Particle physics

Thrill of the magnetic moment

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A new first-principles computation of the effect that creates most uncertainty in calculations of the magnetic moment of the muon particle has been reported. The results might resolve a long-standing puzzle, but pose another conundrum. **See p.51**

The established theory of particle physics is called the standard model, and has passed a vast number of experimental tests with flying colours. But one such test — the determination of the magnetic moment of an elementary particle known as the muon — has resulted in a long-standing discrepancy between theory and experiment. The uncertainty in the theoretical determination is dominated entirely by the effects of the strong interaction, the fundamental force that binds the constituents of atomic nuclei. On page 51, Borsanyi *et al.*[1] report a calculation of the value of the largest of these effects to a precision commensurate with that of the experimental measurement of the magnetic moment. Using this value, they show that the magnetic moment predicted by the standard model is compatible with experimental measurements. At the same time, they find a moderate inconsistency between their result and previous determinations of the strong-interaction effect. The previous determinations are based on a different methodology from that used by Borsanyi and colleagues, and are widely viewed as being on firm ground.

Despite the many successes of the standard model of particle physics, it has patent shortcomings: it neither describes gravity nor contains a candidate particle that could account for the Universe's vast amount of dark matter, which can be observed only indirectly. Physicists are exploring several avenues of research to discover what particles and forces might lie beyond the standard model. These include direct searches for new particles by the Large Hadron Collider at CERN, Europe's particle-physics laboratory near Geneva, Switzerland, and experiments dedicated to detecting dark matter. Another well-established strategy is to precisely measure quantities that can be calculated, using the standard model, to a degree of precision similar to that of the measurements; any differences in the measured and computed values would indicate the existence of physics not accounted for in the standard model.

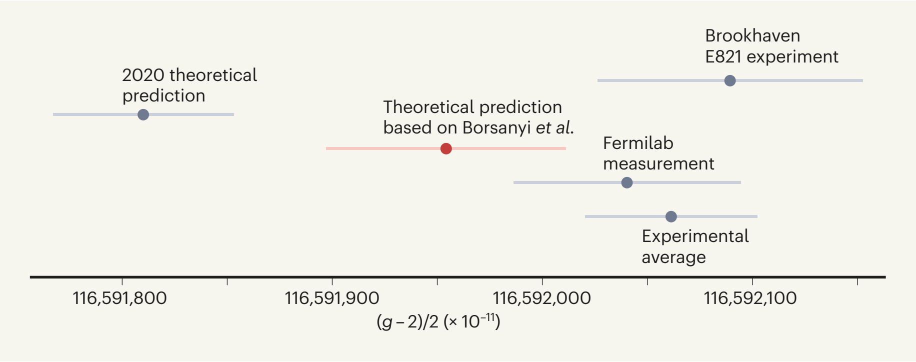

Figure 1 | Determinations of the magnetic moment of the muon particle. The magnetic moment of the muon is close, but not equal, to 2; the difference is quantified as a number known as $(g-2)/2$. A measurement[4] of $(g-2)/2$ carried out in the E821 experiment at Brookhaven National Laboratory in Upton, New York, was published in 2006, and a consensus theoretical prediction was published[5] in 2020. Borsanyi *et al.*[1] now report calculations that bring the theoretical prediction much closer to the E821 measurement. A measurement[8] of $(g-2)/2$ at the Fermi National Accelerator Laboratory (Fermilab) near Chicago, Illinois, was published earlier this year, and is consistent with the E821 value. The average of all of the experimental measurements differs by 4.2 standard deviations from the 2020 consensus prediction. A difference of 5.0 standard deviations between theoretical and experimental values would establish the existence of physics not accounted for by the standard model of particle physics.

The magnetic moments of elementary particles are prime examples of such quantities. They are proportional to the spin (intrinsic angular momentum) of the particle, and to the particle's gyromagnetic factor (g, a proportionality constant that is characteristic of each particle type). In 1928, Paul Dirac showed from his quantum relativistic theory of the electron[2] that g is 2 for that particle, an excellent approximation at that time. However, the actual value of g differs from 2 by a tiny amount called the anomalous magnetic moment, which is quantified as $(g-2)/2$. This difference arises because the magnetic moment is affected by 'virtual' versions of elementary particles, which continually appear and disappear from the vacuum. In 1947, the theoretical physicist Julian Schwinger calculated[3] the main contribution to the anomalous magnetic moment of the electron to be $\alpha/(2\pi)$, where α is a fundamental constant known as the fine-structure constant.

