The impact of the Stern-Gerlach-Experiment on the Development of Quantum Technologies

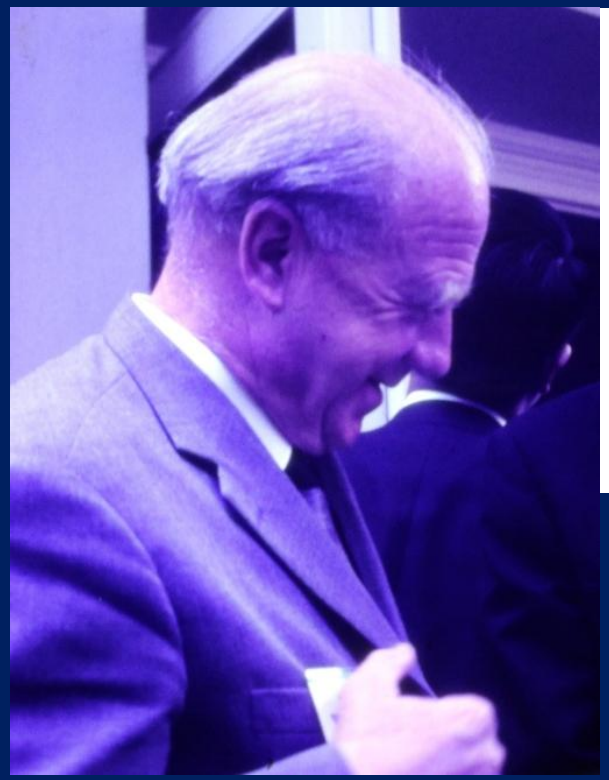
The worldwide Physics community celebrates this year 2025

100 years of Quantum Physics

This seminar is one of the many events with which the DPG remembers the birth of Quantum Physics 100 years ago

and thus we celebrate the birth of many new quantum technologies.

Why 1925: was in 1925 really the "birth" of Quantum Physics?



In 1925 Werner Heisenberg published his famous paper

„Über quantentheoretische Umdeutung kinematischer und mechanischer Beziehungen"

On quantum-theoretical reinterpretation of kinematic and mechanical relationships

Z. Physik 33, 879–893 (1925) (submitted on 29. Juli 1925.)

(first concept developed during vacation on island Helgoland)

What achieved Heisenberg during his vacation on Helgoland

He derived an amplitude relationship for a transition ($n=>n_1=>n_2$) in an anharmonic oscillator, which is the product of two amplitudes corresponding to two successive quantum leaps:

$$b_2(n,n-2) = a_1(n,n-1) \bullet a_2(n-1, n-2)$$

and they do not commute.

which, unlike in classical theory is not a square:

$$b_2(n,n-2) = a_1^2(n,n-1)$$

As David Cassidy had already noted in his 1992 biography of Heisenberg, this quantum-theoretical reinterpretation of classical kinematics was still far from quantum mechanics.

Planck's constant was still completely missing.

How this is seen by an historian?

Arne Schirrmacher, Physik Journal 24, (2025), Nr.1

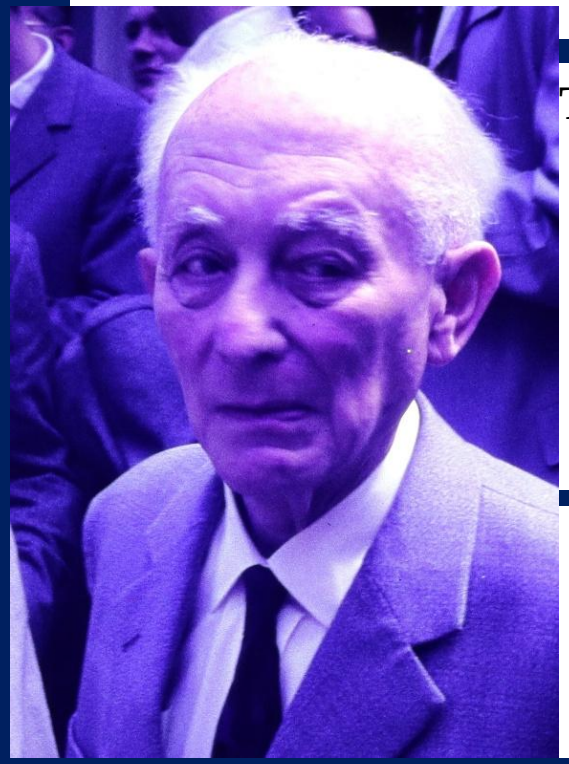
h wie Hilfsgröße und

Auxiliary quantity

Heureka auf Helgoland?

Gibt es eine gute Geschichtsschreibung der Quantenphysik, und wenn ja, wieso sollte sie uns interessieren?

Arne Schirrmacher wrote:
The earliest meaningful source of Heisenberg's achievements is the five-page letter of Heisenberg to Wolfgang Pauli dated June 24, 1925.
The conclusion of this analysis on the history of science is:
Heisenberg's later recollection that matrix mechanics emerged in a single eureka moment during his journey to Helgoland is demonstrably false.



The judgment of MPI researchers makes it clear here that Heisenberg did not yet consider his equations of motion to be the dynamic equations of a new quantum mechanics.

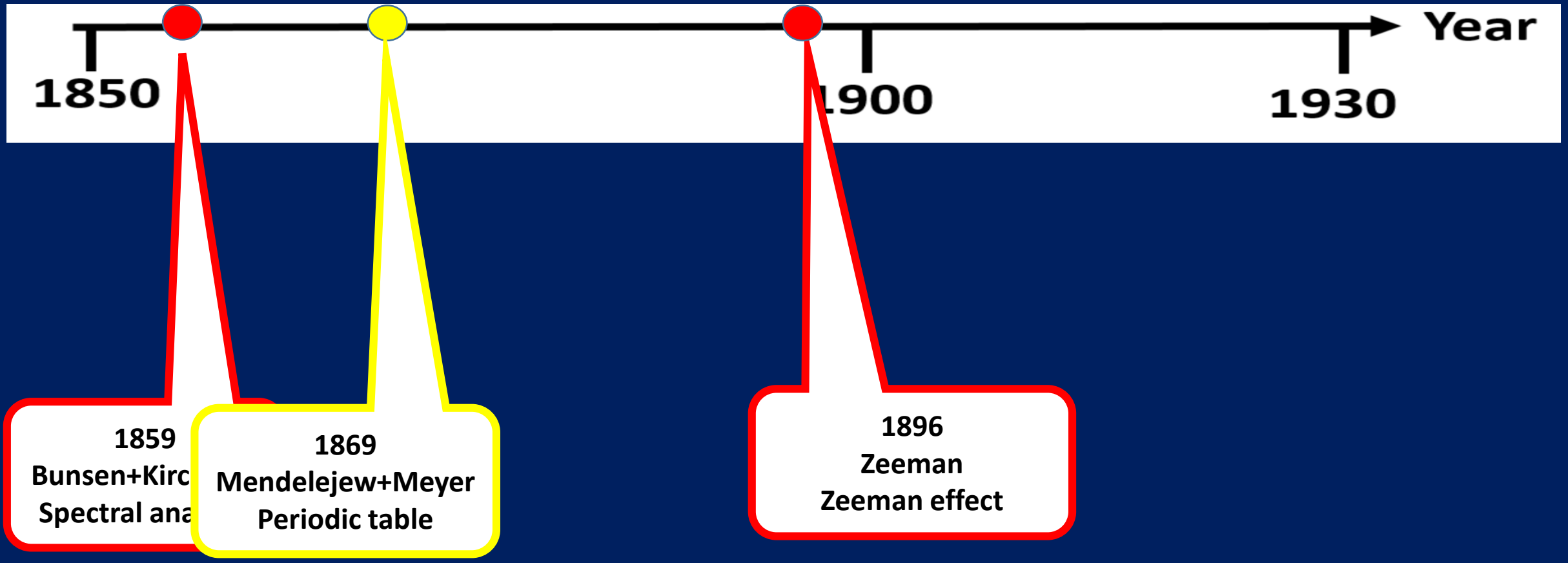
Only Born and Jordan reinterpreted the classical theory at a deeper level, using techniques of analytical mechanics at the level of the Hamiltonian function.
Then the Göttingen matrix mechanics became "a new, independent dynamic theory that actually replaces classical mechanics".

Heisenberg acknowledged this in a letter to Pauli that the commutation relation in matrix notation was a very clever idea of Born!
“Born’s and Jordan's commutation relation was not just a "quantum condition“, but it created "a new fundamental law of this mechanics".

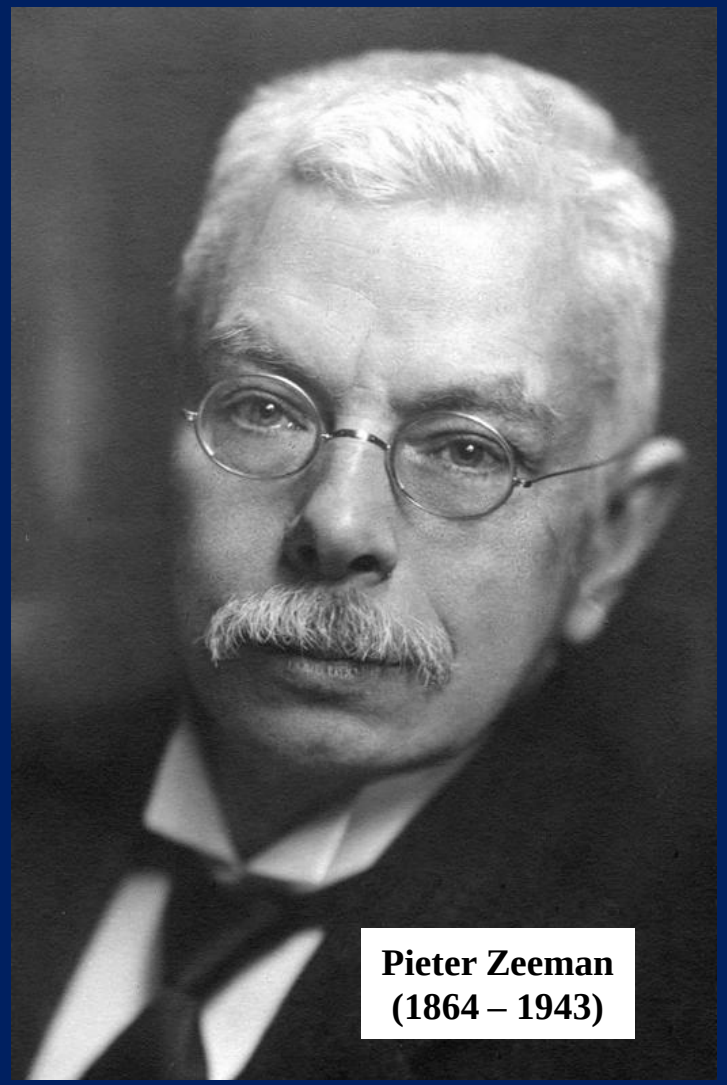
Finally, the famous "three-man paper" by Born, Heisenberg, and Jordan, completed in November 1925, provided all the essential concepts and the mathematical structure of the new quantum mechanics and can be considered its first comprehensive formulation of Quantum Physics.

The status of Quantum Physics before 1925:

Graphic of time series of milestone discoveries of intra-atomic structure.



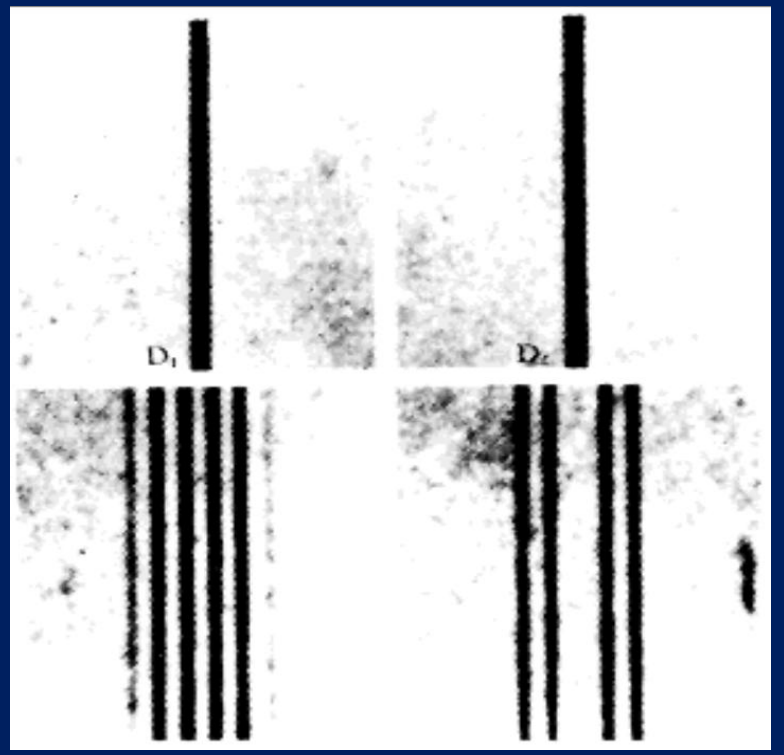
Zeeman effect ZE (1896-7)



Pieter Zeeman
(1864 – 1943)

When atoms emit light in the presence of an external magnetic field, the lines split into further sharp lines, called multiplets.

