Walther Gerlach's Rise to Olympus (1914-1929): From Service in World War One to a Professorship at Munich

Bretislav Friedrich*,†

Fritz-Haber-Institut der Max-Planck-Gesellschaft,
Faradayweg 4-6, D-14195 Berlin, Germany

April 21, 2024

1 Introduction

By the time he earned his PhD in Friedrich Paschen's Tübingen laboratory in 1912 at age 23, Walther Gerlach was a major player in the research area of black-body radiation. The attitude to research that Paschen sought to instill in Gerlach is aptly characterized by the following reminiscence of Gerlach's (Gerlach, 1963a, p. 11):

> Dr. Gerlach, denken Sie nicht, messen Sie!

Gerlach would pursue a related topic, that of light pressure, after an interruption due to World War One and his crucial involvement in the epochal Stern-Gerlach experiment during his time in Frankfurt (1920-1925).

*Email: bretislav.friedrich@fhi-berlin.mpg.de
†Website: https://www.fhi.mpg.de/209437/Friedrich

In 1926, Gerlach received a call from Tübingen to assume the chair of his mentor and launched a research program focused on spectroscopy and magnetism. In 1929, Gerlach moved on to Munich as the successor of Wilhelm Wien (1864-1928), thereby receiving the accolade due to a leading experimental physicist. Gerlach's tenure at Munich – the Olympus of Physics in Germany at the time – lasted until his retirement in 1957. It would only be interrupted by his detention at Farm Hall (1945-1946) and a stint at the University of Bonn (1946-1948).

Gerlach was co-nominated, with Otto Stern, thirty-one times for the Nobel Prize in Physics for the Stern-Gerlach experiment (Huber et al., 2021), p. 122. In the documents and reports of the Nobel Archives there is no indication as to why Gerlach was left out. The reason may have been Gerlach's high-level involvement in the Nazi research establishment, especially in the management of the nuclear program, see Chapter Y. Gerlach's contributions to the fields of black body radiation, light pressure, magnetism, and spectroscopy were no less demanding but remain much less known. In this chapter, we revisit Gerlach's seminal works from the period 1919-1929 – apart from the Stern-Gerlach experiment, which is covered in Chapter X of this volume.

2 World War One and a stint at the *Farbenfabriken* Elberfeld (1914-1920)

After the outbreak of World War One, Gerlach worked in the X-ray laboratory of the gynecological clinic at the University of Tübingen, whose director was a close friend. There he developed an astonishingly simple X-ray device for locating projectiles and metal splinters in soldiers' bodies that was, moreover, well suited for the rough field conditions.

On 24 August 1915, Gerlach was drafted into military service in Ulm as a *Land-*

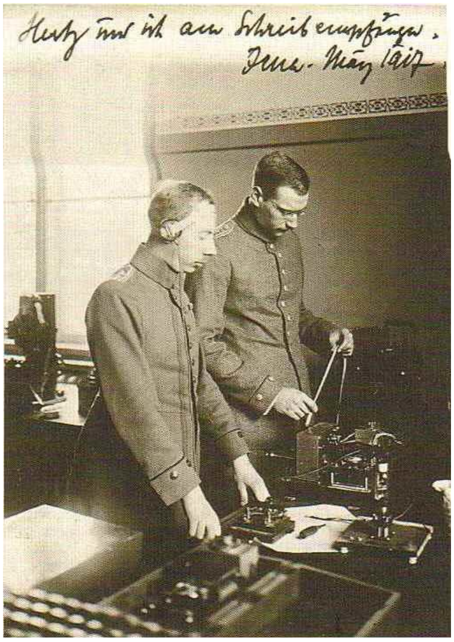


Figure 1: Walther Gerlach with Gustav Hertz (left) working at *Tafunk* in Jena, Mai 1917. The hand-written note by Gerlach reads: “Hertz und ich am Schreibemfänger [Hertz and I at the telegraph], Jena-May 1917.” From J.G. Huber.

Figure 2: Richard Wachsmuth, the founding rector of the Königliche Universität zu Frankfurt am Main, established in 1914, and head of its Institute of Experimental Physics. Archive of the University of Frankfurt.

sturm recruit,[1] but released again in December because of rheumatoid arthritis. In May 1916 he was called up again, this time to *Technische Abteilung der Funkertruppen*, abbreviated as *Tafunk*, with which he stayed until the end of the war. Its head was Max Wien, Willy Wien's cousin. The task of Gerlach's department was to develop and test radio equipment based on the new technology of tube amplifiers. His stay at *Tafunk* was interrupted twice by illness (appendicitis and the "Spanish flu"). While on sick leave in May 1916, he completed his *Habilitationsschrift* and submitted it to the Tübingen Faculty on 22 July 1916.

In the Fall of 1916 he took part in the fighting of the VIth Army in Flanders and Artois and directly experienced the horrors of war. After a dispute with Paschen, who wanted his assistant back at his institute in Tübingen, Gerlach did an *Umhabilitation*,

[1] Infanterieregiment 247

in 1917, in Göttingen. He continued his scientific work and even managed to publish several papers based on his previous research. Most importantly, at *Tafunk* Gerlach met other physicists, among them Max Born (1882-1970), James Franck (1882-1964), Wilhelm Westphal (1882-1978), but also Richard W. Pohl (1884-1976) and Peter Debye (1884-1966), who helped with his move to Göttingen. He also worked for an extended period with Gustav Hertz (1887-1975), Fig. 1, Heinrich Hertz's nephew. Gustav Hertz would become the co-recipient of the 1925 Nobel Prize in Physics together with James Franck. This is how Gerlach reminisced about his time at Tafunk (Gerlach, 1972a):

> Max Wien, damals der Leiter der technischen Abteilung der Funkinspektion Berlin, hatte uns das herrenlose Institut von [Max] Volmer übergeben. ... Wir erfanden u.[nter] a.[nderem] Schaltungen zur Entstörung der kilometrlangen zum Landgrafen hinaufführenden Antenne und untersuchten die elektrischen Verluste des Schottscgen Minoglases mit einer thermischen Methode, die zur Vorstellung des 'Wärmedurchschlags' von Kondensatoren führten. ... Manchmal kochten wir, und wenn die Erbsen wegen eines zu langen Versuchs anbrannten, machten wir daraus Kaffee.

From September 1917 to March 1918, Gerlach was on an inspection tour in Belgium and northern France. Upon his return, he married Wilhelmine Mezger and in 1918 their daughter Ursula was born. On January 27, 1919, he was released from the military where he held the position of chief engineer.

In order to be able to feed his family, Gerlach opted for industrial rather than academic employment (Gerlach, 1963a, p. 8) :

> Ich war Privatdozent in Göttingen damals. Aber ich hatte kein Geld und habe damals so immer zum Staat gesagt: 'Gott ich hab' nun ziemlich viel Physik gelernt, also um hungern zu müssen, dazu kann ich zu-viel. So gehe ich eben in die Industrie und verkauf' das.

Shortly after his demobilization, Gerlach landed an industrial research position as head of the Physics Laboratory of the paint factory *Farbenfabriken vorm. [vormals] Friedrich Bayer & Co.* Elberfeld.[2] The Elberfeld laboratory was quite well-equipped, and Gerlach opened the door of its storeroom to his colleagues in need, among them James Franck and Robert Pohl, and handed out equipment and supplies to them.

However, Gerlach soon realized that industrial research was not his cup of tea and returned to academia once the University of Frankfurt offered him a position.

3 Frankfurt (1920-1924)

As of 1 October 1920, Gerlach became the first assistant to the director of Frankfurt's Institute of Experimental Physics, Richard Wachsmuth (1868-1941), Fig. 2, with the prospect of promotion to *Extraordinarius*, a remunerated teaching position. However, this would not materialize for another year, during which Gerlach was paid from the royalties of a patent awarded to Farbenfabriken Elberfeld for a high-frequency generator that Gerlach had designed.[3] Frankfurt was thus the first station on Gerlach's academic path at which he had his own position. Three more would follow.

Max Born at the adjacent Institute of Theoretical Physics welcomed Gerlach's arrival at Frankfurt with the words (Gerlach, 1963a, p. 3):

> Na, Gottseidank, jetzt kriegen wir einen, der was vom Experimentieren versteht, los, Mensch, helfen Sie hier mal.

Gerlach's time at Paschen's institute in Tübingen proved formative for both his personality and his experimental abilities. Either became a key prerequisite for the success of the Stern-Gerlach experiment and other precision measurements where Gerlach pushed the limits of the possible. Gerlach provided the following definition of a 'precision measurement' in his first book, written in Frankfurt (Gerlach, 1921):

[2] Today, Elberfeld is a district of the city of Wuppertal.

[3] The royalties would, in fact, flow in for an additional three years.

> Unter 'Präzisionsmessung' verstehen wir aber eine Untersuchung, in der alle Fehlerquellen berücksichtigt und alle beobachteten Erscheinungen aufgeklärt sind: Es gehört auch dazu, dass in einer Beschreibung der Messung jede einzelne Maßnahme theoretisch und zahlenmäßig begründet, ihr Einfluß auf den Gang der Versuche durch Abänderungen derselben klargestellt und ausführlich dargestellt ist; kurz, der Leser muß sich aus der Beschreibung der Versuche ein Urteil über die Beweiskräftigkeit und die Sicherheit der Ergebnisse bilden können.

What Gerlach meant was best exemplified by his own work, which became a standard of precision physics.

3.1 Walther Gerlach and the Stern-Gerlach Experiment

A detailed account of the purpose, outcome, and significance of the Stern-Gerlach experiment (SGE) can be found in Chapter X of this volume. Herein we only touch upon Gerlach's contribution to the realization of the SGE. In Sec. 3.2, we glean what the relationship between Stern and Gerlach was like from their mutual correspondence as well as from their correspondence with others.

