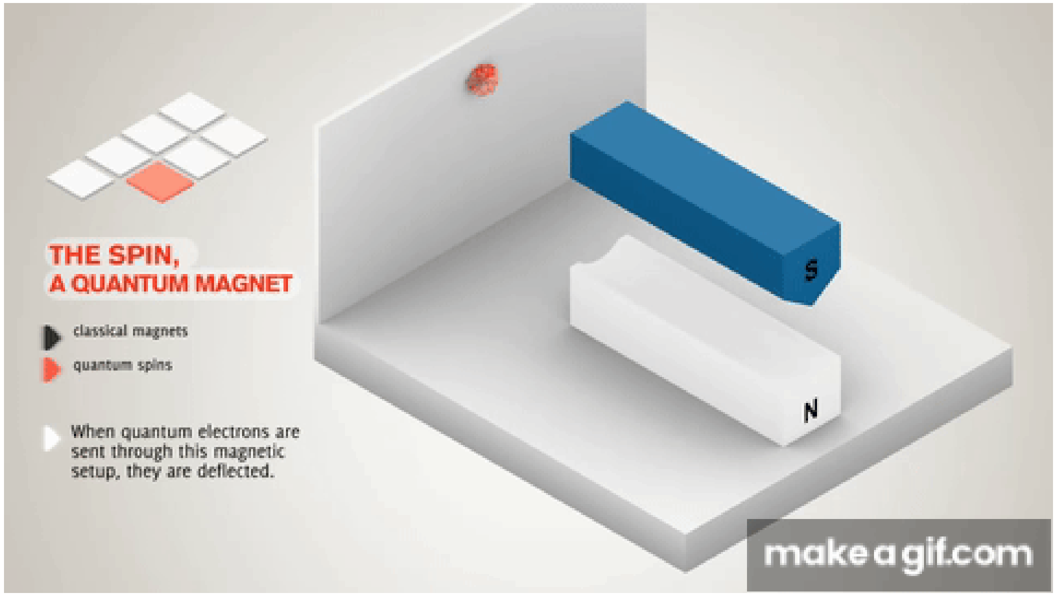
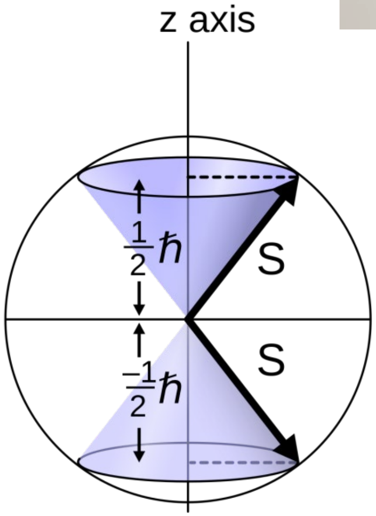
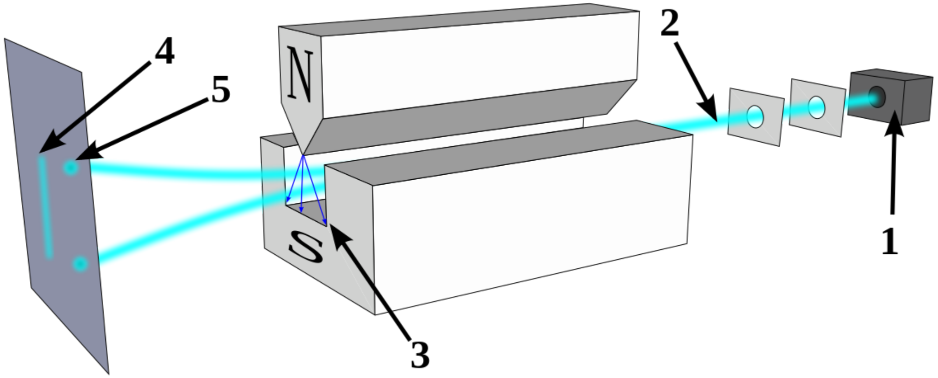
Classic Paper
on
Stern–Gerlach experiment







Deepak Kr Patel
23/03/2024

Ein Weg zur experimentellen Prüfung der Richtungsquantelung im Magnetfeld.

Von **Otto Stern** in Frankfurt a. Main.

Mit zwei Abbildungen. — (Eingegangen am 26. August 1921.)

In der Quantentheorie des Magnetismus und des Zeemaneffektes wird angenommen, daß der Vektor des Impulsmomentes eines Atoms nur ganz bestimmte diskrete Winkel mit der Richtung der magnetischen Feldstärke $\mathfrak{H}$ bilden kann, derart, daß die Komponente des Impulsmomentes in Richtung von $\mathfrak{H}$ ein ganzzahliges Vielfaches von $h/2\pi$ ist[1]). Bringen wir also ein Gas aus Atomen, bei denen das gesamte Impulsmoment pro Atom — die vektorielle Summe der Impulsmomente sämtlicher Elektronen des Atoms — den Betrag $h/2\pi$ hat, in ein Magnetfeld, so sind nach dieser Theorie für jedes Atom nur zwei diskrete Lagen möglich, da die Komponente des Impulsmomentes in Richtung von $\mathfrak{H}$ nur die beiden Werte $\pm h/2\pi$ annehmen kann. Denken wir z. B. an einquantige Wasserstoffatome, so müssen die Ebenen der Elektronenbahnen sämtlich senkrecht auf

A way towards the experimental examination of spatial quantisation in a magnetic field *

from **Otto Stern** in Frankfurt a. Main

With two figures. – (Received on the 26th August 1921)

In the quantum theory of magnetism and the Zeeman effect it is assumed that the angular momentum vector of an atom can only be at certain discrete angles with respect to the direction of the magnetic field strength $\mathfrak{H}$ in such a way that the component of the angular momentum in the direction of $\mathfrak{H}$ is an integer multiple of $h/2\pi$ [1]. If we thus take a gas of atoms, in which the total angular momentum per atom – the vectorial sum of the angular momenta of all the electrons in the atom – has the value $h/2\pi$, and place it in a magnetic field, then according to this theory there are

of magnitude of the effect is of concern, this assumption seems justifiable. Certainty about this, however can only be given by a rational quantum theory of dispersion.

