Max Planck,
Kiel and the beginning of the quantum era

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Chair „Statistical Physics“

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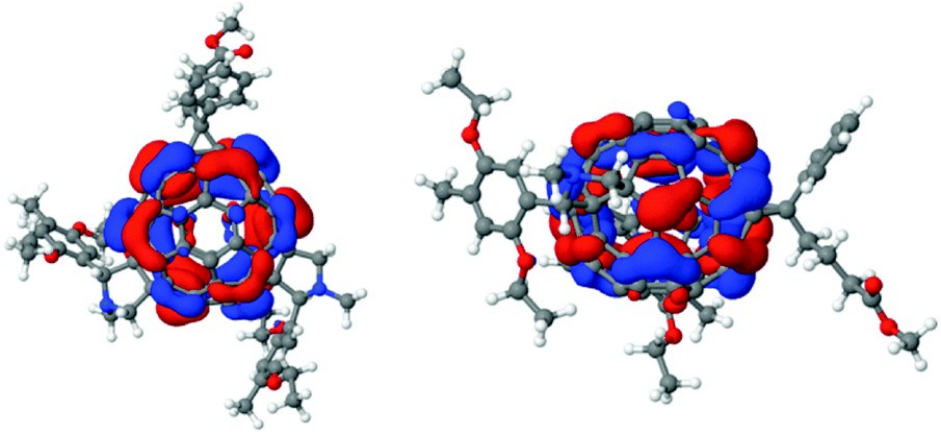
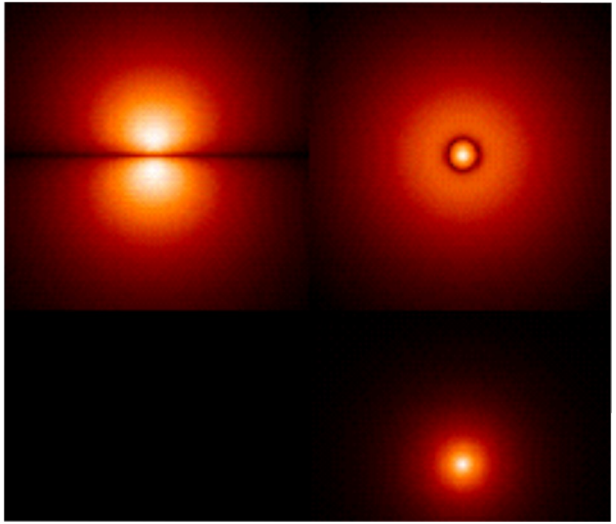
Lund, December 2025

Atoms and molecules

lowest hydrogen atom orbitals
(analytical results)





DFT result for 3 LUMO frontier orbitals for the most probable PPCBMB adducts, phenyl-C61-butyric acid methyl ester,
Stephen *et al.*, Chem. Commun. 2016

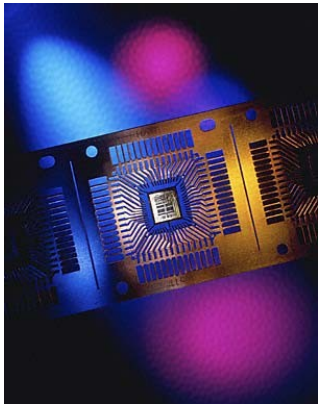
Quantum pysics today

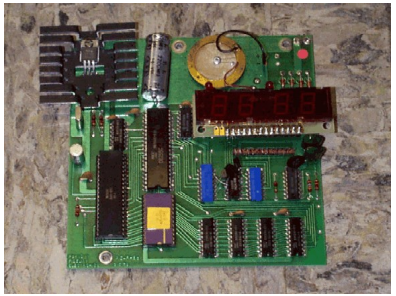
The basis for the description of atoms, molecules, nuclei, elementary particles...

The basis for modern (quantum) chemistry, material science

The basis for electronic conduction: from nanotechnology to electrical engineering

Nanotechnology





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Quantum pysics today

The basis for the description of atoms, molecules, nuclei, elementary particles...

The basis for modern (quantum) chemistry, material science

The basis for electronic conduction: from nanotechnology to electrical engineering

The basis for understanding the Universe and its history

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Quantum physics – a „gold mine“: Recent Nobel prizes in physics

2025: Macro quantum effects: Clarke, Devoret, Martinis
2023: attosecond pulses (atomic physics): L’Huillier, Agostini, Krausz
2022: entangled photons: Aspect, Clauser, Zeilinger
2018: optical tweezer, High intensity lasers: Ashkin, Mourou, Strickland
2016: Topological phase transitions in 2D: Thouless, Kosterlitz, Haldane
2015: Neutrino Oscillations: Kajita, Mc Donald
2014: blue LEDs: Akaski, Amano, Nakamura
2013: Higgs boson: Englert, Higgs

Vast majority of areas in physics

Also chemistry nobel prizes for quantum chemistry (physics)

2025

$$i\hbar\frac{\partial}{\partial t}\psi(\underline{r},t) = \left[-\frac{\hbar^2}{2m}\nabla^2 + V(\underline{r})\right]\psi(\underline{r},t)$$

100 years of Heisenberg's/Schrödinger's equation

honoring the „fathers“ (and „mothers“) of quantum mechanics,
in particular: Bohr, Schrödinger, Heisenberg, Born, Pauli, Dirac, Fermi...