The Frankfurt University recognized Gerlach's *Habilitation* and, in addition, promoted him as of 1 November 1921 to the rank of *Extraordinarius*. Max Born's Institute of Theoretical Physics was a more congenial environment for the curious and enterprising Gerlach than Wachsmuth's Institute of Experimental Physics. All the more so that Born, with his assistants Otto Stern, Elisabeth Bormann, and Alfred Landé, was engaged in experiments as much as in theory and encouraged Gerlach to partake in their discussions as well as to give them a hand with their experiments. Born would even publish with Gerlach – on electron affinity (Gerlach and Born, 1921a) and on light scattering (Gerlach and Born, 1921b). However, Gerlach would also pursue his own agenda: it was at Frankfurt that he launched his investigations of the magnetic properties of materials that would bring him together with Stern and later take center stage in his research at Frankfurt and his subsequent stations. In particular, Gerlach was interested in the relationship between magnetization and structure (Bachmann and Rechenberg, 1989, p. 10). In connection with his investigation at Elberfeld of the magnetic properties of a bismuth alloy, the question arose as to whether atomic bismuth was para- or diamagnetic. At Wachsmuth's Institute, Gerlach set out to answer this question in a molecular beam experiment, in which the deflection of a beam of bismuth atoms by an inhomogeneous magnetic field would be examined (Mehra and Rechenberg, 1982, p. 436). Born tried to dissuade Gerlach from what seemed to be a hopelessly difficult undertaking. Whereupon Gerlach invoked a quip he heard from Edgar Meyer (1879-1960), his professor of theoretical physics at Tübingen: "No experiment is so dumb that it should not be tried" (Estermann, 1975) and continued setting up his bismuth beam experiment and thus collecting experience in much of what was needed for the SGE. We note that Gerlach set up a sodium atom beam already in Paschen's laboratory in Tübingen – to examine optical absorption (Gerlach, 1963a, p. 3). To his time in Paschen's Tübingen laboratory Gerlach also owed his positive attitude toward Bohr's model of the atom – unlike Otto Stern who sought to prove it wrong (Hund, 1975, p. 74). In his interview with Thomas Kuhn, Gerlach paraphrased Paschen as saying (Gerlach, 1963a, p. 11):

> Doktor Gerlach, in diesem Phil[osophical] Mag[azine] Heft ist eine Arbeit [Bohr's Model of the Atom] von einem gewissen Dr. Bohr, die müssen Sie lesen, das ist die Physik der nächsten dreissig Jahre.

In a continuation of the interview, Gerlach lightens things up and notes (Gerlach, 1963b, p. 14):

> Man machte damals solche Modelle,[4] auch nachher noch in Göttingen,

[4][M]ein Modell war die Rolle Closetpapier. Die ist ... ihrem Bau nach ... in Quanten unterteilt. Wenn man daran zieht gibt es eine kontuierliche Strahlung. Wenn man aber die selbe Energie ... stoßweise zuführt, dann gibt es Quantenarten. ... [man] kriegt die Strahlung ohne Ionisation ... ich muß nur langsam ziehen ...

perhaps in 1920, [19]21.

Let us add that Edgar Meyer, Fig. 4, with whom Gerlach had worked on the photo-effect, contested the separation of physics into theoretical and experimental. Max Born was apparently of the same persuasion in this respect. In February 1921, he reported to Einstein (Born, 1969, p. 82):

> Wir haben jetzt den Gerlach hier, der sehr famos ist: energisch, kenntnisreich, geschickt, hilfsbereit. Er hat jetzt ein Angebot der Regierung von Chile, dort (in Santiago) die Physik und Elektrotechnik zu übernehmen; ob das vernünftig ist? Ich glaube, er hat auch hier gute Aussichten, aber er ist ein unternehmender Kerl und für einen solchen Außenposten sehr geeignet.

After the completion of the Stern-Gerlach experiment, Stern and Gerlach continued searching – both in Rostock (where Otto Stern moved in October 1921) and in Frankfurt – for magnetic birefringence that was expected to be a natural manifestation of space quantization of the *orbital* electronic angular momentum within the Bohr-Sommerfeld-Debye model of the atom. But none could be found. Gerlach (Gerlach, 1963a, p. 14):

> Wir haben uns damals ziemlich abgequält damit.

3.2 Personal chemistry between Stern and Gerlach

The personalities of Stern and Gerlach were quite different: while Gerlach enjoyed being in the driver's seat, Stern preferred the back seat. Only few letters exchanged between them have been preserved. The following one, from 16 January1924, concerns the last (Gerlach and Stern, 1924) of their four joint publications, all of which dealt with the SGE (Schmidt-Böcking, 2019, p. 125):

> Lieber Gerlach, besten Dank für Ihre Nachrichten. Ich dachte unsere Arbeit wäre längst bei den *Annalen* [der Physik]. Jedenfalls stimme ich

unbedingt für die *Annalen*, Sie ja in Wirklichkeit auch, so 'n langer Seich ist doch nichts für Z.f.Ph. [Zeitschrift für Physik]. Ich konnte in der Woche nicht[s] herein, nicht nach Frkft [Frankfurt], weil ich nach Breslau mußte, und beides war mir doch etwas zu reichlich. Für die Mol.str. [Molekularstrahlen] erfinde ich immer genialere Apparate und sie gehen immer schlechter, z.K. [zum Kotzen]! Dagegen funktionieren die elektr. [elektrischen] Mol.str. ganz leidlich. Es geht alles nur so furchtbar langsam! Wie ich höre, hat Schaefer einen Ruf nach Freiburg. Da muß er unbedingt hin! Herzliche Grüße an alle Freunde, Ihre Familie und Sie selbst.

> Ihr Otto Stern.

When Gerlach succeeded Paschen at Tübingen, Stern sent him, on 16 November 1925, the following telegram (Schmidt-Böcking, 2019, p. 125):

> = dem grossbonzenund frau gratuliert herzlichst Stern +

Whereupon Gerlach replied (Schmidt-Böcking, 2019, p. 126):

> Lieber Stern, es ist Sonntag der 22. II. und ich kriege eben Ihr Telegramm. Als ich obiges anfing zu schreiben, kamen die Möbelwagen und ich ließ alles liegen. Bitte seien Sie nicht böse, ich hatte [unleserlich] die Notiz direkt an Sch. gesandt, sondern erst später. Also ich fange zu raunzen an und hoffe, dass meine Frau mich einen Moment einmal nicht ruft. Herr S.[5] hat unter obiger Überschrift Ausführungen über die Auswertung unserer Magnetonversuche gemacht die – wie wir durch mehrfache Anfragen merkten, die Meinung aufkommen lassen, dass unsere Berechnung zu 100% falsch sein könne; nur dass ferner die bei der Auswertung vorhandenen Fehlerquellen [faktischen Unsicherheiten] nicht berücksichtigt worden sind, dass uns speziell der Einfluss der Spaltbreite entgangen wäre. Wenn

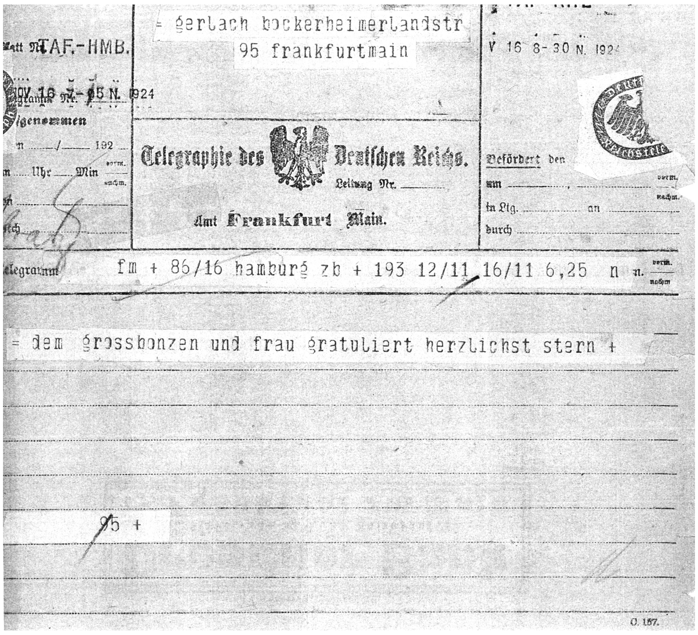
[5] Mr. S. was Nikolay Nikolayevich Semyonov (1896-1986). In 1956, he was awarded the Nobel Prize in Chemistry for his research "into the mechanism of chemical reactions."

auch die Überlegungen von Herrn S. richtig sind, so ist die Auffassung der Notiz in der Tat geeignet, die oben erwähnten Missverständnisse hervorzurufen. Herr S. spricht nämlich immer vom Abstand der Stelle maximaler Intensität im abgelenkten Streifen von dem Ort des [unleserlich] schmal angenommenen unabgelenkten Streifens, für welchen Fall in der Tat die von uns benutzte Formel fast 100% Fehler geben würde. Nun beziehen sich unsere Messungen aber stets auf die Mitte des abgelenkten Streifens, was Herr S. erst gegen Schluss seiner Arbeit diskutiert; für diesen Fall rechnet aber Herr S. selbst ungünstigenfalls eine Abweichung an 20% aus. Ferner scheint Herr S. anzunehmen, dass uns der Einfluss der Spaltweite nicht bekannt gewesen ist. Wir haben an der betr. [betreffenden] Stelle verwiesen auf die Arbeit von Stern, wo der Einfluss der Spaltweite diskutiert ist und die betr. Formeln – entsprechend den Formeln von Sommerfeld – für den Fall der Corioliskraft bereits abgeleitet sind, worüber sich Herr S. beim Nachschlagen der Literatur leicht hätte orientieren können. Wir haben uns damals mit diesem Hinweis begnügt, nur in Anbetracht der Einstellung, welche durch die Entwicklung die Intensitätsverteilung erfährt, einen Fehler der Grössenordnung von 10% als möglich angegeben. Wir wiederholen, dass Herr S.'s Notiz gar keine neuen Gedanken bringt, dass ihr Inhalt sich vielmehr vollkommen mit unserer Darstellung deckt. Wir legen nur gegen die Art seines Angriffs Verwahrung ein.

—

Lieber Stern, wie geht es Ihnen gesundheitlich? Es war zu schade, dass Sie in Göttingen nicht wohl waren. Hier ist eben ein fürchterliches Durcheinander. Hoffentlich komme ich bald zur Ruhe. Ich schreibe Ihnen dann auch über die Atomstrahlversuche. Bitte veröffentlichen Sie oder Estermann doch endlich mal etwas! Herzl. Grüsse auch von meiner Frau

Ihr W. Gerlach


Telegraphie des Deutschen Reichs.

Amt Frankfurt Main.

= gerlach bockerheimerlandstr
95 frankfurtmain

fm + 86/16 hamburg zb + 193 12/11 16/11 6,25 n

= dem grossbonzen und frau gratuliert herzlichst stern +

95 +

Figure 3: Otto Stern's telegram to Walther Gerlach from 16 November 1925. Deutsches Museum München DMA 80/432 u. 80/274.

