Spin's Earliest Evidence, but not its Discovery

The Story of the Stern-Gerlach Experiment

Neeraj Nandan Akella

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"How can one avoid despondency if one thinks of the anomalous Zeeman effect?"

- Wolfgang Pauli

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At the turn of the 20^{th} century, a new paradigm in physics started to form. With Planck's law of Black-Body radiation in 1900, Einstein's explanation for the photoelectric effect in 1905 and Bohr's atomic model in 1913, quantum mechanics has begun.

The ability for a quantum atomic model to reformulate the Rydberg constant was the most impressive feat accomplished by Bohr, since with this approach, he was able to reproduce the Lyman, Balmer and Paschen series, explaining the Hydrogen emission/absorption spectrum theoretically. While many were still sceptical of the various arguments presented by Bohr, such as the quantisation of angular momentum, this derivation cemented the credibility of quantum mechanics to many physicists. One such physicist was Arnold Sommerfeld, who specially focussed on extending the Bohr model to explain the *Stark effect* and the *Zeeman effect* theoretically, phenomena which display the splitting of spectral lines in presence of an electric or magnetic field respectively.

Sommerfeld proposed the idea of elliptical electron orbits alongside the circular ones present in Bohr's model. He argued that these orbits would reproduce the same Hydrogen spectrum (i.e., they would correspond to degeneracies in the atomic energy levels) but would start to dissociate when in the influence of a field. These elliptical orbits introduced additional quantum numbers to determine the shape and size of the orbit. He later sought the help of Schwarzschild and Epstein to explain the Stark effect with this idea, and the scientists produced independent papers in 1916. Once refined, Sommerfeld's theory could explain Stark effect and the *normal* Zeeman effect, however, it still failed to explain the *anomalous* case which appeared at weak magnetic fields.

This was the primary issue which plagued the subsequent development of quantum mechanics. Many theoretical physicists struggle to use the space quantisation described by the Bohr-Sommerfeld theory (referred to as the 'Old Quantum Theory'), where electrons could only occupy distinct orbits, to explain the anomalous Zeeman effect. Alongside, issues seeped the ferromagnetism theory developed by Pierre Weiss. Though the theory presents the useful idea of magnetic domains in a metal, when considering a fully magnetised sample, the average magnetic moment was much smaller than the Bohr magneton (magnetic moment of an electron). Pauli attempted to explain this with space quantisation in 1920 with which he was able to conclude that the magnetic moment of an atom should indeed be smaller than the electron. Of course, the real solution to explaining both was the quantum property *spin*, which was still yet unknown when Pauli proposed this solution. Stern closely followed these developments, developing an idea for an experiment which could confirm Bohr's model.

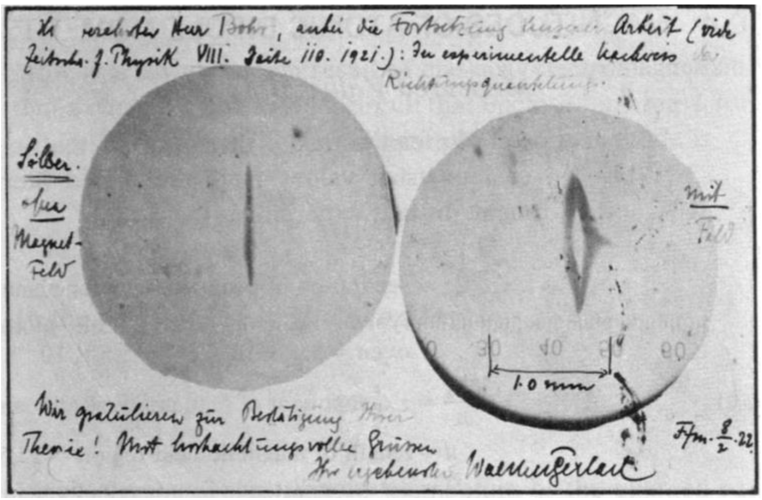
Otto Stern initially started his pursuit in science with physical chemistry. His dissertation was based on investigating the osmotic pressure of various solutions with dissolved carbon dioxide. He later became Einstein's first pupil, which influenced his interests towards light quanta, atomic and statistical physics, and magnetism. However, Stern was not convinced by Bohr's atomic model, claiming to quit physics if his hypotheses were proven true. Stern later became Max Born's assistant at Frankfurt, who encouraged him to pursue molecular beam experiments. His first beam experiment, in 1920, involved determining the thermal velocity of silver atoms, where a similar design of this experiment later aided him in the Stern-Gerlach Experiment.