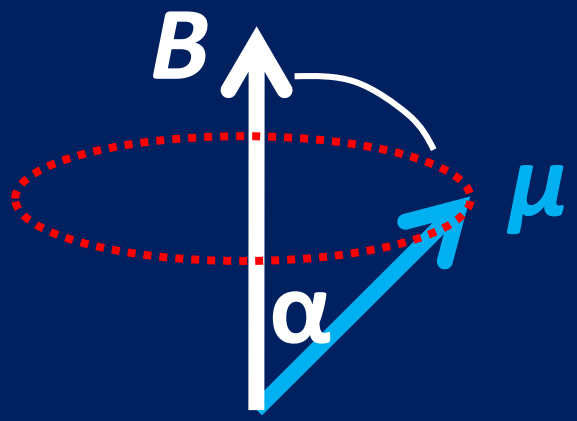
⇒ Normal ZE Triplets, Quintets,
=> Anomal ZE Dublets, Quartets…



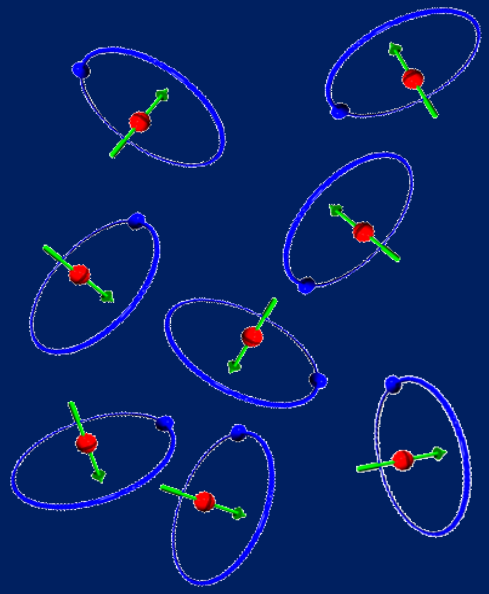
According to the laws of classical physics, the atomic magnetic moment of the electron shell should perform a Larmor precession in an external magnetic field *B*, whereby the angle of inclination α between the vectors *B* and *μ* remains constant. The change in energy ΔE of the electron through interaction with the *B* field is

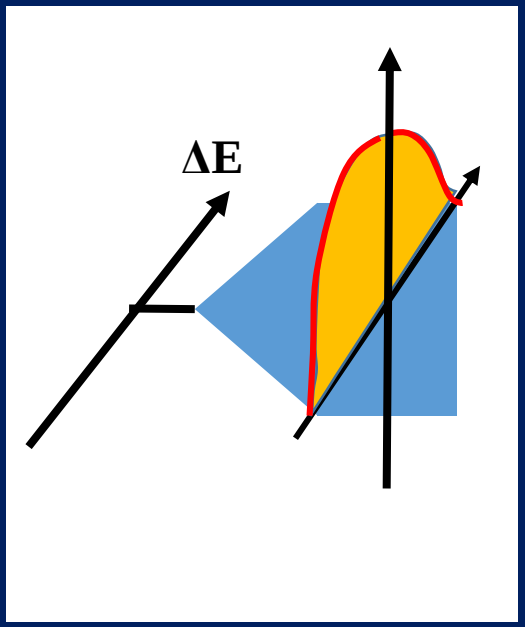
$$\Delta E = h\,(e/\mu)\,B\cos\alpha.$$

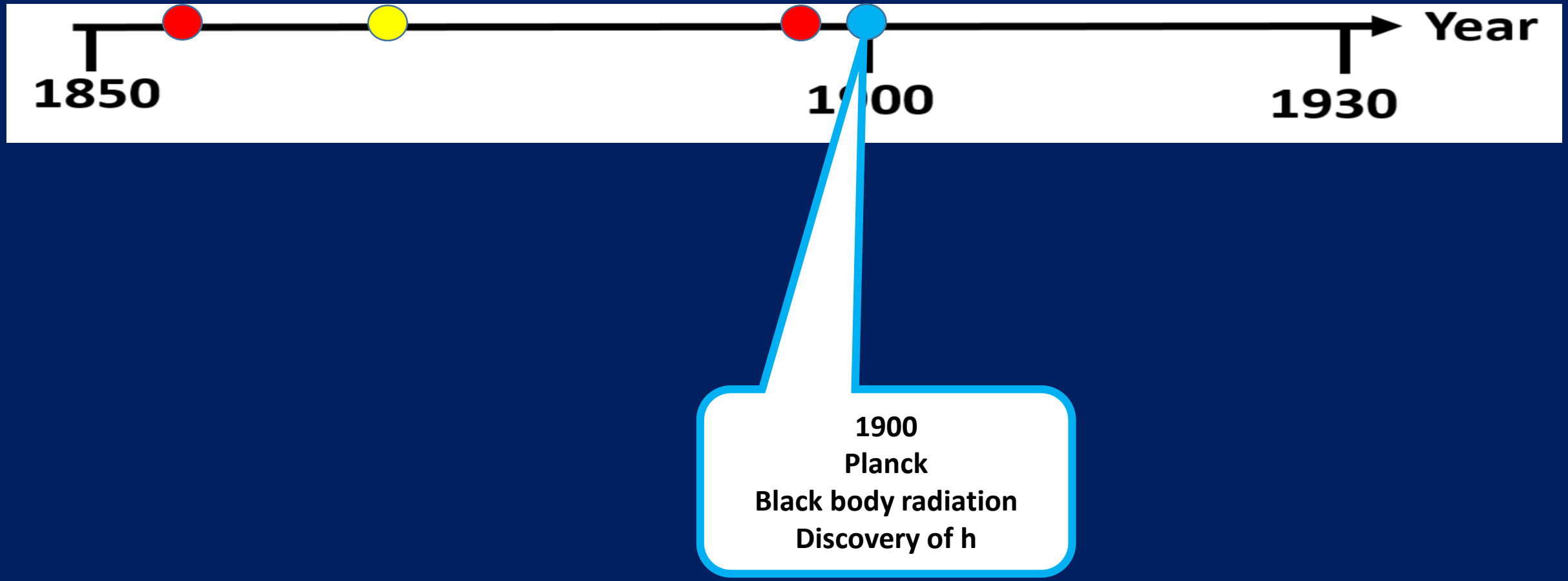
Since all directions α are equally probable before a magnetic field is switched on, the energy of an inner atomic state and thus the photon transition from one state to another must broaden in the presence of a magnetic field.

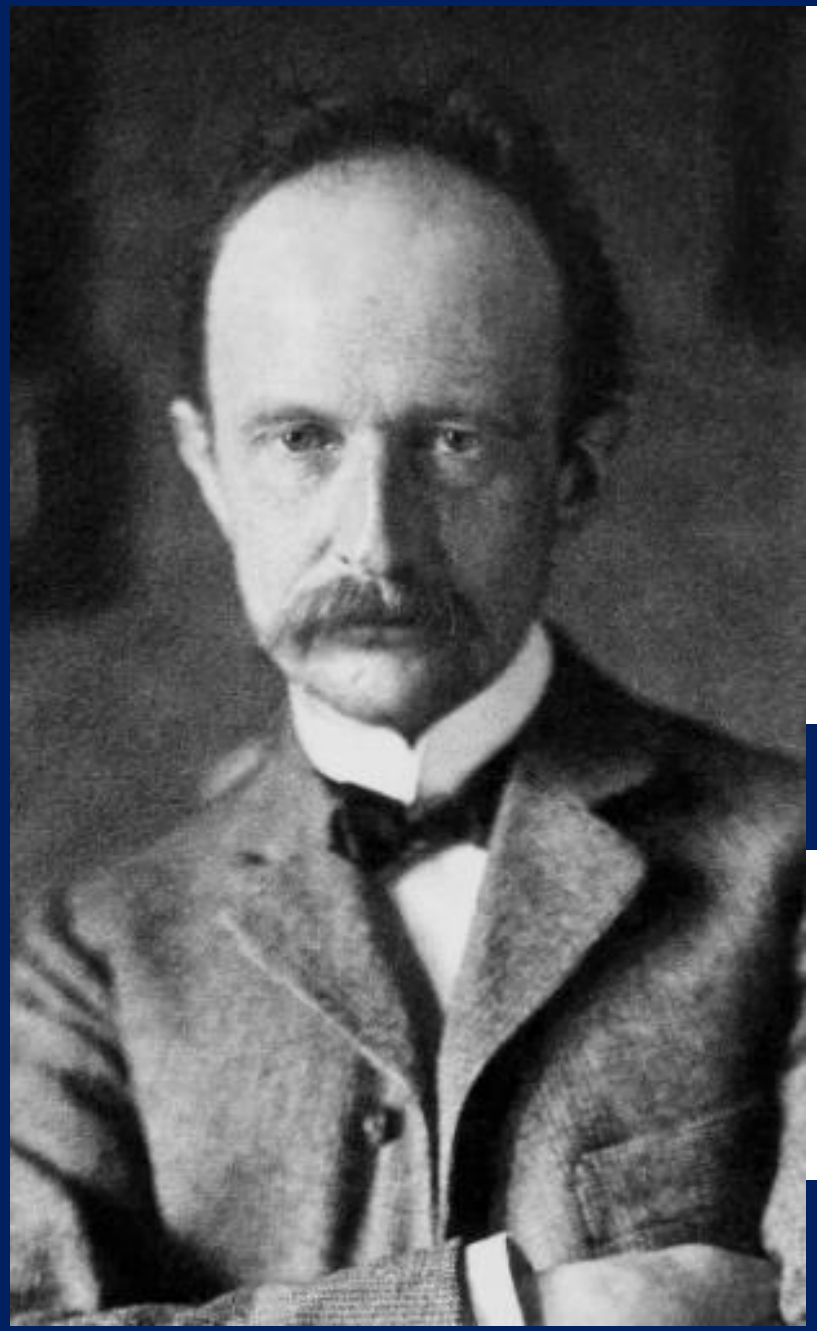


$$\Delta E \sim B \bullet \mu \bullet \cos\alpha$$






Year
1850
1900
1930
1900
Planck
Black body radiation
Discovery of h



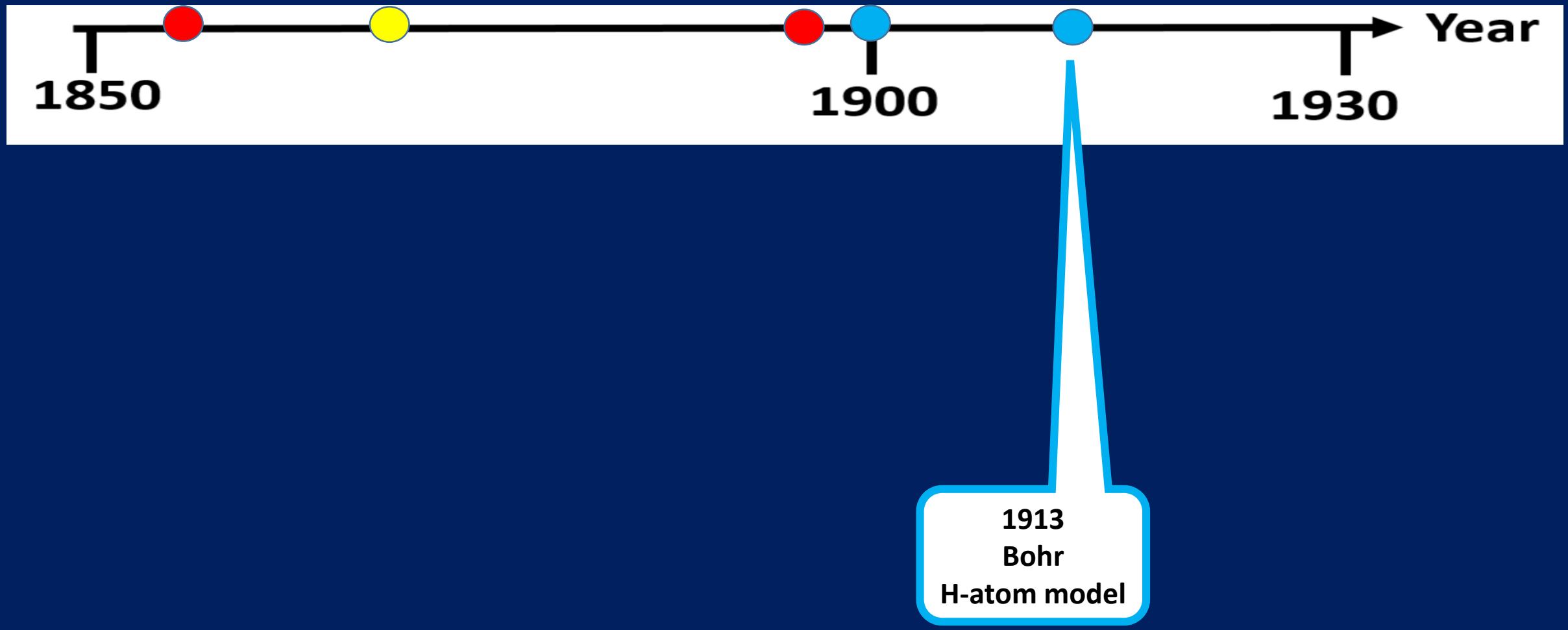
The discovery of the quantum of action, h,
by Max Planck (1858-1947) in 1900
was one of the most important discoveries in quantum physics.
Max Planck was able to describe the radiation spectrum of a black body perfectly by postulating
that light is absorbed and emitted in quanta of energy

$$E_\gamma = h \bullet \nu,$$

where ν is the frequency of the photon wave.