Next in the chronology of the preserved letters that bear upon the relationship between Stern and Gerlach is a note written by Stern from Zurich to Lise Meitner (1878-1968) in 1957 ():[6]

> Liebe Lise Meitner,
>
> Flugzeuge nach Innsbruck verkehren erst ab 24. Mai, Auskunft vom Flugbüro am Hauptbahnhof. Ich bitte also sehr, es bei München zu belassen. Ich kann aber nur 1-2 Tage dort sein, aus zwei Gründen: 1) Frau, resp. [respektive] Lady Simon legt großen Wert darauf, mich zu sprechen. Ich habe ihr versprochen ev. [eventuell?] nach England zu fliegen, hoffe aber, daß sie einer Einladung Weyl-Bär folgend hierher kommen wird, voraussichtlich um dieselbe Zeit, falls sie sich entschließt. Auf 1-2 Tage könnte ich aber immer weg. 2) Ich lege gar keinen Wert darauf, die[?] Münchener

[6] Transcription of Otto Stern's handwriting kindly provided by J.G. Huber.

Physiker, spez. [speziell] Gerlach, zu sehen. Das Datum unseres Rendezvous überlasse ich Ihnen vollständig, nur bitte ich um baldmöglichste Mitteilung. Es war sehr nett, Frisch wieder mal zu sehen und seine Frau kennen zu lernen; sie passen anscheinend sehr gut zueinander.

Wir beiden Alten werden eine Menge zu beschwatzen haben, und ich freue mich schon riesig, Sie wiederzusehen.

Herzlichst,

Ihr Otto Stern

Then there is a postcard to Stern penned jointly by Walther Gerlach, Otto Robert Frisch (1904-1979), Immanuel Estermann (1900-1973), William Nierenberg (1919-2020), Hans Kopfermann (1895-1963), and Peter Toschek (1933-2020) from the Brookhaven Molecular Beam Conference that was organized by Hans Kopfermann and held at Heidelberg in 1959 (Schmidt-Böcking, 2019, p. 245):

Lichtstrahlen sind zum Brechen, Atomstrahlen Z K! [zum Kotzen][7] Zu schade, dass Sie hier fehlen, aber wir denken herzlich an Sie! Ihr Walther Gerlach

Hier habe ich erstaunlicher Weise zum ersten Mal Herrn Gerlach kennen gelernt. Aber die Molekularstrahlen sind furchtbar kompliziert geworden!
Mit herzlichem Gruss

Ihr OR Frisch

Herzliche Grüsse Ihr Estermann

Best regards will see you soon! Nierenberg

[7] This was an affectionate "secret code" between Stern and Gerlach from their Frankfurt time expressing their occasional disgust with their difficult atomic/molecular beam experiments. Gerlach gave an ashtray to Stern with this secret code engraved in it as a farewell present from Frankfurt. Stern would keep it for the rest of his life.

Figure 4: Otto Stern (left), Edgar Meyer (3rd from left), Walther Gerlach (4th from left) in Tübingen in about 1926. Otto Stern Collection, Berkeley.

> Wir haben sehr bedauert, Sie nicht hier zu haben. Ihr Hans Kopfermann
>
> Herzl. Grüße Ihr P. Toschek

It can be gleaned from many letters held at Otto Stern's Estate (Schmidt-Böcking, 2019) that he had quite a friendly relationship with all his correspondents. The above-quoted letter to Lise Meitner from 22 April 1957 suggests that Stern's feelings towards Gerlach were/became less than cordial, at least at the time. Conversely, Walther Gerlach wrote and spoke about Stern with the highest respect and much affection. This transpires in particular in the obituary of Stern that Gerlach wrote for the *Physikalische Blätter* (Gerlach, 1969):

> Wer ihn kannte, schätzte seine Aufgeschlossenheit – er war ein Grandseigneur! –, seine unbedingte Zuverlässigkeit, die bei seiner schnellen Reaktion oft nicht einfachen, aber fruchtbaren Diskussionen und – wer

> Sinn dafür hatte – seine bis zum Sarkastischen gehenden, stets überlegten Urteile über Sachen und Personen; bonzenhaftes, aber auch schlechtes Benehmen waren ihm zuwider. Obwohl von Haus aus Theoretiker, war *Stern* voll von experimentellen Ideen, nie verlegen um einen neuen Vorschlag, wenn die Durchführung des ersten misslang. Beim Abschied von Frankfurt schenkte ich ihm in Erinnerung an die Monate des fast hoffnungslosen Bemühens um die Richtungsquantelungs-Versuche einen Aschenbecher mit der Inschrift "Lichtstrahlen sind zu brechen, Atomstrahlen sind zum K...;" dieser hat die Jahre bis Berkeley überdauert – unsere Verschsapparate, Protokolle und die Originale der Ergebnisse verbrannten im Zweiten Weltkrieg.

A special tribute to the *"Stern-Stunden"* in Frankfurt and their importance for the development of quantum physics was given by Walther Gerlach in his lecture on 2 March 1960 – still during Stern's life – at the *Physikalischer Verein Frankfurt* (Gerlach, 1960):

> Um 1910 hatte der französische Physiker DUNOYER die Methode der sogenannten Atom- oder Molekularstrahlen entwickelt. Darunter versteht man Atome, welche etwa aus einem geheizten Dampfraum durch eine sehr kleine Öffnung geradlinig in einen hochevakuierten Raum fliegen. Hier im Institut haben Max Born, Elisabeth Bormann und vor allen Dingen Otto Stern 1920 diese Idee [der Molekularstrahlen] aufgegriffen und die Methode der Atomstrahlen experimentell entwickelt. Das war damals ein Wagnis, denn die Mittel zur Herstellung eines sehr hohen Vakuums waren noch äußerst beschränkt. Immerhin gelang es, alle diese Größen unmittelbar zu messen. Stern gelang die Messung der mittleren Geschwindigkeit der Atome, Born und Bormann maßen die freie Weglänge, und in späteren Jahren gelang es Stern auch, die Geschwindigkeitsverteilung in einem Atomstrahl zu messen. [...] Schließlich gelang Stern auch der Nachweis, daß ein freifliegendes Atom eine Fallparabel beschreibt, wie jede horizon-

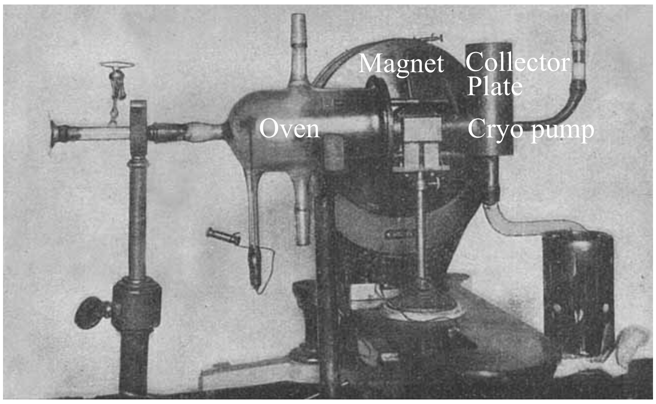


Figure 5: Photograph of the Stern-Gerlach apparatus with improvements of 1922-1924 (4th generation). Adapted from (Gerlach, 1925a).

> tal abgeschossene Kugel. Es gelang weiter in diesem Institut mit Hilfe der Atomstrahlen die sogenannte Richtungsquantelung nachzuweisen, der erste Versuch, in dem ein durch die Quantentheorie gegebener Zustand des Atoms unmittelbar der Messung zugänglich wurde.

3.3 Gerlach's post-Stern-Gerlach experiment explorations of magnetic moments of atoms and molecules

The Stern-Gerlach apparatus evolved over three generations of improvements before the SGE came to a successful conclusion. These entailed different designs of the oven as well as implementations of the magnetic field, the collimation elements, and the handling of the vacuum. FIG. 5 shows a photo of the 4th generation apparatus that Gerlach built for his later (1924-1925) investigations of the magnetic properties of atoms (no photographs of the earlier versions of the apparatus as a whole are available). We note that in all generations of the apparatus, the magnetic field and its gradient were oriented horizontally, with the edge on the left and the furrow on the right with respect to the beam velocity, cf. FIG. 6.

Upon submitting for publication their full-length, 28-page paper on space quanti-

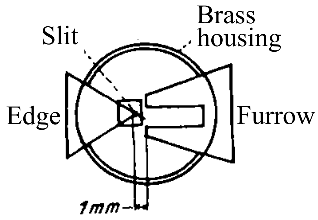


Figure 6: The center-piece of the Stern-Gerlach apparatus viewed along the direction of the silver beam. The pole pieces that generated the inhomogeneous magnetic field were placed inside a brass tube (for mechanical stability) sealed to the source chamber on one end and the detection region with the collector plate on the other. The pole pieces (edge and furrow) were energized by an external water-cooled electromagnet. The 90° edge was slightly flattened; the furrow was just 1.2 mm wide, mounted at a distance of 1 mm from the edge. Adapted from Ref. (Gerlach and Stern, 1924).

zation in the Spring of 1924 (Gerlach and Stern, 1924), Gerlach continued exploring the magnetic properties of atoms and their space quantization in an SGE-type experiment. TABLE 1 gives a summary of the atomic species investigated, their term symbols and magnetic properties as we understand them today, and Gerlach's inferences from his experimental findings presented in his 37-page 1925 paper (Gerlach, 1925a). For this exploratory study, Gerlach built a 4th-generation SGE apparatus capable of producing quality data (beam images) reliably and in half the time needed using the 3rd-generation instrument.

Perhaps the most striking result Gerlach obtained with his advanced SGE-type apparatus was the deflection pattern for a beam of nickel atoms (Gerlach, 1925a), see FIG. 7. Apart from the image of deflected atoms, Gerlach also saw undeflected atoms that had nevertheless passed through the same inhomogeneous field as the deflected ones. As the current understanding suggests, the deflected Ni(^3F) atoms were in the $M = \pm 1$ state and the undeflected ones in the $M = 0$ state. However, an open question remains: the ground state of nickel, with $S = 1$ and $L = 3$, admits $J = 4, 3, 2$ and thus $|M| = 4, 3, 2, 1, 0$. Where are the atoms with $|M| = 4, 3, 2$?

