Wilhelm und Else Heraeus Seminar # 702:

"Otto Stern's Molecular Beam Research and its Impact on Science"

1-5 September 2019

Arthur von Weinberg-Haus (Alte Physik)
Robert-Meyer-Straße 2, 60325 Frankfurt

Honorary Chairs: Dudley Herschbach and Peter Toennies

Organizers: Horst Schmidt-Böcking and Bretislav Friedrich

Aims of the Conference

The year 2019 presents a two-fold opportunity to remember the pioneer of quantum physics and Nobel Laureate Otto Stern (1888-1969). In 1919, at Max von Laue's and Max Born's Institute for Theoretical Physics of the University of Frankfurt, Stern launched the revolutionary molecular beam (or molecular ray) technique. This technique made it possible to send atoms and molecules with well-defined momentum through vacuum and to measure with high accuracy the deflections they underwent when acted upon by transversal forces. Thereby, heretofore unforeseen quantum properties of nuclei, atoms, and molecules could be revealed that became the basis for our current understanding of quantum matter. In the iconic Stern-Gerlach experiment, completed in February 1922, the reality of space quantization of angular momentum had been demonstrated. The momentum resolution achieved corresponded to an energy resolution of a micro electron volt.

This year marks also the fiftieth anniversary of Otto Stern's death. After a heyday period at the University of Hamburg (1923-1933), Stern was forced by the Nazi regime to emigrate. He settled in the U.S., first at Pittsburg (1933-1945) and then in Berkeley (1946-1969). After the Second World War, Stern was generously helping many of his friends and colleagues with CARE packages. And he would not miss an opportunity to visit Europe – to see his friends at conferences and meetings, in particular in Copenhagen, London, and, foremost, in Zurich.

The main aim of this conference is to show that many key areas of modern science, in particular of Physics and Chemistry, originated in the seminal molecular beam work of Otto Stern and his school. The participants will benefit from talks and discussions that will highlight the current state of the art in these areas.

The symposium is funded by grants from the Wilhelm and Else Heraeus Foundation https://www.we-heraeus-stiftung.de/english/, the Deutsche Forschungsgemeinschaft https://www.dfg.de/, and Frontiers Media https://www.frontiersin.org/.

Symposium website: https://indico.fhi-berlin.mpg.de/event/35/

Program

Sunday, 1 September 2019

16:00 – 22:00 Welcome reception

Monday, 2 September 2019

9:00-10:00 Festive Opening in *Alte Aula* (with *Musikalische Umrahmung*)
9:00-9:30 Dudley Herschbach: *Welcome: An homage to Otto Stern*
9:30-10:00 Alan Templeton: *My uncle Otto Stern*

10:00-10:30 Coffee Break

10:30-13:00 History: Karin Reich, Chair
10:30-11:20 Keynote: Tilman Sauer: *Otto Stern's trajectory*
11:20-12:10 Arne Schirrmacher: *From theory to experiment (and back to theory)? On Otto Stern, Max Born and other physicists in the 1920s*
12:10-13:00 Massimiliano Badino: *Otto Sackur, Otto Stern, and the Beginning of the Quantum Theory of Gases*

13:00-14:00 Lunch

14:00-15:45 Magnetic and Electric Resonance Spectroscopy: Horst Kessler, Chair
14:00-14:45 Keynote: Christian Griesinger: *From Stern's beam experiments to modern biomolecular NMR spectroscopy*
14:45-15:15 Hermann Requardt: *Economic aspects of NMR: Analytic devices and medical imagers*
15:15-15:45 Harald Schwalbe: *Protons, Electrons - how they spin and interact to discover major aspects of Chemistry and Biomedicine*

15:45-16:15 Coffee break

16:15-19:00 Foundations of Quantum Mechanics: Wolfgang Demtröder, Chair
16:15-17:00 Keynote: John Briggs: *Quantum or classical perception: The Imaging Theorem and the Ensemble Picture*
17:00-17:30 Michael Devereux: *Reduction of the atomic wave function in the Stern-Gerlach magnetic field*
17:30-18:00 Wolfgang Schleich: *At the interface of gravity and quantum mechanics*
18:00-18:30 Ron Folman: *Stern-Gerlach Interferometry on the Atom Chip*
18:30-19:00 Hendrik Ulbricht: *Prospects for testing quantum mechanics with levitated optomechanics*

19:00-20:00 Dinner

20:00-20:30 Foundations of Quantum Mechanics Cont'd: Hartmut Hotop, Chair
20:00-20:30 Bob Griffith: *What Do Quantum Measurements Measure?*

20:30-22:00 Poster Session with Wine+Beer+Bretzel

Tuesday, 3 September 2019

9:00-10:30 High Precision Measurements: Peter Toschek, Chair
9:00-9:45 Keynote: Joachim Ullrich: *Precision experiments for the revised SI - and the future of time*
9:45-10:30 Klaus Blaum: *Precision Physics in Penning Traps Using the Continuous Stern-Gerlach-Effect*

10:30-11:00 Coffee Break

11:00-13:00 Femto- and Atto-science: Reinhard Dörner, Chair
11:00-11:45 Keynote: Paul Corkum: *Using light to control electrons that, in turn, create new light sources*
11:45-12:10 Olga Smirnova: *Synthetic Chiral Light for Efficient Chiral Light-Matter Interaction*
12:10-12:35 Kiyoshi Ueda: *Ultrafast molecular and electronic dynamics probed by free-electron lasers*
12:35-13:00 Ursula Keller: *Attoclock revisited*

13:00-14:00 Lunch

14:00-16:00 EPS Historic Site Ceremony in *Alte Aula* (with *Musikalische Umrahmung*)

Remarks:
Peter Feldmann, Oberbürgermeister der Stadt Frankfurt
Prof. Dr. Birgitta Wolff, Präsidentin der Goethe Universität
Prof. Dr. Petra Rudolf, Präsidentin der European Physical Society
Prof. Dr. Dieter Meschede, Präsident der Deutschen Physikalischen Gesellschaft
Prof. Dr. Michael Lang, Dekan des Fachbereichs Physik der Goethe Universität
Prof. Dr. Kurt Scharnberg, Grußwort der Universität Hamburg
Prof. Dr. Wolfgang Grünbein, Präsident des Physikalischen Vereins Frankfurt
Prof. Dr. Andreas Mulch, Stellvertretender Generaldirektor der Senckenberg Gesellschaft für Naturforschung

Unveiling of the EPS Historic Site Plaque

Keynote: Michael Eckert: *Frankfurt Physicists*

16:00-16:30 Coffee Break

16:30-18:45 Cold atoms and molecules: Reinhold Schuch, Chair
16:30-17:15 Keynote: Dan Kleppner: *Our Patrimony from Otto Stern and My Memories of Otto Frisch*
17:15-17:45 Kang-Kuen Ni: *Ultracold Chemical reactions with molecules in slow motion*
17:45-18:15 Monika Schleier-Smith: *Choreographing Quantum Spin Dynamics with Light*
18:15-18:45 Klaas Bergmann: *STIRAP: Notes about its history and some news*

19:30-22:00 Conference Dinner (at Dorint Oberursel) with Ludger Wöste's *Physical Amusements*

Wednesday, 4 September 2019

9:00–10:30 Reaction Dynamics: Dudley Herschbach, Chair
9:00–9:40 Keynote: Gerard Meijer: *Manipulation and control of molecular beams*
9:40–10:05 Eva Lindroth: *Time delays in photoionization*
10:05–10:30 Christiane Koch: *Quantum effects in cold and controlled molecular dynamics*

10.30–11.00 Coffee Break

11.00–13:00 Matter Waves: Burkhard Fricke, Chair
11:00–11:40 Keynote: Peter Toennies: *Otto Stern and Wave-Particle Duality*
11:40–12:10 Markus Arndt: *Macromolecular Matter Wave Interferometry and Talbot-Lau Deflectometry*
12:10–12:35 Maksim Kunitski: *Rotating rotationless: nonadiabatic alignment of the helium dimer and trimer*
12:35–13:00 Wieland Schöllkopf: *Grating Diffraction of Molecular Beams: Present Day Implementations of Otto Stern's Concept*

13:00–14:00 Lunch

14:00–16:00 MOTs and Optical Lattices: Hanns-Christoph Nägerl, Chair
14:00–14:45 Keynote: David Pritchard: *Magneto-Optical Trap: Origins and Applications*
14:45–15:10 Dörte Blume: *Interaction effects in ultra cold atom systems*
15:10–15:35 Ana Maria Rey: *Engineering spin squeezing in a 3D optical lattice with interacting spin-orbit-coupled fermions*
15:35–16:00 Mike Tarbutt: *Laser cooling and magneto-optical trapping of molecules*

16:00–16:30 Coffee Break

16:30–18:50 Exotic beams: Udo Strohbusch, Chair
16:30–17:10 Keynote: Dick Zare: *Microdroplet Chemistry*
17:10–17:35 Manfred Faubel: *Liquid micro jet studies of the free vacuum surface of water and of chemical solutions by soft X-ray photoelectron spectroscopy*
17:35–18:00 Gil Nathanson: *From Liquid Rays to Gas Rays: The Non-Maxwellian Evaporation of Helium from Water Microjets*
18:00–18:25 Henrik Stapeldeldt: *Laser-induced rotation and alignment of molecules in helium nanodroplets*
18:25–18:50 Mikhail Lemeshko: *Far-from-equilibrium dynamics of molecules in helium nanodroplets*

19:00–20:00 Dinner

20:00–20:30 Otto Stern's relationships with Pauli and Gerlach: Bretislav Friedrich, Chair
20:00–20:15 Karl von Meyenn: *Stern's friendship with Pauli*
20:15–20:30 Horst Schmidt-Böcking: *Stern's relation to Gerlach*

20:00–22:00 Poster Session with Wine+Beer+Bretzel

Thursday, 5 September 2019

Post-Conference Program 8:30-18:30
8:30 Bus from Frankfurt to Geisenheim am Rhein
10:00 Boat ride on the Rhein from Geisenheim to Braubach and back
Lunch on Boat
17:30 Bus from Geisenheim to Frankfurt

Musikalische Umrahmung
Festive Opening of the Otto Stern Fest

Trompete: Wolfgang Huhn
Orgel: Karsten Schwind

Auftakt:

John Stanley (1712-1786)
Two Trumpet Voluntaries in D
Andante
Adagio
Vivace

Zwischenmusik:

Georg Philipp Telemann (1681-1767)
„Air de Trompette“
Andante

Ausklang:

Jeremiah Clarke (1673-1707)
Suite in D
The Prince Eugene's March
Gigue
Trumpet Tune
Serenade
The Prince of Denmark’s March

Wolfgang Huhn hat die bedeutenden Trompetenkonzerte, Kirchenmusiken und großen sinfonischen Werke aller namhaften Komponisten sowie besonders die herausragenden Werke von Bach und Händel erfolgreich aufgeführt. Er arbeitet freiberuflich, auch als erster Trompeter der Frankfurter Sinfoniker und des Johann-Strauß-Orchester Frankfurt. Als Solist musizierte er beispielsweise auch mit dem China National Symphony Orchestra im China National Center in Peking sowie mit dem Kiev-Kammerorchester. Solistische Konzerte führten ihn auch mehrfach nach Frankreich und Italien.

Sein Diplom als Orchestermusiker erwarb er an der MHS in Frankfurt am Main. Ein Zertifikat für das Studium der ventillosen Barocktrompete erhielt er am Sweelinck Konservatorium in Amsterdam. Er ist Verfasser mehrerer Unterrichtswerke für Trompete, die beim Musikverlag Siebenhüner erschienen und sehr gefragt sind und ist gelegentlich als Konzertmanager tätig.

Karsten Schwind ist als selbständiger Musiker mit den Schwerpunkten Orgel- und Chorleitung tätig.

Er erhielt in den 80er Jahren ersten Klavier- und Orgelunterricht bei Dr. Walter Gleißner. Der Organist studierte Kirchenmusik in Mainz, Instrumental- und Gesangpädagogik in Wiesbaden und Kirchenmusik an der Hochschule für Musik und darstellende Kunst in Frankfurt (Orgel bei Prof. Martin Lücker und Prof. Gerd Wachoski, Chorleitung u.a. bei Christoph Siebert und Gregor Knop). Desweiteren absolvierte er ein künstlerisches Aufbaustudium mit Hauptfach Orgel bei Martin Lücker und Cembalo bei Susanne Kaiser, ebenfalls in Frankfurt am Main.

Musikalische Umrahmung
European Physical Society Historic Site Ceremony

Klarinette: Roman Kuperschmidt

Auftakt:

Johann Sebastian Bach (1685-1750)
***Double* aus Partita Nr. 1 BWV 1002**

Zwischenmusik:

Jüdische Volksmelodie

Ausklang:

Traditionelle jüdische Musik

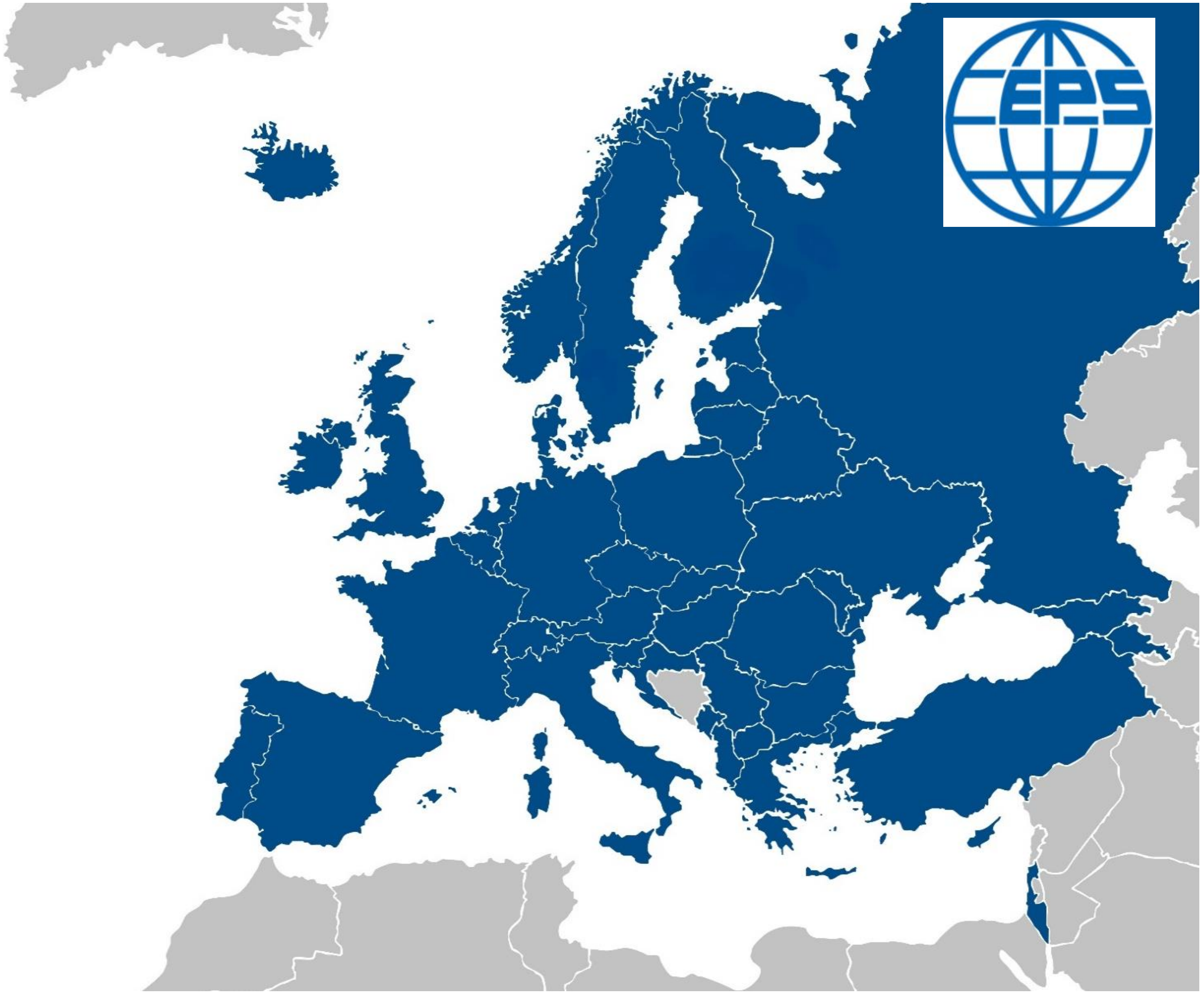
Der von der Presse als „Russischer Edelstein“ gefeierter Ausnahme-Klarinettist **Roman Kuperschmidt** wurde 1974 in Russland geboren und zählt zu den bekanntesten Nachwuchstalenten Russlands. Er spielt Klarinette seit seinem siebten Lebensjahr. Schon im Alter von 12 Jahren trat er als Solist mit der Russischen Staatsphilharmonie auf. Er studierte an dem Russischen Staatskonservatorium, in Karlsruhe beim Prof. Wolfgang Meyer sowie beim Prof. Peter Löffler-Asal an der Hochschule für Musik und Darstellende Kunst Frankfurt, wo er 2006 sein Aufbaustudium mit Auszeichnung absolvierte. Internationale Anerkennung erhielt Roman Kuperschmidt 1995, als er mit dem Grand-Prix des renommierten Internationalen Klarinettenwettbewerbes Moskau ausgezeichnet wurde. Es folgten weitere Auszeichnungen, u.a. beim Internationalen Musikwettbewerb St. Petersburg sowie beim DAAD-Wettbewerb Frankfurt am Main. Sein Repertoire umfasst die wichtigsten Werke der Klassik für Klarinette. Sein besonderes Interesse gilt aber auch der Modernen Musik sowie dem Klezmer, den er mit seinem Kuperschmidt-Ensemble pflegt. Er konzertiert als Solist in ganz Europa, den USA, Israel und Libanon, ist auf zahlreichen von der Kritik hochgelobten Rundfunkaufnahmen und auf CD-Einspielungen (z. B. „Mit Herz und Seele“) zu hören und bei vielen großen internationalen Festivals wie z. B. Al Bustan Music Festival Beirut, Zelt Musik Festival Freiburg und Music Summer Saas-Feé als Solist und Kammermusiker zu Gast. Roman Kuperschmidt lebt heute in Frankfurt am Main.

European Physical Society – EPS Historic Site

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 free-path length 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, of 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).