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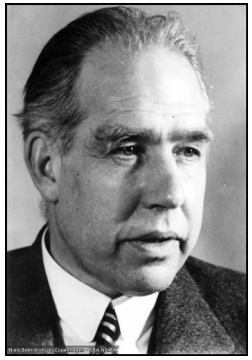
2025

unesco

INTERNATIONAL YEAR OF Quantum Science and Technology



Niels Bohr (1947):
one „researcher who created the foundation on which we all work today“

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Outline

1. Quantum physics today
2. Max Planck and Kiel
3. Planck and the discovery of elementary quanta
4. The Quantum universe: from atoms to galaxies
5. Planck's life and legacy
6. Honoring Planck and quantum science

2. Max Planck.
Childhood in Kiel, 1858-1867

Born in Kiel, 23. April 1858
Father Julius Wilhelm Planck (1817-1900), law professor in Kiel
Mother Emma Planck, (born Patzig)

Uncle Gottlieb Planck (1824-1907), lawyer
Grandfather Gottlieb Jakob Planck (1751-1833), theologist

Parents

Max with brothers and sister, 1862

Max Planck‘s family moves to Munich

German/Austrian-Danish War
Februar-October 1864

for the duchies Holstein, Saxe-Lauenburg, and Schleswig

Reason: passing of the November Constitution, which integrated the Duchy of Schleswig into the Danish kingdom in violation of the London Protocol

1867: Planck‘s father under protest against Prussia leaves Kiel

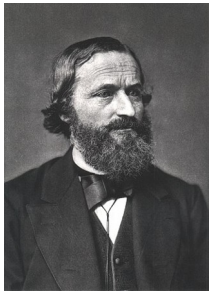
Max Planck retains ties to his hometown and state throughout his life

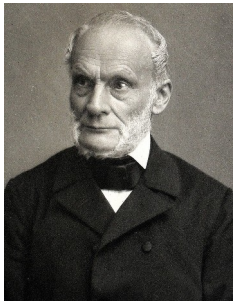
Map: Maximilian Dörrbecker (Chumwa)

Max Planck studies physics

School in Munich: 1867-1874

University: 1874-1879, Munich and Berlin
Lectures by Helmholtz, Kirchhoff, Weierstraß; Self-education: Clausius





Planck was fascinated by theoretical physics, in particular, Clausius' thermodynamics

Continue in Theoretical Physics?

Advise from Prof. Philipp von Jolly*, in Munich, 1877

„Theoretical Physics is close to completion,
… similar as geometry is long complete.“

„in some „corners“ there might be a few tiny „dust grains“ left to explore and categorize, but the system as a whole is well founded.“

*view of an experimentalist

Planck, Naturwiss. **13**, 52-59 (1925)

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Planck: *„I do not desire to discover new ground, but only to understand the existing fundamentals of the physical science and, possibly, to deepen them“*

*view of an experimentalist

Planck, Naturwiss. **13**, 52-59 (1925)

Graduation in physics

PhD thesis 1879: on 2nd law of thermodynamics

Habilitation 1880

No response or recognition from the experts.

Privatdozent: 1879-1885, Munich, unpaid lectures, no position

1885: „Relief“ - Professor in Kiel

1886: Max Planck founds a family
marries his girlfriend from childhood, Marie Merck

the couple has 4 children:
- 1888: son Karl
- 1889: twins Emma, Grete
- 1893: son Erwin

Scientific results in Kiel

Important papers in Kiel: on thermodynamics

- *"Über das Prinzip der Vermehrung der Entropie" (3 papers)*
- *"Über die molekulare Konstitution verdünnter Lösungen"*
- *"Das chemische Gleichgewicht in verdünnten Lösungen"*
- *"Über die Hypothese der Dissoziation der Salze in sehr verdünnten Lösungen"*
- *"Über die Dampfspannung verdünnter Lösungen flüchtiger Stoffe"*
- *"Zur Theorie der Thermoelektrizität in metallischen Leitern"*

1887: wins 2nd prize in Göttingen theory challenge
(supported Helmholtz‘ ideas against W. Weber)

1889: offer to Berlin University (successor of G. Kirchhoff beating L. Boltzmann),
Then center of physics, Planck stays at the university until 1926

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Theoretical physics around 1875

Electrodynamics

Electrical and
magnetic processes, electromagn.
waves, etc.
(Maxwell's eq-s)

Mechanics

dynamics of bodies,
liquids, and planets,
elastic media
(Newton's laws)

Thermodynamics

Heat, gases,
heating and cooling
machines
(1st and 2nd law)

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Theoretical physics around 1875

Radiation of moving bodies

Black-body radiation

ether → **Electrodynamics**

Electrical and magnetic processes, electromagn. waves, etc. (Maxwell's eq-s)

Mechanics

dynamics of bodies, liquids, and planets, elastic media (Newton's laws)

phlogiston → **Thermodynamics**

Heat, gases, heating and cooling machines (1st and 2nd law)

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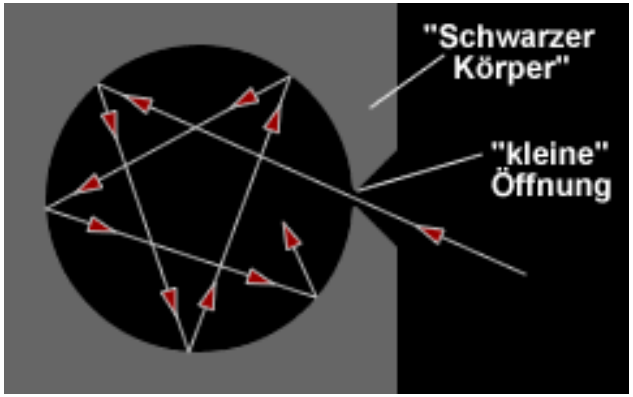
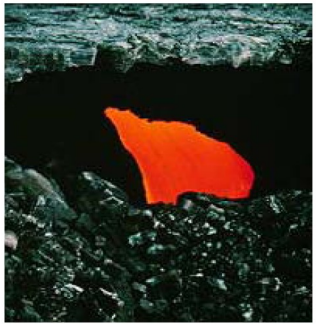
Max Planck and black-body radiation

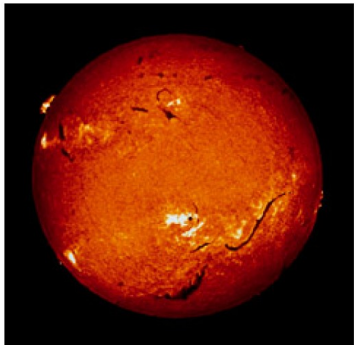
1860: Gustav Kirchhoff formulates model of „black body“:
EM waves in resonator in TD equilibrium



