G R E S H A M

C O L L E G E

LUCIFER'S LEGACY – THE MEANING OF ASYMMETRY

Lecture 6

THE HEART OF THE MATTER

by

PROFESSOR FRANK CLOSE OBE
Gresham Professor of Astronomy

3 April 2001

THE HEART OF THE MATTER

Professor Frank Close OBE

We and everything are made from atoms. Atoms are small but not so small that you cannot imagine them. In the width of a human hair up to a million atoms could sit side by side: an individual atom of hydrogen has a radius of about 10^{-10}m.

But atoms are not the most basic pieces of matter. For nearly a century we have know that they have an internal structure, consisting of electrons encircling a compact heavy nucleus. The nucleus of a hydrogen atom, for example, consists of a single positively charged particle - the proton. The size of a proton is about 10^{-15}m. which is too small to imagine. To give you an idea: think of an atom scaled up to the dimensions of a hole on a golf course. The length of the fairway could be 500m and the size of the hole into which you are trying to put the ball is about 5 cm. So the size of this little hole relative to the length of the fairway is analogous to the size of an atomic nucleus to the size of the atom. Atoms are indeed very empty!

To give you an idea of how empty, let's use another example. It is often the case that one hears analogy between atoms and the solar system: the "planetary electrons whirling around the nuclear sun". There are many problems with this analogy and I shall not dwell on them here except to note that the relative scales are utterly wrong. The relative sizes of Earth, Sun and our orbit around the Sun are roughly in ratios of 100. Contrast this with the atom: the proton relative to the atom is a factor of 10,000. So atoms are a hundred times more structured than the solar system (in each of 3 dimensions!). As we shall see, even the proton is not the end of the story. It is in turn made of quarks. And the ratio of the size of a quark to that of a proton is also about 1:10,000. At the subatomic scale, matter is remarkably structured.

In search of atoms we are entering realms beyond normal vision. Our eyes can resolve things so long as they are no smaller than $10^{-4 \text{ to } 5}$m - 1/10 to 1/100 of a mm. Bacteria are about 10^{-5}m; the wavelength of light ranges across $10^{-6 \text{ to } -7}$m. Atoms are about 10^{-10}m, a thousand times smaller than the wavelength of light. It is for this reason that atoms cannot be resolved by the rainbow of visible light: to "see" things requires the use of waves whose wavelengths are similar or smaller than the object being studied. X-rays and gamma rays are like light but with much smaller wavelengths and these can resolve atoms.

Also we can use particles like electrons thanks to a gift of quantum theory. It turns out that electrons themselves move through space like waves. The wavelength of the electron beam depends on the energy of the electrons. The larger is their energy, so the shorter is their wavelength. High energy electron beams can resolve very small length scales. It is for this reason that electrons are often used in high energy particle accelerators as means of probing distances smaller even than atoms.

The revelation that atoms, atomic nuclei and even the constituent protons and neutrons have a substructure has come from two complementary routes: spectroscopy and scattering experiments. There have been strong parallels, but also important differences, as one proceeds from atoms to the nucleus and ultimately the quark layers of matter.

In the case of atoms, the first clue to the electronic sub-structure was the observation of distinct spectral lines. Subsequently the electron was isolated and identified by J J Thomson. The existence of the central atomic nucleus was inferred by Rutherford in association with the experiments by Geiger and Marsden, which involved the scattering of naturally produced alpha particles by various atomic elements. As is well known, it was the unexpected observation that the alpha particles were, occasionally, scattered through large angles that led Rutherford to his great insight.

The alpha particles produced by natural radioactivity had enough momentum to expose the nucleus but were unable to resolve its structure. In the latter half of the 20th century a range of experiments began in which beams of electrons, of ever increasing energies, were scattered from atoms. If the electrons had energies of the order of hundreds of MeV (millions of electron volts), their wavelengths were small enough to enable nuclear structure to be resolved. By 1960, electron scattering from hydrogen, or in effect from the proton that is its nucleus, had revealed that the proton has a finite extent in space.

