OCTOBER 20-24, 2014. PEKING UNIVERSITY, BEIJING, CHINA

SPIN 2014

The 21st International Spin Physics Symposium

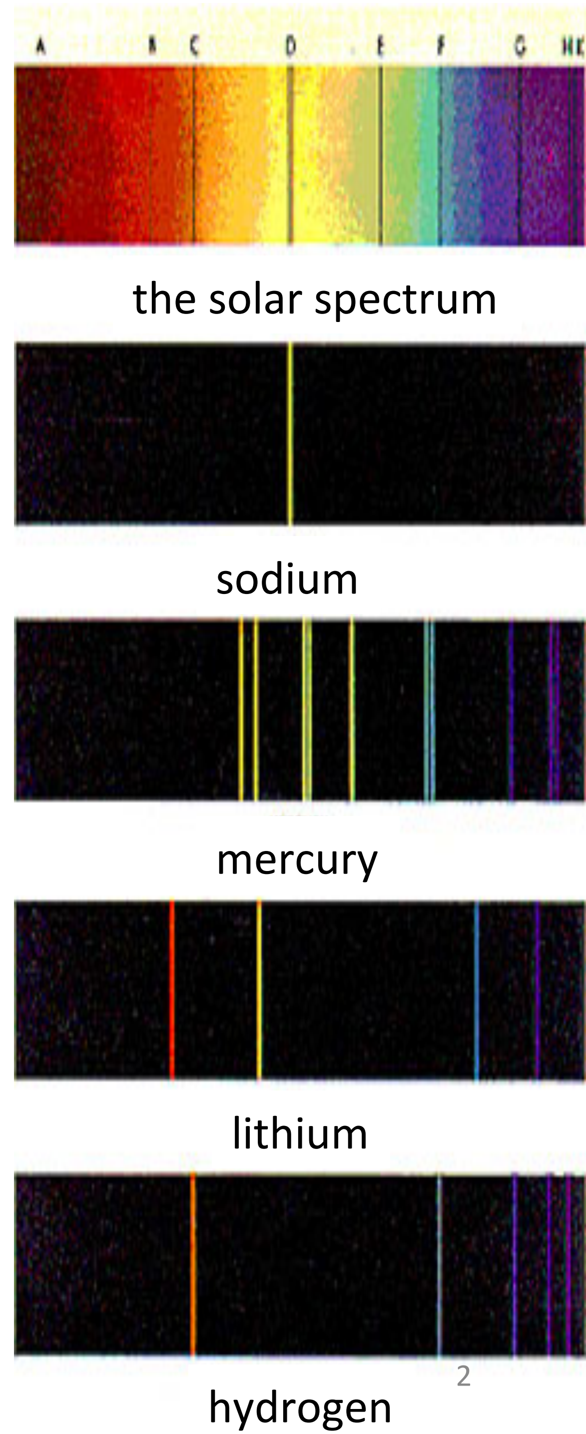
Symposium Summary

The Story of How Spin Came About

- Early 19th century: it was discovered that excited atoms produce spectral lines
- 1885: Balmer determines formula for hydrogen spectral lines
- 1896 Zeeman observes splitting of lines in magnetic field
- 1908: Ritz develops universal formula in terms of frequency differences
- Mysterious doubling of atomic states

Mechanische Zweidentigkeit (German)

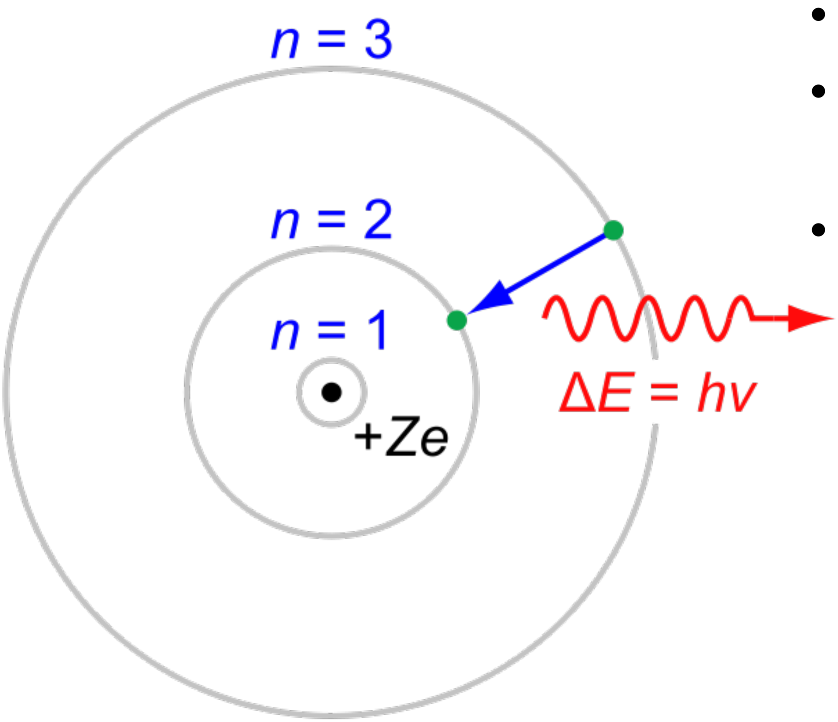
duplexity (English)



Zeeman, Einstein, Ehrenfest c. 1920 Amsterdam

The Bohr Theory of the Atom

N. Bohr, Phil. Mag., July 1913



- Electrons orbit nucleus
- Stationary orbits at discrete distances from nucleus
- Electrons can gain or lose energy by jumping from one allowed orbit to another

