

# Vorlesung Physik-3

Schönenberger group [www.nanoelectronics.ch](http://www.nanoelectronics.ch)



CH

UNI  
BASEL



$\hbar\nu$

## Physik III Atom- und Quantenphysik

Prof. Dr. Christian Schönenberger  
[www.nanoelectronics.ch](http://www.nanoelectronics.ch)



basierend auf der Vorlesung von  
Prof. Dr. Philipp Treutlein  
<http://atom.physik.unibas.ch>

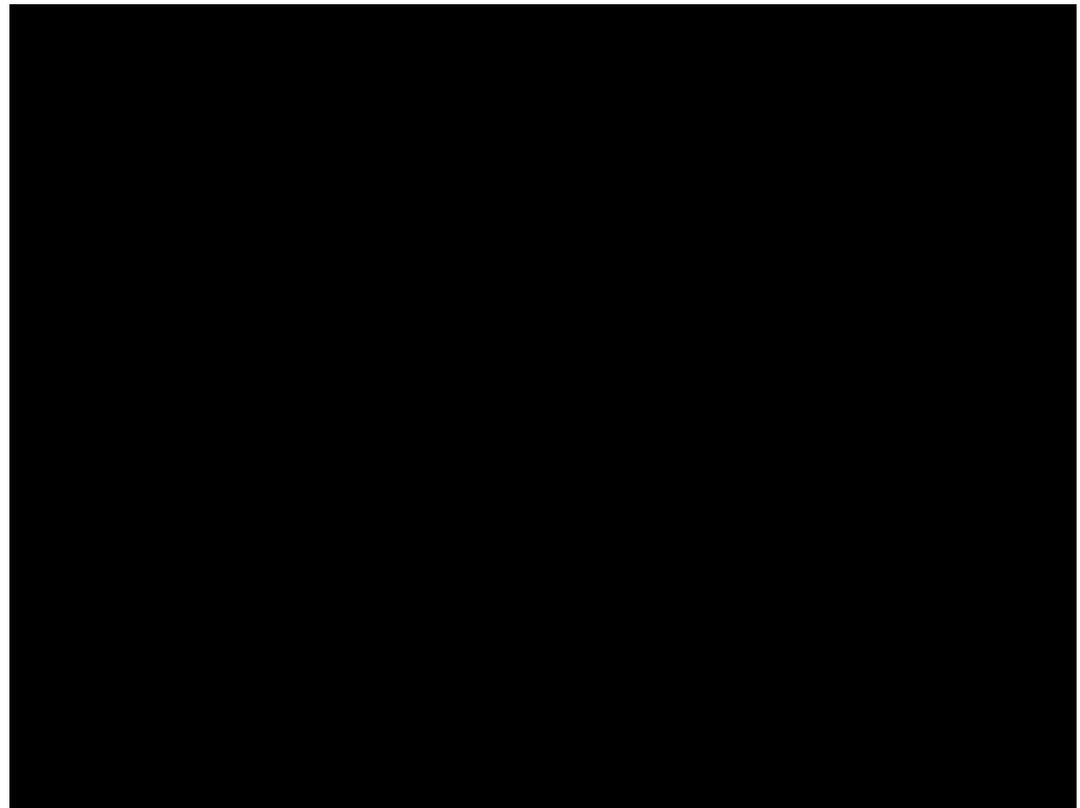
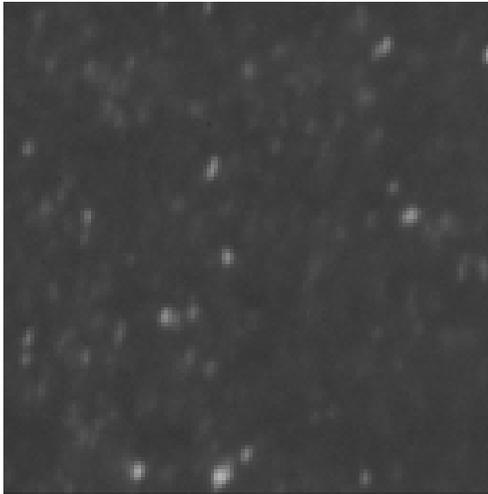
# 1. Elementare Eigenschaften

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kann man Atome sehen ?

indirekt, z.B. Brown'sche Bewegung



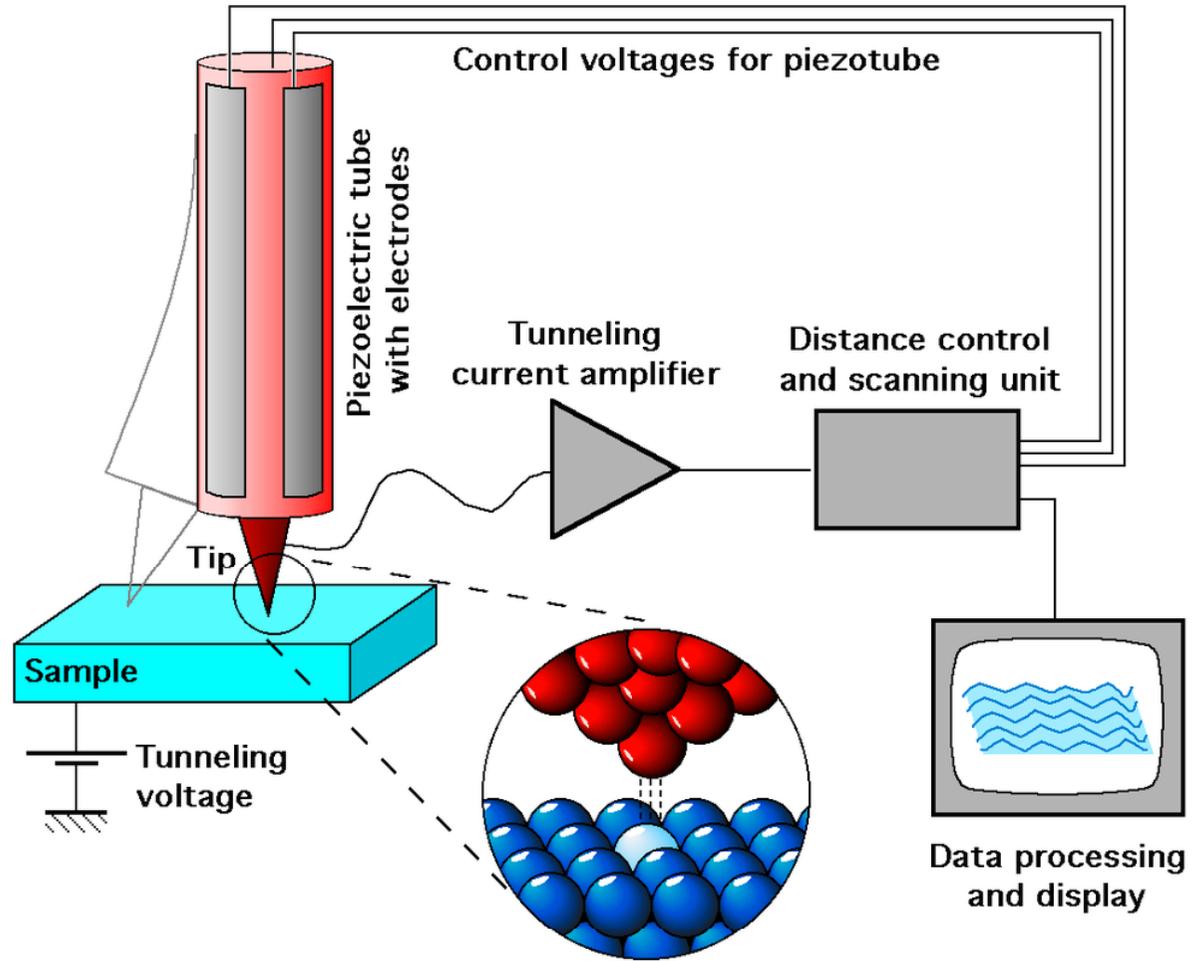
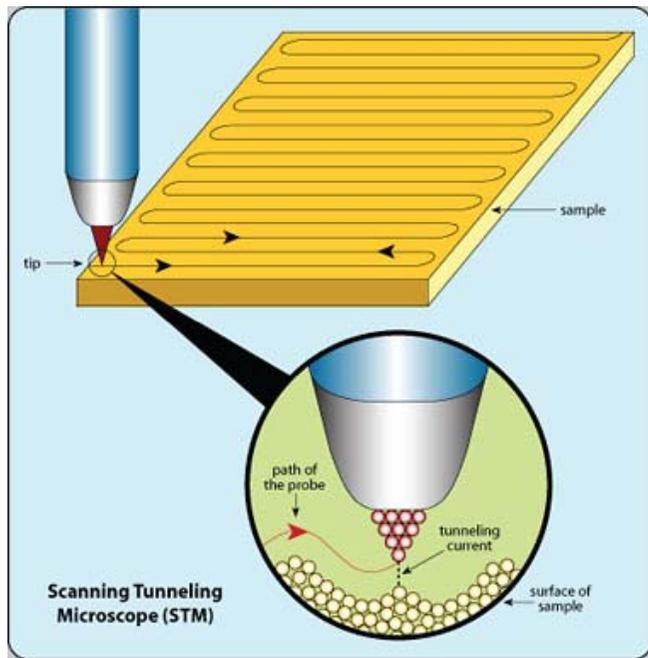
# im Rastertunnelmikroskop

