Nuclear physics

Antimatter in the proton is more down than up

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Protons are found in all atoms, so it might be surprising to learn that they contain antimatter. It now emerges that there is an imbalance in the types of antimatter in the proton — a finding for which there is no agreed theoretical explanation. **See p.561**

Protons and neutrons, which are collectively known as nucleons, are the building blocks of atomic nuclei and account for more than 99% of the visible matter in the Universe. They are not themselves fundamental particles, but are made up of fundamental constituents called quarks and gluons. There are several types, or 'flavours', of quark, the lightest of which — the up and down quarks — are most likely to be found in nucleons. If you could take a snapshot of a proton, you would probably see just three 'valence' quarks (two up and one down) inside it. But you might also see gluons, and quark–antiquark pairs (antiquarks are the antimatter counterparts of quarks), transiently appearing and disappearing inside the proton. On page 561, Dove *et al.*[1] describe their efforts to quantify the probability distributions of different types of antimatter in the proton, and report that down antiquarks are more prevalent than up antiquarks.

A simplistic explanation for the presence of antimatter inside the proton involves gluons, which act as mediators of the strong interaction — the fundamental force of nature that binds quarks into nucleons, and nucleons into atomic nuclei. A quark inside a proton interacts with another quark through a gluon; this gluon can interact with other gluons, but it can also dissociate into a quark–antiquark pair. Such pairs are known as sea quarks (Fig. 1a). There is no reason to expect more up–anti-up quark pairs to form than down–anti-down quark pairs, or vice versa, because the mass of the up quark is very close to that of the down quark.

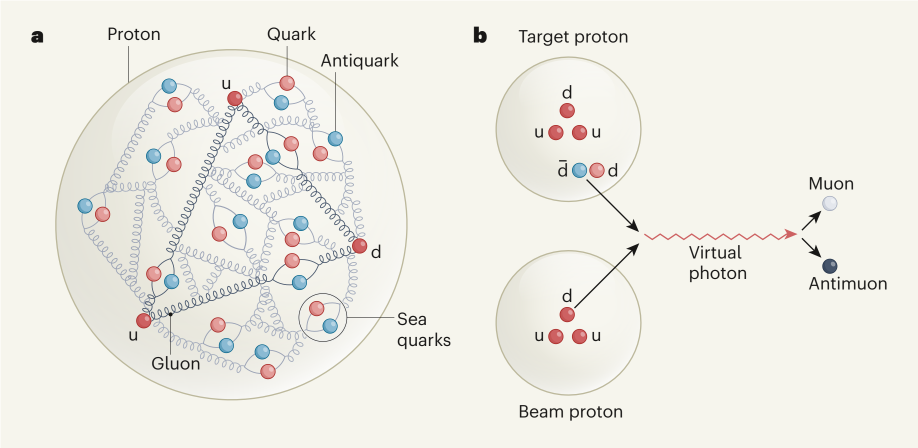

Figure 1 | The internal structure of the proton and the Drell–Yan process. a, Protons consist of fundamental particles called quarks and gluons. The three 'valence' quarks come in two types (flavours), up (u) quarks and down (d) quarks; protons contain two u and one d. Each valence quark interacts with another through a gluon. Gluons can dissociate into quark–antiquark pairs (sea quarks), and can also interact with other gluons (normal quarks are shown here in red, antiquarks in blue). **b,** In the Drell–Yan process, a beam of protons is fired at target atoms. Any quark or antiquark in a beam proton annihilates when it encounters its opposite-sign counterpart in a proton in a target atom, thereby producing a virtual photon (a transient quantum fluctuation). In this example, a down valence quark in the beam proton encounters a down antiquark ($\bar{d}$) in a pair of sea quarks in the target proton; only the valence quarks in the protons, and one pair of sea quarks in the target proton, are shown, for simplicity. The virtual photon decays into a pair of particles, which can be a muon and an antimuon. Dove *et al.*[1] analysed muon–antimuon pairs produced when protons are fired at liquid hydrogen and deuterium, and conclude that there are more anti-down quarks in protons than there are anti-up quarks — a finding for which no theoretical explanation has been agreed.