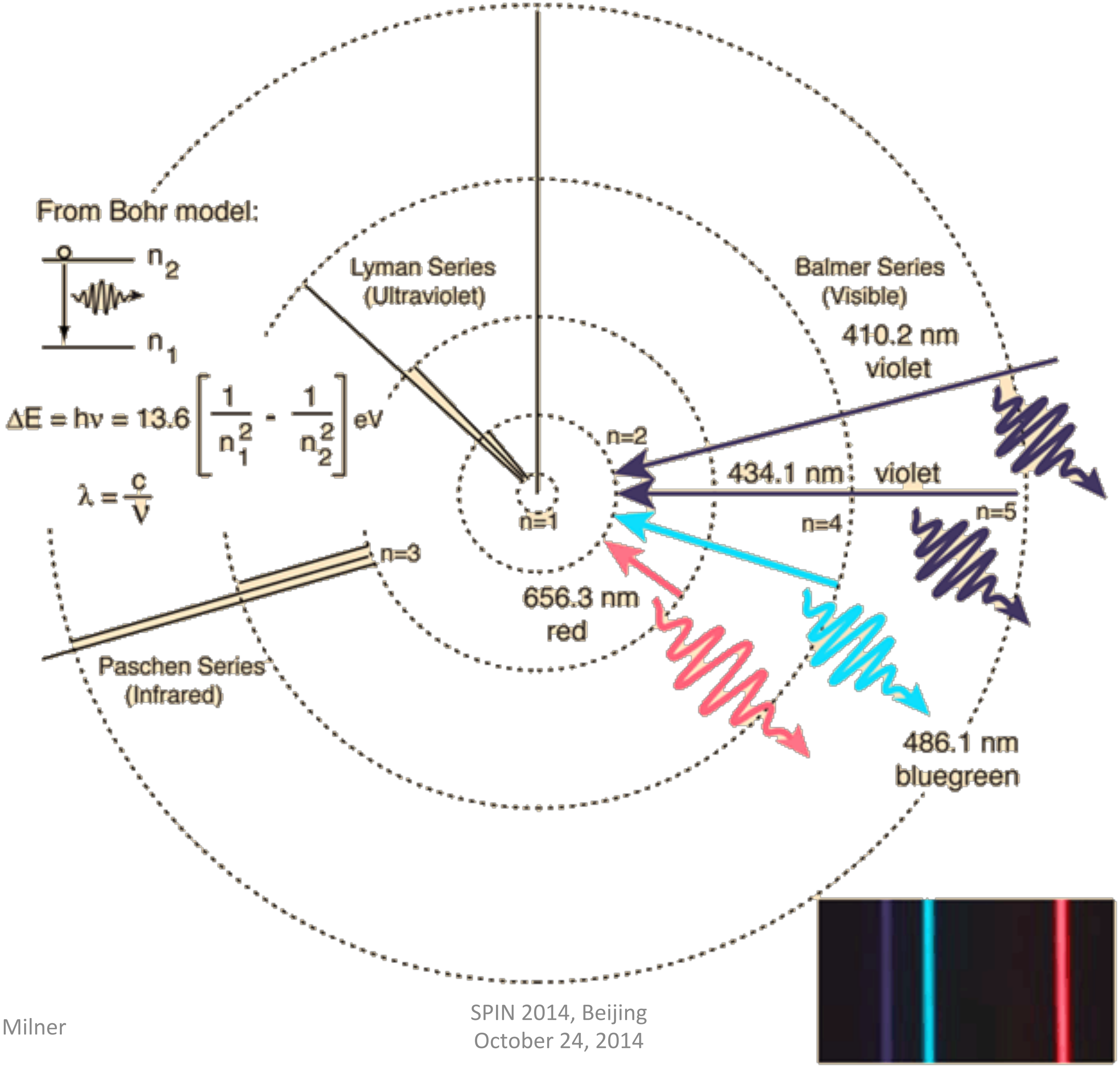
  $\Delta E = E_2 - E_1 = h\nu$ (Planck: photon)

  - Atom had angular momentum

    $L = n\hbar$ $n = 1,2,3,\ldots$..

    n=principal quantum number

  - Electron in n=1 state has a magnetic moment of $e\hbar/2m_e c$ (Bohr magneton)
  - Explains Rydberg formula


From Bohr model:
n2
n1
ΔE = hν = 13.6 [1/n1² - 1/n2²] eV
λ = c/ν
Lyman Series
(Ultraviolet)
Balmer Series
(Visible)
410.2 nm
violet
434.1 nm
violet
n=2
n=1
n=3
n=4
n=5
656.3 nm
red
486.1 nm
bluegreen
Paschen Series
(Infrared)

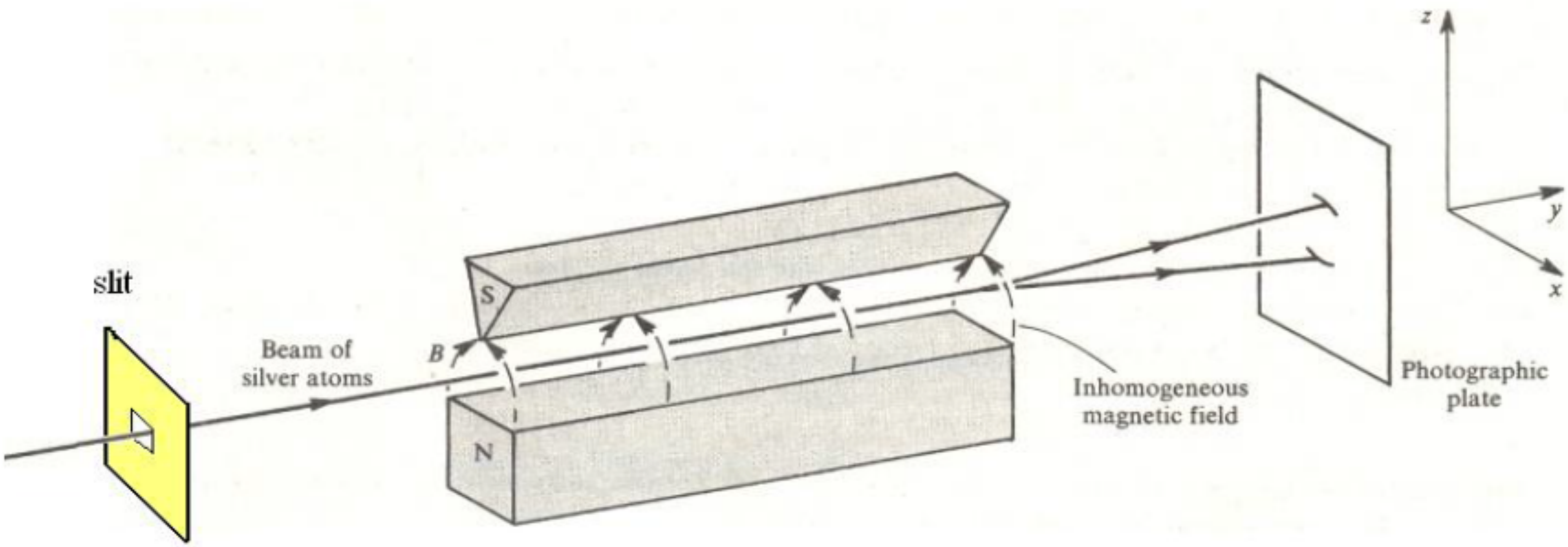
"If this nonsense of Bohr should in the end prove to be right, we will quit physics!"