He postulated that the
phase space is quantized
in multiples of

$$n \bullet h/2\pi.$$

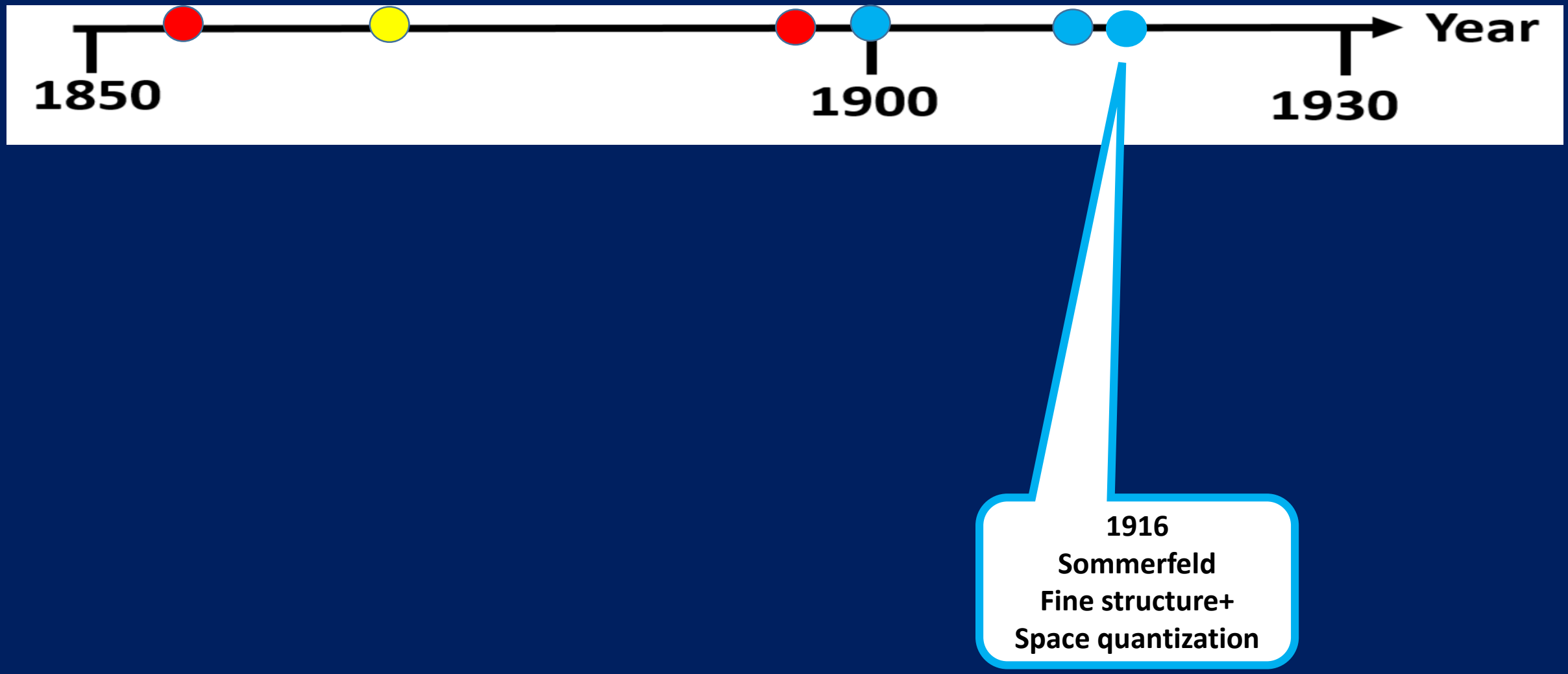

Year
1850
1900
1930
1913
Bohr
H-atom model

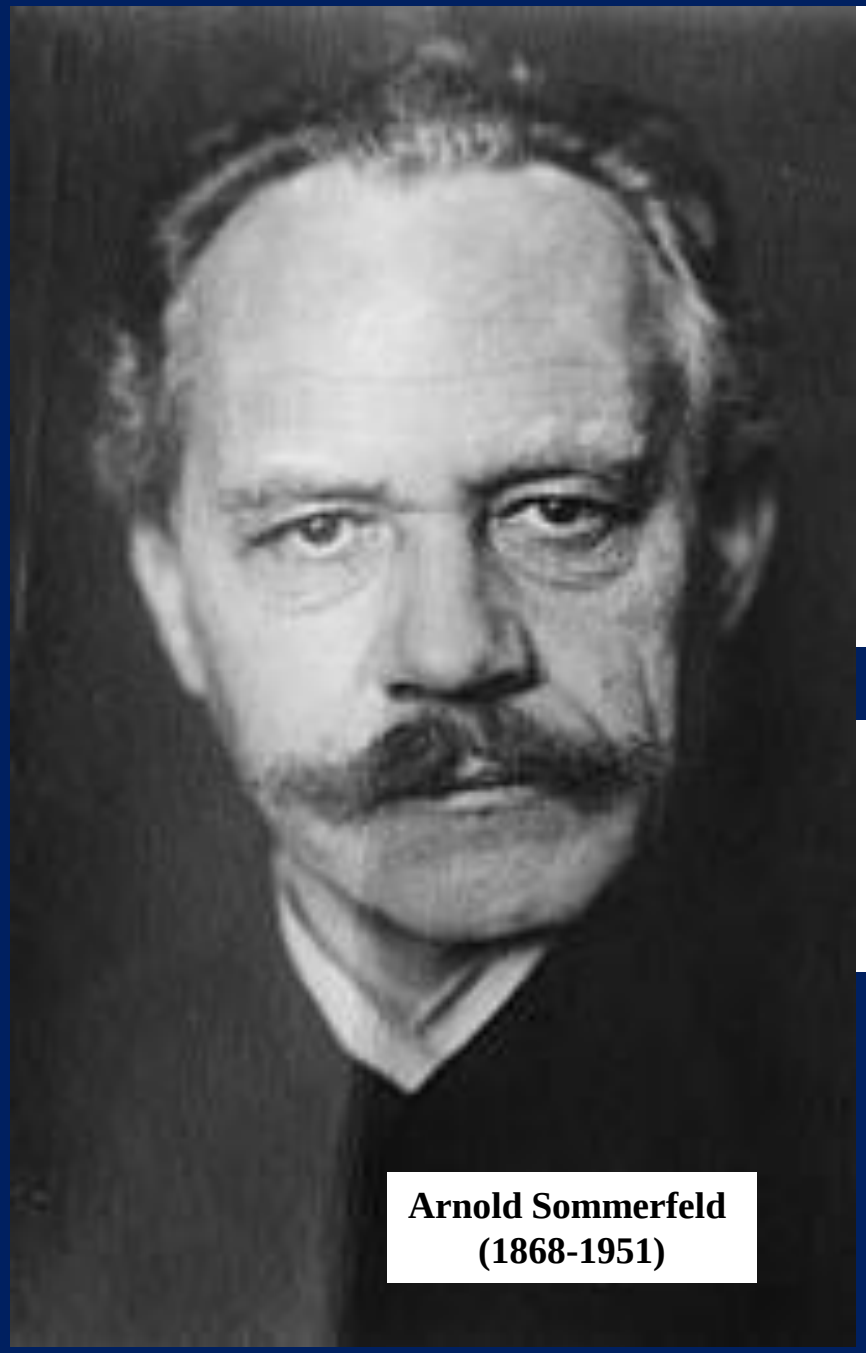
Bohr postulated in 1913 an atomic model in which the Planck constant h/2π defined the intra-atomic dynamics and which perfectly reproduced the energy values of the Balmer series (H-Atom).

In this model the electron moves in the Coulomb field of the atomic nucleus on discrete and stable circular orbits, for which the orbital angular momentum (its phase integral $\int qdp$) is an integer multiple n of h/2π, where n is the so-called main or radial quantum number.

Bohr postulated that the orbiting electrons do not emit energy. According to his model, only an "excited" atom could emit a photon (energy), when an electron suddenly changes from an outer to an inner path.

The status of Quantum Physics before 1925:





Arnold Sommerfeld
(1868-1951)

In 1915-6 Sommerfeld expanded Bohr's model of the atom.
With the help of Karl Schwarzschild (1873-1916) he succeeded in explaining the fine structure of the spectral lines.
Sommerfeld introduced elliptical orbits with eccentricity ε,
similar to the planetary system.

This new degree of freedom ε provided another quantum number,
which is called azimuthal quantum number.

However,

in Bohr's and Sommerfeld’s models,

the Zeeman effect

and the stability of many electron atoms

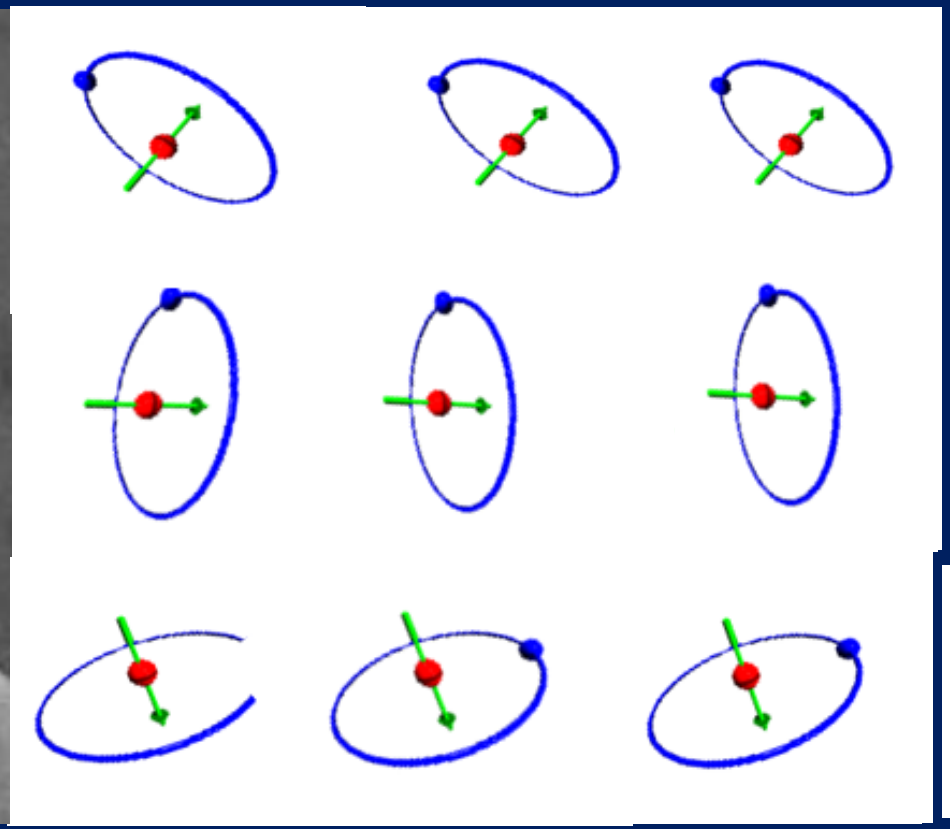
remained mysteries.

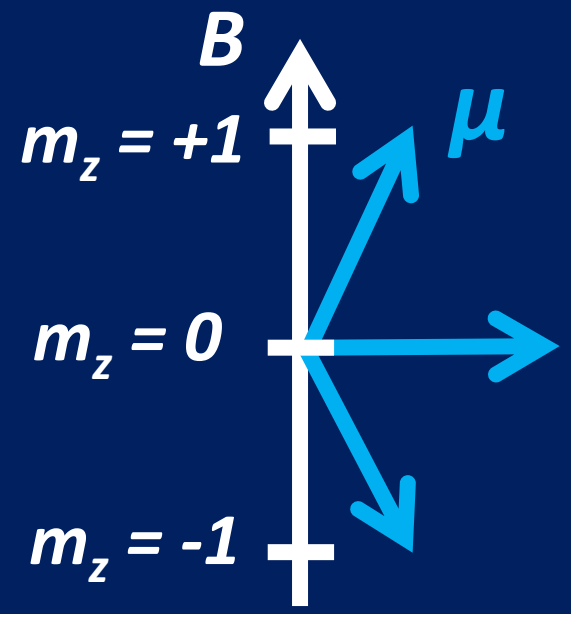
In 1916 Sommerfeld (1868-1951) and Debye (1884-1966) tried to explain the sharp line structure in the Zeeman effect postulating that only discretely oriented directions are allowed.

=>

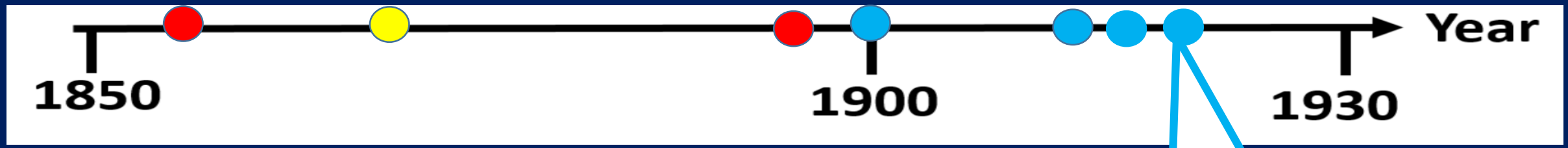
***"Richtungsquantelung"* i.e. space quantization**

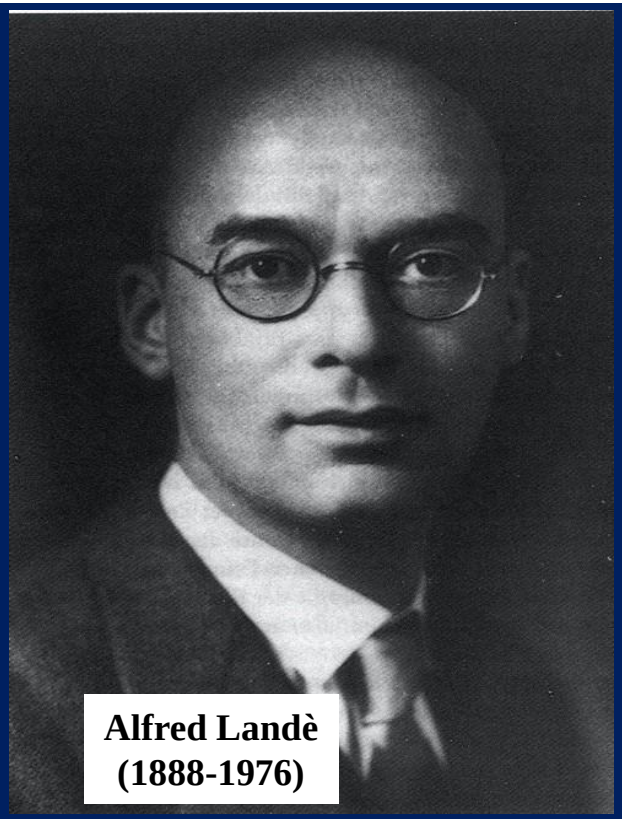
Peter Debye
(1884-1964)





This angular alignment (directional quantization) results in a further quantum number, the so-called magnetic quantum number m_z.





Alfred Landè
(1888-1976)

1919+1921
Landè
postulated „Spin-Orbit Coupling“
and the existance of half-integral angular momenta
and g-factor 2

Planck's phase space quantization with the constant h
is the key for understanding the intra-atomic structure and
the key for the intra-atomic dynamics
and thus for the stability of the atomic shells.

