Chapter 5
Otto Stern's Molecular Beam Method and Its Impact on Quantum Physics

Bretislav Friedrich and Horst Schmidt-Böcking

Abstract Motivated by his interest in thermodynamics and the emerging quantum mechanics, Otto Stern (1888–1969) launched in 1919 his molecular beam method to examine the fundamental assumptions of theory that transpire in atomic, molecular, optical, and nuclear physics. Stern's experimental endeavors at Frankfurt (1919–1922), Hamburg (1923–1933), and Pittsburgh (1933–1945) provided insights into the quantum world that were independent of spectroscopy and that concerned well-defined isolated systems, hitherto accessible only to *Gedanken* experiments. In this chapter we look at how Stern's molecular beam research came about and review six of his seminal experiments along with their context and reception by the physics community: the Stern-Gerlach experiment; the three-stage Stern-Gerlach experiment; experimental evidence for de Broglie's matter waves; measurements of the magnetic dipole moment of the proton and the deuteron; experimental demonstration of momentum transfer upon absorption or emission of a photon; the experimental verification of the Maxwell-Boltzmann velocity distribution via deflection of a molecular beam by gravity. Regarded as paragons of thoroughness and ingenuity, these experiments entail accurate transversal momentum measurements with resolution better than 0.1 atomic units. Some of these experiments would be taken up by others where Stern left off only decades later (matter-wave scattering or photon momentum transfer). We conclude by highlighting aspects of Stern's legacy as reflected by the honors that have been bestowed upon him to date.

1 Prolog

Otto Stern (1888–1969) is primarily known for developing the molecular beam method into a powerful tool of experimental quantum physics. His seminal molecular beam experiments, carried out during the period 1919–1945 in Frankfurt, Ham-

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burg, and Pittsburgh, were conceived as "questions posed to nature." The relentless answers nature provided were often at odds with expectations based either on contemporary theory or on intuition, including Stern's own. Prime examples of Stern's experiments with unexpected—and far-reaching outcomes—include those on space quantization[1] and the magnetic moment of the proton and deuteron. In 1944, Otto Stern was awarded the 1943 Nobel prize in Physics (unshared) "for his contribution to the development of the molecular ray [beam] method and his discovery of the magnetic moment of the proton." In his Nobel lecture, delivered in 1946, Stern extolled the virtues of molecular beams: "The most distinctive characteristic property of the molecular ray method is its simplicity and directness. It enables us to make measurements on isolated neutral atoms or molecules with macroscopic tools. For this reason it is especially valuable for testing and demonstrating directly fundamental assumptions of the theory."

The majority of Stern's publications, fifty-seven out of a total of seventy-two, deal with atomic, molecular, optical, and nuclear physics problems. Besides, Stern maintained an abiding interest in thermodynamics in general and the concept of entropy in particular. Although only fifteen of Stern's publications tackle topics from physical chemistry, among them his acclaimed paper on the electric double-layer (Stern 1924), and thermodynamics, including his last paper (Stern 1962), Stern's recently published correspondence reveals that he exchanged many more letters about these subjects than about his pursuits in atomic and molecular physics—roughly in the inverse ratio of his published works on these two subjects. Stern's correspondents included his friend and mentor Albert Einstein (1879–1955) as well as his friends and colleagues Wolfgang Pauli (1900–1958) and Niels Bohr (1885–1962). What especially preoccupied Stern was the relationship between entropy (degree of order) and quantum mechanics (Stern 1962) and the issue of the reversibility of measurements (Schmidt-Böcking et al. 2019). Stern's principal correspondent on the topic of molecular beams was his former assistant, Isidor Rabi (1898–1988).

Stern's deep interest in thermodynamics dates back to his apprenticeship, Fig. 1, at the University of Breslau with the pioneer of quantum statistical mechanics Otto Sackur (1880–1914). Sackur, Fig. 2, was one of the first to apply quantum ideas to a non-periodic motion, namely to the translation of atoms/molecules in a gas (Sackur 1911; Badino and Friedrich 2013). He recognized that Planck's quantum of action, h, enters the treatment of a gaseous system by quantizing its phase space and, based on this insight, derived a quantum expression for the entropy of a monoatomic gas, known as the Sackur-Tetrode equation (Tetrode 1912).

After completing his doctoral thesis, Stern joined Einstein in April 1912 at the German University in Prague[2] and moved on with him the same year to the ETH Zurich, where, under Einstein's auspices, he became *Privatdozent* for theoretical physics, in 1913 (Fig. 3). On invitation from Max von Laue (1879–1960), Stern

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[1] Space quantization is a commonly accepted translation of the original German term *Richtungsquantelung*.

[2] Stern's contact to Einstein was mediated by Sackur via Sackur's and Einstein's common colleague and friend Fritz Haber (1868–1934).

Fig. 1 Otto Stern (1888–1969), about 1912 (OSC)

would serve in the same capacity at the Royal University of Frankfurt, established in August 1914, two weeks after the outbreak of World War One.

During his time in Prague and Zurich, Stern would attend Einstein's lectures on theoretical physics and, as Einstein's sparring partner, develop a penchant for unconventional, out-of-the-box thinking.[3] Attracted to Einstein mainly because of his work on quantum physics, Stern and Einstein would co-author a paper on the zero-point energy of gaseous systems as exemplified by molecular hydrogen (Einstein and Stern 1913). This paper was written in response to an experiment by Arnold Eucken (1884–1950), which revealed anomalous behavior of hydrogen's heat capacity at low temperatures (Eucken 1912). During the war years, Stern continued mulling over, corresponding (Schulmann et al. 1998; Docs. 191, 192, 198, 201, 205), (Schmidt-Böcking et al. 2019; pp. 32–38), and publishing on related themes (Stern 1916a,b).

After a post-war interlude in the laboratory of Walther Nernst (1865–1941) at the Berlin University, where he worked with Max Volmer (1885–1965) on the kinetics of fluorescence, Stern returned in 1919 to his post at the Institute for Theoretical Physics at Frankfurt. Max von Laue swapped meanwhile his position with his Berlin colleague Max Born (1882–1970), who became the new head of the Frankfurt Institute. The institute occupied just two rooms in the Arthur von Weinberg-Haus on Robert-Meyer-Strasse 2, and consisted, apart from Born, of two assistants—Elisabeth Bormann and

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[3] In German, one would call this ability *Querdenken*.

Fig. 2 Otto Sackur (1880–1914) (Badino and Friedrich 2013)

Otto Stern, and a technician, Mr. Adolf Schmidt. It was in this setting that Otto Stern launched his epochal molecular beam research. But why did he?

Stern revealed his motive in his paper on the thermal molecular velocities (Stern 1920b): as a follow-up to his 1913 paper with Einstein, he set out to examine whether the classical Maxwell-Boltzmann distribution of molecular velocities is the whole story or whether zero-point energy plays a role and manifests itself in distorting the classical thermal velocity distribution. Based on his ingenious experiment, described in detail, along with its reproduction, in Chap. 9, Stern concluded that the velocity distribution of a gas was Maxwell-Boltzmannian, with a root-mean-square velocity $\sqrt{3kT/m}$, with k the Boltzmann constant, T the absolute temperature, and m the atomic/molecular mass. Curiously, the evaluation of the experiment had to undergo an amendment—due to Einstein, who noticed that Stern had not used the correct root-mean-square velocity formula, $\sqrt{4kT/m}$, to compare his experimental result with (Stern 1920c), (Buchwald et al. 2012; p. 355). What remains puzzling is how Stern could have inferred from measuring just the root-mean-square velocity (with an error of about 5%) of a hot silver beam that the velocity distribution was undistorted by the zero-point energy or any other effects. However, at the end of his career as

Fig. 3 1913 in Pierre Weiss' laboratory in Zürich. From left: Karl Herzfeld (1892–1978), Otto Stern, Albert Einstein, and Auguste Piccard (1884–1962) (OSC)

an experimentalist, Stern would undertake a measurement of the complete velocity distribution and find a distorted Maxwell-Boltzmann distribution—due to scattering of slow molecules, see Sect. 2.6.

Hence it was Stern's dual interest in thermodynamics and quantum theory that motivated his work with molecular beams, whose rudimentary form was first implemented by Louis Dunoyer (1880–1963) in 1911 (Dunoyer 1911).

We note that the anomalous behavior of the heat capacity of hydrogen (Eucken 1912) that Stern and Einstein sought to explain in terms of the zero-point energy was in fact due to the existence of hydrogen's ortho and para allotropic modifications, see Sect. 2.4.

Whereas Stern's first molecular beam experiment did not answer his fundamental question about the manifestation of a quantum effect in the affirmative, his second did: the Stern-Gerlach experiment surprisingly confirmed the existence of space quantization, a concept developed, independently, by Arnold Sommerfeld (1868–1951) (Sommerfeld 1916) and Peter Debye (1884–1966) (Debye 1916), with two major corollaries: the quantization of electronic angular momenta in an atom in units of $\hbar \equiv h/(2\pi)$, as predicted by Bohr's model of the atom, and the existence of an elementary atomic magnetic dipole moment, of the size of a Bohr magneton, $\mu_B = e\hbar/(2m_e)$, with e the magnitude of the electron charge and m_e the electron mass. In order to carry out the extremely difficult experiment, Stern teamed up with an able experimentalist, Walther Gerlach (1889–1979), from Frankfurt's Institute for Experimental Physics located in the same building. When Gerlach, trained by Friedrich Paschen in Tübingen, appeared on the scene, Born exclaimed: "Thank God, now we have someone who knows how to do experiments. Come on, man, give us a hand" (Gerlach 1963a; p. 3).

Completed in February 1922, the Stern-Gerlach experiment (SGE) (Stern 1921; Gerlach and Stern 1922a,b, 1924; Gerlach 1925) caused a stir in the community, as everything about it appeared novel and non-classical. Einstein together with Paul

Ehrenfest (1880–1933) rushed to find a physical explanation for the process of space quantization (Einstein and Ehrenfest 1922), but without success (Unna and Sauer 2013). Although Gerlach ended up doing the experiment essentially alone, Einstein and Ehrenfest coined the term Stern-Gerlach experiment rather than Gerlach-Stern experiment, in recognition of the fact that it was Stern who conceived the idea for the experiment that was to "decide unequivocally between quantum-theoretical and classical views" (Stern 1921).

Incredulous about the outcome of the SGE, Stern left Frankfurt in October 1921 for the University of Rostock, where he assumed a Professorship in Theoretical Physics. He would visit Frankfurt and consult with Gerlach regularly until the completion of the SGE. While in Rostock, a place without much experimental infrastructure, Stern received an offer from the University of Hamburg for a Professorship in Physical Chemistry, which he accepted as of 1 January 1923. Founded in 1919, the University of Hamburg created decent conditions for Stern's work, which became excellent from 1929 on as a way of countering an offer that Stern then received from the University of Frankfurt. Stern's Hamburg laboratory had a slow start, with Immanuel Estermann (1900–1973) and Friedrich Knauer (1897–1979) as Stern's assistants, but began flourishing in about 1926. During the heyday period that lasted until the summer of 1933, they were joined by Thomas Erwin Phipps (1895–1990), Otto Robert Frisch (1904–1979), Robert Schnurmann (1904–1955), Otto Brill (1881–1954), Ronald Fraser (1899–1985), Isidor Isaac Rabi, John Bellamy Taylor (1875–1963), and Emilio Segrè (1905–1989) among others see Fig. 4. There were also graduate students around but, as noted by Estermann (1962):

> Stern very rarely put his name on the papers that were published by his more advanced graduate students, as a matter of fact. Practically all the theses were published by the student alone, just with a note somewhere acknowledging the assistance or inspiration or what-not of Stern. The papers or work that was done jointly with some of the grown-up people was published then as a joint paper.

It was in 1926 that Stern wrote programmatic papers (Stern 1926; Stern and Knauer 1926) on the molecular beam method and launched an eponymous series of publications in Zeitschrift für Physik, *Untersuchungen zur Molekulkarstrahlmethode aus dem Institut für physikalische Chemie der Hamburgischen Universität*—U.z.M. The series was cut short at Number 30 by the rise of the Nazis to power in Germany and Stern's subsequent emigration, in September 1933. The programmatic papers discussed improvements of the beam intensity, beam collimation, and the sensitivity of beam detection, as well as projects that such improvements would make feasible. The determination of the de Broglie wavelength of a matter wave and the measurements of the magnetic dipole moment of the proton and of the photon recoil were featured prominently on the list.

In 1928–1929, Stern and Estermann carried out the first matter-wave diffraction experiments in which they scattered a helium-atom or hydrogen-molecule beam off the surface of a LiF or NaCl crystal (Estermann and Stern 1930). The diffraction pattern they observed allowed them to determine the de Broglie wavelength, λ, of the beams. In follow-up experiments, Estermann, Frisch, and Stern made use of velocity selection to define and control the velocity and thereby the momentum, p, of the He atoms or H_2 molecules and corroborated the validity of Louis de Broglie's wavelength formula, $\lambda = h/p$, within an accuracy of 1% (Estermann, Frisch, and Stern 1932). Throughout his life, Otto Stern regarded the experimental confirmation of the wave-particle duality as his most important contribution to physics (Stern 1961).

Still in Hamburg, Stern and Frisch succeeded in measuring the magnetic dipole moment of the proton in an SGE-type deflection experiment that made use of the ortho and para allotropic modifications of molecular hydrogen (Frisch and Stern 1933). They found that proton's magnetic moment, μ_p, was by about a factor of 2.5 larger than the nuclear magneton, $\mu_n = e\hbar/(2m_p)$, with e the magnitude of the elementary charge and m_p the proton mass. The theory of Paul Dirac (1902–1984), until then undisputed, treated the proton as a positively charged point-like particle similar to the electron, but with a different mass (and opposite charge) (Dirac 1928, 1930). The true value of proton's magnetic moment therefore indicated that the proton must have an internal structure and cannot be an elementary particle like the electron. Otto Stern thus became a pioneer of elementary particle physics.

"With the sword of Nazism hanging over [their] heads" (Estermann 1975), Otto Robert Frisch, with Stern's support, demonstrated the existence of a momentum kick atoms receive upon the absorption or emission of a photon (Frisch 1933a), a process predicted by Einstein (1917). We note that such momentum kick is the basis for laser cooling of atoms—and, recently, also of molecules—and thus a key to achieving quantum degeneracy in gases and much more.

Also under the Nazi threat, Thomas Phipps, Otto Robert Frisch, and Emilio Segrè carried out a three-stage SGE (Frisch and Segrè 1933), inspired by a letter to Stern from Einstein (Schmidt-Böcking et al. 2019; p. 129). This experiment made use of two Stern-Gerlach magnets with an additional inhomogeneous magnetic field between them. The three-stage SGE allowed to probe spin-flips of silver atoms due to the intermediate field – and thus anticipated Rabi's resonance method.