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Gerd Binnig

Heinrich Rohrer



# im Rastertunnelmikroskop

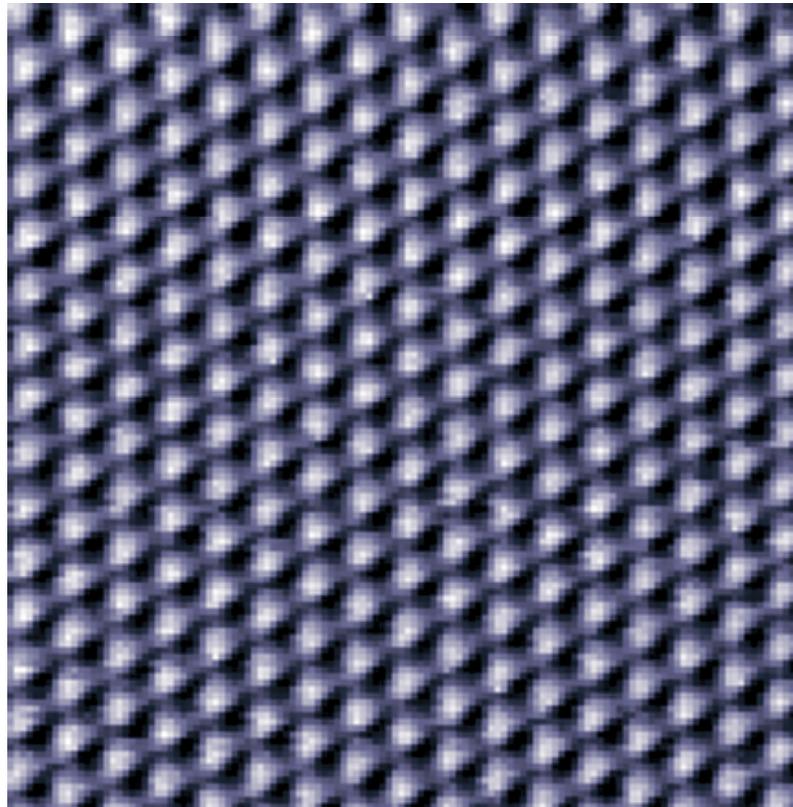
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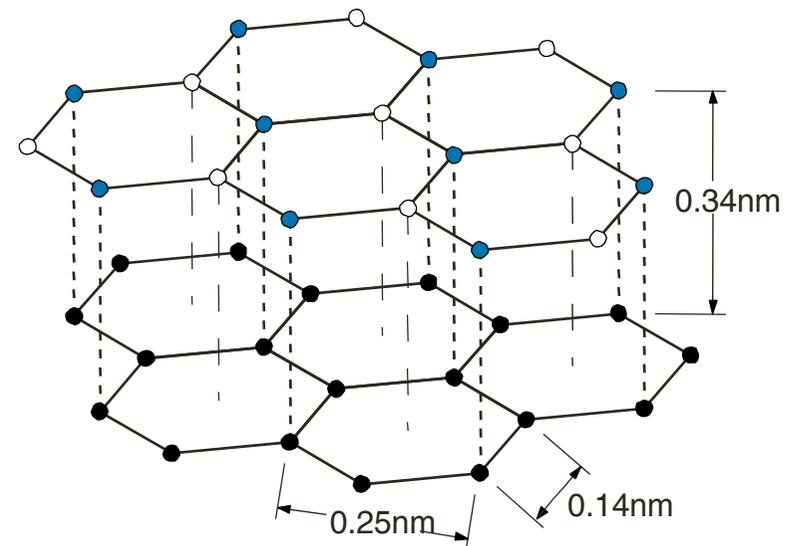
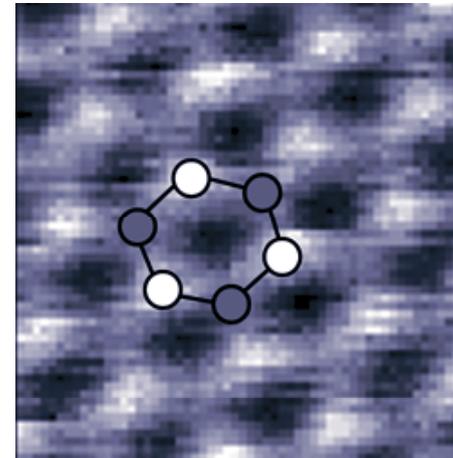


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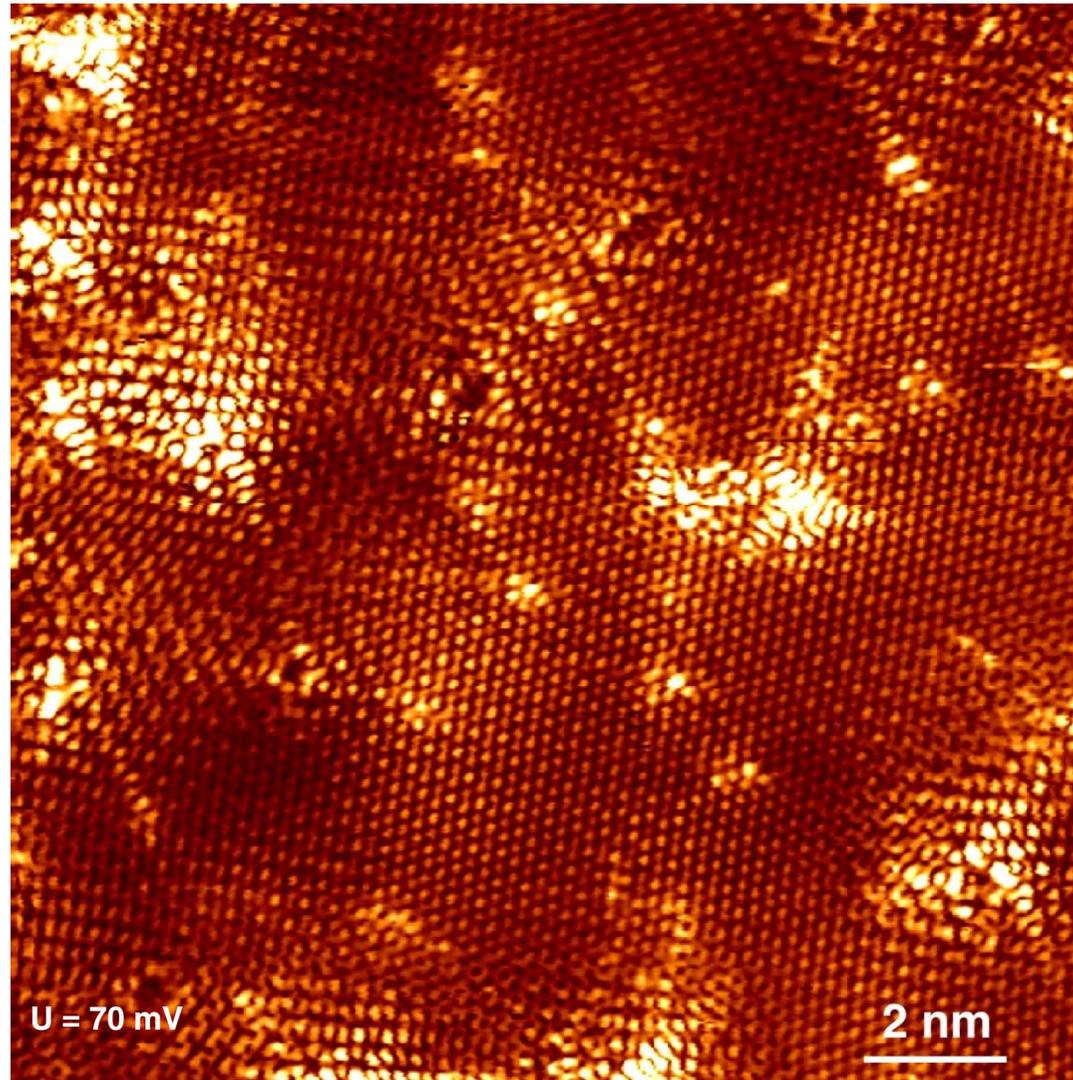
scan size: 4 nm

$U=0.1V$   $I=1nA$



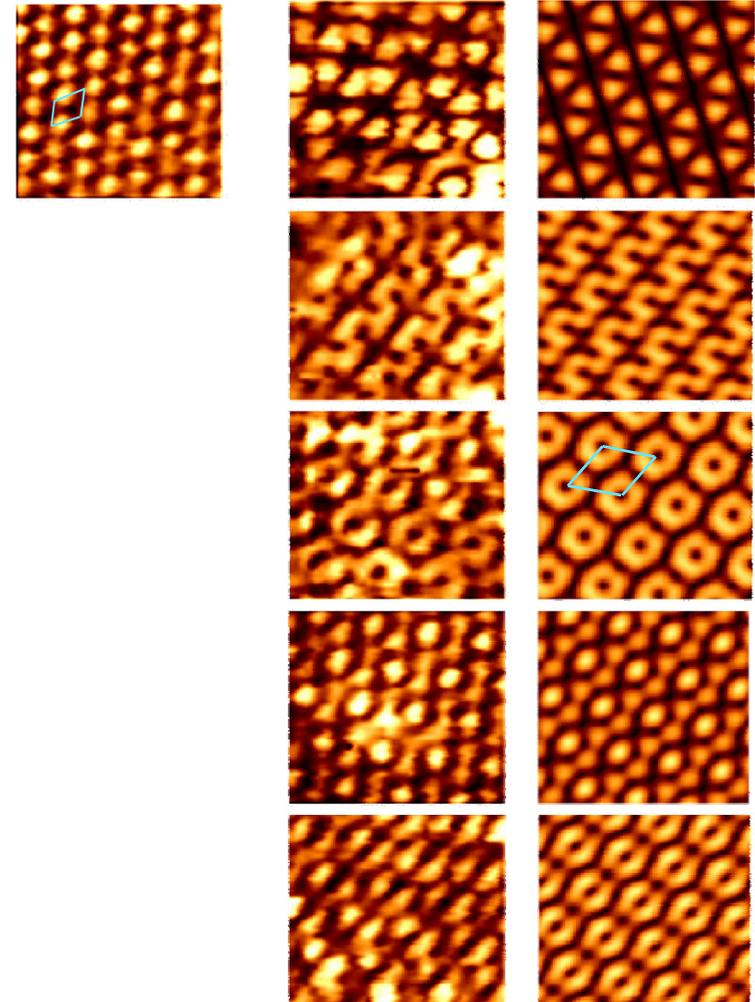
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Exp.