Stern and von Laue 1913

Otto Stern

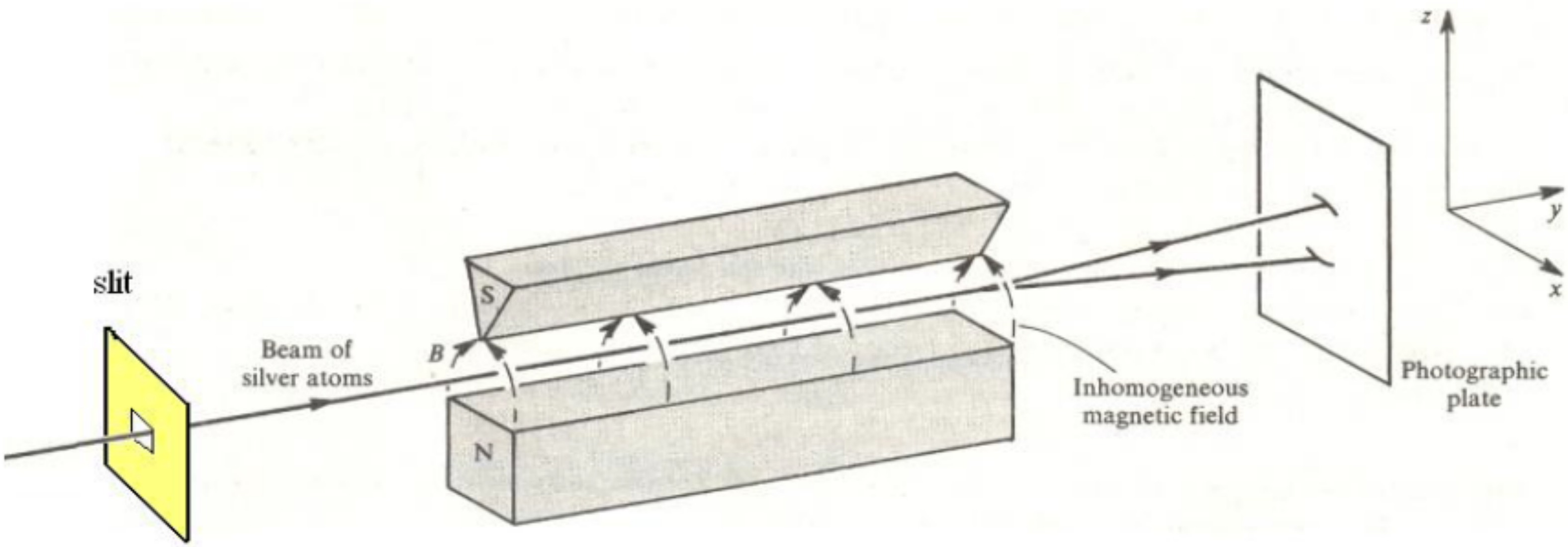
- Ph.D. Physical Chemistry, U. of Breslau, 1912
- First pupil of Albert Einstein
- Interested in light quanta, atoms, magnetism, and statistical physics
- Cigar smoker

The Stern-Gerlach Experiment



- The Stern-Gerlach Experiment (SGE) is performed in 1921
- A beam of hot (neutral) **Silver** ($_{47}$Ag) atoms was used.
- The beam is passed through an *inhomogeneous* magnetic field along **z** axis. This field would interact with the magnetic dipole moment of the atom, if any, and deflect it.
- Finally, the beam strikes a photographic plate to measure, if any, deflection.

The Stern-Gerlach Experiment



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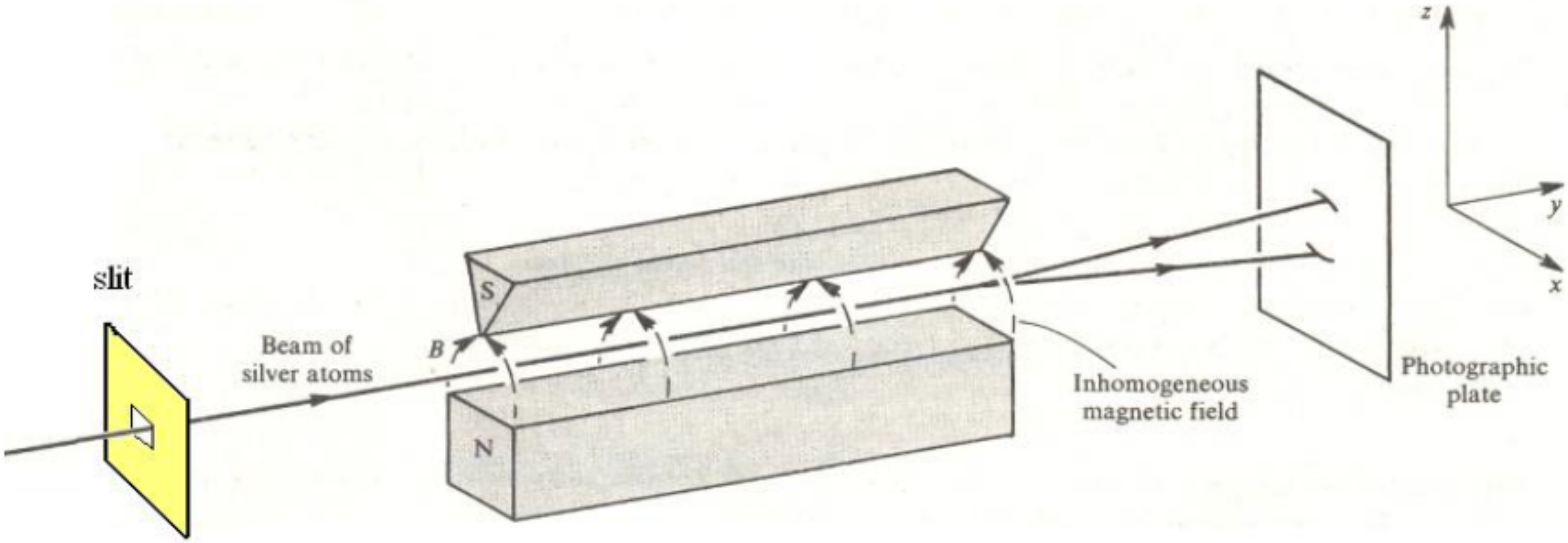