The dynamics of the whole electron shell is stable
due to spin-orbit coupling of all electrons forming one unit
with 4 angular momentum components
= >
4 quantum numbers QN,

Main QN	**n**	**by Bohr (circular orbits)**
Azimuthal QN	**l**	**by Sommerfeld (elliptic orbits)**
Magnetic QN	**m**	**by Sommerfeld (Richtungsquantelung)**
Electron Spin QN	**s**	**(Landè 1921, *Uhlenbeck Goudsmit 1925*).**

Common sense mysteries in Quantum Physics

Planck's and Bohr*s postulates could be still accepted by Common Sense.

But the "Richtungsquantelung" postulated by Sommerfeld clearly contradicted "Common Sense"

and NOBODY in 1916 believed Richtungsquantelung is real.

But Sommerfelds postulate paved the way
into the real secrets of Quantum Physics,
the secrets of the role of angular momentum yielding 4 quantum numbers
for the electron dynamics in many-electron atomic shells.

Thus when Otto Stern heard about “Richtungsquantelung”, he did not believe at all this postulate could be true and he wanted experimentally to disprove this postulate .

Stern was the only one who could measure magnetic ground state properties of single atoms, the size of an atomic magnetic moment and its relative orientation to an outer magnetic fields B.

(* 17.2.1888 in Sohrau/Oberschlesien;
† 18.8.1969 in Berkeley).

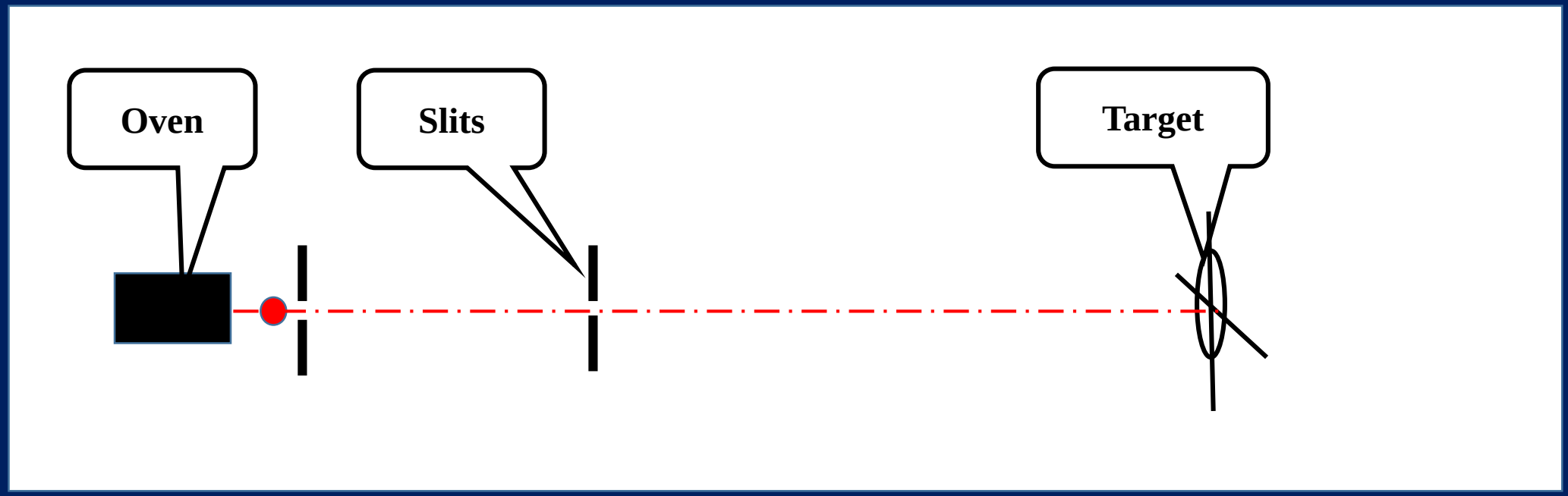
The “theorist” Otto Stern had laid in 1919-20 in Frankfurt the foundations of his

“molecular beam method”,

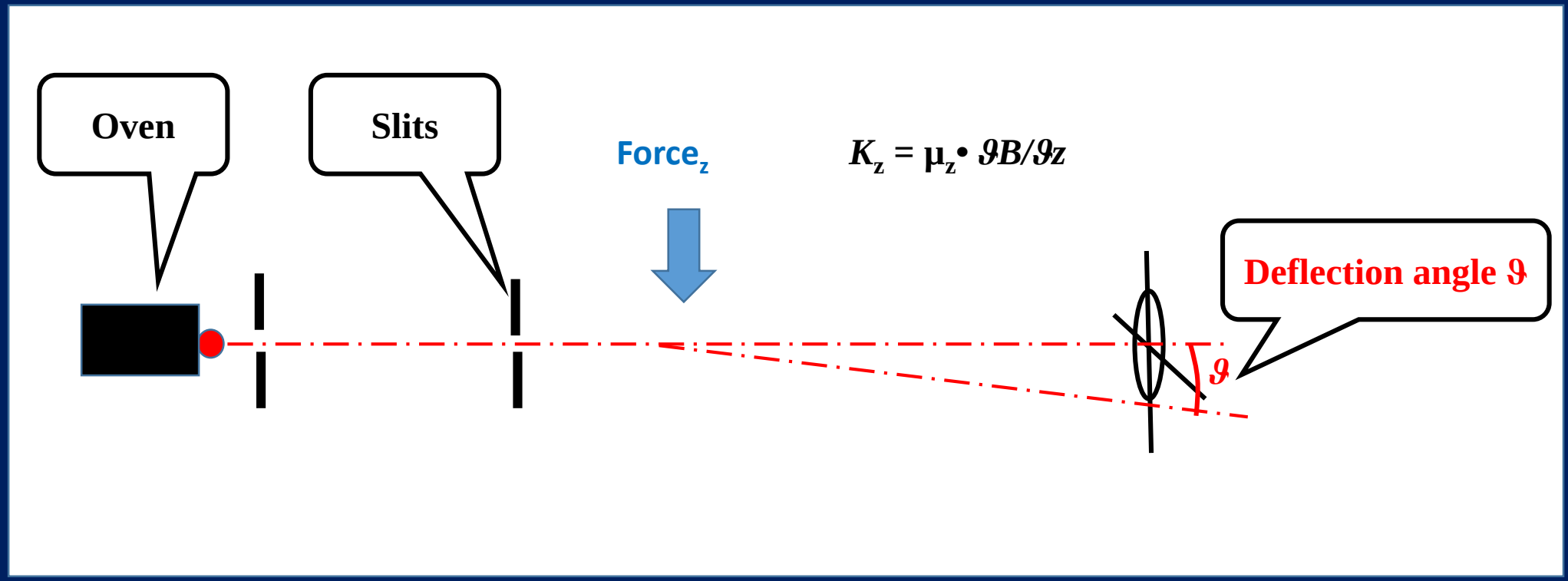
which is an extremely high-resolution momentum spectrometer for in vacuum moving single atoms.

Individual atoms are "shot" at a target in a vacuum.

The direction of flight is adjusted using apertures so that the experimenter always hits the center.

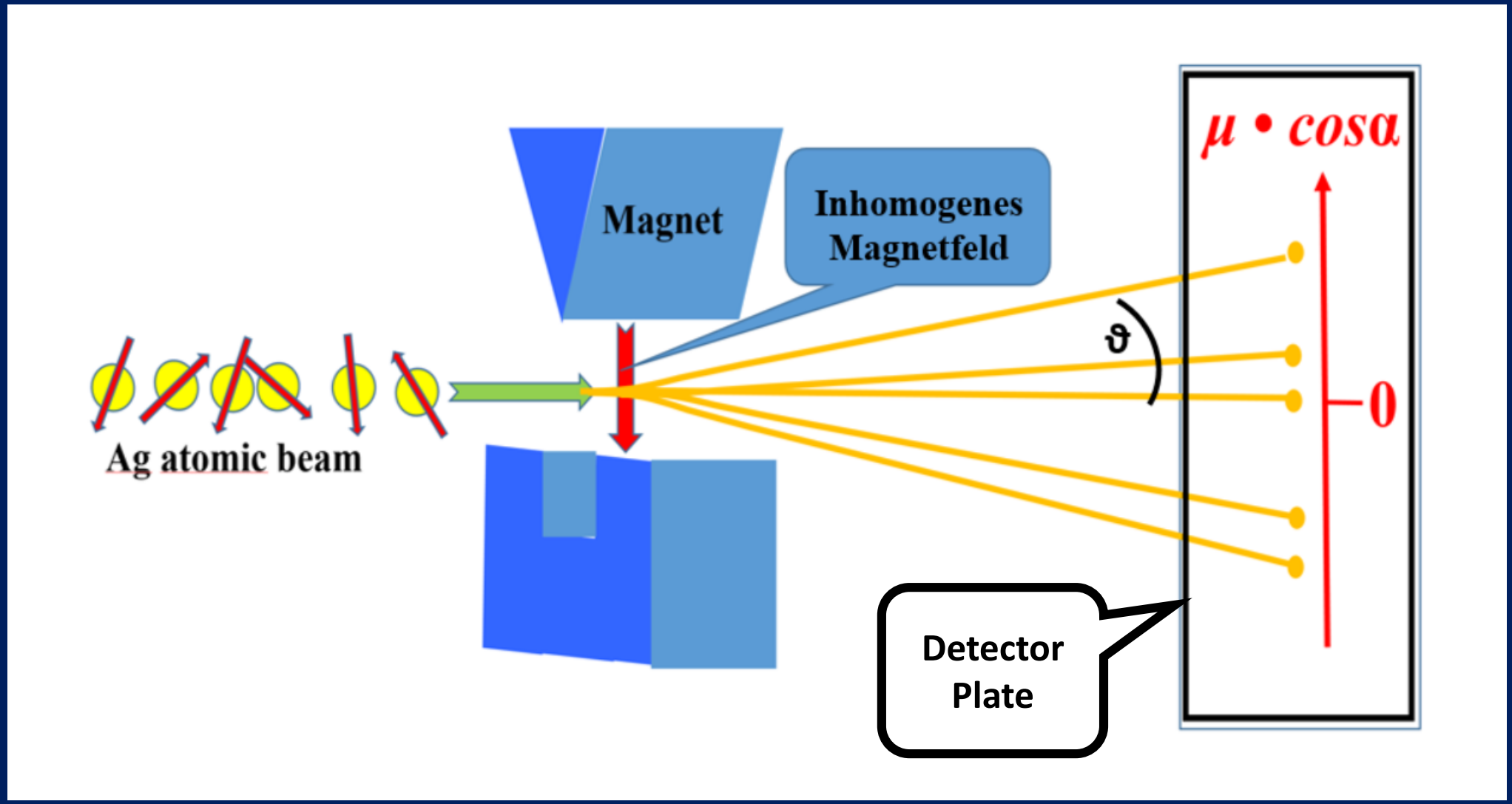


If a lateral force (e.g., a magnetic field) is applied to the flying atom, the Ag atom is deflected.



From the deflection angle ϑ (a few milliradians or tenths of a millimeter), one can determine intra atomic properties (e.g., the magnitude and orientation of the magnetic moment).

ϑ => $|\mu|$ and α

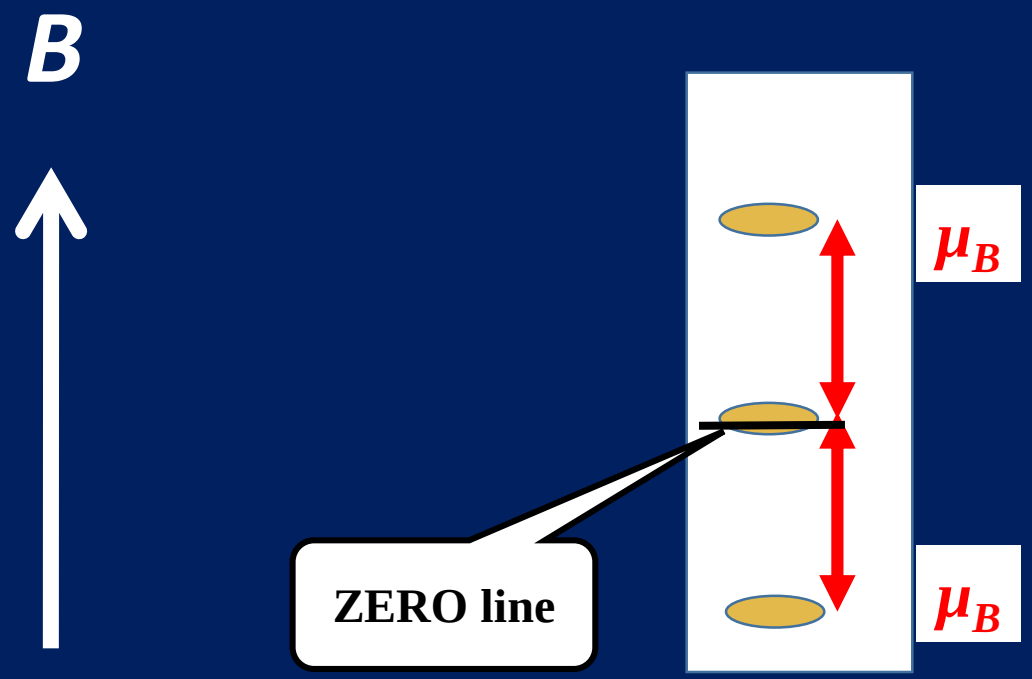

Magnet
Inhomogenes Magnetfeld
Ag atomic beam
μ • cosα
ϑ
0
Detector Plate

Which deflection pattern would the experiment show?