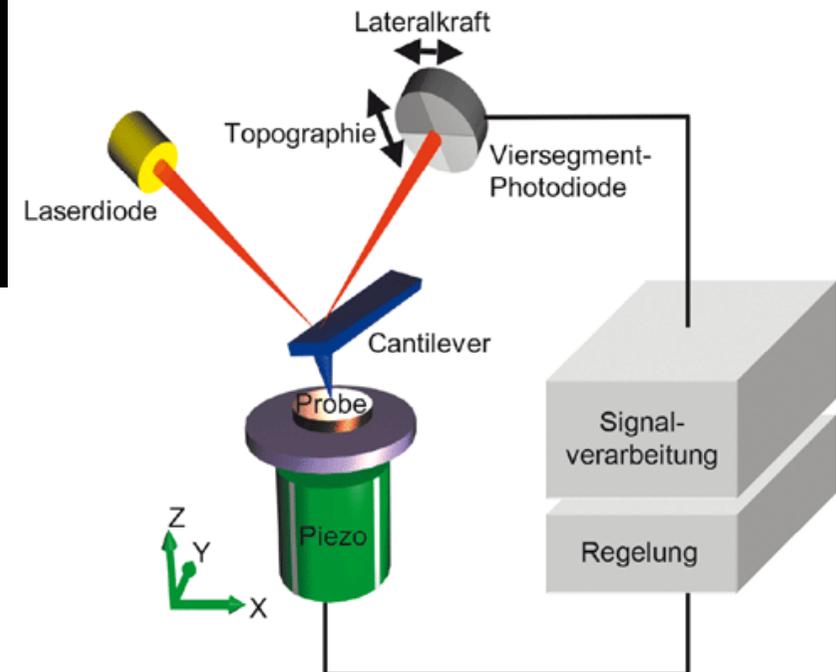
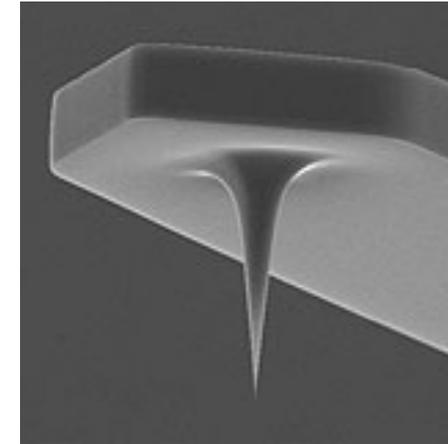
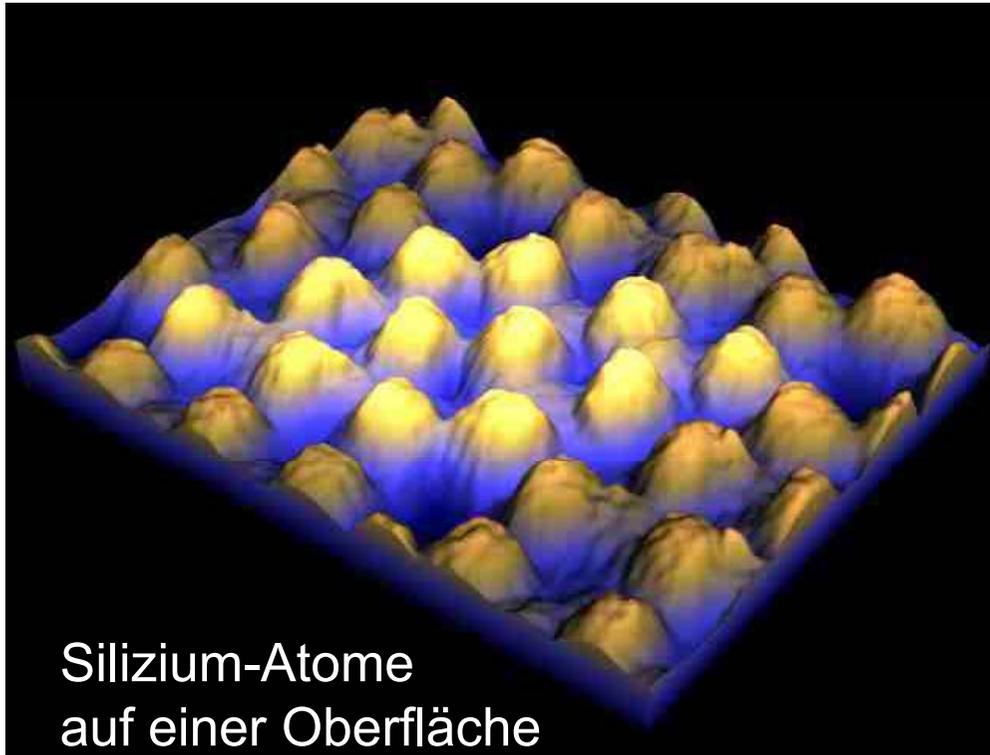
$|\psi|^2$



*P. Ruffieux et al., PRB 71, 153403 (2005), PRL 84, 4910 (2000)*

# im Rasterkraftmikroskop

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# Neues für die Nanoelektronik

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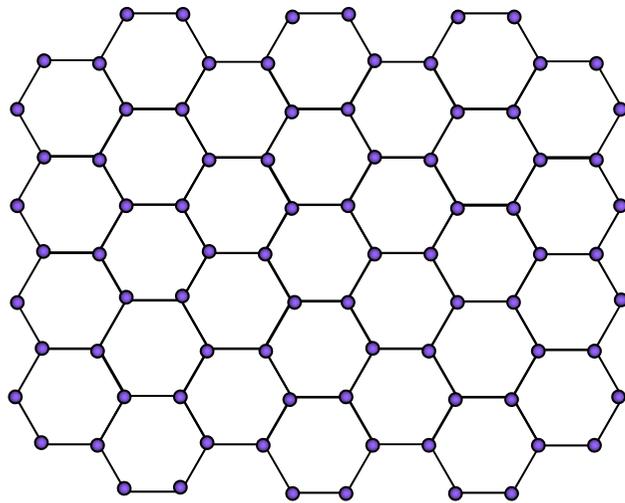
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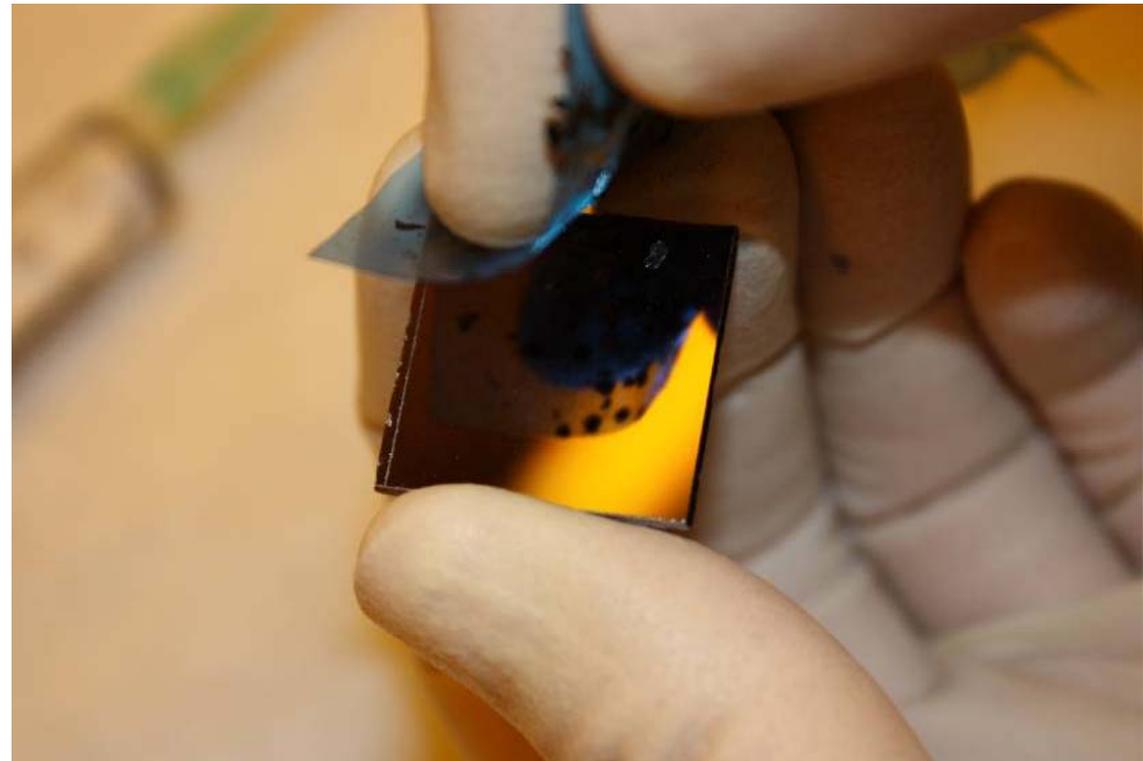
Graphit

...neue Form von Graphit

Graphite wird mittels Klebband  
in seine Einzelschichten getrennt



„Graphene“ = Kohlenstoff-  
Monoschicht



Elektronen in Graphene verhalten sich wie relativistische Fermionen ohne Masse, z.B. wie Neutrinos

# Elektronenmikroskop

PRL 110, 255501 (2013)

PHYSICAL REVIEW LETTERS

week ending  
21 JUNE 2013

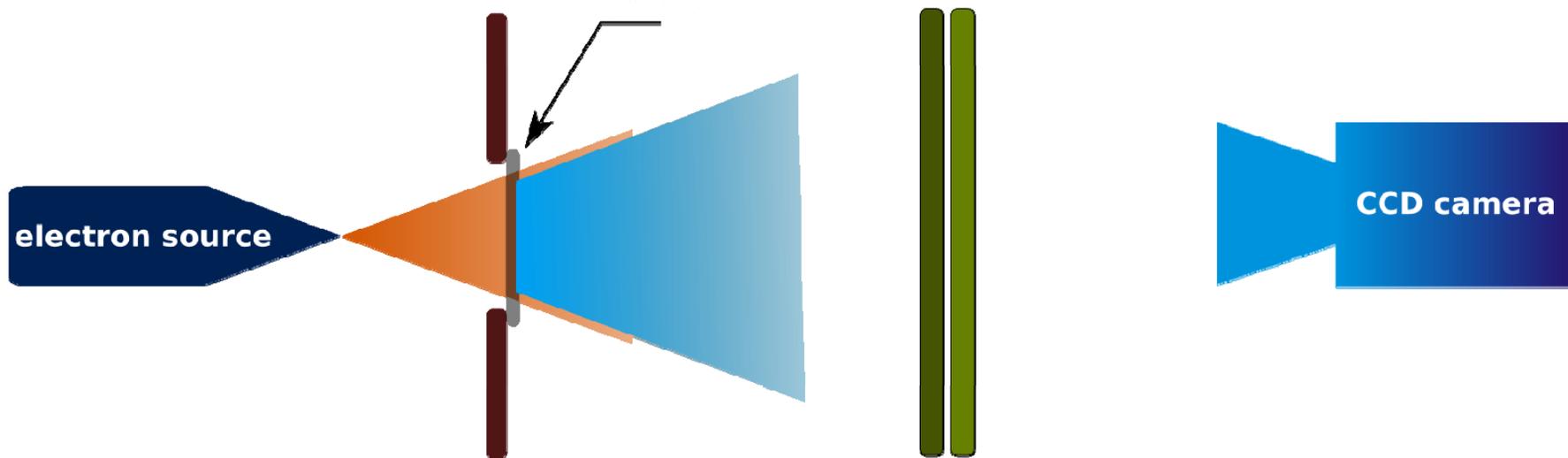
## Graphene Unit Cell Imaging by Holographic Coherent Diffraction

Jean-Nicolas Longchamp, Tatiana Latychevskaia, Conrad Escher, and Hans-Werner Fink

*Physik Institut der Universität Zürich, Winterthurerstrasse 190, CH-8057 Zürich, Switzerland*

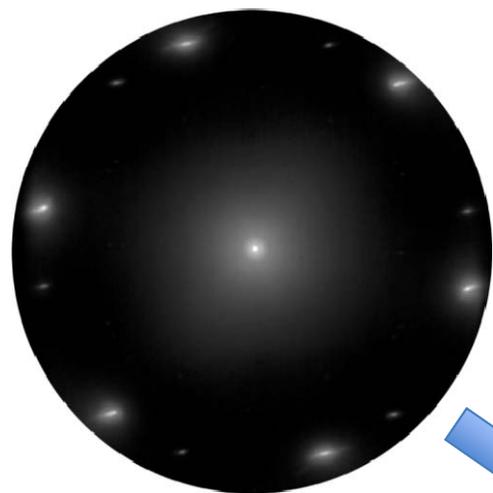
(Received 7 February 2013; published 18 June 2013)

We have imaged a freestanding graphene sheet of 210 nm in diameter with 2 Å resolution by combining coherent diffraction and holography with low-energy electrons. The entire sheet is reconstructed from a single diffraction pattern displaying the arrangement of 660.000 individual graphene unit cells at once. Given the fact that electrons with kinetic energies of the order of 100 eV do not damage biological molecules, it will now be a matter of developing methods for depositing individual proteins onto such graphene sheets.