On 7 April 1933, the "Law for the Restoration of the Professional Civil Service"—designed to exclude Jews and political opponents from civil service positions in Nazi Germany—was promulgated and Stern's assistants of Jewish descent—Immanuel Estermann, Otto Robert Frisch, and Robert Schnurmann (only Friedrich Knauer was "Aryan"—and a Nazi (Stern 1961))—were dismissed in the summer of 1933 as a result. Stern was exempted from the law because of his military service in World War One, but resigned at the end of September 1933 and emigrated to the United States, where he took up a professorship at the Carnegie Institute of Technology in Pittsburgh. Here is how Immanuel Estermann described Stern's—and his own—emigration to the U.S. (Estermann 1962):

> [In] 1933 it became pretty obvious that [our] days [in Germany] were numbered …I would have gotten out even earlier; I sent my family out as early as April or May 1933 – to England. I had a brother [there and an offer for a temporary job] …Now, Stern didn't want to go; he thought that, well, he could survive Nazism in Germany. But he became convinced in June, or so, that it wouldn't work either. So he turned in his resignation. But we were then right in the middle of the proton-deuteron experiment, and decided as long as we would be left

Fig. 4 Stern's group in Hamburg 1928. From left: Friedrich Knauer, Otto Brill, Otto Stern, Ronald Fraser, Isidor Isaac Rabi, John B. Taylor, and Immanuel Estermann. Courtesy of Fritz Thieme, Universität Hamburg

> alone we would continue this work. And we worked until August; then we finally quit. Several months before …the then President of Carnegie Tech …made a trip to Germany to try to find some good scientists who might be induced to come to Carnegie. So he made arrangements with [Stern and myself] to come to Carnegie …I had no thought of ever going back to Germany …and we actually took a considerable part of the equipment with us …We got authorization from Carnegie to buy the same kind of a magnet and pumps and so forth, and they were shipped to Pittsburgh by the manufacturer who duplicated the ones that we had had in Hamburg so that we could reestablish the apparatus. And the parts that were made specifically for the purpose in the local shop I think we got permission from the [Hamburg] University authorities to take along.

Stern, together with Estermann, would thus restore and even improve some of their scientific apparatus in Pittsburgh, but not their leadership role in experimental quantum physics. That role fell to Stern's former affiliate, Isidor Rabi. Stern and Rabi would share the stage at the Nobel ceremony at the Waldorf-Astoria, New York City in 1944, where Rabi received the 1944 Nobel Prize in Physics.

However, at Pittsburgh, Otto Stern with his collaborators carried out additional key experiments, confirming the value of proton's magnetic moment and continuing the measurements of the magnetic dipole moment of the deuteron (Estermann and Stern 1934), begun in Hamburg (Estermann Stern 1933b). Stern and coworkers also verified the Maxwell-Boltzmann velocity distribution in an (effusive) beam of Cs and K atoms by observing the atoms' free fall. "The measurement of the intensity distribution in a beam deflected by gravity represents the velocity distribution of the beam atoms and permits an accurate determination of this distribution" (Estermann, Simpson, and Stern 1947a).

The environment at the Carnegie Institute and Stern's attitude towards it was described by Estermann as follows (Estermann 1962):

> [After the retirement of Carnegie's president because of his illness] there was no support from the top after the first year anymore. Stern was something of a prima donna, as you have probably noticed. If things didn't come his way he would retire into his (corner), and pick up his marbles and go home, so to speak; which made life even more difficult. His whole personality is not suited to an American University …There was probably nobody in the physics department at Carnegie Tech who had ever heard of him before, or heard of anything of modern physics before.

In 1945, Stern retired to Berkeley, where his sister lived, and became a private citizen.

Between 1924 and 1944, Otto Stern received eighty-three nominations for a Nobel Prize in Physics,[4] more than Planck (nominated seventy-four times) and Einstein (nominated sixty-two times) or any other physicists of his time. The attitude of Stern's nominators was aptly expressed by Max Born in his nomination (Schmidt-Böcking et al. 2019; p. 299):

> It seemed to me that Stern's achievements exceed those of all other experimenters so much, both by the boldness of the thoughts and by masterfully overcoming the experimental difficulties, that I do not want to name any other physicist as a candidate for the Nobel Prize besides him.

In 1944, Stern was awarded the Nobel in Physics for 1943.

2 Otto Stern's Seminal Experiments

In what follows, we review briefly six seminal experiments proposed by Otto Stern and/or carried out in his laboratories at Frankfurt, Hamburg, and Pittsburgh during the period 1920–1945.

- The Stern-Gerlach experiment, carried out with Walther Gerlach at Frankfurt in 1920–1922
- The three-stage SGE experiment, carried out together with Thomas Phipps, Otto Robert Frisch, and Emilio Segrè at Hamburg in 1933

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[4] The official number of nominations provided by the Nobel Archives (The Nobel Population 1901–1950, A census 2002, The Royal Swedish Academy, Produced by Universal Academy Press, Inc.) for Otto Stern is eighty-two. Thirty nominations were for the Stern-Gerlach experiment, fifty-two for Stern's other molecular beam work. Einstein nominated Stern twice (in 1924 and in 1940), but the first nomination, of Stern and Gerlach for a shared prize, (Buchwald et al. 2015; Doc. 132), was not counted, because of Einstein's parallel nomination of other scientists that year (James Franck and Gustav Hertz). The rules applicable in 1924 admitted only one set of nominees by a given nominator. We note that Viktor Hess claimed in a letter to Otto Stern, dated 11 November 1944, that he had nominated Stern in 1937 and 1938 for the Nobel Prize in Physics (Schmidt-Böcking et al. 2019; p. 372). The curator of the Nobel Archives, Karl Grandin, determined that Hess's claim was incorrect.

- The experimental verification of de Broglie's relation for the wavelength of matter waves, performed with Friedrich Knauer, Immanuel Estermann, and Otto Robert Frisch at Hamburg in 1929–1933
- The measurement of the magnetic dipole moment of the proton and deuteron, with Otto Robert Frisch, Immanuel Estermann, and Oliver Simpson at Hamburg and Pittsburgh in 1933–1937
- Experimental demonstration of momentum transfer upon absorption or emission of a photon by Otto Robert Frisch, at Hamburg in 1933
- The experimental verification of the Maxwell-Boltzmann velocity distribution via deflection of a molecular beam by gravity, with Immanuel Estermann and Oliver Simpson at Pittsburgh in 1938–1945

2.1 The Stern-Gerlach Experiment

On 26 August 1921, Otto Stern submitted a paper to the *Zeitschrift für Physik*, in which he proposed "a way to examine experimentally space quantization in a magnetic field," i.e., investigate whether "the component of the angular momentum [of an atom] in the direction of the magnetic field can only have values that are integer multiples of [$\hbar$]" (Stern 1921). Stern realized that such a behavior would contrast sharply with a classical one, as classical mechanics did not impose any restriction on the projection of the angular momentum on the field. Stern thus saw the experiment as a way to "decide unequivocally between quantum-theoretical and classical views." All that was needed was "to observe the deflection of a beam of atoms in a suitable inhomogeneous magnetic field." The perception of space quantization as "otherworldly" transpired in Stern's remark that

> one cannot envision at all how the atoms of a gas, whose angular momenta [in the absence] of a magnetic field point in all possible directions, would acquire the preordained directions upon entry into the magnetic field.

In addition, Stern realized that space quantization of orbital angular momentum of atoms would lead to magnetic birefringence, which he would attempt to observe—in vain—in later experiments with Gerlach in Rostock.

By his own admission, Stern was prompted to publish his proposal when he came across the page proofs of a paper by Hartmut Kallmann (1896–1978) and Fritz Reiche (1883–1969) on the analogous deflection of polar molecules in an inhomogeneous electric field (Kallmann and Reiche 1921). According to Gerlach, upon learning about the work of Kallmann and Reiche, Stern exclaimed: "For God's sake, now they are going to start and take space quantization away from us. I'd better publish it fast" (Gerlach 1963b).

Stern's "prophetic paper" (Stern 1921) exemplifies the meticulous preparations of Stern's experiments that invariably entailed detailed feasibility calculations as well as quantitative assessments of the expected outcomes.

Fig. 5 Members of the Frankfurt Physics faculty in 1920. From right: sitting Otto Stern, Max Born, and Richard Wachsmuth (1868–1941), standing: 3rd from right Alfred Landé (1888–1976), and 4th Walther Gerlach. Standing left of Gerlach is likely Elisabeth Bormann (1895–1986) (OSC)

Stern's calculations suggested that the experiment to "decide unequivocally between quantum-theoretical and classical views" will be very difficult to carry out. Therefore, as noted, Stern invited Walther Gerlach, an assistant to Richard Wachsmuth (1868–1941), the director of Frankfurt's Institute for Experimental Physics, Fig. 5. Gerlach was regarded as an excellent experimentalist and had even attempted his own molecular beam experiment to study dia- and para-magnetism, see Chap. 8.

The actual Stern-Gerlach apparatus, which comprised an oven to produce an effusive beam of silver atoms, beam stops, the deflection region, and the beam collecting plate, was small, not much larger than a fountain pen, Fig. 6. The high vacuum needed to produce and sustain the atomic beam was produced by two glass mercury diffusion pumps, one for the source chamber and one for the detector chamber. The deflection region was squeezed between the pole pieces—edge and groove, a design proposed by Erwin Madelung (1881–1972) (Stern 1961)—of an electromagnet. The required transverse-momentum resolution was about 0.1 a.u. (an electron with a kinetic energy of 13.6 eV has a momentum of 1 a.u.). The expected angular deflection of the beam (just a few mrads) required high mechanical precision, on the order of a μm. For its operation, the apparatus required a delicate balance between heated (oven) and cooled (detector plate) components. A more detailed description of the apparatus and its operation is given in Chap. 8 by Gerlach's student Wilhelm Schütz.

The apparatus was constructed and operated during the hyperinflation period that beset Germany in the aftermath of World War One. Support for the experiment came from several sources, most notably the *Physikalischer Verein Frankfurt*, founded in 1824. The *Verein's* long-time chairman was Wilhelm Eugen Hartmann (1853–1915), founder of the *Hartmann & Braun* company that provided Stern and Gerlach with

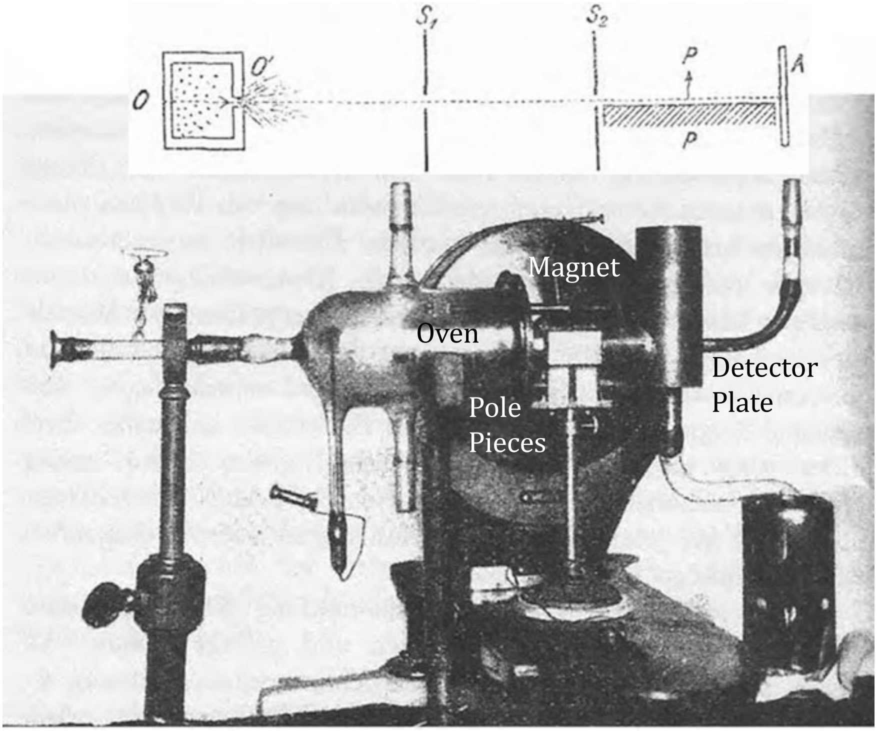


Fig. 6 The Stern-Gerlach apparatus of 1922, with improvements of 1924 and 1925. The schematic in the inset shows the silver beam effusing from an oven (O) and passing through a pinhole (S_1) and a rectangular slit (S_2) before entering the magnetic field (whose direction is indicated by the arrow) between the pole pieces (P) and finally reaching the detector plate (A) (Gerlach and Stern 1924; Gerlach 1925)

a small Dubois magnet. The *Messer* company donated some liquid air (Gerlach and Stern 1922a). Einstein, then director of the Kaiser Wilhelm Institute for Physics in Berlin, provided 20,000 Marks for the purchase of an electromagnet from *Hartmann & Braun* (Buchwald et al. 2012; p. 802), 813 (AEA 77681, 77355). Additional funding came from the *Association of Friends and Sponsors of the University of Frankfurt* as well as from the entrance fee to Max Born's popular lectures on general relativity (Stern 1961). Silver of high purity was acquired from *Heraeus*.

Unfortunately, original documents and drawings related to the SGE are no longer available. Gerlach took the documents with him to Tübingen and then to Munich where he kept them at the Physics Institute of the *Ludwig-Maximilians-Universität*. But in March 1943, almost everything was destroyed by fire following a bombing raid (Huber 2014).

On the night of 5 November 1921, Gerlach—with Stern absent—scored his first major success by observing a broadening of the silver beam consistent with a magnetic moment of 1 to 2 Bohr magnetons (Gerlach 1969; Huber 2014; Schmidt-

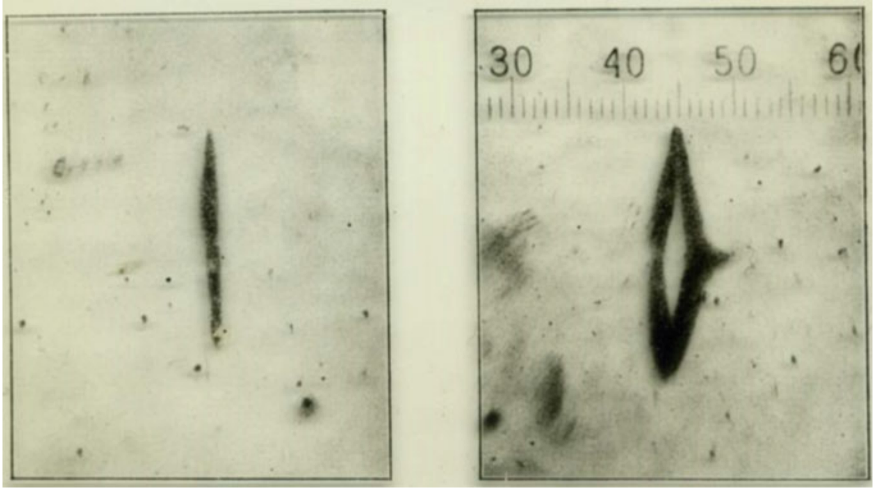


Fig. 7 Silver sulfide (Ag_2S) deposits obtained in the SGE. The microphotographs are from Otto Stern's personal collection, published images were included in (Gerlach and Stern 1922b). Left side: Ag beam deposit obtained in the absence of the magnetic field (deposit length about 1.1 mm, width about 0.06 to 0.1 mm). Right: Beam deposit with the magnetic field switched on; the deposit is split into two components broadened due to the beam velocity distribution. The asymmetry of the magnetic field strength between the two magnetic pole pieces is reflected by the shape of the deposit as atoms passing near the tip of the S pole are more strongly deflected

Böcking and Reich 2011). However, the low angular resolution of the apparatus left the key question about the existence of space quantization unanswered.

In early February 1922, Gerlach and Stern met at a physics conference in Göttingen and discussed further improvements of the apparatus, especially the arrangement and the shape of the apertures. An invitation letter to Stern from David Hilbert (1862–1943) to come over for a cup of coffee corroborates that Stern was indeed in Göttingen at the time (Schmidt-Böcking et al. 2019; p. 115). Like most beam experiments, the SGE suffered from a low beam intensity which was, in this case, partly due to beam scattering off the tiny platinum apertures, needed, in turn, for achieving sufficient angular resolution. With some more time on their hands—thanks to a railroad strike (Friedrich and Herschbach 1998, 2003)—Gerlach and Stern finally decided to replace the circular aperture in front of the magnetic field with a rectangular slit (0.8 mm × 30 μm). Upon his return to Frankfurt, Gerlach implemented the slit, which led quickly to a breakthrough: During the night of 7 February 1922, Gerlach was able to observe, for the first time, the splitting of the silver beam into two components, with nothing in between, Fig. 7.

