above. One explanation for this might lie in imprinting marks — sex-specific chemical modifications to DNA that are inherited from an embryo's parents. Imprinting ensures that only copies of certain genes inherited specifically from the mother or father are expressed in the embryo, preventing the genes' overexpression. A mismatch in imprinting marks could lead to some genes being erroneously under- or overexpressed, which can cause developmental defects[10,11].

The risk of aneuploidy in routine cell culture is a double-edged sword. It calls for the development of improved culture conditions, particularly for cell-based therapies. But it also provides insights into fundamental cellular processes. The relative rarity of chromosome loss observed by Murakami and colleagues implies that pluripotent stem cells have active DNA-repair and genome-surveillance mechanisms to protect them from harmful mutations. These as-yet-unknown mechanisms are much more robust *in vivo* — in mouse and human embryos, aneuploid cells are diverted to extra-embryonic supportive lineages such as the placenta to safeguard the embryo proper[1,12–14]. This contrast in behaviour between cells *in vitro* and *in vivo* indicates that we have much to learn before we use cultured stem cells to make human eggs in a dish.

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Particle physics

A glimpse at the inner structure of the proton

Anna M. Stasto

The size of the space taken up by a proton's mass has been measured, and it's much smaller than previously thought. The result is a key step towards understanding the complex structure of this fundamental building block. **See p.813**

Most of the visible mass of the Universe is contained in atomic nuclei, which are made up of protons and neutrons. Protons consist of tiny particles known as quarks and gluons, but the mass of the quarks adds up to only a fraction of a per cent of the total proton mass. The gluons and their interactions with the quarks are responsible for making up the rest of the proton's mass[1], but gluons have no mass and no electric charge, so probing them is an experimental challenge. On page 813, Duran *et al.*[2] report a measurement of the proton's 'mass radius', a quantity that can reveal how its mass is distributed and thus inform the understanding of the structure of matter.

Much is already known about the proton's electric charge; it arises because of the electrically charged quarks whizzing around inside the proton. This motion defines the proton's 'electric charge radius', by analogy with its mass radius.

The electric charge radius of the proton was first measured in 1955, in experiments that involved high-speed electrons being shot at a target of hydrogen atoms[3]. The way in which the electrons were deflected off the target was used to deduce the electric charge radius of hydrogen's proton. The constituents of the proton were revealed 14 years later, in an experiment that relied again on the scattering of electrons, albeit with higher energies[4]. The results of this experiment suggested that the proton must be made of particles that were more fundamental than itself, and researchers concluded that those particles must be quarks.

Quarks carry another type of charge, known as colour charge, which is responsible for the strong interaction — the fundamental force that confines quarks within a proton. Gluons are the elementary particles that mediate this interaction, and because they have no electric charge, they cannot be probed directly with electrons. They do, however, have colour charge, so the challenge is to perform measurements that are sensitive enough to reveal the gluons' dynamics through their colour charge.

A suitable process from which one can extract information about the mass

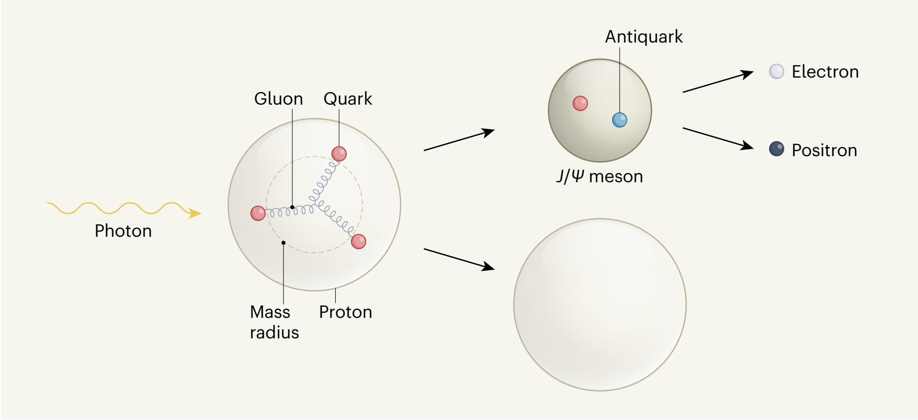

Figure 1 | A process for measuring the mass radius of the proton. The mass of a proton is determined by interactions between tiny particles in the proton, called quarks and gluons. The region in which this mass is confined is defined by a distance known as its mass radius. Duran *et al.*[2] undertook an experiment to estimate the proton's mass radius by measuring the production of a particle called the J/ψ meson, which can be generated when a photon strikes a proton. The J/ψ meson comprises a quark and its antiparticle, an antiquark, and quickly decays into an electron and a positron (the antiparticle of an electron), both of which Duran *et al.* measured. They then used theoretical models to extract the value of the mass radius.

distribution of the proton[5] involves the production of a particle called the J/ψ meson. This is made up of a specific type of quark, known as a heavy charm quark, and its antiparticle, a charm antiquark (Fig. 1). The J/ψ meson can be generated when electrons radiate photons that then interact with protons. But these mesons are unstable and quickly decay, producing other types of particle. By measuring the decay products of the J/ψ meson, it is possible to extract quantities called the gluonic gravitational form factors, which provide information about the distribution of the mass in the proton. Duran *et al.* succeeded in doing just this.

The authors used an electron beam to produce a beam of photons, and then passed both beams through a container filled with liquid hydrogen. They observed an electron and its antiparticle, a positron, resulting from the decay of the J/ψ meson. From this experiment, the authors extracted the cross-section, which is a measure of the probability that the photon's interaction with the proton will produce a J/ψ meson, as a function of the momentum transferred in the interaction.

This measurement enabled Duran *et al.* to calculate the gluonic gravitational form factors and estimate the mass radius of the proton. They found that the measured value of the mass radius was smaller than the electric charge radius reported previously[6]. This is an intriguing result because it implies that the region in which the quarks generate charge is measurably larger than the space in which the proton's mass is concentrated. This information, in turn, suggests that the proton has a complicated structure that is yet to be fully understood.

Further theoretical and experimental work is needed to pin down the details of this fascinating structure. The way that Duran *et al.* calculated the mass radius required input from theory[5,7,8], and was therefore dependent on the models that they chose. These theoretical approaches were based on the quantum theory describing the interaction between quarks and gluons, which is known as quantum chromodynamics. Duran and colleagues first used these models to extract values of the mass radius from their experimental data. They then compared the measured values against numerical calculations that were also based on quantum chromodynamics. In some cases, the values were consistent; in others, the results differed slightly. This indicates that the theoretical models might need to be refined to match the measurements.

The experiments could also be improved. There are already plans at Duran and colleagues' laboratory to perform experiments that are designed to measure the J/ψ meson with greater precision than that reported here. The mass radius can also be measured using other mesons, such the Υ meson, which contains a 'bottom' quark and its antiquark. Such measurements will soon be possible at a facility that is being custom-built to probe the internal structure of protons and neutrons using electron–ion collisions[9]. These future experimental measurements will help to improve theoretical modelling and solve the mystery of the proton mass and its structure.

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