European Physical Society – EPS Historic Site

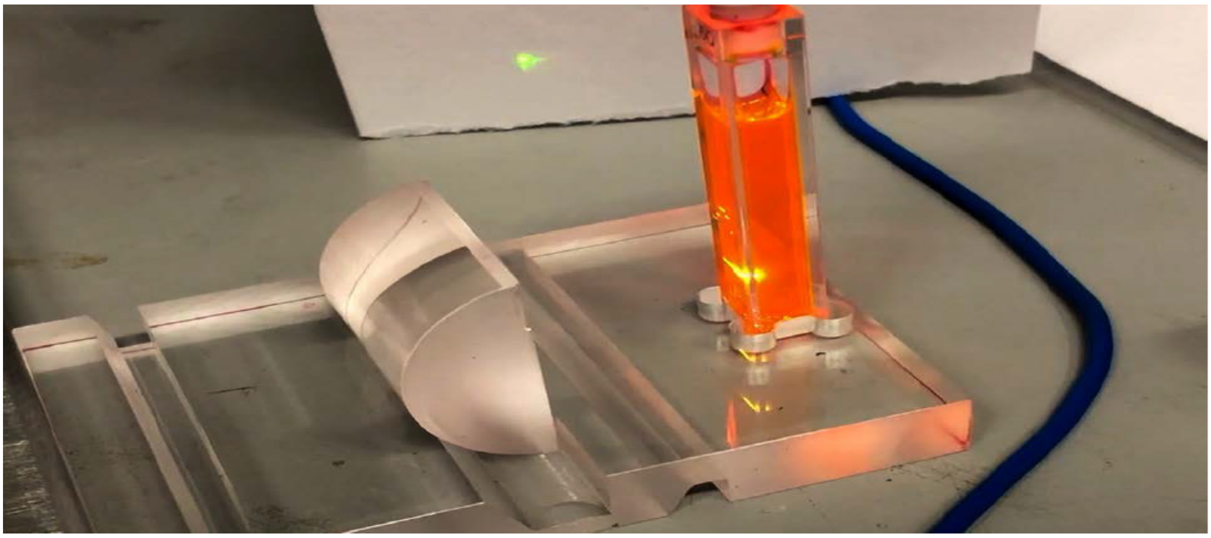
In diesem Gebäude wurden in den Jahren 1919 bis 1922 im Institut von Max Born bahnbrechende physikalische Entdeckungen gemacht, die entscheidend zur Entwicklung der Quantenmechanik beigetragen haben. Das sind die Entwicklung der Molekularstrahlmethode im Jahre 1919 durch Otto Stern, für die er den Nobelpreis für Physik des Jahres 1943 erhielt, sowie der im Jahre 1922 erbrachte experimentelle Nachweis der Richtungsquantelung atomarer magnetischer Momente durch Otto Stern und Walther Gerlach, die damit auch erstmals die Drehimpulsquantelung in Atomen nachgewiesen haben. Max Born zusammen mit Elisabeth Bormann haben hier 1920 erstmals die freie Weglänge von Atomen in Gasen und die Größe von Molekülen gemessen. Alfred Landé hat hier 1921 erstmals die Drehimpulskopplung als die Grundlage der inneratomaren Elektronendynamik postuliert. In diesem Gebäude ist der Physikalische Verein Frankfurt (der älteste Deutschlands, gegründet 1824), zu Hause.



Ludger Wöste: *Physical Amusements*

After having worked for forty-five years as an experimental scientist, I began a new career five years ago as a "Senior Professor." Generously supported by the Physics Department of the *Freie Universität Berlin* and the *Wilhelm und Else Heraeus-Stiftung,* the objective of my present endeavor is to pass on a sense of wonder about modern science to school kids and their teachers. Our approach is this: Let's play together, let's do experiments! So we collected a small stock of simple but fascinating toys that invite to play – and experiment, thereby revealing basic physical phenomena.

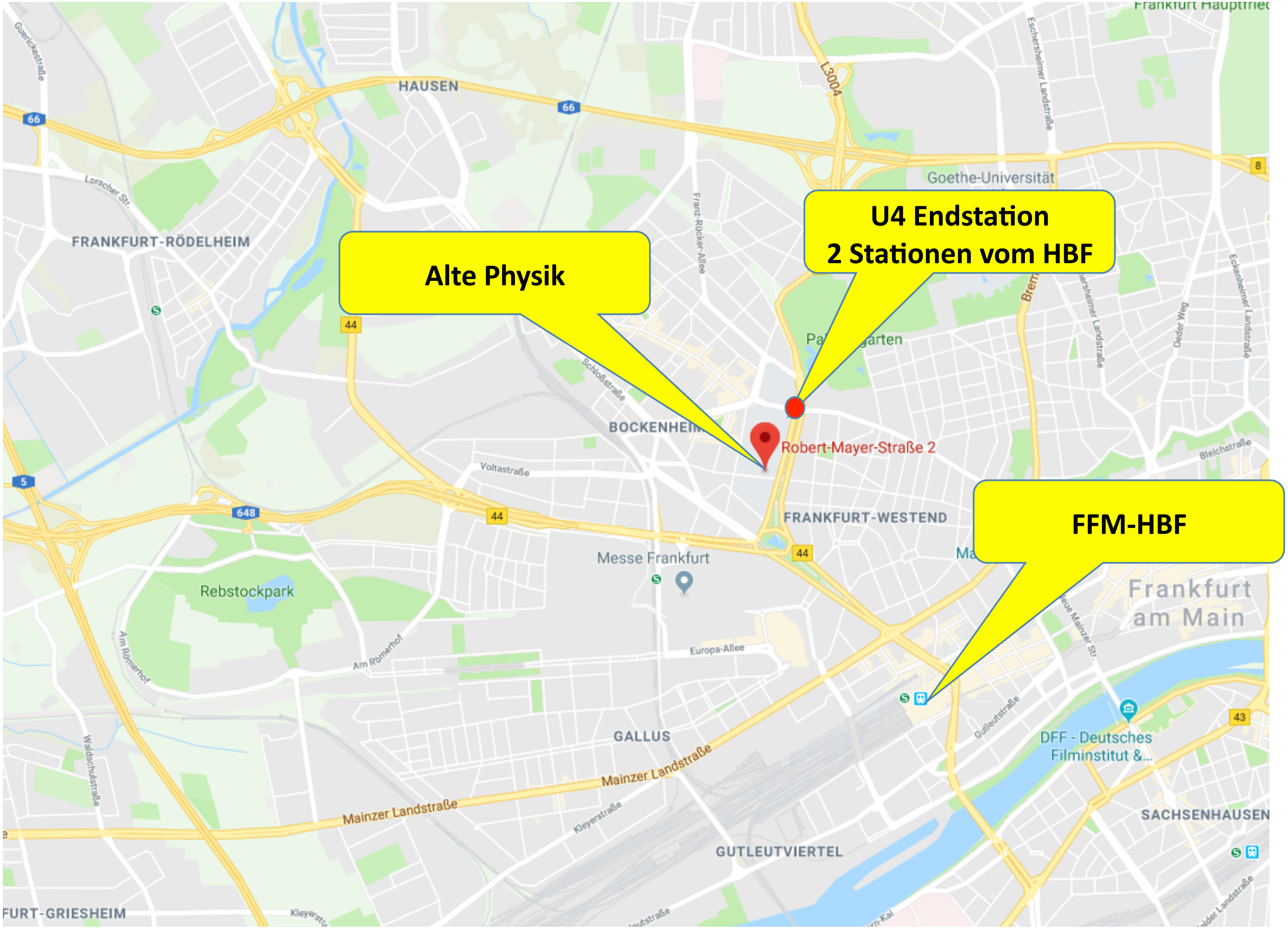
Some of these charming toys I brought along with me so that you can also "wonder." Hopefully you will see the "light mill" turning in the wrong sense and Gerlach's interpretation(1) thereof, the tippe top – marveled at by Pauli and Bohr – performing spontaneous spin flips, the chirality of fire, an electric motor comprising only three components, and a dye laser that consists likewise just of three elements. The dye laser – including its nitrogen pump laser – will be assembled and operated before your eyes.

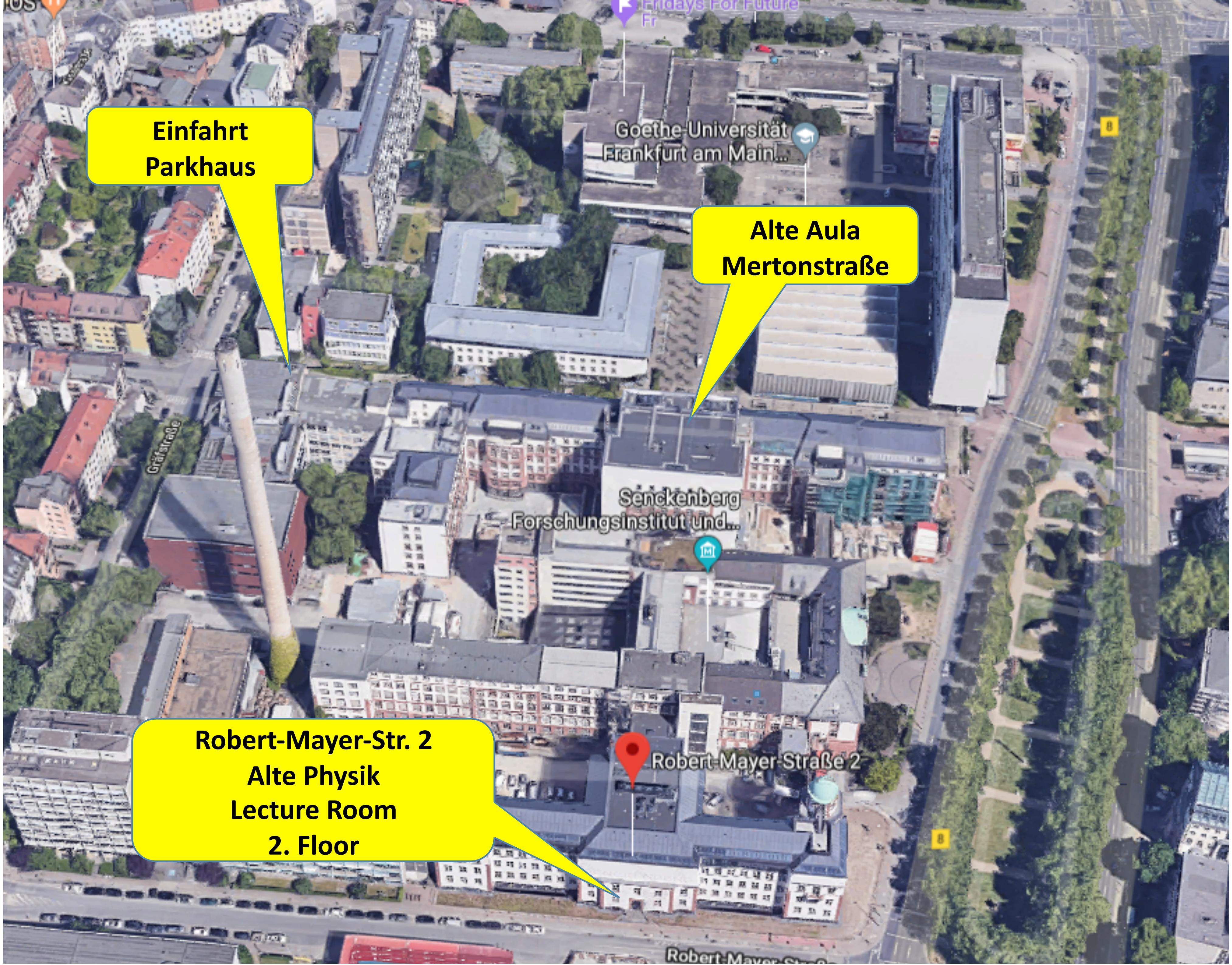


The didactic dye laser Photo: T. Hänsch

Some of the numerous spectacular applications of this laser will be discussed and related to Otto Robert Frisch's famous first experimental observation of Einstein's radiation recoil(2). The observation, which Frisch submitted for publication shortly before his emigration from Nazi Germany, he carried out in Otto Stern's molecular beam laboratory in Hamburg. And, as Frisch acknowledged, the idea for the experiment came from Stern as well(3).

(1) W. Gerlach und A. Golsen, Zeitschrift für Physik **14**, 285 (1923)
(2) O.R. Frisch, Zeitschrift für Physik **86**, 42 (1933)
(3) O. Stern, Zeitschrift für Physik **39**, 751 (1926)


U4 Endstation
2 Stationen vom HBF
Alte Physik
FFM-HBF
Robert-Mayer-Straße 2
HAUSEN
FRANKFURT-RÖDELHEIM
BOCKENHEIM
FRANKFURT-WESTEND
Goethe-Universität
Messe Frankfurt
Rebstockpark
GALLUS
GUTLEUTVIERTEL
SACHSENHAUSEN
Frankfurt am Main
DFF - Deutsches Filminstitut &...
Mainzer Landstraße
Europa-Allee
Schloßstraße
Voltastraße
Franz-Rücker-Allee
Am Römerhof
Eschersheimer Landstraße
Eckenheimer Landstraße
Oeder Weg
Bleichstraße
Gutleutstraße
Kleyerstraße
Waldschulstraße
Lorscher Str.
Guerickestraße
L3004
66
44
648
5
8
43


Einfahrt
Parkhaus
Goethe-Universität
Frankfurt am Main...
Fridays For Future
Fr
Alte Aula
Mertonstraße
Senckenberg
Forschungsinstitut und...
Gräfstraße
Robert-Mayer-Straße 2
Robert-Mayer-Str. 2
Alte Physik
Lecture Room
2. Floor
8
8

Conference Dinner on Tue, September 3 at 19:30

Hotel Dorint Oberursel

Königsteiner Str. 29, 61440 Oberursel (Taunus),

Boat departure
Sept. 5th 10.00
In Geisenheim

List of Participants

Otto Stern Fest, Frankfurt, 1–5 September 2019

A: Attendee; C: Chair; Ce: Speaker at the EPS Ceremony; HC: Honorary Chair of the Symposium;, K: Keynote Speaker;
O: Organizer; S: Speaker

Arndt, Markus	S	Universität Wien	markus.arndt@univie.ac.at
Badino, Massimiliano	S	Universita di Verona	massimilianobadino@gmail.com
Bauch, Andreas	A	PTB	andreas.bauch@ptb.de
Bergmann, Klaas	S	TU Kaiserslautern	bergmann@rhrk.uni-kl.de
Birke, Dietmar	A		dietmar.birke@t-online.de
Blaum, Klaus	S	MPI für Kernphysik	sekretariat.blaum@mpi-hd.mpg.de
Blatt, Rainer	A	Universität Innsbruck	rainer.blatt@uibk.ac.at
Blume, Dörte	S	Washington State Univ.	doerte@wsu.edu
Briggs, John	K	Universität Freiburg	briggs@physik.uni-freiburg.de
Corkum, Paul	K	University of Ottawa	pcorkum@uottawa.ca
Czasch, Achim	A	Universität Frankfurt	czasch@atom.uni-frankfurt.de
Deiss, Bruno	A	Physikalischer Verein	deiss@physikalischer-verein.de
Demtröder, Wolfgang	C	TU Kaiserslautern	demtroed@rhrk.uni-kl.de
Demtröder, Harriet	A		
Devereux, Michael	S	LANL	md_bar_x@centurylink.net
Dörner, Reinhard	C	Universität Frankfurt	doerner@atom.uni-frankfurt.de
Dreisigacker, Ernst	A	Heraeus-Stiftung	dre30a@web.de
Eckart, Sebastian	A	Universität Frankfurt	eckart@atom.uni-frankfurt.de
Eckert, Michael	K	Deutsches Museum	m.eckert@deutsches-museum.de
Efremov, Maxim	A	Universität Ulm	maxim.efremov@uni-ulm.de
Epple, Moritz	A	Universität Frankfurt	epple@em.uni-frankfurt.de
Fantz, Ursel	Ce	Universität Augsburg	fantz@physik.uni-augsburg.de
Faubel, Manfred	S	MPI für Dynamik	manfred.faubel@mpibpc.mpg.de
Faubel, Christine	A		ffaubel@t-online.de
Fein, Yaakov	A	Universität Wien	yaakov.fein@univie.ac.at
Feldmann, Peter	Ce	Stadt Frankfurt	
Folman, Ron	S	Ben Gurion University	folman@bgu.ac.il
Freudenberger, Claudia	A	Universität Frankfurt	Freudenberger@atom.uni-frankfurt.de
Fricke, Burkhard	C	Universität Kassel	fricke@uni-kassel.de
Friedrich, Bretislav	O,C	FHI-MPG	bretislav.friedrich@fhi-berlin.mpg.de
Friedrich, Christine	A		christinefriedrich@ymail.com
Frische, Stefan	A	GSI Jena	s.fritzsche@gsi.de
Griesinger, Christian	K	MPI für biophys. Chem.	cigr@nmr.mpibpc.mpg.de
Griffith, Bob	S	Carnegie-Mellon Univ.	rgrif+@cmu.edu
Groeneveld, Karl Ontjes	A	Universität Frankfurt	groeneveld@em.uni-frankfurt.de

Gruber, Gernot	A	Universität Frankfurt	gechrigru@t-online.de
Grünbein, Wolfgang	Ce	Physikalischer Verein	wk.gruenbein@web.de
Grünbein, Sabine	A		
Grundmann, Sven	A	Universität Frankfurt	grundmann@atom.uni-frankfurt.de
Gruppe, Axel	A		axel.gruppe@t-online.de
Hänel, Heinz	A	Sanofi	Heinz.Haenel@sanofi.com
Hagmann, Siegbert	A	GSI Darmstadt	s.hagmann@gsi.de
Hammerstein,	A	Universität Frankfurt	hammerstein@em.uni-frankfurt.de
Hänsch, Theodor	A	LMU & MPQ	t.w.haensch@mpq.mpg.de
Herschbach, Dudley	HC,K,C	Harvard University	dherschbach@gmail.com
Herschbach, Georgene	A		gbherschbach@gmail.com
Hofmann, Max	A	Universität Frankfurt	hofmann@atom.uni-frankfurt.de
Hofmann, Werner	A	MPI für Kernphysik	werner.hofmann@mpi-hd.mpg.de
Hohmann, Eckehard	A		eck.hohmann@googlemail.com
Hotop, Hartmut	C	TU Kaiserslautern	hotop@physik.uni-kl.de
Huber, Josef Georg	S		jghuber@gmx.de
Jagutzki, Ottmar	A	Universität Frankfurt	jagutzki@roentdek.de
Janke, Christian	A	Universität Frankfurt	C.Janke@atom.uni-frankfurt.de
Jahnke, Till	A	Universität Frankfurt	jahnke@atom.uni-frankfurt.de
Jorda, Stefan	A	Heraeus-Stiftung	Jorda@we-heraeus-stiftung.de
Kalinin, Anoton	A	GSI Darmstadt	A.Kalinin@gsi.de
Kaltenborn, Olaf	A	Universität Frankfurt	kaltenborn@pvw.uni-frankfurt.de
Karra, Mallikarjun	A	FHI-MPG	mkarra@fhi-berlin.mpg.de
Kastirke, Gregor	A	Universität Frankfurt	kastirke@atom.uni-frankfurt.de
Keller, Usula	S	ETH Zürich	keller@phys.ethz.ch
Kessler, Horst	C	TU München	kessler@tum.de
Khan, Arnab	A	Universität Frankfurt	khan@atom.uni-frankfurt.de
Killen, Diana	A		dkillen@comcast.net
Killen, Joel	A		
Kircher, Max	A	Universität Frankfurt	kircher@atom.uni-frankfurt.de
Kleinknecht, Konrad	A	Universität Mainz	kleinkne@uni-mainz.de
Kleppner, Daniel	K	MIT	kleppner@mit.edu
Kleppner, Bea	A		
Koch, Christiane	S	Univesität Kassel	christiane.koch@uni-kassel.de
Kornilov, Oleg	A	Max-Born-Institut	kornilov@mbi-berlin.de
Krakow, Karsten	A		k.krakow@asklepios.com
Krasilovskaja, Sabina	A	Universität Frankfurt	sabina.krasilovska@gmx.de
Kruse, Jan	A	Universität Frankfurt	kruse@atom.uni-frankfurt.de
Kunitski, Maksim	S	Universität Frankfurt	kunitski@atom.uni-frankfurt.de
Labedzke, Robert	A	DPG	labedzke@dpg-physik.de
Lahee, Angela	A	Springer	Angela.Lahee@springer.com
Lang, Michael	Ce	Universität Frankfurt	michael.lang@physik.uni-frankfurt.de

