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Quantum Spin

The Intrinsic Angular Momentum of Particles

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Introduction

Every electron in the universe is spinning, and no electron in the universe is spinning. Both statements are true, and the gap between them is the subject of this book. Spin is the intrinsic angular momentum that every fundamental particle carries, always, as an un removable feature of what it is; and yet it is not a rotation in any classical sense, and the picture of a tiny charged ball whirling on its axis, the picture that gave the property its name, fails at every point where it is examined. What remains when the picture fails is one of the deepest and most consequential properties in all of physics, the key to the structure of the atom, the behavior of matter, the periodic table, chemistry, magnetism, medical imaging, and the architecture of the quantum world.

Spin entered physics as a solution to a crisis in spectroscopy. In the first quarter of the twentieth century, physicists mapping the light emitted by atoms found splittings and doublings that the quantum mechanics of the day could not explain. The lines of atomic spectra divided in magnetic fields in ways that defied the existing rules, and the electrons in the outermost shells of atoms seemed to need a property that no one could name. Wolfgang Pauli, in 1924, proposed that each electron carries a "two- valuedness not describable classically," a fourth quantum number with no classical counterpart, and he resisted every attempt to picture it as a literal rotation. He was right to resist. The name that eventually stuck, spin, is a fossil of the wrong picture, kept for its charm and its convenience.

The story of how that two-valuedness acquired its modern form is one of the most human in the history of physics. It features a young physicist, Ralph Kronig, who had the right idea first and was talked out of publishing it. It features two Dutch students, George Uhlenbeck and Samuel Goudsmit, who published it anyway, then tried to withdraw their paper in embarrassment when the giants of the field objected, and were saved from the withdrawal by a wise adviser who saw that the idea was too good to bury. It features a factor of two, the famous discrepancy between their prediction and the observed fine structure of hydrogen, resolved at the last moment by Llewellyn Thomas's calculation of a relativistic wobble, the piece that convinced even Pauli. And behind all of it stands the Stern- Gerlach experiment of 1922, in which a beam of silver atoms split cleanly in two, showing the world spatial quantization years before anyone knew what was doing the quantizing.

The physics that grew from those events is the backbone of this book. Spin is quantized: a particle's spin magnitude is fixed, and its component along any chosen direction can take only discrete values. For the electron, those values are exactly two, up and down along whatever axis you choose, and that two-

valuedness is what Pauli had glimpsed. Particles divide by their spin into two great families, fermions with half-integer spin and bosons with integer spin, and the division runs impossibly deep: it determines whether particles can share a quantum state, which determines whether matter can be solid, which determines that the world exists at all. The connection between spin and statistics, proved by Pauli in 1940 from the union of quantum mechanics and special relativity, is widely considered one of the most important results of either theory.

This book follows spin from the crisis to the consequences. The chapters ahead trace the discovery through the Stern-Gerlach experiment and the spectroscopic puzzles, explain what spin is and, as importantly, what it is not, follow Pauli and Dirac as they built the mathematics that now carries the property, and show how spin is measured in modern laboratories with exquisite precision. Later chapters place spin in its contexts: the atom, the periodic table, magnetism, the chemistry of matter, and the technologies that spin has made possible, from magnetic resonance imaging to atomic clocks to the young field of spintronics, which aims to build electronics out of spin itself. The final chapters treat the open questions and the future, because spin is still yielding: it is now the workhorse of quantum computers and the sharpest test of quantum field theory that exists. The journey begins with an experiment that split a beam of silver atoms in two and, in doing so, split the classical world from the quantum one forever.

Chapter 1: The Discovery of Quantum Spin

The discovery of quantum spin begins, as so many discoveries do, with a stubborn anomaly that everyone could see and no one could explain. Between 1916 and 1925, physicists made rapid progress in understanding how electrons arrange themselves in atoms, building the periodic table from Bohr's model of the atom and Arnold Sommerfeld's quantum numbers. But the arrangement kept demanding something extra. The anomalous Zeeman effect, the pattern in which spectral lines split in weak magnetic fields, refused to match any assignment of the known quantum numbers. Alfred Landé's empirical rules fitted the data, but their meaning was opaque. The electron in the outermost shell of an atom behaved as if it possessed one more property, one more degree of freedom, than the three quantum numbers already assigned to it.

The decisive step into the dark was taken by Wolfgang Pauli in 1924. Following a hint from Edmund Stoner's paper on the distribution of electrons among atomic levels, published in October 1924, Pauli concluded that the number of electrons in each closed shell equaled the number of possible values of a full set of quantum numbers, and that completing the set required a fourth quantum number capable of exactly two values. He was blunt about its nature: it was a two-valuedness, he wrote, that could not be described classically. This was an extraordinary admission from a physicist of Pauli's temperament, an assertion that a real property of real particles simply had no picture. His exclusion principle followed at once: no two electrons in the same system can occupy the same complete quantum state. The periodic table snapped into place. But the fourth number itself remained a riddle, a bookkeeping device with no meaning.