Wilhelm Schütz (1900–1972), Gerlach's PhD student at the time, described in 1969 the toil of the Stern-Gerlach experiment in detail (Schütz 1969). For an extended quote, see Chap. 8 on Gerlach. After the successful completion of the experiment

> [Schütz] was tasked with sending a telegram to Professor Stern in Rostock, with the text: "Bohr is right after all!"

On March 1, 1922, Walther Gerlach and Otto Stern submitted their paper entitled "Experimental evidence of space quantization in the magnetic field" to the *Zeitschrift für Physik* (Gerlach and Stern 1922b). Most of their physics colleagues expressed surprise about or even bewilderment over the reported result. After all, even Stern himself had not believed that the "quantum-theoretical view" will prevail over the classical one. However, as Gerlach would point out, Stern remained open-minded: "The dissection will tell" was their motto (Gerlach 1969). The protagonists of the SGE are shown together in the company of Stern's confidant Lise Meitner (1878–1968) in Fig. 8, Fig. 9 shows Frankfurt Physics (Arthur von Weinberg-Haus) while Fig. 10 shows the emblematic splitting of the silver beam once more with an angular scale added.

Here is a sampling of the responses from the physics community to the outcome of the SGE: Wolfgang Pauli wrote on 17 February 1922 a postcard to Gerlach (Hermann, von Meyenn, and Weisskopf 1979; p. 55):

> My heartfelt congratulations on a successful experiment! Hopefully it will convert even the nonbeliever Stern. I would just like to mention one detail. It is not easy to explain that one side is stronger than the other. Shouldn't it be some secondary perturbation? You mentioned me in your letter to Franck. However, the paramagnetic effect that I calculated at the time (based on Langevin) is far too small and is out of the question here. So I'm innocent on this matter. Best regards to you, and to Prof. Madelung and to Landé.

In his 1922 letter to Max Born, Einstein emphasized (Buchwald et al. 2012; Doc.191):

> 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 Ehrenfest. [Heinrich] Rubens considers the experimental result to be absolutely certain.

Niels Bohr wrote to Gerlach (Gerlach 1969):

> 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.

James Franck wrote to Gerlach (Gerlach 1969):

> 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.

Friedrich Paschen stated (Gerlach 1969):

> Your experiment proves for the first time the reality of Bohr's [stationary] states.

Arnold Sommerfeld noted (Sommerfeld 1924):

> 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.

But even after the SGE was completed, Stern remained incredulous—contrary to the hope that Pauli expressed in his postcard to Gerlach. In his Zurich interview with Res Jost, Stern said (Stern 1961):

> What was really interesting was the experiment that I did together with Gerlach on space quantization. I had thought that [quantum theory] couldn't be right ... I was still very skeptical about quantum theory and thought that a hydrogen or alkali atom must exhibit birefringence in a magnetic field ... At that time I had thought about [space quantization] and realized that one could test it experimentally. I was attuned to molecular beams through the measurement of molecular velocities and so I tried the experiment. I did it jointly with Gerlach, because it was a difficult matter, and so I wanted to have a real experimental physicist working with me. It went quite nicely ... for instance, I would build a little torsional balance to measure the electric [magnetic] field that worked but not very well. Then Gerlach would build a very fine one that worked much better. Incidentally, I'd like to emphasize one thing on this occasion, [namely] that we did not cite [acknowledge] sufficiently at the time the help that we received from Madelung. Born was already gone then [moved to his new post at Göttingen] and his successor was Madelung. Madelung essentially suggested to us the [realization of the inhomogeneous] magnetic field [by making use] of an edge [and groove combination]. But the way the experiment turned out, I didn't understand at all. [How could there be] the discrete beams—and yet, [there was] no birefringence. We [even] made some additional experiments about it. It was absolutely impossible to understand. This is also quite clear, one needed not only the new quantum theory, but also the magnetic electron. These two things weren't there yet at the time. ... I still do have objections against the idea of beauty of quantum mechanics. But she is correct.

As has been noted elsewhere (Friedrich and Herschbach 1998, 2003), the splitting of the beam of ground-state silver atoms Ag(^2S) into two components as well as the apparent magnitude of the magnetic dipole moment involved was the result of a

Fig. 8 From left: Walther Gerlach, Lise Meitner, and Otto Stern in Zürich, about 1927. Photo: Ruth Speiser and Bruno Lüthi, private communication

Fig. 9 Building where the Stern-Gerlach experiment was carried out. Left: photo from 1910, Archiv der Universität Frankfurt, Johann Wolfgang Goethe-Universität Frankfurt am Main, Senckenberganlage 31–33, 60325 Frankfurt. Right: photo from 2020 by Horst Schmidt-Böcking

"kind conspiracy of nature:" Firstly, it was not the orbital angular momentum (which is zero for a ^2S state and not 1 $\hbar$ as assumed by Bohr) that was space-quantized, but rather the spin angular momentum of the electron with quantum number $s = 1/2$ and projections $m_s = \pm 1/2$, which would be discovered only in 1925 (Uhlenbeck and Goudsmit 1925). Secondly, it was electron's anomalous gyromagnetic ratio, $g_e \approx 2.002319$, combined with the half-integral quantum number $s = 1/2$ that created the impression that the magnitude of the observed magnetic dipole moment $\mu = g_e \mu_B m_s$ was that of a Bohr magneton.

Interestingly, a similar "duplicity of nature" played a role in the treatment of the anomalous Zeeman effect by Alfred Landé (1888–1976), then also at Max Born's Frankfurt Institute for Theoretical Physics. Based on the available Zeeman spectra and the recognition of the role of the coupling of electronic angular momenta in determining atomic structure, Landé found a formula for the atomic magnetic dipole moment (Landé 1921a,b). Landé's empirical formula also rendered correctly the double-splitting of the silver atom beam as observed in the SGE, with $k = 1/2$ the angular momentum of the atom's "interior" and a g-factor of 2 (Landé 1923), cf. also (Tomonaga 1997). Thus Landé's insight presaged the role of half-integral quantum numbers and thus of electron spin in shaping the electronic structure of atoms. Even Born, who shared an office with Landé, had underestimated the significance of Landé's formula.

The SGE has raised a number of interpretative questions (Ribeiro 2010; Wennerström and Westlund 2012; Devereux 2015; Utz et al. 2015; Griffiths 2015; Sauer 2016) that inspired a large body of experimental work, some of it still ongoing. Among them are: What is the role, if any, of diffraction of the molecular beam off the apertures? Is there spin relaxation? Do the atoms on their way from the source to the detector have to be treated as quantum mechanical waves or as classical particles? Is there interference between the two spin states of the silver atoms? The last two questions have been answered in the affirmative (Machluf et al. 2013; Margalit et al. 2015; Zhou et al. 2018; Margalit et al. 2018; Amit et al. 2019; Zhou et al.

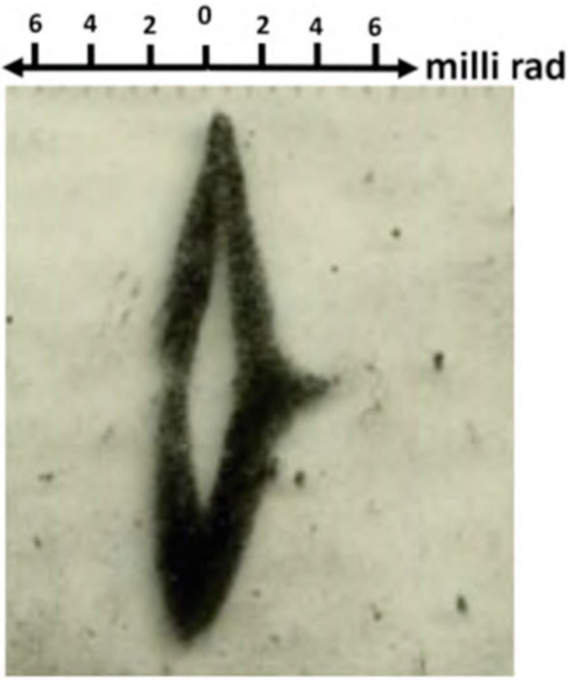


Fig. 10 The SGE result plotted in scattering angles (milli rad). Otto Stern's private slide collection. Senckenberg Bibliothek der Universität Frankfurt, Johann Wolfgang Goethe-Universität Frankfurt am Main, 60325 Frankfurt. Calculation of the deflection angles by Horst Schmidt-Böcking

2020). These questions and more are addressed in separate chapters in this volume, especially in Chaps. 11, 12, 14, and 15.

There seems to be a consensus that the following questions have been answered by the SGE definitively:

1. The SGE has determined that each silver atom has a magnetic dipole moment of about one Bohr magneton.
2. The SGE presented the first direct experimental evidence that angular momentum is quantized in units of $\hbar$.
3. The SGE confirmed Sommerfeld's and Debye's hypothesis of "Richtungs-Quantelung" (space quantization) of angular momenta in magnetic (and electric) fields.
4. The SGE was the first measurement that examined the ground-state of an atom—without involvement of higher states, as is the case in spectroscopy.
5. The SGE produced the first fully spin-polarized atomic beam.
6. The SGE produces population inversion—a crucial ingredient for the development of the maser and laser (Friedrich and Herschbach 1998, 2003).
7. Deflecting atoms in a well-defined momentum state by an external field makes it possible to study their internal properties (electronic and nuclear). Measuring the kinematics of particles with high momentum resolution (0.1 a.u.) amounts to a new kind of microscopy, similar to mass spectrometry (Aston 1919; Downard 2007).

8. The SGE demonstrated that angular momentum “collapses” into a classically inexplicable projection on the direction of the external magnetic field, only accounted for upon the discovery of quantum mechanics, see, e.g., (Utz et al. 2015). To date, the SGE serves as a paradigm for the notorious quantum measurement problem.

2.2 *The Three-Stage Stern-Gerlach Experiment*

Stern kept in touch with Einstein throughout the time they both lived and worked in Germany (1914–1932) not only via correspondence but also by visiting him every now and then in Berlin (Stern 1961). In keeping with his quip that “On quantum theory I use up more of my brains [Hirnschmalz] than on relativity”, Einstein continued mulling over space quantization. On 21 January 1928, he wrote a letter to Stern (as well as to Ehrenfest) (Schmidt-Böcking et al. 2019; pp. 128–131), in which he described a far-reaching idea for an experiment to explore further aspects of space quantization, see also Fig. 11:

> On the occasion of our quantum seminar, two questions have come up that concern the behavior of a molecular beam in a magnetic field, so they just fall within your work area. Perhaps you have already made equivalent experiments and if not then this suggestion could be of some use.
>
> I. Assume that an atom is oriented this ↑ or this ↓ way in a vertical magnet[ic field]. Assume the magnetic field is slowly changing its direction. Does the orientation of each individual atom follow [the direction of] the field?
>
> Test: An atomic beam passes consecutively through two oppositely oriented inhomogeneous magnetic fields. Assume that an atom is oriented in such a way as to be deflected upward in the first field. If [the atom] flips its orientation [in the region between the two fields], then, because of the reversal [of the orientation] of both the [second] field and the dipole, the beam must [be deflected by the second field] as if the two magnetic fields were oriented in the same direction.
>
> This is all the more paradoxical given that the deflection increases linearly with field strength.
>
> II. It is a part of our current understanding that the field determines the orientation of the atom and the field gradient the magnitude of the deflection. The field and the field gradient

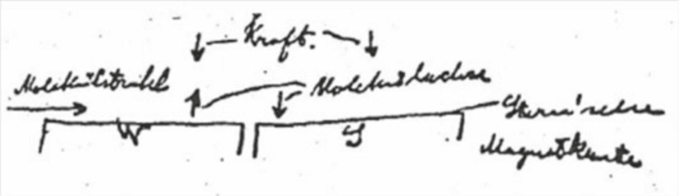


Fig. 11 Einstein’s sketch of a three-stage SGE (letter to Ehrenfest) (Schmidt-Böcking et al. 2019; p. 131)

> can be varied independently of one another. Let us consider that the field gradient is fixed and the field is varied; in which case only the direction of the [field] but not its magnitude should matter. The field can be arbitrarily weak, without affecting the deflection. It should therefore be possible to entirely change the [sense of the] deflections by a mere change of the direction of the arbitrarily weak magnetic field. This is surely paradoxical, but consistent with our current view. Perhaps it would be convenient to generate the inhomogeneous field by running [electric] current through a water-cooled pipe.
>
> If you already have data available that answer the two questions, please communicate these to me. Should this not be the case, it would be worthwhile to answer these questions experimentally.

Hence Einstein recognized that if reorientation of the dipoles (i.e., spin flip) took place in the intermediate region between the two oppositely oriented Stern-Gerlach fields, the second Stern-Gerlach field would have pushed the atoms further away from the original beam direction. But this also meant that in the absence of reorientation of the atoms' magnetic dipoles (without a spin flip), the atomic beam could be refocused by the second Stern-Gerlach field on the same spot that the beam would have hit in the absence of the deflecting fields (i.e., along the original beam direction). Reorientation (spin flip) would then result in a dip in the beam intensity along the original direction. This idea, whose variant was implemented by Stern and his coworkers, would later resonate with Isidor Rabi, see below.

The possibility of a spin flip was considered by a number of workers, including Charles Galton Darwin (Darwin 1928), Landé (Landé 1929), Werner Heisenberg, as noted in (Phipps and Stern 1932), and P. Güttinger (Güttinger 1932), who concluded that the magnetic dipoles would flip if their interaction with the intermediate magnetic field were non-adiabatic. Heisenberg formulated a criterion for a non-adiabatic interaction, which was subsequently refined by Güttinger: What matters is the ratio of the Larmor period of the dipole to the dipole's interaction time with the field. Should this ratio be large, the interaction will tend to be non-adiabatic and hence the spin flip likely.

Otto Stern together with Guggenheim Fellow Thomas Phipps took it from there. On 9 September 1931 they submitted a paper that described their attempt to observe spin flips in a beam of potassium atoms (Phipps and Stern 1932). In their experiment, they implemented the intermediate field by placing three tiny spatially separated electromagnets in series and letting the spin-selected beam run between their pole pieces. Adjacent magnets were rotated by 120° with respect to one another, effecting a 360° overall rotation of the magnetic field direction. The spatially varying magnetic field became a time-varying magnetic field once the atoms flew through it. The time variation of the field was such that the above non-adiabaticity condition needed for spin flips was fulfilled. The triple-magnet contraption was placed in a magnetic shield [*Panzerkugel*] fashioned with apertures to let the beam through. The magnetic shield was supposed to keep the magnetic fields generated by the two Stern-Gerlach magnets (selector and analyser) out of the region where the small magnets interacted with the spin-selected potassium beam. Otherwise the field of the triple-magnets would have been overshadowed by that of the Stern-Gerlach fields and there would be no spatial/time variation of the intermediate triple-magnet field. The potassium

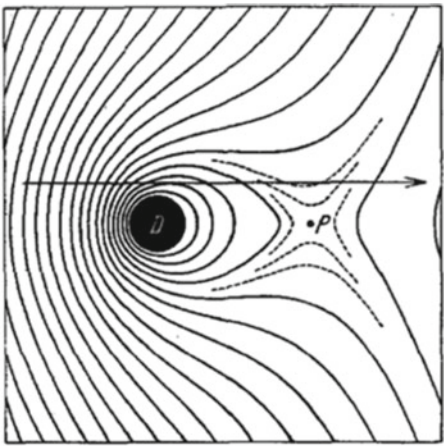


Fig. 12 Magnetic field lines in the intermediate region of the Frisch-Segrè apparatus. *D* is the current-carrying wire, *P* is where the magnetic field vanishes, and the arrow shows the path of the potassium beam (Frisch and Segrè 1933)

beam was sensitively detected with excellent angular resolution using a Langmuir-Taylor (hot tungsten wire) detector. Unfortunately, the outcome of the Phipps-Stern experiment was negative—no spin flips had been observed—likely due to insufficient shielding of the intermediate region.