Sommerfeld's prediction was:

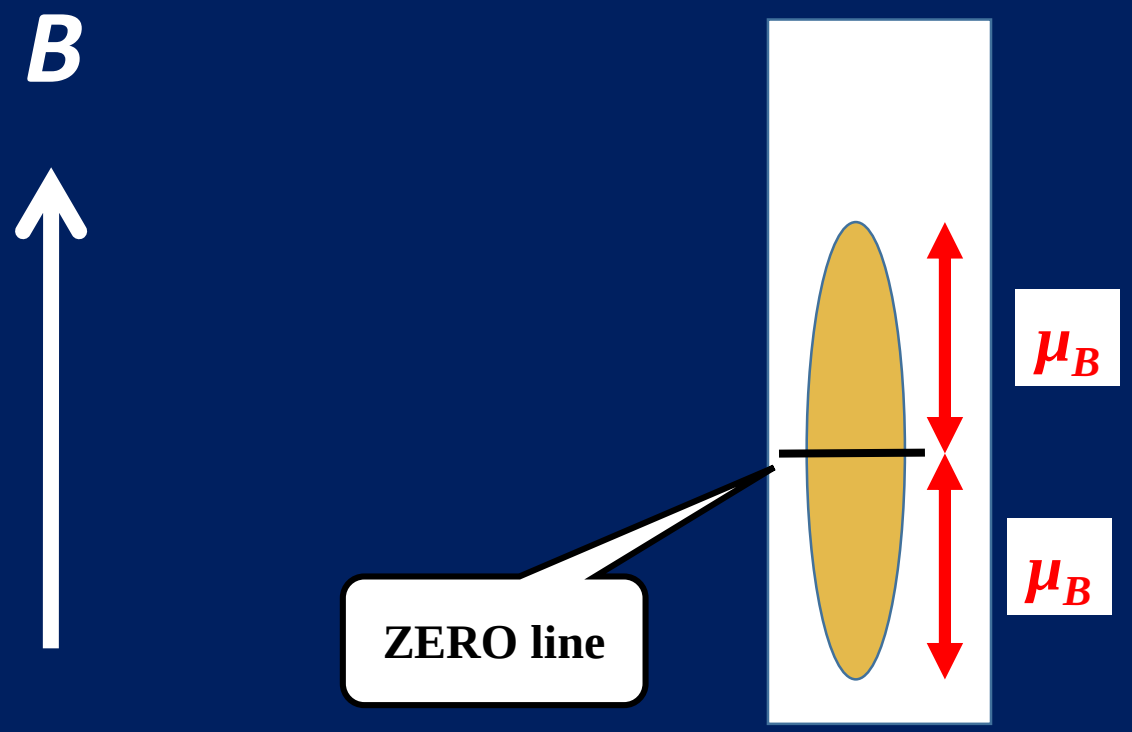
analogy to the normal Zeeman effect (for l = 1 triplet structure).

Pattern on detector



Classical Physics => Larmor –Precession

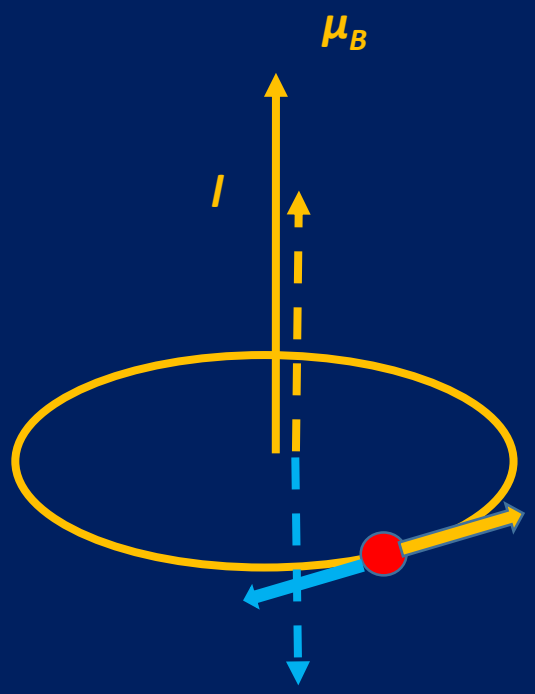
Pattern on detector



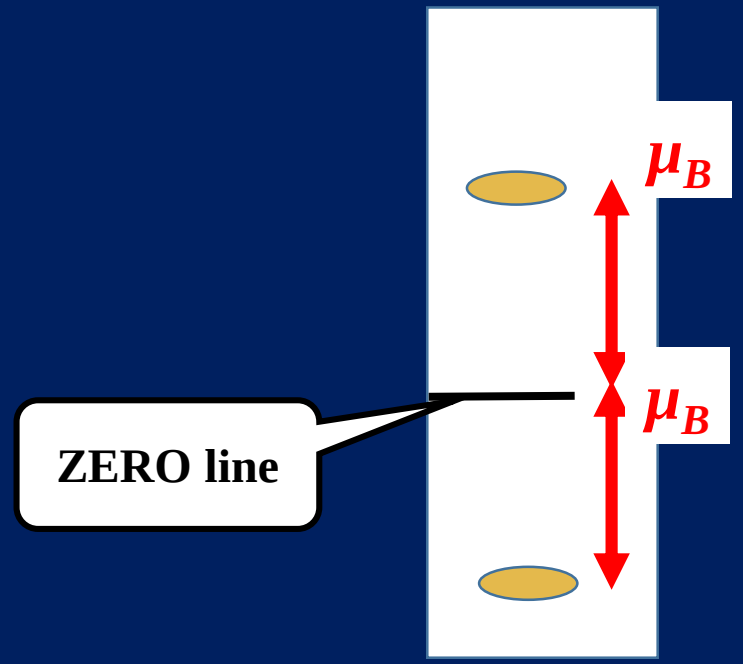
Bohr expected that in the case of directional quantization:

The magnetic moment can only be perpendicular to the orbital plane.

Direction of the magnetic moment



Pattern on Detector



The SGE 1921 -22
Otto Stern, Walther Gerlach and Adolf Schmidt, the three „Fathers“ of the SGE.

The term “Stern-Gerlach experiment” was introduced by Albert Einstein in 1922.

Otto Stern (1888-1969) delivered the concept and designed the SGE

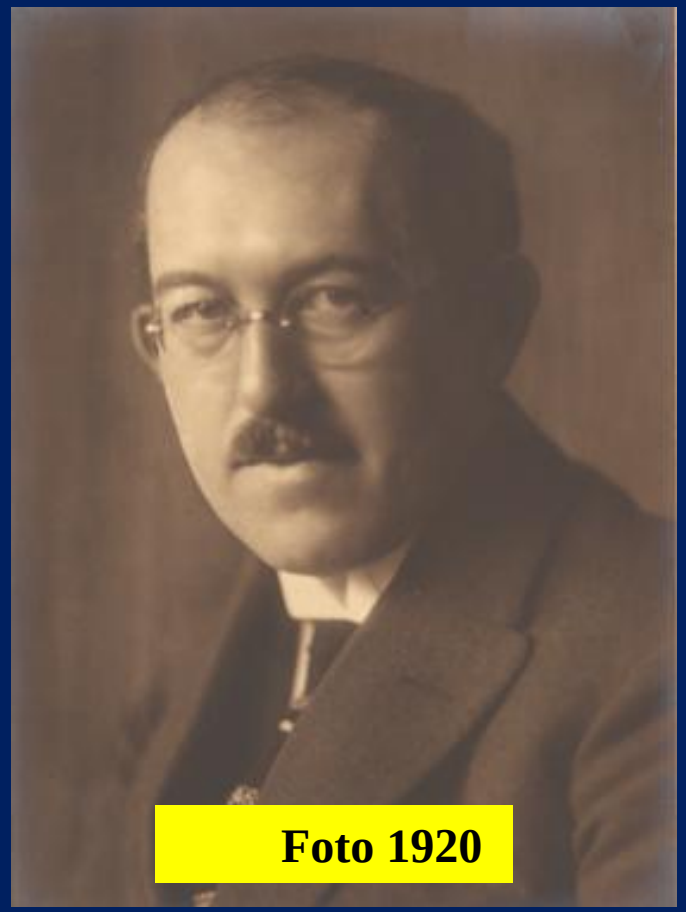


Foto 1920

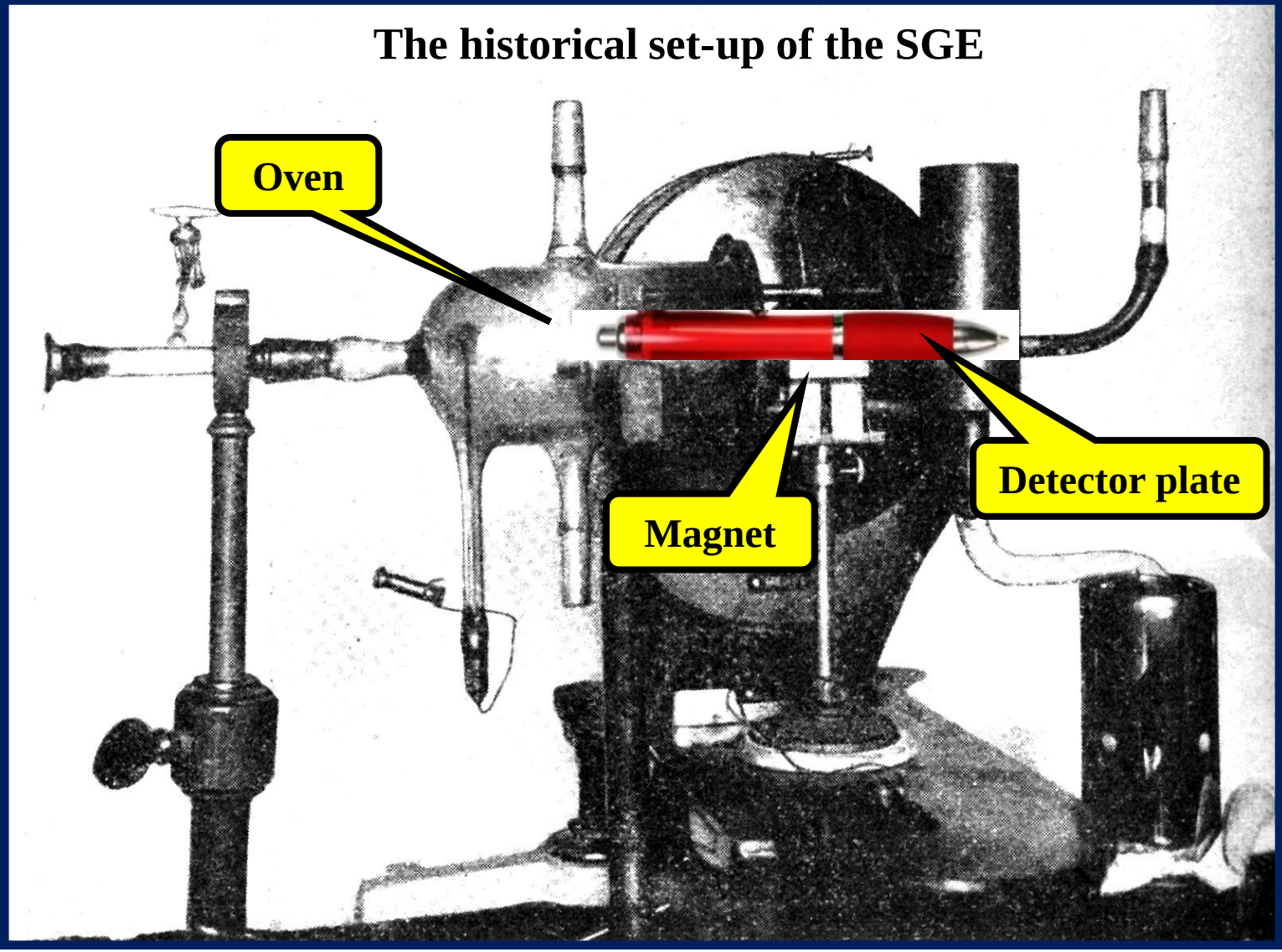
Adolf Schmidt (1893-1971) was the master precision mechanic, without whom the SGE would never have succeeded.

Foto 1946

Walther Gerlach (1889-1979) was the ingenious creator

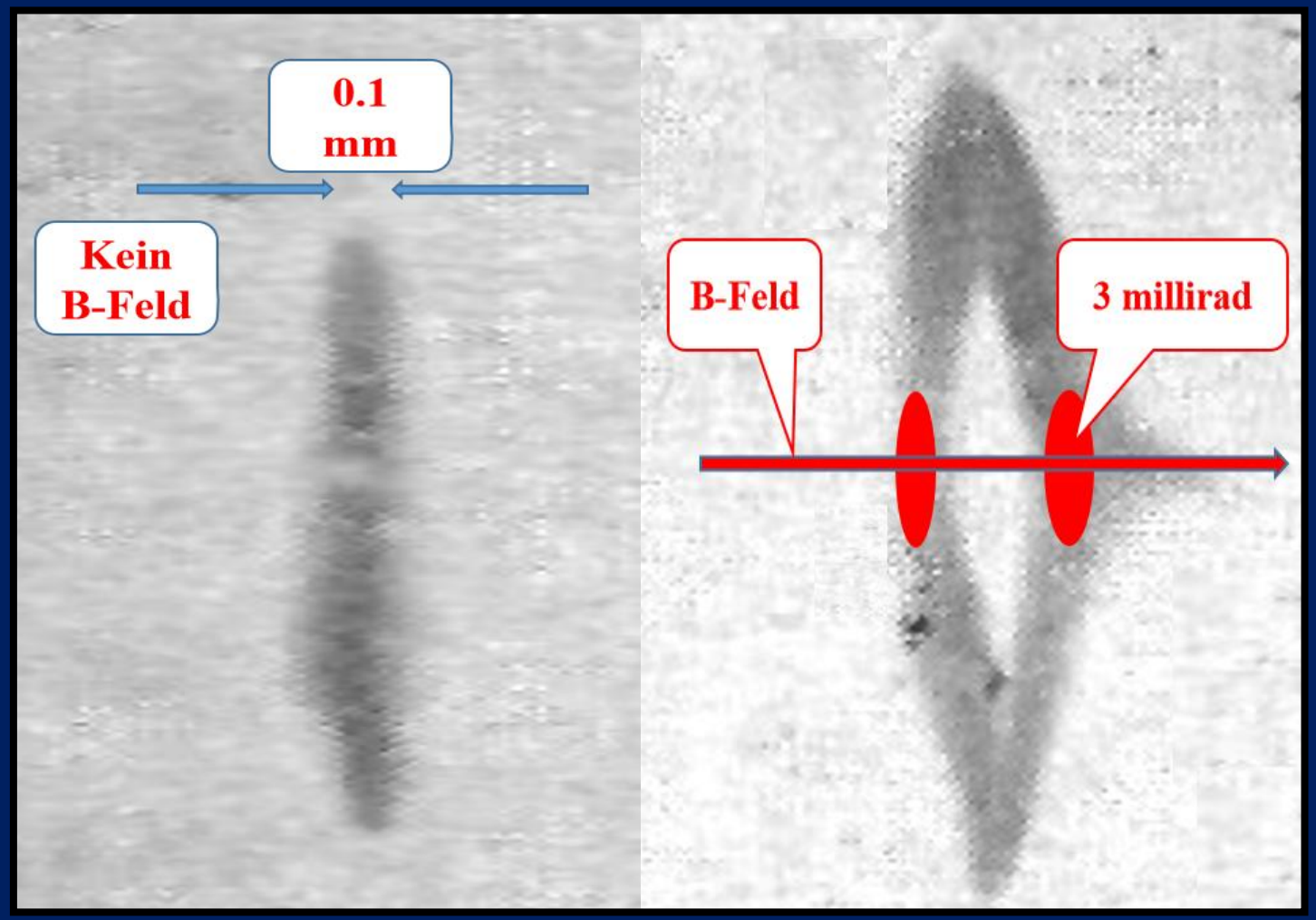
Foto 1920

The historical set-up of the SGE



Stern and Gerlach achieved an angular resolution of approximately 0.03° with a flight path of approximately 10 cm! This corresponded to a transverse "energy resolution" of approximately 2 micro eV for Ag atoms evaporated at 962°C.