1894: Berlin – Experimentalists at PTRA produce new data at longer λ
– successful theory of W. Wien
– Planck starts to look for his own thermodynamic approach

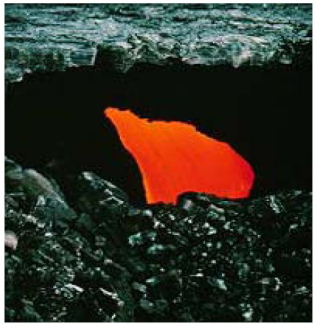
Every body radiates, only T matters

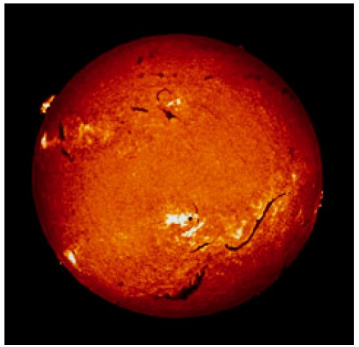




universal relation between color and temperature (W. Wien)

Every body radiates, only T matters





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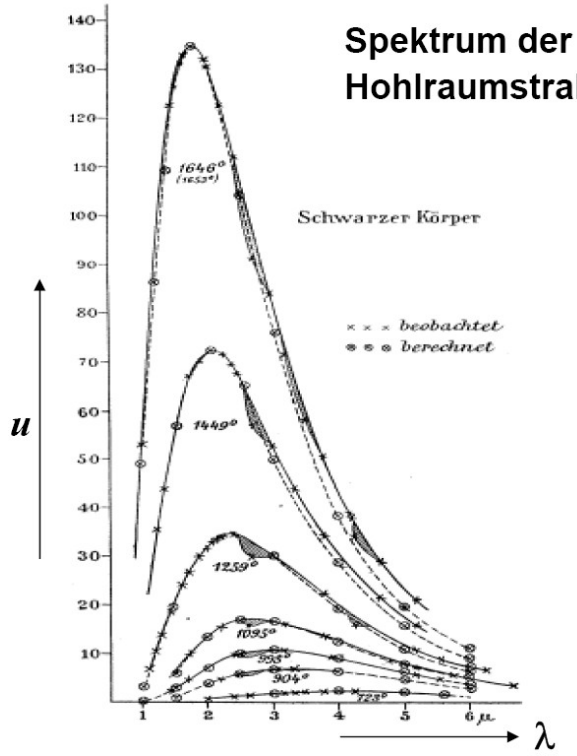
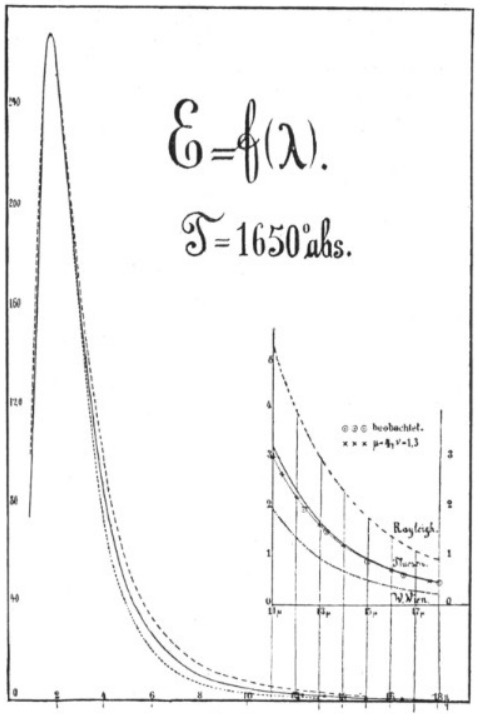
New accurate experimental data in the far infrared



Messung von Lummer und Pringsheim (1900)

Excellent agreement
of Wien's theory
with experiment…

...fades at large λ



modern textbooks: „Planck resolves ultraviolet catastrophe, interpolates…“ … *pure fiction*

Planck finds the radiation law

I. Wien-Formel (große Frequenzen)	II. Rayleigh-Rubens-Gesetz (kleine Frequenzen)
$U(\beta) = b\, e^{-a\beta}$	$U(\beta) = \frac{d}{\beta},\ \beta = 1/kT$
$R = \left(\frac{d^2 S}{dU^2}\right)^{-1} = -aU$	$R = -U^2/d$

Kombination: $R = -aU - U^2/d$

Integration: $\frac{dS}{dU} = \beta(U) = \frac{1}{a}\ln\left[1 + \frac{ad}{U}\right]$

Auflösen nach U: $U(\beta) = \frac{ad}{e^{a\beta} - 1}$

DPG Berlin,
19.10. 1900

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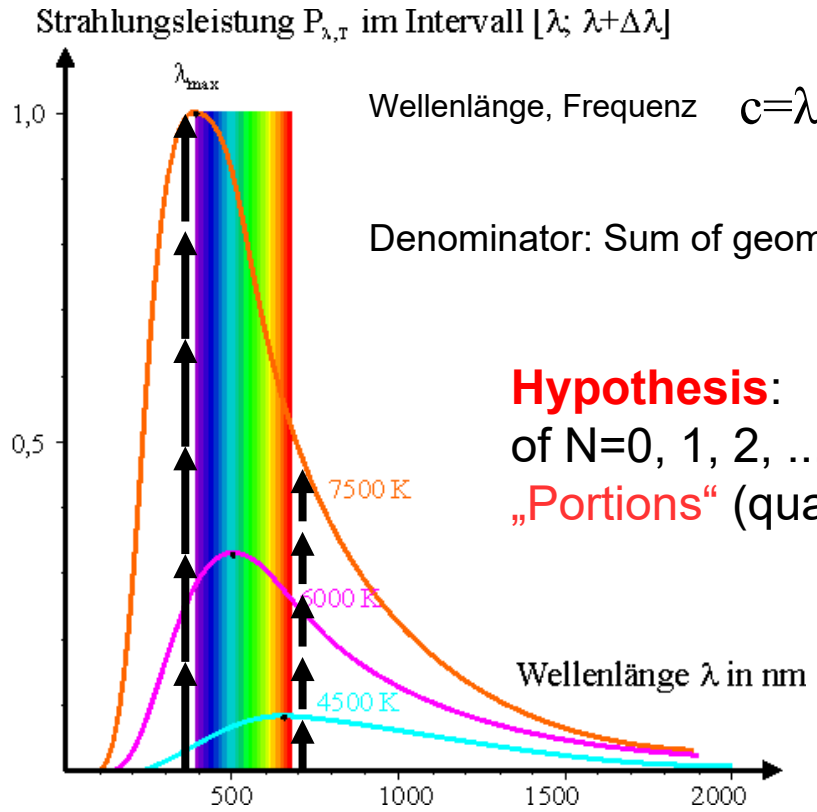
Plancks derivation of the radiation law