Upon Phipps's return to America, the experiment was continued by Otto Robert Frisch and Rockefeller Fellow Emilio Segrè, who made use of the Phipps-Stern apparatus, but designed the intermediate flipping field quite differently: As Segrè recollected (Segrè 1973)

> I inherited [Phipps's] apparatus, but could not make much headway until on reading Maxwell's Electricity I found a trick by which one could achieve a certain magnetic field configuration essential to the success of the experiment.

Incidentally, this configuration was the same as the one proposed by Einstein in his letter to Stern (Schmidt-Böcking et al. 2019; pp. 128–129). It consisted of a current-carrying wire at right angles to the atomic beam but slightly displaced so that the beam would nearly miss it. The wire generated a spatially varying magnetic field that upon superposition with the field from the two sets of Stern-Gerlach magnets led to the field depicted in Fig. 12. The atomic beam traversing this field "felt" a rotation of the field direction by 360°.

A schematic of the apparatus constructed by Phipps and modified by Frisch and Segrè is shown in Fig. 13. With this apparatus, Frisch and Segrè were able to observe spin flips of the potassium atoms, Fig. 14. The curves show the beam intensity (ordinate) as measured by the hot-wire detector whose position could be vertically scanned (abscissa). Curve 1 shows the beam intensity distribution at the detector in the absence of the flipping field (the current through the wire *D* in the intermediate region was switched off, $i = 0$). Curves 2 and 3 were obtained with the intermediate field on ($i = 0.1$ A). The additional peaks to the right correspond to flipped atoms. Curve

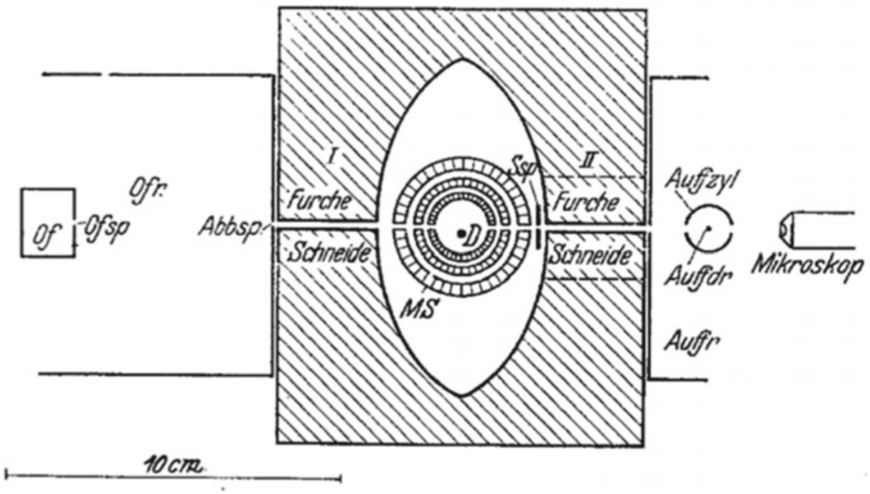


Fig. 13 The three-stage SGE of Frisch and Segrè: *Of* [Ofen] oven, *Ofsp* [Ofenspalt] oven aperture, *Ofr* [Ofenraum] source chamber, I and II Stern-Gerlach fields, *Abbsp* [Abbildungsspalt] entrance slit into the Stern-Gerlach field I, *Ssp* [Selektorspalt) selection slit, *MS* [Magnetischer Schutz – Panzerkugel] magnetic shield (later made out of high-permeability alloy obtained from *Heraeus*, *D* [Draht] current-carrying wire to produce the intermediate flipping field, *Auffzyl* [Auffangzylinder] detector chamber, *Auffdr* [Auffangdraht] wire detector. The angular deflection by either of the two Stern-Gerlach magnets was about 10 mrad. (Frisch and Segrè 1933)

3 was obtained for a different setting of the selection slit that picked out slower atoms. The separation between the two peaks of curves 2 and 3 corresponds to twice the deflection in a single Stern-Gerlach field and is larger for the slower atoms, as expected. However, the fraction of atoms whose magnetic dipole was flipped could not be reproduced quantitatively by theory. Ettore Majorana (1906–1938) developed a theory tailored to the Frisch and Segrè experimental setup, but his formula accounted only for about a half of the observed spin flips (Majorana 1932). Frisch and Segrè, Fig. 15, conjectured that this was likely because the flipping magnetic field was not properly accounted for in Majorana's model that only included effects arising from the vicinity of point P, see Fig. 12. However, as Isidor Rabi would point out in a 1934 letter to Stern, the discrepancy was in fact largely due to the neglect of the nuclear spin of the potassium atoms in Majorana's treatment (Schmidt-Böcking et al. 2019; p. 167).

In 1927, Isidor Rabi came to Europe as a Barnard Fellow (later a Rockefeller Fellow) and worked intermittently with Sommerfeld, Heisenberg, Bohr, and Pauli. As Norman Ramsey recounted (Ramsey 1993),

> The Stern-Gerlach experiment …had earlier sparked Rabi's keen interest in quantum mechanics and so, while working in Hamburg with Pauli, Rabi became a frequent visitor to Stern's molecular beam laboratory. During one of these visits Rabi suggested a new form of deflecting magnetic field; Stern in characteristic fashion invited Rabi to work on it in his laboratory, and Rabi in an equally characteristic fashion accepted. Rabi's work in Stern's laboratory was decisive in turning his interest toward molecular beam research.

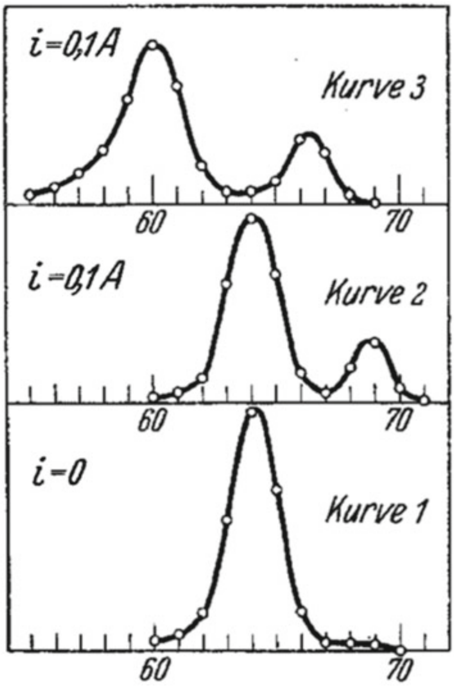


Fig. 14 Intensity distribution of a potassium beam behind the second Stern-Gerlach magnetic field in the Frisch-Segrè experiment (Frisch and Segrè 1933). The smaller peaks to the right of the main maxima of curves 2 and 3 are due to reorientation of the magnetic dipole moments of the atoms (spin flips). Shown is also the current *i* through the wire *D* placed in the intermediate (flipping) region, cf. Figure 12. Curve 3 was obtained for a different setting of the selection slit whereby slower atoms were selected than those that gave rise to curves 1 and 2

The new magnetic deflecting field alluded to above was based on Rabi's realization that magnetic dipoles can be deflected in a homogeneous magnetic field as well. Rabi's analysis was based on the analogy with Snell's law, i.e., on the change of the velocity of the atoms/molecules upon entering the conservative magnetic field due

Fig. 15 Otto Robert Frisch (left) and Emilio Segrè (right). Courtesy Fritz Thieme (University of Hamburg)

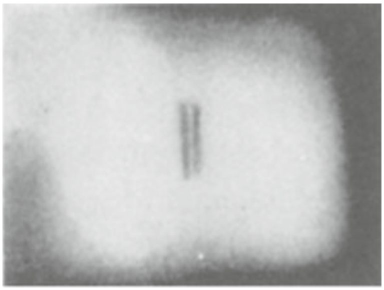


Fig. 16 Photograph of the splitting pattern of a potassium beam in a horizontal homogeneous magnetic field (Rabi 1929)

to a loss or gain of their Zeeman energy. Rabi showed that the deflection—which amounts to refraction—depends on the angle of incidence, initial kinetic energy, and the Zeeman energy. Rabi also carried out a proof-of-principle experiment in Stern's laboratory in which he measured the magnetic dipole moment of potassium (with a 5% accuracy) by splitting a beam of potassium atoms in the homogeneous field according to the different Zeeman energies of the spin-up and spin-down states (Rabi 1929).

The key advantage of using a homogeneous field was captured by Rabi in the following statement:

> [In the] new deflection method …only the energy difference of the molecules in the deflecting field matters, in consequence of which only the strength and not the inhomogeneity of the field is to be measured [controlled] …Homogeneous fields are not only easier to generate, but can be measured much more accurately.

Moreover, as shown in Fig. 16, the two traces corresponding to the $+1/2$ and $-1/2$ spin states of potassium are linear when the states are split by a homogeneous field.

Well-provided with ideas from Hamburg and elsewhere in Europe and flush with his own, Rabi departed for America in the summer of 1929 to assume a lecturership at Columbia University. Rabi's Molecular Beam Laboratory would become a major school of atomic, molecular, and optical physics and since about the mid-1930s play a pace-setting role in physics, see Chap. 7.

In December 1935, Rabi submitted a paper on spin reorientation (Rabi 1936), in which he discussed previous theoretical (Güttinger 1932; Majorana 1932) and experimental work (Phipps and Stern 1932; Frisch and Stern 1933). The next paper by Rabi on the spin reorientation problem, which appeared in the wake of related works (Motz and Rose 1936; Schwinger 1937), considered an applied field that changed its direction ("gyrated") at a fixed frequency (Rabi 1937). According to Norman Ramsey,

> A few months after the publication of that paper, following a visit by C. J. Gorter, Rabi directed the major efforts of his laboratory toward the development of the molecular beam magnetic resonance method with the magnetic fields oscillating in time.

The papers that introduced what became known as Rabi's magnetic resonance method followed in due course (Kellog, Rabi and Zacharias 1936; Rabi et al. 1939, 1938a,b).

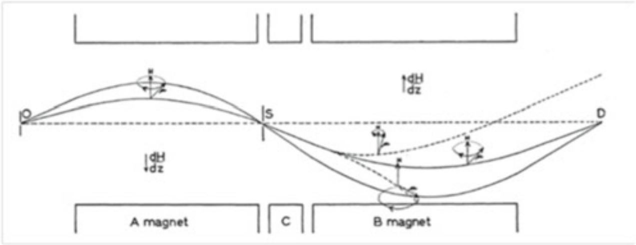


Fig. 17 The Rabi three-stage apparatus (Rabi et al. 1939)

In Rabi's method, see Fig. 17, a molecular beam is state-selected by passing through an inhomogeneous magnetic field (A field) and refocused by an identical but oppositely oriented inhomogeneous magnetic field (B field). Intermediate between the two fields A and B is a third field (C field), which is oscillatory. For an oscillation frequency of the C field that is resonant with an atomic/molecular transition, the atoms/molecules fail to refocus upon making the transition, which results in a dip in the signal. Thereby the energy differences between atomic/molecular levels, including hyperfine ones, could be accurately measured. One of the great virtues of Rabi's technique is that the refocusing is velocity-independent.

Rabi was awarded the 1944 Nobel Prize in Physics "for his resonance method for recording the magnetic properties of atomic nuclei."

Finally, we note that Heisenberg discussed a variant of the SGE in 1927 (Heisenberg 1927a) and remarked that Bohr had suggested earlier to make use of resonant photo-absorption in order to change the internal quantum state of the moving atom.

2.3 *Experimental Evidence for de Broglie's Matter Waves*

In his programmatic paper (Stern 1926), Stern envisioned "an experiment of the greatest fundamental significance" to demonstrate the existence of the de Broglie waves by examining whether "molecular beams, in analogy with light beams, exhibit diffraction and interference phenomena." Although he expected the de Broglie wavelengths of the molecular beams to be only on the order of an Ångström (0.1 nm), Stern was hopeful about the feasibility of the experiment. Stern's programmatic paper preceded the Davisson-Germer experiment on electron diffraction (Davisson and Germer 1927), whose serendipitous outcome was published on 1 December 1927.

When Stern—and his coworkers, Knauer, Estermann, and Frisch—succeeded, he would hardly contain his pride even thirty-five years hence: "I'm particularly fond of this experiment, which hasn't been properly appreciated" (Stern 1961).

The first attempt to find experimental evidence for the reality of matter waves was made in early 1927 in Stern's Hamburg laboratory. A preliminary report about its outcome was presented by Stern at the Lake Como conference in September 1927 and the first paper, written jointly with Friedrich Knauer (Knauer and Stern 1929a), published on 24 December 1928. This paper reflected the authors' struggle with a great number of daunting technical difficulties and reported only qualitative results—on the specular reflection and diffraction of molecular beams (mainly He and H_2) from optical gratings and crystal surfaces.

For the specular reflection off gratings, Stern and Knauer concluded that the reflected beam intensity increases with decreasing angle of incidence with respect to the surface (i.e., is at maximum at grazing incidence); the angle at which reflection becomes observable is on the order of mrad, in keeping with the calculated de Broglie wavelength of about 1 Å and a surface corrugation of 100–1000 Å; the reflected intensity sharply increases upon cooling the beam source/increasing the de Broglie wavelength, thereby conforming to the behavior expected for waves.

Of the crystal surfaces examined, the most intense reflection was obtained for a helium beam scattered from a rock salt (sodium chloride) crystal surface. For this system, it was found that at low angles of incidence (with respect to the crystal surface), the reflected intensity of the beam increases with the temperature of the beam source (lower de Broglie wavelength); at larger angles of incidence, such as 30°, it is the other way around. However, the most compelling evidence that the helium beam behaved in fact as a matter wave came from the observation of first-order diffraction maxima. For a cold helium beam (100 K), these could be observed at diffraction angles α fulfilling the condition

$$\cos\alpha - \cos\alpha_0 = n\frac{\lambda}{d} \tag{1}$$

with $\lambda = 0.8$ Å the de Broglie wavelength, $d = 2$ Å the lattice constant, α_0 the angle of incidence, and n the diffraction order.

One of the great challenges of these experiments was dealing with the contamination of the surfaces by the adsorbed background gas in a vacuum chamber that could be evacuated to only about 10^{-5} torr. In order to keep the cleaved surfaces clean, the crystals—in fact much of the apparatus—were constantly heated to 100°C. Prior to an experiment, the crystals were baked out at 300°C.

The first, 1928 version of the Hamburg diffraction apparatus is shown in Fig. 18.

The incidence angle of the atomic beam on the crystal surface was fixed. The reflected/diffracted beam intensity was measured by a Pirani-type gauge (Knauer and Stern 1929b).