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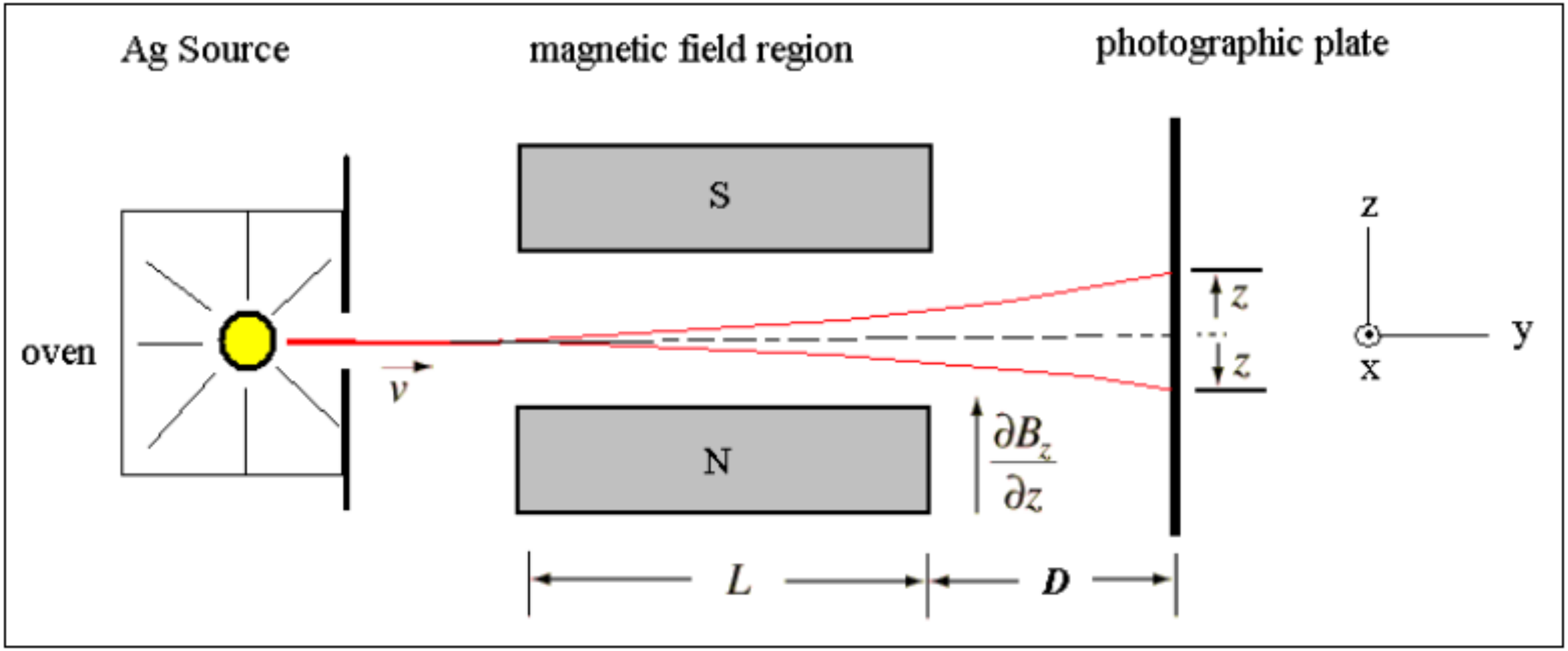


- From Bohr's theory, in the ground state, the silver atom has L=1 so there are two possible states
- In fact, silver has L=0 and the magnetic moment is due to the electron
- The S-G experiment measured (to ±10%) the magnetic moment of the silver atom to be 1 Bohr magneton

Ein Weg zur experimentellen Prüfung der Richtungsquantelung im Magnetfeld.

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

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

A Method Using a Magnetic Field to Demonstrate Space Quantization

Setzen wir z. B. $\frac{\partial \mathfrak{H}}{\partial s} = 10^4$ Gauß pro Zentimeter, $l = 3{,}3$ cm und $T = 1000^0$, so wird $s = 1{,}12 . 10^{-3}$ cm, d. h. $\frac{1}{100}$ mm.

Frankfurt a. M., August 1921. Institut für theoretische Physik.

Stern-Gerlach Experiment

- Stern thought of the idea for the experiment one cold morning while lying in his warm bed.
- Initially, Born was unimpressed: *"I thought always that this space quantization was a kind of symbolic expression for something which you don't understand.....I tried to persuade Stern that there was no sense in it but then he told me it was worth a try."*
- The experiment took more than a year to accomplish.
- Funding was a big problem.
  - Born gave public lectures on Einstein and relativity and charged a fee.
  - A check from Henry Goldman (founder of Goldman-Sachs) from New York saved the experiment.
- Stern and Gerlach discovered that the silver on the photographic plate only became visible when the plate came in contact with the smoke from Stern's cigar!

Das magnetische Moment des Silberatoms.

Von **Walther Gerlach** in Frankfurt a. M. und **Otto Stern** in Rostock.

(Eingegangen am 1. April 1922.)

In drei vorangegangenen kurzen Abhandlungen wurde 1. darauf hingewiesen, daß die Untersuchung der Ablenkung eines Molekularstrahles im Magnetfeld eine Prüfung der Richtungsquantelung ermöglicht [1]), 2. der Nachweis erbracht, daß das normale Silberatom im Gaszustand ein magnetisches Moment besitzt [2]), 3. der experimentelle Beweis der Richtungsquantelung im Magnetfeld [3]) mitgeteilt. Die folgende Notiz bringt die Messung des magnetischen Moments des Silberatoms.

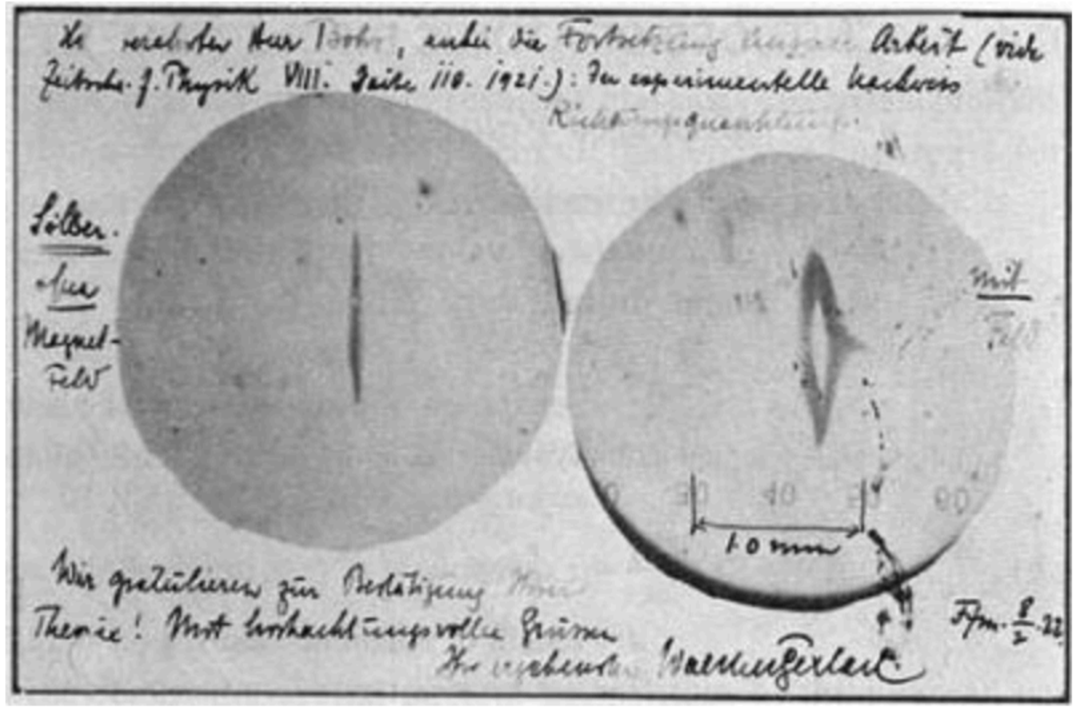
Hierzu ist zweierlei nötig: Erstens muß der Abstand z des Atomstrahls von der Polschneide sowohl im unabgelenkten (Magnetfeld 0) wie im abgelenkten (Magnetfeld $\mathfrak{H}$) Zustand genau bekannt sein. Zweitens muß in den Entfernungen, in denen die abgelenkten Atome längs der Schneide vorbeilaufen, die Inhomogenität des Feldes in Richtung senkrecht zum Strahl $\left(\frac{\partial \mathfrak{H}}{\partial z}, \text{ s. I}\right)$ gemessen werden.