A further difficulty for the quantum interpretation, as has already been noted from various quarters, is that one just cannot imagine how the atoms of the gas, whose angular momenta without magnetic field have all possible directions, are able, when brought into a magnetic field, to align themselves in the pre-ordained directions. Really, something com-

Stern and Gerlach: How a Bad Cigar Helped Reorient Atomic Physics

The history of the Stern–Gerlach experiment reveals how persistence, accident, and luck can sometimes combine in just the right ways.

Bretislav Friedrich and Dudley Herschbach

The demonstration of space quantization, carried out in Frankfurt, Germany, in 1922 by Otto Stern and Walther Gerlach, ranks among the dozen or so canonical experiments that ushered in the heroic age of quantum physics. Perhaps no other experiment is so often cited for elegant conceptual simplicity. From it emerged both new intellectual vistas and a host of useful applications of quantum science. Yet even among atomic physicists, very few today are aware of the historical particulars that enhance the drama of the story and the abiding lessons it offers. Among the particulars are a warm bed, a bad cigar, a timely postcard, a railroad strike, and an uncanny conspiracy of Nature that rewarded Stern and Gerlach. Their success in splitting a beam of silver atoms by means of a magnetic field startled, elated, and confounded pioneering quantum theorists, including several who beforehand had regarded an attempt to observe space quantization as naive and foolish.

time, which brought them to collaborate in Frankfurt. We also describe the vicissitudes and reception of the SGE, before and after the discovery of electron spin, and report how cigar smoke led us to a "back-to-the-future" deposition detector.[1] Mindful of the memorial plaque at Frankfurt, depicting Stern and Gerlach on opposite sides of their split molecular beam, we also invite readers to reflect on the later trajectories of these two fine scientists—impelled in opposite directions by the tragic rise to power of Adolf Hitler.

From osmotic soda to atomic beams

Otto Stern received his doctorate in physical chemistry at the University of Breslau in 1912. In his dissertation, he presented theory and experiments on osmotic pressure of concentrated solutions of carbon dioxide in various solvents—just generalized soda water. His proud parents offered to support him for postdoctoral study anywhere he liked. "Motivated by a spirit of adventure," Stern became the first pupil of Albert Einstein, then in Prague; their discussions were held "in a cafe which was attached to a brothel."[2] Soon Einstein was recalled to Zürich. Stern accompanied him there and was appointed *privatdozent* for physical chemistry.

Under Einstein's influence, Stern became interested in light quanta, the nature of atoms, magnetism, and statistical physics. However, Stern was shocked by the iconoclastic atomic model of Niels Bohr. Shortly after it appeared in mid-1913, Stern and his colleague Max von Laue made an earnest vow: "If this nonsense of Bohr should in the end prove to be right, we will quit physics!"[3] When Einstein moved to Berlin in 1914, Stern became *privatdozent*

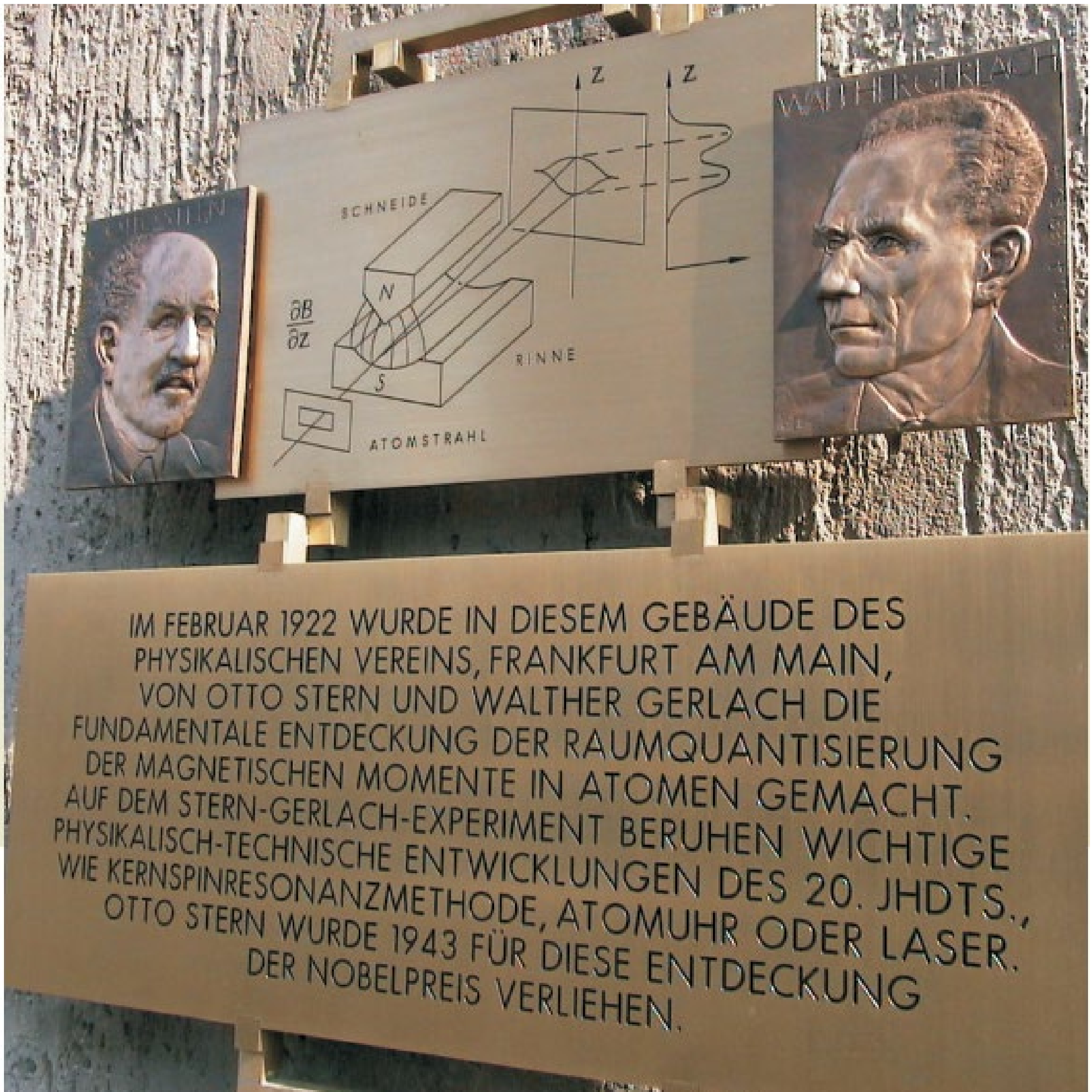
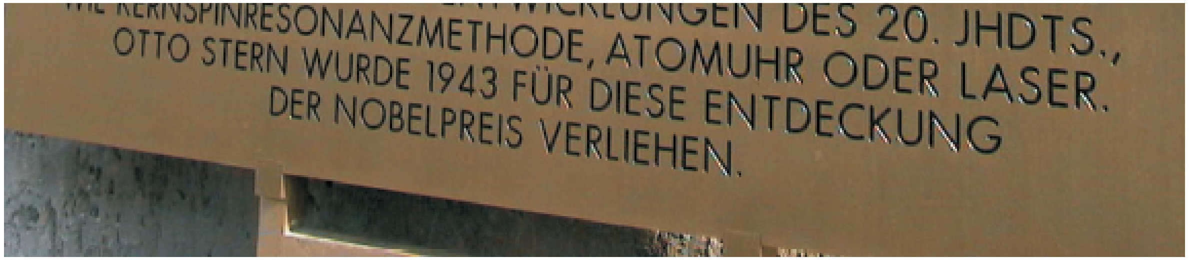


