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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.

Descendants of the Stern–Gerlach experiment (SGE) and its key concept of sorting quantum states via space quantization are legion. Among them are the prototypes for nuclear magnetic resonance, optical pumping, the laser, and atomic clocks, as well as incisive discoveries such as the Lamb shift and the anomalous increment in the magnetic moment of the electron, which launched quantum electrodynamics. The means to probe nuclei, proteins, and galaxies; image bodies and brains; perform eye surgery; read music or data from compact disks; and scan bar codes on grocery packages or DNA base pairs in the human genome all stem from exploiting transitions between space-quantized quantum states.

A new center for experimental physics at the University of Frankfurt was recently named in honor of Stern and Gerlach (see figure 1). The opportunity to take part in the dedication prompted us to reenact the cigar story, as told to one of us (Herschbach) by Stern himself more than 40 years ago. Here we briefly trace the antecedent trajectories of Stern and Gerlach and the perplexing physics of the

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* for theoretical physics at Frankfurt. World War I soon intervened, but even while serving in the German army, Stern managed to do significant work, including an unsuccessful but prescient experiment, an attempt to separate by diffusion a suspected hydrogen isotope of mass two.

After the war, Stern returned to Frankfurt and became assistant to Max Born in the Institute for Theoretical Physics. There began Stern’s molecular beam odyssey (see figure 2). He had learned of the rudimentary experiments of Louis Dunoyer in 1911, which demonstrated that “molecular rays” of sodium, formed by effusion into a vacuum, traveled in straight lines. Stern was captivated by the “simplicity and directness” of the method, which “enables us to make measurements on isolated neutral atoms or molecules with macroscopic tools. . . [and thereby] is especially valuable for testing and demonstrating directly fundamental assumptions of the theory.”⁴

Born strongly encouraged Stern to pursue molecular beam experiments. Indeed, in 1919, Born himself undertook,

Bretislav Friedrich (bretislav.friedrich@thi-berlin.mpg.de) has recently moved from Harvard University in Cambridge, Massachusetts, to become a senior scientist at the Fritz Haber Institute of the Max Planck Society in Berlin. **Dudley Herschbach** (hbach@chemistry.harvard.edu) is a professor in the department of chemistry and chemical biology at Harvard.



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 ob-

serve 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.”⁶

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.)

Copenhagen said to me in a friendly manner, “You look very unhappy,” whereupon I answered fiercely, “How can one look happy when he is thinking of the anomalous Zeeman effect?”⁶

Pauli, as well as Stern, had also made efforts to refine the theory of ferromagnetism advanced in 1913 by Pierre Weiss. That theory, still useful today, envisioned magnetic domains within a metal. However, it implied that the average magnetic moment of an atom in a fully magnetized sample of iron was much smaller than the Bohr magneton—the magnetic moment of an electron, $\mu_B = (e/2mc)(\hbar/2\pi)$ —by about a factor of five. In an attempt to account for the difference, Pauli invoked space quantization. In 1920, by carrying out a statistical average over the projection quantum numbers, he concluded that the net effective atomic moment should indeed be much smaller than the Bohr magneton. Pauli’s basic model was wrong, as it considered only orbital magnetism; spin, still undiscovered in 1920, has a major role both in ferromagnetism and in the anomalous Zeeman effect. Nevertheless, Pauli’s appeal to space quantization of atomic magnets helped make colleagues, including Stern, mindful of the idea.

For Stern, the immediate stimulus for the SGE was a property implied by space quantization of the Bohr model that had *not* been observed. The model appeared to require that a gas of hydrogenic atoms would be magnetically birefringent, because the electron would orbit in a plane perpendicular to the field direction. Stern recalled that the birefringence question was raised at a seminar. The next morning he woke up early, but it was too cold to get out of bed, so he “lay there thinking and had the idea for the experiment.”⁷

He recognized that, according to the Bohr model, the space quantization should be only twofold, as the projection of the orbital angular momentum was limited to $\pm\hbar/2\pi$ (although Bohr, among others, had become uneasy that his model excluded a zero value). The twofold character made feasible a decisive test of spatial quantization using magnetic deflection of an atomic beam. Despite the smearing effect of the velocity distribution, in a strong enough field gradient the two oppositely oriented components should be deflected outside the width of the original beam. Classical mechanics, in contrast, predicted that the atomic magnets would precess in the field but remain randomly oriented, so the deflections would only broaden (but not split) the beam. Thus, Stern thought he had in prospect an experiment that, “if successful, [will] decide unequivocally between the quantum theoretical

