Empty matter and the full physical vacuum

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Experiments with elementary particles have shown that much of matter is made up of empty space, but this vacuum is not really empty. The uncertainty principle allows the temporary existence of virtual particles, and these have been shown experimentally to have measurable effects.

Particle accelerators make use of high vacuum to prevent destruction of the beam by residual gas. The vacuum in the CERN accelerators is the highest between these machines and the Moon. The former Intersecting Storage Ring machine, the world's first proton–proton collider, could keep its beams coasting for over a month, during which time the protons travelled more than 50 times the diameter of the Solar System. However, this article is not about the technological wonders of vacuum systems, but about fundamental physics.

Firstly let us consider upper limits to the size of elementary particles. The nucleus was discovered by Ernest Rutherford, who noted that alpha particles, the high energy particles of that era, were occasionally scattered at large angles, even backwards, when fired at thin foils. This could be explained if the positive charge was concentrated in a very small volume rather than being spread all over the atom. He showed that, whereas atoms were around 10^{-10} m in radius, nuclei were smaller than 10^{-14} m. To investigate the size of nuclei, higher energy probes were required. These would have high momentum p and hence smaller quantum-mechanical wavelengths $\lambda = h/p$ where h is the Planck constant.

In the mid-1950s, when I was a postgraduate student, I hoped to measure nuclear radii, which were not well known at that time, by scattering electrons from nuclei and observing the angular distribution. We had to build our own accelerator—a 29 MeV microtron. It worked, but the energy, and hence wavelength, was too marginal, $\lambda \sim 4 \times 10^{-14}$ m. Robert Hofstadter and his colleagues at Stanford had the use of a linear accelerator with much higher energies, up to around 1 GeV, and their experiments were better too, so they measured not only nuclear sizes, but also their shapes—the distribution of electric charge. Hofstadter received the Nobel Prize and I received a PhD, which was, I suppose, a measure of our relative contributions to physics. As an amusing aside: one of my earliest publications described a simple flexible vacuum joint which connected a scattering chamber to a microtron.

Electron scattering from hydrogen and deuterium showed that protons and neutrons have radii of 10^{-15} m. When even higher energies became available in the late 1960s, so-called 'deep' inelastic scattering of electrons showed that the proton itself had constituents—the quarks, which had been suggested earlier to explain various regularities in the properties of elementary particles. Deep inelastic scattering from a proton is equivalent to elastic scattering from just one of its constituents. So far experiments are consistent with electrons and quarks being pointlike. Electron–proton scattering (and proton–antiproton scattering) at much higher energies have shown that quarks cannot have radii greater than about 10^{-18} m. Similar experimental limits can be placed on the size of the electron. Hence an atom has a radius at least 10^8 times greater than its constituents, and thus less than 1 part in 10^{24} of a solid is occupied by its elementary constituents: in this sense normal matter is extremely empty!

However, the influence of these elementary objects is felt more widely. The concept of a field is well established. The electromagnetic field, which together with the laws of quantum physics binds electrons within atoms, is present everywhere. In quantum theory it is transmitted or mediated by the exchange of virtual photons. Hence these virtual particles are present in the vacuum. The strong force, which acts on quarks, binds them into protons or neutrons, and whose residual effects bind these into nuclei, also has an associated field. It is transmitted by gluons. Unlike the electromagnetic force, it has a short range, around 10^{-15} m, the size of a proton.

Hence particles that feel neither the electromagnetic nor the strong force can pass freely through matter of normal density, and hardly ever come close enough to a quark or an electron for another short-range force, the weak interaction which is felt by all particles, to be felt. Neutrinos are such particles. The mean free path of MeV neutrinos in iron is several light years. About 10^{14} neutrinos from the Sun are passing through each person every second, both day and night, since the Earth provides no effective shielding.

The weak force is mediated by the W and Z intermediate vector bosons. Unlike the photon, which has no rest mass, the W and Z particles have masses that are about a hundred times that of the proton. In beta decay, a neutron changes spontaneously into a proton. Since the neutron contains two *down* (d) quarks and one *up* (u) quark, and the proton one d and two u, beta decay can be illustrated in the Feynman diagram of figure 1. A d quark emits a W^- particle and turns into a u quark. The u and d quarks have similar masses, both very much smaller than that of the W. Hence energy conservation appears to be violated at the first vertex. Later the W decays into an electron and an antineutrino, which have modest kinetic energies compared with the W rest energy. Again energy conservation appears to be violated, this time in the opposite sense. These apparent violations are covered by the uncertainty principle. It is impossible to specify both energy E and time t to absolute precision in the same quantum system. The product of uncertainties in the two quantities is of the order of the Planck constant, $\Delta E\, \Delta t \sim h$. Hence we can 'borrow' energy ΔE provided that it is paid back within a time given by $\Delta t \sim h/\Delta E$. In the short time

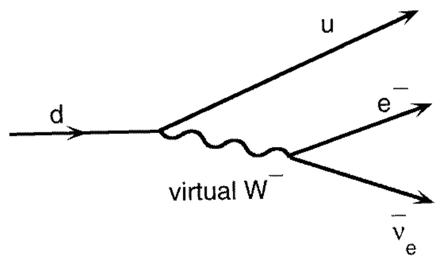

Figure 1. Feynman diagram for beta decay.

that we can borrow enough energy to create the virtual W, it can only travel a short distance, and this gives rise to the short range of the weak interaction.