# Elektronenmikroskop

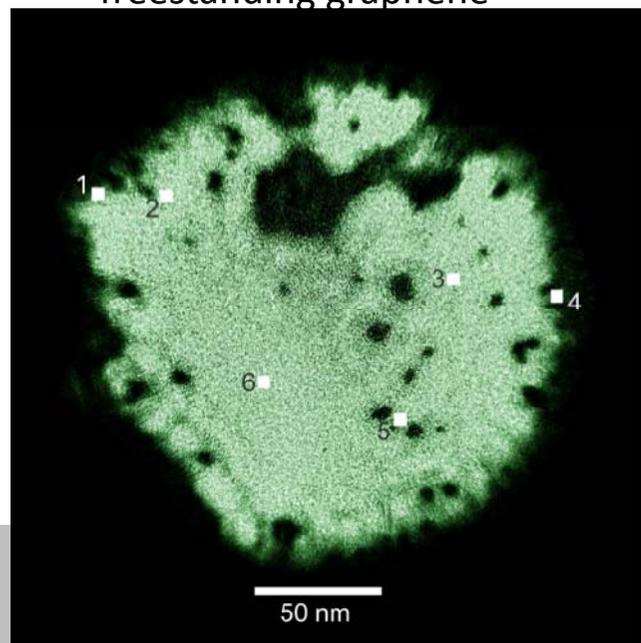
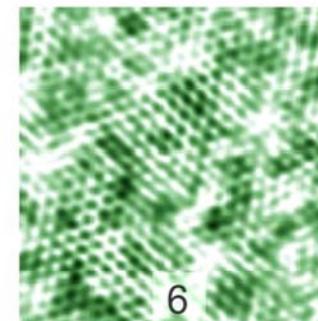
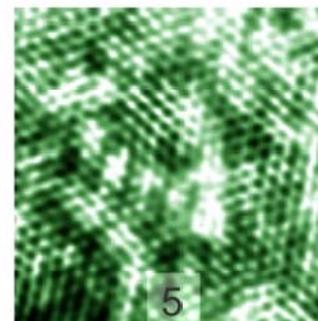
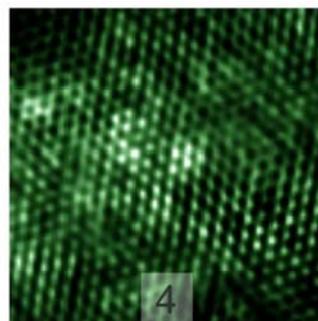
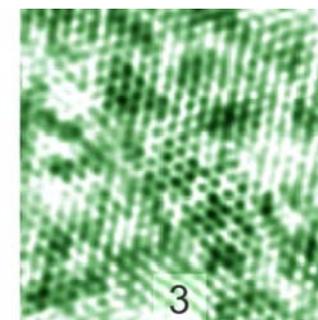
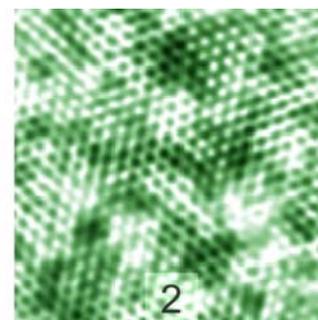
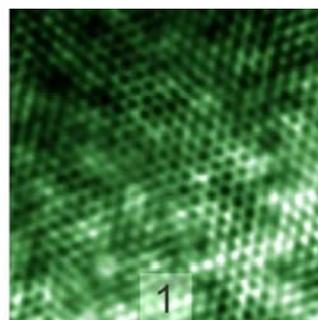
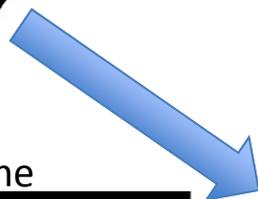
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236eV diffraction pattern

210nm in diameter  
freestanding graphene

reconstruction

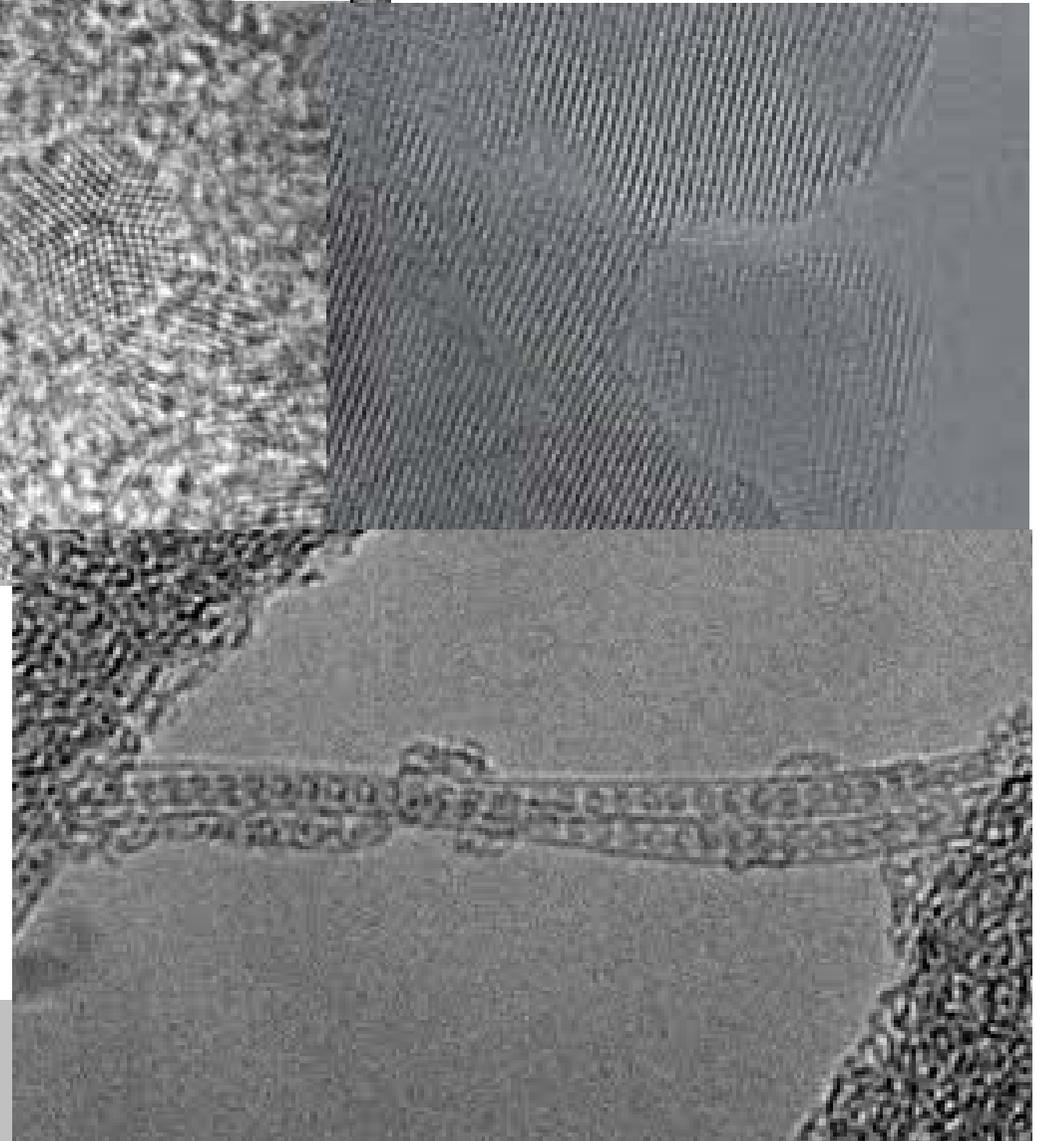
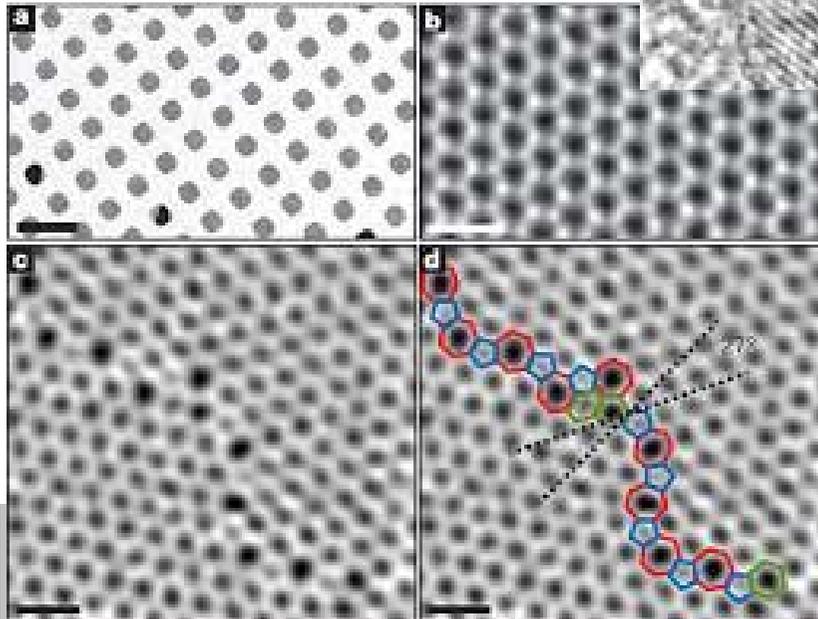
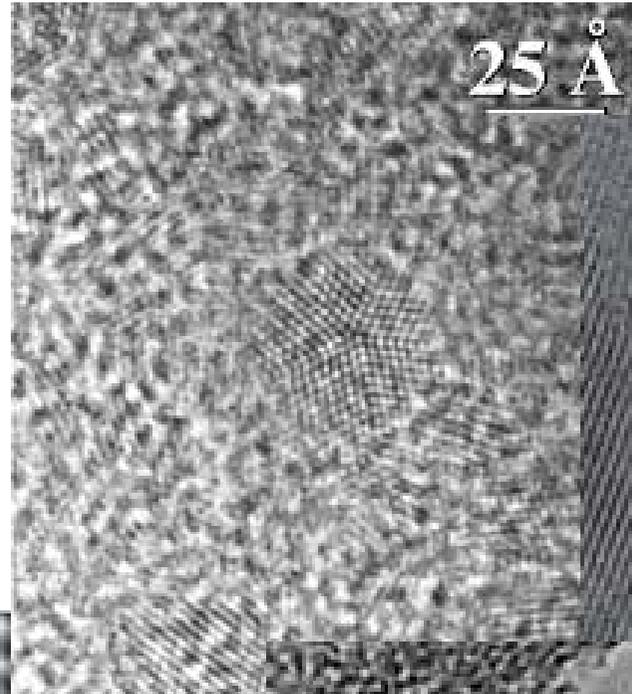
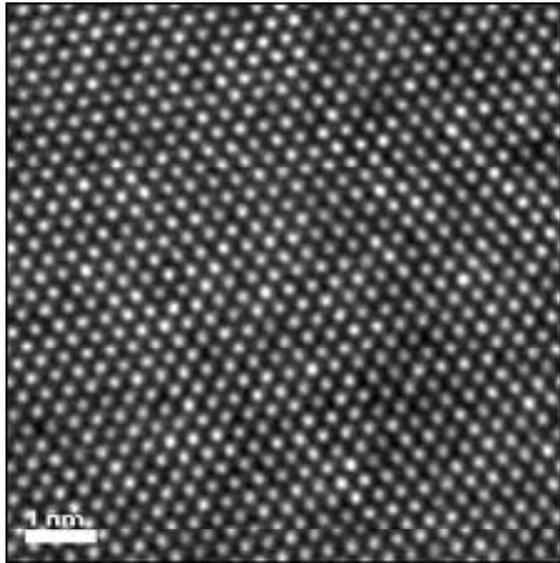