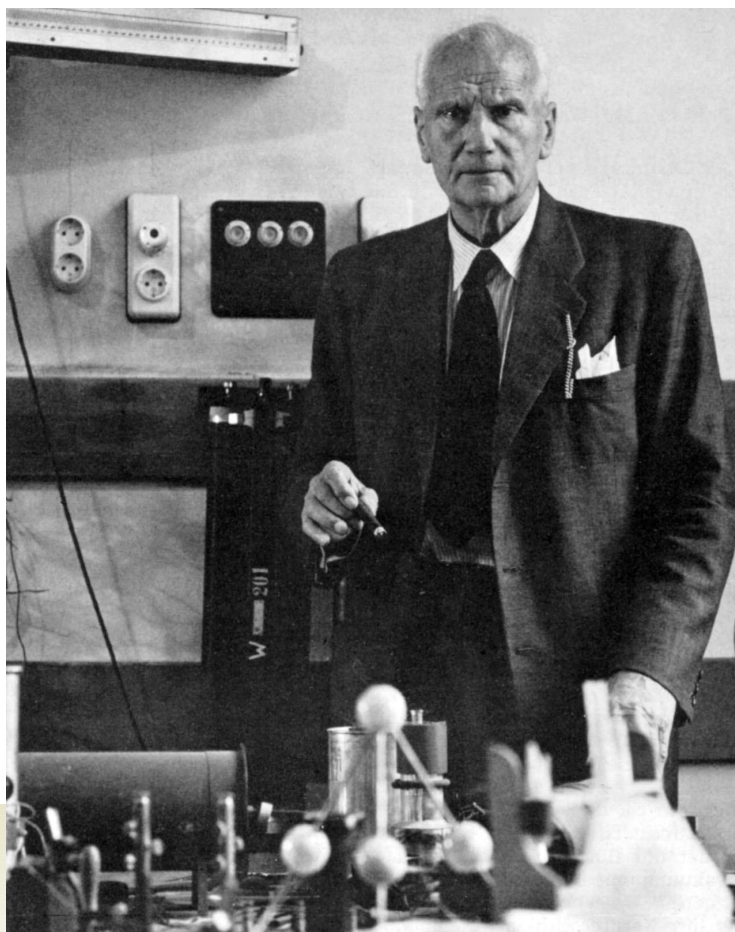


Figure 3. Walther Gerlach (1889–1979), cigar in hand, in his laboratory at the Institute for Physics in Munich, about 1950. (Photo courtesy of W. Schütz, *Phys. Bl.* 25, 343, 1969.)

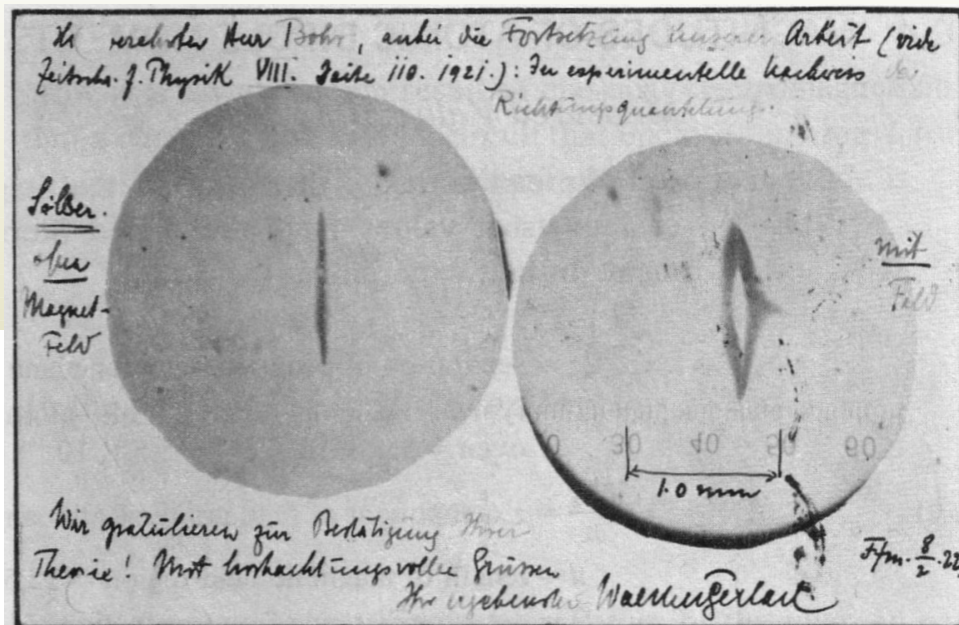


Figure 4. Gerlach's postcard, dated 8 February 1922, to Niels Bohr. It shows a photograph of the beam splitting, with the message, in translation: "Attached [is] the experimental proof of directional quantization. We congratulate [you] on the confirmation of your theory." (Courtesy AIP Emilio Segrè Visual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

and classical views."⁸

From Gedanken to Danken

After hatching his idea in a warm bed, Stern hastened to Born, but met a cool reception. In his autobiography, Born said,

It took me quite a time before I took this idea seriously. I thought always that [space] quantization was a kind of symbolic expression for something which you don't understand. But to take this literally like Stern did, this was his own idea. . . . I tried to persuade Stern that there was no sense [in it], but then he told me that it was worth a try.⁹