Figure 1. A memorial plaque honoring Otto Stern and Walther Gerlach, mounted in February 2002 near the entrance to the building in Frankfurt, Germany, where their experiment took place. The inscription, in translation, reads: "In February 1922 . . . was made the fundamental discovery of space quantization of the magnetic moments of atoms. The Stern–Gerlach experiment is the basis of important scientific and technological developments in the 20th century, such as nuclear magnetic resonance, atomic clocks, or lasers. . . ." The new Stern–Gerlach Center for Experimental Physics at the University of Frankfurt is under construction about 8 km north of the original laboratory. (Photo courtesy of Horst Schmidt-Böcking.)



with his student Elisabeth Borman, to measure the mean free path for a beam of silver atoms attenuated by air. In Stern's first beam experiment, reported in 1920 and motivated by kinetic theory, he determined the mean thermal velocity of silver atoms in a clever way. He mounted the atomic beam source on a rotating platform—a miniature merry-go-round—that spun at a modest peripheral velocity, only 15 meters per second. That produced a small centrifugal displacement of the beam indicative of its velocity distribution as imaged by faint deposits of silver. From the shift of those deposits, caused by reversing the direction of rotation, Stern was able to evaluate the far larger mean velocity of the atoms—about 660 m/s at 1000°C. Soon thereafter, his design for the SGE would invoke an analogue to test the Bohr model: A magnetic field gradient should produce opposite deflections of the beam atoms, according as the planetary electron rotates clockwise or counterclockwise about the field axis.

From thermal radiation to magnetic deflection

Walther Gerlach received his doctorate in physics at the University of Tübingen in 1912. His research dealt with blackbody radiation and the photoelectric effect. While serving in the military during World War I, Gerlach worked with Wilhelm Wien on the development of wireless telegraphy. After a brief interlude in industry, Gerlach obtained an appointment in 1920 at Frankfurt as assistant in the Institute for Experimental Physics, adjacent to Born's institute.

Gerlach's interest in molecular beams went back to 1912. Impressed by Dunoyer's observation of fluorescence from a sodium beam, Gerlach (see figure 3) had tried to observe emission from beams of a few different metals, without success.[5] At Frankfurt, he wanted to investigate whether a bismuth atom would show the same strong diamagnetism exhibited by a bismuth crystal. His plan was to deflect a beam of bismuth atoms in a strongly inhomogeneous field. In order to design a magnetic field with the highest practical gradient, he undertook experiments to test various geometrical configurations. Born doubted that the deflection experiment would prove worthwhile. Gerlach's response was to quote a favorite saying, later apt for the SGE as well: "No experiment is so dumb, that it should not be tried."[5]

Quandaries about space quantization

In 1921, the most advanced quantum theory was still the Bohr model, as generalized for a hydrogenic atom in 1916 by Arnold Sommerfeld and, independently, by Peter Debye. Their proposed quantization conditions implied that Bohr's quasiplanetary electron orbits should assume only certain discrete spatial orientations with respect to an external field. They were disappointed that invoking space quantization failed to elucidate the vexing problem of the "anomalous" Zeeman effect, the complex splitting patterns of spectral lines in a magnetic field. Although the "normal" Zeeman effect (much less common than the anomalous case) appeared consistent with space quantization, it was equally well accounted for by a classical model proposed in 1897 by Hendrick Lorentz. This spread bafflement and gloom among atomic theorists, as described by Wolfgang Pauli:

> The anomalous type . . . was hardly understandable, since very general assumptions concerning the electron, using classical theory as well as quantum theory, always led to the same triplet. . . . A colleague who met me strolling rather aimlessly in the beautiful streets of

