Deviations from 2

Alberto Moscatelli surveys a series of experiments on the electron *g*-factor that marked the departure from the Dirac equation and contributed to the development of quantum electrodynamics.

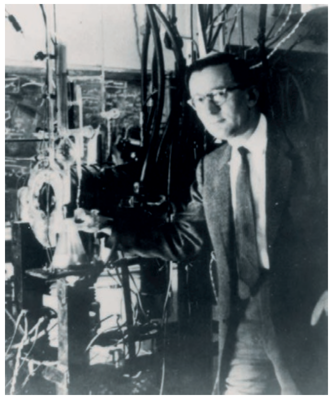
Sometimes a new experimental technique, improving the precision of certain measurements, can unveil unexpected deviations from an accepted theory. Such was the case with the molecular-beam magnetic-resonance method developed by Isidor Rabi in the 1930s. Rabi showed how to induce and detect transitions between states with different nuclear- or spin-magnetic moments using radio and microwave frequencies, in principle enabling the direct measurement of magnetic moments.

From the Dirac equation, established in 1928, it followed that electrons possess an intrinsic angular momentum (spin), and that the proportionality between the spin magnetic moment and angular momentum is given by $g_e\mu_B/\hbar$, with μ_B the Bohr magneton, $\hbar$ the reduced Planck constant and g_e — the electron *g*-factor — exactly equal to −2. There was no experimental ground to doubt the validity of the equation. In fact, the assumption that an electron's spin magnetic moment was equal to the Bohr magneton was used by Rabi and his students to calibrate their setup for the determination of magnetic moments of various nuclei.

Then, in May 1947, Nafe, Nelson and Rabi reported measurements of the hyperfine splitting of both hydrogen and deuterium. Because the hyperfine theory for these two atoms was considered to be complete, the experimental values should have matched the theoretical ones. But Nafe *et al.* observed a discrepancy of about 0.25% — well above the error associated with the calculated values, prompting the authors to comment, "Clearly this interesting deviation is worthy of further study"[1].

In September of the same year, Breit advanced the hypothesis that this discrepancy would not be at odds with the assumption that the electron may possess an intrinsic magnetic moment — that is, a small contribution to the Bohr magneton. There is a clear sense of tentativeness in Breit's communication: quite respectful of the Dirac description of the electron, he admits that "Aesthetic objections could be raised against such a view"[2].

Nevertheless, experimental techniques had by then evolved enough to probe directly the fine and hyperfine structure of atoms. In another seminal 1947 experiment[3], Lamb and Retherford reported that the $^2S_{1/2}$ and the $^2P_{1/2}$ levels in the hydrogen atom are not degenerate, conflicting with the Dirac description of hydrogen's fine structure.



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Investigations about the existence of an anomalous magnetic moment were carried out by Kusch and Foley. Their approach was to choose atoms with only one electron in the outer shell, so that the Russell–Saunders relationship linking the *g*-factors of the angular and spin magnetic moments (g_L and $g_S = -g_e$, respectively) to that of the total angular momentum (g_J) was valid to a high degree of precision. An important issue at the time was the accurate determination of the magnetic field, the uncertainty being much higher than required for such a measurement. The trick was to determine the ratio of the transition frequencies associated with a change in the total electronic angular momentum of two atoms in two different spectroscopic states in the same magnetic field. This would yield g_S without needing the actual value of the field. In November 1947, using this approach for gallium in the $^2P_{1/2}$ and $^2P_{3/2}$ states, they obtained $g_S = 2.00229 \pm 0.00008$, assuming $g_L = 1$ (ref. 4). The authors acknowledged, however, the alternative possibility that $g_L < 1$ and g_S exactly equals 2. Moreover, gallium was not an ideal atom, because of the presence of quadrupolar interactions possibly perturbing the magnetic energy levels; theory predicted these perturbations to be small, but the interpretation of the results could be debatable, calling for caution.

In December 1947, Kusch and Foley corroborated their previous conclusion, using results obtained with sodium in the $^2S_{1/2}$ state[5]. The fact that the discrepancy was observed with another atom implied that if some perturbation was in fact in operation, it would have to be of the same magnitude, which made it an unlikely proposition. In a footnote, they pointed to a parallel development in the theory of the electron: a personal communication with Julian Schwinger indicated that g_L is necessarily 1, whereas g_S may not be exactly 2.

Finally, the conclusive paper containing more accurate measurements using three atoms (gallium, sodium and indium) appeared in August 1948 with the confident title "The magnetic moment of the electron", reporting a value of $g_S = 2(1.00119\pm0.00005)$ (ref. 6). Meanwhile, Schwinger had calculated the deviation from 2 based on concepts from quantum electrodynamics.

From that moment on the goal of measuring the *g*-factor of the electron was not so much to ascertain whether or not it deviates from 2, but to improve the precision for testing the theory of quantum electrodynamics. In 1955, Polykarp Kusch (pictured) shared the Nobel Prize in Physics for "his precision determination of the magnetic moment of the electron". The current accepted value of the electron *g*-factor is −2.00231930436182(52) (ref. 7).

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References

1. Nafe, J. E., Nelson, E. B. & Rabi, I. I. *Phys. Rev.* **71,** 914–915 (1947).
2. Breit, G. *Phys. Rev.* **72,** 984 (1947).
3. Lamb, W. E. Jr & Retherford, R. C. *Phys. Rev.* **72,** 241–243 (1947).
4. Kusch, P. & Foley, H. M. *Phys. Rev.* **72,** 1256–1257 (1947).
5. Foley, H. M. & Kusch, P. *Phys. Rev.* **73,** 412 (1948).
6. Kusch, P. & Foley, H. M. *Phys. Rev.* **74,** 250–263 (1948).
7. *Fundamental Physical Constants: Electron g Factor* (NIST, 2014); http://go.nature.com/2ogBXkn

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