It is ironic that it was in that period that the explosion of particles was being discovered in cosmic rays and, latterly, in customised experiments at high energy particle accelerator laboratories. Some of these turned out to be short lived "resonance" excitations of the proton and neutron. A spectroscopy of states emerged and with hindsight it is obvious, (though it was not so at the time!), that here was evidence that the proton and neutron are composite systems made (as we now know) from ``quarks". It is these quarks that provide the electric charge and magnetic moment of a proton or neutron; it is the spread of their wave-functions that give the proton and neutron their finite sizes; and although the electric charges of the quarks that form a neutron add up to zero, their individual magnetism does not cancel out, which leads to the magnetic moment of the neutron. It is when the quarks are in the state of lowest energy that the configurations that we call proton and neutron arise; excite one or more quarks to a higher energy level in the potential that binds them and one forms a "particle" with a correspondingly larger rest-energy, or mass. Thus the spectroscopy of short lived resonance states is due to the excitation of the constituent quarks.

This far is akin to the case of atoms. However, no-one has ever ionised a proton: the quarks appear to be permanently confined within a region of about $10^{-15}m$ - the "size" of the proton. Apart from this, which is a consequence of the nature of the forces between the quarks, the story is qualitatively similar to that of electrons within atoms. The excited levels are short lived, and release excess energy, falling back to the ground state (proton or neutron) by radiating energy, typically in the form of gamma ray photons. Conversely one can excite these resonance states by scattering electrons from protons and neutrons.

The final piece on the analogy came around 1970. Beams of electrons, which had been accelerated to energies of over 20GeV (billions of electron volts), were scattered from protons at Stanford in California. Similar to what had occurred for Rutherford half a century earlier, the electrons were observed to scatter through large angles. The source of this large angle scattering was the quarks, the point-like fundamental particles that comprise the proton.

If quarks have a size, it is smaller than we can yet resolve. They are smaller than 10^{-18}m, the limit of resolution available currently.

There are two varieties of quark needed to make the proton and neutron. They are known as "up" (u) and "down" (d), with electric charges +2/3 and -1/3 in units where the proton has +1 and the neutron zero electric charge. The proton is then uud while the neutron is ddu. You can learn the full story of how quarks behave in my book *The Cosmic Onion*, published by Heinemann (if you have difficulty getting a copy I still have some paperbacks available at £13 - contact me at f.e.close@rl.ac.uk and I can bring some at a future lecture).

There are two great mysteries that I would like to end with today. First, the fact that (unionized) atoms are electrically neutral. This is because the amount of negative negative electric charge on the electrons exactly balances the positive on the central protons. But the latter comes about because the proton is made of quarks, which group in threes, and each carries +2/3 or -1/3 such that the sums miraculously balance. Electrons are not made of quarks - they appear to be fundamental particles like quarks are. So how is it that the electron and quarks "know" about each other such that these remarkable conspiracies happen? If it was not like this, matter as we know it would not exist. Somehow the electron and quarks must be related, but exactly how, we do not yet know.

There is another bizarre conspiracy. There are six varieties of quark overall. The u and d have two heavier version each. The heavier versions of the u are the charmed and top quarks, each with the same +2/3 charge, differing only in their masses (a top quark has as much mass as an atom of gold!). The heavier versions of the d quarks are strange and bottom, each with -1/3 charge, and again differing only by their masses.

This triplication also occurs for the electron. There are two heavier versions of the electron, known as muon and tau. In the previous talk we met the neutrino - an electrically neutral sibling of the electron. There are three versions of neutrino too. So in all, there are six members of the electron family: namely, electron, muon, tau and three neutrinos. And there are six varieties of quark: up charm top; down, strange and bottom.

Six of one and half a dozen of the other. Why? We don't know but suspect that the answer to this puzzle may also reveal the answer to the puzzle of why is there no antimatter in the universe. But that is for another time.

GRESHAM COLLEGE

Policy & Objectives

An independently funded educational institution, Gresham College exists

- to continue the free public lectures which have been given for 400 years, and to reinterpret the 'new learning' of Sir Thomas Gresham's day in contemporary terms;
- to engage in study, teaching and research, particularly in those disciplines represented by the Gresham Professors;
- to foster academic consideration of contemporary problems;
- to challenge those who live or work in the City of London to engage in intellectual debate on those subjects in which the City has a proper concern; and to provide a window on the City for learned societies, both national and international.

Gresham College, Barnard's Inn Hall, Holborn, London EC1N 2HH
Tel: 020 7831 0575 Fax: 020 7831 5208
e-mail: enquiries@gresham.ac.uk