Langfeld, Roland	A	SCHOTT	roland.langfeld@schott.com
Lehr, Sabine	A	Springer	sabine.lehr@springer.com
Lemeshko, Mikhail	S	IST Austria	mikhail.lemeshko@ist.ac.at
Lenkiewicz, Richard	A	Universität Frankfurt	lenkiewicz@itp.uni-frakfurt.de
Lindroth, Eva	S	Stockholm University	eva.lindroth@fysik.su.se
Mahnke, Reinhard	A	Universität Rostock	reinhard.mahnke@uni-rostock.de
Meijer, Gerard	K	FHI-MPG	meijer@fhi-berlin.mpg.de
Meschede, Dieter	Ce	Universität Bonn, DPG	meschede@iap.uni-bonn.de
Meyenn, Karl von	S	Universität Ulm	
Meyenn, Felicitas von	A		felicitasvm@gmx.de
Mirahmadi, Marjan	A	FU Berlin	marjan.mirahmadi@fu-berlin.de
Mokler, Paul	A	GSI Darmstadt	p.mokler@gmx.de
Müntz, Christian	A	GSI Darmstadt	C.Muentz@gsi.de
Mulch, Andreas	Ce	U Frankfurt & Senckenberg	mulch@em.uni-frankfurt.de
Nägerl, Hans-Christoph	C	Universität Innsbruck	christoph.naegerl@uibk.ac.at
Nail, Giamarco	A	Universität Frankfurt	nalin@atom.uni-frankfurt.de
Nathanson, Gil	S	U of Wisconsin-Madison	nathanson@chem.wisc.edu
Ni, Kang-Kuen	S	Harvard University	kangkuenni@g.harvard.edu
Nunner, Bernhard	A	DPG	nunner@dpg-physik.de
Pitzer, Martin	A	Weizmann Institute	martin.pitzer@weizmann.ac.il
Pohle, Sabine	A		sabine.pohle@freenet.de
Pritchard, Dave	K	MIT	dpritch@mit.edu
Pritchard, Andy	A		andypritchard@rocketmail.com
Reich, Karin	C	Universität Hamburg	reich@math.uni-hamburg.de
Requardt, Hermann	S	Siemens Healthcare	hermann.requardt@t-online.de
Rey, Ana Maria	S	JILA/NIST/U of Colorado	arey@jilau1.colorado.edu
Rieser, Philip	A	University of Vienna	philipp.rieser@univie.ac.at
Rudolf, Petra	Ce	U Groningen, EPS	P.Rudolf@rug.nl
Sauer, Tilman	K	Universität Mainz	tsauer@uni-mainz.de
Scharnberg, Kurt	A	Universität Hamburg	scharnberg@physnet.uni-hamburg.de
Schartner, Karl-Heinz	A	Universität Giessen	karl-heinz.schartner@exp1.physik.uni-giessen.de
Schicke, Alexander	A	VPV Versicherungen	Alexander.Schicke@vpv.de
Schirrmacher, Arne	S	Humboldt Universität	arne.schirrmacher@hu-berlin.de
Schleier-Smith, Monika	S	Stanford University	schleier@stanford.edu
Schleich, Wolfgang	S	Universität Ulm	wolfgang.schleich@uni-ulm.de
Schneck, Tobias	A	Senckenberg	tobias.schneck@senckenberg.de
Schöller, Otmar	A		otmar.schoeller@t-online.de
Schöllkopf, Wieland	S	FHI-MPG	wschoell@fhi-berlin.mpg.de
Schmidt-Böcking, Horst	O,S	Universität Frankfurt	hsb@atom.uni-frankfurt.de
Schmidt-Böcking, Marlies	A		
Schmidt, Lothar	A	Universität Frankfurt	lothar.schmidt@atom.uni-frankfurt.de
Schmoeger, Lisa	A	MPI für Kernphysik	lisa.schmoeger@mpi-hd.mpg.de

Schuch, Reinhold	C	Stockholm University	schuch@fysik.su.se
Schulz, Claus Peter	A	Max-Born-Institut	cps@mbi-berlin.de
Schulz, Mirjam	A		mirjam.schulz@gmx.net
Schumacher, Samuel	A		sschumach@gmx.net
Schwalbe, Harald	S	Universität Frankfurt	schwalbe@nmr.uni-frankfurt.de
Smirnova, Olga	S	MBI, TU Berlin	olga.smirnova@mbi-berlin.de
Stapelfeldt, Henrik	S	Aarhus University	henriks@chem.au.dk
Steglich, Frank	A	MPI für Chem. Phys. f. K.	Frank.Steglich@cpfs.mpg.de
Stiebing, Kurt Ernst	A	Universität Frankfurt	stiebing@em.uni-frankfurt.de
Stöhlker, Thomas	A	HI Jena, GSI Darmstadt	t.stoehlker@gsi.de
Strohbusch, Udo	C	Universität Hamburg	udo.strohbusch@desy.de
Tarbutt, Mike	S	Imperial College London	m.tarbutt@imperial.ac.uk
Tempelton, Alan	S	Berkeley	alantempca@yahoo.com
Toennies, Peter	HC,K	MPI für Dynamik	jtoenni@gwdg.de
Tomar, Raghu	A	Universität Frankfurt	tomar@atom.uni-frankfurt.de
Toschek, Peter	C	Universität Hamburg	ptoschek@physnet.uni-hamburg.de
Trabert, Daniel	A	Universität Frankfurt	trabert@atom.uni-frankfurt.de
Trageser, Wolfgang	A	Universität Frankfurt	w.trageser@em.uni-frankfurt.de
Trinter, Florian	A	DESY Hamburg, FHI-MPG	florian.trinter@desy.de
Troe, Jürgen	A	Universität Göttingen	shoff@gwdg.de
Tsitsonis, Dimitrios	A	Universität Frankfurt	dtsitson@atom.uni-frankfurt.de
Tulsky, Vasily	A	Universität Rostock	tulskyva@mail.ru
Ueda, Kiyoshi	S	Tohoku University	kiyoshi.ueda@tohoku.ac.jp
Ulbricht, Hendrik	S	University of Southampton	h.ulbricht@soton.ac.uk
Ulrich, Joachim	S	PTB	joachim.ullrich@ptb.de
Vela Perez, Isabel	A	Universität Frankfurt	vela-perez@atom.uni-frankfurt.de
Weber-Bruls, Dorothee	A	Universität Frankfurt	dweber@jonesday.com
Weiner, Joachim	A		J.Weinert@gsi.de
Weller, Miriam	A	Universität Frankfurt	weller@atom.uni-frankfurt.de
Werth, Günter	A	Universität Mainz	werth@uni-mainz.de
Wolf, Birgitta	Ce	Universität Frankfurt	praesidentin@uni-frankfurt.de
Wöste, Ludger	S	FU Berlin	woeste@physik.fu-berlin.de
Wöste, Martita	A		
Zare, Dick	K	Stanford University	rnz@stanford.edu
Zare, Susan	A		susanz62@icloud.com

(154)

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

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

Bretislav Friedrich and Dudley Herschbach

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

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

A new center for experimental physics at the University of Frankfurt was recently named in honor of Stern and Gerlach (see figure 1). The opportunity to take part in the dedication prompted us to reenact the cigar story, as told to one of us (Herschbach) by Stern himself more than 40 years ago. Here we briefly trace the antecedent trajectories of Stern and Gerlach and the perplexing physics of the time, which brought them to collaborate in Frankfurt. We also describe the vicissitudes and reception of the SGE, before and after the discovery of electron spin, and report how cigar smoke led us to a "back-to-the-future" deposition detector.[1] Mindful of the memorial plaque at Frankfurt, depicting Stern and Gerlach on opposite sides of their split molecular beam, we also invite readers to reflect on the later trajectories of these two fine scientists—impelled in opposite directions by the tragic rise to power of Adolf Hitler.

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

From osmotic soda to atomic beams

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

Under Einstein's influence, Stern became interested in light quanta, the nature of atoms, magnetism, and statistical physics. However, Stern was shocked by the iconoclastic atomic model of Niels Bohr. Shortly after it appeared in mid-1913, Stern and his colleague Max von Laue made an earnest vow: "If this nonsense of Bohr should in the end prove to be right, we will quit physics!"[3] When Einstein moved to Berlin in 1914, Stern became *privatdozent* for theoretical physics at Frankfurt. World War I soon intervened, but even while serving in the German army, Stern managed to do significant work, including an unsuccessful but prescient experiment, an attempt to separate by diffusion a suspected hydrogen isotope of mass two.

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

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

IM FEBRUAR 1922 WURDE IN DIESEM GEBÄUDE DES
PHYSIKALISCHEN VEREINS, FRANKFURT AM MAIN,
VON OTTO STERN UND WALTHER GERLACH DIE
FUNDAMENTALE ENTDECKUNG DER RAUMQUANTISIERUNG
DER MAGNETISCHEN MOMENTE IN ATOMEN GEMACHT.
AUF DEM STERN-GERLACH-EXPERIMENT BERUHEN WICHTIGE
PHYSIKALISCH-TECHNISCHE ENTWICKLUNGEN DES 20. JHDTS.,
WIE KERNSPINRESONANZMETHODE, ATOMUHR ODER LASER.
OTTO STERN WURDE 1943 FÜR DIESE ENTDECKUNG
DER NOBELPREIS VERLIEHEN.

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

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

From thermal radiation to magnetic deflection

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

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

Quandaries about space quantization

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

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

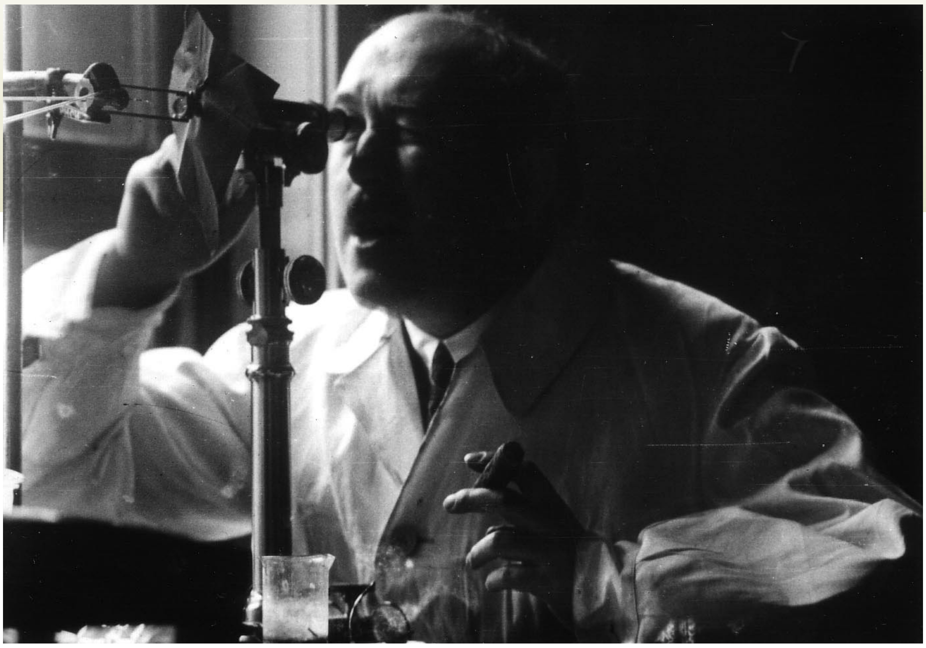


Figure 2. Otto Stern (1888–1969), cigar in hand, working in his molecular beam laboratory at the Institute for Physical Chemistry in Hamburg, about 1930. (Photo courtesy of Peter Toschek.)

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

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

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

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

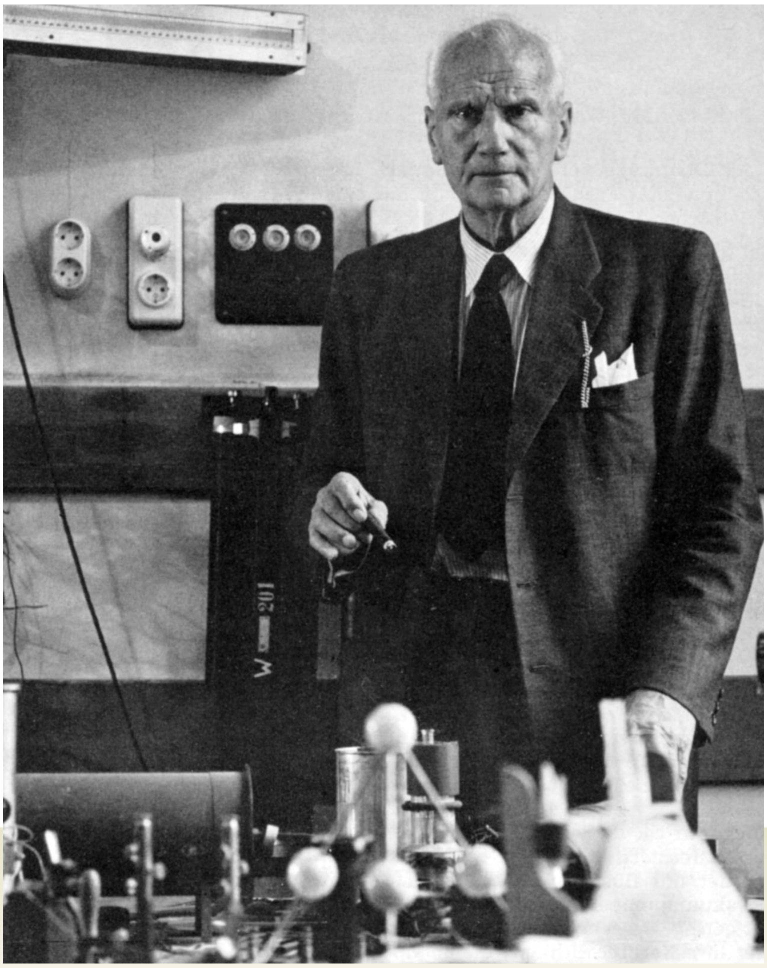
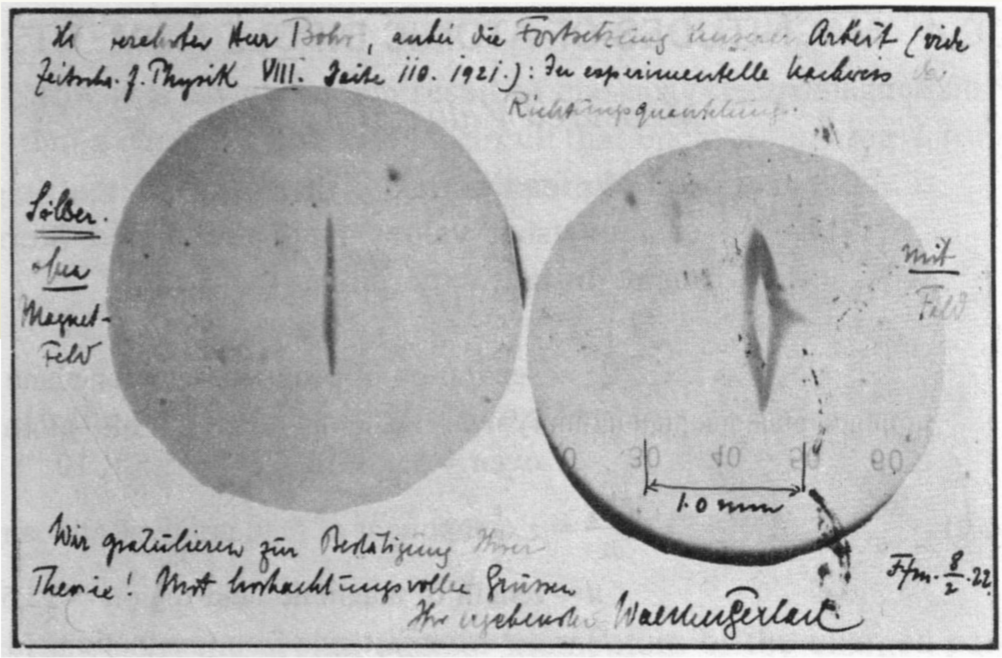


Figure 3. Walther Gerlach (1889–1979), cigar in hand, in his laboratory at the Institute for Physics in Munich, about 1950. (Photo courtesy of W. Schütz, *Phys. Bl.* **25**, 343, 1969.)



Hochverehrter Herr Bohr, anbei die Fortsetzung unserer Arbeit (vide Zeitschr. f. Physik VIII. Seite 110. 1921.): Der experimentelle Nachweis der Richtungsquantelung.

Silber. ohne Magnet-Feld

mit Feld

1.0 mm

Wir gratulieren zur Bestätigung Ihrer Theorie! Mit hochachtungsvollen Grüssen Ihr ergebenster Walther Gerlach

Ffm. 8/2. 22

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

and classical views."[8]

From *Gedanken* to *Danken*

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

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

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

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

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

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

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

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

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

Meanwhile, Stern had moved to the University of Rostock as a professor of theoretical physics. In early 1922, he and Gerlach met in Göttingen to review the situation and decided to give up. However, a railroad strike delayed Gerlach's return to Frankfurt, giving him a long day to go over all the details again. He decided to continue, improved the alignment, and soon achieved a clear splitting into two beams.[5] Stern recalled that his own surprise and excitement were overwhelming when he received a telegram from Gerlach with the terse message: "Bohr is right after all."[11] Gerlach also sent a postcard to Bohr with a congratulatory message, showing a photograph of the clearly resolved splitting (see figure 4).

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

Those and other puzzles, such as the anomalous Zeeman effect, could not be cleared up until several years later, after the development of quantum mechanics and the inclusion of electron spin in the theory. Those advances made the Bohr model obsolete but enhanced the scope and significance of space quantization. The gratifying agreement of the Stern–Gerlach splitting with the old theory proved to be a lucky coincidence. The orbital angular momentum of the silver atom is actually zero, not $h/2\pi$ as presumed in the Bohr model. The magnetic moment is due solely to a half unit of spin angular momentum, which accounts for the twofold splitting. The magnetic moment is nonetheless very nearly one Bohr magneton, by virtue of the Thomas factor of two, not recognized until 1926. Nature thus was duplicitous in an uncanny way.

Reactions to the Stern–Gerlach Experiment

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

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

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

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

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

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

—***James Franck*** **(1882–~~1951~~)** 1964

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

—***Niels Bohr*** **(1885–1962)**

This should convert even the nonbeliever Stern.