# Elektronenmikroskop

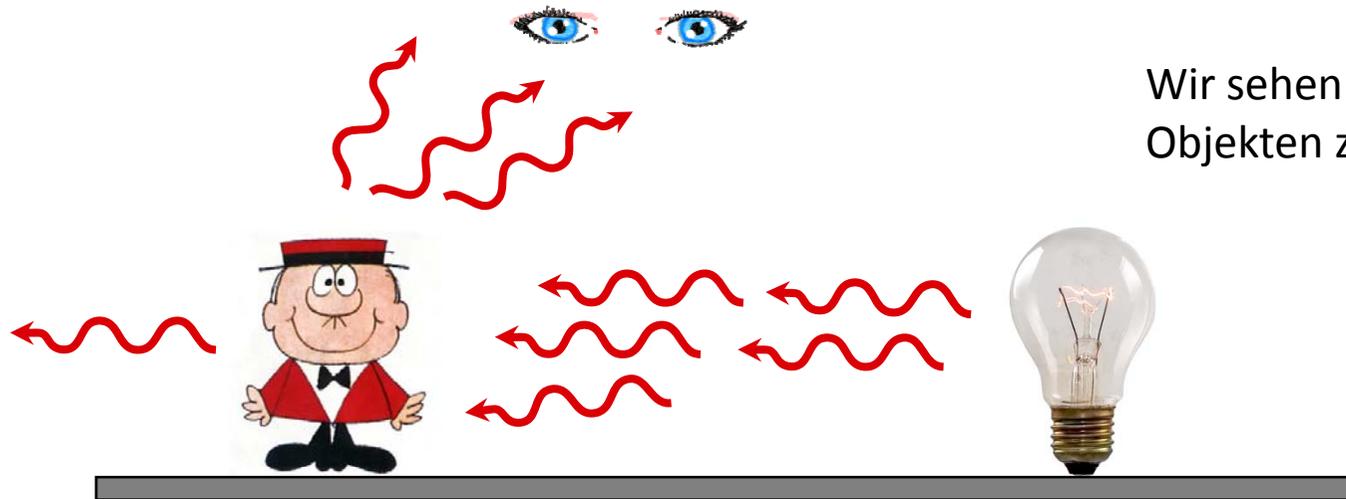
Schönenberger group [www.nanoelectronics.ch](http://www.nanoelectronics.ch)



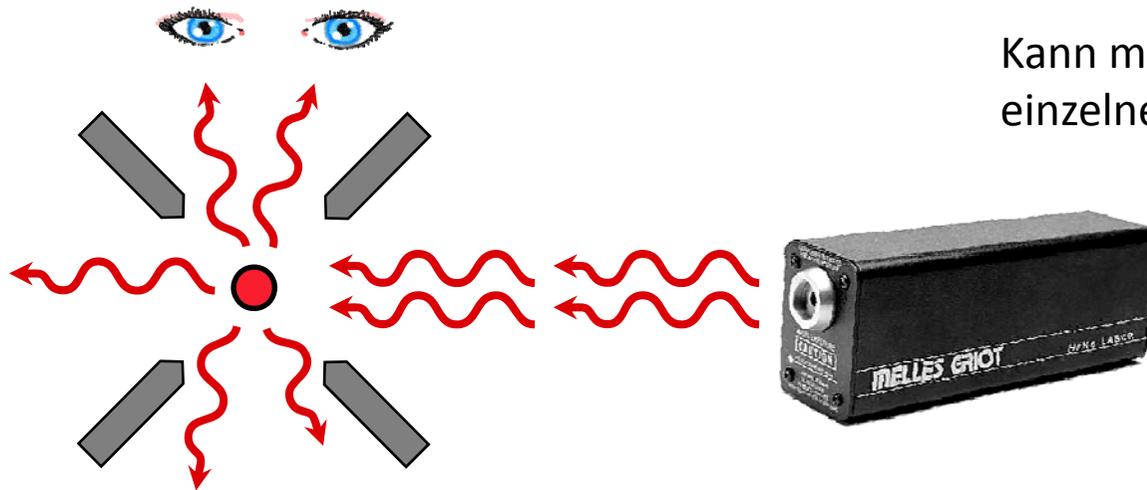
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# Kann man einzelne Atome sehen?



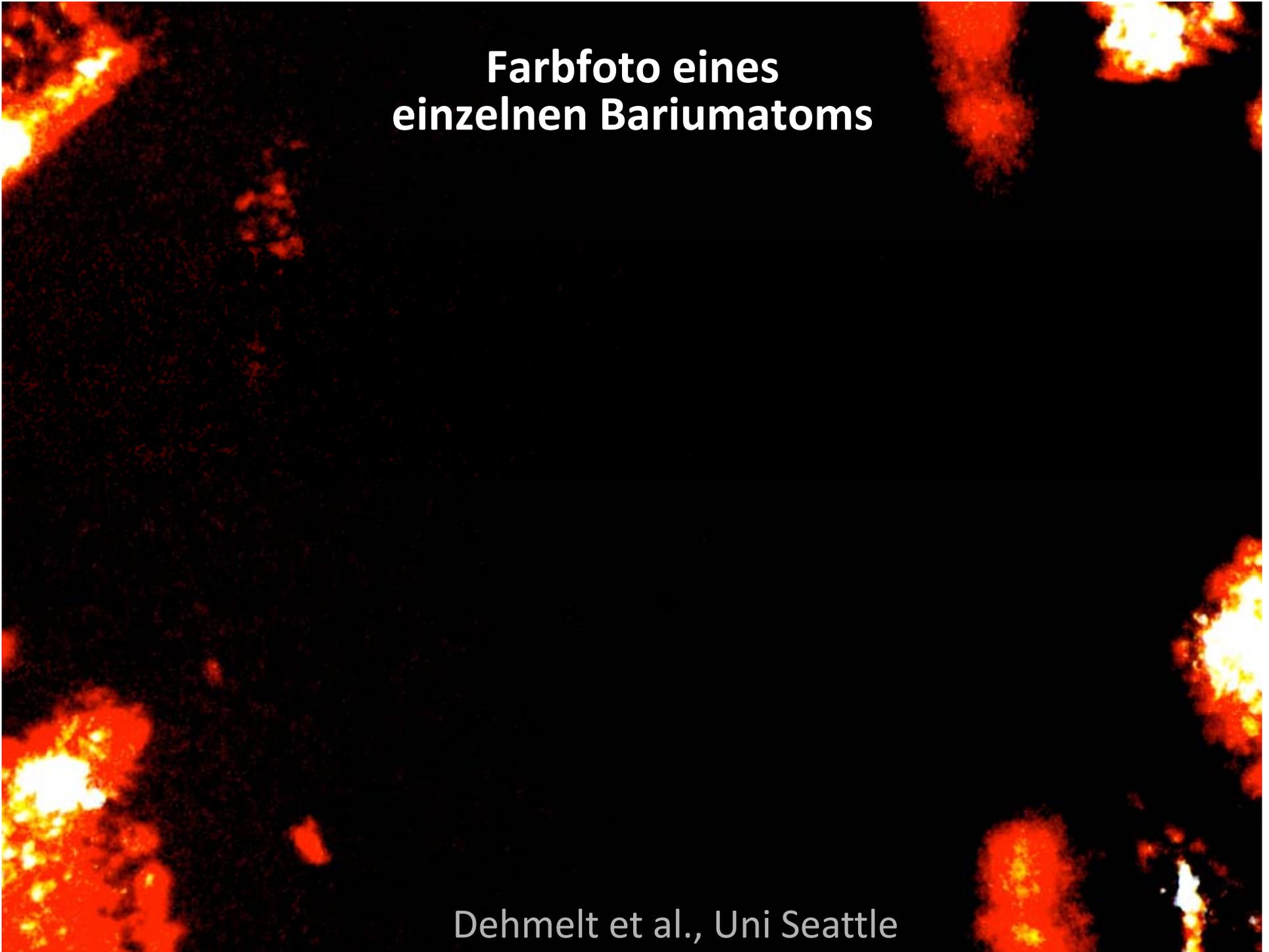
Wir sehen das Licht, das von den Objekten zurückgeworfen wird



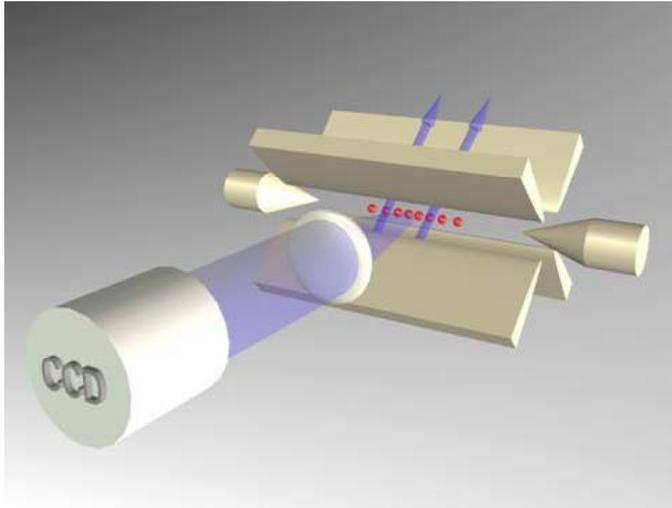
Kann man so auch ein einzelnes Atom sehen?

