Image courtesy of Lida Lopes Cardozo Kindersley.

MILESTONE 4

A relative success

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The idea of the spinning electron, as proposed by Samuel Goudsmit and George Uhlenbeck in 1925 (Milestone 3), and incorporated into the formalism of quantum mechanics by Wolfgang Pauli, was a solution of expediency. Yet this contrivance threw up a more fundamental question: as a 25-year-old postdoctoral fellow at the University of Cambridge formulated the problem in 1928, why should nature have chosen this particular model for the electron, instead of being satisfied with a point charge?

The young postdoc's name was Paul Dirac, and in two papers published in the *Proceedings of the Royal Society of London,* he set out to explain why. Using the clear, austere prose and adroit mathematics that were his hallmarks, he showed how spin emerged as a natural consequence of the correct application of special relativity to the quantum mechanics of the electron.

Dirac was able to remove the nonlinearities in space and time derivatives that had confounded other attempts to marry those two great new physical theories. The corollary of his logic was that the wavefunction of the electron must have four components, and must be operated on by four-dimensional matrices. These matrices required an additional degree of freedom beyond position and momentum in the physical description of the electron. Inspection revealed them to be extensions of the two-dimensional spin matrices introduced by Pauli in his earlier *ad hoc* treatment. Applied to an electron in an electromagnetic field, the new formalism delivered the exact value of the magnetic moment assumed in the spinning electron model.

What had emerged was an equation that, in its author's words, "governs most of physics and the whole of chemistry". Dirac was a famously modest man, and was not wont to exaggerate. The Dirac equation is still today the best description not just of the electron, but of all spin-1/2 particles — including all the quarks and leptons from which matter is made.

When asked what had led him to his formula, Dirac replied simply "I found it beautiful". His equation is indeed a powerful example of the deep and mysterious connection between the language of mathematics and the expressions of the physical world.

Yet, however much beauty might be indicative of rightness, a physical theory is judged on its predictive power. The Dirac equation did not disappoint. The interpretation of two of its four solutions was clear: they were the two spin states of the electron. But the other two solutions seemed to require particles exactly like electrons, but with a positive charge.

Dirac did not immediately and explicitly state the now-obvious conclusion — out of "pure cowardice", he explained later. But when, in 1932, Carl Anderson confirmed the existence of the positron, Dirac's fame was assured. He shared the 1933 Nobel Prize in Physics — its second-youngest-ever recipient — and his equation went on to become the bedrock of quantum electrodynamics, the quantum field theory of the electromagnetic interaction. Following his death in 1984, a stone was set into the floor of Westminster Abbey in London. It was inscribed with his name and $i\gamma \cdot \partial\Psi = m\Psi$ — the shortest and sweetest rendering of his extraordinary brainchild.

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