Table 1: Magnetic properties of Group 10 to 15 atoms explored by Gerlach with a 4th-generation SGE apparatus (Gerlach, 1925a). In modern notation, the ground state of each atom is characterized by the term symbol ${}^{2S+1}L_J$. Note that the maximum expected deflection is proportional to the magnetic dipole moment $\mu_Z = -Jg\mu_B$, where g is the g-factor (Herzberg, 1944; Friedrich et al., 2021; Schmidt-Böcking et al., 2022), J the total angular momentum quantum number, and μ_B the Bohr magneton. See text.

Atom	Term Symbol	Number of M states	g-factor	Maximum μ_Z/μ_B	Gerlach's inference
Fe	${}^5D_4$	9	3/2	6	Appears diamagnetic
Bi, Sb	${}^4S_{3/2}$	4	2	3	No deflection due to molecule formation?
Cu, Au	${}^2S_{1/2}$	2	2	1	"Regular" deflection
Ni	${}^3F_4$	9	5/4	5	Zero deflection for $M = 0$ and significant deflection for $M \neq 0$
Pb, Sn	${}^3P_0$	1	Undefined	0	No deflection
Tl	${}^2P_{1/2}$	2	2/3	1/3	"Tiny" deflection

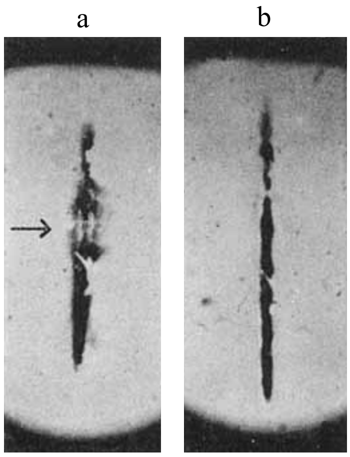


Figure 7: Images of the deflection patterns for nickel (a) in an inhomogeneous magnetic field of 200 kG/cm and (b) without a field. The maximum deflection is about 180 μm as compared with 120 μm for silver in the 4th generation apparatus. This is the only image published by Gerlach that shows both deflected and undeflected atoms that passed through the same magnetic field. The undeflected atoms have $M = 0$. The arrow marks the maximum inhomogeneity of the magnetic field. See also text and TABLE 1. Reproduced from (Gerlach, 1925a).

A similar question arises for the deflection pattern Gerlach observed for iron atoms, whose ground state, ^5D, has $S = 2$ and $L = 2$ and thus admits $J = 4, 3, 2, 1, 0$. However, Gerlach observed no deflected atoms at all, see FIG. 8, as if all the iron atoms Fe(^5D) were in an $M = 0$ state. Assuming that the Fe atoms formed Fe_2 molecules would not help explain the observed lack of magnetic deflection as the ground state of Fe_2 is the highly paramagnetic $^9\Sigma_g$ state (Hoyer, 2014; Kolemos, 2015; Hoyer, 2016).

Electron spin had not been mentioned or the term symbols (Russel and Saunders, 1925) used in Stern's and Gerlach's subsequent work on magnetic deflection of atoms and molecules, see Sec. 3.3, with only one exception: in the 1933 paper on magnetic deflection of oxygen molecules (Schnurmann, 1933), it is noted that the ground state

Figure 8: Image of the deflection pattern for iron atoms in an inhomogeneous magnetic field of 200 kG/cm. No deflected Fe atoms were detected. The arrow marks the maximum inhomogeneity of the magnetic field. See also text and TABLE 1. Reproduced from Ref. (Gerlach, 1925a).

of O_2 is a $^3\Sigma$ state.

3.4 Radiation Pressure

Upon concluding his studies of magnetic properties of atoms in a Stern-Gerlach-type experiment, Gerlach returned to what he called his "hobby," namely his research on radiation pressure that he had started already in 1913 in Tübingen (Huber, 2015, p. 351). The pursuit of this "hobby" was deemed to be about as difficult as the SGE (Rollwagen, 1980). Gerlach's interest was likely triggered by the inherent connection between radiation pressure and the Stefan-Boltzmann law, the topic of his dissertation.

In 1884, Ludwig Boltzmann (1844-1906) succeeded in deriving the law, $I(T) \propto T^4$, that Josef Stefan (1835-1893) found in 1879 empirically (Boltzmann, 1884). In his derivation, Boltzmann invoked Maxwell's theory of electromagnetism and the second law of thermodynamics, prompted by an earlier attempt by Adolfo Bartoli (1851-

1896) to arrive at Stefan's law by the same route. Boltzmann was able to show that substitution of the pressure $p = I(T)/(3c)$ exerted by black-body radiation of energy density $I(T)/c$ into the second law of thermodynamics in the form $Tdp - pdT = [I(T)/c]dT$ yields

$$\frac{dI(T)}{4I(T)} = \frac{dT}{T} \tag{1}$$

which upon integration indeed gives Stefan's law – since then also known as the Stefan-Boltzmann law.

During his detention at Farm Hall, Gerlach reminisced (Gerlach, 1945) about his early attempts to come to terms with the effects he observed with a Crookes radiometer (light mill), a contraption invented by William Crookes (1832-1919) in 1873:

> In Tübingen hatte ich 1913/14 versucht, die Empfindlichkeit von Radiometern zu erhöhen durch andere Formgebung der Empfängerflügel. Dabei fand ich 'negative' Ausschläge, d.h. die Radiometerflügel drehten sich gegen die Strahlung. Ehrenhaft hatte ich die sogenannte 'negative Photophorese' veröffentlicht.

Gerlach's original idea that he could measure radiation pressure with a Crookes radiometer turned out to be overly optimistic, as the processes involved in the radiometer physics are all but simple. It would take Gerlach and his coworkers two decades (1913-1932) to clarify the "positive" and "negative" radiometer effects and to carry out an absolute measurement of radiation pressure. Was it worth the effort? For sure it was, as those who were (and, in some quarters, still are) credited with first measurements of radiation pressure – Pyotr Lebedev (1866-1912), Ernst Nichols (1869-1924), and Gordon Hull (1870-1956) – did not and could not have measured anything else than spurious radiometer effects. As Gerlach and coworkers would show in their work, these only disappear at a vacuum better than 10^{-6} torr, which was not attainable during the period 1901-1903 when Lebedev, Nichols, and Hull published their radiation pressure studies. (Gerlach, 1963a, p. 29):

> Wir haben damals ausgepumpt so lange bis die Dämpfung unseres schwingenden Systems unabhängig vom Druck geworden ist.

Gerlach reentered the fray in 1919 when he published, jointly with Wilhelm Westphal, a theory of the radiometer (Gerlach and Westphal, 1919) that, however, had to be quickly retracted (Westphal, 1919):

> Eine genauere Betrachtung der von mir kürzlich aufgestellten Theorie des Radiometers bei höherem Druck hat ergeben, daß sie sich nicht aufrechterhalten läßt, trotzdem die Übereinstimmung mit dem Experiment vielfach eine sehr gute ist. Insbesondere hatte Herr [Albert] Einstein die Freundlichkeit, mich auf einen Widerspruch gegen den Impulssatz aufmerksam zu machen.

At the 1920 meeting of the German Physical Society in Berlin, Westphal noted (Westphal, 1920):

> Zweck der Untersuchung ist die Sammlung experimenteller Grundlagen für eine vollständige Theorie des Radiometers. Untersucht wurde die Abhängigkeit der Radiometerwirkung von Druck und Art des umgebenden Gases.

Gerlach answered the challenge implied by Westphal's talk with a series of four papers entitled *Untersuchungen an Radiometern I-IV* [Investigations of the Radiometer I-IV] published between 1923 and 1932. The first paper of the series opens with the statement (Gerlach und Albach, 1923):

> Es ist bekanntlich noch nicht gelungen, eine vollständige Theorie des normalen Radiometers aufzustellen.“

The paper then describes a compensation radiometer consisting of a single vane with thermally insulated sides enclosed in a bulb filled with gas of variable pressure (in the range of 10^{-1} to 10^{-4} torr). One side of the vane is a receptor of radiation, the other is an electrically heatable bolometer. Like in his pyrheliometer used for his measurement of Stefan's constant (Huber et al., 2021), the carefully controlled electric heating of the bolometer side made it possible to compensate for the heating of the other side by the incident radiation. The compensation was carried out as a function of pressure for various absorption and thermal isolation materials. The instrument proved to be capable of sensitively measuring small changes of intense radiation.

However, Gerlach's goal was to directly measure light pressure rather than to investigate radiometer effects. To that end, he teamed up with Alice Golsen (Gerlach, 1945):

> Mit Frl. [Fäulein] Alice Golsen aus Wiesbaden – mit der ich wie sich im Laufe der Zeit herausstellte im Jahre 1896 zusammen zur Schule gegangen war! – machte ich die erste absolute Strahlungsdruckmessung als Praecisionsmessung – mit absolut gemessener Strahlungsenergie. Es war eine sehr mühsame, aber wunderschöne saubere Arbeit, eine Erholung nach den ewigen Fehlschlägen bei der Richtungsquantelungssuche. Mit Frl. Golsen fand ich eine physikalisch und vor allem menschlich wunderbare Hilfe.