**Farbfoto eines  
einzelnen Bariumatoms**

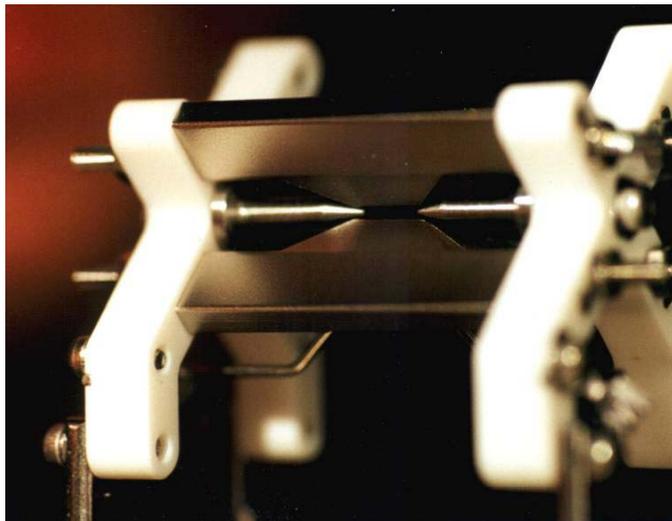
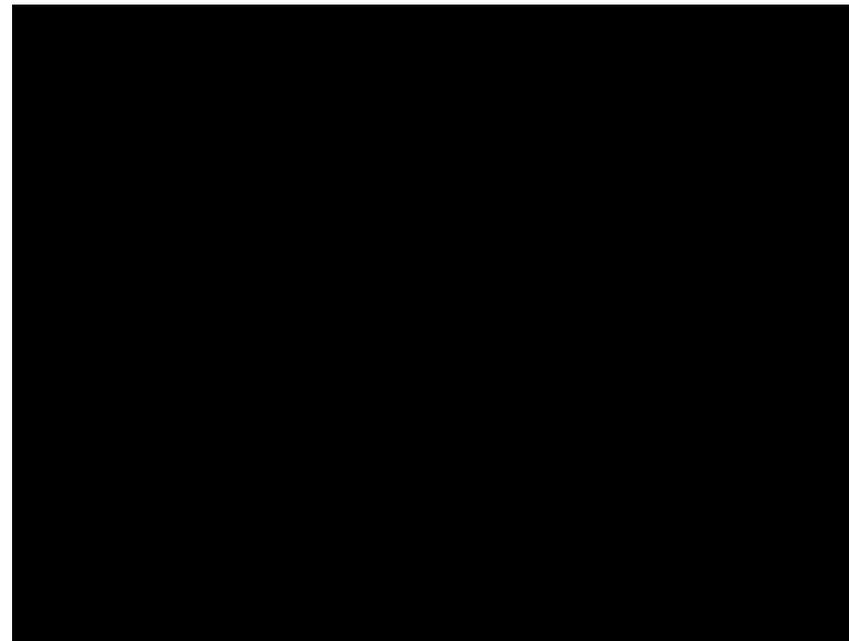
Dehmelt et al., Uni Seattle



# Dynamik einzelner Ionen in Ionenfallen

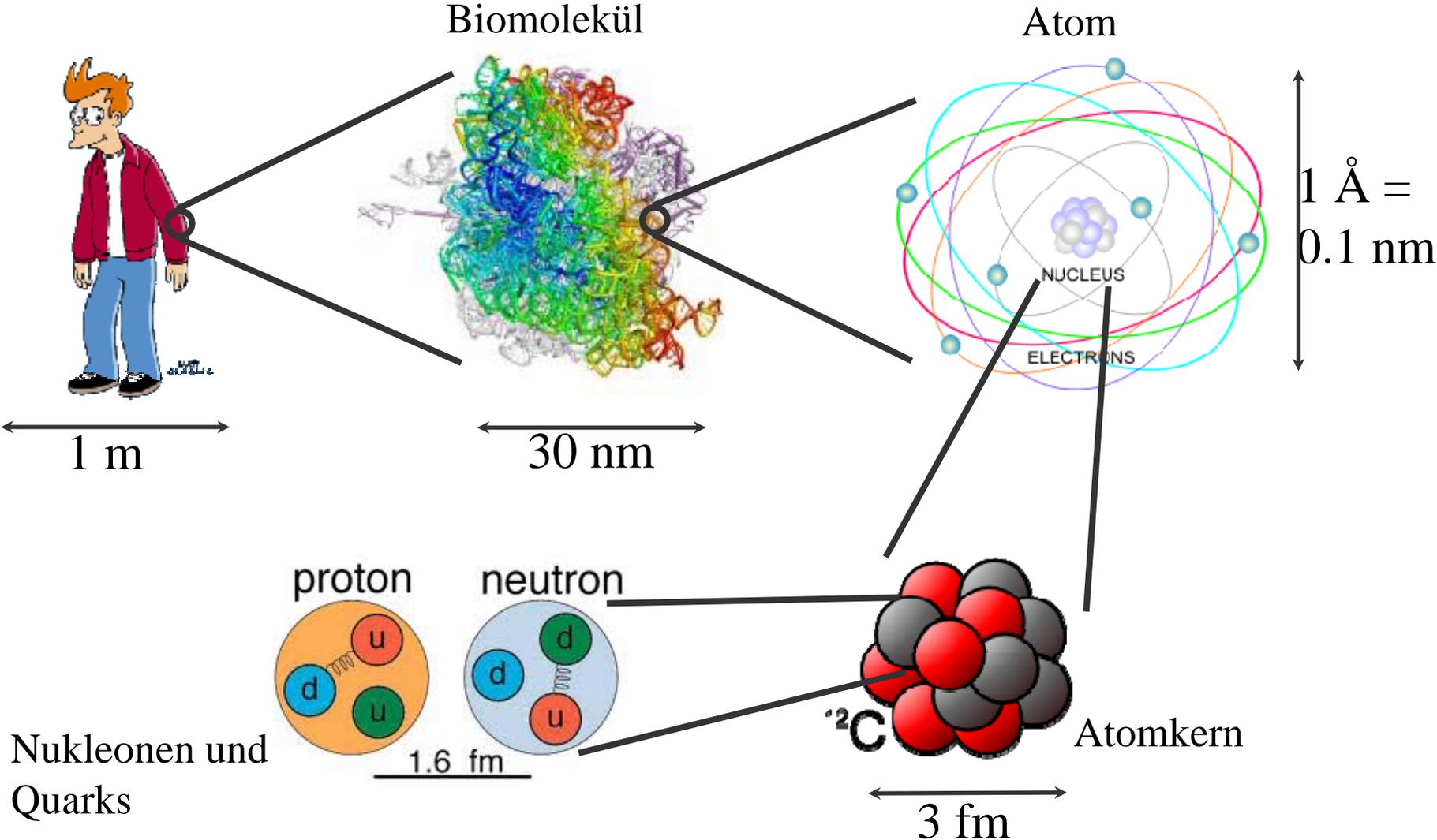


Kette von Ionen in einer Paul-Falle



(R. Blatt et al., Innsbruck)

# Grösse und Struktur der Atome



# Kathodenstrahlen

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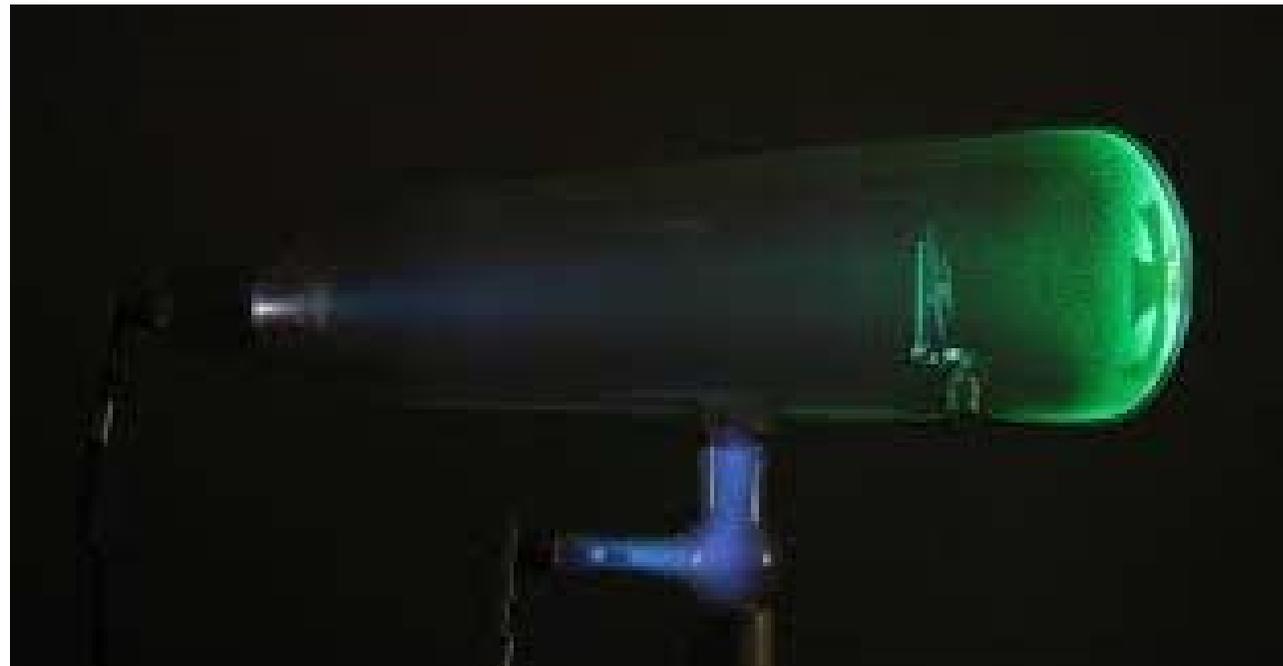
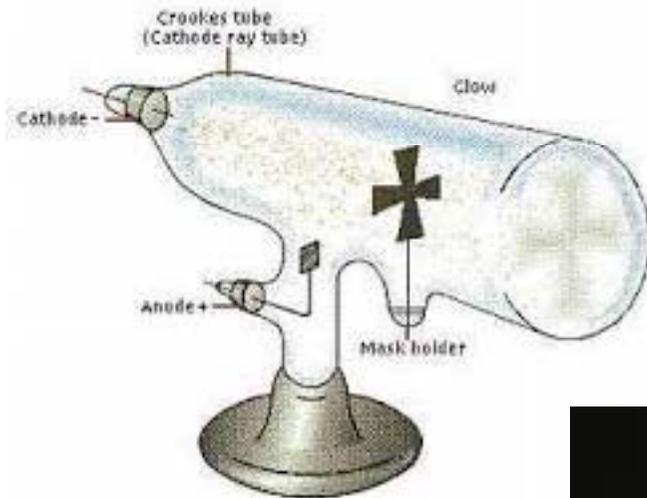


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Crooks tube (1870)

