quantum theory laid out by Paul Dirac in 1928, it was asserted that every known particle has an antiparticle of opposite charge of the same mass, with particles spinning to the left and their antiparticles spinning to the right. Sakharov showed that three conditions are necessary for creating a baryon excess. One is that there must be processes in which the net difference between the number of matter and antimatter particles is changed. We call this a violation of the net number of baryons Secondly, the charge (really the net number of positive minus negative charges) symmetry and the mirror (differentiating left-handed from right-handed) symmetry of these processes must be violated, otherwise the reverse processes, in which every particle is replaced by an antiparticle, would re-establish the balance between matter and antimatter. Finally the universe must be out of thermal equilibrium, namely in our case expanding, so that there could not be compensation between processes changing the number of baryons. These three conditions are present in all modern explanations of why there is so little antimatter in the universe.

Electrons

Atoms consist of a central positively charged nucleus of protons and neutrons surrounded by a cloud of electrons. It is the electromagnetic forces that control the energies and movements of the electrons which are responsible for all of chemistry. The periodic table of the elements is determined by nuclear charge and mass. When chemical compounds form, the atoms and molecules join together via exchanging electrons.

Electrons are particles but also waves, albeit of very small wavelength. However focusing of electron beams has enabled the electron microscope. Electron oscillations produce electromagnetic waves. The theory of propagation of electromagnetic waves at the speed of light was worked out by a Scot, James Clerk Maxwell, in 1865, and radio waves were first transmitted and received in 1888 by German physicist Heinrich Hertz. Applications soon followed, first by transmission of electromagnetic waves in wires, when Alexander Graham Bell patented the first telephone in 1876. Then, wireless techniques were developed, with the first transatlantic radio transmission by Guglielmo Marconi in 1902. Modern society flourishes thanks to electrons.

Neutrons

Beta decays are a manifestation of the weak nuclear force. They describe radioactivity when isotopes are created with an excess or a deficit of neutrons. Such deviations introduce nuclear instability. In the case of an excess of neutrons, an electron and an antineutrino are ejected: this is negative beta decay. There are also positive beta decays, when a positron and a neutrino are ejected in the case of a deficit of neutrons. In this way isotopes return to the 'valley of stability' where they are no longer radioactive.

Nuclear fusion is the process by which neutrons, slightly heavier than protons, release the excess mass as energy as protons fuse together to make heavier elements. When helium is formed out of hydrogen, about 0.7 percent of the rest mass of hydrogen is released as energy, in the form of positrons, photons and neutrinos. The neutrinos escape, but the energy from the other debris is retained in the centre of the star.

Neutrinos

The standard solar model predicts a flux at the earth of 100 billion neutrinos per square centimetre per second from the centre of the sun. When a neutrino of just the right energy (about 0.8 MeV), albeit very rarely, reacts with an atom of chlorine, it produces an atom of radioactive argon and an electron. This should happen about once per week in a tank containing countless atoms, more precisely 100000 gallons, of inexpensive chlorine-containing cleaning fluid. The argon is allowed to accumulate for a few months, then helium gas is bubbled through the tank and the radioactive argon atoms are counted. The experiment ran from 1968 to 1972, in a tank constructed one mile underground at the Homestake Mine in Lead, South Dakota. Neutrinos were detected from the boron-8 channel, an unstable isotope that is produced and immediately decays to give a neutrino during the reactions that convert hydrogen into helium in the centre of the sun. But at only 1/3 of the predicted rate. This result was confirmed by the Kamiokande experiment in Japan sensitive to the high energy boron-8 neutrinos (above 7 MeV) and using highly purified water, in 1994. Then in 1997, two new and higher precision solar neutrino experiments were completed. Both used some 30 tons of liquid gallium. One was SAGE in the Baksan Neutrino Observatory in the Caucasus, the other was and GALLEX in the Gran Sasso Laboratory near L'Aquila in Italy. Solar neutrino detection was confirmed down to 0.2 MeV from proton fusion interactions.