—***Wolfgang Pauli*** **(1900–58)**

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

—***Isidor I. Rabi*** **(1898–1988)**

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

Yet another cigar

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

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

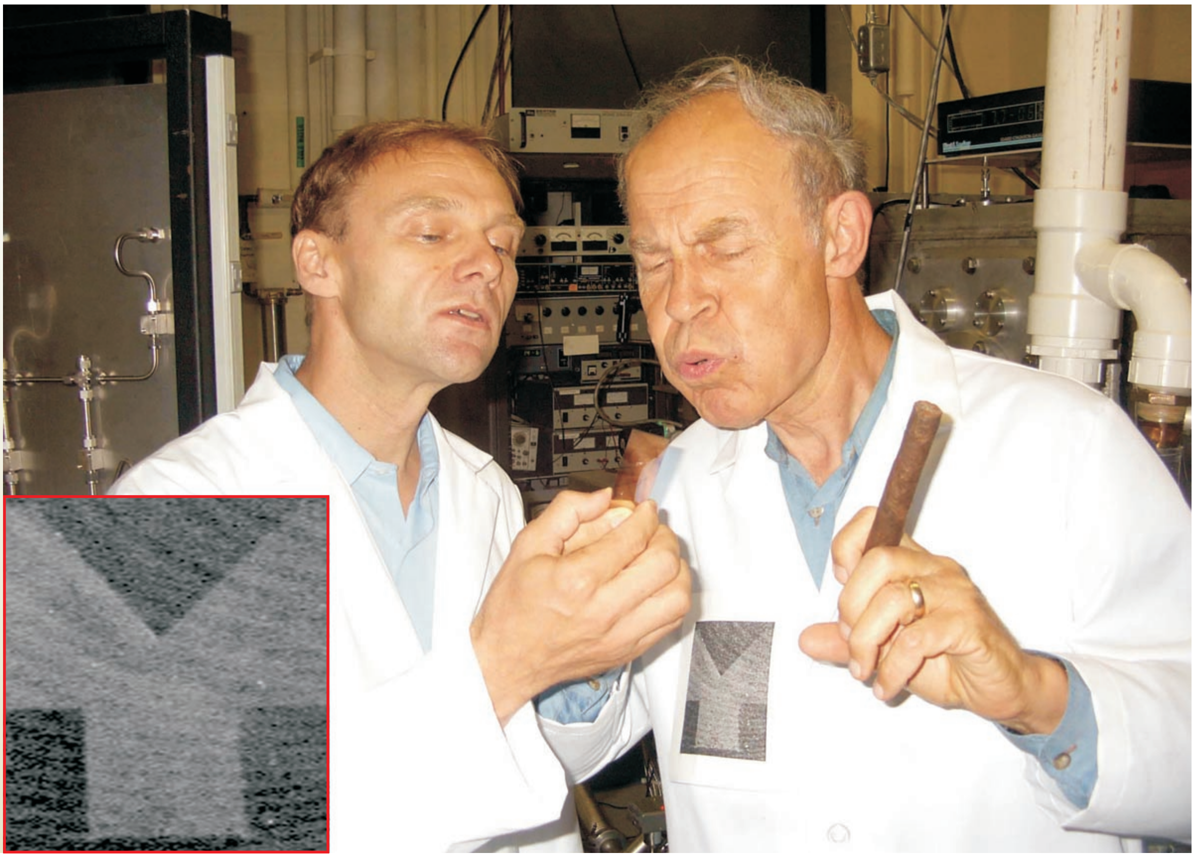


Figure 5. Reenactment of the Stern–Gerlach cigar episode by the authors. Bretislav Friedrich holds the slide as Dudley Herschbach blows sulfurous cigar breath onto a silver-coated glass slide to test his hearing (or Otto Stern's telling) of the story more than 40 years ago. The silver film turns out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

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

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

Abiding legacy amid bitter ashes

Late in 1922, Stern became professor of physical chemistry at the University of Hamburg. There he undertook an ambitious program to develop molecular beam methods.[8] The program included major tests of several fundamental aspects of quantum mechanics.[13] His crowning achievement, in collaboration with Immanuel Estermann and Otto Frisch, was the discovery of the anomalous magnetic moments of the proton and deuteron in 1933. That discovery astounded theorists and had a profound impact on nuclear physics: It revealed that the proton and neutron were not elementary particles but must have internal structure. The experiments were far more difficult than the original SGE, because the magnetic moments of nuclei are a thousand times smaller than those for electrons. Moreover, as Estermann describes it, the work had to be done "with the sword of Nazism hanging over our heads."[5] Stern and his colleagues soon had to emigrate; Stern came to the US but never regained a pacesetting role in research. That role passed to I. I. Rabi, who had become imbued with molecular beams as a postdoctoral fellow at Hamburg.[14,15]

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

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

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

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

Frankfurt, I gave him, in memory of the months of hopeless striving to see space quantization, an ashtray with an inscription. . . . This ashtray endured all those years till Berkeley—but our experimental apparatus, lab books, and the originals of our results had burned during the Second World War."[10] Like so much else, reduced to ashes.

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

References

1. For fuller descriptions of the context and legacy of the Stern–Gerlach experiment, see J. Mehra, H. Rechenberg, *The Historical Development of Quantum Theory,* vol. 1, part 2, Springer-Verlag, New York (1982), p. 433, and B. Friedrich, D. Herschbach, *Daedalus* **127**, 165 (1998).
2. K. Mendelssohn, *The World of Walther Nernst: The Rise and Fall of German Science,* Macmillan, London (1973), p. 95.
3. F. Hund, *Geschichte der Quantentheorie* [*The History of Quantum Theory*], Bibliographisches Institut, Mannheim, Germany (1975).
4. O. Stern, in *Les Prix Nobel en 1946,* Imprimerie Royale Norstedt and Soner, Stockholm (1948), p. 123. Available online at http://www.nobel.se/physics/laureates/1943/stern-lecture.html
5. I. Estermann, *Am. J. Phys.* **43**, 661 (1975). See also I. Estermann in I. Estermann, ed., *Recent Research in Molecular Beams: A Collection of Papers Dedicated to Otto Stern,* Academic Press, New York (1959).
6. W. Pauli, *Science*, **103**, 213 (1946).
7. D. Herschbach, *Angew. Chemie Int. Ed. Engl.* **26**, 1225 (1987). The reminiscences by Stern included in this article are not actual quotations, but recollections cast in a first-person voice to capture his way of telling stories.
8. A list of all of Stern's papers is contained in *Z. Phys. D: At. Mol. Clusters* **10**, 114 (1988); that issue also includes an English translation of his 1921 paper in which he proposed the Stern–Gerlach experiment. See also refs. 5 and 11.
9. M. Born, *My Life: Recollections of a Nobel Laureate,* Scribner, New York (1978), p. 78.
10. W. Gerlach, *Phys. Bl.* **25**, 412 (1969); **25**, 472 (1969); H.-R. Bachmann, H. Rechenberg, eds., *Walther Gerlach: Eine Auswahl aus seinen Schriften und Briefen,* Springer-Verlag, Berlin (1989).
11. E. Segrè, *Biogr. Mem. Natl. Acad. Sci.* **43**, 215 (1973).
12. R. G. J. Fraser, *Proc. R. Soc. A* **114**, 212 (1927).
13. N. F. Ramsey, in ref. 8, p. 121; D. Herschbach, *Ann. Phys. (Leipzig)* **10**, 163 (2001).
14. J. S. Rigden, *Rabi: Scientist and Citizen,* Harvard U. Press, Cambridge, Mass. (2000). See also J. S. Rigden, *Hydrogen: The Essential Element,* Harvard U. Press, Cambridge, Mass. (2002).
15. Advances in molecular beam research are abundantly illustrated in B. Bederson, ed., *More Things in Heaven and Earth: A Celebration of Physics at the Millennium,* Springer and American Physical Society, New York (1999), and R. Campargue, ed., *Atomic and Molecular Beams: The State of the Art 2000,* Springer, New York (2001).
16. D. C. Cassidy, *Uncertainty: The Life and Science of Werner Heisenberg,* W. H. Freeman, New York (1992), p. 501; see also J. Bernstein, *Hitler's Uranium Club: The Secret Recordings at Farm Hill*, 2nd ed., Copernicus Books, New York (2001).
17. A. Sommerfeld, *Atombau und Spektrallinien,* 3rd ed., Vieweg, Braunschweig, Germany (1922), p. 338.
18. Max Born, ed., *Albert Einstein, Max und Hedwig Born, Briefwechsel 1916–1955*, Nymphenburger Verlagshandlung, Munich, Germany (1969), p. 82. ■

Ann. Phys. (Berlin) **523**, No. 12, 1045 – 1070 (2011) / **DOI** 10.1002/andp.201100228

Historical Article

Otto Stern (1888–1969): The founding father of experimental atomic physics

J. Peter Toennies[1], **Horst Schmidt-Böcking**[2], **Bretislav Friedrich**[3,*], and **Julian C. A. Lower**[2]

[1] Max-Planck-Institut für Dynamik und Selbstorganisation, Bunsenstrasse 10, 37073 Göttingen, Germany
[2] Institut für Kernphysik, Goethe Universität Frankfurt, Max-von-Laue-Strasse 1, 60438 Frankfurt, Germany
[3] Fritz-Haber-Institut der Max-Planck-Gesellschaft, Faradayweg 4–6, 14195 Berlin, Germany

Received 22 September 2011, revised 1 November 2011, accepted 2 November 2011 by G. Fuchs

Key words History of science, atomic physics, Stern-Gerlach experiment, molecular beams, magnetic dipole moments of nucleons, diffraction of matter waves.

We review the work and life of Otto Stern who developed the molecular beam technique and with its aid laid the foundations of experimental atomic physics. Among the key results of his research are: the experimental test of the Maxwell-Boltzmann distribution of molecular velocities (1920), experimental demonstration of space quantization of angular momentum (1922), diffraction of matter waves comprised of atoms and molecules by crystals (1931) and the determination of the magnetic dipole moments of the proton and deuteron (1933).

Introduction

Short lists of the pioneers of quantum mechanics featured in textbooks and historical accounts alike typically include the names of Max Planck, Albert Einstein, Arnold Sommerfeld, Niels Bohr, Max von Laue, Werner Heisenberg, Erwin Schrödinger, Paul Dirac, Max Born, and Wolfgang Pauli on the theory side, and of Wilhelm Conrad Röntgen, Ernest Rutherford, Arthur Compton, and James Franck on the experimental side. However, the records in the Archive of the Nobel Foundation as well as scientific correspondence, oral-history accounts and scientometric evidence suggest that at least one more name should be added to the list: that of the "experimenting theorist" Otto Stern. With 81 nominations, Otto Stern was the most nominated candidate for the Physics Nobel Prize during the period from 1901 until 1950, with 7 nominations more than Max Planck and 15 more than Albert Einstein [1].

In 1919, Stern conceived an experimental approach to measuring internal quantum properties of single isolated atoms. In 1922, jointly with Walther Gerlach, he implemented this approach in the laboratory and proved that *Richtungsquantelung* (space quantization), predicted on theoretical grounds by Arnold Sommerfeld [2] and Peter Debye [3], was not just a figment of the mathematician's imagination but that it really existed. The Stern-Gerlach experiment turned out to be one of the milestones on the winding road to modern quantum physics, one which offered other-than-spectroscopic evidence that quantum objects (atoms) exhibit behavior incompatible with classical physics.

At the core of the Stern-Gerlach experiment, carried out at the University of Frankfurt, was the so-called *Molekularstrahlmethode* (molecular beam method), which Stern and his coworkers would further advance

---

[*] Corresponding author E-mail: brich@fhi-berlin.mpg.de

and make use of between 1923 and 1933 at the University of Hamburg. During the Hamburg period, Stern's group's experiments provided evidence for other key manifestations of the quantum nature of matter, such as diffraction of He-atom matter waves by a crystal surface or the anomalous magnetic moments of the proton and deuteron [4]. In 1943, the Nobel Prize for Physics was awarded to Stern "for his contribution to the development of the molecular ray method and his discovery of the magnetic moment of the proton".

Fig. 1 (online colour at: www.ann-phys.org) Otto Stern about 1891, 1897, 1904, 1925, 1930, 1945 and 1960 [8].

In subsequent decades, Stern's molecular beam method had been widely adopted by the physics and physical chemistry communities worldwide, and about 20 Nobel Prizes were awarded for work based on the method, including that on the MASER, NMR, and the atomic clock. In 1988, on Dudley Herschbach's initiative, the *Zeitschrift für Physik* featured a special issue "In memoriam Otto Stern on the 100^{th} anniversary of his birth" [5] comprised of contributions by Stern's kindred spirits of more recent vintage. Four of the contributors to the Stern special issue have since become Nobel laureates.

Otto Stern was born on February 17, 1888 as the eldest child of the well-to-do Jewish miller and grain dealer Oskar Stern and Eugenie, nèe Rosenthal, in *Sohrau* (Zory) in Upper Silesia. The family moved in 1892 to *Breslau* (Wroclaw) where Stern went to the humanistic *Johannes Gymnasium*. After the *Abitur* (high-school graduation) in 1906, Stern took ten semesters of physical chemistry at the Breslau University and one at Freiburg and Munich each. His PhD adviser was the *Privatdozent* Otto Sackur, who had derived, simultaneously with but independently of Hugo Tetrode, a quantum statistical expression for the entropy of a monoatomic gas. It was due to Sackur's influence that Stern developed an abiding interest in entropy, which he maintained throughout his life. Stern received his PhD in April 1912 with a thesis on a topic of his own choice, namely the osmotic pressure of carbon dioxide in highly concentrated solutions.

Assistant to Einstein 1912–1914

After earning his PhD, Otto Stern joined in May 1912 Albert Einstein as his first postdoctoral student and co-worker. Sackur, who was friendly with Fritz Haber, asked the renowned physical chemist to weigh in and introduce Stern to Einstein, Haber's personal friend. Stern himself considered joining Einstein an impudence, but went nevertheless. Einstein was then at Prague's German University, his first station as full professor. As Stern later recounted in his Zurich interview with Res Jost [6]:

> I expected to meet a very learned scholar with a large beard, but found nobody of that kind. Instead, sitting behind a desk was a guy without a tie who looked like an Italian roadmender. This was Einstein. He was terribly nice. In the afternoon he was wearing a suit and was shaven. I had hardly recognized him.

When Einstein, in Spring of 1912, had accepted a call to the *Eidgenössische Technische Hochschule* (ETH) Zurich, he invited Stern to come along and appointed him his scientific assistant. During the Zurich period, Stern and Einstein published a joint paper *Einige Argumente für die Annahme einer molekularen Agitation beim absoluten Nullpunkt* (Some arguments in favor of the conjecture of a zero-point molecular motion) [7] which examined aspects of the problem of zero-point energy. Characteristic for Einstein and Stern is a footnote added to the paper, which reflects their unconventional way of thinking and open-mindedness (*Querdenken*):

> It hardly needs to be emphasized that our way of handling this problem is only justified by our lack of knowledge of the correct laws governing the resonators.

On June 26, 1913 Otto Stern submitted his application for *Habilitation* and *Venia Legendi* in the field of physical chemistry and later that year became a *Privatdozent* at the ETH Zurich [9]. His 8-page *Habilitationschrift* was entitled *Zur kinetischen Theorie des Dampfdruckes einatomiger fester Stoffe und über die Entropiekonstante einatomiger Gase* (Kinetic theory of the vapor pressure of monoatomic solids and of the entropy constants of monoatomic gases).

At Zurich, Stern met Max von Laue, who held a professorship at the University of Zurich since 1912, the year of his momentous discovery of X-ray diffraction from crystals. Stern and von Laue shared, apart from what would become a life-long friendship, profound misgivings about the model of the atom proposed by Niels Bohr in 1913. Bohr's model combined the planetary model of the atom developed by Ernest Rutherford in 1911 with postulates about the angular momenta of the orbiting electrons and the light quanta emitted or absorbed when the electrons changed their orbits. In order to give an expression to their horror over the departure from classical physics Bohr's model entailed, Stern and von Laue vowed that "if this nonsense of Bohr should prove to be right in the end, we will quit physics". The vow was later dubbed by another scientist-in-residence at Zurich at the time, Wolfgang Pauli, the *Ütlischwur* – in a double-reference to a hill on Zurich's outskirts and the *Rütlischwur* from Friedrich Schiller's *Wilhelm Tell* [10]. Ironically, it was the Stern-Gerlach experiment which would provide further evidence that Bohr – or rather quantum mechanics – was right. In his Zurich interview, Stern added a twist to the story [6]:

> Einstein mentioned to me that he had thought about something like Bohr's atom himself. Well, Einstein was not as silly as we were.

Although Stern earned his *Habilitation* in theoretical physical chemistry, he was not a theorist by training. However, at both Prague and Zurich, he faithfully attended Einstein's lectures, which amounted to an apprenticeship in theoretical physics, whose intensity was enhanced by the absence of any other interlocutors than Stern during Einstein's stint in Prague. As Stern pointed out in his Zurich interview:

> Einstein never prepared his lectures. Einstein just improvised, but in a physically interesting and sophisticated way. [...] I learned the "*Querdenken*" from him. [...] I also learned from Einstein to talk nonsense every now and then. Einstein registered with pleasure when he had made a mistake. He would admit his mistake and remark: it's not my fault that *der liebe Gott* (the dear Lord) didn't make things the way I had imagined.

Immanuel Estermann, a close co-worker and friend of Stern's characterized the relation between Stern and Einstein as follows [11]:

> From his collaboration with Einstein, the real benefit was to learn how to distinguish which problems of contemporary physics were important and which were not so important; which questions to ask and which experiments to undertake in order to answer the questions. Thus from a brief scientific collaboration evolved a close, life-long friendship, which would be the basis for Stern's great achievements.

Stern's beginnings in Frankfurt and the intervening Great War (1914–1918)

In 1914, Max von Laue accepted a professorship in theoretical physics at the newly established *Königliche Stiftungsuniversität Frankfurt* (The Royal University of Frankfurt) and appointed his friend Otto Stern to the post of his assistant; this post was augmented when the Frankfurt University recognized Stern's Zurich habilitation and appointed him, as of November 10, a *Privatdozent* in theoretical physics (although, formally, Stern remained tied to Zurich until the end of 1915). After the outbreak of the First World War, Stern reported to the German Army as a volunteer and was sent to Berlin to train as a meteorologist, whereafter he served as a non-commissioned officer at army headquarters. Among his tasks was to assist a captain in building up a physics laboratory in Belgium. However, there was no physics equipment available, except for some air pumps. In order to be able to fulfill his mission nevertheless, the captain came up with the idea of dismantling the near-by Solvay Institute and confiscate its physics apparatus for the military laboratory. Otto Stern set out to prevent, at any cost, the scavenging of the Solvay Institute. He secretly contacted Walther Nernst in Berlin, who used his influence to preserve the Solvay Institute. As Stern recalled in his Zurich interview, the captain would come to Stern two weeks later to complain that "Berlin" had stopped his efforts.

From the end of 1915 on, Stern served as a meteorologist at a field weather station in Lomsha in Russian Poland. Since this job provided him with plenty of free time, he kept busy thinking about topics in thermodynamics, "in order to keep his sanity". While in Lomsha, Stern wrote two extensive papers on entropy. Throughout his life, Stern was no great letter-writer, often admitting that this was not his cup of tea.

However, in Lomsha Stern seems to have deviated from his patterns. The collection of Otto Stern's family (Family Templeton-Killen) and the Bancroft Archive at Berkeley [12] hold several letters from the Lomsha period that Einstein and Stern had exchanged, which contain a discussion on the topics covered by Stern's Lomsha papers. However, as the correspondents were unable to come to the same conclusion, the papers were authored by Stern alone; Einstein's contribution to the published material was likely insignificant, as also attested by the absence of an acknowledgment of Einstein's help in the papers.

Alan Templeton, a grandnephew of Otto Stern, told one of the authors (HS-B) that a weather surveillance aircraft based in Lomsha had been shot down by the Russians with Otto Stern onboard. However, Stern survived the accident unscathed. This episode was the apparent reason for Stern's reluctance later in life to board a plane and for his predilection toward travel between America and Europe by ocean liners.

During World War I, many scientists, not just in Germany, had been engaged in military research. One of the centers of such research in Germany was Walther Nernst's laboratory at the Berlin University. Otto Stern joined Nernst's laboratory in November 1918, to work with the experimentalists James Franck and Max Volmer there. The three-month collaboration between Stern and Volmer resulted in three experimental papers on the kinetics of intermolecular deactivation processes, such as the quenching of fluorescence, governed by what is known today as the Stern-Volmer relationship [13]. More importantly, Stern's experience in Nernst's laboratory converted him from a theorist to an experimentalist.