The result of the SGE



This direct visualization and proof of quantization of the intra-atomic dynamics is,

in my understanding,

the actual moment of the birth of quantum physics!

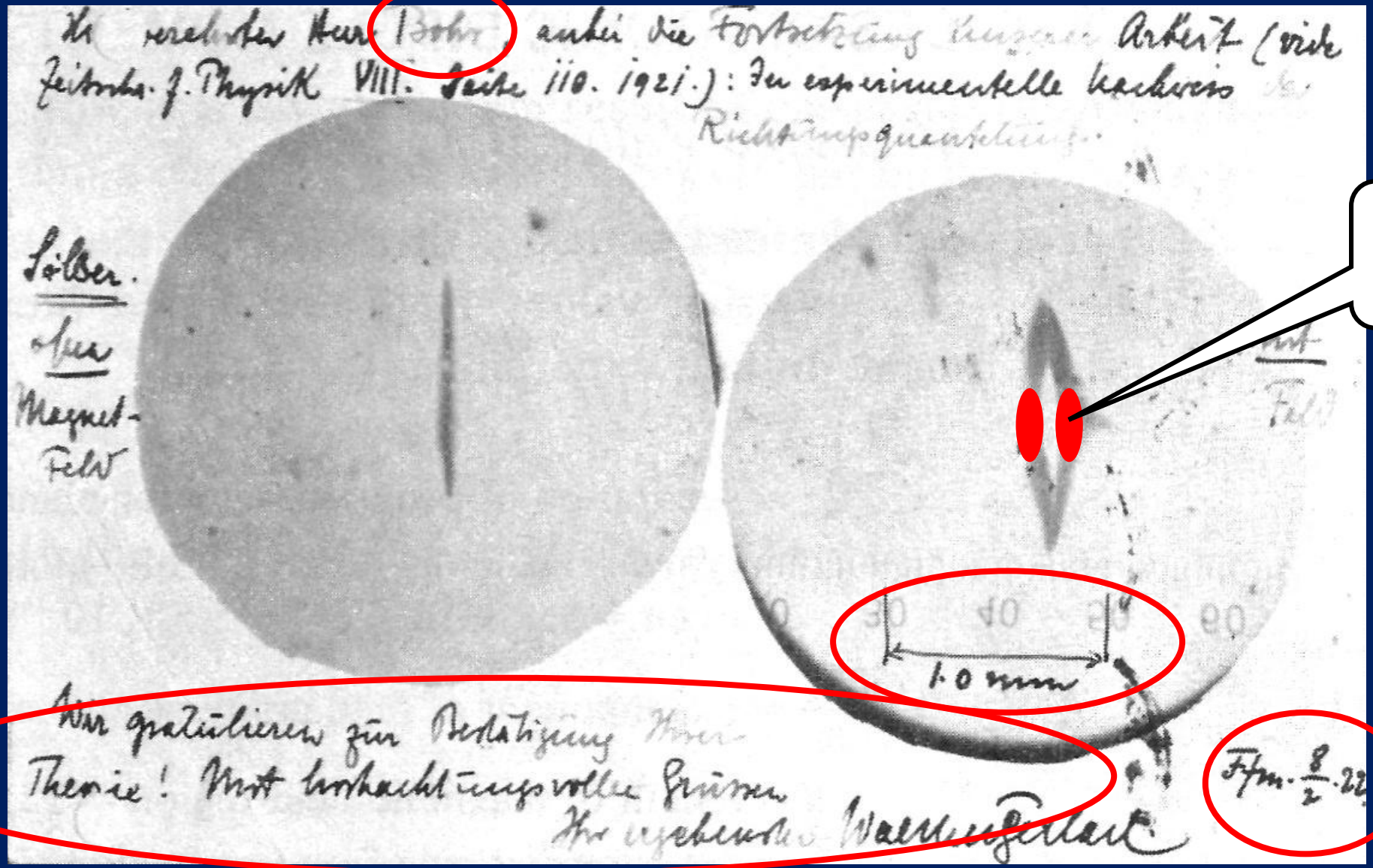
A child is only born, when it appears visible in the real world!
Not when it is later baptized (by theorist).

Before this moment
all theories
were based only
on unproven postulates!

With this microsope
Walther Gerlach
saw on February 8th 1922
for the first time
that the postulated quantization
of intra-atomic dynamics
was real.

The microscope was baught
in 1919 by Otto Stern
from Fa. Seibert/Leitz-Wetzlar
(Serial number 18771)

The famous post card send to Bohr



But Bohr's explanation was also wrong!

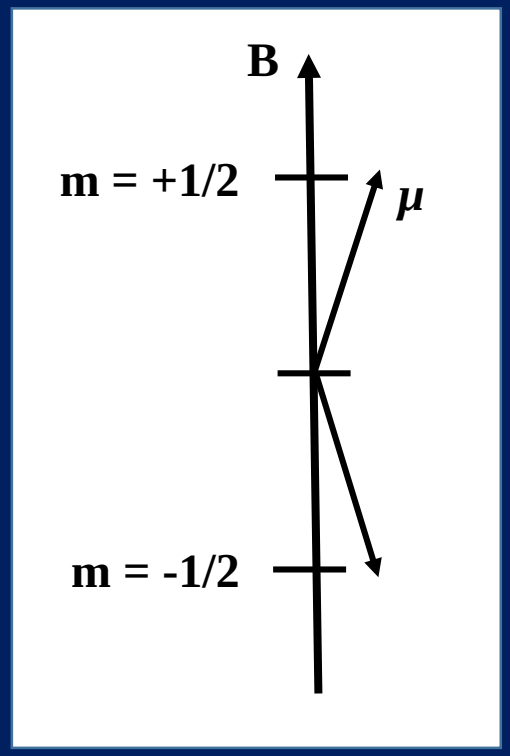
Alfred Landè gave the correct explanation by analogy with the doublet structure of the anomalous Zeeman effect (1923):

There must be half-integer angular momenta (electron spin s = 1/2) with a g-factor of 2.

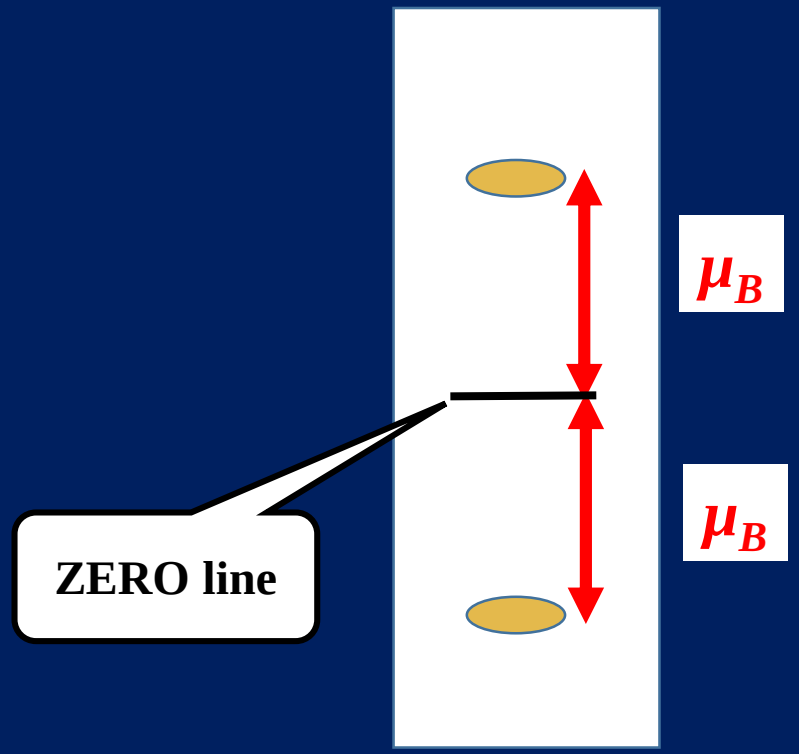
Directions of the magnetic moments

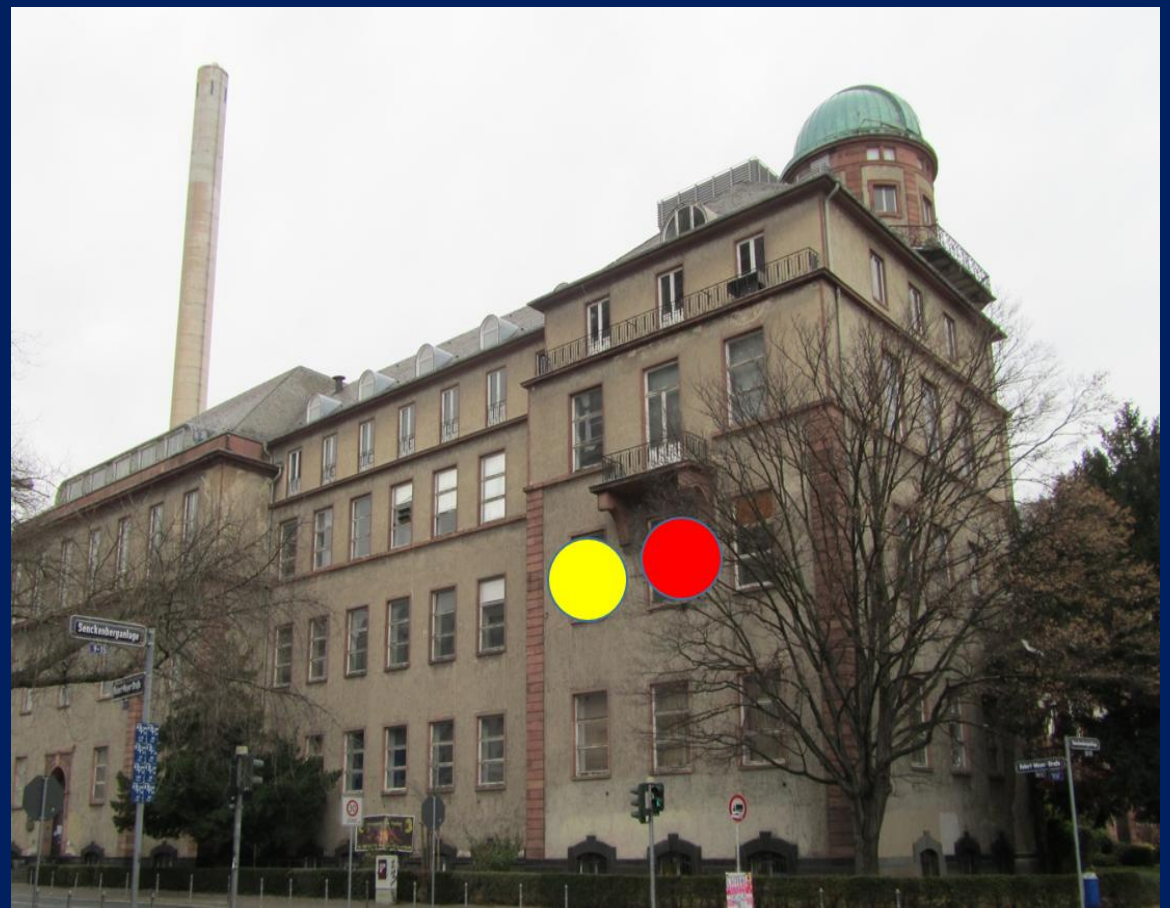
for s = 1/2 (Dublet),

g-Factor = 2



Pattern on Detector





Former physics building (photo taken in 2011). Max von Laue, Max Born, Alfred Landè, and Erwin Madelung sat in the yellow room.

Otto Stern and Walther Gerlach conducted their famous experiments in the red room.

The famous Stern-Gerlach experiment took place in this room in 1922.
Right:
Alan Templeton, the great-nephew of Otto Stern / Oakland and Otfried Madelung, the son of Erwin Madelung who succeeded Max Born in Frankfurt in 1921.

The importance of the SGE for physics and its impact on the development on quantum technologies

The Milestone results of the SGE

The SGE proved that Ag atoms have a magnetic moment. Their size was first determined by Gerlach and Stern.

The SGE provided evidence that Debye and Sommerfeld's hypothesis of directional quantization of the intra-atomic magnets in a magnetic field is correct.

The SGE provided direct evidence that the intra-atomic angular momenta (spins) are quantized.

The SGE provided the first experimental evidence that half-integer quantum numbers exist in atoms.
This was first postulated by Landè between 1921 and 1923.
But it it lasted till 1925 and 1927 that it was recognized
that the half-integer spin of the electron was responsible for the doublet splitting in the Ag atom.

The SGE produced a beam of atoms that was 100% pure quantum.
=> Charles Townes used an SGE device to develop the maser

The SGE was the first application of the molecular beam method proving the extremely high-resolution power as momentum spectrometer, providing groundbreaking insights into atoms and nuclei.

Which important technologies originate in the SGE ?