However the measured flux was a third of the predicted flux. What happened to the neutrinos en route to the earth?

Theory predicted that neutrinos could change their flavour. There are three types of neutrino: those associated with electrons, those with mu mesons (or muons), and those with tau mesons. The early experiments measured only electron neutrinos. If the electron neutrinos emitted by their un oscillated into equal amounts of mu and tau neutrinos over the 96 million mile trajectory from the sun, this could explain the shortfall. A new experiment was developed in a deep, 2 km underground, nickel mine in Sudbury, Canada, using heavy water, to add the capability to trace mu neutrinos. The experiment succeeded in 2001, and demonstrated that once neutrino oscillations were accounted for, that solar neutrinos indeed confirmed the thermonuclear origin of solar energy

Natural reactors

The Oklo uranium mine in Gabon contains a natural nuclear reactor. In several uranium deposits, isotope ratios reveal that nuclear fission reactions naturally went critical about 1.7 billion years ago and continued self-sustaining nuclear chain reactions for several hundred thousand years. This mine is a unique environment on the earth for such an event. It is thought that a sudden release of ground water inundated the uranium–rich rock deposits and acted as a neutron enhancer. This led to chain reactions, with the radioactive uranium isotopes undergoing fission. We know this occurred because the isotope uranium-235 is anomalously low in abundance relative to uranium-238. The only explanation is that it underwent fission long ago. Its half-life is 0.7 billion years, much shorter than that of uranium-238, which undergoes very slow fission. Indeed, the half-life of U-238 4.5 billion years is about as old as the earth, and indeed is one of the most important probes of the age of the universe.

The Standard Model of Elementary Particles

Protons and neutrons are not elementary particles, they are made of 3 quarks and their antiquarks. Quarks and gluons have never been directly detected. The theory of quantum electrodynamics describes the electromagnetic force, and all interactions involving matter and light. It was generalized to the electroweak theory, combining electromagnetic and weak nuclear forces, leading to an understanding of the properties of neutrons and neutrinos. It remained to bring in the strong nuclear forces, with the theory of quantum chromodynamics. Here, a quantity called colour replaces charge in quantum electrodynamics, and accounts for the strong interactions that hold nuclei together. The interactions are assumed to be weak on small scales, so nuclei are held together, but to become progressively stronger on larger scales. This meant one could never pull gluons or quarks out of nuclei to observe them. The great triumph of the standard model of elementary particles is that it unifies three of the major interactions between particles, the electromagnetic interaction with the weak and strong nuclear forces. This led to the notion of grand unification, that only at sufficiently high energies would the three forces be unified. The hope was that all three forces might unify at a unique energy, but the standard model made no such prediction.

Enter SUSY

Our standard model of elementary particles is not the last word. It fails to predict the fact that positive and negative charges of particles in the universe cancel to high precision. It fails to predict that neutrinos have mass. It does not predict dark matter particles. And it does not include gravity. Physicists are still searching for the ultimate theory.

Gravity is essential for understanding the beginning of the universe. One can take Einstein's theory of gravity back in time just so far, until the size of the observable universe, if its horizon as determined by the distance light has travelled since the beginning, is comparable to the size of a black hole. Although this gets us to within 10^{-37} second of the beginning, to go back further requires a new theory that is an amalgam of Einstein's gravity with quantum theory. Such a theory is called quantum gravity. Failures of earlier theories led to the search for models that could unify electromagnetic forces with the weak and strong nuclear forces, and even the gravitational force.