The first quantitative measurements of matter wave diffraction in Stern's laboratory were carried out using a more advanced apparatus built by Estermann and Stern that allowed to rotate the crystal surface (NaCl or LiF) with respect to the incident molecular beam (H_2 or He) as well as to scan the scattering angle for a fixed angle of incidence. Typical reflected/diffracted intensity distributions for a He beam incident on NaCl are shown in Fig. 19. The velocity distribution of the molecular beam was

Maxwell-Boltzmannian, controlled by the temperature of the beam source. The de Broglie wavelengths, obtained from the first-order diffraction maxima, cf. Equation (1), and the most probable velocities of the Maxwell-Boltzmann distribution, were found to be in the range 0.405 Å for a He beam produced at a source temperature 590 K to 1.37 Å for a H_2 beam produced at a source temperature of 100 K (Estermann and Stern 1930).

Direct verification of de Broglie's expression for the wavelength of matter waves was performed in two more machines, built by Estermann, Frisch, and Stern in 1932 (Estermann, Frisch, and Stern 1932). One apparatus allowed to velocity-select the molecular beam by reflection off a crystal, Fig. 20, the other by passing the incident beam through a pair of spatially offset cogwheels/slotted discs spinning about a common axis, Fig. 21. The latter method simultaneously allowed to accurately measure and control the beam velocity, v. Combined with the measured diffraction patterns, such as those in Fig. 22 which yielded the de Broglie wavelength, λ, Estermann, Frisch, and Stern were able to directly verify de Broglie's relationship $\lambda = h/(mv)$ for a beam of atoms or molecules of mass m—and thus the quantum-mechanical concept of matter-wave duality. In their landmark investigation, they used a helium beam impinging on a LiF crystal surface. The accuracy achieved in verifying de Broglie's relation was an admirable 1 %. As described in more detail in Chap. 23 by Peter Toennies, it would take decades before the next generation of matter wave diffraction experiments reached the accuracy of those by Stern and coworkers.

The series of papers written by Stern with Knauer, Estermann, and Frisch on the wave-particle duality are a paragon of thoroughness and ingenuity. They also illustrate Otto Stern's style of work in experimental physics. At the beginning there

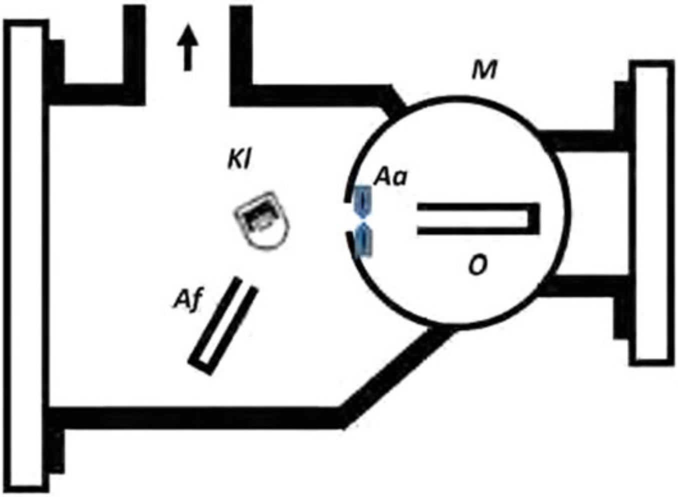


Fig. 18 Top view of the 1928 apparatus to measure the reflection of H_2 or He beams off crystals. *O* is the beam source orifice, *Aa* the collimating aperture, *Kl* the crystal and *Af* the detector (Knauer and Stern 1929a)

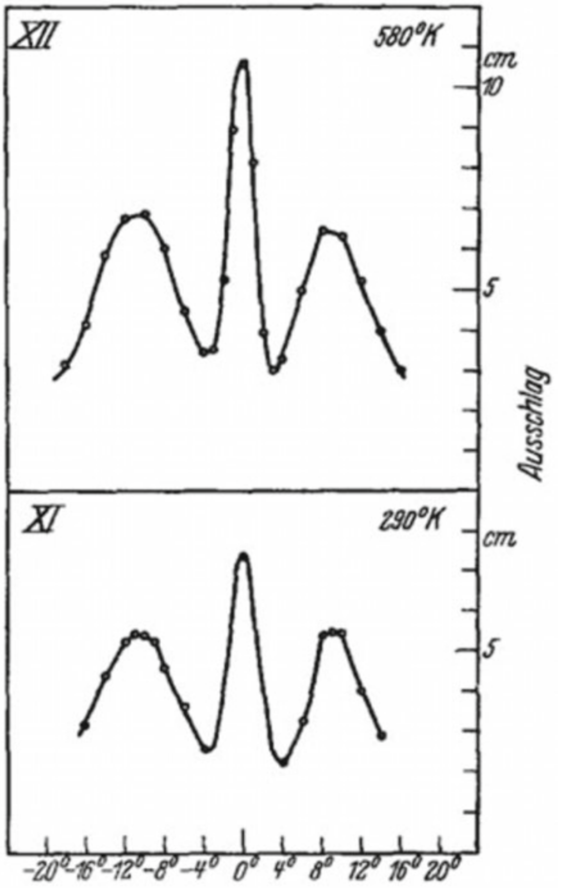


Fig. 19 Scattered intensity distributions as a function of the scattering angle for a He beam impinging on an NaCl crystal surface. The angle of incidence was fixed at 11.5° with respect to the surface (this angle defines the zero scattering angle). The He beam originated in a source of the indicated temperature. The first-order diffraction maxima (left and right from the reflection maximum in the center) are well resolved and allow for an accurate readout of their angular position (Estermann and Stern 1930)

is a fundamental question and an idea how to answer it. After thorough feasibility considerations that include calculations of everything that can be calculated comes a series of experiments each of which teems with innovations and pushes the limits of the possible. No effort is spared in order to answer the question posed at the outset. Here's how Immanuel Estermann described Stern's work habits (Estermann 1962):

> [Stern] could sit in the laboratory, and when an experiment didn't want to go, he wouldn't give up. Well, he had no other interests in life practically. He would sit until 1:00 or 2:00, or 3:00 in the morning; it didn't matter to him at all; he wouldn't go out for dinner, he would bring an apple to the laboratory, and that was his dinner. And it was hard on the younger ones, especially those of us who were married. I think I was the only married one in the laboratory in those days.

The paper (Estermann, Frisch, and Stern 1932) provides an additional illustrative episode of the workings of Stern's research group. When evaluating the experimental results, the de Broglie wavelength was found to deviate by 3% from the one calculated from the molecular velocity as determined by the velocity selector. According to

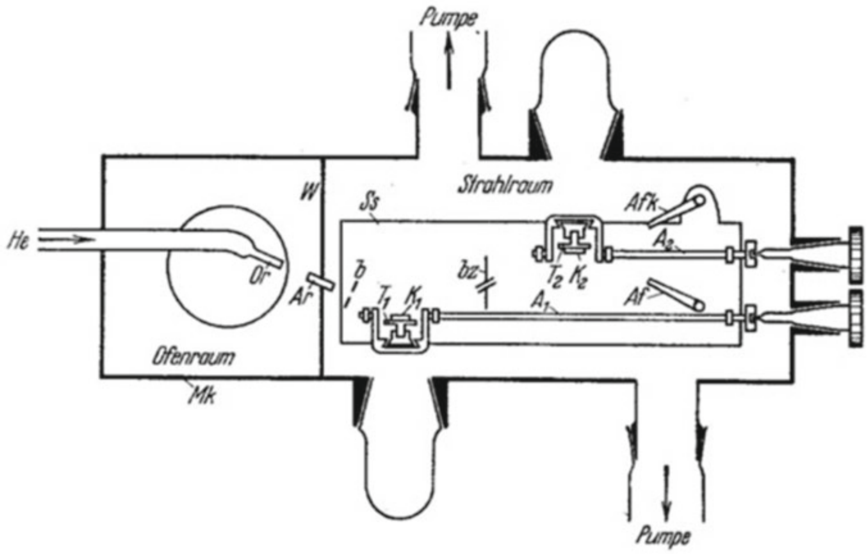


Fig. 20 Apparatus to verify the de Broglie wavelength formula for molecular beams with velocity selection by reflection. The He beam emanating from the source *Or* is collimated and velocity-selected by reflection off a crystal surface K_1. Upon collimation by slit bz, the velocity-selected beam is incident on the surface of crystal K_2. The twice-scattered He atoms are then detected in tube *Af* (Estermann, Frisch, and Stern 1932)

Stern's prior analysis, this lay outside the error bars of the measurements, which admitted a deviation of at most 1%. The problem was found upon inspecting the apparatus (Estermann, Frisch, and Stern 1932):

> The slotted discs had been made on a precision milling machine (*Auerbach-Dresden*), with the help of an indexing disc, which, according to the specifications, was supposed to divide the circumference of the wheel into 400 parts. Therefore, we took it for granted that the number of slits was 400. When we counted the slits, unfortunately only after completion of the experimental runs, we found that there were actually 408 of them (the indexing disk was indeed incorrectly labeled), which reduced the above mentioned deviation from 3 to 1%.

Thus Stern's masterful experiments on the diffraction of molecular beams provided definitive quantitative evidence for wave-particle duality.

More on matter waves can be found in Chaps. 23, 24 and 25.

2.4 Measurements of the Magnetic Dipole Moment of the Proton and the Deuteron

Measurements of nuclear magnetic moments were high on Stern's to-do list already in 1926 (Stern 1926). With the publication of Paul Dirac's "unified" quantum theory of the electron and the proton (Dirac 1930), the experimental determination of

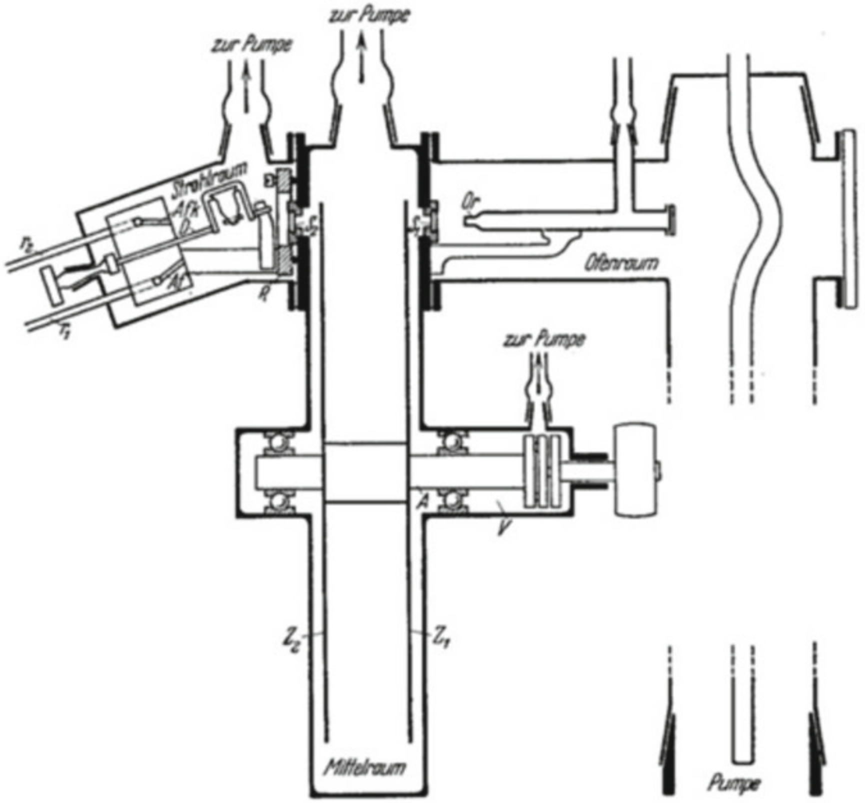


Fig. 21 Apparatus to verify the de Broglie wavelength formula for molecular beams with velocity selection by passage through spinning cogwheels/slotted discs–a *"Molekularstrahlspektrograph"*. The He beam produced in the "*Ofenraum*" is collimated and passed through spinning cogwheels Z_1 and Z_2 defining its velocity. The monochromatized beam is incident on the crystal surface attached to the rotatable axle D and its scattering detected at the catcher *Afk* (Estermann, Frisch, and Stern 1932)

proton's magnetic dipole moment became a priority for Stern and his coworkers. Dirac's theory posited that both the electron and the proton were point-like, carrying an elementary charge opposite in sign, and having magnetic dipole moments—the Bohr magneton and the nuclear magneton—whose magnitudes were mutually related by the ratio of their masses, i.e., $\mu_p/\mu_B = m_e/m_p$, with m_p and m_e the mass of the proton and of the electron, respectively, cf. Sect. 1. The feasibility of such an undertaking—the measurement of a dipole moment 1836-times smaller than the Bohr magneton—had only increased during the intervening time, thanks to both a refinement of the molecular beam detection methods (Knauer and Stern 1929b) and a better understanding of molecular hydrogen that became the species of choice to make the measurement on.

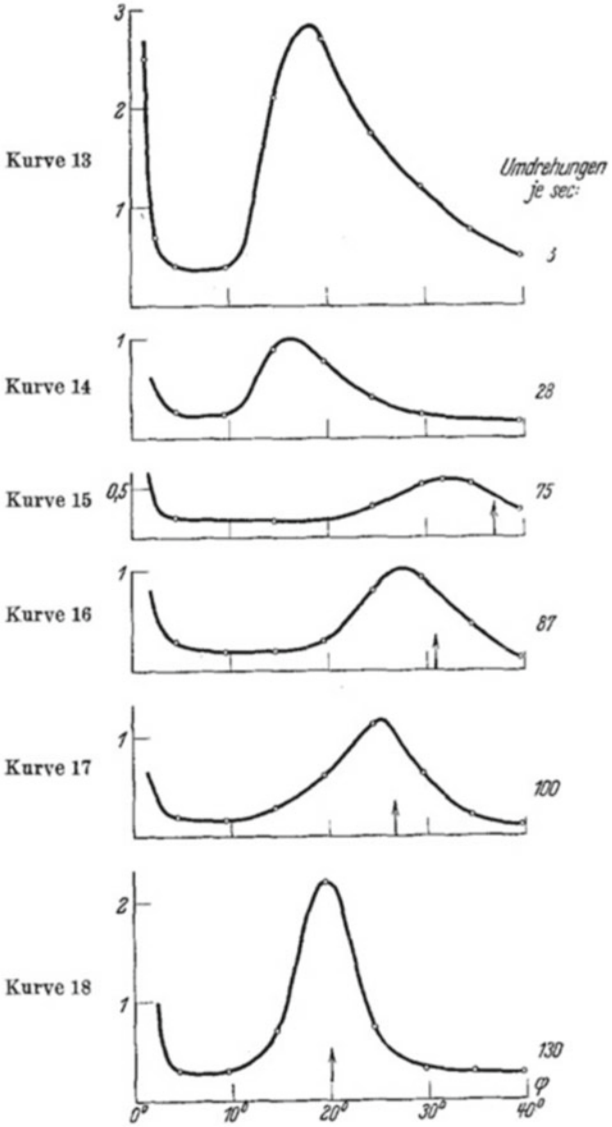


Fig. 22 Scattered intensity distributions as a function of the scattering angle for a He beam impinging on an LiF crystal surface. The individual curves, which correspond to the reflected and the right-hand diffracted peak of Fig. 19, were measured at different rotation rates (rpm shown on the right) of the spinning-cogwheel velocity selector. The diffraction peak of curve 13 (taken at a low rotation rate of 3 rpm) mirrors the Maxwell-Boltzmann velocity distribution. With increasing rotation rate (curves 14–18) of the spinning cogwheels, the distributions become narrower and eventually peak at a diffraction angle (shown by an arrow) corresponding to the de Broglie wavelength calculated via cf. Eq. (1) from the velocity defined by the velocity selector (Estermann, Frisch, and Stern 1932)

Prompted by the then mysterious line intensity alternations observed in the spectra of homonuclear diatomics (Slater 1926), Werner Heisenberg (Heisenberg 1927b) and Friedrich Hund (Hund 1927) postulated in 1927 the existence of two allotropic modifications of molecular hydrogen: ortho (parallel proton spins, odd-J rotational levels) and para (antiparallel proton spins, even-J rotational levels). In the same year, David Dennison (Dennison 1927) invoked these allotropic modifications to explain the anomalous behavior of molecular hydrogen's heat capacity at low temperatures, as observed by Arnold Eucken (Eucken 1912). Karl Friedrich Bonhoeffer (1899–1957) and Michael Polanyi (1891–1976) at Fritz Haber's Kaiser Wilhelm Institute for Physical Chemistry and Electrochemistry in Berlin-Dahlem (Friedrich et al. 2011; James et al. 2011; Friedrich 2016) took Heisenberg's and Hund's postulate literally and launched a search for molecular hydrogen in either of the two presumed allotropic forms. Their effort, joined by Paul Harteck (1902–1985), Adalbert (1906–1995) and Ladislaus Farkas (1904–1948) as well as Erika Cremer (1900–1996), provided in 1928-29 non-spectroscopic experimental evidence for the existence of molecular hydrogen's two allotropic modifications and led to the discovery of methods for their interconversion (Farkas and Sachsse 1933; Wigner 1933).