Back to Frankfurt (1919–1921)

In order to help the veterans of WWI to catch up with their studies, the University of Frankfurt set up a trimester system, and Stern was called upon to give an introductory course on thermodynamics in the extra trimester running from February 3 until April 16, 1919 [14]. By that time, Max von Laue had left Frankfurt and assumed an *Ordinarius* professorship at his alma mater, the Berlin University, side by side with his mentor Max Planck. Laue's move to Berlin was a part of a swap that brought Max Born from Berlin, where he held an *Extraordinarius* professorship, to Frankfurt, where he was appointed an *Ordinarius* for theoretical physics, thereby "inheriting" Otto Stern as his assistant. Born's Institute at Frankfurt consisted of another *Privatdozent*, Alfred Landé, and another assistant, Elizabeth Bormann. In addition, Born's Institute for Theoretical Physics also comprised a machine shop, run by a distinguished fine-mechanic, Adolf Schmidt, who proved instrumental for the later success of Born's small Institute. Here is how in his autobiography [15] Born described Stern's beginnings at his Institute:

> I was fortunate enough to have found in Otto Stern a Privatdozent of the highest quality, a good-natured, cheerful man, who had soon become a good friend of ours. The work in my department was guided by an idea of Stern's. He wanted to measure the properties of single atoms and molecules in gases by making use of molecular beams, which were first employed by Louis Dunoyer in 1911. Stern's first apparatus was designed to produce direct evidence for the velocity distribution law of Maxwell and to measure the mean velocity. I was so fascinated by the idea that I put all the means of my laboratory, workshop and mechanic at his disposal.

Max Born's institute in Frankfurt was not a big operation. Born in his interview with Paul Ewald [16]:

> I had only two rooms in Frankfurt. And in one room there were some students . . . Stern's apparatus was made up in my little room, so I saw it from the beginning and watched. And I was quite envious of how he managed: he did not touch it at all, for he is also, just like me, not very good with his hands. But we had a very good mechanic [Mr. Adolf Schmidt] and he did it for him. He [Stern] told him what to do and it came out.

In his first benchmark experiment at Frankfurt, Stern set out to verify the Maxwell-Boltzmann distribution of the velocities of gaseous molecules. Stern had made use of a beam of atoms produced by heating silver to a given temperature. In this way, he had not only corroborated a theoretical result dating back to the 1860s by a cogent experiment, but also secured a future for the molecular beam method. With its aid, Dunoyer showed that sodium atoms travel in vacuum (at a pressure of about 10^{-3} millibar) along straight lines like light and produce a well-defined shadow image of an obstacle placed in their way, and thereby confirmed one of the key assumptions of the kinetic theory of gases [17].

A molecular beam consists of myriads of single atoms/molecules separated from one another by a distance large enough to preclude interactions among them. Therefore, a molecular beam in effect offers the possibility to experiment with single, isolated atoms or molecules. However, in order for the molecular beam experiments to be quantitative, the molecular beams have to be well characterized. The velocity distribution of the beam molecules is one such key characteristic, and so Stern's first Frankfurt experiment prepared the soil for much of what would come later in his own laboratory as well as in the laboratories of others who would implement the molecular beam technique.

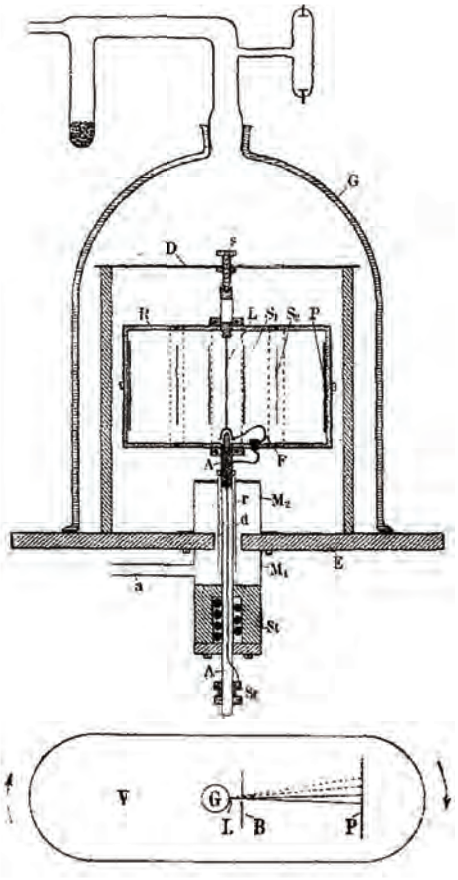


Fig. 2 Stern's apparatus for measuring the Maxwell-Boltzmann distribution of molecular velocities, in side-view (top) and top-view (bottom) [19].

Stern's simple, ingenious apparatus to determine the Maxwell-Boltzmann velocity distribution was designed as follows, see Fig. 2: An electrically-heated thin platinum wire (L) dipped in silver soldering paste served as a source of silver atoms, radially emitted into the gas phase by evaporation. The effusive beam was narrowly collimated by a pair of horizontal and vertical slits (S_1 and S_2) and, like in Dunoyer's experiment, captured on a cold plate (P), where the atoms condensed and turned visible. The position and shape of the condensate spot could be accurately measured with a microscope. The slits and the cold plate were mounted on a platform which could be rotated around the beam source at a rate of up to 2,400 rotations per minute. When rotated, the Coriolis force acting on the silver atoms in the rotating frame of the platform resulted in a shift of their position on the cold plate with respect to the position at which the atoms impinged when the platform was at rest. From the measured shift, the geometry of the apparatus, and the speed of rotation it was then possible to determine the mean radial velocity of the atoms. Although Stern originally intended to determine the entire velocity (speed) distribution, he submitted in April 1920 a paper to *Physikalische Zeitschrift* entitled *Eine direkte Messung der thermischen Molekulargeschwindigkeit* (A measurement of the thermal molecular speed) [18] in which he only reported the atoms' mean velocity. This came out as 650 m/s for an assumed source temperature of 961°C [18]. However, the Maxwell-Boltzmann formula predicted 534 m/s, about 20% less, which Stern first blamed on the uncertainty in determining the source temperature. The real cause of the discrepancy was pointed out to Stern by his mentor Einstein: Stern omitted a key transformation required when the molecules pass through a slit (and their flux rate rather than density is measured) – in which case their transmission differs for different molecular velocities. By applying the transformation to the Maxwell-Boltzmann distribution, Stern obtained a mean velocity greater by about 15% than before, and was able to enjoy its gratifying agreement with his old data as well with new measurements he undertook at different source temperatures and rotation rates [19]. Stern's concluding remark aptly captures the significance of the work reported:

> The experimental set up employed herein makes it possible to prepare, for the first time, molecules with a uniform velocity.

This proved to be a key moment for physics: from then on, especially in later incarnations of the technique, it would be possible to prepare isolated molecules in a well-defined momentum state and thus to accurately measure any momentum changes imparted to the molecules by external fields or other molecules. Stern's first Frankfurt experiment was a milestone on the path to quantum physics.

With his training by Einstein in theory, Stern was able to conceive the most imaginative ideas for experiments and experimental apparatus. However, as he admitted in his Zurich interview, he lacked the skills and the dexterity needed to implement them in the laboratory, at least at the beginning of his Frankfurt time. Therefore, he sought the help of an experienced experimentalist, whom he found in his Frankfurt colleague Walther Gerlach. The Stern-Gerlach experiment they carried out together in 1921–1922 [20]

> ranks among the dozen or so canonical experiments that ushered in the heroic age of quantum physics. Perhaps no other experiment is so often cited for elegant conceptual simplicity. From it emerged both new intellectual vistas and a host of useful applications of quantum science.

In their first and last joint venture, Stern and Gerlach undertook to find out whether the so called "space quantization" was real. The idea of space quantization was developed in 1916 nearly simultaneously but independently by Arnold Sommerfeld [2] and Peter Debye [3] in an attempt to amend Niels Bohr's 1913 model of the atom to account for the normal Zeeman effect, i.e., the splitting of spectral lines of (hydrogenic) atoms by a magnetic field. Whereas the anomalous Zeeman effect (which arises for atoms in other than singlet states) would baffle atomic physicists for one more decade, until the discovery of electron spin in 1925, space quantization as an archetypal manifestation of the quantum world would remain striking up to the present.

Classically, the atomic magnetic moments could be oriented at an arbitrary angle with respect to an external magnetic field. In contrast, Sommerfeld's and Debye's idea amounted to postulating that the magnetic moment could only take certain discrete orientations with respect to the field – that its direction is "spatially quantized" and not "classically continuous". To add to the strangeness, the discrete orientations of the magnetic moments were to change if their "observer" picked another direction of the external magnetic field. Even Debye himself did not believe in the reality of space quantization and confided his misgivings to Gerlach [21]:

> You surely don't believe that [space quantization] is something that really exists; it is only a computational recipe, a timetable of the electrons.

Max Born let his voice be heard (a little later) as well [15]:

> I always thought that space quantization was only a symbolic expression for something you don't understand.

And Otto Stern, according to his Zurich interview, did not believe in the existence of space quantization either. He wanted to prove that the whole concept was flawed.

On August 26th 1921, Stern submitted a paper to *Zeitschrift für Physik* entitled *Ein Weg zur experimentellen Prüfung der Richtungsquantelung im Magnetfeld* (A way towards the experimental examination of spatial quantization in a magnetic field) in which he described how to test whether space quantization was for real. As he put it [22]:

> Whether … the quantum theoretical or classical interpretation is correct can be decided by a basically very simple experiment. One only needs to investigate the deflection which a beam of atoms experiences in an appropriate inhomogeneous magnetic field.

Stern's superior at the time, Max Born, recalled later in his interview with Paul Ewald [16]:

> I tried to persuade Stern that there was no sense, but then he told me that it was worth a try.

Stern himself expressed in the paper his own misgivings about space quantization [22]:

> A further difficulty for the quantum interpretation, as has already been noted from various quarters, is that one just cannot imagine how the atoms of the gas, whose [magnetic moments] without magnetic field have all possible directions, are able, when brought into a magnetic field, to align themselves in the pre-ordained directions. Really, something completely different is to be expected from the classical theory. The results of the magnetic field, according to Larmor, is that all the atoms perform an additional uniform rotation with the direction of the magnetic strength as axis, so that the angle which the direction of the [magnetic moment] makes with [the magnetic field] continues to have all possible values for the different atoms.

There is a footnote added to Stern's paper which provides an explanation as to why Stern published about an experiment much of which was yet to be done: Hartmut Kallmann and Fritz Reiche, working together at Fritz Haber's Kaiser Wilhelm Institute in Berlin-Dahlem (the latter a *Privatdozent* at the Berlin University), had submitted a paper on closely related research. Although Kallmann and Reiche's goal was different, namely to test whether the electric dipole moment of polar molecules was an individual or a bulk property, there had been a considerable methodological overlap between their and Stern's and Gerlach's work, and Stern sought to make this known [22]:

> Mr. Gerlach and I have been occupied for some time with the realization of [the Stern-Gerlach] experiment. The reason for the present publication is the forthcoming paper by Messrs. Kallmann and Reiche concerning the deflection of electric dipolar molecules in an inhomogeneous electric field.

In early 1921, Stern and Gerlach started working in earnest on the design and execution of their experiment to test the concept of space quantization. Technically, this was a difficult experiment to carry out. The molecular beam part of the apparatus had to be rather small – not much bigger than a fountain pen – in order to fit into a glass vacuum chamber, and likewise restricted by the size of the electro-magnet. This core of the apparatus was subject to a large temperature gradient, as the beam source – a silver oven – had to be heated to about 1,300°C and the Gaede mercury diffusion pumps, used to generate a vacuum, as well as the condenser plate had to be cooled to the temperature of liquid air. At the same time, the set up (oven, slits, magnet, condenser plate) had to be very accurately aligned, as the deflection of the silver atom beam by the inhomogeneous magnetic field was expected to be only on the order of 0.1 mm, and an inaccuracy in the alignment on the order of 10 µm could not be tolerated. Because of the small intensity of a molecular beam, the experimental runs took several hours, during which the delicate apparatus had to remain aligned and otherwise well behaved [23].

Apart from a shortage of funding [24], the experiment was hindered by other external circumstances as well. In May 1920, Max Born received a call to the University of Göttingen. However, since he was quite happy in Frankfurt, he wanted to stay. In a letter of June 7, 1920 addressed to the city's Mayor Georg Voigt [14], Born made five requests whose fulfillment would have kept him put. All of them were granted, except for the one which mattered to Born the most: to appoint Otto Stern as Professor at Frankfurt. On June 10, 1920, Born wrote to Voigt:

> Unfortunately, it seems impossible to fulfill my main wish, namely to attach my co-worker, Prof. Stern, to Frankfurt through a professorship. Exactly this point, namely the recruitment of outstanding faculty, is handled much more favorably by the Ministry in Göttingen.

As a result, in 1921 Born moved to Göttingen. In the Fall of 1921, Stern too received an offer, to become *Extraordinarius* (associate professor) for theoretical physics at the University of Rostock. In the winter semester 1921/22, he was already lecturing there on the subject. Hence, since autumn 1921, the Stern-Gerlach experiment was run by Walther Gerlach alone.

Fig. 3 Schematic of the set up used in the Stern-Gerlach-experiment: Silver oven (O), collimator slits $(Sp_1$ and $Sp_2)$, inhomogeneous magnetic field (M), and condenser plate (P).

Figure 3 shows a schematic of the set up used for the Stern-Gerlach experiment [25]. An effusive beam of silver atoms, produced by heating silver metal in an oven, was collimated by a pair of slits, passed along the sharp pole piece of an electro-magnet, and detected on a condenser plate attached behind the magnet. The total length of the apparatus (including the oven) was about 12 cm. Figure 4 shows a photo of the apparatus, with part of the Hartmann & Braun magnet (a small Dubois magnet) removed, enabling to see the key components. The glass bell-shaped vacuum chamber on the left housed the oven. The chamber was connected to a vacuum pump and its double walls cooled by refrigerated air. The slits as well as the sharp pole piece were located behind the white quadratic structure in a vacuum tube (center). The condenser plate was housed in the cooling cylinder on the right.

Because Stern was required to teach in Rostock, he could visit Frankfurt only during breaks such as Christmas (1921) and Easter holidays (1922). The apparatus had been steadily improved by Gerlach and in the course of a run during the night of November 5, 1921, Gerlach scored his first great success. A 0.05 mm diameter silver beam collimated by a pair of circular apertures 3 cm apart was dispersed by an inhomogeneous magnetic field acting upon the beam over a length of 3.5 cm in a vacuum of about 10^{-5} millibar, leaving behind a broadened spot on the condenser plate [26]. The width and shape of the spot allowed to infer that the internal magnetic moment of the silver atoms had a magnitude between 1 and 2 Bohr magnetons (μ_B). On November 18, 1921, Gerlach and Stern submitted this result to *Zeitschrift für Physik* [27]. Because of the limited angular resolution, the outcome of the experiment would remain inconclusive as to the issue of space quantization in general, and the details of its manifestation in particular: Sommerfeld had predicted a triplet structure, in analogy to the normal Zeeman splitting, for the detected silver beam, with one component deflected downward, one upward, and one undeflected. The Bohr model, in contrast,

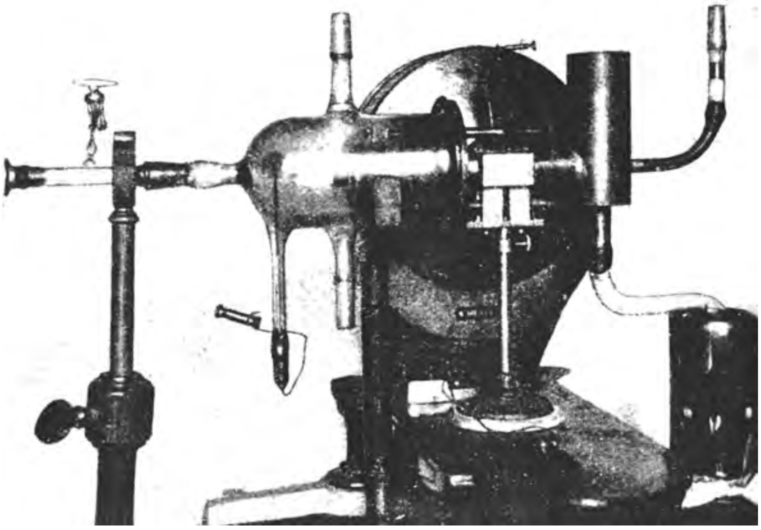


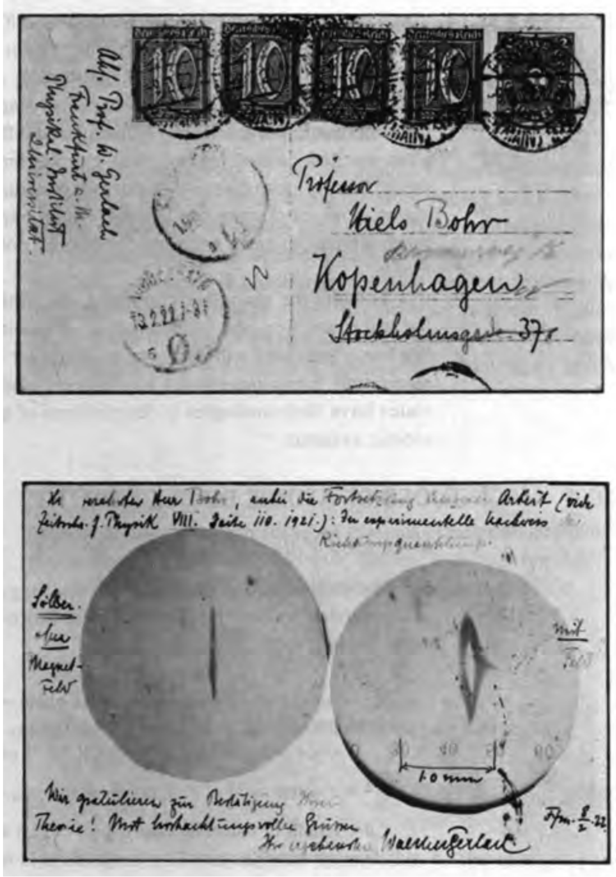
Fig. 4 Stern-Gerlach apparatus.

predicted a doublet splitting, corresponding to an electron orbiting around the atom nucleus clock-wise or counter-clockwise with respect to the direction of the magnetic field and resulting in two components, one deflected upward and one downwards, but no undeflected beam.