Wellenlänge, Frequenz $c=\lambda\nu$

$$\rho(\lambda,T)=\frac{8\pi ch}{\lambda^5}\frac{1}{e^{hc/kT\lambda}-1}$$

Denominator: Sum of geom. progression: $e^{\frac{h\nu}{kT}}+e^{2\frac{h\nu}{kT}}+e^{3\frac{h\nu}{kT}}+\ldots$

Hypothesis: energy composed of N=0, 1, 2, ... identical „Portions“ (quanta)

$$U_\nu = N_\nu \cdot \varepsilon_\nu = N_\nu \cdot h\nu$$

DPG Berlin, **14.12. 1900**
„Birthday of quantum theory“

Planck computes the entropy of radiation

Integration of the combined R yields:

$$\left.\frac{dS}{dU}\right|_{V,N} = \frac{1}{a\nu}\ln\left(1+\frac{h\nu}{U}\right) \equiv \frac{1}{T}\,,$$

$$S = \frac{h}{a}\left[\left(\frac{U}{h\nu}+1\right)\ln\left(\frac{U}{h\nu}+1\right) - \frac{U}{h\nu}\ln\frac{U}{h\nu}\right]$$

Derivation via partition function of (discrete) random process (*a la* Boltzmann): $S = k_B \ln Z_\mu$

model: N identical oscillators containing
P equal energy portions (P, N large):

$$U_N = N\cdot U = P\cdot\epsilon$$

$$Z_\mu = \frac{(P+N)!}{P!N!} \approx \frac{(P+N)^{P+N}}{P^P N^N}$$

$$S = k_B\left\{\left(\frac{P}{N}+1\right)\ln\left(\frac{P}{N}+1\right) - \frac{P}{N}\ln\frac{P}{N}\right\}$$

$$\frac{1}{k_B}S_N = \frac{N}{k_B}S$$

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Planck discovered the N-body Bose system

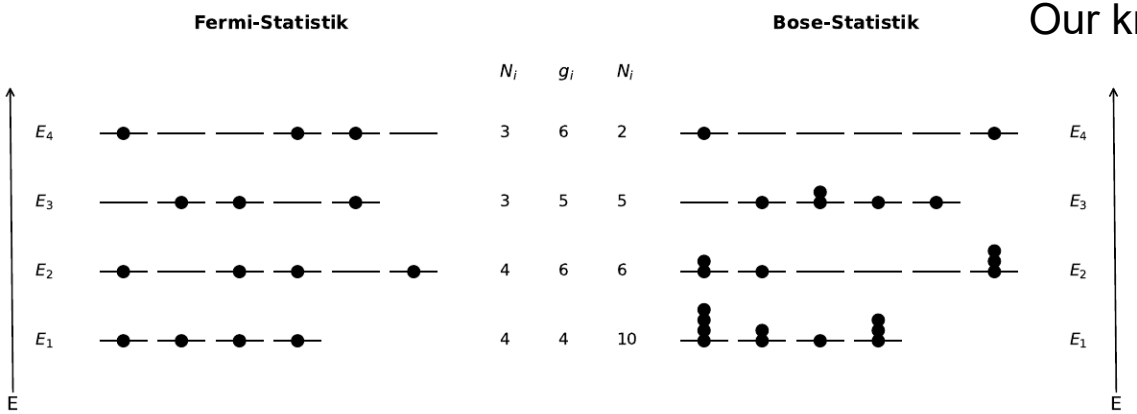

Abbildung 6.14: Besetzungszahlen N_i der Energiezustände E_i, die g_i-fach entartet sind, für Fermionen links und für Bosonen rechts. Die Zahl N_i der Teilchen auf Energieniveau E_i kann bei Fermionen g_i nicht übersteigen (Pauli-Prinzip), für Bosonen ist sie nur durch die Gesamtteilchenzahl begrenzt. Abb.: C. Makait.

M. Bonitz, „Statistical Phyiscs“. Lecture notes

Our knowledge of Fermi/Bose statistics

$$Z^B_{\mu,i} = \frac{(N_i + g_i - 1)!}{N_i!(g_i - 1)!}$$

$$\frac{1}{g_i}\frac{S^B_{\mu,i}}{k_B} = \left(1 + \frac{N_i}{g_i}\right)\ln\left(1 + \frac{N_i}{g_i}\right) - \frac{N_i}{g_i}\ln\frac{N_i}{g_i}$$

Entropy of Bose gas

$$U_N = N \cdot U = P \cdot \epsilon$$

$$S = k_B\left\{\left(\frac{P}{N} + 1\right)\ln\left(\frac{P}{N} + 1\right) - \frac{P}{N}\ln\frac{P}{N}\right\}$$

$$\frac{1}{k_B}S_N = \frac{N}{k_B}S$$

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Broad scepticism against Planck‘s quanta

- Striking contradiction to radiation laws of classical electrodynamics
- Criticism from Rayleigh, Jeans, Ehrenfest, H.A. Lorentz and many other theoreticians
- Planck remained skeptical himself

1911: Nobel prize for Wilhelm Wien, "for his discoveries regarding the laws governing the *radiation of heat*"

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"for his discoveries regarding the
laws governing the *radiation of heat*"

