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 \( g \mu_B / \hbar \), with \( \mu_B \) the Bohr magneton, \( \hbar \) the reduced Planck constant and \( g \) — 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”.

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”.

Nevertheless, experimental techniques had by then evolved enough to probe directly the fine and hyperfine structure of atoms. In another seminal 1947 experiment, Lamb and Retherford reported that the \( ^2S_{1/2} \) and the \( ^2P_{3/2} \) states, they obtained \( g_J = 2.00229 \pm 0.00008 \), assuming \( g_\ell = 1 \) (ref. 4). The authors acknowledged, however, the alternative possibility that \( g_\ell \approx 1 \) and \( g_J \approx 2 \) more likely.

In December 1947, Kusch and Foley corroborated their previous conclusion, using results obtained with sodium in the \( ^2S_{1/2} \) state. The fact that the discrepancy was observed with another atom implied that if some perturbation was in fact 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 \( g \) is necessarily 1, whereas \( g_J \) 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 \( g_e = 2(1.00119 \pm 0.00005) \) (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 \( \pm 0.0231930436182(52) \) (ref. 7).

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References
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