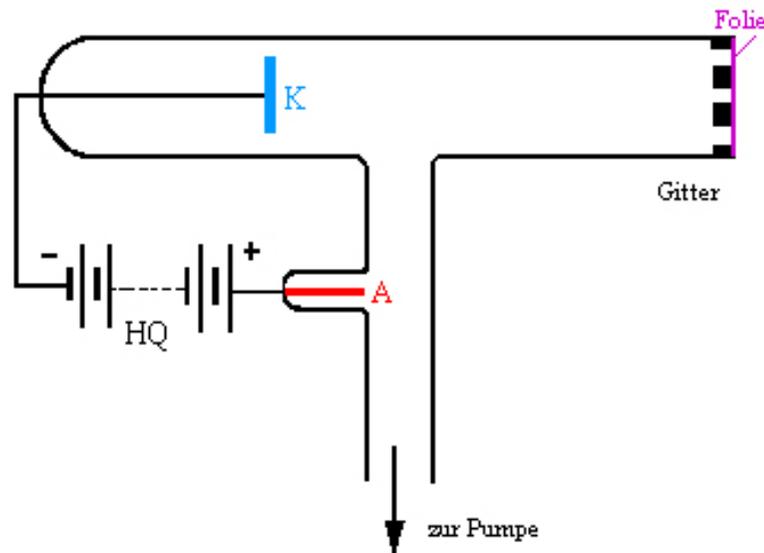


# Lenard'sche Folienexperiment

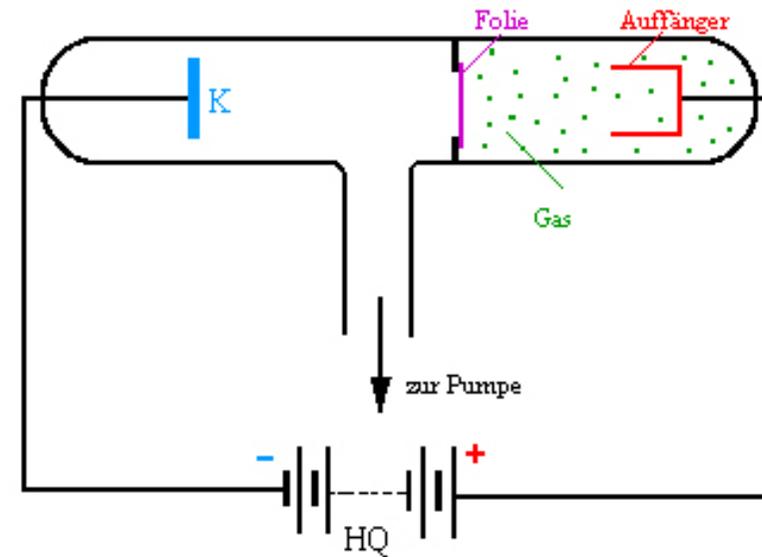
Schönenberger group [www.nanoelectronics.ch](http://www.nanoelectronics.ch)



~ 1892 im Labor von Heinrich Hertz



Untersuchung der Schwächung von Elektronenstrahlung durch verschiedene Metallfolien



Untersuchung der Schwächung von Elektronenstrahlung durch verschiedene Gasschichten

Bilder Leifi Physik

Durchgang von Elektronen durch eine 5  $\mu\text{m}$  dünne Alufolie

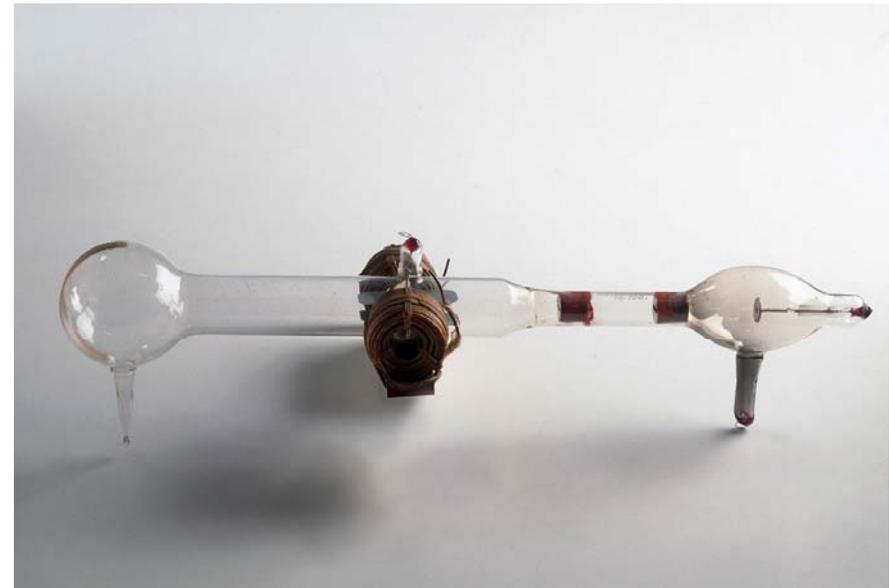
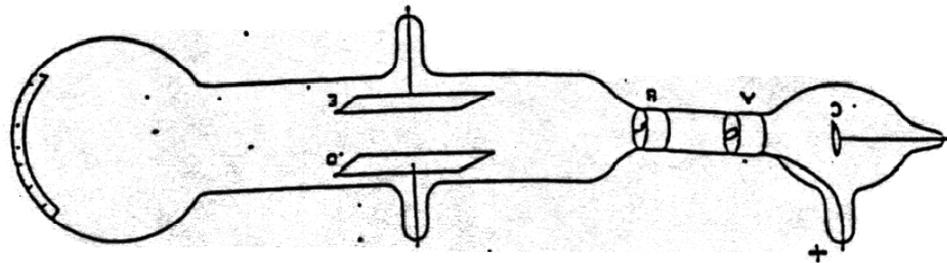
“Das Innere des Atoms ist so leer wie das Weltall” (P. Lenard)

# Entdeckung des Elektrons

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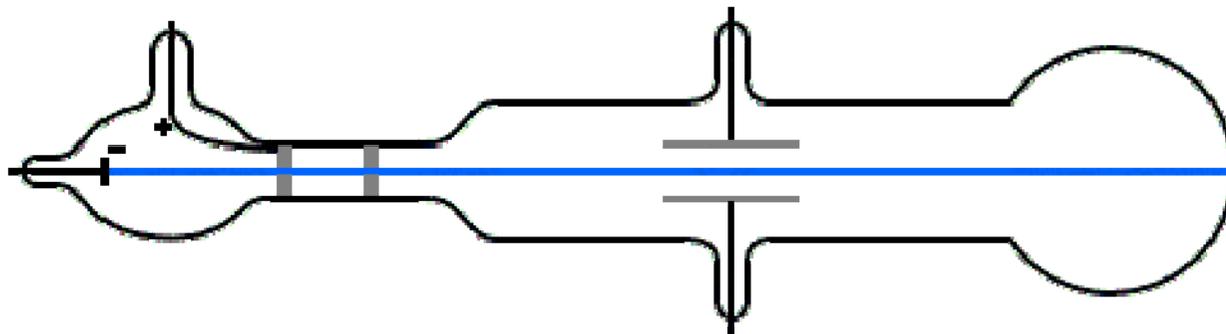


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J.J. Thomson (1897)

Ablenkung und Bestimmung von  $e$  und  $m$  ergab, dass  $m$  ca. 1000 mal kleiner sein muss als die Masse von H

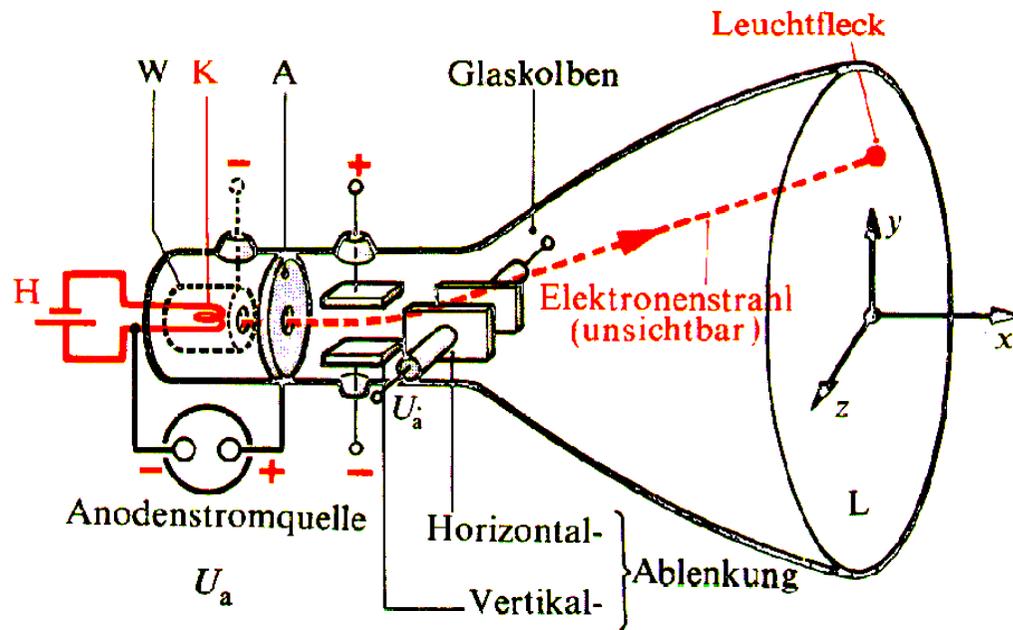


# Anwendung: Braunsche Röhre

Schönenberger group [www.nanoelectronics.ch](http://www.nanoelectronics.ch)



Bsp: Fernsehschirm (Kathodenstrahlrohr, CRT, Braunsche Röhre)



# Rutherford Streuung

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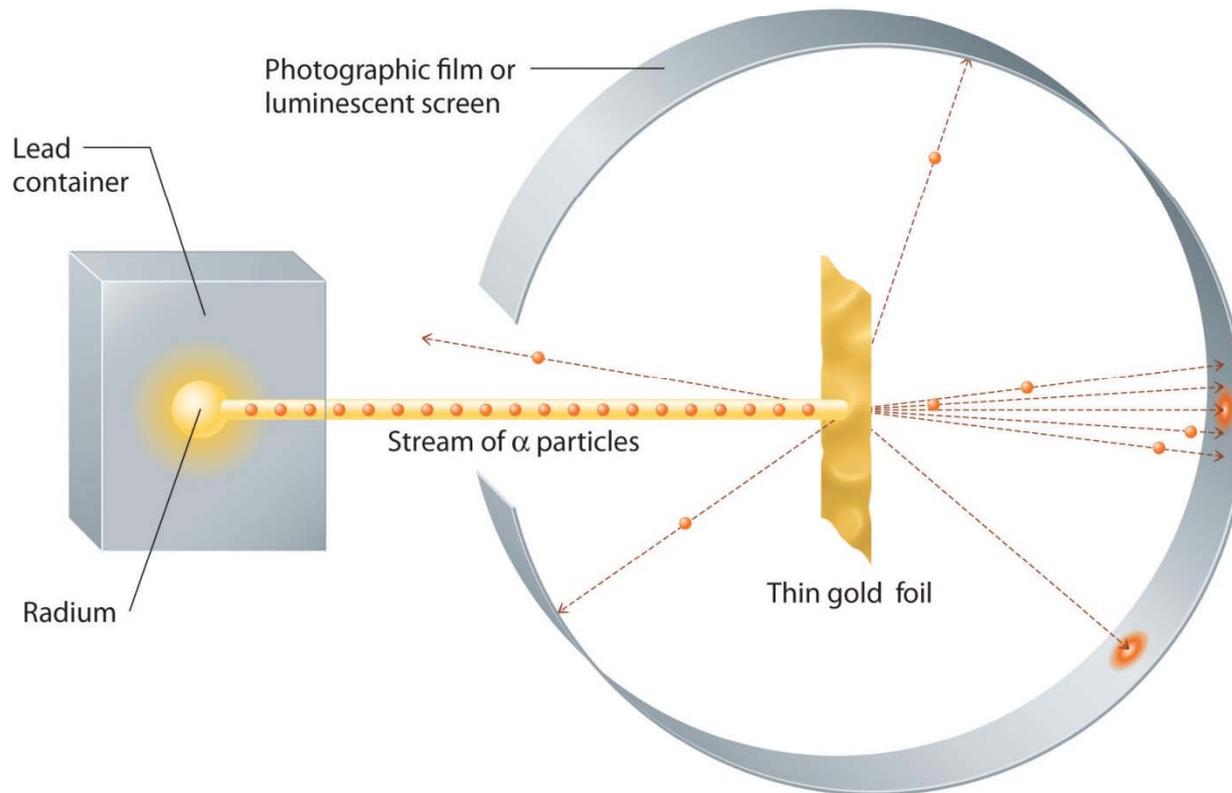