Gradual confirmation of concept of elementary quanta
- 1905 Einstein: theory of photoelectric effect
- 1907 Einstein, Debye 1912: theory of heat capacity of solids
- 1908 Rutherford, Geiger: measurement of elementary charge
- 1913 Bohr: „planetary“ model of hydrogen atom

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1919: Nobel prize for Max Planck (for 1918)

„for his work on the establishment and development
of the theory of elementary quanta“

Planck‘s „theoretical conclusion stands in very sharp opposition to our earlier concept of the radiation phenomenon. Experience had to provide powerful confirmation, therefore, before Planck’s radiation theory could be accepted. In the meantime this theory has had unheard-of success.“

A.G. Ekstrand, President of the Royal Swedish Academy of Sciences, 1. June 1920

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„Planck’s radiation theory is, in truth, the most significant lodestar for modern physical research, and it seems that it will be a long time before the treasures will be exhausted which have been unearthed as a result of Planck’s genius.“

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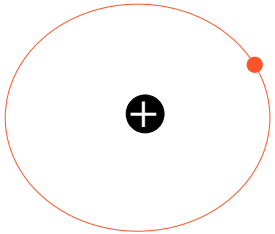
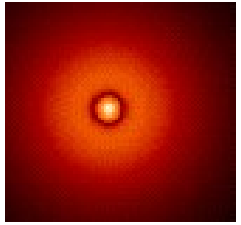
1925-28: Quantum mechanics

Systematic mathematical theory (initiated by Planck 1900)

Bohr, DeBroglie, Heisenberg, Schrödinger, Born,
Jordan, Sommerfeld, Fermi, Dirac, Born, Einstein, Pauli u.v.a.

basis of our picture of the Micro world
excellent agreement with experiments

Universe

	classiscal	quantum
EM radiation Light	 continuous „flow“ of EM field energy	EM field energy composed of discrete quanta
Micro particles Electron Atom	discrete point particles 	continuously distributed particles 

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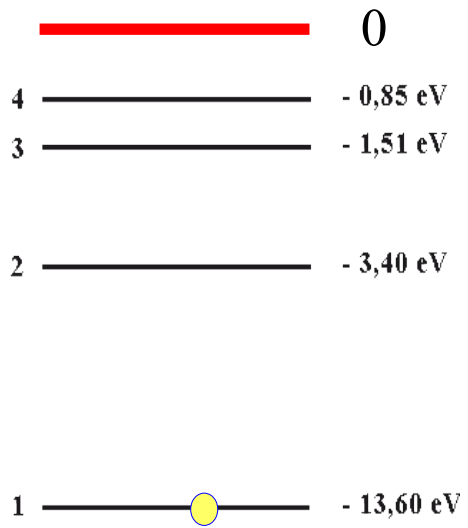
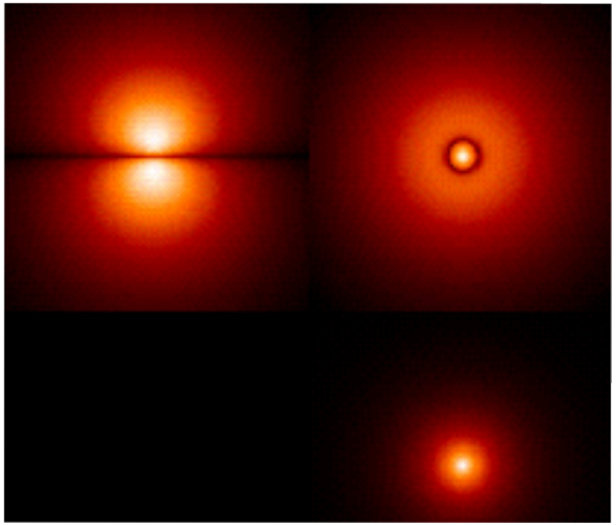
Quantum mechanics

Strict mathematical description of electrons, Atoms, Molecules

Energy of electrons quantized



Example: hydrogen atom



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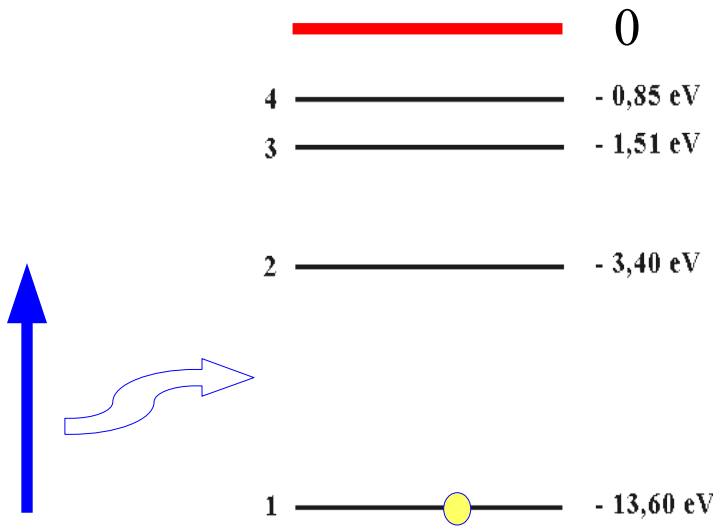

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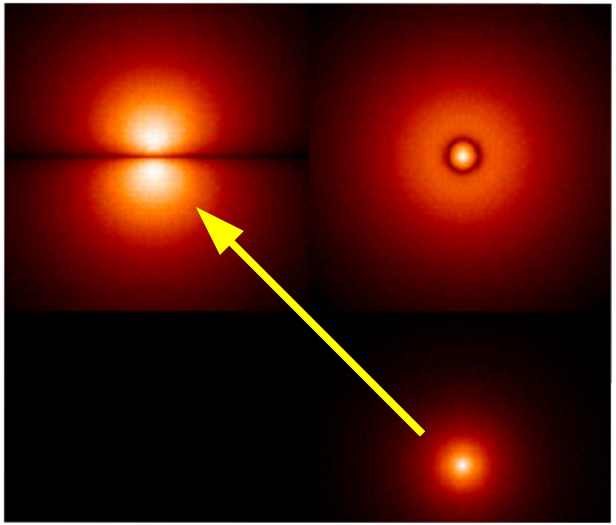