Their collaboration resulted in the second paper (Gerlach and Golsen, 1923) of the series as well as a detailed summary written by Alice Golsen (Golsen, 1924). The aim of the experiment was to provide an unequivocal measurement of radiation pressure, free of radiometer effects and any disturbances. That meant that the radiometer measurements had to be done as a function of gas pressure all the way down to 10^{-6} or even 10^{-7} torr where a pressure dependence would vanish. A new apparatus was built, Fig. 9, that amounted to a torsion balance with a platinum vane attached to a quartz filament suspended in a glass ball. Its "rest-amplitude" observed at pressures below 10^{-6} torr was then attributed to radiation pressure. The measurements proceeded as follows: after several days of pumping, the dependence of the amplitude of the vane would be measured as a function of gas pressure at constant irradiation by a tungsten

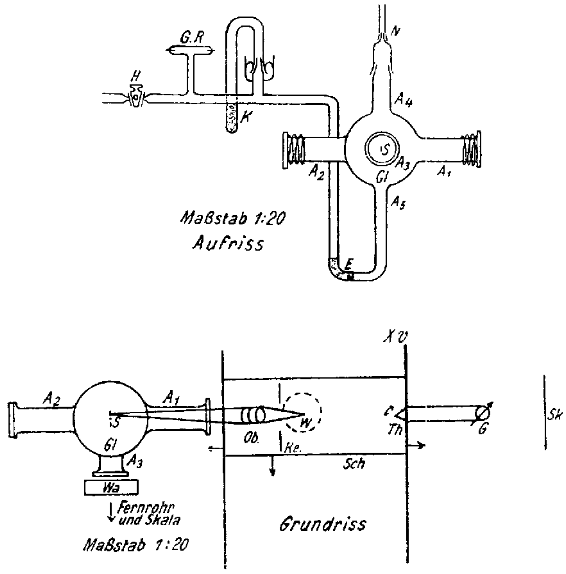


Figure 9: The torsional radiometer of Gerlach and Golsen in side-view (top) and top-view (bottom) (Golsen, 1924). The vane (not shown) used in the first quantitative measurement of radiation pressure was made of platinum foil (1.45×1.05 cm^2 and 7 μm thick). Its weight was balanced out by a platinum wire. The radiometer was housed in a glass ball (Gl) equipped with arms (A_1-A_5) for pumping and access and to allow to bring the radiation in and to take it out. It was evacuated by a Volmer diffusion pump combined with a cryo- and sorption pump (a *Volmeraggregat*) separated by a valve (H). The pressure was measured using a McLeod gauge and below 10^{-5} torr inferred from the damping of the torsional oscillations of the radiometer suspended on an 11 cm long quartz filament. A mirror (S) was attached to the filament to facilitate the read-out of the amplitude of the torsional oscillations. The radiation source was a tungsten arc lamp (W) whose output was focused on the vane by a camera lens (Ob). The power of the lamp was calibrated using a Hefner lamp and monitored during the measurements by a thermopile (Th) connected to a galvanometer (G). Except for the windows, the glass ball was shielded by a cotton-wool wrapping.

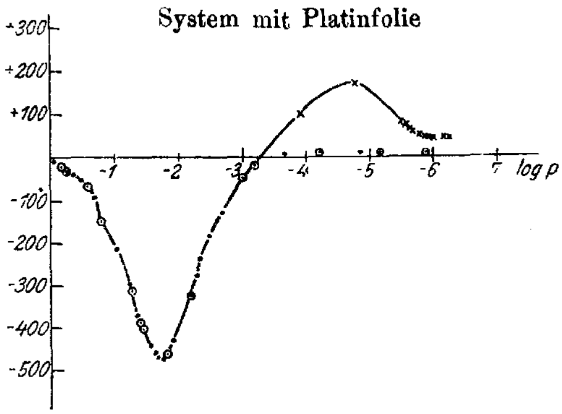


Figure 10: The dependence of the vane amplitude (ordinate) on the logarithm of gas pressure, $\log p$ (abscissa). The negative and positive amplitudes of the platinum vane refer, respectively, to deflections against and along the direction of the incident light beam. The various series of data points (•, ×, and ⊙) correspond to different irradiances and are all found to follow the same curve (Golsen, 1924).

arc lamp, see caption to Fig. 9. The power of the lamp was monitored [normalized] by a thermopile. Achieving a steady-state amplitude lasted often for hours and was perturbed by outgassing as well as by the vibrations of the institute building. A typical dependence of the amplitude on gas pressure is shown in Fig. 10; it would take on the order of 100 hours to acquire the data points shown. As one can see, at gas pressures between 1 torr and 10^{-4} torr, the amplitude is "negative," meaning that, upon irradiation, the vane moves against the incoming light beam. Only at pressures below 10^{-3} torr would the amplitude become "positive" (i.e., along the light beam direction), inching towards the pressure-independent "rest-amplitude" at pressures below 10^{-6} torr. In order to access the requisite pressure range, sorption pumping with charcoal and cryo-pumping with liquid oxygen (!) had to be applied – for days ... As stated by Gerlach and Golsen, cryo-pumping with dry ice had not sufficed to reach the "rest-amplitude" regime. The radiation pressure was then evaluated from the observed "rest-amplitude" and the measured properties of the torsion balance, such as its force constant. The measured light pressure (light force per illuminated surface area of the vane), p, and the calibrated irradiance, I^*, were then compared and found to obey the relationship

$$p = \frac{I^*}{c} \tag{2}$$

with an accuracy of about 2%. This was the first-ever quantitative measurement of radiation pressure.

Gerlach and Golsen summarized their results thus (Gerlach and Golsen, 1923):

> 1. Im Vakuum von etwa 10^{-6} bis 10^{-7} mm Hg wird ein konstanter Restausschlag des Radiometers gefunden, welcher als reiner Strahlungsdruck gedeutet wird.
>
> 2. Dieser Ausschlag ist proportional der auffallenden Energie und unabhängig von der Wellenlänge der Strahlung.
>
> 3. Der aus dem Restausschlag errechnete Strahlungsdruck stimmt mit dem theoretischen Wert überein.

In the third paper of the radiometer series (Gerlach and Madelung, 1923), Gerlach and Erwin Madelung (1881-1972) debunk the radiometer theory published in 1922 by Edith Einstein. Finally, in 1932 Gerlach and Wilhelm Schütz publish the final, fourth sequel of the series (Gerlach and Schütz, 1932) that deals with the radiometer effects at "high pressures" and corroborates the recent model put forward by P.S. Epstein (Epstein, 1928).

In 1975, Gerlach wrote a rebuttal (Gerlach, 1975) to an article published in *Physik in unserer Zeit*[8] whose author repeated the claim that radiation pressure was measured for the first time in the experiments of Lebedev, Nichols, and Hull:

> In den Jahren 1919 bis etwa 1930 habe ich mich vielfach mit dem "Radiometer" befaßt, außerdem Westphal, Hettner, E. Einstein u.a. Der

[8]Gerlach provided an impetus in 1970 for the founding of *Physik in unserer Zeit.*

Nachweis "negativen" Radiometereffektes und andere Untersuchungen ließen erkennen, daß Lebedew sicher nicht den Lichtdruck gemessen hat und daß die Messung von Nichols und Hull im Übergangsgebiet vom "positiven" zum "negativen" Effekt (das damals ganz unerforscht war) keinen Beweis enthalten kann. Ich habe deshalb "eine neue Messung des Strahlungsdruckes" in so hohem Vakuum gemacht, daß ein Gaseinfluß nicht mehr bestand (Dämpfungsmessung mit der Drehwaage) und außerdem alles absolut gemessen ...

It is mind-boggling that Gerlach's work on radiation pressure is still not widely known and that most textbooks keep attributing the first measurements of radiation pressure to experiments in which it could not have been observed.

In addition to his time-consuming research projects at Frankfurt, Gerlach wrote two books: *Experimentelle Grundlagen der Quantentheorie* (Gerlach, 1921) and the acclaimed *Materie, Elektrizität, Energie* (Gerlach, 1923), a survey of the development of atomism over the previous decade. The latter book, aimed at the younger reader with the objective of closing the gap left by World War One in available atomic physics textbooks, was well-received and followed by a second edition three years later (Gerlach, 1926a) as well as an English translation (Gerlach, 1928). This is what Gerlach would say later about how the book came about (Gerlach, 1908-1950):

So nebenbei schrieb ich für den Verlag Steinkopff ein Buch 'Materie, Elektrizität, Energie. Die Entwicklung der Atomistik in den letzten 10 Jahren.' Mein Freund Liesegang (der mit den Liesegangschen Ringen) überredete mich dazu; es war das Ergebnis eines Seminars, in dem wir den Übergang von der klassischen zu der modernen (1922!) Physik behandelten. Ich schickte es James Franck, der meinte, man merke doch, dass es nachts zwischen 2 und 4 geschrieben sei! In der zweiten Auflage wurden solche Nachmitternachtssünden ausgemerzt – immerhin hat das Buch (auch in England und Amerika erschienen) der damaligen jüngeren Generation genützt. Ich wurde noch in viel späteren Jahren darauf angesprochen. Mir scheint es heute noch pädagogisch entscheidend zu sein, dass die Grundgedanken physikalisch richtig und anregend dargestellt werden – einzelne Fehler (so bedauerlich sie sind!)

We note that among Gerlach's students at Frankfurt was Hans Bethe (1906-2005), who began his physics studies in 1924. In his reminiscence (Bethe, 1979), Bethe acknowledged that Gerlach's stimulating lectures on atomic physics became a decisive influence on his further work in physics.

In hindsight, Gerlach regarded his Frankfurt period as the "happiest years" of his life (Gerlach, 1950):

> 'Frankfurt' waren meine glücklichsten Jahre. Damals hatte ich Zeit, denn ich brauchte keinen Schlaf. Ich arbeitete – ich darf sagen – nicht wenig, aber ich liess sonst auch nichts aus! Ich hatte ja pro Tag 20-21 Stunden zur Verfügung.

After completion of the radiation pressure work at Frankfurt, Gerlach moved on to his second academic station, the University of Tübingen, his alma mater, as *Ordinarius*.

4 Tübingen (1925-1929)

Gerlach's accession to a full professorship had been in the air at least since his appointment as *Extraordinarius* at Frankfurt in 1921. However, after the success of the Stern-Gerlach experiment, Gerlach's appointment to a physics chair – an *Ordinariat* – became overdue. Among those rooting for Gerlach with particular enthusiasm were Max Born, Richard Gans, Friedrich Paschen, and Arnold Sommerfeld. As a result, by 1924, two prime universities with vacancies – Königsberg and Tübingen – were in competition with one another to attract Gerlach to their faculties (Huber, 2015, pp.

Figure 11: Tübingen, an oil on canvas by the co-founder of “Brücke,” Erich Heckel (1920). Brücke-Museum, ©VG Bild-Kunst, Bonn 2019.

Figure 12: Walther Gerlach as director of the Physics Institute in Tübingen. Courtesy of Werner Kittel, Hamburg.

469-482). The chair of the hiring committee at Tübingen, which was searching for a successor to Paschen,[9] was Gerlach's former colleague from Frankfurt, Alfred Landé (1888-1976), an *Extraordinarius* at Tübingen since 1922. Among others, Landé asked Einstein for a letter, which resulted in the following push for Gerlach (Rechenberg, 1979):

> Nach meiner Meinung wäre Herr Gerlach der richtige Nachfolger für Paschen. Er ist unter den jüngeren deutschen Experimentalphysikern, die in Betracht kommen, wohl der beste. Er ist vielseitig, ideenreich und dabei sicher und zuverlässig. Menschlich macht er auch einen guten Eindruck.

Although Gerlach had a clear preference for Tübingen, he kept both places in suspense for several months before finally accepting – as of 1 January 1925 – the offer from the city on the Neckar, FIG. 11.