Medical instruments such as magnetic resonance imaging (Rabi, Bloch, Purcell, Ernst, etc.)

High-precision measurement methods (atomic clock => time measurement) (Ramsey, Hall, Hänsch, etc

Masers and lasers (worldwide, unlimited information exchange) (Townes, Mayman)

Measurement standards with quantum constants etc.

Stern and Gerlach's Nobel Prize story

From 1924 to 1929, Stern was nominated 16 times and Gerlach 15 times.

From 1924 to 1944, Stern was nominated 83 times and Gerlach 31 times.

Stern received the 1944 Nobel Prize 1943 in Physics for his development of the molecular beam method and his determination of the magnetic moment of the proton.

In his 1944 laudation, however, Eric Hulthèn praised the SGE almost exclusively.

Number of Nobel Prizes awarded for the SGE and Stern's molecular beam method (Daniel Kleppner).

Physics

1943 Otto Stern	Molecular beam method
1944 Isidor Rabi	Magnetresonance method
1952 Felix Bloch and Henry Purcell	Nuclear spin resonance
1955 Phyllis Lamb and Polykarb Kusch	Lambshift
1964 Charles Townes, Nikolay Basov and Alexander Prokhorov	Maser+Laser
1965 Sin I.Tomonaga, Julian Schwinger and Richard P. Feynman	Quantenelectrodynamics
1966 Alfred Kastler	Optical Resonances in Atoms
1981 Nicolas Bloombergen and Arthur L. Schawlow	Laser spectroscopy
1989 Norman Ramsey and Hans Dehmelt	Atomic clock
1997 Bill Phillips, Claude Cohen-Tannoudji and Steve Chu	Laser cooling
2001 Eric Cornell, Wolfgang Ketterle and Carl Wieman	Bose-Einstein-Condensate
2005 Roy J. Glauber Theo Hänsch and John Hall	Frequency comb
2012 Serge Haroch and David W. Wineland	Manipulation of Individual Quantum Systems
2017 Rainer Weiss, Barry C. Barish and Kip S. Thorne	Gravitational Waves
2018 Arthur Ashkin, Gerard Mouróu and Donna Strickland	Optical Tweezers Ultra Short Laserpulses

34 Laureats

Chemie

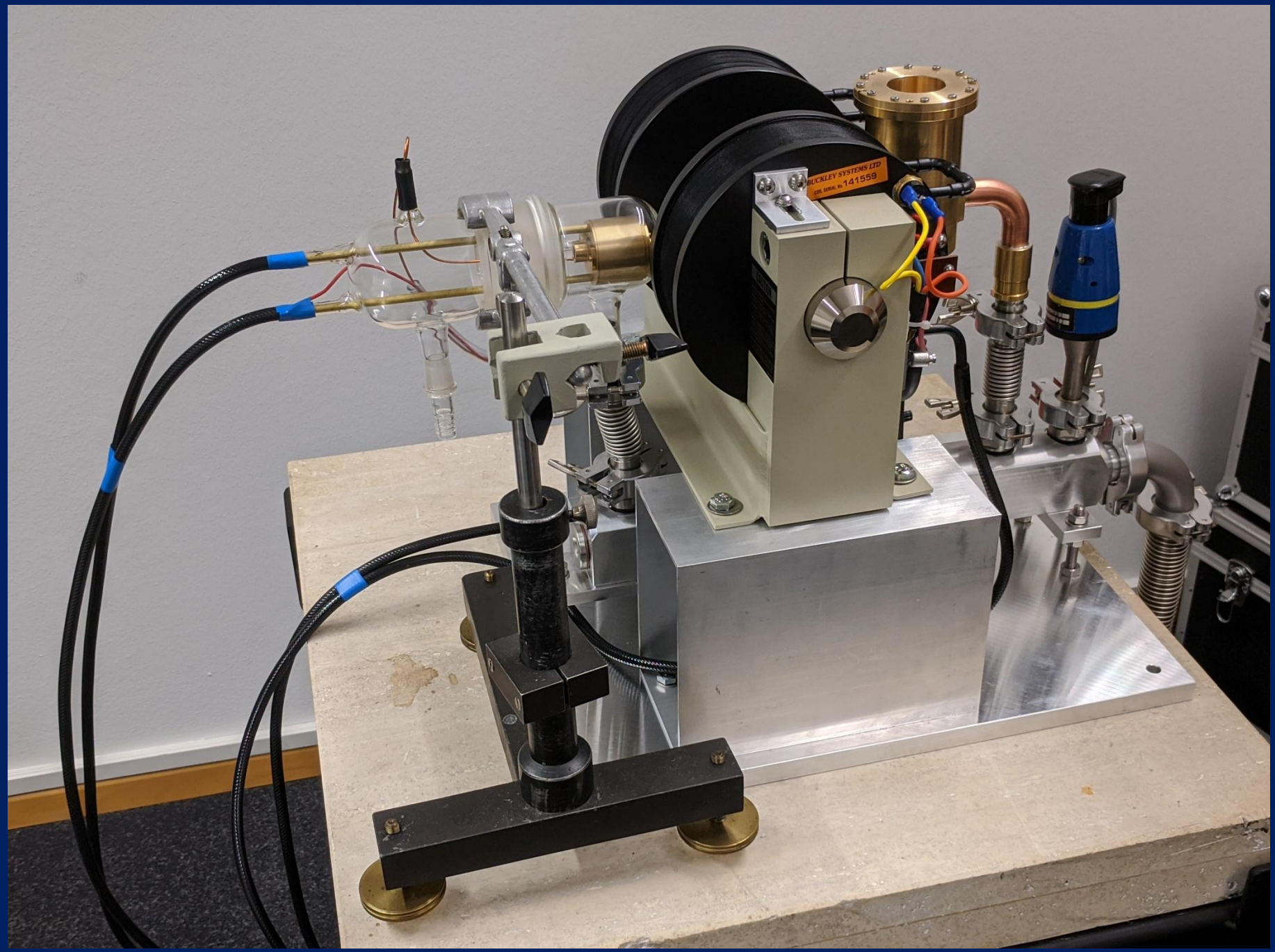
1986 Dudley Herschbach, Yuan Lee and Michael Polyani	Crossed beam Experiments
1991 Richard Ernst	Nuclear spintomographie
1996 Robert Curl, Harold Kroto and Richard Smalley	Fullerens
1999 Ahmed Zewail	Femtosecond Pump&Probe Lasertechnik
2002 John Fenn and Koichi Tanaka	Mass Analysis
2007 Gerhard Ertl	Chemical Reactions on Surfaces

11 Laureats

GOETHE
UNIVERSITÄT
FRANKFURT AM MAIN

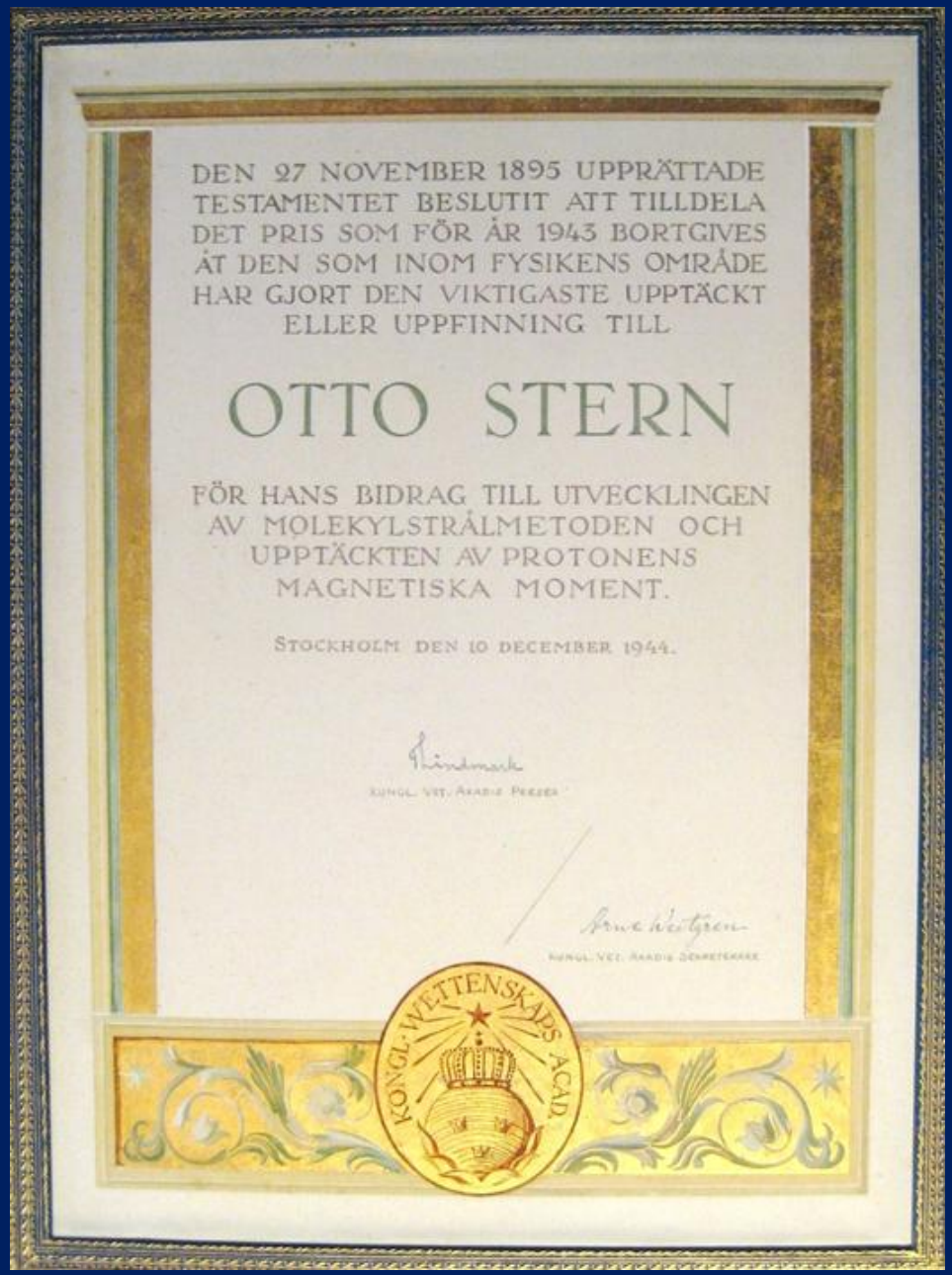
Mikroskop, mit dem Stern und Gerlach zum ersten Male ihre Entdeckungen sichtbar machten, gebaut 1919 bei der Fa. Seibert/Leitz-Wetzlar (Seriennummer 18771)

Vakuumpumpen von Stern und Gerlach.
Links die einstufige Volmer-Hochvakuumpumpe 10^{-2} bis 10^{-6} Torr und rechts die Gaede-Vorpumpe (Arbeitsbereich 20 bis 10^{-2} Torr).


BUCKLEY SYSTEMS LTD
141559

1919 kam dann Walther Gerlach nach Frankfurt (Privatdozent bei Wachsmuth)

In diesem Raum fand 1922 das berühmte Stern-Gerlach-Experiment statt. rechts: Alan Templeton, der Großneffe Otto Sterns / Oakland und Otfried Madelung, der Sohn von Erwin Madelung der ab 1921 Nachfolger von Max Born in Frankfurt war.


DEN 27 NOVEMBER 1895 UPPRÄTTADE TESTAMENTET BESLUTIT ATT TILLDELA DET PRIS SOM FÖR ÅR 1943 BORTGIVES ÅT DEN SOM INOM FYSIKENS OMRÅDE HAR GJORT DEN VIKTIGASTE UPPTÄCKT ELLER UPPFINNING TILL

OTTO STERN

FÖR HANS BIDRAG TILL UTVECKLINGEN AV MOLEKYLSTRÅLMETODEN OCH UPPTÄCKTEN AV PROTONENS MAGNETISKA MOMENT.

STOCKHOLM DEN 10 DECEMBER 1944.

KONGL. VET. AKADIEN PRESES

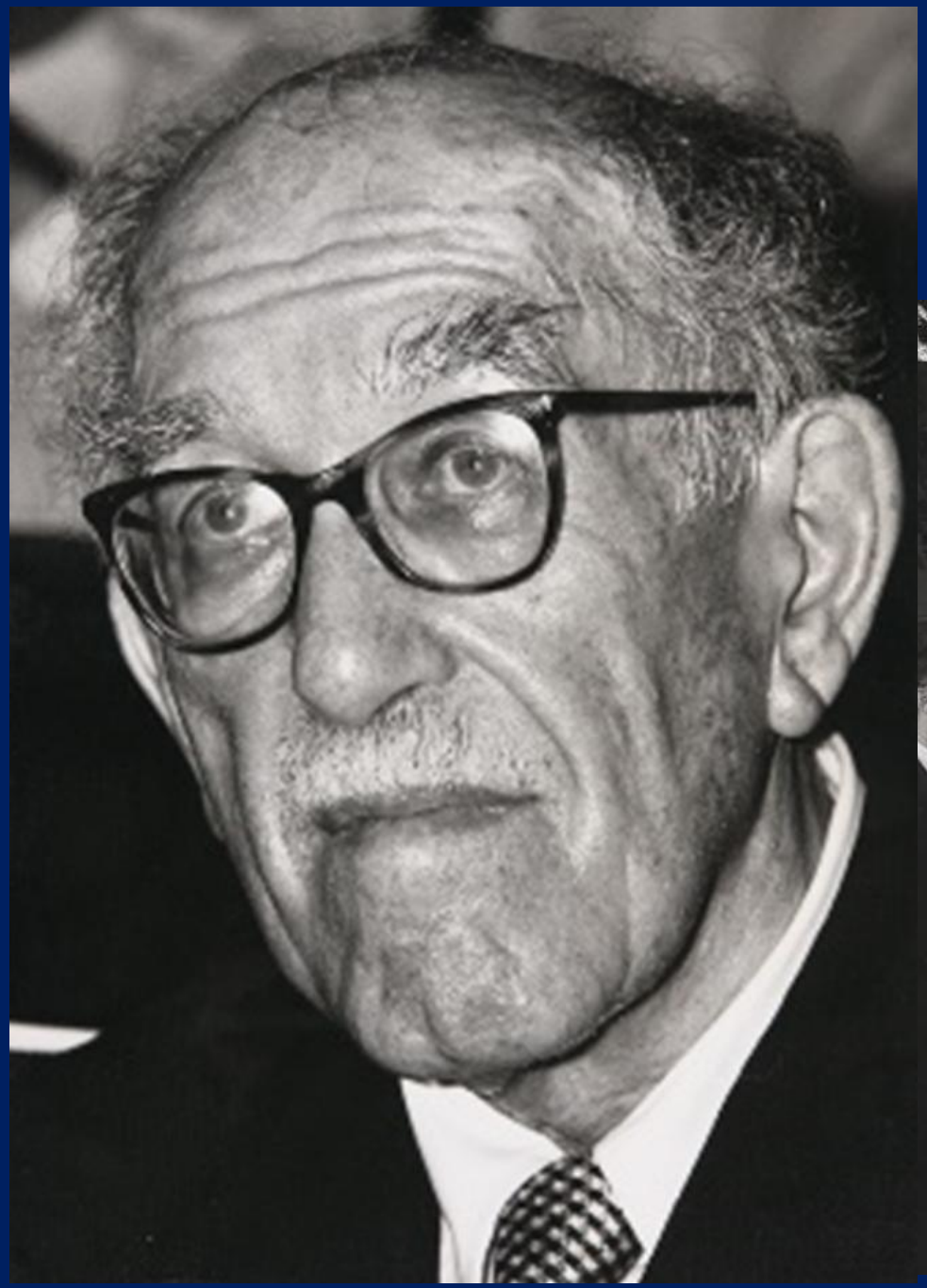
KONGL. VET. AKADIEN SEKRETERARE

KONGL. VETTENSKAPS ACAD.