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Quantum mechanics

Strict mathematical description of electrons, Atoms, Molecules

→ *Videos*: solution of Schrödinger equation Sebastian Bauch

Freies Elektron

Elektron an Hindernis

Quantenphysik an der CAU

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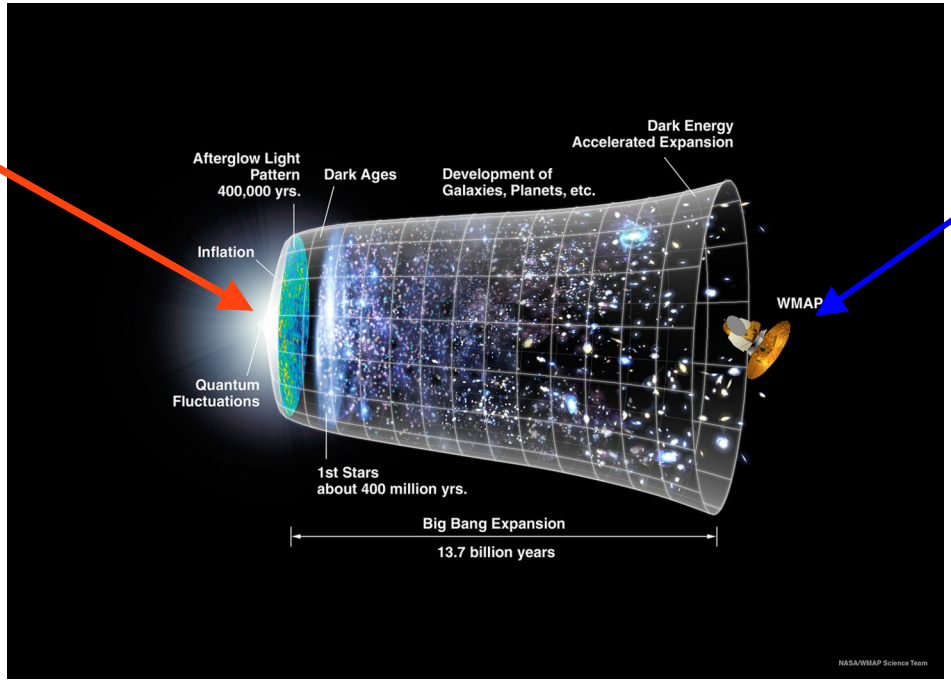
Quantum effects on cosmic scales

Expansion, cooling, condensation

time

Big bang

today



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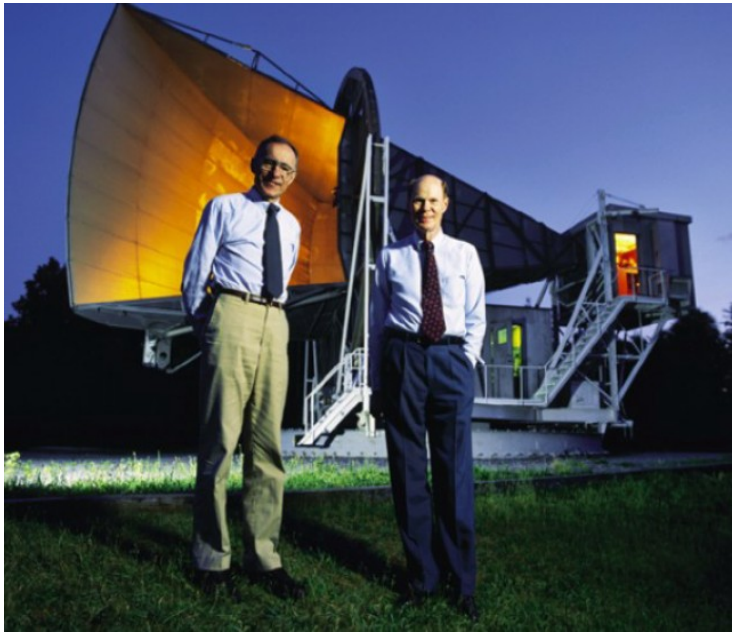
Discovery of cosmic Microwave background

1964: Penzias, Wilson



Measurement of cosmic radio waves

Expansion and cooling 3000K → 2.73K
Wave lengths increases by factor ~1000

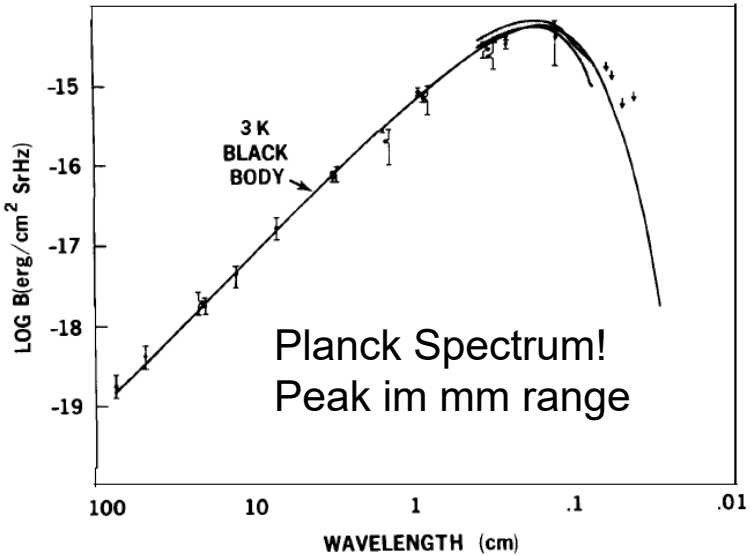
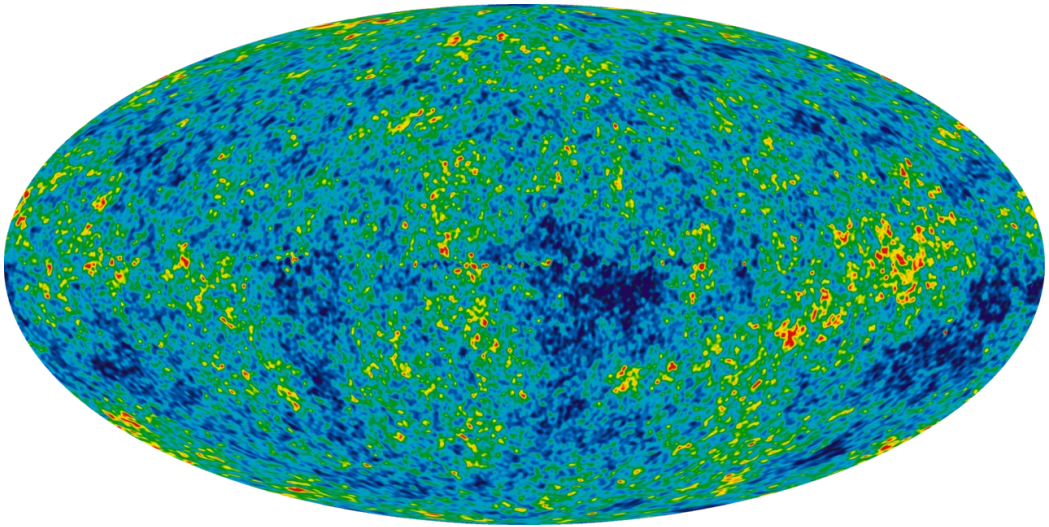