Ersteres wurde durch weitere Verbesserungen an der Justierungsmethode sowie durch am Ende der Schneide angebrachte Marken aus Quarzfäden, welche im Silberniederschlag als „Schatten" zu sehen sind und Bezugspunkte für die Ausmessung geben, erreicht. Auch wurden noch engere Spaltblenden (als in III) verwendet, wodurch die Niederschläge schmaler wurden.

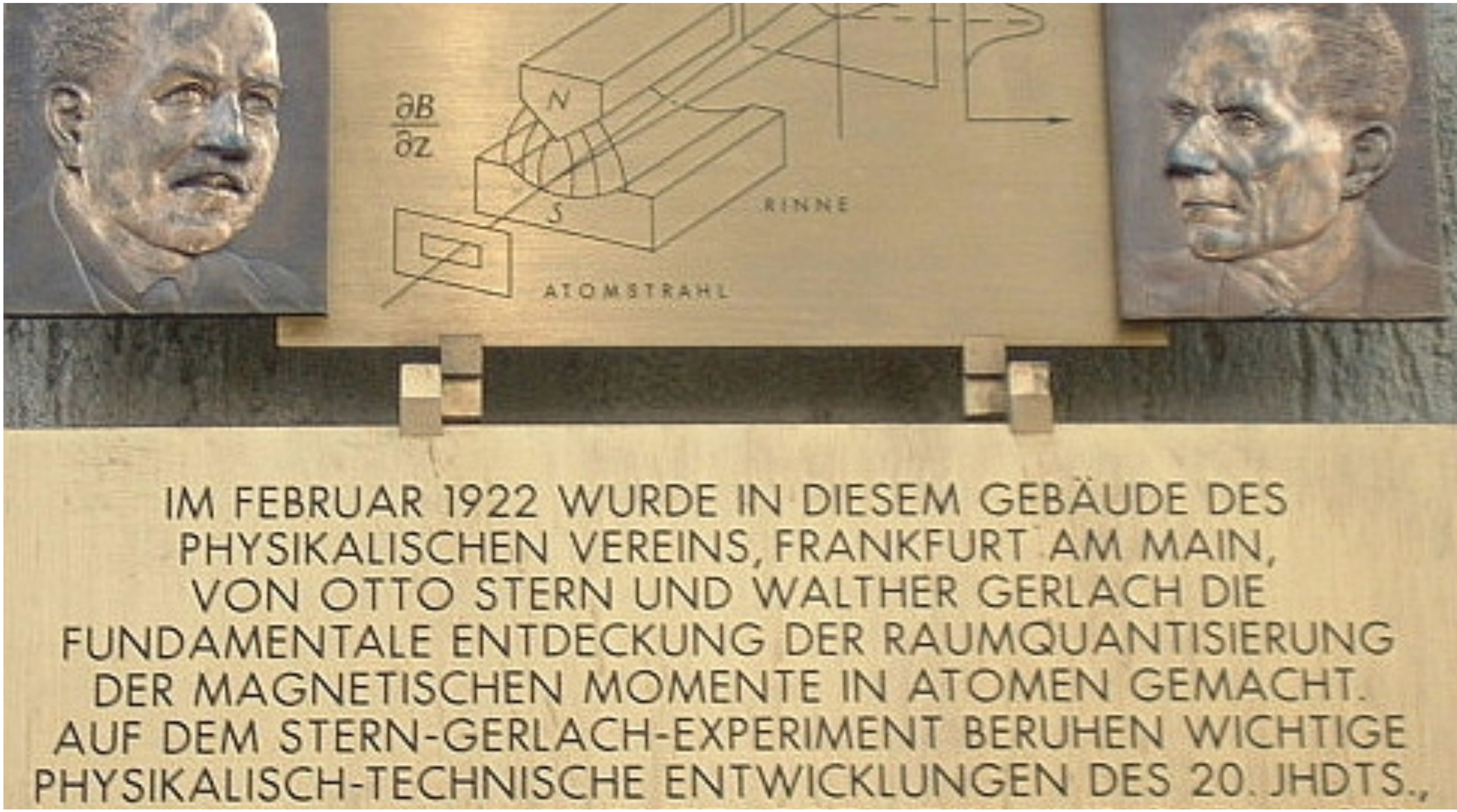
Die Inhomogenität des Magnetfeldes wurde über die ganze Feldbreite bestimmt aus Messungen von grad $\mathfrak{H}^2$ durch direkte Wägung der Abstoßungskraft auf einen sehr kleinen Probekörper aus Wismut von Punkt zu Punkt und der Messung der Feldstärke durch Widerstandsänderung eines dünnen parallel zur Schneide gespannten Wismutdrahtes. Die folgende Tabelle gibt die Inhomogenität in Gauß pro cm

z mm	$\frac{\partial \mathfrak{H}}{\partial z} \times 10^{-4}$
0,15	23,6
0,20	17,3
0,30	13,5
0,40	11,2

[1]) O. Stern, ZS. f. Phys. 7, 249, 1921 (zitiert als I).
[2]) W. Gerlach und O. Stern, ebenda 8, 110, 1921 (zitiert als II).
[3]) W. Gerlach und O. Stern, ebenda 9, 349—352, 1922 (zitiert als III).



The postcard Walther Gerlach sent to Niels Bohr on 8 February 1922 to tell him about the discovery of space quantisation. It shows a photograph of the beam splitting (actually, the width of the splitting is only 0.2 millimetre), with the note: "Attached the continuation of our work (Zeitschrift für Physik **8** (1921) 110): The experimental proof of directional quantisation. Silver without magnetic field / with magnetic field. We congratulate on the confirmation of your theory." (Source: Physics Today, Courtesy AIP Emilio Segrè Visual Archives). The same photos are also shown in the short discovery paper by Otto Stern and Walther Gerlach: *Der experimentelle Nachweis der Richtungsquantelung im Magnetfeld*, Zeitschrift für Physik **9** (1922) 349.