As Professor für Experimentalphysik and Director of the Institut für Experimentalphysik der Universität Tübingen, Gerlach further diversified his research, branching out into areas ranging from optics to spectroscopy to the study of magnetic properties of materials to crystallography to photochemistry. Among the 41 articles written in Tübingen during the 1925-1929 period (Nida-Rümelin, 1982, pp. 14-17), there is even a piece on the ball-lightning. However, spectroscopy and magnetic properties would remain the focus of Gerlach's research throughout his career. FIG. 12 shows Gerlach during his Tübingen period.

4.1 Coherence properties of light

One of the first projects Gerlach undertook upon assuming full professorship at Tübingen was concerned with coherence properties of light. Alfred Landé, who in the previous year had written two papers on the quantum theory of light (Landé, 1925a,b),

[9] Paschen was on the move to Berlin to assume the Presidency of the Physikalisch-Technische Reichsanstalt.

likely sparked Gerlach's interest in this topic and made him think of an experiment that would examine aspects of light interference whose understanding Landé found wanting. In particular, Landé was uneasy about explaining interference in terms of superposition of light quanta: In (Landé, 1925b), he noted that the occupation number of the electromagnetic modes [in today's parlance] in the visible and UV spectral regions as emitted by a hot black body (i.e., the light source used at the time – typically a hot wire) would be less than one. Therefore, in the introduction to their joint paper, Gerlach and Landé (Gerlach and Landé, 1926) concluded, "Die Interferenzfähigkeit Wienschen Lichtes [i.e., UV] verlangt also Superposition von Lichtquantenbruchteilen" – an idea they were not willing to accept.[10]

In their joint experiment, Gerlach and Landé set out to examine the Young-type double-slit interference of light modes [referred to here as Strahlenbündel], each derived from interference fringes produced in a preceding double-slit interference (Gerlach and Landé, 1926).[11] The results of their observations are only described in words – no images are shown:

> Liegen ... beide Spalte [of the secondary double slit] in – in beliebig verschiedenen – primären Beugungsmaximis [maxima of the primary double-slit interference pattern], so treten wieder scharfe schwarze Interferenzen auf, obwohl die Gesamthelligkeit durch die Wirkung der beiden [primary] Maxima nochmals gesteigert ist.

This constitutes

[10]They were not alone to think of light interference in this way, i.e., as a superposition of (whole) light quanta [photons]. A similar view was later expressed, e.g., by P.A.M. Dirac. A way out of this quandary was found only decades later by Roy Glauber, who pointed out that it is not the photons that undergo superposition but rather their probability amplitudes (Glauber, 1995; Friedrich et al., 2023).

[11]Gerlach's and Landé's double double-slit experiment bears some conceptual similarity with the later three-stage Stern-Gerlach experiment (Friedrich and Schmidt-Böcking, 2021, pp. 54-60).

> ... nach der klassischen Theorie selbstverständliches, vom Standpunkt der Lichtquanten [photons] aber kaum zu verstehendes Resultat [in light of the nearly empty electromagnetic modes].

Gerlach and Landé conclude by noting the consistency of their result with that obtained earlier by Erwin Schrödinger in an experiment (Schrödinger, 1920) to examine the interferences within a wide-angle cone of light whose Strahlenbündel were presumed to be comprised of different electromagnetic modes.[12]

4.2 Magnetic properties of materials

Chronologically, Gerlach's second focus in Tübingen was on magnetic properties of materials. As noted in Sec. 3.1, Gerlach developed a penchant for this line of research already during his Elberfeld-Frankfurt periods. In 1921, he investigated the Barkhausen effect[13] in ferromagnetic materials and concluded that it is magnetostriction that is primarily responsible for the observed magneto-elastic properties of these materials.

In Tübingen, Gerlach undertook a series of studies on magnetization of the monocrystals of iron. In (Gerlach, 1926b), the "alchemy" of the preparation of iron monocrystals, typically shaped as rods of various sizes, is described, and their magnetization curves reported. These imply that the ferromagnetic properties are either given by pre-existing magnetic domains [magnetische Elementarkörper] or by magnetic domains that are generated by the superimposed magnetic field. The interplay between magnetization and stretching and bending ("kalte Bearbeitung") as well as effects of mechanical deformation (elastic or inelastic) on the observed hysteresis are reported

[12]Schrödinger's setup differed from that of Albert A. Michelson devised to measure the angular size of astrophysical objects only in the positions of object and image and their correspondingly larger angular dimensions (Michelson, 1890).

[13]A discontinuous change of magnetization of a material with increasing magnetic field strength, originally detected acoustically as crackling (Barkhausen, 1919).

in (Gerlach, 1926c). Interestingly, the aforementioned Barkhausen effect was found to occur only for bending but not for stretching deformations of the magnetized monocrystals. The shapes of the magnetization curves as functions of the magnetic field were found to exhibit characteristic knicks whose positions vary depending on the magnetization direction with respect to the crystals' axes (Dussler and Gerlach, 1927). In the above works Gerlach acknowledges funding from the *Notgemeinschaft der Deutschen Wissenschaft*.[14]

Instructive is Gerlach's joint study with his Tübingen PhD student Erwin Lehrer (Gerlach and Lehrer, 1926)[15] on the susceptibility of para- and diamagnetic gases. Apart from taking issue with the work of Michael Faraday on the same topic, the paper presents convincing quantitative data and detailed descriptions of how to obtain them in the laboratory – or indeed in the lecture hall as part of a demonstration for a class of students.

A schematic of the apparatus used is shown in FIG. 13. A gas stream (shown as an array of vertical dashed lines (labeled a) is generated by resistively heating a glass capillary enclosed in a glass or metal tube fashioned with windows (labeled b). The gas-to-be-examined (such as air or oxygen), which fills the tube at near-ambient pressure, is enriched with mercury vapor. A mercury-vapor lamp (L) combined with a mercury-containing bulb (R) produces resonant light that illuminates the mercury-enriched gas stream before hitting a fluorescence screen (labeled S). The image of the gas stream appears as a shadow on the fluorescence screen due to the absorption of the resonant light by the mercury atoms contained in the gas stream. The gas stream is subject to an inhomogeneous magnetic field oriented perpendicular to the plane of the paper and generated by an electromagnet (not shown).

The effect of the magnetic field on the stream of the paramagnetic gas is revealed by the shift of the shadow along the field gradient, i.e., to the left, see FIG. 14 for

[14] Die Notgemeinschaft der Deutschen Wissenschaft, founded in 1920, was the forerunner of today's Deutsche Forschungsgemeinschaft (DFG).

[15] Lehrer's dissertation was published separately (Lehrer, 1926).

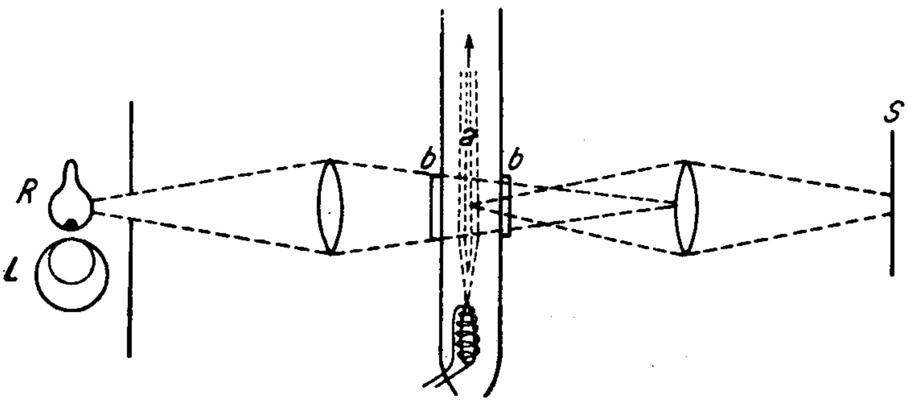


Figure 13: An apparatus to generate and image a stream of gas subject to an inhomogeneous magnetic field. See text. Reproduced from (Gerlach and Lehrer, 1926) with permission.

air. Gerlach and Lehrer sum up:

> Die Durchführung einer – wegen der schwer zu erfassenden Strömungsverhältnisse nur ungefähren – Berechnung führt zu der richtigen Grössenordnung der Suszeptibilität bzw. zum Nachweis des Curieschen Gesetzes.

Curie's law (Curie, 1895), which governs the dependence of the magnetic susceptibility $\chi \equiv M/B$ (where M is the magnetization and H the magnetic field strength) of a paramagnetic substance on the number N of molecular magnetic dipoles μ and temperature T, $\chi = \frac{N\mu^2}{3kT}$, was derived classically by Langevin (Langevin, 1905) for $\frac{\mu B}{kT} \ll 1$. Lucy Mensing and Wolfgang Pauli showed, albeit for the electric analog, that the law obtains quantum mechanically in the same form as well (Mensing and Pauli, 1926), a result extolled by Van Vleck in his Nobel lecture (Van Vleck, 1978).

Lucy Mensing (1901-1995) was Alfred Landé's assistant at Tübingen. In 1928, she would marry Wilhelm Schütz (1900-1972), Gerlach's Frankfurt PhD student whom Gerlach took along with him to Tübingen as his assistant (Münster and Janssen, 2025).

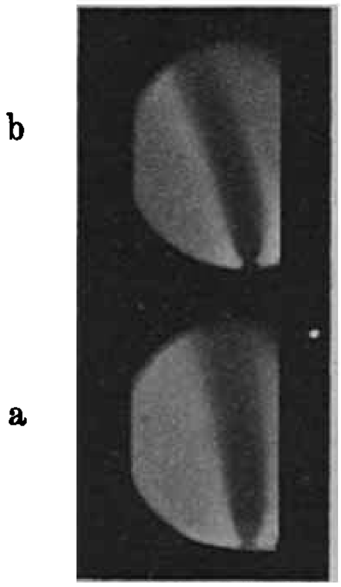


Figure 14: Images of a stream of air (a) without a magnetic field and (b) with a magnetic field of 3000 Gauss and inhomogeneity of 2000 Gauss/cm. Reproduced from (Gerlach and Lehrer, 1926) with permission.