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

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

Another handicap was the financial disarray that began to beset Germany. Born was unstinting in efforts to raise funds to support the SGE. He took advantage of the great interest in Einstein and relativity theory by presenting a series of public lectures "in the biggest lecture hall of the University . . . and charged an entrance fee. . . . The money thus earned helped us for some months, but as inflation got worse . . . new means had to be found."⁸ Born mentioned this situation "jokingly" to a friend who was departing on a trip to New York; he was incredulous when, a few weeks later, a postcard arrived simply saying that he should write to Henry Goldman and giving the address:

At first I took it for another joke, but on reflection I decided that an attempt should be made. . . . [A] nice letter was composed and dispatched, and soon a most charming reply arrived and a cheque for some hundreds of dollars. . . . After Goldman's cheque had saved our experiments, the work [on the Stern–Gerlach experiment] went on successfully.⁹

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

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–Gerlach splitting with the old theory proved to be a lucky coincidence. The orbital angular momentum of the silver atom is actually zero, not $\hbar/2\pi$ 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,

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)

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/cm²). 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.)



rather than just bad breath, might have been missed 40 years later in the telling (or the hearing) of the cigar story.⁷

The reenactment inspired us to try a silver coated silicon wafer as a deposition detector for molecular beams, using an optical microscope backed by a charge-coupled device camera to read the images. In work carried out with Doo Soo Chung, a professor of chemistry at Seoul University in Korea, and Sunil Sheth, an undergraduate student at Harvard University, we found that the setup provided a simple means to detect beams at monolayer intensities with spatial resolution of a few microns. The detector is not limited to sulfur compounds; it responds well to hydrogen bromide and other halogens and likely will work well for many molecules that react with silver.

Abiding legacy amid bitter ashes

Late in 1922, Stern became professor of physical chemistry at the University of Hamburg. There he undertook an ambitious program to develop molecular beam methods.⁸ The program included major tests of several fundamental aspects of quantum mechanics.¹³ His crowning achievement, in collaboration with Immanuel Estermann and Otto Frisch, was the discovery of the anomalous magnetic moments of the proton and deuteron in 1933. That discovery astounded theorists and had a profound impact on nuclear physics: It revealed that the proton and neutron were not elementary particles but must have internal structure. The experiments were far more difficult than the original SGE, because the magnetic moments of nuclei are a thousand times smaller than those for electrons. Moreover, as Estermann describes it, the work had to be done “with the sword of Nazism hanging over our heads.”⁹ Stern and his colleagues soon had to emigrate; Stern came to the US but never regained a pacesetter role in research. That role passed to I. I. Rabi, who had become imbued with molecular beams as a postdoctoral fellow at Hamburg.^{14,15}

Gerlach, his reputation enhanced by the SGE, also did much further enterprising research. However, after studying the magnetic deflection of bismuth and several other

metals, he did not continue using molecular beams. Rather, he pursued a major series of experiments to elucidate mysterious aspects of the radiometer effect. Already by 1923, he and his student Alice Golsen had made the first accurate measurements of radiation pressure. In accord with classical theory, their results showed that the pressure was proportional to the light intensity and independent of the wavelength. Much of his later research dealt with chemical analysis, ferromagnetism, and materials science. In 1925, Gerlach returned to Tübingen as professor of experimental physics; there he inherited the chair that had been held by his mentor Friedrich Paschen. Four years later, Gerlach moved on to Munich as successor to Wilhelm Wien and continued there until retirement in 1957.

During the Third Reich, Gerlach steadfastly resisted fanatics who attacked Einstein and “Jewish science”; he never joined the Nazi party. Yet in 1944, he became head of the German nuclear research program. At the end of the war, Gerlach was among the ten leading German scientists detained at Farm Hall by Allied forces. When news came of the nuclear bomb dropped on Hiroshima, Gerlach “behaved like a routed general and apparently suffered a nervous breakdown of sorts;” some colleagues even feared he was contemplating suicide.¹⁶ Later, he contributed much to the rebuilding of German science and campaigned to ban nuclear weapons.

Stern became a US citizen in 1939 and, during World War II, served as a consultant to the War Department (since renamed). In 1945, he retired and settled in Berkeley, California. He often traveled to Europe, but “never revisited Germany and refused to collect the pension due him, expressing in this way his abomination for Nazism.”¹¹ He kept in touch with some German friends, and during the postwar trauma sent them care packages.

Stern and Gerlach met again only once—in Zürich in the early 1960s. In an obituary written for Stern a few years later, Gerlach emphasized: “Whoever knew [Stern] appreciated his open-mindedness [and] . . . unconditional reliability.” Then Gerlach closed with: “At his farewell from

Frankfurt, I gave him, in memory of the months of hopeless striving to see space quantization, an ashtray with an inscription. . . . This ashtray endured all those years till Berkeley—but our experimental apparatus, lab books, and the originals of our results had burned during the Second World War.⁷¹⁰ Like so much else, reduced to ashes.

We are grateful to Horst Schmidt-Böcking and Helmut Rechenberg for helpful information, to Doo Soo Chung and Sunil Sheth for undertaking a project that involves cigar smoke and silver mirrors, and to NSF, the US Department of Energy, and Petroleum Research Fund for financial support.

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