∂B
∂z
N
S
RINNE
ATOMSTRAHL
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.,

The Spinning Electon

- 1921: A.H. Compton suggests that the electron has a magnetic moment
- There was the mysterious doubling of the atomic states.
- Kronig suggested to Pauli that the origin might be the spin of the electron. Pauli was very hostile to the idea.
- In 1925, the idea of spin also occurred to Uhlenbeck and Goudsmit, who were students of Ehrenfest at Leiden. They showed it to Ehrenfest who strongly encouraged them and they wrote it up. They discussed it with Lorentz and he again was hostile.
- They went back to Ehrenfest and asked to withdraw their paper. Ehrenfest said. "It is too late, I have already sent it in for publication."

FIFTY YEARS OF SPIN: Personal reminiscences
George E. Uhlenbeck

Citation: Phys. Today **29**(6), 43 (1976); doi: 10.1063/1.3023519

FIFTY YEARS OF SPIN: It might as well be spin
Samuel A. Goudsmit

Citation: Phys. Today **29**(6), 40 (1976); doi: 10.1063/1.3023518

George Uhlenbeck

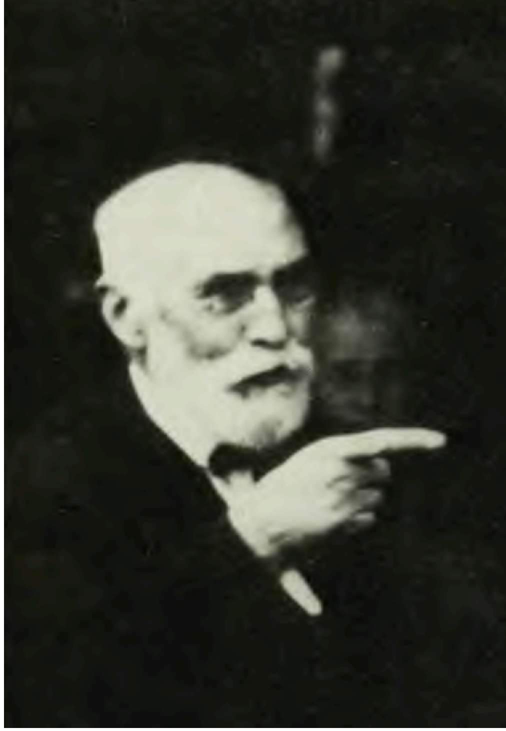
Samuel Goudsmit

Ehrenfest's students, Leiden 1924. Left to right: Gerhard Dieke, Samuel Goudsmit, Jan Tinbergen, Paul Ehrenfest, Ralph Kronig, and Enrico Fermi.

Goudsmit and Pauli 1931

Spin, Leiden University and all that. The class of Paul Ehrenfest (near the center) stands in front of the door of the Institute for Theoretical Physics at the University of Leiden, probably in 1923. Albert Einstein stands in the doorway, but the reason for the picture was a visit by Douglas Hartree (between Einstein and Ehrenfest). The author, Sam (then Sem) Goudsmit, is on the right. Jan Tinbergen (left, no hat) switched fields after obtaining his PhD in physics, and received a Nobel Prize in economics. The tall man next to Ehrenfest is Gerhard Dieke, who later became physics chairman at Johns Hopkins. The woman beside Einstein is Ini Roelofs; Jaap Voogt and Bernard Polak are fourth and fifth from left.

Criticism: electron has a classical radius r_e (Lorentz)



Electrostatic energy = rest mass energy
$e^2/4\pi\varepsilon_0 r_e = m_e c^2$ =>

$r_e = (1/4\pi\varepsilon_0)(e^2/m_e c^2) = 2.8 \times 10^{-15}$ m

$L=[⅖ m_e r_e^2]\omega = ⅖ m_e r_e (r_e\omega) = ⅖ m_e r_e V_s$ where V_s is the velocity at the surface of the electron

If L = 1 Bohr magneton (as proposed by Uhlenbeck and Goudsmit) then

$⅖ m_e r_e V_s \approx ½\hbar$ => $V_s \approx 1.25\, \hbar/(m_e r_e) = 3.25 \times 10^9\ ms^{-1} >$ c

Letters to the Editor.

[*The Editor does not hold himself responsible for opinions expressed by his correspondents. Neither can he undertake to return, nor to correspond with the writers of, rejected manuscripts intended for this or any other part of* NATURE. *No notice is taken of anonymous communications.*]

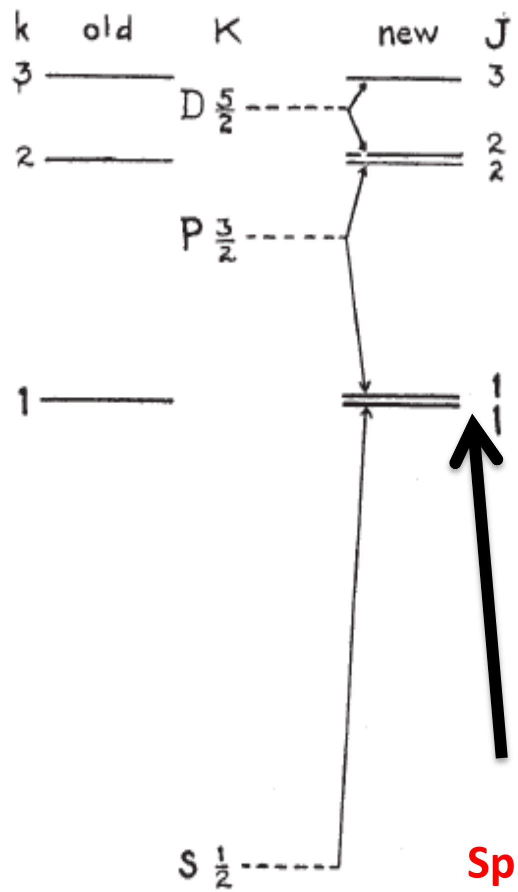


Fig. 1.

Spin doublets

In conclusion, we wish to acknowledge our indebtedness to Prof. Niels Bohr for an enlightening discussion, and for criticisms which helped us distinguish between the essential points and the more technical details of the new interpretation.

G. E. UHLENBECK.
S. GOUDSMIT.
Instituut voor Theoretische Natuurkunde,
Leyden, December 1925.

HAVING had the opportunity of reading this interesting letter by Mr. Goudsmit and Mr. Uhlenbeck, I am glad to add a few words which may be regarded as an addition to my article on atomic theory and mechanics, which was published as a supplement to NATURE of December 5, 1925. As stated there, the attempts which have been made to account for the properties of the elements by applying the quantum theory to the nuclear atom have met with serious difficulties in the finer structure of spectra and the related problems. In my article expression was given to the view that these difficulties were inherently connected with the limited possibility of representing the stationary states of the atom by a mechanical model. The situation seems, however, to be somewhat altered by the introduction of the hypothesis of the spinning electron which, in spite of the incompleteness of the conclusions that can be derived from models, promises to be a very welcome supplement to our ideas of atomic structure. In fact, as Mr. Goudsmit and Mr. Uhlenbeck have described in their letter, this hypothesis throws new light on many of the difficulties which have puzzled the workers in this field during the last few years. Indeed, it opens up a very hopeful prospect of our being able to account more extensively for the properties of elements by means of mechanical models, at least in the qualitative way characteristic of applications of the correspondence principle. This possibility must be the more welcomed at the present time, when the prospect is held out of a quantitative treatment of atomic problems by the new quantum mechanics initiated by the work of Heisenberg, which aims at a precise formulation of the correspondence between classical mechanics and the quantum theory.