Similar to Stern, Walther Gerlach too was heavily invested in research related to molecular beams, though his interest began earlier than Stern's, dating to 1912. At Frankfurt, Gerlach investigated whether a Bismuth atom would display strong diamagnetism like the Bismuth crystal. He thought to experiment this by deflecting a beam of Bismuth in a strong inhomogeneous field, though Born believed that the experiment would not bear much fruit.

Stern realised a property of Bohr's model which could be proven or disproven via an experiment. He recognised that space quantisation implied that electrons in a Hydrogen atom could only exist in two possible states of angular momentum ($\pm\hbar$), making them birefringent in the presence of an external field. In his design, Stern exploited this fact by considering the displacement of an atomic beam when entering a strong magnetic field gradient. If the quantisation hypothesis were to be true, the beam of atoms would align in only two ways (due to the twofold nature of angular momentum) while if the classical picture was true, the random precession of the atoms would cause the beam to only broaden as a result of the field.

Stern presented his proposal to Born and recruited Gerlach to conduct the experiment. Despite Stern's effort at carefully devising the details of the experiment, *SGE* still required more than a year to finish. The final experimental design involved a beam of silver atoms (from a metallic vapour produced by an oven heated to 1000^{o}C) collimated by two narrow slits (0.03 mm wide) travelling through a magnetic field 3.5 cm long with a field strength of 0.1 T and a gradient of 10 T/cm. By the end the displacement of silver atoms they achieved was of 0.2 mm. The experiment was extremely fragile, where a small misalignment of the collimators could disrupt the results of an entire run. This meant that the experiment could only be operated for a few hours, hence only a thin film of silver atoms was deposited on the collector plate, invisible to the naked eye. However, when Stern looked at the collector plate, he noticed that the silver atoms quickly blackened, due to a reaction with his cigar's smoke, similar to the process of developing a photograph. This motivated them to use photographic development process for subsequent trails.

Yet, after continuous efforts, Stern and Gerlach were still unable to produce a conclusive result, disheartening them and raising scepticism among their colleagues, who believed that space quantisation was not meant to be taken literally, thus claiming that the experiment would be unsuccessful. Stern eventually moved to the University of Rostock to become a professor of theoretical physics and in 1922, he and Gerlach decided to give up on SGE. However, when railroad strikes delayed Gerlach's trip back to Frankfurt, he decided to revise the details of the experiment to improve its alignment, eventually allowing him to produce a clear splitting of two beams. Stern was shocked by this result, claiming to be overwhelmed with surprise and excitement when Gerlach sent him a message saying 'Bohr was right after all' through telegram. Gerlach later congratulated Bohr by sending a postcard with these results:



Gerlach's postcard from 8th February 1922 (From AIP Emilio Segrè Visual Archives)

With further analysis, they determined the magnetic moment of the silver atoms, which were within 10% of the Bohr magneton. Although the experiment was considered as a significant piece of evidence for space quantisation, the likes of Einstein and Ehrenfest contemplated on its implications and pondered how atoms could have a predetermined magnetic orientation. Later experiments also failed to show the magnetic birefringence implied by the theory. These issues and the anomalous Zeeman effect could only be solved by the later development of quantum mechanics, with the addition of electron spin. This reveals the misconception behind the Stern-Gerlach experiment. It is often thought to be the direct cause of the discovery of spin, while spin was developed independently of it. When viewing the results of SGE, it was believed to prove space quantisation, though it was a lucky case of spin quantisation. Since the angular momentum of the electron in the silver atom was zero, it was quantised according to its spin of $\pm\hbar/2$, accounting for the twofold split observed. Therefore, while SGE was the first evidence of spin, it was not recognised as such until the theoretical discovery of it.

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