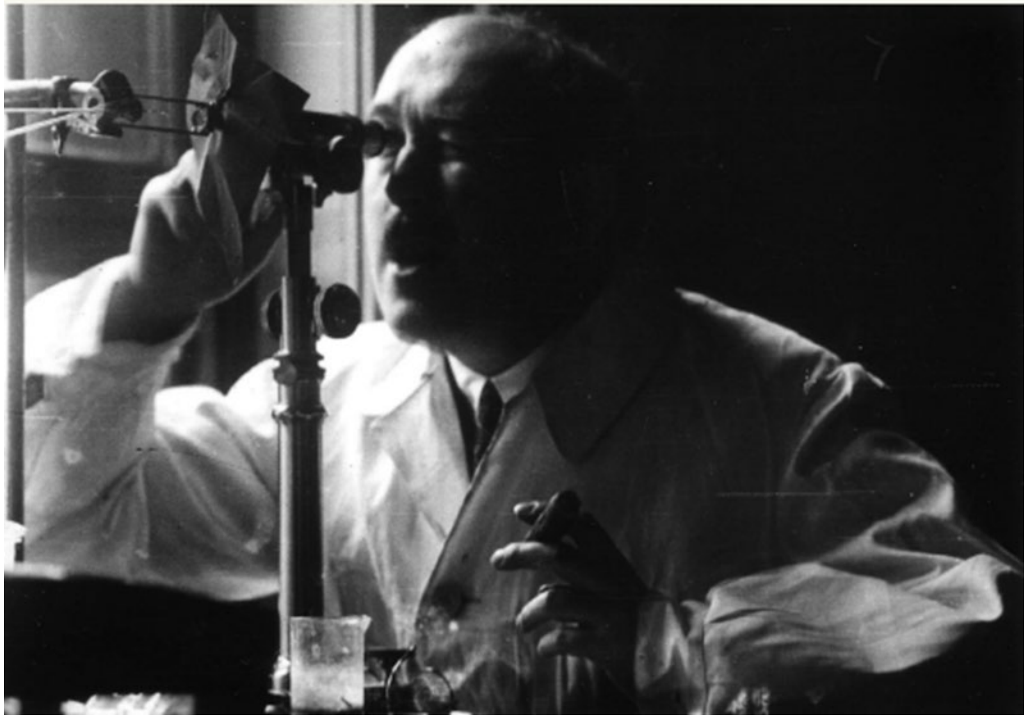


Figure 2. Otto Stern (1888–1969), cigar in hand, working in his molecular beam laboratory at the Institute for Physical Chemistry in Hamburg, about 1930. (Photo courtesy of Peter Toschek.)

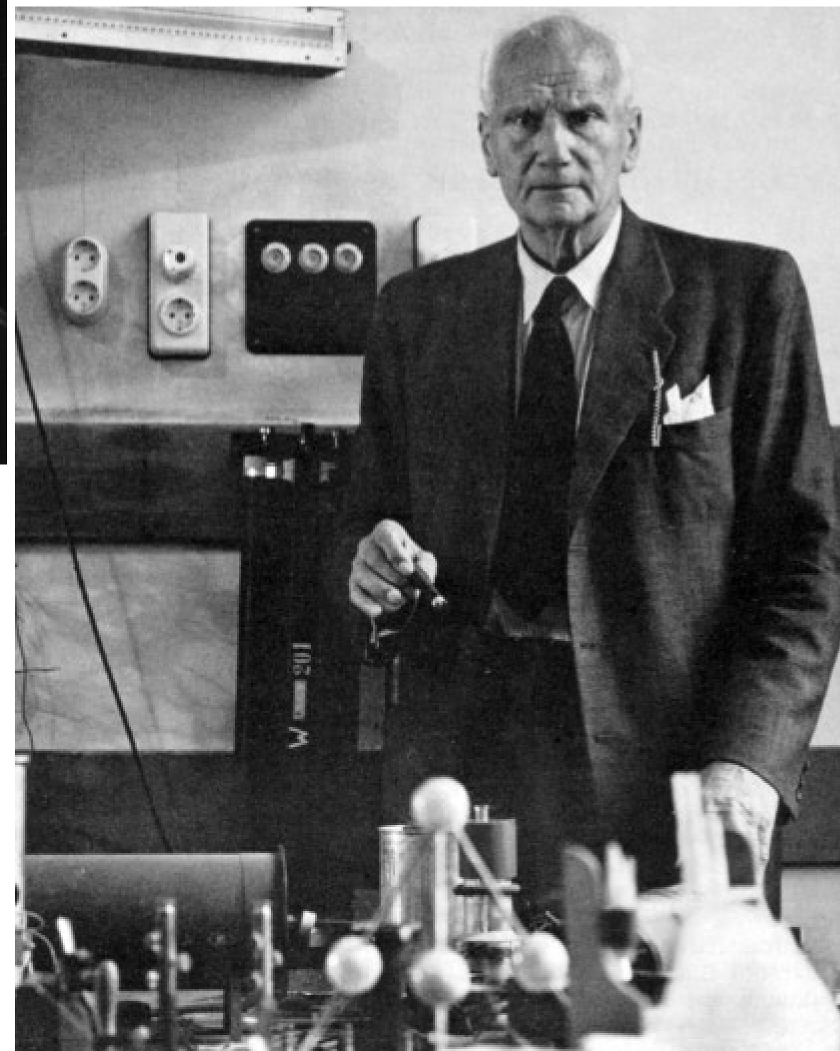
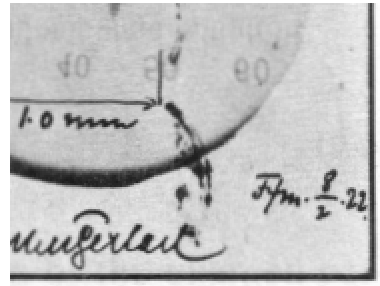


Figure 3. Walther Gerlach (1889–1979), cigar in hand, in his laboratory at the Institute for Physics in Munich, about 1950. (Photo courtesy of W. Schütz, *Phys. Bl.* **25**, 343, 1969.)

Happily, Stern found an eager recruit in Gerlach, who until then had not heard of space quantization.[10]

Despite Stern's careful design and feasibility calculations, the experiment took more than a year to accomplish. In the final form of the apparatus, a beam of silver atoms (produced by effusion of metallic vapor from an oven heated to 1000°C) was collimated by two narrow slits (0.03 mm wide) and traversed a deflecting magnet 3.5 cm long with field strength about 0.1 tesla and gradient 10 tesla/cm. The splitting of the silver beam achieved was only 0.2 mm. Accordingly, misalignments of collimating slits or the magnet by more than 0.01 mm were enough to spoil an experimental run. The attainable operating time was usually only a few hours between breakdowns of the apparatus. Thus, only a meager film of silver atoms, too thin to be visible to an unaided eye, was deposited on the collector plate. Stern described an early episode:

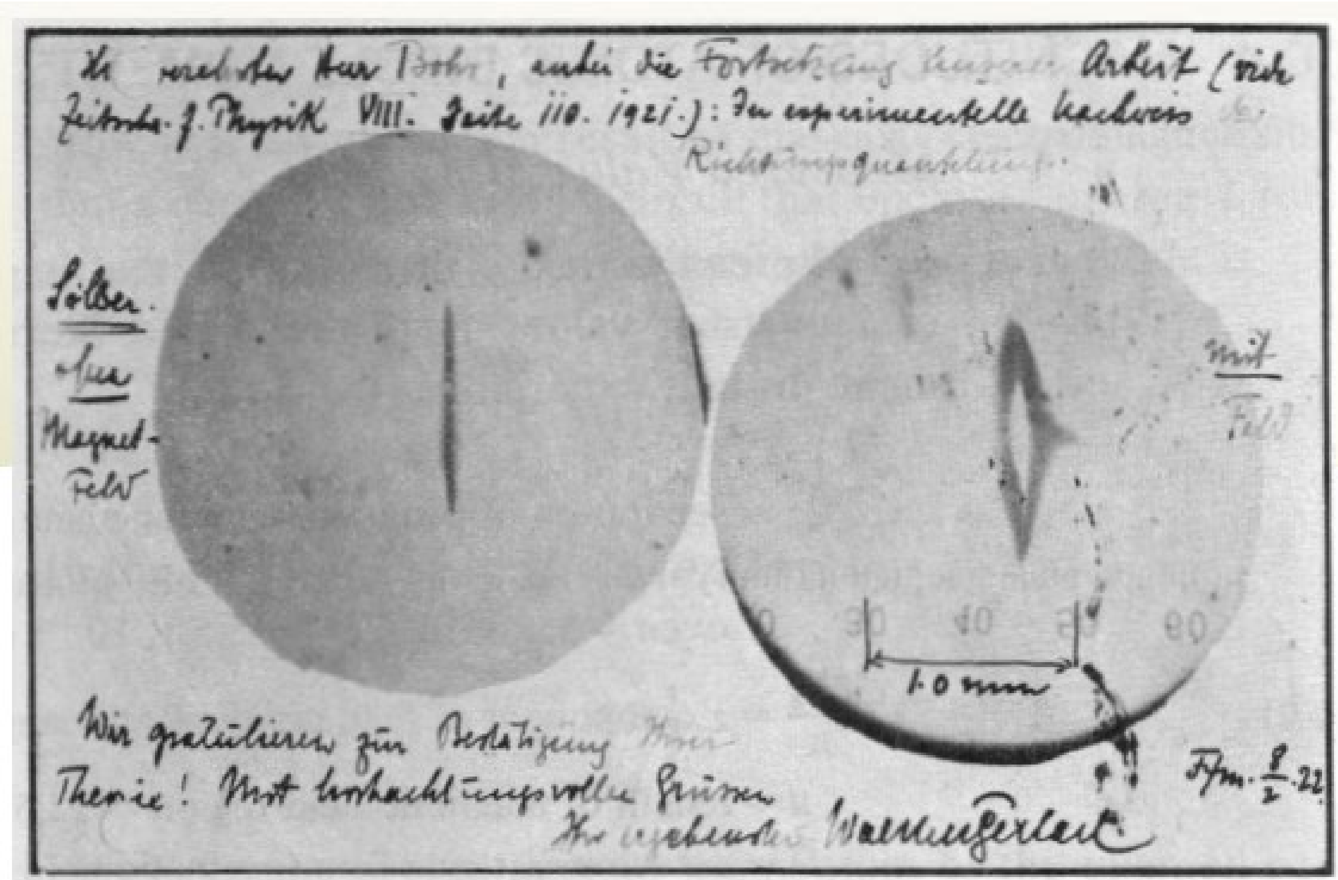
> After venting to release the vacuum, Gerlach removed the detector flange. But he could see no trace of the silver atom beam and handed the flange to me. With Gerlach looking over my shoulder as I peered closely at the plate, we were surprised to see gradually emerge the trace of the beam. . . . Finally we realized what [had happened]. I was then the equivalent of an assistant professor. My salary was too low to afford good cigars, so I smoked bad cigars. These had a lot of sulfur in them, so my breath on the plate turned the silver into silver sulfide, which is jet black, so easily visible. It was like developing a photographic film.[7]



After that episode, Gerlach and Stern began using a photographic development process, although both continued puffing cigars in the lab. Still, recalcitrant difficulties persisted. As inconclusive efforts continued for months, Stern's assessment of space quantization wavered between conviction and rejection. Gerlach also encountered doubtful colleagues, including Debye, who said, "But surely you don't believe that the [spatial] orientation of atoms is something physically real; that is [only] a timetable for the electrons."[10]

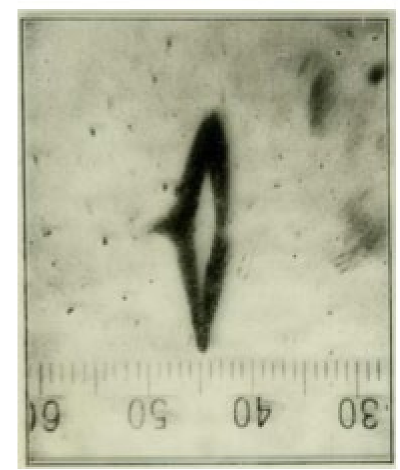
Goldman, a founder of the investment firm Goldman Sachs and progenitor of Woolworth Co stores, had family roots in Frankfurt.

Meanwhile, Stern had moved to the University of Rostock as a professor of theoretical physics. In early 1922, he and Gerlach met in Göttingen to review the situation and decided to give up. However, a railroad strike delayed Gerlach's return to Frankfurt, giving him a long day to go over all the details again. He decided to continue, improved the alignment, and soon achieved a clear splitting into two beams.[5] Stern recalled that his own surprise and excitement were overwhelming when he received a telegram from Gerlach with the terse message: "Bohr is right after all."[11] Gerlach also sent a postcard to Bohr with



Postcard dispatched by Gerlach to Niels Bohr on the day of the triumph, 8 February 1922,[18] p. 116. The microphotographs show the silver beam deposits obtained in the absence (left) and presence (right) of the magnetic field. In the absence of the magnetic field, the deposit corresponds to an image of the second collimation slit.

Figure 4. Gerlach's postcard, dated 8 February 1922, to Niels Bohr. It shows a photograph of the beam splitting, with the message, in translation: "Attached [is] the experimental proof of directional quantization. We congratulate [you] on the confirmation of your theory." (Courtesy AIP Emilio Segrè Visual Archives.)



a congratulatory message, showing a photograph of the clearly resolved splitting (see figure 4).