The electron has a cousin called the muon, which is 207 times heavier. The muon's greater mass means that measurements of its $g-2$ value are much more sensitive to the fleeting presence of any heavy virtual particles not described by the standard model than are measurements of $g-2$ for the electron. After decades of improvements, the E821 experiment at Brookhaven National Laboratory in Upton, New York, provided measurements[4] of $g-2$ for the muon reaching an astounding precision of 0.54 parts per million (p.p.m.).

An equally impressive, decades-long effort in theoretical physics aims to match the exquisite precision of the experiments in computations of the value of the muon $g-2$ predicted on the basis of the standard model. A white paper[5] published in 2020 summarized the status of these efforts: a precision of 0.37 p.p.m. had been achieved, but the value of $g-2$ obtained was slightly smaller than the experimentally derived value, corresponding to a difference of 3.7 standard deviations.

The uncertainty of the theoretical predictions for the muon $g-2$ is dominated by the effects of hadron particles. Hadrons are composite particles bound by the strong interaction, examples of which are the proton and neutron. In the white paper[5], the leading hadronic contribution was obtained from a mathematical formula known as a dispersion relation, using as input the rates of hadron formation measured in experiments in which electrons collide with positrons, the antiparticles of electrons.

A different approach to calculating the leading hadronic contribution, first proposed[6] in 2003, is to use lattice quantum chromodynamics (QCD) — a first-principles method to handle the strong interaction that relies on high-performance computing. The pace of improvement of lattice QCD calculations has accelerated tremendously in the past few years as a result of dedicated efforts and several methodological advances (reviewed in ref. 7). Borsanyi and colleagues' study is the latest stride towards reducing the uncertainty of lattice QCD-based calculations in this field to a level that competes with the uncertainty of determinations based on dispersion relations.

Intriguingly, when Borsanyi *et al.* use their calculations to predict the value of $g-2$, the result obtained is compatible with the value found by the E821 experiment (Fig. 1). The authors' result also differs by a moderate 2.2 standard deviations from the value of $g-2$ reported in the white paper[5], which was determined using dispersion relations – a finding that certainly deserves further scrutiny.

Borsanyi and colleagues' comprehensive treatment of the many effects that become relevant to $g-2$ at the quoted precision is an impressive achievement. As is standard in the lattice-QCD framework, the quantity of interest is computed by dividing space-time into a lattice of points, calculating the quantity for several values of the lattice spacing and then extrapolating to determine the value when the spacing is zero (this value is known as the continuum limit). The systematics of obtaining the continuum limit turn out to be the dominant source of uncertainty in the authors' results. Ongoing calculations by other groups using different variants of lattice QCD will provide an important consistency check of the current findings.

Since 2018, the Muon $g-2$ Collaboration has been running an experiment at the Fermi National Accelerator Laboratory (Fermilab) near Chicago, Illinois, to check and improve on the findings of the E821 experiment. The first result was announced[8] on 7 April 2021: the reported value of $g-2$ agrees well with that obtained by E821. Moreover, when all the experimental measurements are combined, the discrepancy with the theoretical prediction reported in the white paper[5] rises to the level of 4.2 standard deviations. The announcement was a truly thrilling moment for particle physicists, because a discrepancy of 5.0 standard deviations between experiment and theory is conventionally regarded as conclusive evidence of the discovery of physics not accounted for by the theory.

> **"The authors' comprehensive treatment of the many effects that become relevant to this key property at the quoted precision is impressive."**

However, the value of the muon $g-2$ inferred from Borsanyi and colleagues' calculation agrees with the new experimental average. The top priority for the future is therefore to clarify the discrepancy between Borsanyi and co-workers' result and the dispersion-theory result reported in the white paper. In the next few years, the precision of the Muon g − 2 experiment is expected[9] to increase to about four times that of the E821 experiment, and similarly precise measurements will be made[10] at the Japan Proton Accelerator Research Complex (J-PARC) near Tokai, using a completely different technique for determining $g-2$. More thrills are bound to come.

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