Wilhelm Schütz, at the time a PhD student under Gerlach, was allowed to watch Gerlach at work, and has provided a testimonial of what he saw [28]:

> Anyone who has not been through it cannot at all imagine how great were the difficulties with an oven to heat the silver up to a temperature of 1300°C within an apparatus which could not be fully heated [the seals would melt] and where a vacuum of 10^{-5} torr had to be produced and maintained for several hours. The apparatus was cooled with dry ice and acetone or with liquid air. The pumping speed of the Gaede mercury pumps or the Volmer mercury diffusion pumps was ridiculously small in comparison with the performance of modern pumps. And then, their fragility; the pumps were made of glass and quite often they broke, either from the thrust of boiling mercury – despite an addition of lead – or from the dripping of condensed water vapor. In that case the several-day effort of pumping, required during the warming up and heating of the oven, was lost. Also, one could by no means be certain that the oven would not burn through during the four- to eight-hour exposure time. Then both the pumping and the heating of the oven had to be started from scratch. It was a Sisyphus-like labor and the main load and responsibility was carried on the broad shoulders of Professor Gerlach. In particular, W. Gerlach took over the night watches. He would get in at about 9 p.m. equipped with a pile of reprints and books. During the night he would then read the proofs and reviews, write papers, prepare lectures, drink plenty of cocoa or tea and smoke a lot. When I arrived the next day at the Institute, heard the intimately familiar noise of the running pumps, and found Gerlach still in the lab, it was a good sign: nothing broke during the night. … I arrived one morning in February 1922 at the institute; it was a gorgeous morning; cold air and snow! W. Gerlach was in the middle of developing the silver deposit left by an atom beam which ran for 8 hours through the inhomogeneous magnetic field. Full of expectation, we watched the development process and have experienced the success of many months of hard work: the first splitting of a silver beam by an inhomogeneous magnetic field. After Meister Schmidt and, if I remember correctly, also E. Madelung, saw the splitting, the image was recorded micro-graphically in the mineralogical Institute. Then I got the job to send a Telegram to Herrn Professor Stern in Rostock, which read "Bohr is right after all!" ("*Bohr hat doch recht!*").

Wilhelm Schütz's apt description of the weather conditions "the morning after" made it possible for us to unambiguously date the fateful night when space quantization was demonstrated: a comparison with the records of the *Wetteramt* (Weather Service) attests that it was the night from the 7th to the 8th of February, 1922 [29]. The above-mentioned telegram sent to Stern has probably been lost; at least it is not present in the Stern collection at the Bancroft Archive. However, a postcard dispatched to Niels Bohr has been preserved, see Fig. 5. It was sent on February 8, as can be discerned by inspecting the right bottom corner of the rear side of the card with the silver beam deflection pattern.



Abs. Prof. W. Gerlach
Frankfurt a. M.
Physikal. Institut
Universität

Professor
Niels Bohr
Kopenhagen
~~Stockholmsgade 37~~

Hochverehrter Herr Bohr, anbei die Fortsetzung unserer Arbeit (vide Zeitschr. f. Physik VIII. Seite 110. 1921.): Der experimentelle Nachweis der Richtungsquantelung.

Silber ohne Magnetfeld

mit Feld

1,0 mm

Wir gratulieren zur Bestätigung Ihrer Theorie! Mit hochachtungsvollen Grüssen
Ihr ergebenster Walther Gerlach

Ffm. 8/2. 22

Fig. 5 Gerlach's postcard to Niels Bohr, dated February 8, 1922. Courtesy of the Niels Bohr Archive in Copenhagen and the Emilio Segré Visual Archives.

Gerlach's postcard message to Bohr reads:

> Hochverehrter Herr Bohr, attached a sequel to our work (see Zeitschrift f. Physik VII, page 110, 1921). The experimental proof of space quantization (silver without and with magnetic field). We congratulate you on the confirmation of your theory. With respectful greetings faithfully yours Walther Gerlach (Frankfurt, February 8, 1922).

On March 1, 1922, Walther Gerlach and Otto Stern submitted their landmark paper *Der experimentelle Nachweis der Richtungsquantelung im Magnetfeld* (The experimental proof of space quantization in magnetic fields) to *Zeitschrift für Physik*, with the paper's main message printed with emphasis [30]:

> Space quantization in a magnetic field has been proven as a fact.

The paper featured the same images of the split and unsplit silver beam as the postcard to Bohr did: without a magnetic field there is no deflection of the beam; with an inhomogeneous magnetic field applied there is a kiss-like spot affirming a splitting of the silver beam. In the experimental run that led to the final success, Gerlach used a 0.8 mm long and 0.03 mm wide platinum slit instead of a circular aperture. Since the slit's long side was oriented perpendicular to the direction of the magnetic field, only the fraction of the beam passing directly underneath the sharp edge of the magnetic pole piece (where the field strength was largest) showed a splitting. The splitting of the beam at the center of the slit clearly revealed a doublet structure. Thereby Sommerfeld's and Debye's concept of space quantization was corroborated.

The Stern-Gerlach experiment had thus unambiguously demonstrated that space quantization was not a mathematical artifact, but real physics. The finding that the atoms "knew" the direction of the magnetic field that the experimentalist has randomly chosen was deplored as particularly puzzling. Einstein together with Paul Ehrenfest tried in vain to find a possible classical explanation for the Stern-Gerlach effect and showed that a classical mechanism for orienting the magnetic dipoles, such as externally-induced radiative processes, was altogether lacking [31].

We know today that aside from possible stray fields, it was solely the direction of the Stern-Gerlach magnetic field that provided the reference frame for space quantization and that there is no classical analog for the entanglement between the dipoles and the field direction. Gerlach and Stern had been the first to provide evidence for this entanglement.

Another puzzling issue was the splitting pattern observed in the Stern-Gerlach experiment. Since the data seemed to conform to Bohr's prediction, the prevalent perception was that Bohr was "right" and Sommerfeld and Debye "wrong". In hindsight, neither was "right", since the magnetic moment of the silver atom was not due to the electron's orbital angular momentum (moreover incorrectly presumed as having the value of $h/2\pi$) [32] but rather to the electron's "internal" angular momentum, i.e., spin, which would be discovered only three years later. However, in the early 1920s, there was one scientist who could have sounded an alarm and pointed out that the Stern-Gerlach doublet splitting was hinting at something other than the electron's orbital degree of freedom. But he kept quiet. This researcher was Alfred Landé, who had received his *Habilitation* under Born in 1919 on the theory of many-electron atoms and was sharing with Stern the premises of Born's Institute at Frankfurt.

Landé published in 1921 a semi-empirical formula, which described quantitatively both the normal and the anomalous Zeeman splitting of atomic levels [33]. His key idea was that both the normal and the anomalous Zeeman effects have the same origin. By playing with experimental values, he found his famous g-factor formula relating the magnetic dipole moment of an atom to its angular momentum, which is identical with the correct quantum mechanical result. Had Landé considered the Zeeman and the Stern-Gerlach splitting as mutually related, he could have discovered the spin degree of freedom already in 1922 at Frankfurt. Here is how Max Born described Landé's work in the Ewald interview [16]:

> As far as I remember the main indications of the crisis were the multiplets and the Zeeman effect, and these things. That we called the zoology of terms. Landé came to my department – I don't know the period exactly – and was my student in Göttingen. [...] Then he came to Frankfurt again, and his head was completely occupied with the paper which I didn't grasp at first. It was these whole number relations between the intensities of multiplet lines and Zeeman-effect lines. And he did it in a way which seemed to me horrible, namely, simply by guessing about numerical values. He wrote long lists of numerical values and said they must be contained in one formula – how can one construct it? And he tried the most impossible things. And at last it came out. At last came a formula which gave all the results he wanted. I couldn't check it – I can never do numerical calculation problems. So I didn't take much notice of him, and he also did not take much notice of our work, though we were sitting all the time in the same room. But two years later, or three, when we derived the square root of integers formula from quantum mechanics, we saw at once that it was very important. Some of these formulae were known before for multiplets from the Dutchman Ornstein. But for the multiplets, I think, and the expression of this "g" were first given by Landé.

According to Landé's formula, electrons with angular momentum $h/2\pi$ would assume three orientations with respect to a magnetic field, in agreement with the prediction of Sommerfeld and Debye. However, Landé's formula is also compatible with a doublet splitting, provided the Zeeman effect is due to an angular momentum of $1/2(h/2\pi)$ with a g-factor of 2. Classically, it was impossible to explain the source of such a half-integral angular momentum: since an electron on a Bohr orbit could never have it, it would have to be a property of the electron itself. However, only in 1925 would Landé's former student assistant Ralph de Laer Kronig [34], working at the time at Columbia University towards his PhD, and a few months later, the Dutch physicists George Eugene Uhlenbeck and Samuel Abraham Goudsmit [35] have the audacity to talk in public about the electron's "internal" angular momentum. In the case of Kronig, this loquaciousness had the unfortunate consequence of him being dissuaded by one of his interlocutors, Wolfgang Pauli, from pursuing the idea of electron spin any further [36]:

> Kronig would have found the spin, had not Pauli frightened him.
> (*Der Kronig hätt den Spin entdeckt, hätt Pauli ihn nicht abgeschreckt*).

Although a proponent of the "fourth quantum number" for an atomic shell electron already since 1924 [37], Pauli was himself "frightened away" by an apparent incompatibility of a spinning electron with special relativity theory. However, this incompatibility was not there, as shown in 1926 by Llwellyn Hilleth Thomas [38], whose relativistic analysis put the heuristic concept of a spinning electron on a firm footing. The hypothesis that the electron itself, spinning like a tiny gyroscope, is probably the ultimate magnetic particle was expressed already in 1921 by Arthur Compton [39] based on evidence from X-ray diffraction by magnetic crystals and the curvature of the tracks of beta rays through air and was taken into account by Uhlenbeck and Goudsmit when they introduced their electron spin hypothesis. Apparently, at that time no one discussed Compton's hypothesis in connection with either the Zeeman or the Stern-Gerlach effect.

What seems particularly puzzling today is that neither in 1922 nor in 1925 had the Stern-Gerlach experiment been discussed in terms of electron spin [20]. The first mention that it was in fact electron spin which was responsible for the magnetic deflections observed in the Stern-Gerlach experiment appeared as late as 1937 as an aside in the second edition of Ronald Fraser's book [40].

In 1922 much of the physics community, including Stern, was astonished by the experimental proof that space quantization existed. Pauli wrote to Gerlach [21]:

> This should convert even the nonbeliever Stern.

Sommerfeld provided this comment on the outcome of the Stern-Gerlach experiment [21]:

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

Einstein wrote [21]:

> The most interesting achievement in quantum physics at this point is the experiment of Stern and Gerlach. The alignment of the atoms without collisions or via radiation cannot be explained by existing theory; it should take the atoms more than 100 years to become aligned. I have done a little calculation about this with [Paul] Ehrenfest.

Stern himself expressed his feeling about the experimental result in his 1961 Zurich interview [6]:

> I was unable to understand anything about the outcome of the experiment, the two discrete beams. It was totally incomprehensible. It is obvious [today] that [in order to comprehend the experiment] one needs not only the new quantum theory but also a magnetic electron. These are the two things which were still missing at the time. I was fully confused and did not know what to do with such a result. Even today, I have objections against the beauty of quantum mechanics. But it is correct.

During Easter break of 1922 Otto Stern came to Frankfurt to work with Gerlach on improving the quantitative aspects of the Stern-Gerlach experiment. Special attention was paid to determining accurately the inhomogeneity and strength of the magnetic field employed to impart a deflection to the silver atoms. As they described in their paper *Das magnetische Moment des Silberatoms* (The magnetic moment of the silver atom) [41], this

> was measured by weighing the repulsive force of a very tiny probe made out of bismuth from point to point [of the field] and the measurement of the field strength from the variation of the resistance of a thin bismuth wire strung parallel to the sharp edge of the pole piece.

The alignment technique as well as the design of the magnetic pole pieces was apparently proposed to Stern and Gerlach by Born's successor at Frankfurt, Erwin Madelung. In his Zurich interview, Stern expressed regret that the acknowledgment of Madelung's help in the paper was not more emphatic.

By taking into account the geometry of the apparatus, the inhomogeneity of the magnetic field, and the mean velocity of the beam atoms, Stern and Gerlach had found that the value of the magnetic dipole moment of the silver atoms was equal, within 10%, to one Bohr magneton. This appeared to be in gratifying agreement with the available Bohr-Sommerfeld-Debye theory. However, this agreement was only fortuitious, brought about by an "uncanny conspiracy of Nature" [20], consistent with the submission of the paper on the 1^{st} of April: the anomalous gyromagnetic ratio of the electron (≈ 2.0023) roughly canceled the electron spin of of $1/2$. But there was no way to tell. Thereby ended Stern's stint at Frankfurt.

Stern in Rostock (1921–1922)

Otto Stern's appointment at Rostock was connected with little funding, a heavy teaching load and, after the retirement of his only colleague, the professor of experimental physics, also time consuming administrative duties. However, it was at Rostock where Stern was joined by Immanuel Estermann, who would work with Stern until Stern's retirement in 1946. Stern's Rostock period was brief: in the fall of 1922 he received – and accepted – an offer for a full professorship from the University of Hamburg.

Stern's position in Rostock was held by a string of first-class physicists: Wilhelm Lenz (1920-1921), Walter Schottky (1923-1927), Friedrich Hund (1927-1928) and Pascual Jordan (1929-1944).

Otto Stern's golden years in Hamburg (1923–1933)

On January 1, 1923 Otto Stern took up his new position as Professor (*Ordinarius*) of Physical Chemistry and Director of the Institute for Physical Chemistry at the University of Hamburg, which was founded shortly before, in 1919. The following ten and a half years in Hamburg were Stern's most successful, golden years of his research career. In Hamburg Stern established an outstanding research group which through many spectacular pioneering contributions soon achieved world-wide fame and became the leading international center for atomic, molecular and nuclear physics. In 1926 he published the first in a series of 30 remarkable papers which were all subtitled *Untersuchung zur Molekularstrahlmethode*, UzM (Investigations by the molecular-beam method). In the first of two visionary introductory articles [42] Stern discussed for the first time all the special advantages of the molecular beam method and laid out a program for future research with 8 major scientific goals, all of which were far ahead of their time. Among these were such boldly ambitious projects as measuring nuclear magnetic moments, which he estimated to be only "about 1/2000" of a Bohr magneton, in a Stern-Gerlach type of experiment; determining Einstein's photon recoil; and confirming Louis de Broglie's 1924 prediction of wave-particle duality. In the introduction he proclaimed that [42]

> The molecular beam method must be made so sensitive that in many instances it will become possible to measure effects and tackle new problems which presently are not accessible with known experimental methods.

He was fully aware that the molecular beam method stood in direct competition with optical spectroscopy, but in contrast to spectroscopy, which can only observe differences in the energies of two states of a given molecule, the molecular beam method can measure a variety of physical properties of an isolated molecule in a specified quantum state. In the second far-sighted article, published with Friedrich Knauer [43], Stern described in detail how to produce highly collimated intense molecular beams required to increase the precision while, at the same time, greatly reducing the measuring times of molecular beam experiments. He proposed to replace the thin (0.4 mm dia.) silver-coated platinum wire evaporator, used as the beam source in his 1920 measurements of velocity distributions, by a heated source chamber, which he called an "oven". With this new source the beam exit slit could be narrowed without losing intensity since, according to the Knudsen condition, it would be possible to raise the source pressure and thereby compensate fully for the loss of intensity due to a reduced transmission. Thanks to the increased intensity the deposited beam would be detectable with a chemical developer after only 3 to 4 seconds. With these and other measures, Stern and Knauer predicted on the basis of extensive numerical calculations that the angular and momentum resolution could be improved to the extent that the resolution of the magnetic moment in magnetic deflection experiments could be increased to 1 part in 100,000 of a Bohr magneton, more than sufficient for measuring even nuclear magnetic moments. He also predicted that the increase in sensitivity and angular resolution should make it possible to detect the scattering from surfaces or even from gases and in this way to determine the corresponding van der Waals forces.

Up to 1929, Stern's laboratory in Hamburg consisted of four rooms in the basement of the Physics Institute, which provided reasonable conditions by the standard of those times [44–46]. Then in 1929 Stern was offered a position as Professor of Physical Chemistry at the University of Frankfurt [45]. Since the city of Hamburg and his Hamburg colleagues were quite anxious to keep Stern, the ensuing negotiations led to a significant improvement in his working conditions. Despite the hard times in Germany resulting from the global financial crisis of 1929, which triggered the Great Depression, he was offered a brand new building, additional staff positions and more than ample funds for the workshop and technicians. This explains why in 1930, when Max von Laue offered him a highly prestigious professorship at the Kaiser-Wilhelm Institute for Physical Research in Berlin, Stern felt strongly committed to Hamburg and turned down Laue's offer [14]. Undoubtedly the excellent working conditions in Stern's laboratory significantly contributed to its scientific successes in the remaining four years in Hamburg. During this period, Stern's research staff consisted of four assistants, a large number of foreign research fellows and four to five PhD students. His closest assistant was Immanuel Estermann who had come shortly before Stern as a *Privatdozent* from Rostock and would later emigrate with him to Pittsburgh. At Hamburg, jointly with Estermann, Stern had developed several lecture courses and seminars and established and ran a colloquium [46]. Stern's Hamburg group was joined by Friedrich Knauer, Robert Schnurmann and later in 1930 by Otto Robert Frisch, the nephew of Lise Meitner. The short, three-year collaboration with Otto Frisch was extremely rewarding for both Frisch and Stern. In his book "What little I remember" [47], Frisch describes his first impressions after arriving in Stern's laboratory as follows:

> My first recollection of the laboratory is standing in front of what looked like a forest of glass, a sort of glass blowers nightmare; tubes and bulbs and cylinders and mercury pumps blown from glass, with stopcocks by the dozen connected in a manner that made no more sense to me than the twigs in a hedge. And there I watched Stern and his chief assistant, Immanuel Estermann, turning stopcocks apparently at random, closing this one and then after a few seconds opening that one, and so on for what seemed like half an hour. I felt I would no more learn this than a totally unmusical person would ever learn to play the organ.

With great candor Frisch goes on to describe Stern's way of doing experiments:

> Stern was rather clumsy, and moreover one of his hands invariably held a cigar (except when it was in his mouth); so he was disinclined to handle any breakable equipment and always left that to his assistants. I still remember what he did when anything appeared to topple. He would never

> try to catch it; he lifted both hands in a gesture of surrender and waited. As he explained to me: You do less damage if you let the thing fall than if you try to catch it. Yet Stern was, in a higher sense, a superb experimenter. In using a new apparatus he left nothing to chance. Everything had been worked out beforehand and every detail of the performance was carefully checked. Stern would calculate, for instance, how much beam intensity he expected to get, even though that was a very lengthy and tedious calculation, which he always did himself. He could not predict the intensity very accurately; but if it fell short by more than 30% he felt something must be wrong, and the fault had to be tracked down. I have never seen anybody keeping such strict control of his instruments, and it surely paid off. As a rule the experiments we did were so difficult that nobody else in the world was attempting them. That created an oddly relaxed atmosphere.

Fig. 6 Otto Stern at work in his Hamburg laboratory.

The research fellows came mostly from Italy, England and the United States. Two of them, Isidor Isaac Rabi (USA) and Emilio Segré (Italy), would later become especially famous and would be awarded Physics Prizes for research which was inspired by their stays with Stern in Hamburg. Rabi received the Nobel Prize in 1944 “for his resonance method for recording the magnetic properties of atomic nuclei” and Segré shared the 1959 Nobel Prize with Owen Chamberlain “for their discovery of the antiproton”. Isidor Rabi had come to Hamburg to work with Wolfgang Pauli. In an interview in 1988 shortly before he passed away, Rabi told the science writer and author John Rigden how Otto Stern and his experiments affected his career [48]:

> I first met Stern in the fall of 1927. I had been in Copenhagen at the Niels Bohr Institute of Theoretical Physics and Bohr [who at the time had too many visitors] made an arrangement for Yoshio Nishina and me to go and work with Wolfgang Pauli at the University of Hamburg. When I got there, I was pleased to find that Stern and his associates were engaged in very exciting molecular beam experiments. While my prime interest was with Pauli in theory, I spent time in Stern’s laboratory talking with Ronald Fraser, a Scotsman, and John Taylor, an American. I came to understand the subtleties of the molecular beam experiments and recognized that the components of an atomic beam could be separated with a homogeneous [in place of the inhomogeneous field used in the Stern-Gerlach experiment] magnetic field. I explained the idea to Stern

> and he suggested do the experiment. I was told what an honor it was to be invited by Stern to do an experiment in his laboratory. I had no job and I had a wife to support. I was in no position to refuse the honor. My experiment was a success and when it came time to write up the results, I saw a demonstration of Stern's generosity, his fairness, and his pride. "First, publish a letter in Nature", said Stern. "If you publish it first in German, they'll think it's my thing, and it's yours.