After further experimental refinements and careful analysis, Gerlach and Stern were even able to determine, within an accuracy of about 10%, that the magnetic moment of the silver atom was indeed one Bohr magneton. This direct demonstration of spatial quantization was immediately accepted as among the most compelling evidence for quantum theory (see the box at right). Yet the discovery was double-edged. Einstein and Paul Ehrenfest, among others, struggled to understand how the atomic magnets could take up definite, preordained orientations in the field. Because the interaction energy of atoms with the field differs with their orientation, it remained a mystery how splitting could occur when atoms entered the field with random orientations and their density in the beam was so low that collisions did not occur to exchange energy. Likewise, the lack of magnetic birefringence became a more insistent puzzle. Gerlach came to Rostock later in 1922 and tried in vain to observe it in sodium vapor; similar efforts by others had the same outcome.[5]

Those and other puzzles, such as the anomalous Zeeman effect, could not be cleared up until several years later, after the development of quantum mechanics and the inclusion of electron spin in the theory. Those advances made the Bohr model obsolete but enhanced the scope and significance of space quantization. The gratifying agreement of the Stern–

Reactions to the Stern–Gerlach Experiment

The following quotes from James Franck, Niels Bohr, and Wolfgang Pauli are among the messages that Walther Gerlach received in immediate response to postcards (like the one shown in figure 4) he had sent;[10] the quote from Arnold Sommerfeld appeared in the 1922 edition of his classic book;[17] that from Albert Einstein is in a March 1922 letter to Born;[18] that from I. I. Rabi is from reference 8, page 119. (See also Rabi's obituary for Otto Stern in PHYSICS TODAY, October 1969, page 103.)

Through their clever experimental arrangement Stern and Gerlach not only demonstrated *ad oculos* [for the eyes] the space quantization of atoms in a magnetic field, but they also proved the quantum origin of electricity and its connection with atomic structure.

—***Arnold Sommerfeld*** **(1868–1951)**

The most interesting achievement at this point is the experiment of Stern and Gerlach. The alignment of the atoms without collisions via radiative [exchange] is not comprehensible based on the current [theoretical] methods; it should take more than 100 years for the atoms to align. I have done a little calculation about this with [Paul] Ehrenfest. [Heinrich] Rubens considers the experimental result to be absolutely certain.

—***Albert Einstein*** **(1879–1955)**

More important is whether this proves the existence of space quantization. Please add a few words of explanation to your puzzle, such as what's really going on.

—***James Franck*** **(1882–1951)**

I would be very grateful if you or Stern could let me know, in a few lines, whether you interpret your experimental results in this way that the atoms are oriented only parallel or opposed, but not normal to the field, as one could provide theoretical reasons for the latter assertion.

—***Niels Bohr*** **(1885–1962)**

This should convert even the nonbeliever Stern.

—***Wolfgang Pauli*** **(1900–58)**

As a beginning graduate student back in 1923, I . . . hoped with ingenuity and inventiveness I could find ways to fit the atomic phenomena into some kind of mechanical system. . . . My hope to [do that] died when I read about the Stern–Gerlach experiment. . . . The results were astounding, although they were hinted at by quantum theory. . . . This convinced me once and for all that an ingenious classical mechanism was out and that we had to face the fact that the quantum phenomena required a completely new orientation.

—***Isidor I. Rabi*** **(1898–1988)**

Gerlach splitting with the old theory proved to be a lucky coincidence. The orbital angular momentum of the silver atom is actually zero, not $h/2\pi$ as presumed in the Bohr model. The magnetic moment is due solely to a half unit of spin angular momentum, which accounts for the twofold splitting. The magnetic moment is nonetheless very nearly one Bohr magneton, by virtue of the Thomas factor of two, not recognized until 1926. Nature thus was duplicitous in an uncanny way.

A curious historical puzzle remains. In view of the interest aroused by the SGE in 1922, we would expect that the postulation of electron spin in 1925 should very soon have led to a reinterpretation of the SGE splitting as really due to spin. However, the earliest attribution of the splitting to spin that we have found did not appear until 1927, when Ronald Fraser noted that the ground-state orbital angular momentum and associated magnetic moments of silver, hydrogen, and sodium are zero.[12] Practically all current textbooks describe the Stern–Gerlach splitting as demonstrating electron spin, without pointing out that the intrepid experimenters had no idea it was spin that they had discovered.

Yet another cigar

The late Edwin Land, when told the cigar story many years ago, immediately responded: "I don't believe it!" Therefore, for the Frankfurt dedication in February 2002, we reenacted the 80-year old event. In the original SGE, the beam image deposited on the collector plate comprised only about a monolayer of silver atoms (roughly 10^{16} atoms/cm^2). By heating a wire in vacuum, we evaporated a comparable amount of silver onto three glass slides. Then one of us (Friedrich), in the role of Gerlach, vented the chamber with dry nitrogen, removed the slides, and masked portions of them into the shape of the magnet pole pieces. Meanwhile, the other (Herschbach), in the role of Stern, had been puffing on a cheap cigar, to prepare tainted breath. One slide was then exposed at short range to that sulfurous breath; the second to puffs of smoke; the third only to the laboratory air a few meters distant. We looked for contrast between the masked and unmasked portions of the slides (see figure 5).

In accord with Land's skepticism, merely exhaling sulfurous breath on a slide, even vigorously, turned out to have no discernible effect. But exposure to cigar smoke quickly blackened the regions of the slide outside the mask, within a few seconds to a few minutes depending on whether the dose of smoke was profuse or mild. We think it likely that Stern did have a cigar in hand and baptized the detector plate with smoke, whereas Gerlach, busy venting the apparatus and removing the plate, was without his typical cigar. The fact that smoke did the trick,