Stern and Frisch (Frisch and Stern 1933) recognized that the allotropic modifications of H_2 and the ability to vary their relative concentrations via interconversion were a godsend that would allow them to determine the contribution from molecular rotation to the overall magnetic dipole moment. The magnetic dipole moment of the hydrogen molecule arises namely from two sources: the nuclear spin dipole moments of the nuclei (protons) and from molecular rotation, i.e., from the spinning of the proton and electron charges. Whereas in ortho-hydrogen (parallel nuclear spins), both proton spin and molecular rotation contribute to the overall magnetic dipole moment, in para-hydrogen (antiparallel nuclear spins) the magnetic dipole moment is solely due to molecular rotation. Figure 23 shows schematically the two corresponding kinds of splittings. Hence by deflecting a beam of pure para-hydrogen, Stern and Frisch were able to determine the rotational contribution to the magnetic dipole moment. This came out as somewhat less than a nuclear magneton, $\mu_n (\mu_n = \mu_p)$. The rotational contribution could then be subtracted—in accordance with the schematic of Fig. 23—from the overall magnetic dipole moment found by deflecting a beam of ordinary hydrogen (25% para-H_2 and 75% ortho-H_2). This procedure yielded a magnetic dipole moment of the proton of 2.5 μ_n (with an error of about 20%)—and not 1 μ_n as predicted by the Dirac theory. The value of proton's magnetic moment would be refined in subsequent measurements by Stern and coworkers, see below. And so would the rotational magnetic moment. Its first theoretical estimate, by Hans Bethe (1906–2005), yielded a value of about 3 μ_n (Schmidt-Böcking et al. 2019; pp. 148–150); by including the effect of slippage of the electrons, recognized by Enrico Fermi (1901–1954), the theoretical value of the rotational magnetic dipole moment of H_2 in $J = 1$ dropped just below one nuclear magneton, in agreement with the measurements of Frisch and Stern.

That the magnetic dipole moment of the proton turned out to be quite different from one nuclear magneton brought the demise of Dirac's 1930 theory and a magnificent vindication of the imperative that guided Stern's work, namely to test the assumptions of theory—however plausible they may appear—by experiment. As Stern noted (Stern 1961):

> As the measurements of the magnetic moment of the proton were in progress, I was scolded by the theorists, who believed they knew what the outcome will be. Although our first runs had an error of 20%, the deviation [of our experimental results] from the expected theoretical value was [by] at least a factor of two.

The Frisch-Stern paper (Frisch and Stern 1933) with the revolutionary result was submitted on 27 May 1933. The technical details of the experiment described in it are astounding even today. A top view of the apparatus is shown in Fig. 24. The overall length of the molecular beam (from the source to the detector) was about 30 cm (nearly three times as much as in the SGE). The distance between the pole-pieces (edge and groove) of the Stern-Gerlach magnet was about 0.5 mm, producing a magnetic field gradient of about 2.2 T/cm. The deflection of a beam of H_2 molecules produced by a source at 90 K was about 40 μm per nuclear magneton. The molecular beam was collimated by a beak-like slit with platinum spacers 20 μm thick. The detector was a miniaturized Pirani gauge capable of registering pressure variation on the order of 10^{-8} torr within less than a minute. The entrance into the detector was defined by another 20 μm slit whose position along the direction of the deflection had to be scanned over a range of several tenths of a mm. Sample deflection data are shown in Fig. 25.

In a sequel, co-authored by Estermann and Stern (Estermann and Stern 1933a), and submitted on 12 July 1933, the error bars were reduced to just 10% for the magnetic dipole moment of the proton of 2.5 μ_n and the rotational moment per one rotational quantum of 0.85 μ_n. The main source of error were uncertainties in the inhomogeneity of the applied magnetic field, which were reduced by constructing the pole pieces of a new Stern-Gerlach magnet with greater accuracy. On 19 August 1933,

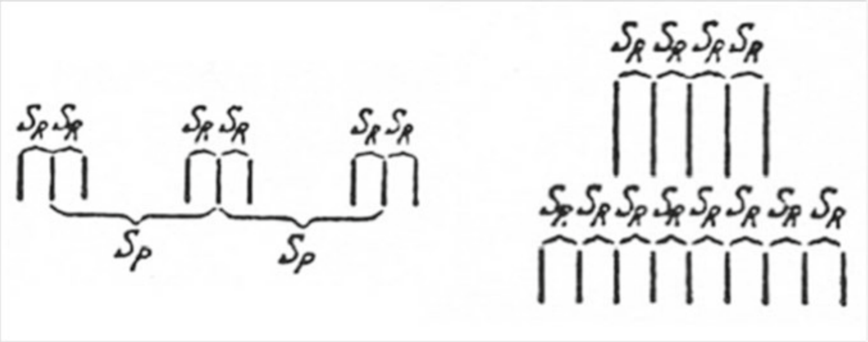


Fig. 23 Schematic diagrams of the splitting in a strong magnetic field of ortho-hydrogen (left) and of para-hydrogen (top right for $J = 2$ and bottom right for $J = 4$). Here S_P stands for the splitting due to the proton magnetic moment and S_R due to the rotational magnetic moment (Frisch and Stern 1933). The diagram on the left takes into account the Paschen-Back uncoupling of the rotational and proton moments in the magnetic field of 2 T used in the experiment

still from Hamburg, Estermann and Stern reported preliminary—and inconclusive—results (Estermann Stern 1933b) on the magnetic moment of the deuteron. It was Gilbert Newton Lewis (1875–1946) who is acknowledged for having provided 0.1 g of heavy water to his Hamburg colleagues for use in their experiment.

Upon their emigration—and settling with some of the Hamburg equipment at the Carnegie Institute of Technology in Pittsburgh— Estermann and Stern reported on 10 May 1934 their first conclusive result on the magnetic moment of the deuteron. This turned out to be only about 0.7 μ_n (Estermann and Stern 1934), which gave another jolt to the emerging nuclear physics community.

Given the paramount importance of the experimental values of the nuclear magnetic dipole moments of the proton and the deuteron, Stern and coworkers kept refining their measurements until 1937. Much of their effort went into reducing uncertainties in the inhomogeneity of the applied inhomogeneous magnetic field

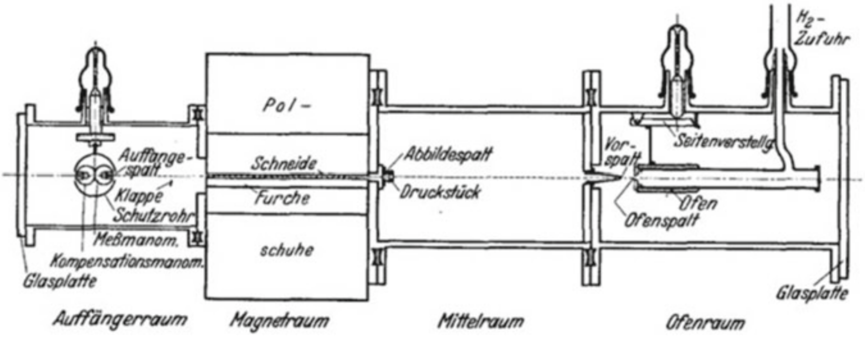


Fig. 24 Top view of the deflection apparatus designed for the measurement of nuclear and molecular magnetic moments (Frisch and Stern 1933)

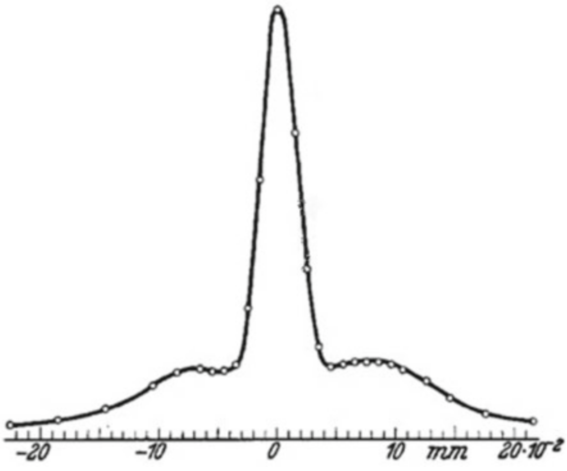


Fig. 25 Deflection curve of a molecular beam of ordinary molecular hydrogen produced by a source held at 95 K (Frisch and Stern 1933). The wings that flank the central peak of undeflected molecules arise mainly from the magnetic deflection of ortho-H_2 in $J = 1$ as the population of $J = 2$ of para-H_2 is negligible at this beam temperature

(Estermann et al. 1937). However, the molecular beams used in these experiments were not velocity-selected. This may have contributed to the deviation of the values obtained by Stern et al. for the magnetic moment of the proton and deuteron by about 10% from today's values of 2.793 μ_n and 0.855 μ_n, respectively. We note that a 1934 measurement by Isidor Rabi et al. on atomic hydrogen yielded 3.25 μ_n for the proton (Rabi et al. 1934).

Otto Stern and his Hamburg and Pittsburgh co-workers had thus provided unequivocal evidence that the proton has an internal structure and, unlike the electron, is not a point-like particle. Moreover, Stern's finding that the deuteron has a smaller magnetic dipole moment than the proton indicated that the neutron possessed a magnetic dipole moment as well, one oriented oppositely to that of the proton. Today we know that the magnetic dipole moment of the neutron is $-1.913\ \mu_n$, which implies that the neutron has an internal electric charge distribution that, however, perfectly "neutralizes itself" on the outside, as a neutron consists of one up quark (charge 2/3) and two down quarks (charge $-1/3$ each).

2.5 *Experimental Demonstration of Momentum Transfer Upon Absorption or Emission of a Photon*

The very last paper of the U.z.M. series, Number 30, was written by Otto Robert Frisch and submitted on 22 August 1933 (Frisch 1933a). Encouraged by Stern's programmatic paper (Stern 1926) as well as personal discussions, Frisch set out on a last-ditch effort to verify Einstein's 1917 premise (Einstein 1917) that atoms receive a tiny momentum kick upon absorption or emission of a photon.

Figure 26 shows the arrangement of Frisch's experiment: a beam of sodium atoms would be deflected by light from a sodium lamp (D-lines at 589.0 and 589.6 nm) propagating at right angles to the sodium beam either parallel (A) or perpendicular (B) to the collimation slit. The deflection would be detected by a hot-wire detector (tungsten, 10 μm diameter) whose position could be scanned perpendicular to the plane defined by the source and collimation slits. In the case of parallel illumination (A), only a broadening of the sodium beam was expected due to the photon recoil upon spontaneous emission whereas in the case of perpendicular illumination (B), the sodium beam was expected to be not only broadened but also shifted along the propagation direction of the photons from the sodium lamp due to the photon momentum transfer upon absorption.

The photon momentum involved was $h\nu/c$, with ν the frequency of the D-lines, which gave rise to a recoil velocity $h\nu/(m_{Na}c)$ of about 3 cm/s (m_{Na} is the mass of the sodium atom). Given that the mean velocity of the sodium atoms was about 9×10^4 cm/s, the angular deflection due to the absorption or emission of a photon was only about 29 μrad. For a length of the beam of about 30 cm (upon illumination behind the collimation slit), this corresponded to a perpendicular deflection of about 10 μm.

Fig. 26 Schematic of the photon-momentum transfer experiment (Frisch 1933a)

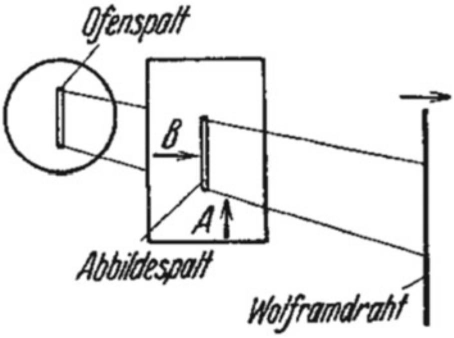
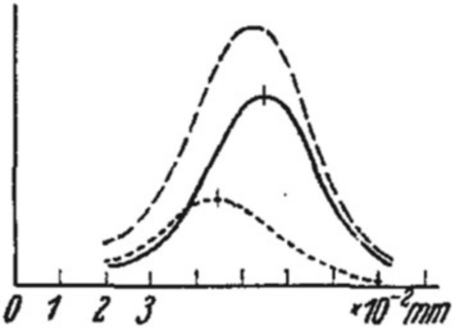


Fig. 27 Deflection of the sodium atom beam upon illumination perpendicular to the collimation slit (B), cf. Figure 26. Top dashed curve: illuminated sodium beam; full curve: 2/3 of the unilluminated sodium beam; bottom dashed curve: the difference of the two above curves corresponding to the distribution of the deflected sodium atoms (Frisch 1933a)



In order to estimate the fraction of the sodium atoms in the beam that were excited by the [*Osram*, double-filament] sodium lamp, Frisch determined from a photometric measurement on a sodium-vapor-filled resonance bulb that each atom was excited about 5×10^3 times a second, i.e., once in 2×10^{-4} s. Given that the atom would cover a distance of 20 cm during this time and that the illuminated stretch of the sodium beam by the *Osram* sodium lamp was 6 cm, Frisch concluded that about a third of the sodium atoms in the beam would be excited.

Figure 27 shows the results for an illumination perpendicular to the collimation slit, i.e., configuration B, see Fig. 26. The difference of the spatial distribution of the illuminated and unilluminated beam (after correction for the fraction of the atoms excited) gave the distribution of the deflected atoms. This distribution was found to peak at about 10 μm along the direction of the incident light from the sodium lamp, in agreement with the above theoretical expectation based on Einstein's theory. The deflection curve illustrates the key difference between (stimulated) absorption, which is directional, and spontaneous emission, which is not: Whereas the absorption momentum kick is imparted to the atom in the direction of the incident photon, the spontaneous emission (recoil) kick has a random direction and only results in a broadening of the spatial distribution.

The results presented by Frisch are convincing but only qualitative, as there was no time left for further work. The concluding sentence of the paper reads:

> No doubt it would have been possible to achieve clearer and more impeccable results, for instance through more accurate measurements with narrower beams but, for external reasons, the experiments had to be interrupted.

Upon emigrating from Germany, Frisch would never return to this line of research. It would take more than four decades for the principles he demonstrated to surface in the work on laser cooling of atoms and ions by Theodor Hänsch and Arthur Schawlow (Hänsch and Schawlow 1975) and David Wineland and Hans Dehmelt (Wineland and Dehmelt 1975), who took up where Frisch left off. Chapters 20, 21 and 22 of this volume amply illustrate where the research on cold atoms and molecules has led so far.