The meaning nearly arrived a few months later, and its near-miss is one of the most instructive episodes in the history of science. Ralph Kronig, a young assistant to Landé, suggested in early 1925 that the two-valuedness was the self-rotation of the electron: if the electron spun on its own axis, it would carry angular momentum of its own and, being charged, a magnetic moment. It was a natural idea, and it was correct in essence. But when Kronig described it to Pauli, the response was devastating. Pauli pointed out that for a rotating charged sphere the size of an electron to generate the needed magnetic moment, its surface would have to move faster than light, in flagrant violation of relativity; and the classical model predicted other wrong numbers besides. Discouraged by the severest critic in physics, Kronig let the idea lie, and published nothing.

In the autumn of 1925 the same thought came, independently, to two young

physicists at Leiden, George Uhlenbeck and Samuel Goudsmit. Goudsmit, a spectroscopist, knew the puzzles of the quantum numbers; Uhlenbeck knew the classical physics of rotation. Together they saw that electron self-rotation, whatever its faults as a picture, explained Pauli's fourth quantum number, the anomalous Zeeman effect, and the doubling of spectral lines all at once. They wrote a paper and showed it to their adviser, Paul Ehrenfest. When they returned the next day, full of second thoughts after Hendrik Lorentz and Werner Heisenberg raised objections to the spinning-electron picture, hoping to withdraw it, Ehrenfest told them they were both young enough to afford a stupidity, and sent it off anyway. Their note was published, and the spin of the electron entered physics.

The objections were real and the young men's embarrassment was justified, but the idea survived them. Lorentz's arithmetic was right: a literal rotating sphere could not produce the effect. Heisenberg's worry was right too: the model as first written gave wrong numbers for the fine structure of hydrogen, the small splittings of spectral lines, by a factor of two, exactly as Kronig's unpublished version had. That factor of two was the crisis of the new theory's first months, and its resolution is the reason the discovery chapter of this story has a happy ending. In February 1926, Llewellyn Thomas, an American physicist visiting Bohr's institute in Copenhagen, calculated a relativistic correction: the electron, moving through the electric field of the nucleus, rotates between two frames of reference, and the accounting of that rotation contributes a factor of exactly two.

The effect is called Thomas precession, and with it the theory's predictions matched the hydrogen spectrum. Pauli, who had rejected Kronig, objected to Uhlenbeck and Goudsmit, and distrusted the entire picture, was convinced. He accepted electron spin as the true interpretation of his fourth quantum number, while insisting, correctly, that the classical rotating-charge model was not merely incomplete but wrong.

While the theorists argued, the experimental record had already spoken, and in retrospect the first direct evidence of spin had been in hand for three years. In 1922, at Frankfurt, Otto Stern and Walter Gerlach passed a beam of silver atoms through a strongly inhomogeneous magnetic field and found the beam split into two distinct bands, where classical physics predicted a continuous smear and the old quantum theory of orbital motion predicted no clean splitting at all. Silver atoms in their ground state have no orbital angular momentum from their outermost electron, so the two bands were inexplicable in orbital terms; the original interpretation, which attributed them to quantized orbital angular momentum, could not survive, and in 1927 Ronald Fraser showed that the relevant atoms were isotropic, with no orbital angular

momentum to quantize.

The correct explanation arrived with spin: the two bands were the two orientations of a single electron's intrinsic angular momentum. In the same year, 1927, Thomas Phipps and John Taylor repeated the technique with hydrogen atoms in their ground state, which have exactly zero orbital angular momentum, and again found two peaks. The beam had split in two because the electron's spin has exactly two values along any axis, and the experiment of 1922 was recognized retroactively as the first direct observation of the property that Uhlenbeck and Goudsmit had named three years later.

The experimental background that Pauli was organizing deserves one more pass, because the spectroscopic crisis was not a single anomaly but a catalog. The alkali metals, whose atoms have a lone outer electron orbiting a closed shell, showed spectral lines split into pairs of close spacing, the doublets, whose separations did not follow the patterns the orbital quantum numbers predicted. The multiplet structure of the heavier elements grew more tangled, and the Landé g-factor, an empirical number that scaled each element's

Zeeman splittings, took fractional values that no orbital model could justify. Every expedient was tried, from inner quantum numbers to core angular momenta, and Pauli's December 1924 paper closed the door on the last of them, showing the atom's core contributed nothing of the kind. What remained, once every classical escape had been tried, was the electron itself, carrying a two-valued something that no picture could hold.

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ABOUT THE AUTHOR

Aira Astralis is a science writer specializing in astronomy and space exploration. Her work spans the full breadth of humanity's relationship with the cosmos -- from the earliest naked-eye observations to the engineering marvels of modern space missions.

Her books are built on a foundation of primary sources: peer-reviewed research, mission archives, and direct engagement with the scientific community. She writes for readers who want to understand not just what we know about the universe, but how we came to know it.

She believes that the most important frontier is not out there but in the gap between what scientists discover and what the public understands. Her books exist to close that gap.