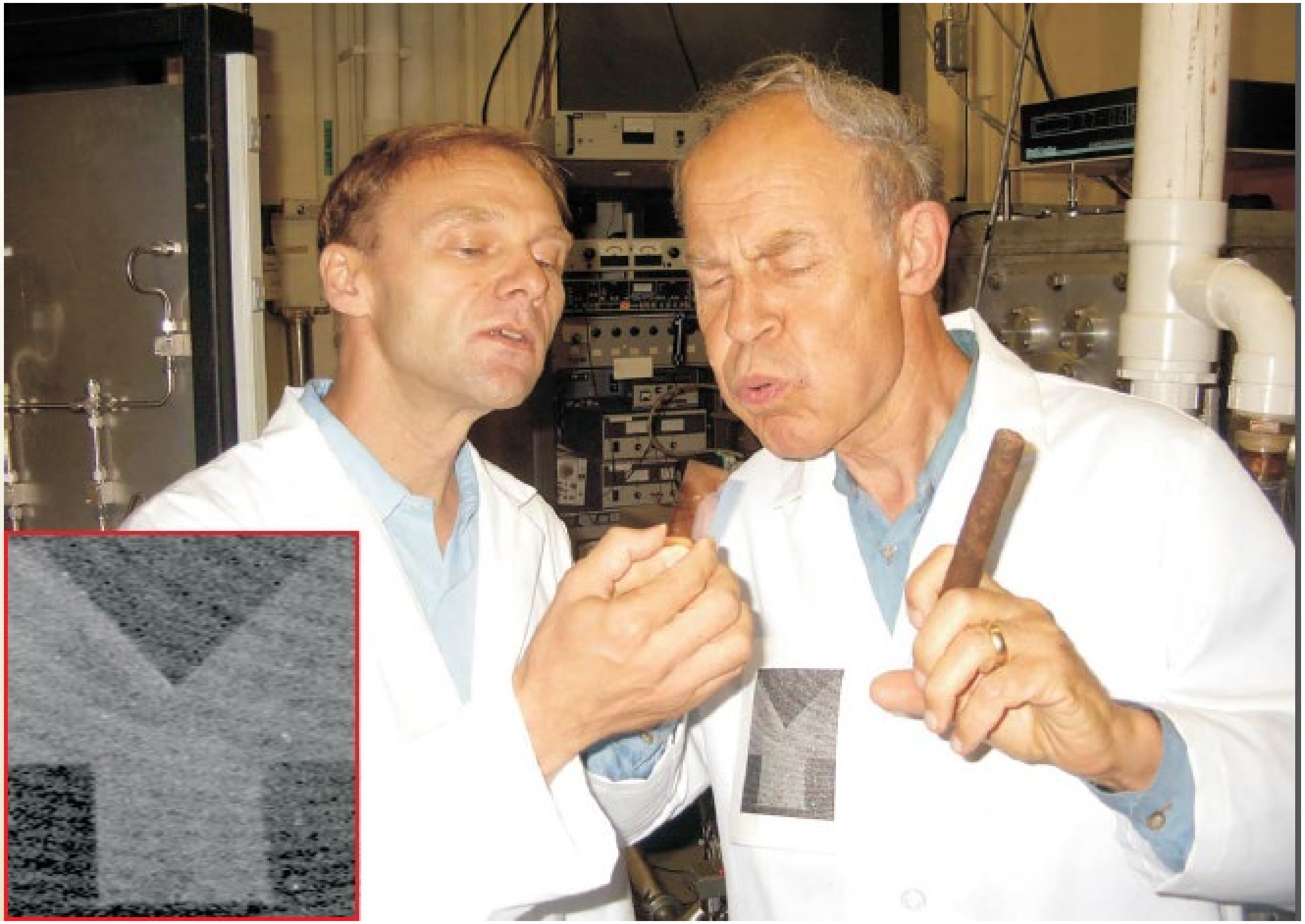


Figure 5. Reenactment of the Stern–Gerlach cigar episode by the authors. Bretislav Friedrich holds the slide as Dudley Herschbach blows sulfurous cigar breath onto a silver-coated glass slide to test his hearing (or Otto Stern's telling) of the story more than 40 years ago. The silver film turns out to require exposure to cigar smoke (not simply sulfurous breath) to form any visible contrast between the masked (light) part of the slide—shaped in the form of the magnet pole pieces—and the outer (dark) part of the slide exposed to the smoke (see inset). (Courtesy of Doo Soo Chung and Sunil Sheth.)

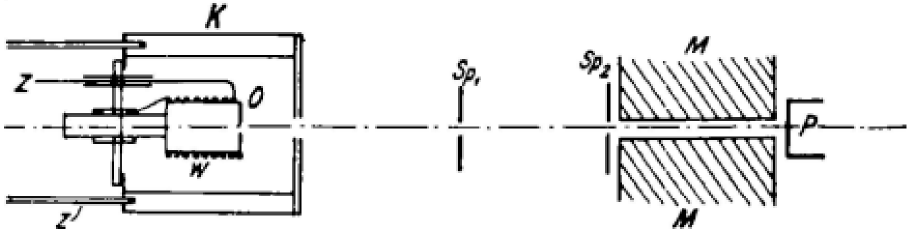


Figure 6. Schematic of the Stern–Gerlach apparatus. The silver beam effuses from an oven (O), passes through a pinhole (Sp_1) and a rectangular slit (Sp_2) before it enters the magnetic field generated by the pole pieces (M) and finally reaches the collector plate (P). The distances between the components of the 3rd generation apparatus (that made it possible to see the splitting of the silver beam for the first time) were as follows: O to exit pinhole from cooler, 2–3 cm; exit pinhole from cooler to rectangular collimation slit Sp_2, 7–12 cm; path through the magnetic field, 3 cm. The measured maximum inhomogeneity of the magnetic field in the beam region was about 23 kG/cm. Reproduced from Ref. [20].