2.6 *The Experimental Verification of the Maxwell-Boltzmann Velocity Distribution via Deflection of a Molecular Beam by Gravity*

The ability to measure tiny deflections of a molecular beam led Stern to revisit the topic that set him on his path to becoming a leading 20th century experimental physicist: the verification of the Maxwell-Boltzmann distribution of velocities. Unlike in his 1919 attempt (Stern 1920a,b), which was based on a deflection of a molecular beam by the Coriolis force (and that only provided a mean Maxwell-Boltzmann velocity), his 1937–1947 work relied on a deflection imparted by gravity. The idea for the experiment appeared in Stern's solo paper (Stern 1937) whose main concern, however, was the accurate determination of the fine-structure constant from a measurement of the Bohr magneton. Stern considered a horizontal atomic beam passing through a horizontal collimating slit placed half-way between the source and the horizontal wire of a Langmuir-Taylor detector, see Fig. 28. Assuming that the distance $AB = BC = \ell$, Stern obtained for the vertical distance S_v of free fall at the horizontal distance 2ℓ from the source A, $S_v = g\ell^2/v^2$. For cesium effusing from a source at a temperature 450 K and for $\ell = 100$ cm, this gives a free-fall distance for the most probable Maxwell-Boltzmann velocity $\alpha = \sqrt{2k_BT/m_{Cs}}$ of $S_\alpha = 0.177$ mm—by then an easily measurable deflection. Stern further considered compensating this free-fall deflection by an inhomogeneous magnetic field, H, whose gradient, $\partial H/\partial r$, would be oriented oppositely to the gravitational field and thus result in lifting up the atoms by interacting with their magnetic moment, μ. For a magnetic field gradient of a conductor (wire) running parallel to the atomic beam at a distance d and carrying an electric current I, the balance between the gravitational and magnetic force would be reached for $mg = \mu|\partial H/\partial r| = \mu(2I_0/d^2)$. In order to determine the compensating current I_0, Stern considered two options (Stern 1937): (a) lifting the atomic beam to the point C', see Fig. 28, by increasing the current I:

> The instant I becomes larger than I_0, half of the atoms regardless of their velocity are deflected upwards and some atoms strike the wire. Since the amount of the deflection depends on the velocity, the slowest atoms strike the wire first, then with increasing $I - I_0$ the faster ones. No matter how far above the beam we set the detecting wire, we shall get an ion current as soon as I becomes larger than I_0.

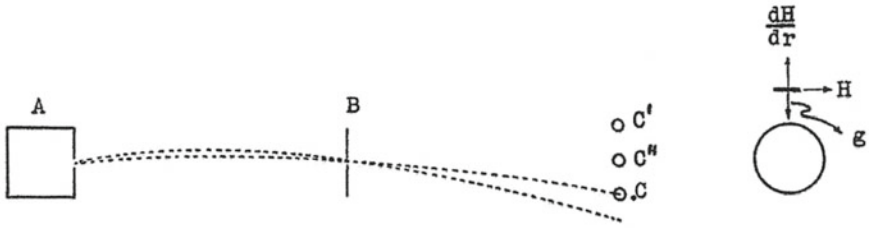


Fig. 28 Left: Schematic of the deflection of a horizontal atomic beam by the gravitational field. The beam originating in source A passes through a collimating slit B to a detector whose vertical position can be scanned through any of the points C. Right: View along the atomic beam. A current-carrying wire (circle) producing at a distance r a magnetic field H whose gradient is $\partial H/\partial r$. Note the opposite orientations of the magnetic gradient and the gravitational field whose acceleration is g (Stern 1937)

Option (b) would be to place the detector wire in the path of the beam, see point C" in Fig. 28, and

> measure [the ion current] i as a function of [the current through the conductor] I. Then i should have a maximum for $I = I_0$ because if I is larger or smaller than I_0 we [would] deflect atoms upward or downward and diminish the intensity.

Stern points out that the beam should be running in the north-south direction, as in this case the Coriolis force produced by Earth's rotation would have no vertical component that might reduce the accuracy of determining I_0.

A decade later, Estermann, Simpson, and Stern published a tour-de-force paper on the velocity distribution of cesium and potassium atoms based on gravitational deflection and its compensation by an inhomogeneous magnetic field (Estermann, Simpson, and Stern 1947a). The apparatus built for the purpose of the measurements was quite elaborate—and 2 m long. It entailed nothing less than two molecular beams that were run in parallel and whose deflections served to provide an average deflection intended to reduce the error due to mechanical distortions of the current-carrying "conductor tube" (of up to 50 A) producing the compensating magnetic field.

Representative data for a cesium beam obtained for a deflection by gravity are shown in Fig. 29. The beam intensity (ordinate) as determined by the hot-wire detector is plotted against the deflection S, i.e., the vertical position of the detector wire, in units of 10 μm (abscissa). Also shown on the abscissa are the multiples of the deflection S_α corresponding to the most probable velocity of Cs at a source temperature of 450 K. Note that slower atoms that suffer larger deflections are to the right. The authors conclude:

> The experiments serve as a demonstration that individual atoms follow the laws of free fall in the same way as other pieces of matter. Moreover, they permit a more accurate determination of the velocity distribution in molecular rays than those carried out earlier. The knowledge of this distribution is of great importance for many molecular beam experiments. It has usually been assumed that the Maxwell distribution law is valid as long as the mean free path of the molecules in the oven is several times as large as the width of the oven slit. These experiments show, however, that there is a considerable deficiency of slow molecules even at much lower

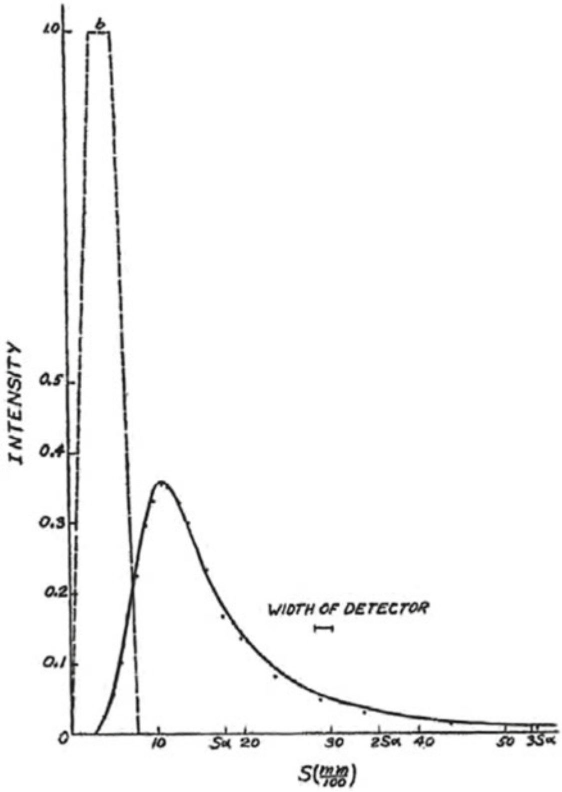


Fig. 29 Gravity deflection of cesium atoms—both calculated (full curve) and measured (points). The trapezoid on the left shows the "shape" of the undeflected beam, with *b* the vertical size of the collimation slit (Estermann, Simpson, and Stern 1947a)

> pressures. This deficiency is probably caused by collisions in the immediate vicinity of the oven slit.

In his last molecular beam paper, submitted together with the above paper on 29 November 1946 and published back-to-back with it, Stern and coworkers reported on gas-phase scattering of a cesium beam by helium, molecular nitrogen, and cesium vapor and corroborated the above conclusion (Estermann et al. 1947b). The gravity deflection curves served to infer the collision velocity.

3 Epilog

While at Hamburg, Otto Stern developed close friendships with a trio of colleagues who are all captured, together with Stern, in the 1935 photo shown in Fig. 30: Niels Bohr, Wolfgang Pauli, and Lise Meitner. Bohr was in fact the only (European) colleague with whom Stern was "*per Du*," i.e., on first-name terms. Stern's closeness with the three can be inferred from Stern's correspondence. Stern had also a close,

Fig. 30 Copenhagen Conference 1935. From left: Niels Bohr, Wolfgang Pauli, Otto Stern, and Lise Meitner (OSC)

family-like relationship with Pauli's second wife Franca and with Bohr's wife Margarete. Judging, again, from his correspondence, Stern had a friendly rapport with all his colleagues and coworkers, although there may have been some clouds hanging over his relationship with Walther Gerlach. During the Nazi era, Gerlach would take up a leading role in the German nuclear program, see Chap. 8. Gerlach's brother was a high-ranking member of the SS, but apparently Gerlach himself would never join the NSDAP, see also Chap. 8. Unlike Stern, Gerlach enjoyed the limelight. In a note to Gerlach, Stern addressed him, apparently jocularly, as the "Grossbonze" [big shot]. In 1957, writing to Lise Meitner, Stern ostentatiously expressed a lack of interest to see Gerlach during his trip to Munich that year. In contrast, Gerlach expressed his admiration and fondness for Stern in his speech at the "Physikalischer Verein" in Frankfurt in 1960 (Gerlach 1960)—and did the same in his recollections of the Stern-Gerlach experiment—and of Stern—following Stern's death (Gerlach 1969).

Stern did his best to help those who needed help. This became especially manifest after Stern's emigration in 1933, when he would spend considerable amounts of time—and his own money—to help his colleagues to find a job or bridge times without one. He would be similarly helpful to his relatives (Schmidt-Böcking et al. 2018).

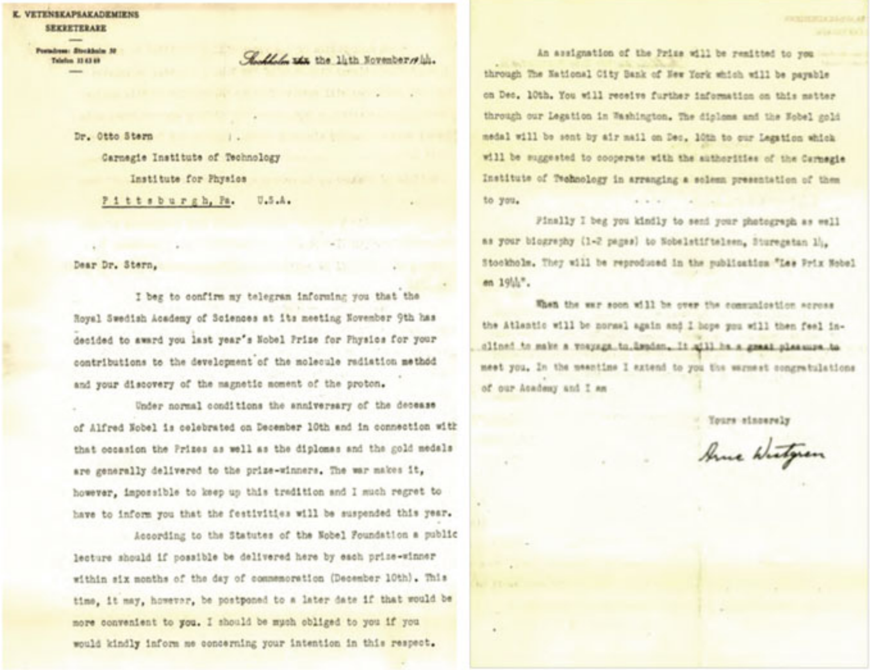
Stern enjoyed traveling, mostly by boat and train, although he would fly on occasions as well. He would be a frequent visitor in Copenhagen, attend the Solvay conferences in Brussels, meetings in Italy, Fig. 31, and later the meetings of the American Physical Society. Starting in 1946, Stern would spend several months each year in Europe, most notably in Zurich. Pension Tiefenau at Steinwiesenstrasse 8 became something of a second home to him, right after his house on 757 Cragmont Avenue in Berkeley where he lived since 1945, not far from his sister Berta's

Fig. 31 Stern in Rome at the Volta conference (OSC)

apartment. After 1950, he would come to Germany, at least eight times, to see his friends Max von Laue, Max Born, and Max Volmer (Schmidt-Böcking et al. 2018).

During his twelve-year tenure at the Carnegie Institute of Technology, Stern remained for the most part unnoticed by the Pittsburgh society. This changed abruptly following the arrival of a letter from Stockholm dated 14 November 1944, see Fig. 32. Here's what Stern said on 8 December 1944 at a gathering in Pittsburgh held in his honor (Schmidt-Böcking et al. 2019; p. 350):

> I realize that this award is only in part a recognition of my personal work, but mainly of the work of all scientific physicists. Progress in pure science can only be achieved in a scientific atmosphere where everyone is allowed to choose his own problem and can discuss his work freely with other scientists. Both conditions for scientific work will be in danger in the future. First, the growing importance of the results of pure science for the industrial and military



K. VETENSKAPSAKADEMIENS
SEKRETERARE

Stockholm the 14th November 1944.

Dr. Otto Stern
Carnegie Institute of Technology
Institute for Physics
Pittsburgh, Pa. U.S.A.

Dear Dr. Stern,

I beg to confirm my telegram informing you that the Royal Swedish Academy of Sciences at its meeting November 9th has decided to award you last year's Nobel Prize for Physics for your contributions to the development of the molecule radiation method and your discovery of the magnetic moment of the proton.

Under normal conditions the anniversary of the decease of Alfred Nobel is celebrated on December 10th and in connection with that occasion the Prizes as well as the diplomas and the gold medals are generally delivered to the prize-winners. The war makes it, however, impossible to keep up this tradition and I much regret to have to inform you that the festivities will be suspended this year.

According to the Statutes of the Nobel Foundation a public lecture should if possible be delivered here by each prize-winner within six months of the day of commemoration (December 10th). This time, it may, however, be postponed to a later date if that would be more convenient to you. I should be much obliged to you if you would kindly inform me concerning your intention in this respect.

An assignation of the Prize will be remitted to you through The National City Bank of New York which will be payable on Dec. 10th. You will receive further information on this matter through our Legation in Washington. The diploma and the Nobel gold medal will be sent by air mail on Dec. 10th to our Legation which will be suggested to cooperate with the authorities of the Carnegie Institute of Technology in arranging a solemn presentation of them to you.

Finally I beg you kindly to send your photograph as well as your biography (1-2 pages) to Nobelstiftelsen, Sturegatan 14, Stockholm. They will be reproduced in the publication "Les Prix Nobel en 1944".