On the basis of this simple picture, the probability of up and down antiquarks appearing in the proton is the same — the antiquarks are said to be flavour symmetric. This picture seemed to hold until the 1990s, when several experiments[2–4] provided tantalizing hints that such flavour symmetry could be broken. Various explanations have been posited[5–8] to explain how this symmetry breaking might occur.

In 1970, the theoretical physicists Sidney Drell and Tung-Mow Yan proposed a process (Fig. 1b) that can be used to probe the presence of antimatter inside the proton directly[9]. In this process, a proton beam is fired at a target, such as the atoms of a chosen element. Any quark or antiquark in a beam proton will be annihilated when it encounters its opposite-sign equivalent inside a nucleon in a target atom, thereby producing a virtual photon — a transient quantum fluctuation that exhibits some of the characteristics of an ordinary photon. This virtual photon then decays into a pair of particles: often, an electron and an antielectron (a positron), or a muon and an antimuon. By detecting and analysing the muon–antimuon pairs produced in experiments that use liquid hydrogen and deuterium as targets, it is possible to extract quantitative information about the probability distributions of anti-up and anti-down quarks inside the proton, measured as a function of the fractional momentum of the antiquarks (the fraction of the proton's momentum that is carried by the antiquarks).

Two such Drell–Yan experiments have previously been carried out: the NA51 experiment[10] at CERN (Europe's particle-physics laboratory near Geneva, Switzerland), reported in 1994; and the E866/NuSea experiment[11] at Fermilab in Batavia, Illinois, reported in 2001. The NA51 experiment produced only one data point, and suggested that there are more anti-down quarks in the proton than anti-up quarks, at the fractional momentum studied in the experiment. The E866/NuSea data were consistent with that result; however, both studies have large experimental uncertainties. Furthermore, the E866/NuSea experiment covered a range of fractional momenta, and showed an interesting trend as the fractional momentum increases from values typical of sea quarks to those associated with valence quarks: the probability distribution seems to switch from a deficit to an excess of anti-up quarks, compared with anti-down quarks. Theoretical physicists have yet to reach a consensus on why this might be[5–8].

The SeaQuest Drell–Yan experiment (E906) now reported by Dove *et al.* was also carried out at Fermilab, and was specifically designed to investigate this potential flavour asymmetry of antimatter. The authors built a new experimental apparatus to measure muon–antimuon pairs, with the aim of reproducing and extending the range of valence-quark fractional momenta studied in E866/NuSea. The researchers report a significant improvement, compared with E866/NuSea, in the precision of the quantity measured in the experiments: namely, the ratio of the probability distribution of anti-down quarks to that of anti-up quarks at different fractional momenta (this ratio directly corresponds to the antimatter asymmetry in the proton). The new results unambiguously show that there is an excess of anti-down quarks over anti-up quarks, and that this asymmetry seems to be constant for the measured range of fractional-momentum values, within the experimental uncertainties.

The E906/SeaQuest results provide the best picture yet of antimatter probability distributions in the proton, whose internal structure continues to amaze physicists despite advances made over the past several decades. However, the inconsistency between the trend reported in these results and that seen in the E866/NuSea experiment is unsettling and requires further study. To help resolve this issue, future experiments should have a precision at least comparable to that of E906/Seaquest. Nevertheless, the precision of the current results is already sufficient to disprove certain models of flavour asymmetry, and has potential implications for collider experiments[12,13] that are searching for physics beyond the standard model of particle physics.

The origin of the observed antimatter asymmetry remains elusive. Future studies should help cast light on this matter — for example, by measuring the spin and orbital angular momentum contributions of antiquarks to a quantum property of the proton known as spin. Ultimately, the experimentally determined antimatter asymmetry will be compared with predictions from computer simulations based on the first principles of quantum chromodynamics (the theory of the strong interaction), when such predictions can be made with a precision at least comparable to that of the measurements made in E906/SeaQuest. Such a comparison will be a good test of quantum chromodynamics: deviations of the experimental data from the predictions would mean that the theory needs to be refined.

> **“The origin of the observed antimatter asymmetry remains elusive.”**

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