This may seem counter-intuitive, but it works. We can extend this argument for electromagnetism. The carrier of electromagnetism, the photon, has no rest mass. To create a virtual photon zero energy needs to be borrowed, $\Delta E = 0$; hence this can be borrowed for an infinite time, $h/\Delta E$. The photon can travel an infinite distance, giving rise to the infinite range of electromagnetism, consistent with the classical inverse square law. Physics is brilliant! A similar reasoning, however, is not valid for the strong interaction. Unlike photons, which only couple to charged particles, gluons, which are also massless, interact with other gluons as well as with quarks. If we attempt to separate two quarks, a gluon 'tube' or 'string' is formed between them. The separation energy therefore increases with distance. At a certain separation it becomes energetically more favourable to create a new quark–antiquark pair than to pull the original quarks further apart. Hence quarks are confined within hadrons, particles like the proton which feel the strong force. If a quark is struck in a high energy collision, and receives a large momentum kick, this results in the emission of a 'jet' of normal particles (pions, protons etc) which form in the recombination of the quarks and antiquarks produced by the string.

The creation and annihilation of particles is another quantum phenomenon. For the creation or annihilation of real particles, the conservation of energy and momentum must be obeyed. However, this is not required for virtual particles, which within the confines of the uncertainty principle can appear and disappear, provided that certain quantities, such as electric charge, are conserved at each Feynman vertex.

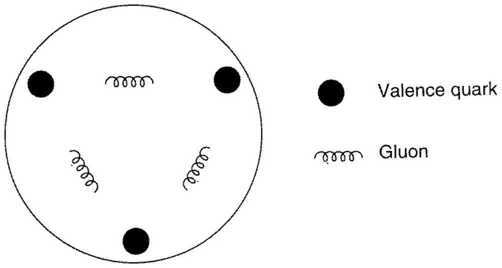

Figure 2. The proton probed at low energy.

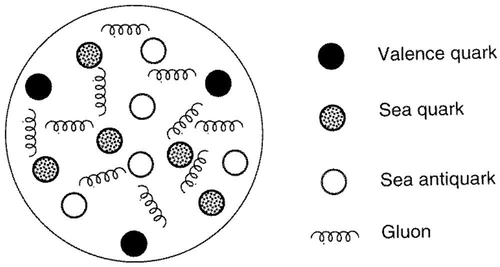

Figure 3. The proton probed at high energy.

Consider the proton. For many purposes we can regard this as made of three quarks, two u and one d, held together by gluons, as shown in figure 2. However, the gluons can temporarily form quark–antiquark pairs, which can in turn annihilate each other or interact with gluons. The proton is therefore a complex structure: a bag of quark, antiquark and gluon constituents, which appear and disappear. The world's only electron–proton collider, HERA, started operation a few years ago. In a 6 km circumference tunnel under the suburbs of Hamburg, a beam of 820 GeV (now 900 GeV) protons was made to collide head-on with a beam of 27 GeV electrons or positrons. The collisions are observed and analysed in two large detectors. I was fortunate to be a participant in one of these international projects, returning to electron scattering after 30 years. The high energy allowed us to probe deeply inside the proton, and hence to interact sometimes with the virtual quarks in the proton's vacuum. As seen by the electron, the constituents of the proton are rushing towards it, and deep inelastic scattering can determine how this momentum is shared amongst these constituents. Some unexpected results emerged.

Their interpretation is as follows. If we examine the proton in such a way as to see only quarks that possess more than 1% of the proton momentum, we would see only the three so-called valence quarks. If, however, we observe those which have momenta much less than 1%, we would see many quarks. The valence quarks are floating in a sea of gluons, which by quantum-mechanical fluctuations can turn into quark–antiquark pairs for very short times, during which they interact with the colliding electron. Figure 3 shows how the proton appears when probed at high energies. The proton is not so empty!

Vacuum interactions are not confined within the proton. In atoms the interaction between the electrons and the nucleus is modified by vacuum effects. Consider the hydrogen atom. The first excited state exists in two forms with different orbital angular momentum, called 2s and 2p in spectroscopic notation. The Schrödinger equation, and also Dirac's relativistic version, predicts that these have precisely the same energy, although the shapes of the electron clouds, the probability distributions, are different. Virtual photons are continuously emitted and reabsorbed by the electron, so part of the mass energy of the electron resides in the photon cloud. The charge resides in the bare electron so the charge-to-mass ratio is changed slightly and this affects the energy levels.