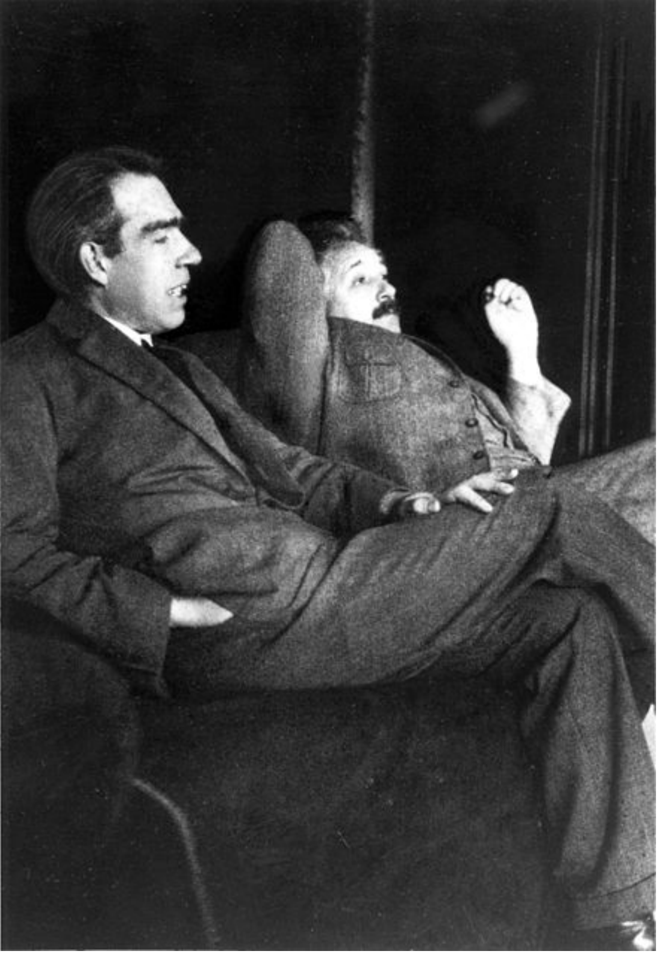
N. BOHR.
Copenhagen, January 1926.

Note well!

- Stern-Gerlach was the right experiment but was explained by the wrong theory at the time.
- Two graduate students, Uhlenbeck and Goudsmit, postulated spin over the strong criticism of their senior colleagues.
- Their advisor (Ehrenfest) fully supported them.
- At the time, the S-GE was not connected to spin – no mention of it in Uhlenbeck and Goudsmit's paper.
- None of this work was recognized by the Nobel Prize Committee.

Spatial quantization and spin are cornerstones of the physicists description of the universe

- Nuclear magnetic resonance
- Shell model of the nucleus
- Optical pumping
- The laser
- Lamb shift => QED
- Anomalous moments of the leptons
- Digital communication
- Atomic clocks => GPS
- ……………………………….

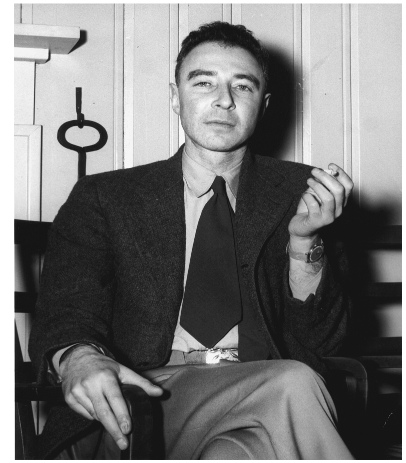


Bohr and Einstein in
Ehrenfest's house,
Leiden, December 1925

Bohr to Ehrenfest (1919)

I am sitting and thinking of all what you have told me about so many different things, and whatever I think of I feel that I have learned so much from you which will be of great importance for me; but, at the same time, I wish so much to express my feeling of happiness over your friendship and of thankfulness for the confidence and sympathy you have shown me, I find myself so utterly incapable of finding words for it.

Kamerlingh-Onnes Lab,
Leiden, 1926



Ehrenfest to Oppenheimer 1928

If you intend to mount heavy mathematical artillery again during your coming year in Europe, I would ask you not only not to come to Leiden, but if possible not even to Holland, and just because I am really so fond of you and want to keep it that way. But if, on the contrary, you want to spend at least your first few months patiently, comfortably, and joyfully in discussions that keep coming back to the same few points, chatting about a few basic questions with me and our young people- and without thinking much about publishing (!!!)-why then I welcome you with open arms!!

Spin key to explaining the physical universe: 1920-50

- 1920s: Quantum mechanics developed to describe atomic systems
- 1922: Stern-Gerlach experiment carried out with silver atoms
- 1925: Pauli exclusion principle formulated
  Uhlenbeck and Goudsmit hypothesize intrinsic spin as a property of the electron
- 1926: Thomas correctly applied relativistic calculations to spin-orbit coupling in atomic systems; resolved missing factor of two in the derived *g*-values
- 1927: Wrede, Phipps&Taylor: observed deflection of atomic hydrogen in magnetic field gradient
- 1928: Dirac equation for spin-½ particles: predicted the existence of the positron
- 1929: Mott wonders if we can observe electron spin directly: proposes scattering electrons from nuclei to measure the scattering asymmetry due to electron spin-orbit coupling

Essential role of electron spin in explaining the Periodic Table of the chemical elements established

- 1942: Shull *et al*. verifies Mott's predictions: electron spin is an experimental tool
- 1946: Schwinger suggests double scattering to determine the sign of the spin-orbit splitting
- 1949: Nuclear shell model: strong spin-orbit coupling

Essential role of proton and neutron spin in explaining the structure of atomic nuclei established

Symposia on Polarization Phenomena in Nuclear Reactions

- Started at Basel in 1960 (Basel: first working polarized ion source and scattering experiments with polarized beam from source)
- Following every 5 years:
  - Karlsruhe (1965)
  - Madison (1970)
  - Zurich (1975)
  - Santa Fe (1980)
  - Osaka (1985)
  - Paris (1990)
  - Bloomington (1994)

PROCEEDINGS OF THE INTERNATIONAL SYMPOSIUM ON POLARIZATION PHENOMENA OF NUCLEONS

Basel, July 4–8, 1960

Editors: P. HUBER and K. P. MEYER

HELVETICA PHYSICA ACTA
SUPPLEMENTUM VI

1961
BIRKHÄUSER VERLAG BASEL
UND STUTTGART

Basel Convention

In nuclear interactions the positive polarization of particles with spin $^1/_2$ is taken in the direction of the vector product $\boldsymbol{k}_i \times \boldsymbol{k}_0$, where $\boldsymbol{k}_i$ and $\boldsymbol{k}_0$ are the circular wave vectors of the incoming and outgoing particles respectively.