4.3 Spectroscopy

Gerlach's long-standing interest in spectroscopy only intensified in Tübingen as he launched a program to amend – or replace – traditional chemical methods of analytical chemistry with spectroscopic, i.e., physical ones. While still in Frankfurt, Gerlach reviewed available spectroscopic methods with an eye on quantitative analysis of the elemental composition of chemical samples, such as alloys, and demonstrated that (Gerlach, 1925b):

> Die "empfindlichen" [spektroskopischen] Linien sind die physikalisch unter den gewählten Aufnahmebedingungen stärksten Linien. Hiermit ist die chemische quantitative Spektralanalyse wissenschaftlich begründet.

Through numerous studies of particular cases, carried out in Tübingen, on the spectroscopic determination of trace concentrations of, for instance, lead in gold-copper-silver alloys (Gerlach and Schweitzer, 1929a) or iridium, rhodium, and palladium in platinum (Gerlach and Schweitzer, 1929b), Gerlach achieved much progress and made the program flourish. In 1929, he published a book, *Foundation and methods of chemical analysis by the emission spectrum* (Gerlach and Schweitzer, 1929c, 1930), that provided recipes for obtaining reproducible spectra suitable for elemental analysis. Apart from discussing specifics (such as dissolving metals in acids), spectroscopic excitation techniques (such as flames, discharges, and sparks), dispersion elements (such as prisms and their spectral resolution), recording techniques (such as photography and the evaluation of the spectro-photographs), Gerlach urged caution in making use of spectroscopy (Gerlach, 1931):

> Vor allem ist nicht zu vergessen, dass jedes spezielle Problem auch eine ihm angepasste Versuchsmethodik verlangt.

and goes on to emphasize that

> Aber unter diesen Voraussetzungen kann ihr Prinzip [der Emissionsspektralanalyse] zur weitgehenden Verwendung als Hilfe sowohl bei physikalis-

chen wie chemischen, metallographischen und biologisehen Untersuchungen empfohlen werden.

Gerlach also branched out into molecular spectroscopy. Especially well-known, from the Tübingen period, is his paper on the Raman spectrum of benzene (Gerlach, 1929) and its sequel (Gerlach, 1932), where he interpreted the weak Raman line at 984 cm^{-1} accompanying the strong line at 991.6 cm^{-1} as due to $^{12}C_5{}^{13}CH_6$ (Herzberg, 1945, p. 368).

4.4 Personal aspects

Unfortunately, the affection between their assistants, Lucy Mensing and Wilhelm Schütz, was not shared by Landé and Gerlach. Apparently, they had a falling out over Gerlach's authoritarian manner which came about during – or preceded – Gerlach's professorial appointment at Tübingen. In her 1989 recollections, Lucy Schütz, née Mensing provided the following description of Gerlach's Tübingen operation (Münster and Janssen, 2025):

> Die Situation in Tübingen war folgende: Gerlach beherrschte das Institut, hatte wohl etwa 25–28 Doktoranden. Sein einziger Assistent war [Wilhelm] Schütz. Landé als A[ußer]O[rdentlicher]-Professor hatte ein Zimmer im Erdgeschoß, in das für mich ein 2. Tisch gestellt wurde. Dann hatte Dr. [Ernst] Back noch einen Arbeitsraum."

The animosity between Gerlach and Landé went so far that Landé sought a position elsewhere – and found one at the Ohio State University in Columbus, Ohio, and moved there in effect already in 1929 (Schmidt-Böcking et al., 2022). In his 1969 letter to Lucy and Wilhelm Schütz, Landé noted sarcastically (?) about Gerlach (Münster and Janssen, 2025):

> Aber ich bin ihm [Gerlach] sehr dankbar, denn er hat stark dazu beigetragen, dass ich den Ruf nach USA annahm.

Figure 15: The Gerlach family in Weimar in about 1927. From left: Walther Gerlach (WG), Wolfgang Gerlach, Ruth Probst (WG's partner and since 1939 his 2nd wife), Valentin Gerlach (WG's father), Ingeborg Gerlach (daughther of Werner and Henny Gerlach, later mother of W. Kittel), Marie Gerlach, neé Niederhäuser (mother of WG), Henny Gerlach, neé Syffert (wife of Werner Gerlach), and Werner Gerlach. From W. Kittel, Hamburg.

Gerlach would leave Tübingen in 1929 as well. According to Lucy Schütz's recollection, this is what she happened to have learned after her wedding day, on September 1, 1928 (Münster and Janssen, 2025):

> Am nächsten Tag las ich in der Zeitung [über] den Tod von W[ilhelm] Wien und sagte: 'da wird Gerlach sein Nachfolger.' Das war dann wirklich so, Ende [19]29 zogen Gerl[ach] u[nd] wir [Lucy & Wilhelm Schütz] nach München.

Thus, after a five-year vetting period in Tübingen, Walther Gerlach ascended, on October 1, 1929, to the Physikalisches Institut der Universität München as ordentlicher Professor für Experimentalphysik.

Regarding Gerlach's personal life, it was in Tübingen where he separated from his first wife Wilhelmine Gerlach, née Mezger (1889-1974) and their daughter Ursula (1918-1940) and began to live with his future second wife, Ruth Probst (1905-1994), a physician (Hagmann, 2023). Chapter X of this volume provides a detailed account of the breakup and its disturbing aspects. FIG. 15 shows a photo of Gerlach's extended family taken during his Tübingen period.

5 In Conclusion

We close by quoting from a letter the 88-year-old Gerlach wrote to the former president of the Max-Planck-Gesellschaft, Adolf Butenand (1903-1995) (Gerlach, 1978). In this letter, Gerlach calls up for

> Gründung aller Ausbildung und "Bildung" auf die Naturwissenschaften, auf naturwissenschaftliches Denken, auf Unterordnung unter die Natur ...

and concludes with what could be regarded as his credo:

Ist es dafür zu spät? Ich meine, *etwas Gutes kommt nie zu spät.* [my emphasis]

Acknowledgments

I'm grateful to Josef Georg Huber for our past collaboration on the life, work, and legacy of Walther Gerlach as well as for our present discussions and the sources he shared on Gerlach's 1914-1929 period. His 2015 PhD Thesis stands out as an invaluable resource on Gerlach. I'm also grateful to Gernot Münster and Michel Janssen for initiating me into the intricacies of the Landé-Gerlach relationship through their kindly shared manuscript on Lucy Mensing. Last but not least, I'd like to thank Gerard Meijer and the Fritz-Haber-Institut der Max-Planck-Gesellschaft for continued support.

References

Bachmann, H.-R. and Rechenberg, H. (1989). *Walther Gerlach (1889-1979): Eine Auswahl aus seinen Schriften und Briefen*." Heidelberg: Springer.

Barkhausen, H. (1919). "Zwei mit Hilfe der neuen Verstärker entdeckte Erscheinungen." *Physikalische Zeitschrift* 20: 401.

Bernstein, J. (1979). "Profiles: Master of the Trade-I" (Hans Albrecht Bethe). The New Yorker, December 3, pp. 50-107.

Boltzmann, L. (1884). "Ableitung des Stefan'schen Gesetzes betreffend die Abhängigkeit der Wärmestrahlung von der Temperatur aus der elektromagnetischen Lichttheorie." *Annalen der Physik* 22: 291-294.

Born, M. (1969). "Max Born to Albert Einstein 12 February 1921." In Born, M.

(ed.) *Albert Einstein, Hedwig und Max Born: Briefwechsel (1916-1955)*. München: Nymphenburger Verlagshandlung.

Curie, P. (1895). "Propriétés magnétique des corps a diverse températures." *Annales de Chimie et de Physique* 5: 289.

Dussler, E. and Gerlach, W. (1927). "Eisenkristalle. III. Mitteilung: Die Magnetisierung in verschiedenen Kristalrichtungen" *Zeitschrift für Physik* 44: 279.

Epstein, P.S. (1928). "Zur Theorie des Radiometers." *Zeitschrift für Physik* 54: 537.

Estermann, I. (1975). "History of molecular beam research: Personal reminiscences of the important evolutionary period 1919-1933." *American Journal of Physics* 43: 661.

Friedrich, B. and Schmidt-Böcking, H. (2021). *Otto Stern's Molecular Beam Method and its Impact on Quantum Physics* in *Molecular Beams in Physics and Chemistry: From Otto Stern's Pioneering Exploits to Present-Day Feats*. Cham: Springer.

Huber, J.G., Schmidt-Böcking, H., Friedrich, B. (2021). *Walther Gerlach (1888-1979): Precision Physicist, Educator, and Research Organizer, Historian of Science* in *Molecular Beams in Physics and Chemistry: From Otto Stern's Pioneering Exploits to Present-Day Feats*. Friedrich, B., Schmidt-Böcking, H. (eds.). Cham: Springer.

Friedrich, B., Meijer, G., Schmidt-Böcking, H., Gruber, G. (2021). "One hundred years of Alfred Landé's g-factor." *Natural Sciences* 1: e20210068.

Friedrich, B., Kleppner, D., Herschbach, D. (2023). "About Roy Glauber." *Natural Sciences* 3: e20220064.

Gerlach, W. (1908-1950). "Autobiographische Notizen 1908-1950." Nr. 17, Archiv des Deutschen Museums in München, NL 80/053.

Gerlach, W. (1921). *Experimentelle Grundlagen der Quantentheorie.* Braunschweig: Vieweg.

Gerlach, W. (1923). *Materie, Elektrizität, Energie. Die Entwicklung der Atomistik in den letzten 10 Jahren.* Dresden und Leipzig: Steinkopf (Wissenschaftliche Forschungsberichte, Naturwissenschaftliche Reihe 7).

Gerlach, W. (1925a). "Über die Richtungsquantelung im Magnetfeld II. Experimentelle Untersuchungen über das Verhalten normaler Atome unter magnetischer Kraftwirkung." *Annalen der Physik* 76: 163–199.

Gerlach, W. (1925b). "Zur Frage der richtigen Ausführung und Deutung der "quantitativen Spektralanalyse." *Zeitschrift für anorganische und allgemeine Chemie* 142: 383.

Gerlach, W. (1926a). *Materie, Elektrizität, Energie. Grundlagen und Ergebnisse der experimentellen Atomforschung.* Dresden und Leipzig: Steinkopf (Wissenschaftliche Forschungsberichte, Naturwissenschaftliche Reihe 7).

Gerlach, W. (1926b). "Eisenkristalle. I. Mitteilung: Magnetisierungskurven" *Zeitschrift für Physik* 38: 828.

Gerlach, W. (1926c). "Eisenkristalle. II. Mitteilung: Magnetisierung, Hysterese und Verfestigung." *Zeitschrift für Physik* 39: 327.