Fig. 12 Measurements of the spectrum of the cosmic microwave background radiation.

Fig..: Wilson, Nobel lecture 1978

A window into the Universe
13.7 billion years ago!



source: Wikipedia

2006: Physics Nobel prize for Mather and Smooth, COBE satellite (1989-93)
today: Satellites measure anisotropy, mass distribution etc., WMAP (2001-10), Planck (2009-13)

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Max Planck: tragic personal life

- 1909 **death of wife** Marie
- 1911 marriage with Marga von Hoeßlin,
  Son Herrmann (1911-1954, mentally ill)

- Death of three children within 3 years
  - **Son Karl: died** in 1916 in World War I
  - **dauther Grete died** 1917 when giving birth
  - **daughter Emma died** 1919 when giving birth

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World War II: Planck stayed in Nazi Germany (conservative, loyal, patriot)

- 1943, October: during a lecture in Kassel Planck barely survived bombing of the city
- 1944: Planck‘s house in Berlin was bombed, he lost everything
- 1945, Jan. 23.: **son Erwin executed** (participant in Hitler assessination attempt of Stauffenberg and others)
- May 1945: brought from Rogätz (near Magdeburg) to Göttingen (Kuipers)
- Oct 4 1947: Planck dies in Göttingen (89 years old)

Planck‘s public activities (selection)

- permanent Secretary of Prussian Academy of Sciences (1912/38)
- Rector of Berlin University (1913/14), supported Einstein, many colleagues
- President of German Physical Society (4 times, 1905-09, 1915-16)
- President of Kaiser-Wilhelm-Society (1930-37)

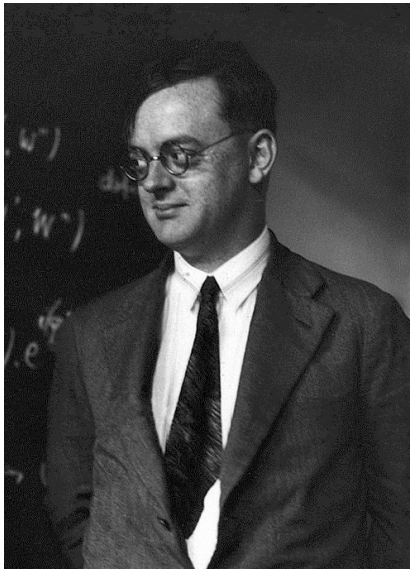
- many public lectures about science, ethics, philosophy

highly respected among scientists world-wide
well known to the general public

Influenced several generations of scientists
Impressively documented in the **Max-Planck estate in Kiel**

Planck in the words of colleagues

condolence letter to Marga Planck, 1947*



Pascual Jordan
1902-1980 (Wikipedia)

„...I personally am indebted to him - as are most of the physicists of my generation – for the entire content and the entire purpose of my own scientific life's work..."

*C. Pitschellis, E. Schroedter, and M. Bonitz (2024)
English: R. Lackner, P. Ludwig, and M. Bonitz (2025)

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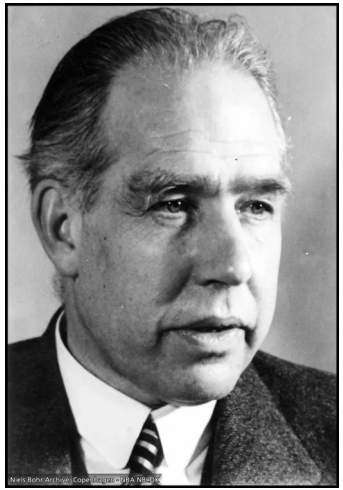

Niels Bohr, Nobel prize 1922 (Wikipedia)

„...The deep impression of his splendid and pure personality is one of my most treasured experiences, and I will always remember with gratitude the friendship which he extended to me for many years…"

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Max Born, Nobel prize 1954 (Wikipedia)

„...It is impossible for me to express what I have lost through the death of your husband. I owe him my scientific development and my career; above and beyond that, he was a sterling example of noble humanity for me……"

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Liese Meitner
(1878-1958)
In Washington DC 1946

„...Your husband's life was unusual, as he himself was unusual, with his wonderful, pure personality, which made everyone who even came near him a better person.…"

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Max Planck – conservative patriot and humanist

- Supported the Kaiser at the beginning of WWI, disctanced himself lateron
- After WWI strong engagement for German science
- 1933: as president of Kaiser-Wilhelm Gesellschaft Planck tries to convince Hitler to abstain from repressing jewish scientists. Unsuccessful
- Defended DPG and KWG against Nazi indoctrination.
  Supported jewish colleagues and their families (F. Haber, Fam. Rubens u.a.)
- Defended understanding between nations (Dialogue with Francois-Poncet 1938)
- Opposed to public protests or declarations

Max Planck – Respect abroad

- 1946 British scientists celebrated the 300th birthday of Isaac Newton with many international guests
- German scientists (those who had not emigrated) were not invited because the discredited themselves during the Nazi period.