Let us first put gravity aside. The first major step towards unification arose with the theory of supersymmetry (or SUSY). This was designed to help understand the enormous difference between the electromagnetic force, the nuclear forces and even the gravitational force. The first two aspects come within highly constraining experimental probes. Supersymmetry postulates the existence of vast numbers of new particles, indeed it doubles the number of particles. Light particles, or leptons, and heavy particles, or hadrons, are intimately connected at the high energies where supersymmetry prevails. For every boson (a particle of integer spin, such as a photon), e.g. a photon, there is a partner fermion (a particle of fractional spin, such as an electron), and vice versa. The new supersymmetric partners are abundant at high energy but very short-lived, and hence essentially unobservable in the low energy universe. Below some energy scale, supersymmetry is broken, but its legacy is that we now have a simple understanding of why some particles are light and others are heavy. This theory led to an attractive hypothesis for dark matter.

The lightest supersymmetric particle is stable, and it is an ideal candidate for dark matter, being very weakly interacting, like neutrinos in fact. Indeed the hypothesised partner of the photon has a name, the photino, and is a massive, neutral fermion that could be the source of dark matter. Remarkably, it is predicted to have about the observed abundance of dark matter if supersymmetry existed in the first microseconds of the Big Bang. Another elegant prediction is that the electromagnetic, the weak and strong nuclear forces become unified together at a single energy, of about 10^{16} GeV. We call this the epoch of grand unification, and it occurred about 10^{-36} second after the Big Bang.

The breaking of grand unification as the universe cooled led to a sudden injection of energy. This in turn generated a brief period of inflation. Much evidence that inflation occurred has come from the distribution on the sky of temperature fluctuations in the cosmic microwave background. These are distributed across such large regions of the sky that only a theory like inflation, in which the cosmic horizon grew exponentially for a brief period, can be responsible for the size and near homogeneity of the universe.

But the theory of supersymmetry had to be experimentally tested. This attractive scenario came to a harsh confrontation with reality when the Large Hadron Collider at CERN in Geneva failed to detect evidence for SUSY. Particle theorists insisted that the natural scale for SUSY had to be close to that of the most massive particle of the standard model, the recently discovered Higgs boson (in 2012) at 125 GeV. The latest LHC searches find no evidence for SUSY particles up to a TeV.

Particle physicists continue to search. One option is to build a larger particle collider. This would require an unprecedented budget and might take up to half a century. Then one could search for SUSY up to 10 TeV. Theoreticians, ever adaptive, believe that this scale could the final frontier for SUSY, if only because one could never conceive of building a much more costly pure science machine. Another argument is that the higher the scale one has to probe for SUSY, the less likely is the prospect of finding it, because of the fine tuning of special parameters that result in the cancelations needed to guarantee the lightness of particles such as the proton.

Meanwhile cosmologists persevere with inflation, since there is no compelling alternative. Meanwhile the flood gates have opened for dark matter particle candidates, if SUSY has to be abandoned. The possibilities for dark matter are only limited by theorists' imagination.

Enter String Theory

Given the lack of success in finding any evidence for SUSY, the fall back is to a theory at such high energies that it is beyond the reach of any feasible accelerator, apart possibly from that provided by Nature at the very beginning of the Big Bang. But the beauty of string theory is that it offers the prospect of unifying gravity to the other fundamental forces of nature.

String theory is the closest we have come to a theory of quantum gravity. The father of string theory is physicist Ed Witten. It is the only viable attempt to go beyond the standard model and explain the masses of all of the elementary particles, their interactions and gravity. It is best described in Witten's own words:

> *String theory is an attempt at a deeper description of nature by thinking of an elementary particle not as a little point but as a little loop of vibrating string. Strings can oscillate in many different forms—analogously to the overtones of a piano string…. And those different forms of vibration are interpreted as different elementary particles: quarks, electrons, photons.. Unity of the different forces and particles is achieved... Spreading out the particle into a string is a step in the direction of making everything we're familiar with fuzzy… It's as surprising in its own way as the fuzziness that much of physics acquired in light of quantum mechanics and the Heisenberg uncertainty principle…the equations that really work in describing nature with the most generality and the greatest simplicity are very elegant and subtle… Quantum mechanics brought an unexpected fuzziness into physics because of quantum uncertainty, the Heisenberg uncertainty principle…in string theory, space-time becomes fuzzy.*