When the war soon will be over the communication across the Atlantic will be normal again and I hope you will then feel inclined to make a voyage to Sweden. It will be a great pleasure to meet you. In the meantime I extend to you the warmest congratulations of our Academy and I am

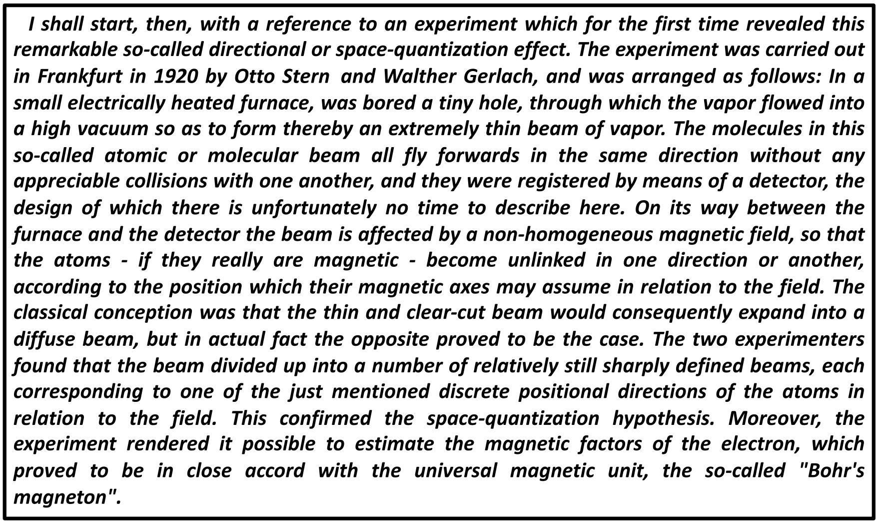
Yours sincerely

Arne Westgren

Fig. 32 Official letter from the Swedish Royal Academy to Stern (Bancroft Library, see (Schmidt-Böcking et al. 2018; p. 347)

> development will make it necessary to maintain a certain degree of secrecy and will seriously impede the free interchange of ideas. Secondly, the basis and root of all scientific work is the absolute freedom of the scientist to choose his problems. Because of the fundamental importance of the results of scientific work for practical purposes the material resources for research will be concentrated on the solution of practical problems and the scientists themselves will hesitate to devote their work to problems without apparent significance for defense, social and industrial progress.
>
> We must find the right balance between pure and applied science. We must maintain a high standard of pure science. We will have to do this even if we disregard the educational and cultural significance of science if only for the reason that without a vigorous pure science there will be no real progress in its applications.
>
> For these reasons I am deeply grateful to the Royal Swedish Academy, not only for the great honor bestowed on me, but even more for the help given to pure science through the great prestige of Nobel and the Nobel foundation.

Although Stern's Nobel citation, see Sect. 1, mentions only the development of the molecular beam method and the measurement of the magnetic dipole moment of the proton, Eric Hulthén, a Nobel Committee member, extolled in his laudation—broadcast by the Swedish Radio—especially the Stern-Gerlach experiment, see Fig. 33.



I shall start, then, with a reference to an experiment which for the first time revealed this remarkable so-called directional or space-quantization effect. The experiment was carried out in Frankfurt in 1920 by Otto Stern and Walther Gerlach, and was arranged as follows: In a small electrically heated furnace, was bored a tiny hole, through which the vapor flowed into a high vacuum so as to form thereby an extremely thin beam of vapor. The molecules in this so-called atomic or molecular beam all fly forwards in the same direction without any appreciable collisions with one another, and they were registered by means of a detector, the design of which there is unfortunately no time to describe here. On its way between the furnace and the detector the beam is affected by a non-homogeneous magnetic field, so that the atoms - if they really are magnetic - become unlinked in one direction or another, according to the position which their magnetic axes may assume in relation to the field. The classical conception was that the thin and clear-cut beam would consequently expand into a diffuse beam, but in actual fact the opposite proved to be the case. The two experimenters found that the beam divided up into a number of relatively still sharply defined beams, each corresponding to one of the just mentioned discrete positional directions of the atoms in relation to the field. This confirmed the space-quantization hypothesis. Moreover, the experiment rendered it possible to estimate the magnetic factors of the electron, which proved to be in close accord with the universal magnetic unit, the so-called "Bohr's magneton".

Fig. 33 Eric Hulthén's Nobel laudatio of Stern broadcast by the Swedish Radio on 10 December 1944 (CHS)

Felix Bloch together with his wife Lore penned the following poem to congratulate Stern on his Nobel Prize (Schmidt-Böcking et al. 2019; p. 381):

1. Twinkle, twinkle Otto Stern
how did Rabi so much learn?
He rose in the world so high
Like a diamond in the sky.
Twinkle, twinkle Otto Stern
how did Rabi so much learn?

2. The infant cried when he was born:
In Austria I feel forlorn.
And he said: The stupid stork
Should have brought me to New York.
Twinkle, twinkle Otto Stern
how did Rabi so much learn?

3. He crossed the sea a baby small
But that didn't hurt at all.
Great was his intelligence
In a certain narrow sense.
Twinkle, twinkle Otto Stern
how did Rabi so much learn?

4. Talmud and philosphie
Didn't really satisfy
So he thought as physicist
He perhaps would not be missed
Twinkle, twinkle Otto Stern
how did Rabi so much learn?

5. He together with his team
wiggled the atomic beam
Up and down through slits so fine
Saw the light of reason shine
Twinkle twinkle Otto Stern
How did Rabi so much learn.

6. Soon the moments made him
and he said: I'm awfully sorry.
Gentlemen, we have no chance
What we need is resonance.
Twinkle, twinkle Otto Stern
How did Rabi so much learn?

7. Well you know, he's always right,
This time he was even bright,
And a quadrupole he found.
Deuterons were no more round
Twinkle twinkle Otto Stern
How did Rabi so much learn.

8. At R.L. he said: Why not
Should I be a great big shot?
and again he was quite right
he almost made it, but not quite.
Twinkle twinkle Otto Stern
How did Rabi so much learn.

9. So he finally grew wise
Got himself the Nobel prize.
Back to physics now he is
With undreamt possibilities.
Twinkle twinkle Otto Stern
How did Rabi so much learn.

10. Twinkle, twinkle Otto Stern
How did Rabi so much learn?
He rose in the world so high
like a diamond in the sky.
Twinkle twinkle Otto Stern
How did Rabi so much learn.

Figure 34 shows the poem's dedication to Stern by Felix and Lore Bloch as well as its "endorsement" by the signatures of Isidor I. Rabi—the host of the celebratory gathering, George E. Uhlenbeck, Jerold Zacharias, Reg Turner, Wheeler Loomis, Walton N, J.H. Van Vleck, Luis Lederman, L.J. Haworth, Marshall, E.M. Purcell, James L. Lawson, Jane K. Lawson, Beth Purcell, Louis C. Turner, Edith Loomis, Anette Hugh, Goudsmit, Helen Rabi, John Slater, and others.

The molecular beam method made inroads into both physics and chemistry starting in the 1960s, especially in Europe and the U.S. Stern's former PhD student, Lester C. Lewis (1902-?),[5] drew a scientific family tree shown in Fig. 35. In his

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[5] L. C. Lewis (born 1902) joined Stern in Hamburg in 1930 as a Charles A. Coffin Fellow and graduated there in 1931 with a thesis on chemical equilibria, "Die Bestimmung des Gleichgewichts

Lore C. Bloch

Entstanden anlässlich einer Feier bei den Rabi's bei der wir alle an Sie dachten

Viele herzliche Glückwünsche F. Bloch

Auch von mir die herzlichsten Glückwünsche Lore Bloch

I. I. Rabi
George E. Uhlenbeck
Felix Bloch
Jerrold Zacharias
Peg Turner
Wheeler Loomis
Milton G. White

J H Van Vleck
Louis N. Ridenour
L. J. Haworth
J B Horner Kuper
Lucile Marshall
E. M. Purcell

James L. Lawson
Jane K. Lawson
Beth Purcell
Louis A. Turner
Edith Loomis
John C Slater

Fig. 34 Entstanden anlässlich einer Feier bei den Rabi's bei der wir alle an Sie dachten. Viele Herzliche Glückwünsche F. Bloch Auch von mir die herzlichsten Glückwünsche Lore Bloch

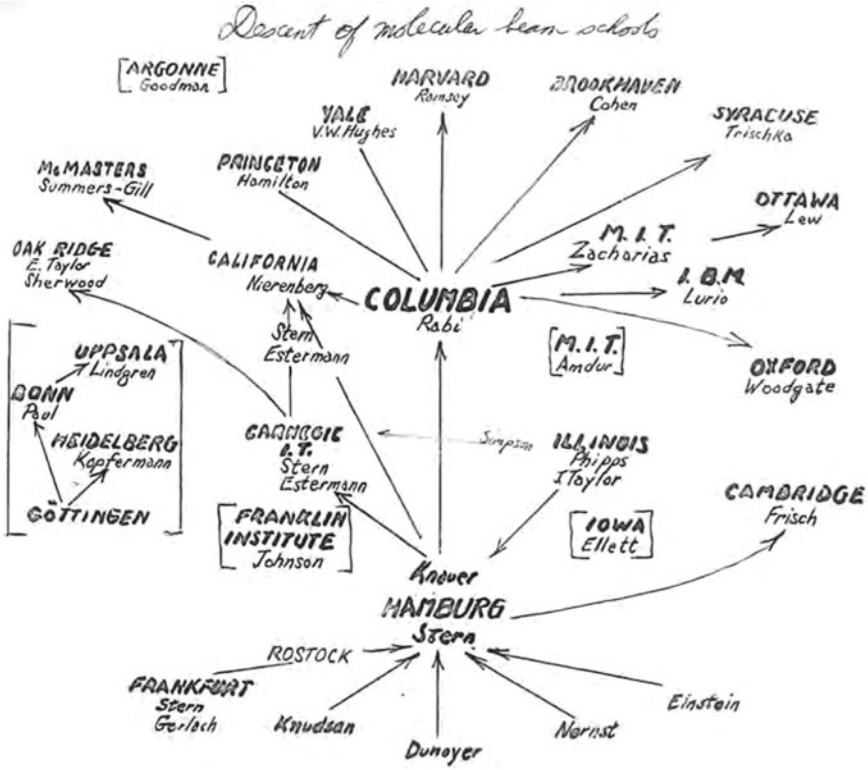

Fig. 35 Family tree of the molecular beam method in Europe and the United States by L.C. Lewis (Bancroft Library, see (Schmidt-Böcking et al. 2019; p. 257)

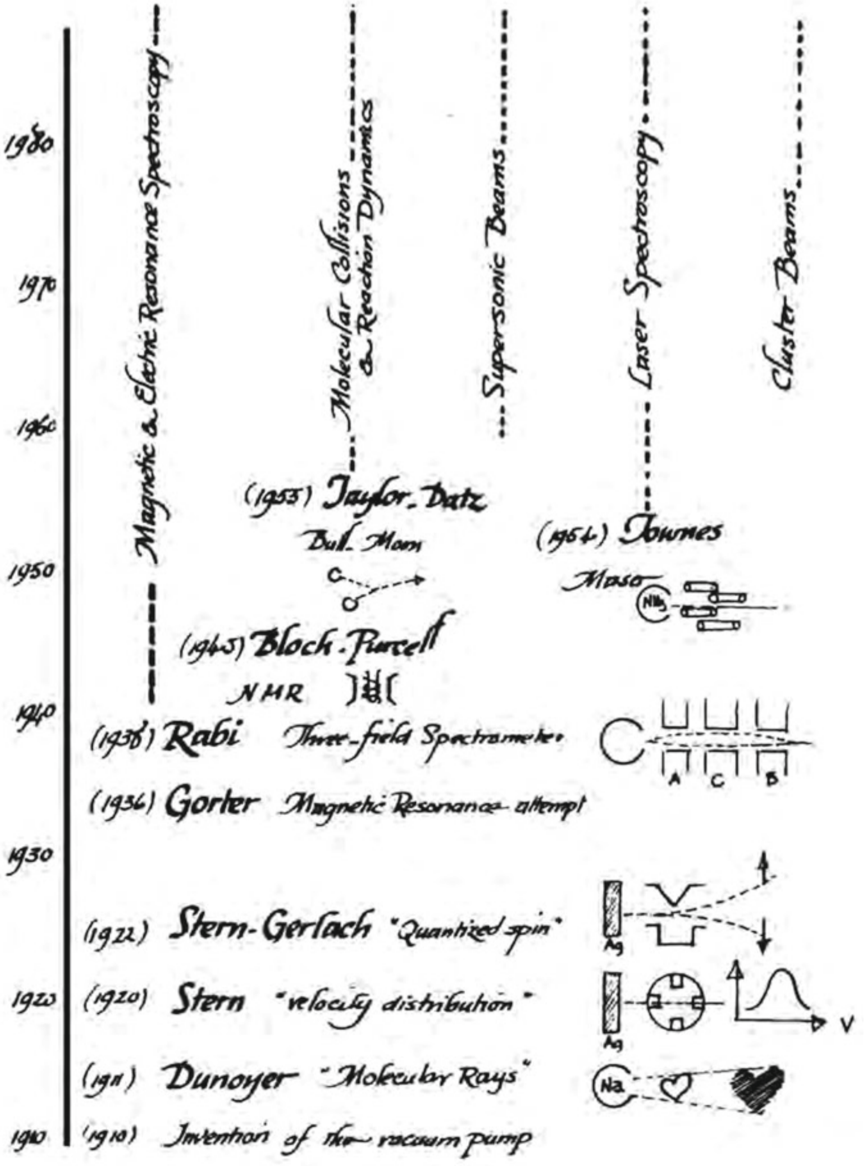

Fig. 36 Evolution of molecular beam and kindred methods according to Dudley Herschbach (Herschbach 1987)

1986 Nobel Lecture, Dudley Herschbach presented his depiction of the evolution and consequences of the molecular beam method, see Fig. 36.

In addition to the Nobel Prize, Stern received many additional honors, such as honorary degrees from Berkeley (1930) or Zurich (1960) or academy memberships in Europe and the U.S. After his death, the German Physical Society named its highest award in experimental physics the "Stern-Gerlach-Preis" (1988–1992), renamed in 1993 the "Stern-Gerlach-Medaille," see Fig. 37.

At the University of Hamburg, a lecture hall was named after Otto Stern and at the University of Frankfurt a new auditorium and library complex on the Riedberg campus was named the "Otto Stern Zentrum" (Fig. 38). Last but not least, the building in Frankfurt where Otto Stern launched his molecular beam experiments was declared in 2019 a "European Physical Society Historic Site." The plaque reads:

> This building housed Max Born's Institute for Theoretical Physics where key discoveries were made during the period 1919-1922 that contributed decisively to the development of quantum mechanics. The Institute launched experiments in 1919 via the molecular beam technique by Otto Stern, for which he was awarded the 1943 Nobel Prize in Physics. Experiments done in 1920 by Max Born and Elisabeth Bormann sent a beam of silver atoms measuring the mean free path in gases and probing various gases to estimate sizes of molecules. An iconic experiment in 1922 by Otto Stern and Walther Gerlach demonstrated space quantization of atomic magnetic moments and thereby also, for the first time, the quantization of atomic angular momenta. In 1921, Alfred Landé postulated here the coupling of angular momenta as the basis of the electron dynamics within atoms. This building is the seat of the Physical Society of Frankfurt (the oldest in Germany, founded in 1824).

Let us conclude with the words of one of Otto Stern's most prominent associates, Isidor Rabi, as told to John Rigden just a few days before Rabi's death (Rabi 1988):

> Stern had this quality of taste in physics and he had it to the highest degree. As far as I know, Stern never devoted himself to a minor question.

Archives

AEA	Albert Einstein Archives, The Hebrew University of Jerusalem, Jerusalem, Israel
CHS	Center for History of Science, The Royal Swedish Academy of Sciences, Box 50005, SE-104 05 Stockholm, Sweden
CMA	Archives Carnegie Mellon Institute, Pittsburgh, PA, USA
OSC	Otto Stern Picture Collection, Bancroft Library, Berkeley, CA, USA

Numbers (Sx) and (Mx) in the following list of references refer to the list of publications by Stern and his collaborators as given in *Otto Sterns Veröffentlichungen*, ed. H. Schmidt-Böcking *et al.*, Springer, 2016. Numbers (U.z.M. x) refer to the series of papers in Zeitschrift für Physik entitled Untersuchungen zur Molekularstrahlmethode.

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zwischen den Atomen und den Molekülen eines Alkalidampfes mit einer Molekularstrahlmethode." He would become Curator and later Executive Director for Physical Sciences at the Smithsonian Museum in Washington, D.C.

Fig. 37 Stern-Gerlach Medal of the German Physical Society

Fig. 38 One of the authors (HS-B) in front of the "Otto Stern Zentrum" at the Riedberg Campus of the University of Frankfurt

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