Otto Sterns Nobelurkunde im Besitz von Diana Templeton/Stanford

Konferenz am Niels Bohr Institute in Kopenhagen

Lise Meitner, Otto Stern, Wolfgang Pauli, und Niels Bohr,



Probably the last foto of Otto Stern, when he attended in 1968 in Lindau /Lake Konstanz the Nobellaureate meeting

4. Sterns und Gerlachs Nobelpreisgeschichte

Von 1924 bis 1944 wurden Stern 83 mal und Gerlach 31 mal für den Nobelpreis der Physik nominiert.

Stern erhielt 1944 für 1943 den Nobelpreis für Physik für die Entwicklung der Molekularstrahlmethode und die Bestimmung des magnetischen Momentes des Protons.

In der Laudatio 1944 aber würdigte Eric Hulthèn fast ausschließlich das SGE.

Max-Planck-Medaille seit 1929

Stern-Gerlach-Medaille seit 1992

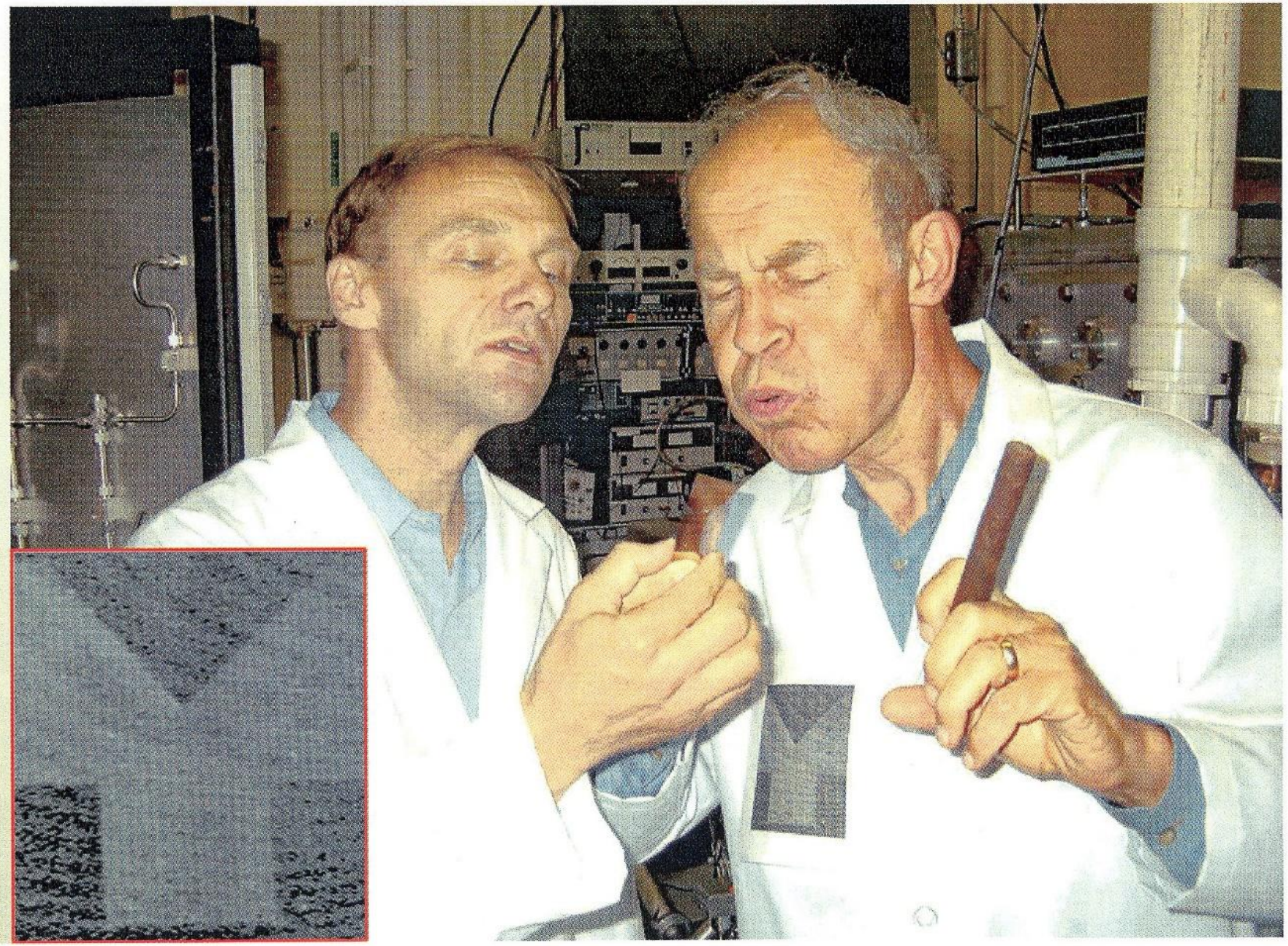


Figure 5. Reenactment of the Stern–Gerlach cigar episode by the authors. Bretislav Friedrich holds the slide as Dudley Herschbach blows sulfurous cigar breath onto a silver-coated glass slide to test his hearing (or Otto Stern's telling) of the story more than 40 years ago. The silver film turns out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

The very close scientific scholarship relation between Stern and Rabi was expressed by Felix Bloch in 1944 by this poem, when they celebrated in Rabi‘s house Rabi‘s Nobel Prize.

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

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

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

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

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

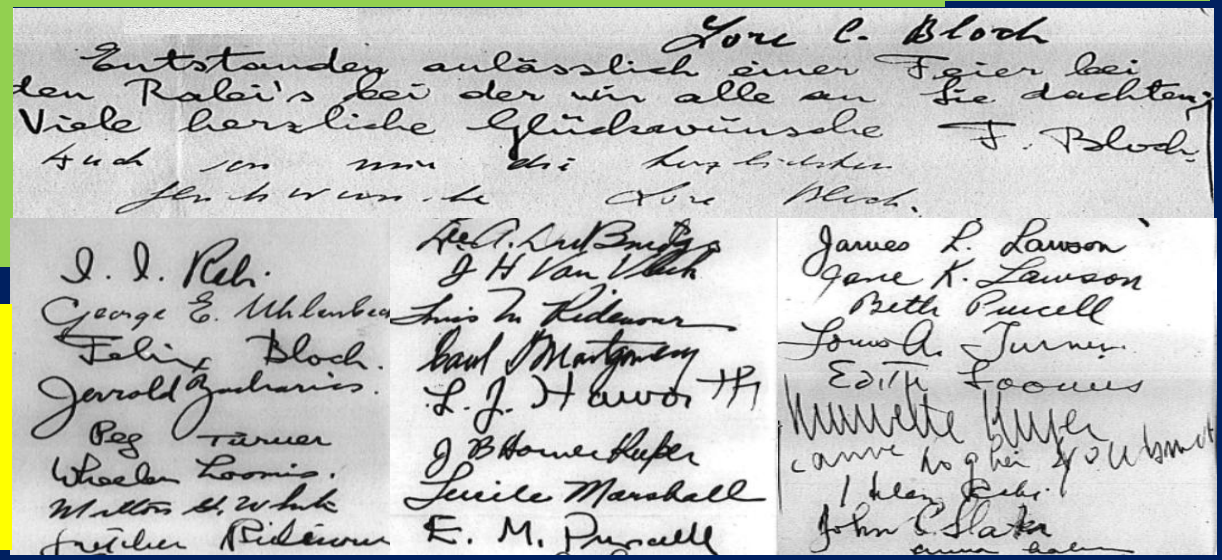
6. Soon the moments made him
and he said: I'm awfully sorry.
Gentlemen, we have no chance
What we need is resonance.
Twinkle, twinkle Otto Stern
how did Rabi so much learn?

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

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

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

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



Isidor I. Rabi; George E. Uhlenbeck; Felix Bloch; Jerold Zacharias; Reg Turner; Wheeler Loomis; Walton N….; …..; J.H. Van Vleck; Luis Lederman; L.J. Haworth; ….; Marshall; E.M. Purcell; James L. Lawson; Jane K. Lawson; Beth Purcell; Louis C. Turner; Edith Loomis; Anette Hugh; Goudsmit; Helen Rabi; John Slater;

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

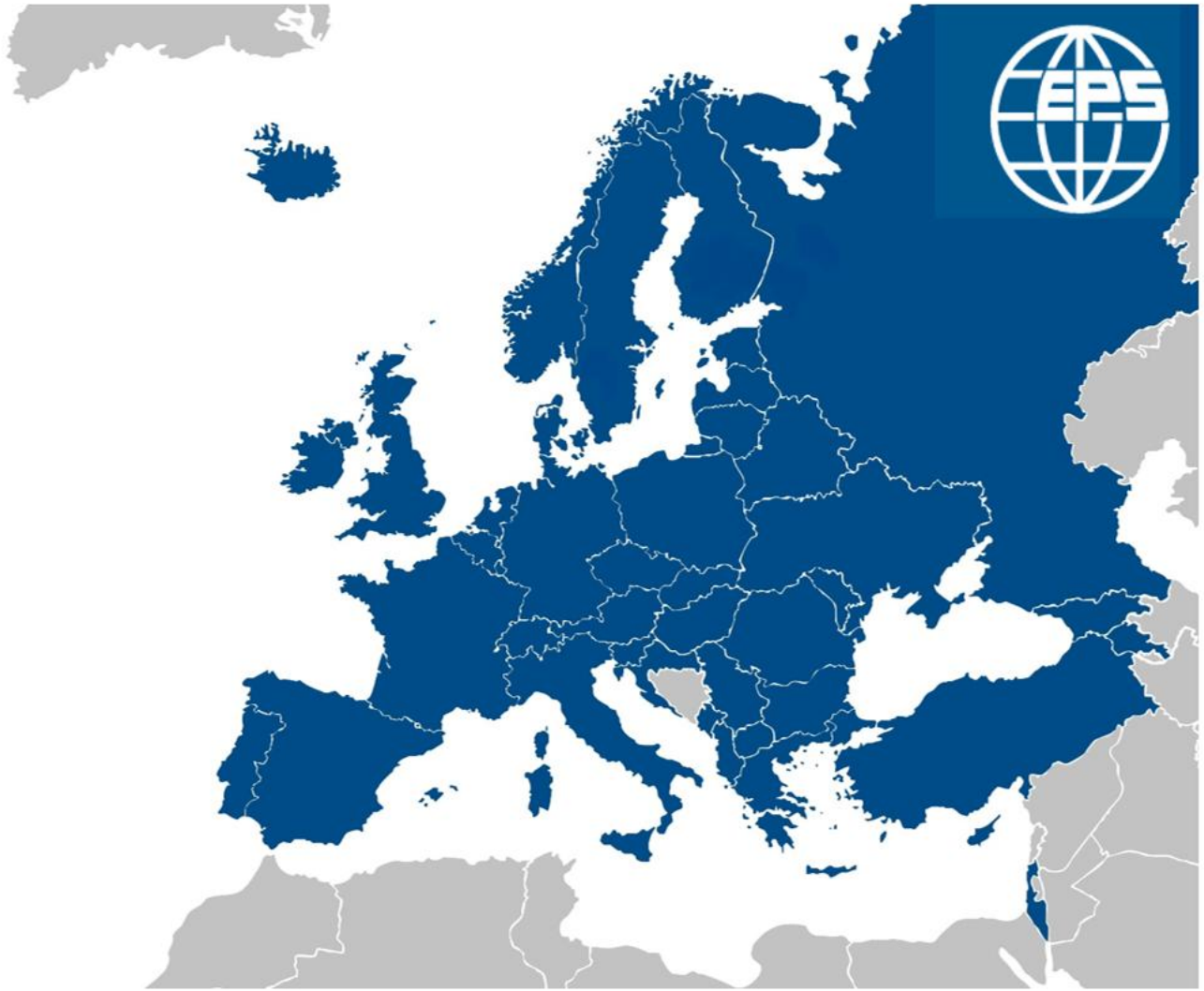
„Historic Site“- Plakette Frankfurt 2014 / 2019

European Physical Society – EPS Historic Site

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

European Physical Society – EPS Historic Site

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



Theory:

T-H: Thomson and Helmholtz; Pl: Planck; E: Einstein; Bo: Bohr; S: Sommerfeld; H: Heisenberg; S: Schrödinger and D: Dirac

Empirical:

M-M: Mendelejew and Meyer; Ba: Balmer; R: Rubinowicz; L: Landè; P: Pauli;