In fact, this was the rule with Stern. Of the 30 articles in the UzM series 16 were published under the name of a single author without Stern's name. These included the PhD dissertations of Alfred Leu, Erwin Wrede, Berthold Lammert and Lester C. Lewis [49].

In an earlier interview with Thomas S. Kuhn in 1963 [50], Rabi described the daily scientific life in Stern's Institute in the following way:

> I got to work and shared a lab with Taylor, who really taught me the technique. I saw very little of Stern himself, during that time. I did the experiment. All the time Walter Gordon was there, and later on Jordan came, and, of course, there was Lenz who was the professor; there was Pauli, and Bohr used to come, and Born. It was a place where people were in and out all the time. And of course there was Stern. The seminars were marvelous and the colloquium was very interesting, very high level, in the sense that there were different kinds of minds; Lenz, for instance, had a mind like a steel trap. He could make up things on the spot, although he never accomplished very much. Then there was Stern with his marvelous physical intuition and point of view, and Pauli with his tremendous solidity.

Emilio Segré, who joined the group in 1931, describes Stern's influence on him as follows [51]:

> Stern taught me a way of experimenting that I had not seen before. He calculated everything possible about his apparatus, such as the shape and intensity of the molecular beams he expected to generate, and did not proceed until preliminary experiments were in complete quantitative agreement with his calculations. This modus operandi slowed down the preliminary work, but it shortened the total time by making it possible to avoid errors and was absolutely necessary for the extremely difficult experiments Stern was conducting. The method allowed him to localize sources of misbehavior in the apparatus and of failures, and to come to a firm decision as to whether there were new and unexpected results, which occurred repeatedly. It was a rigorous and most useful schooling.

Not only were his excellent assistants and the many highly motivated fellows and students, cf. Fig. 7, instrumental in fostering a stimulating and creative atmosphere in Stern's laboratory but also his outstanding university colleagues. The director of the theoretical institute was Wilhelm Lenz, Stern's predecessor in Rostock, who had assembled a group of excellent young *Privatdozents*, which included Wolfgang Pauli, Ernst Ising and Hans Jensen. Both Pauli and Jensen would receive Nobel Prizes in Physics, Pauli in 1945 "for the discovery of the Exclusion Principle, also called the Pauli Principle" and Jensen (jointly with Maria Goeppert Mayer) in 1963 "for their discoveries concerning nuclear shell structure" (this Prize was shared, in addition, with Eugene Wigner, who was cited for his work on symmetry). Wolfgang Pauli, as one of the most renowned theoreticians of the new quantum mechanics, had a strong influence on Otto Stern. Pauli who had received his PhD in 1921 under Sommerfeld, had arrived in Hamburg nearly simultaneously with Stern, following a year-long stay with Bohr in Copenhagen. In his conversation with Rigden, Rabi described the relationship between Pauli and Stern as follows [48]:

> When I was at Hamburg University, it was one of the leading centers of physics in the world. There was a close collaboration between Stern and Pauli, between experiment and theory. For example, Stern's questions were important in Pauli's theory of magnetism of free electrons in metals. Conversely, Pauli's theoretical researches were important influences in Stern's thinking. Further, Stern's and Pauli's presence attracted many illustrious visitors to Hamburg. Bohr and Ehrenfest were frequent visitors.

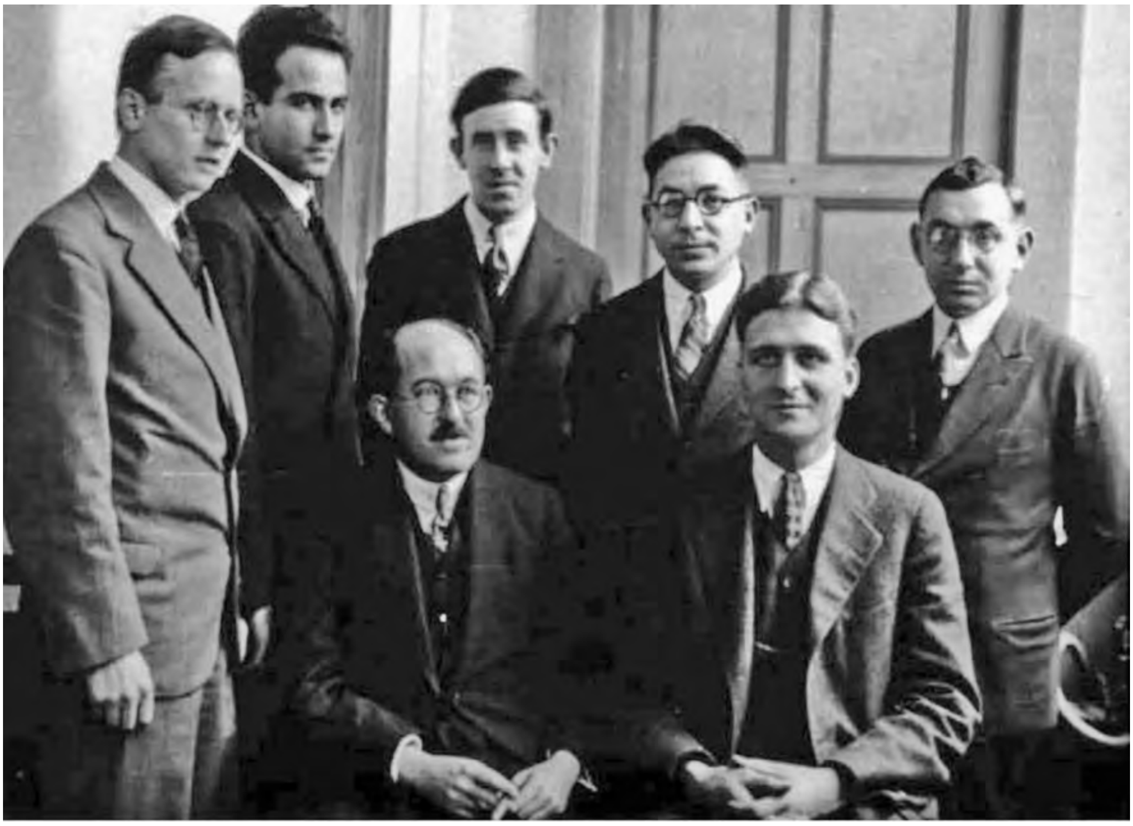


Fig. 7 Stern's research group at Hamburg, 1929 [44,46]. From left to right: Friedrich Knauer, Otto Brill, Otto Stern, Ronald Fraser, Isidor Isaac Rabi, John Bradshaw Taylor, Immanuel Estermann.

As Stern himself recollected in his Zurich interview, he invariably had lunch with Pauli at which time they discussed such scientific issues as "what is entropy", "how to explain the symmetry of the hydrogen molecule?" or "the problem of the zero point energy". Pauli was someone with whom Stern could test his "crazy" ideas.

> When I had a run of bad luck with the experiments, I would invite Pauli to dinner and pour out my troubles and invariably this helped [6].

Since Stern was quite superstitious he was convinced that each time Pauli would enter the laboratory something would break. As a result, despite their friendship, Pauli was not permitted to enter Stern's laboratory. After Pauli left Hamburg for a professorship in Zurich in 1928 they continued their close contacts and remained lifelong friends.

Among the many pioneering experiments coming from the Hamburg laboratory, Stern considered the diffraction of atoms and molecules from surfaces to be his major contribution to the development of quantum mechanics. In his Zurich interview he explained [6]:

> I like this experiment best of all, but it is not properly understood. It has to do with the determination of the de Broglie wavelength. The apparatus consists entirely of mechanical components from the shop with the exception of the lattice constant. The atom velocity was specified with rotating slotted disks. Hitler is to be blamed that we could not finish these experiments in Hamburg where it was part of our program.

In actual fact, these experiments were highly successful and were the subject of 6 publications in the UzM series. In the first of these publications, with Knauer, Stern attempted to detect the diffraction of He and H_2 beams from ordinary surfaces. Because of the inherent roughness of such surfaces, they realized that they would stand a chance only if they achieved a glancing angle of 10^{-3} radian. And indeed, in this way they succeeded in measuring reflection coefficients and even observe a hint of a diffraction peak. An attempt to diffract from an optical grating with 100 grooves per mm was, however, without success [52]. In the following spring of 1929 Stern, working alone on the very same apparatus, after some modifications finally succeeded in observing the diffraction of He and H_2 from a freshly cleaved NaCl crystal [53]. Then in collaboration with Immanuel Estermann and using the more inert and perfect LIF crystals, Stern obtained diffraction peaks which were sufficiently resolved to test whether they obeyed de Broglie's formula for the wavelength of matter waves [54]. That formula had already been confirmed for electrons in 1927 by Clinton Davisson and Lester Germer, but whether the wave-particle dualism also applied to composite particles, such as atoms or molecules, was an open issue. A year later, in a remarkable experimental tour-de-force, Estermann, Frisch and Stern succeeded in observing much sharper diffraction patterns, by first velocity-selecting the incident beams [55]. Two novel techniques were implemented for velocity selection. In one, the beam was first diffracted from a LiF crystal, which served as a grating monochromator. Only molecules scattered into a narrow angular and correspondingly narrow velocity range were then diffracted from a second LiF target crystal. In the second technique, the beam was velocity selected using two 19 cm dia. discs separated by 3.1 cm rotating on a common axis. The disks had nominally 400 equidistant radial slots each and were slightly shifted with respect to one another so that only a narrow range of velocities would be transmitted. This time the diffraction peaks were sufficiently sharp to enable quantitative testing of the de Broglie relationship, with a systematic error of only 1%, according to Stern's characteristically detailed prior analysis. Much to their disappointment, the initial value for the de Broglie wavelength deviated from the predicted one by 3%. They finally found the cause of the discrepancy as reported in a final footnote of their publication [55]

> The deviation was explained when after completion of the experiments the apparatus was dismantled. The slots in the velocity selector discs had been milled with a pitch circle which the manufacturer (Auerbach–Dresden) had specified to have 400 divisions on the circumference and thus we expected 400 slots. Since unfortunately we only noticed that they had 408 slots (the pitch circle was incorrectly labeled) afterwards we could then reduce the error from 3% to 1%.

Thus Estermann, Frisch and Stern were the first to demonstrate the validity of the de Broglie relationship for matter waves made out of atoms and molecules.

In the course of these experiments they observed a sequence of unexpected intensity dips in the otherwise smooth diffraction peak distributions. Although unable to explain the anomalies, Frisch and Stern realized their potential significance, suspecting that they might be due to the transient adsorption of the beam particles on the surface [56]. In a later article Frisch systematically analyzed the surface components of the incident wave vector corresponding to the dips [57]. These carefully performed and documented experiments later enabled John Lennard-Jones and A. F. Devonshire to explain the dips in terms of a depletion of the scattered beam as a result of a resonant trapping into van der Waals bound states at the surface [58]. Much later in the 1960's this phenomenon became known as "selective adsorption" and today is widely used to determine with high precision the attractive van der Waals potential of atoms and molecules with surfaces. Thus Stern's pioneering surface scattering experiments ultimately were continued and further perfected and would eventually become a major area of surface science research.

Two other experiments were also well before their time and pointed in directions which evolved into major fields of research only much later. Knauer in 1933 succeeded in measuring the differential cross sections for scattering of He, H_2, O_2 and H_2O molecules from each other as well as H_2 and He from Hg atoms out to very large scattering angles [59]. Gas-phase molecular beam scattering had a renaissance in the 1960's and in 1986 led to a Nobel Prize for Dudley Herschbach, Yuan Lee and John Polanyi "for their contributions concerning the dynamics of chemical elementary processes". In the last article of the UzM series, Frisch was able to detect the minute atomic recoil of a highly collimated sodium atom beam upon resonant photon absorption. This work was resumed in the 1970s and ultimately led to laser cooling and trapping of neutral atoms (1997 Nobel Prize in Physics, shared by Steve Chu, Claude Cohen-Tannoudji and Bill Phillips).

Most important for the later course of the then fledgling field of nuclear physics were the first measurements of nuclear magnetic moments, the most ambitious of the 8 goals proclaimed in Stern's 1926 manifesto. These were the experiments that were to garner him the Nobel Prize. Frisch and Stern in the spring of their last year in Hamburg, "with the sword of Nazism hanging over their heads" [60], finally succeeded in magnetically deflecting a beam of molecular hydrogen [61]. Even today the sensitive detection of beams of hydrogen molecules is a challenging undertaking. In their article the authors describe in meticulous detail the many modifications needed to make these experiments possible. In his 1961 Zurich interview Stern remarked [6]:

> While we were measuring the magnetic moment of the proton we were strongly chided by the theoreticians since they thought they already knew the answer.

These experiments were complicated by the fact that normal hydrogen molecules consist of 25% para-hydrogen and 75% ortho-hydrogen of which only the latter has parallel nuclear spins and a magnetic dipole moment. Since for reasons of symmetry the lowest rotational state of ortho molecules is $j = 1$, the interaction of the small magnetic moment associated with the rotation of the molecules (resulting from a small slippage of the electrons) with the nuclear magnetic moment also had to be accounted for. From their first deflection experiments they estimated that the ortho-component had a nuclear magnetic moment of about 2–3 nuclear magnetons (μ_N) for each of the protons. A nuclear magneton is equal to the Bohr magneton, μ_B, for the electron, reduced by the ratio of the electron-to-proton mass, i.e., $\mu_N = \mu_B/1836$. According to the then prevalent theory due to Dirac of particles with spin $1/2$, the magnetic moment of the proton should have been equal to μ_N. Hence Stern's result was in clear contradiction with theory and implied that the proton had an inner structure. Less than two months later, Estermann and Stern repeated the measurements and reported a value of $2.5\ \mu_N$ for protons with an error of only 10% [62], which is within their error bars consistent with the present-day value of $2.7896\ \mu_N$. They also reported a value of 0.8–0.9 nuclear magnetons for the rotational magnetic moment, obtained from the deflection of a specially prepared beam of pure para-hydrogen, in excellent agreement with the presently accepted value of $0.88291\ \mu_N$.

The numerous spectacular achievements of Stern's group were documented in 45 publications, including the 30 in the UzM series. Hamburg was an international hub of physics, which had attracted many distinguished visitors. Stern had been invited to numerous national and international meetings. In connection with the importance of his year in Hamburg Rabi told Rigden [48]:

> From Stern and from Pauli I learned what physics should be. For me it was not a matter of more knowledge. ... Rather it was the development of taste and insight; it was the development of standards to guide research, a feeling for what is good and what is not good. 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 problem.

Shortly after leaving Hamburg in early 1929, Rabi was offered a lectureship at Columbia University. Although intending to do theory he soon revived his interest in magnetic moments of the nuclei. After trying a number of different magnetic field arrangements with his students S. Millman, Polykarp Kusch and Jerrold Zacharias, Rabi finally, in January 1938, successfully implemented a new scheme for measuring nuclear magnetic moments, illustrated in Fig. 8. The new scheme was spurred by a colloquium at Columbia in September 1937, given by the Dutch physicist Cornelis Jacobus Gorter, the discoverer of paramagnetic relaxation, about his failed attempt to detect magnetic resonance transitions of ^{1}H and ^{7}Li nuclei in alum and LiF crystals [63].

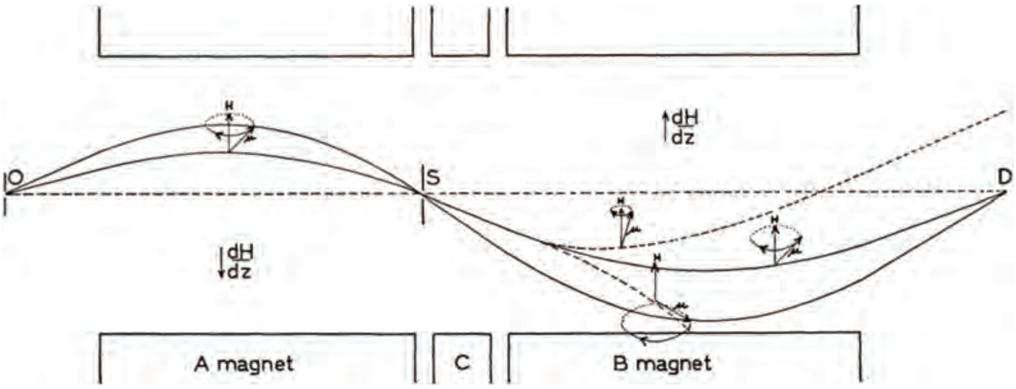


Fig. 8 Schematic diagram of Rabi's 1939 apparatus for measuring nuclear magnetic moments [64].

Instead of using only one magnetic field as in the Stern-Gerlach apparatus, now two identical inhomogeneous magnets denoted the A and B magnets were introduced. On Gorter's suggestion [63], in sector C a radio frequency electromagnetic field was applied to induce transitions from one hyperfine magnetic state to another and a superimposed homogeneous magnet insured that the spin orientation was not lost in passing from one magnet to the next, see Fig. 8. The advantage of this arrangement with respect to Stern's is, as illustrated by the solid line trajectories in Fig. 8, that atoms with a wide range of velocities, which are focused by magnet A on the slit s, are refocused on the detector at D by magnet B. As a result of a transition induced by the radio frequency field C to an atomic state with a different magnetic moment, the affected atoms undergo a different deflection in the B magnet (dashed lines in Fig. 8); since such atoms no longer arrive at the detector, a decrease in the detector signal is observed. Compared with Gorter's unsuccessful scheme, Rabi's arrangement enabled a pre-selection of the magnetic hyperfine states on which to induce the transitions. Rabi called this new technique "Molecular Beam Resonance Method for Measuring Nuclear Magnetic Moments". This method was soon adopted by many other groups world-wide. It has the advantage of combining the high precision of spectroscopy with the state selectivity of the molecular beam method, independent of the beam's velocity spread. This development brought Rabi the 1944 Nobel Prize in Physics and later to several of his former students, including Polykarp Kusch (1955), Norman Ramsey (1989) and Charles Townes (1964). It also led to the development of the nuclear magnetic resonance spectroscopy of solids and biomolecules and nuclear magnetic resonance imaging in medicine.

In 1939 Rabi and his coworkers succeeded in a precision measurement of the nuclear magnetic dipole moment of the proton: $2.78 \pm 0.02\mu_N$ and of the deuteron: $0.853 \pm 0.007\,\mu_N$ and were able to establish that nuclei have a quadrupole moment. Thus not only did they confirm and perfect the early measurements of Frisch and Stern, but they also introduced a new powerful method for the spectroscopy of nuclei.