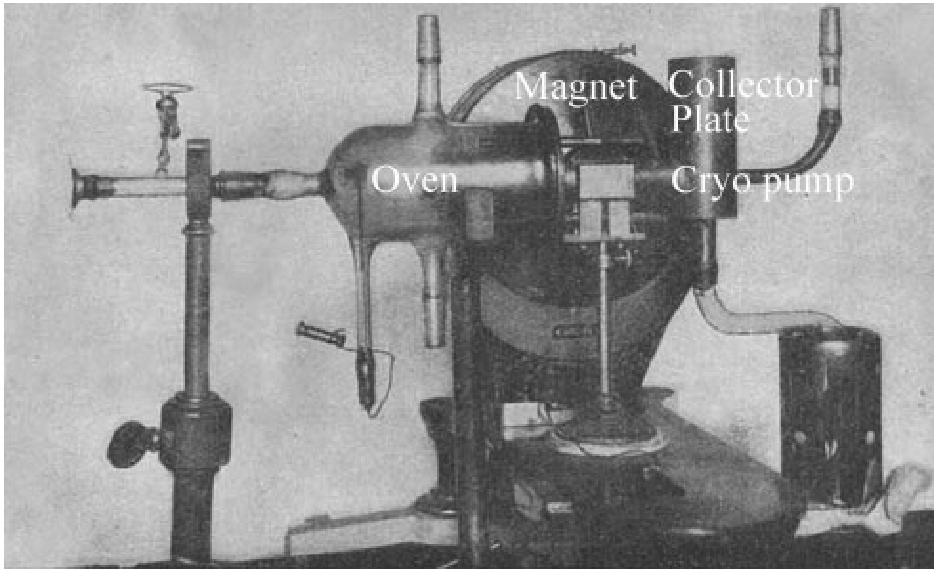
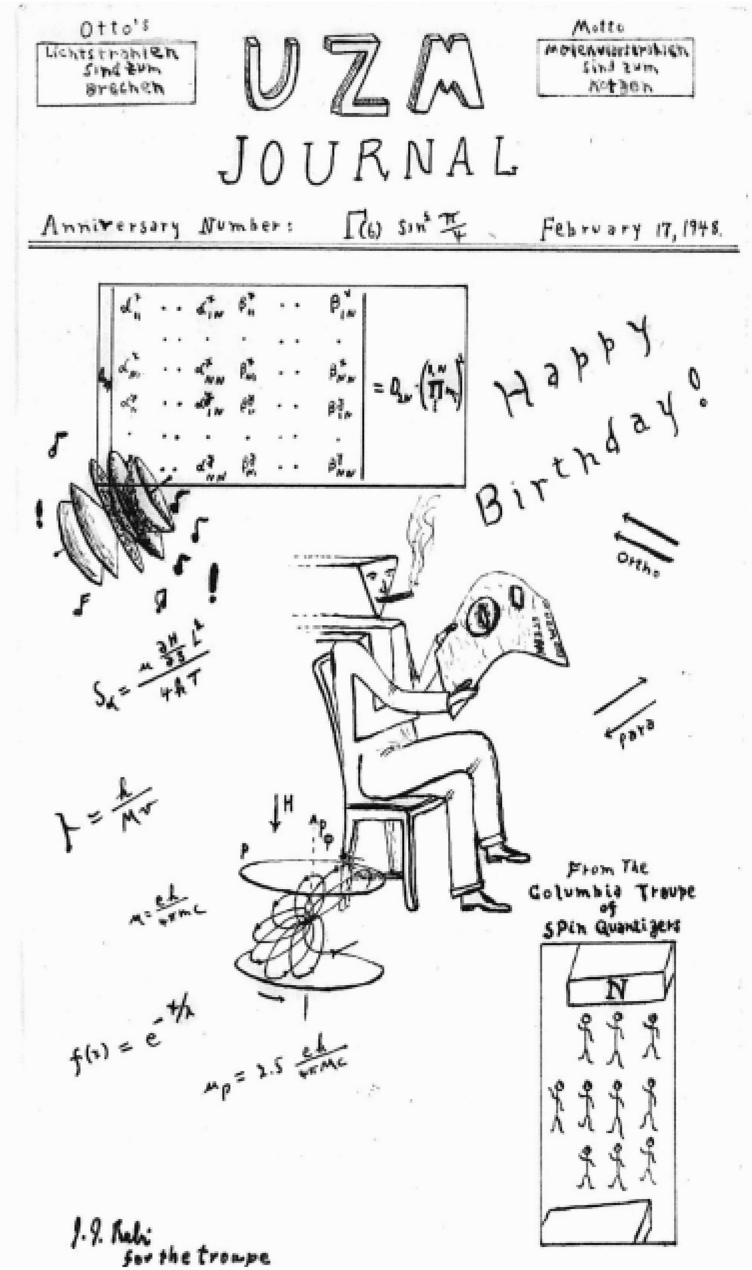
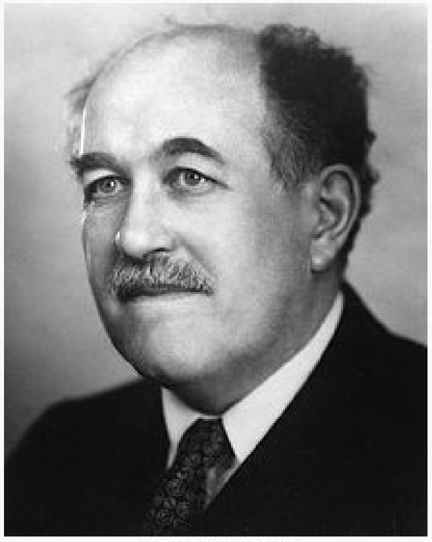


Figure 7. Photograph of the Stern–Gerlach apparatus with improvements of 1922–1924 (4th generation). See also Figure 6. Adapted from Ref. [25].



A drawing by Isidor Rabi presented to Otto Stern on his 60th birthday, on 17 February 1948. The drawing features a smorgasbord of milestone achievements of Stern's Hamburg group in the format of a page from an "Anniversary Number" of a fictitious journal dedicated to publishing Stern's molecular beam research. The name of the journal, "UZM," is an allusion to the series entitled Untersuchungen zur Molekularstrahlmethode (UzM) [Investigations by the Molecular Beam Method] of thirty numbered papers published between 1926 and 1933 by Stern's Hamburg institute in Zeitschrift für Physik

Otto Stern



Stern in 1950s

Born	17 February 1888 Sohrau, Kingdom of Prussia, German Empire (today Żory, Poland)
Died	17 August 1969 (aged 81) Berkeley, California, United States
Nationality	Germany, United States
Alma mater	University of Breslau University of Frankfurt
Known for	Stern–Gerlach experiment Stern model Spin quantization Molecular beam Stern–Volmer relationship
Awards	Nobel Prize in Physics (1943)
Scientific career	
Fields	Physics
Institutions	University of Rostock University of Hamburg Carnegie Institute of Technology University of California, Berkeley ETH Zurich
Doctoral advisor	Otto Sackur

He was the second most nominated physicist for a Nobel Prize, with 82 nominations in the years 1925–1945[1] (most times nominated is Arnold Sommerfeld with 84 nominations), ultimately winning in 1943.

It was awarded to Stern alone, "for his contribution to the development of the molecular ray method and his discovery of the magnetic moment of the proton" (not for the Stern–Gerlach experiment)

Thank You!

Walther Gerlach

Born	1 August 1889 Biebrich, Hessen-Nassau, German Empire
Died	10 August 1979 (aged 90) Munich, West Germany
Nationality	German
Alma mater	Eberhard Karls University of Tübingen
Known for	Stern–Gerlach experiment
Scientific career	
Fields	Experimental Physics
Institutions	Johann Wolfgang Goethe University of Frankfurt am Main Eberhard Karls University of Tübingen
Academic advisors	Friedrich Paschen
Doctoral students	Gertrude Scharff Goldhaber[1] Heinz Billing[2]