This agreement is called the 'Basel Convention'.

In 1970 the Madison convention for spin-1

Symposia on High Energy Spin Physics

- Started at Argonne in 1974 at ANL: First polarized HE proton beam in the 12 GeV **Z**ero-**G**radient-**S**ynchrotron)
- Following, every two years:
  - Argonne (1976, 1978)
  - Lausanne (1980)
  - BNL (1982)
  - Marseille (1984)
  - Protvino (1986)
  - Minneapolis (1988)
  - Bonn (1990)
  - Nagoya (1992)
  - Bloomington (1994)

1st International High Energy Spin Physics Symposium at Argonne, 1974

SPIN 2014 at Beijing is 40th anniversary!

Joint International Symposia on Spin Physics

- Started at Amsterdam in 1996
- Following every 2 years:
  - Protvino (1998)
  - Osaka (2000)
  - BNL (2002)
  - Trieste (2004)
  - Kyoto (2006)
  - Charlottesville (2008)
  - Juelich (2010)
  - Dubna (2012)
  - Beijing (2014)

International Spin Physics Committee

International Spin Physics Committee

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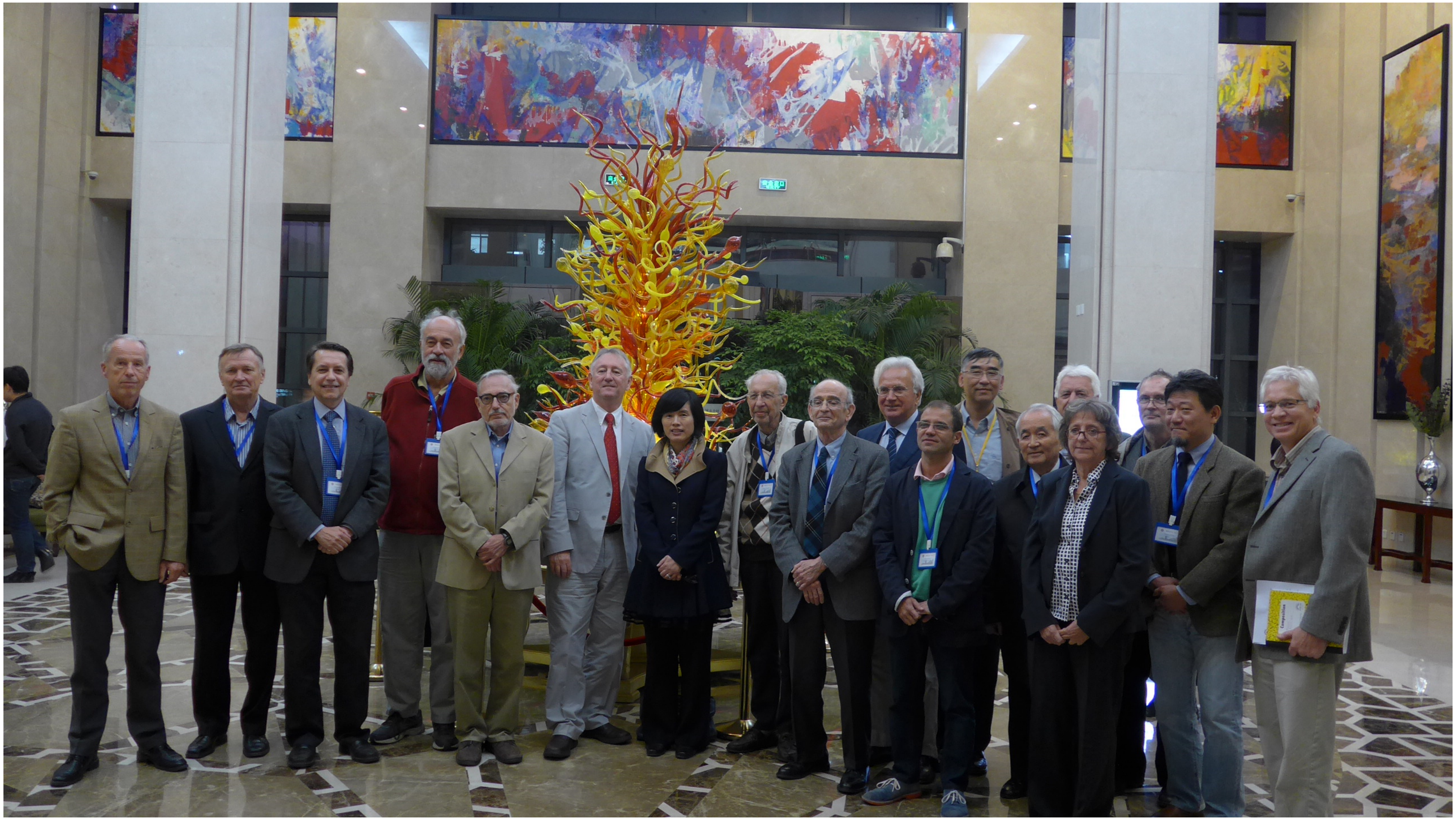
Meeting of ISPC at SPIN 2014, Beijing, October 21, 2014



The ISPC this week elected our next Chair to serve 2017-2020

The ISPC this week elected our next Chair to serve 2017-2020

Haiyan Gao

ISPC Chairs 1974-2020

Workshop on Polarized Sources, Targets and Polarimetry PSTP 2015

- It was decided by the ISPC that PSTP 2015 will be held at the Ruhr University, Bochum, Germany in mid-September, 2015
- The co-organizers are Werner Meyer and Gerhard Reicherz

22nd International Spin Physics Symposium 2016

- It was decided by the ISPC that the next International Spin Physics Symposium will be held at the University of Illinois in Urbana-Champaign, Illinois, USA in late September or early October, 2016.
- The co-organizers are Matthias Grosse Perdekamp from University of Illinois at Urbana-Champaign and Anselm Vossen from Indiana University.

Summary

- Spin is the foundational concept that has allowed physicists to understand and explain the atom.
- Over 90 years, spin physics has produced increasingly more powerful experimental tools with which to explore the structure of the universe.
- The 21st International Spin Physics Symposium here in Beijing has showcased the exciting frontier research in progress worldwide.
- We look forward to the 22nd Symposium in 2016 in Urbana-Champaign, USA.