On April 7, 1933, the Nazis promulgated the *Gesetz zur Wiederherstellung des Berufsbeamtentums* (Law for the Restoration of Professional Civil Service), which served to enforce the political conformity of civil servants, including university employees, and formed an early peak in the persecution and disenfranchisement of citizens of Jewish descent in Germany [65]. The law provided a basis for the ouster of all of Stern's Jewish coworkers: Estermann, Schnurmann and also Frisch – even though he was an Austrian citizen – received their letters of dismissal on June 23, 1933. Since Stern had served in the First World War, he was exempt from the law. However, it had become clear that more anti-semitic legislation and other discriminatory measures were imminent, as exemplified by a prohibition issued by the University and directed at Stern, according to which he was no longer allowed to display in his office a portrait of Einstein [24]. As a result, Stern submitted his letter of resignation just a few days later, on June 30, 1933. His resignation was to take effect on October 1, 1933. Before leaving Germany, Stern made sure that Friedrich

Knauer could complete his habilitation. The final paper of the UzM series, on photon recoil, authored by Otto Robert Frisch and submitted on August 22, 1933, closed with the following statement [66]:

> It would have been possible to obtain significantly improved results, but the experiments had to be prematurely terminated for external reasons.

The expulsion of Otto Stern and his coworkers from their posts at Hamburg and ultimately from Germany is among the most manifest examples of the injustice and insanity of early Nazi policies toward the Jewish members of German academia [67].

After the departure of Stern and his group and a similarly wide-ranging purge of Jewish scientists from Haber's institute in Berlin, with Kallmann among them, molecular beam research in Germany came to a halt. In the following years atomic physics in Germany relied heavily on spectroscopy, which was further developed, mainly in Hans Kopfermann's group in Kiel, to explore nuclear moments [68]. It was nearly 20 years later when in 1952 one of Kopfermann's former students and later his coworker Wolfgang Paul (Nobel Prize in Physics with Hans Dehmelt and Norman Ramsey in 1989) became professor of physics at the University of Bonn that molecular beam research was reinstated in Germany.

Emigration to the USA in 1933

Stern was more fortunate than many of his Jewish contemporaries in that he was offered academic positions abroad, one as professor of physical chemistry at the Hebrew University of Jerusalem [69] and another as a research professor at the Carnegie Institute in Pittsburgh. He accepted the latter, and moved to Pittsburg along with his longtime colleague Immanuel Estermann. However, they were disappointed by the poor conditions they found in Pittsburgh. Estermann wrote [11]:

> The support provided for Stern during the depression was quite meager. Stern was unable to regain the drive of the Hamburg laboratory although a number of important publications originated at the Carnegie Institute.

Six publications appeared in the 12 years until 1945 that Stern had spent in Pittsburgh but the significance of none of them would come even close to the significance of the papers produced in Frankfurt and Hamburg. In the US Stern was in great demand as a speaker. Already in 1930 he received an honorary degree from Berkeley and in 1936 he was invited to become a member of the Royal Danish Academy. On March 8, 1939 Stern became a US citizen enabling him to participate in secret military research projects. On November 9, 1944 he was informed that he would receive an unshared Nobel Prize in Physics (for the year 1943), a recognition which was long overdue.

As noted in the Introduction, Otto Stern was, with eighty one nominations for a Nobel Prize in Physics, the most nominated candidate between 1901 and 1950. Only Arnold Sommerfeld, who did not receive the Prize, had nearly as many nominations (80). Stern's nominators were James Franck, Max Planck, Albert Einstein, Niels Bohr, Max Born, Wilhelm Wien, Johannes Stark, Pierre Weiss, Max von Laue, Chandrasekhara Venkata Raman, Oscar Klein, Werner Heisenberg, Friedrich Hund, Wolfgang Pauli, Gregor Wentzel, Peter Pringsheim, Rudolf Ladenburg, Eugen Wigner, Carl David Anderson, Manne Siegbahn, Arthur Compton, Hans Bethe, and many others. In 1934 and 1940 the Nobel Prize in Physics was not awarded even though Stern had been nominated 15 and 14 times, respectively. The reason put forth by the five-member Nobel Committee behind the slow coming of the Prize for Stern was that space quantization was nothing fundamentally new since it had been predicted by Sommerfeld already in 1916. Moreover, Stern's value for the magnetic moment of the proton of 2.5 disagreed with other published results. Dirac's rudimentary theory had predicted a value of 1, Landé a value of 2 [70], and Rabi had in 1934 reported a value of $3.25\mu_N$ with a 10% error. But Stern's 1933 value had in fact come closest to the present-day accepted value. Stern's former Hamburg postdoctoral fellow and friend Isidor Rabi received the Nobel Prize for Physics for the subsequent year 1944. They must have had a happy reunion on December 10, 1944 in New York City at the Waldorf Astoria Hotel where, because of the ongoing war, the Nobel ceremony took place. The Nobel medals were bestowed on both of them and other laureates by the Swedish ambassador Eric Boström. In his 1946 Nobel Lecture, Stern extolled the molecular beam method [71]:

> 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.

Interestingly, Stern himself had submitted only two Nobel nominations (up until 1950) [1]: in 1933 of Gilbert N. Lewis (unsuccessful) and in 1949 of Hideki Yukawa (successful).

In 1945–1946 Stern retired from the Carnegie Institute and moved to Berkeley where some of his close relatives lived. The bachelor Otto Stern bought a house on Cragmont Avenue with a nice view of the San Francisco Bay. There he planned to live with his unmarried younger sister Elise, but she died unexpectedly in 1945. His elder sister Berta lived there as well, with her husband Walter Joseph Kamm and their children. As Emilio Segré reports in his brief biographical article [72], Stern was a frequent visitor in the colloquia and seminars given at the University of California at Berkeley.

After the war Stern generously helped many of his friends with CARE packages. He supported von Laue even with clothing, since von Laue had lost his property when his house was bombed during the war. Their rich correspondence revolved about everyday issues as well as bigger themes, such as Stern's relation to his former homeland. In a letter from October 1, 1947, von Laue pointed out that:

> We all must throw our resentments [about the wrongs suffered during the Nazi era – however understandable] overboard, if human kind should be saved from going under.

As implied by his correspondence with Lise Meitner, Max von Laue and Hans Jensen, Stern would not miss an opportunity to visit Europe – to see his friends at conferences and meetings, in particular in Copenhagen, London, and foremost in Zurich. Stern would visit Zurich almost every year for a period of several months and usually stay in pension *Tiefenau* at *Steinwiesenstrasse* 8. Nearly always Stern would cross the ocean by ship. When he arrived by ship in England or The Netherlands he would on occasion pass through Germany en route to Zurich. Despite being deeply rooted in German culture, Stern took pains to meet his German friends outside of Germany. He invited several of them at his own expense on holidays in Zurich, but he never again "officially" visited Germany. In the 1950s, on his only private trip to Germany, he visited his friend Max Volmer in East Berlin in the GDR. After the war he turned down the offer by the city of Hamburg to pay him his life annuity and never accepted the offers by von Laue and others to become a member of the Academy of Sciences in Göttingen. Stern's last trip to Germany was in the summer of 1968, when he attended the annual Nobel Laureate meeting in Lindau. On August 17, 1969, he suffered a heart attack while in a cinema in Berkeley and died a few days later in a hospital. According to Peter Toschek's article [44], Stern once remarked during his Hamburg golden years that

> it would be nice to die while watching a good movie. Whether the movie was good or not has not been passed on.

Stern's ashes are buried at the "Sunset View Cemetery" in El Ceritto near Berkeley.

Otto Stern was known for his kind and gentlemanly personality. Rabi wrote in his obituary for Stern [73]:

> Stern was one of the antistuffy generation of German professors who observed with a mixture of amusement and contempt the pomposity of their predecessors.

Or, as a US newspaper put it [74]:

> Looks – the jovial type, fine smile, personality and temperament. He has the best traits of the European gentleman.

Gerlach survived Otto Stern by nearly 10 years. When Stern died, Gerlach wrote in the *Physikalische Blätter* [21]:

> Those of us who knew Stern valued his openness – he was a Grand seigneur! – his absolute reliability, his often spontaneous but not always conciliatory (*einfach*) but fruitful discussions and for those, who had a sense for such, his even sarcastic but always well considered judgment about objects and persons. He deplored arrogance and bad manners. Although trained as a theoretician he was full of ideas for experiments, never at a loss for a new suggestion when the first attempt failed.

The German Physical Society honored Otto Stern's and Walther Gerlach's legacy in 1992 by establishing in parallel to the existing Max Planck Medal for excellence in theory a new distinction, "The Stern-Gerlach Medal", for excellence in experimental physics. Recently, the first monograph on Otto Stern's life and work has come out [75].

Acknowledgements We are grateful to the Stern family (Liselotte and David Templeton as well as Diana Templeton-Killen and Alan Templeton) for their private communications as well as for providing invaluable documents and photographs. We gratefully acknowledge the help we received from the archives in Berkeley (Bancroft library, David Farrel), in Frankfurt (Goethe Universität Frankfurt, Wolfgang Trageser and Michael Maaser) and in Stockholm (Nobel archive, Karl Grandin). Additional help was generously provided by the Institut für Physikalische Chemie of the Universität Hamburg (Horst Förster und Fritz Thieme) as well as by Karin Reich (Universität Hamburg), Bruno Lüthi (Goethe Universität Frankfurt and ETH Zürich), Sascha Warnecke (Universität Göttingen) and Joshua Jortner (University of Tel Aviv). We also thank our Hamburg colleagues Volkmar Vill and Peter Toschek for helpful correspondence. Last but not least, we are grateful to Dudley Herschbach (Harvard University and Texas A&M University) for his invaluable comments on the manuscript.

References

[1] Center for History of Science, The Royal Swedish Academy of Sciences, Box 50005, SE-104 05 Stockholm, Sweden, http://www.center.kva.se/engelska/index.htm.
[2] A. Sommerfeld, Phys. Z. **17**, 491 (1916).
[3] P. Debye, Phys. Z. **17**, 507 (1916).
[4] D. Herschbach, Ann. Phys. (Berlin) **10**, 161 (2001).
[5] Z. Phys. D **10**, 109–392 (1988).
[6] Interview of Otto Stern by Res Jost, 1961: tape recording, ETH-Bibliothek Zürich, Bildarchiv, (Sign.: D 83:1-2); also available as transcript, ETH-Bibliothek Zürich, Archive, (Sign.: Hs 1008:8) http://www.sr.ethbib.ethz.ch/ (ETH Zürich, Zürich, 1961).
[7] A. Einstein and O. Stern, Ann. Phys. (Berlin) **40**, 551 (1914).
[8] Otto Stern family, Diana Templeton-Killen, Stanford and Alan Templeton, Oakland/CA.
[9] Dossier on Otto Stern, ETH-Bibliothek Zürich, Archive, (Sign.: SR 3, 1913, Nr. 677); also available in the manuscript archives, ETH-Bibliothek Zürich, Archive, (Sign.: Hs 1008: 1-7) http://www.sr.ethbib.ethz.ch/.
[10] F. Hund, Geschichte der Quantentheorie (Bibliographisches Institut Mannheim, Mannheim, 1975) p. 74.
[11] I. Estermann, Biographie Otto Stern in: Physiker und Astronomen in Frankfurt, edited by K. Bethge und H. Klein, (Metzner, Neuwied, 1989) p. 46–52, http://www.uni-frankfurt.de/fb/fb13/Dateien/paf/paf46.html.
[12] The Bancroft Library (University of California, Berkeley CA 94720); David Farrell, University Archivist Curator, History of Science and Technology Program, dfarrell@library.berkeley.edu.
[13] O. Stern and M. Volmer, Phys. Z. **20**, 183–188 (1919).
[14] Archiv der Universität Frankfurt, Personalakte Otto Stern, Max Born, and Max von Laue (Johann Wolfgang Goethe-Universität, Frankfurt am Main) Dr. M. Maaser, Maaser@em.uni-frankfurt.de.

[15] M. Born, My Life: Recollections of a Nobel Laureate (Charles Scribner's Sons, New York, 1978), p. 190.

[16] Interview with M. Born by P.P. Ewald at Born's home (Bad Pyrmont, West Germany) June 1, 1960, session III. Niels Bohr Library & Archives (American Institute of Physics, College Park, MD USA) www.aip.org/history/ohilist/4522_1.html.

[17] L. Dunoyer, Le Radium **8**, 142, 1911.

[18] O. Stern, Phys. Z. **21**, 582 (1920).

[19] O. Stern, Z. Phys. **2**, 49 (1920); Z. Physik **2**, 417 (1920).

[20] B. Friedrich and D. Herschbach, Phys. Today **56**, 53 (2003).

[21] W. Gerlach, Phys. Blätter **25**, 412 (1969);
W. Gerlach, Phys. Blätter **25**, 472 (1969).

[22] O. Stern, Z. Physik **7**, 249 (1921).

[23] In his Zurich interview, Stern describes the beneficial effects of a wooden hammer that he kept in his laboratory and used to threaten the experimental apparatus with if it did not behave.

[24] B. Friedrich and D. Herschbach, Daedalus **127**, 165 (1998).

[25] W. Gerlach and O. Stern, Ann. Phys. (Berlin) **74**, 673 (1924).

[26] About the ways and means of developing the spot, see [20].

[27] W. Gerlach and O. Stern, Z. Phys. **8**, 110–111 (1922).

[28] W. Schütz, Phys. Blätter **25**, 343 (1969).

[29] H. Zankl, Deutscher Wetterdienst, Offenbach am Main (private Mitteilung), www.dwd.de.

[30] W. Gerlach and O. Stern, Z. Phys. **9**, 349–352 (1922).

[31] A. Einstein and P. Ehrenfest, Z. Phys. **11**, 31 (1922).

[32] B. Friedrich and D. Herschbach, in: Sternstunden – Höhepunkte Frankfurter Physik, edited by W. Trageser (Johann-Wolfgang-Goethe-Universität Frankfurt, 2005) p. 153–156.

[33] A. Landé, Z. Phys. **5**, 231 (1921); Z. Phys. **7**, 398 (1921).

[34] http://de.wikipedia.org/wiki/Ralph_Kronig as accessed on November 4, 2011.

[35] G. E. Uhlenbeck and S. A. Goudsmit, Naturwissenschaften **47**, 953 (1925).

[36] A. Herman and K. von Meyenn, Wolfgang Pauli, Scientific Correspondence, Vol. I: 1919–1929 edited by A. Herman and K. von Meyenn (Springer, New York, 1979) p. iv.

[37] F. Hund, Geschichte der Quantentheorie (Wissenschaftsverlag, Mannheim, 1975) p. 108 ff.

[38] L. H. Thomas, Nature **117**, 514–515 (1926).

[39] A. H. Compton, J. Franklin Inst. **192**, 145–155 (1921).

[40] R. G. J. Fraser, Molecular Beams (Methuen, London, 1937) p. 33. In his article in Proc. R. Soc. Lond. A **114**, 212 (1927), Fraser pointed out that the magnetism of ^{2}S atoms (such as silver) is due to electron spin.

[41] W. Gerlach und O. Stern, Z. Phys. **9**, 353–355 (1922).

[42] O. Stern, Z. Phys. **39**, 751 (1926).

[43] F. Knauer and O. Stern, Z. Phys. **39**, 764 (1926).

[44] P. E. Toschek, Otto Stern (1888–1969) in Hamburg, in: Hamburgs Geschichte einmal anders. Entwicklung der Naturwissenschaften, Medizin und Technik, edited by G. Wolfschmidt. Nuncius Hamburgensis: Beiträge zur Geschichte der Naturwissenschaften, Band 2 (Norderstedt, 2006).

[45] Staatsarchiv Hamburg, Kattunbleiche 19, 22041 Hamburg; Personalakte Otto Stern, http://www.hamburg.de-/staatsarchiv/ Bestand Hochschulwesen Dozenten- und Personalakten (361-6, Sign.: I 0080).

[46] H. Förster, STERN-Jahre der Physikalischen Chemie (Universität Hamburg, Hamburg, 2008), Institut für Physikalische Chemie, Grindelallee 117, 20146 Hamburg, private communication.

[47] R. O. Frisch, What Little I Remember (Cambridge University Press, Cambridge, 1979) pp. 41–42.

[48] J. S. Rigden, I. I. Rabi as told to J. S. Rigden Z. Phys. D **10**, 119–120 (1988).

[49] Institut für Physikalische Chemie (Universität Hamburg, Hamburg, 2011) http://www.chemie.uni-hamburg.de/pc/publikationen/Dissertationen.html.

[50] Interview with Dr. I. I. Rabi by Th. S. Kuhn at his New York home, December 8, 1963 Niels Bohr Library and Archives, (APS, College Park, MD, USA) www.aip.org/history/ohilist/4836.html.

[51] E. Segré, A Mind Always in Motion, The Autobiography of Emilio Segré (University of California Press, Berkeley, 1993) p. 70.

[52] F. Knauer and O. Stern, Z. Phys. **53**, 779 (1929).

[53] O. Stern, Naturwissenschaften **17**, 391 (1929).

[54] I. Estermann and O. Stern, Z. Phys. **61**, 95 (1930).
[55] I. Estermann, R. Frisch, and O. Stern, Z. Phys. **73**, 348 (1931).
[56] R. Frisch and O. Stern, Z. Phys. **84**, 430 (1933).
[57] R. Frisch, Z. Phys. **84**, 443 (1933).
[58] A. F. Devonshire, Proc. R. Soc. Lond. A **156**, 37 (1936);
J. E. Lennard-Jones and A. F. Devonshire, Proc. R. Soc. Lond. A **158**, 242 (1937).
[59] F. Knauer, Z. Phys. **80**, 80 (1933).
[60] I. Estermann, Am. J. Phys. **43**, 661 (1975).
[61] R. Frisch and O. Stern, Z. Phys. **85**, 4 (1933).
[62] I. Estermann and O. Stern, Z. Phys. **85**, 17 (1933).
[63] J. H. van der Waals, Encyclopedia of Nuclear Magnetic Resonance, edited by D.M. Grant and R.K. Harris, Vol. 1 (Wiley, New York, 1996).
[64] I. I. Rabi, S. Millman, P. Kusch, and J. R. Zacharias, Phys. Rev. **55**, 526 (1939).
[65] J. James, T. Steinhauser, D. Hoffmann, and B. Friedrich, One Hundred Years at the Intersection of Chemistry and Physics (De Gruyter, Berlin, 2011).
[66] R. Frisch, Z. Phys. **86**, 42 (1933).
[67] Both Friedrich Knauer (1897–1979) and Walther Gerlach (1889–1979) were involved in the German uranium project during the Third Reich, the latter in the capacity of its head.
[68] H. Kopfermann, Kernmomente (Akademische Verlagsgesellschaft, Leipzig, 1940).
[69] M. Chayut, Hist. Stud. Phys. Biol. Sci. **24**, 237–263 (1994).
[70] A. Landé, Phys. Rev. **44**, 1028 (1933).
[71] O. Stern, Nobel Lectures, Physics 1942–1962 (Elsevier Publishing Company, Amsterdam, 1964).
[72] E. Segré, Biogr. Mem. Natl. Acad. Sci. **43**, 215 (1973).
[73] I. I. Rabi, Phys. Today **103**, 105 (1969).
[74] W. J. Walter, in: Hochschulalltag im “Dritten Reich”. Die Hamburger Universität 1933–1945, edited by E. Krause, L. Huber, and H. Fischer (D. Reimer Verlag, Hamburg, 1991).
[75] H. Schmidt-Böcking und K. Reich, Otto Stern – Physiker, Querdenker, Nobelpreisträger, Herausgeber: Goethe-Universität Frankfurt, Reihe: Gründer, Gönner und Gelehrte (Societätsverlag, Frankfurt, 2011).