Gerlach, W. (1928). *Matter, electricity, energy: the principles of modern atomistics and experimental results of atomic investigation.* New York: D. Van Nostrand Company.

Gerlach, W. (1929). "Über die Breite der Spektrallinien der Raman-Streustrahlung von Benzol." *Annalen der Physik* (5) 1: 301.

Gerlach, W. (1931). "Aufgaben der quantitativen chemischen Spektralanalyse" *Die Naturwissenschaften* 19: 25.

Gerlach, W. (1932). "Über zwei mit Hilfe des Raman-Effektes beobachtete Erscheinungen" *Sitzungsberichte der mathematisch-naturwissenschaftlichen Abteilung der Bayrischen Akademie der Wissenschaften zu München* 39.

Gerlach, W. (1945). "Geschichtliche Notizen – geschrieben in Farm Hall 1945." *Archiv des Deutschen Museums in München, Privat Nachlass Gerlach.*

Gerlach, W. (1950). *Autobiographische Notizen 1908-1950, Nr. 17.* Archiv des Deutschen Museums in München NL 80/053.

Gerlach, W. (1960). "Über die Entwicklungen atomistischer Vorstellungen." Physikalischer Verein Frankfurt, 2 March 1960.

Gerlach, W. (1963a). "Interview with Thomas Kuhn, February 16, 1963." *Sources for History of Quantum Physics.* College Park, MD: American Institute of Physics.

Gerlach, W. (1963b). "Interview with Thomas Kuhn, February 23, 1963." *Sources for History of Quantum Physics.* College Park, MD: American Institute of Physics.

Gerlach, W. (1969). "Otto Stern zum Gedenken." *Physikalische Blätter* 25: 412-413.

Gerlach, W. (1972a). "Geburtstagsgruß an Gustav Hertz." *Physikalische Blätter* 28: 321-322.

Gerlach, W. (1975). "Lebedew misst nicht Strahlungsdruck. Zu dem Artikel K. Treml 'Der Strahlungsdruck des Lichtes' [Physik in unserer Zeit 5: 100 (1974)]." *Physik in unserer Zeit* 6: 32.

Gerlach, W. to Butenand, A. (1978). Letter dated 24 March 1978. In (Bachmann and Rechenberg, 1989, p. 253).

Gerlach, W. and Albach, H. (1923). "Untersuchungen an Radiometern. I. Über ein Kompensationsradiometer." Zeitschrift für Physik 14: 285-290.

Gerlach, W. and Born, M. (1921a). “Elektronenaffinität und Gittertheorie.” Zeitschrift für Physik 5: 433-441.

Gerlach, W. and Born, M. (1921b). “Über die Zerstreuung des Lichtes in Gasen.” *Zeitschrift für Physik* 5: 374-375.

Gerlach, W. and Golsen, A. (1923). “Untersuchungen an Radiometern. II. Eine neue Messung des Strahlungsdrucks.” *Zeitschrift für Physik* 15: 1-7.

Gerlach, W. and Landé, A. (1926). “Ein Experiment über Kohärenzfähigkeit von Licht.” *Zeitschrift für Physik* 36: 169.

Gerlach, W. and Lehrer, E. (1926). “Suszeptibilität der Gase, Curiesches Gesetz und Diamagnetismus der Flammengase.” *Annalen der Physik* 81: 1129.

Gerlach, W. and Madelung, E. (1923). “Untersuchungen an Radiometern. III. Notiz zur Radiometertheorie von E. Einstein.” *Annalen der Physik* 74: 674-699.

Gerlach, W. and Schütz, W. (1932). “Untersuchungen an Radiometern IV. Experimentelle Beiträge zur Prüfung der Theorien des gewöhnlichen Einplatten-Radiometers.” *Zeitschrift für Physik* 78: 43-58.

Gerlach, W. and Schweitzer, E. (1929a). “Spektroskopischer Bleinachweis in Gold-Kupfer-Silber-legierungen.” *Zeitschrift für anorganische und allgemeine Chemie* 181: 101.

Gerlach, W. and Schweitzer, E. (1929b). “Spektralanalytische Schnellmethode zur quantitativen Bestimmung von Iridium, Rhodium, Palladium in Platin.” *Zeitschrift für anorganische und allgemeine Chemie* 181: 103.

Gerlach, W. and Schweitzer, E. (1929c). *Foundation and methods of chemical analysis by the emission spectrum.* London: Hilger.

Gerlach, W. and Schweitzer, E. (1930). *Die quantitative chemische Emissionsspektralanalyse*. Leipzig: Leopold Voss.

Gerlach, W. and Stern, O. (1924). "Über die Richtungsquantelung im Magnetfeld." *Annalen der Physik* 74: 673-699.

Gerlach, W. and Westphal, W. (1919). "Über positive und negative Radiometerwirkungen." *Verhandlungen der Deutschen Physikalischen Gesellschaft* 21: 218-226.

Glauber, R. (1995). "Dirac's famous dictum on interference: one photon or two?" *American Journal of Physics* 63: 12.

Golsen, A. (1924). "Über eine neue Messung des Strahlungsdrucks." *Annalen der Physik* 73: 624-642.

Hagmann, J-G. (2023). "Die Lücke als Fund: Über eine Fehlstelle zur Familiengeschichte im Nachlass von Walther Gerlach (1889–1979)." *Berichte zur Wissenschaftsgeschichte* 46: 320-335.

Herzberg, G. (1944). *Atomic Spectra and Atomic Structure*. New York: Dover Publications.

Herzberg, G. (1945). *Molecular Spectra and Molecular Structure. II. Infrared and Raman Spectra of Polyatomic Molecules*. New York: Van Nostrand Reinhold Company.

Hoyer, C. E., Manni, G. L., Truhlar, D. G., Gagliardi, L. (2014). "Controversial electronic structures and energies of Fe_2, Fe_2^+, and Fe_2^- resolved by RASPT2 calculations." *The Journal of Chemical Physics* 141: 204309.

Hoyer, C. E., Manni, G. L., Truhlar, D. G., Gagliardi, L. (2016). "Comment on "Fe_2: As simple as a Herculean labour. Neutral (Fe_2), cationic (Fe_2^+), and anionic (Fe_2^-)

species" [J. Chem. Phys. 142, 244304 (2015)]." *The Journal of Chemical Physics* 144: 027101.

Huber, J.G. (2015). *Walther Gerlach (1888-1979) und sein Weg zum erfolgreichen Experimentalphysiker bis etwa 1925*. Augsburg: Dr. Erwin Rauner Verlag.

Huber, J.G., Schmidt-Böcking, H., Friedrich, B. (2021). *Walther Gerlach (1888-1979): Precision Physicist, Educator, and Research Organizer, Historian of Science* in *Molecular Beams in Physics and Chemistry: From Otto Stern's Pioneering Exploits to Present-Day Feats*. Friedrich, B., Schmidt-Böcking, H. (eds.). Cham: Springer.

Hund, F. (1975) *Geschichte der Quantentheorie*. Mannheim: Bibliographisches Institut.

Landé, A. (1925a). "Zur Quantentheorie der Strahlung." *Zeitschrift für Physik* 33: 317.

Landé, A. (1925b). "Lichtquanten und Kohärenz." *Zeitschrift für Physik* 33: 571.

Langevin, P. (1905). "Sur la théorie du magnétisme." *Journal de Physique* 4: 678.

Lehrer, E. (1926). "Über die magnetische Suszeptibilität der Gase und ihre Abhängigkeit von Druck und Temperatur." *Annalen der Physik* 81: 229.

Kolemos, A. (2015). "Fe_2: As simple as a Herculean labour. Neutral (Fe_2), cationic (Fe_2^+), and anionic (Fe_2^-) species." *The Journal of Chemical Physics* 142: 244304.

Mehra, J. and Rechenberg, H. (1982). *The Historical Development of Quantum Theory*." Volume 1, Part 2. Heidelberg: Springer.

Mensing, L. and Pauli, W. (1926). "Über die Dielektrizitätskonstante von Dipolgasen nach der Quantenmechanik." *Physikalische Zeitschrift* 27: 509.

Michelson, A.A. (1890). "On the Application of Interference Methods to Astronomical Measurements." *Philosophical Magazine* 80: 1.

Münster, G., Janssen, M. (2025). *Angular and Career Momentum: What Lucy Mensing Contributed to Physics and Why She Left the Field* in *Hidden Variables: Women in the History of Quantum Physics*. Charbonneau, P., Frank, M., Monaldi, D., van der Heijden, M. (eds.). Cambridge: Cambridge University Press.

Nida-Rümelin, M. (1982). *Bibliographie Walther Gerlach. Veröffentlichungen von 1912-1979*. München: Forschungsinstitut des Deutschen Museums für die Geschichte der Naturwissenschaften und der Technik.

Rechenberg, H. (1979). "Walther Gerlach zum Neunzigsten." *Physikalische Blätter* 35: 370-374.

Rollwagen, W. (1980). "Gedenkkolloquium zu Ehren von Walther Gerlach." München, 25 February. Tape recording DMA AV-T 0433.

Russell, H. N., Saunders, F. A. (1925) "New Regularities in the Spectra of the Alkaline Earths," *Astrophysical Journal* 61:38.

Schmidt-Böcking, H., Gruber, G., Friedrich, B. (2022). "One hundred years ago Alfred Landé unriddled the Anomalous Zeeman Effect and presaged electron spin." *Physica Scripta* 98: 014005.

Schmidt-Böcking, H., Templeton, A. and Trageser, W. (eds.) (2019). *Otto Sterns gesammelte Briefe. Band 2: Sterns wissenschaftliche Arbeiten und zur Geschichte der Nobelpreisvergabe*. Springer Spektrum.

Schnurmann, R. (1933). "Die magnetische Ablenkung von Sauerstoffmolekülen." *Zeitschrift für Physik* 85:212.

Schrödinger, E. (1920). "Über die Kohärenz in weitgeöffneten Bündeln." *Annalen der Physik* 61: 69.

Van Vleck, J.H. (1978). "Quantum Mechanics: The Key to Understanding Magnetism." *Science* 201: 113.

Westphal, W. (1919). "Zur Theorie des Radiometers." *Verhandlungen der Deutschen Physikalischen Gesellschaft* 21: 669.

Westphal, W. (1920). "Messungen am Radiometer." In: *Verhandlungen der Deutschen Physikalischen Gesellschaft* 22: 10-11.