Max Planck – Respect abroad

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There was one exception: Max Planck

Laid the foundation for Max Planck society

“Max Planck, Kiel and the beginning of the quantum era”, M. Bonitz, 2025

Planck in the words of German humanists

condolence letter to Marga Planck, 1947*

Elisabeth Schiemann
(1881-1972)
Biologist, part of Resistance
2014: „Righteous among the nations“

„...For us he was the exponent of the good German conscience throughout all the evil years; and therefore his name, which today is well known in the entire world, will be our best defender, so that we may maintain the belief in a better Germany...”

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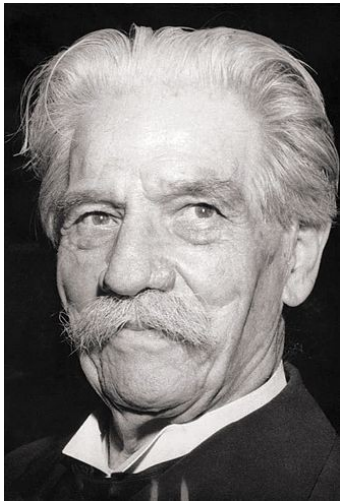

Albert Schweitzer
(1865-1948)
Nobel peace prize 1952
1955, © Bundesarchiv

``He represented eternal ethical cultural values in the face of those who attempted to change and devalue them. Thereby he gave comfort and strength in terrible times to many who did not want to take part in the general confusion....

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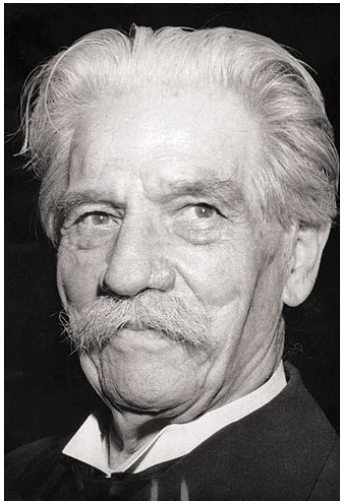

Albert Schweitzer
(1865-1948)
Nobel peace prize 1952
1955, © Bundesarchiv

``....In a time when so many learned men showed themselves to be much smaller as human beings, he preserved a most noble humanity and exhibited a quiet imperturbability..."

*C. Pitschellis, E. Schroedter, and M. Bonitz (2024)
English: R. Lackner, P. Ludwig, and M. Bonitz (2025)

Summary and Outlook

„I do not desire to discover new ground, but only to understand the existing fundamentals of the physical science and, possibly, to deepen them“

“Max Planck, Kiel and the beginning of the quantum era”, M. Bonitz, 2025

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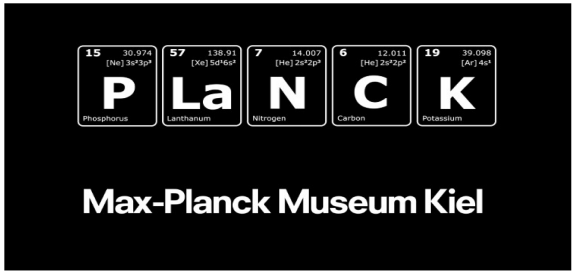
Quantum theory: Revolution in science, technology – comparable to Kopernikus, Newton, Darwin
A unique example of scientific discovery and personal integrity
A story that should be kept and told

“Max Planck, Kiel and the beginning of the quantum era”, M. Bonitz, 2025

14.12. 2013 - Opening of a Museum for Max Planck and quantum physics in Kiel



Physikzentrum of CAU Kiel
Presenting Planck's discovery *(after 5 years of struggle)*

"Max Planck, Kiel and the beginning of the quantum era", M. Bonitz, 2025

14.12. 2013 - Opening of a Museum for Max Planck and quantum physics in Kiel

2 grandgranddaughters of Max Planck – Christine Roos und Cornelia Kulenkampff - Attended the opening. Support of our museum by the family

Museum for Max Planck and quantum physics

Museum in the Physics Library, Physikzentrum of CAU Kiel today

“Max Planck, Kiel and the beginning of the quantum era”, M. Bonitz, 2025

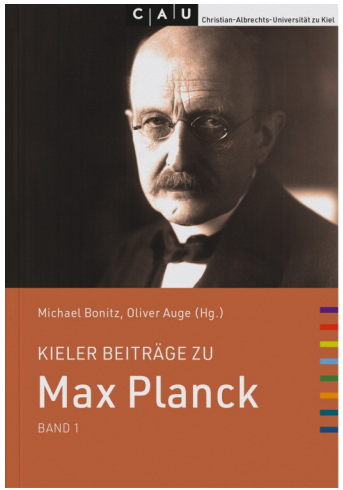
Support of the Museum by the Planck family: the Planck estate arrives at Kiel

Frank Homann and Patrick Ludwig, October 8 2020, Kiel

Walhalla, July 15. 2022: Gabriele Taylor, signs the lease of the estate

Planck estate: first publications

11.12. 2024 Start of
Open access book series in CAU-Verlag
M. Bonitz, O. Auge (Eds.)



vol. 1: M. Bonitz,
"Max Planck, Kiel und der Beginn der Quantentheorie"

vol. 2: C. Pittschellis, E. Schroedter und M. Bonitz, „Die Kondolenzen von Wissenschaftlerinnen und Wissenschaftlern zum Tode Max Plancks 1947“

Results on display at Museum

In press:
vol. 3: english translation of condolences
vol. 4: Letters from Liese Meitner and Max von Laue

In progress:
Digitazation of entire estate (2,000 letters, 10,000 pages)

Parts available online:

Planck-Repositorium

The future: Max Planck quantum science center

Supported by Planck family, Max Planck foundation,

State of Schleswig-Holstein

Sponsors welcome