Edward Witten, NOVA interview 2003:
http://www.pbs.org/wgbh/nova/elegant/view-witten.html

String theory attracts many theoretical physicists because of its beauty, a recurring theme in our search for a deeper understanding of nature. Here is Witten again: *the beauty of Einstein's equations, for example, is just as real to anyone who's experienced it as the beauty of music… the equations that work have inner harmony.*

Interestingly the physicists' notion of beauty is an inner form of beauty. Ancient philosophers, notably Aristotle and Plato, preferred the symmetry of circles. Ptolemy tried to explain planetary orbits with circular epicycles, and even Copernicus and Tycho Brahe could not shake off circles. But Kepler empirically and Newton theoretically showed us that planetary orbits were ellipses. The symmetry now was hidden:

> *Dynamical beauty transcends specific objects and phenomena, and invites us to imagine the expanse of possibilities. For example, the sizes and shapes of actual planetary orbits are not simple. They are neither the (compounded) circles of Aristotle, Ptolemy, and Nicolaus Copernicus, nor even the more nearly accurate ellipses of Kepler, but rather curves that must be calculated numerically, as functions of time, evolving in complicated ways that depend on the positions and masses of the Sun and the other planets. There is great beauty and simplicity here, but it is only fully evident when we understand the deep design. The appearance of particular objects does not exhaust the beauty of the laws.*

Frank Wilczek: A Beautiful Question: Finding Nature's Deep Design

String theory has inner beauty in spades. It has not yet succeeded in living up to its promise, but it has many advocates. The real problem is that no-one has yet thought of a way to test string theory. Strings are folded up in extra dimensions on inconceivably small scales. The one prediction, unification of the fundamental forces by the theory of supersymmetry, can be tested at the Large Hadron Collider. It would be a wonderful discovery, not only boosting our confidence in string theory, but also providing a likely candidate for dark matter. So far, no evidence has been found. Witten seems desperate, he goes on to speculate that: *it's conceivable that the big bang could have produced a string so large that it would be present in today's universe and visible in telescopes, perhaps discoverable by the satellites that are now mapping out the microwave sky.* To give string theory its due, its explicatory power is remarkable. It is only lacking in predictive power that could result in experimental confirmation. A vigorous debate rages in the inner circles of particle physics as to whether a combination of beauty and successful retrodiction suffices as proof of the relevance of string theory to physics.

And Dark Matter?

String theory's main candidate for dark matter consists of relic loops of cosmic string. These are left behind from the multidimensional Planck epoch when strings prevailed. Extra dimensions, required in string theory, collapsed as the universe cooled, but relic strings and loops of ultrahigh density matter survived. They stretch out as the universe expands, occasionally intersecting and producing wiggling, short-lived loops of string. One signature of a cosmic string is image splitting of distant stars or galaxies. This has not been seen. Another is a background of gravity waves as string loops wiggle and dissipate. This has not been seen, and there are strong limits from the absence of such a background on the possible properties of strings.

The best candidate for a dark matter particle remains the lightest stable particle predicted by supersymmetry, despite the lack of evidence to date for this theory. Advocates argue that the theory is so compelling that future, more ambitious, experiments may provide the missing evidence. But there are many other possibilities for the elusive dark matter particles. These include particles so light that they are virtually undetectable.

What is certain is that the matter of the universe is predominantly dark. Since most dark matter avoids the denser parts of galaxies and stars, we infer that is very weakly interacting compared to ordinary matter. The most logical explication is that of a novel particle, perhaps created in the very early universe when a host of new particles abounded. Most self-annihilated as the particle energies decreased with the expansion of the universe. But the dark matter particle remained, at first a tiny and inconspicuous constituent of matter since the universe was full of radiation. As the radiation cooled, dark matter emerged as the dominant constituent of matter. One of our greatest challenges in cosmology is to identify this elusive particle.