Perhaps a simpler illustration of such a vacuum effect is shown in figure 4. A virtual photon linking the electron and the nucleus can, amongst other possibilities, create a virtual electron–positron pair out of the vacuum. The pair will be polarized: the positive particle will be attracted towards the original electron, and the negative towards the proton. This has the effect of decreasing, very slightly, the effective interaction between the orbital electron and the nucleus. In

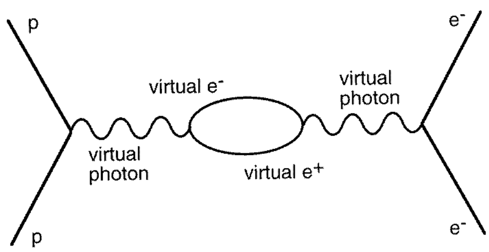

Figure 4. Vacuum polarization in the hydrogen atom.

the 2s state the probability of finding the orbital electron near the nucleus is greater than in the 2p state, and this causes a small energy difference, a few micro-electron-volts between the states. The totality of the vacuum effects can be calculated by summing Feynman diagrams of various orders, and there is extremely good agreement with experiment. The energy difference, known as the Lamb shift, was first measured in 1951, using microwave transitions between states. Willis Lamb received the Nobel Prize for Physics in 1955.

We have considered vacuum effects within the proton and within atoms. However, the free electron also interacts with the vacuum. The electron has intrinsic angular momentum, called spin, and hence a magnetic moment. For a pointlike particle this would equal 1 Bohr magneton. Vacuum interactions modify this by just over one part in a thousand. The electron magnetic moment has been measured to 1 part in 10^{11}. To compare this with theory, high-order Feynman diagrams must be computed and summed. Theory and experiment agree within 2 parts in 10^{10}, the limit being set by the accuracy of the theoretical calculation: a brilliant result for quantum electrodynamics, making it, I believe, the most precisely tested theory in physics.

Vacuum fluctuations do not exist only for photons and electrons. They exist for all particles. Other particles, apart from neutrinos, have masses considerably larger than that of the electron. The lightest of these is the muon, a heavy version of the electron, which has 200 times its mass. Much more energy must be borrowed to create muon pairs or heavier objects, and hence in our normal 'low energy' world the effects of virtual fluctuations are smaller. In today's particle physics experiments, and even more so in the early stages of the Big Bang, energies much higher than those required to create the rest masses are available, and hence real particles can be created out of the vacuum. Pictures from today's colliders, such as figure 5, show many real particles coming out from a collision between two particles.

Vacuum effects exist also for macroscopic objects. Two neutral flat metal plates attract each other if sufficiently close, because of the vacuum fluctuations between them. The theory of this was proposed in 1948 by Hendrick Casimir. The simplest explanation is that the reflective plates exclude virtual photons having wavelengths greater than the plate separation. This would make the vacuum energy density between the plates less than that outside them, and hence push the plates together. Strangely, however, the force depends on the geometry: hemispherical shells experience a repulsive force. I can think of no intuitive explanation for this. An accurate measurement of the Casimir effect has been made very recently (November 1998) by Umar Mohideen and Anushree Roy, who used an atomic force microscope. A 200 micrometre diameter sphere was brought to within 100 nanometres of a flat plate. The authors claim that the theory has been verified to within 1%.

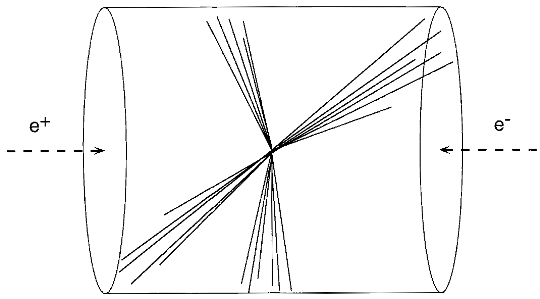

Figure 5. An electron–positron collision at high energy creates four 'jets' of hadrons out of the vacuum.

Having considered microscopic and macroscopic objects, we now move to outer space. Vacuum fluctuations occur everywhere. Hence virtual particle–antiparticle pairs will be formed near the event horizons of black holes. The gravitational gradient there is very steep, particularly for small black holes. The slight separation between particle and antiparticle during their fleeting existence can result in one falling into and one escaping from the black hole. Hence a black hole should radiate particles. This was predicted by Stephen Hawking.

We conclude that in the classical sense of the volume occupied by small hard 'material' constituents, matter is extremely empty. However, we cannot have truly empty space. Fields pervade everything. The vacuum is full. It is a dynamic entity teeming with objects that continuously appear and disappear. The effects of these have been observed in many experiments, in some with exquisite precision.

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