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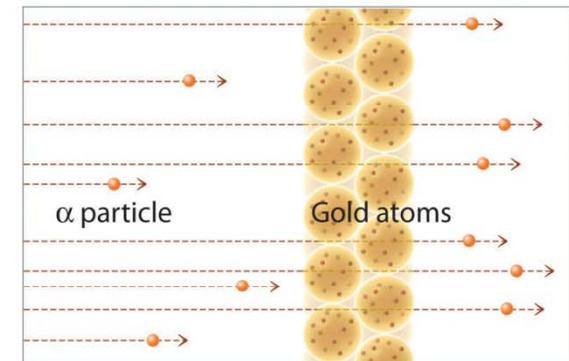
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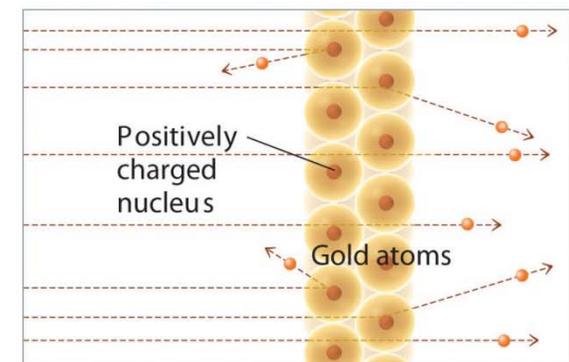
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(a) Rutherford's experiment



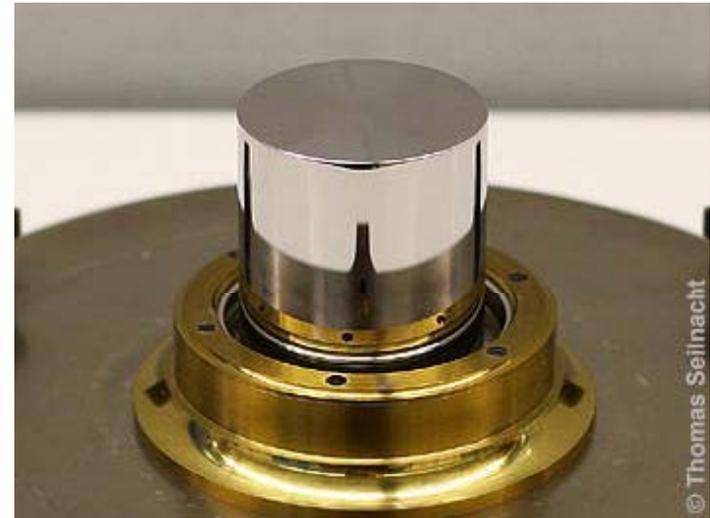
(b) What Rutherford expected if Thomson's model were correct



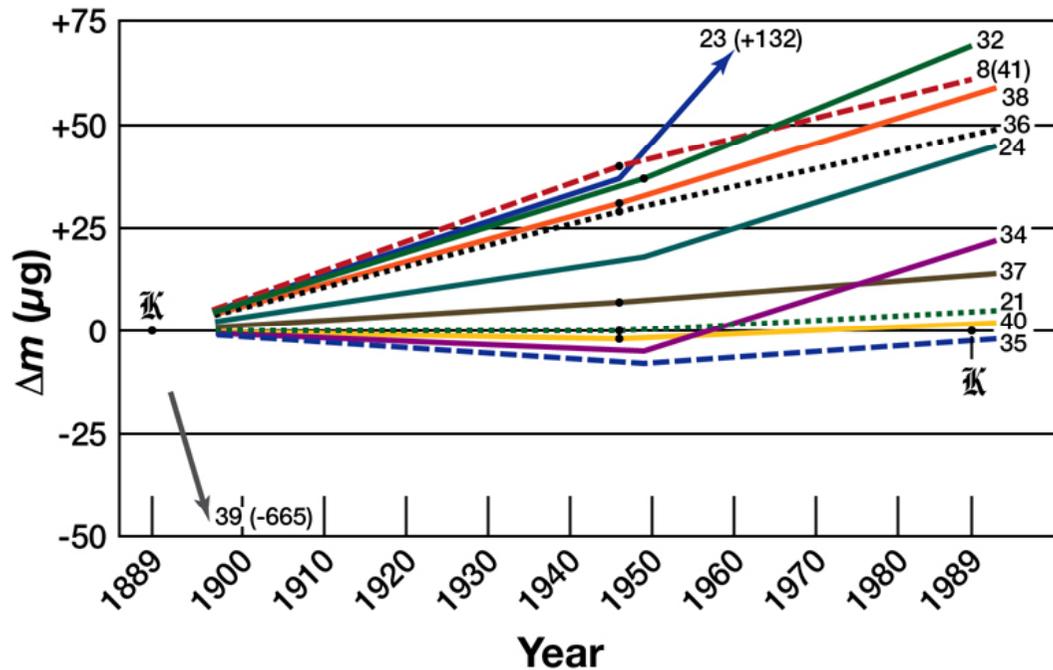
(c) What Rutherford actually observed

# Urkilogramm

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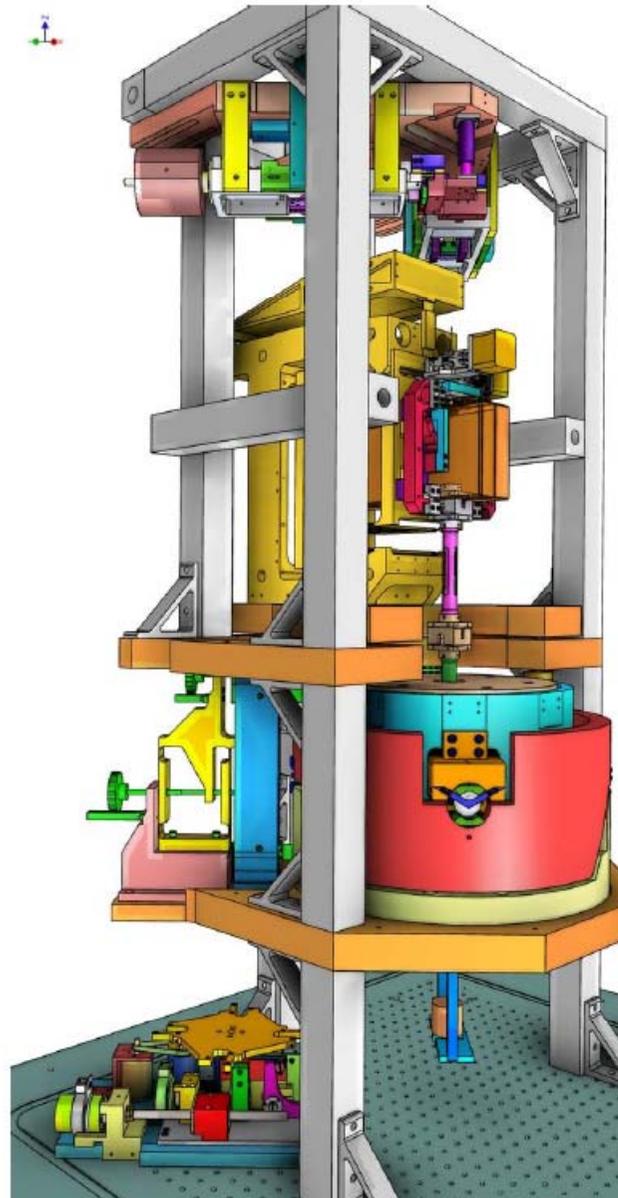
© Thomas Seinnacht



change of mass of copies relative to the initial one

# Wattbalance

BWMII: In the lab



METAS  
Switzerland  
(status report  
2013)



CH

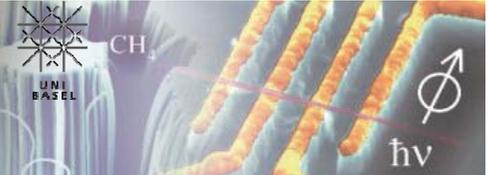
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# Avogadro-Projekt

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- Redefinition des Kilogramms:  $1 \text{ kg} = \text{Masse von } (1000/12) \times N_A \text{ } ^{12}\text{C-Atomen}$
- Erfordert genau Bestimmung von  $N_A$
- Methode: Zählen der Atome in einer Si-Kugel



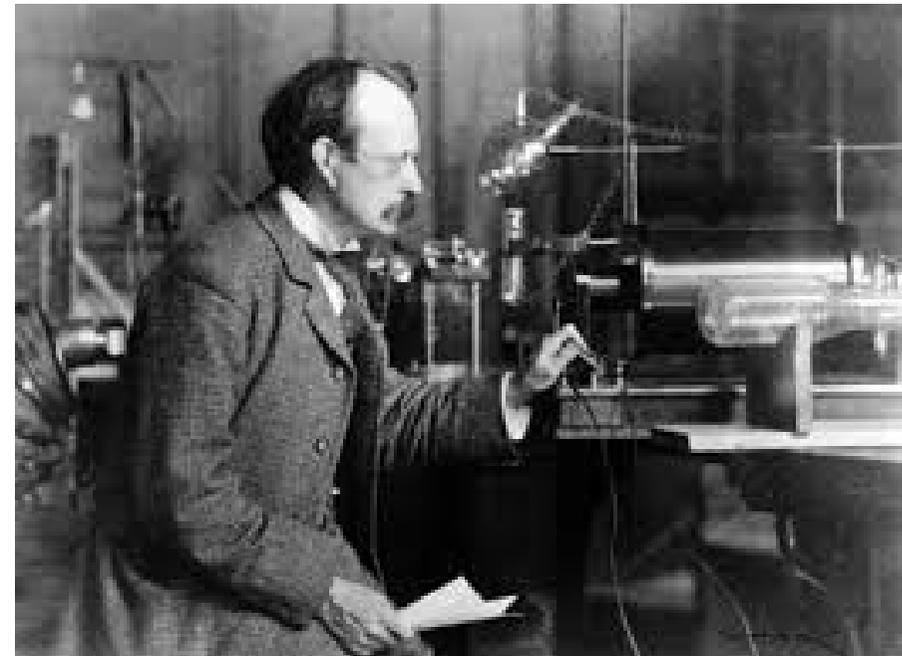
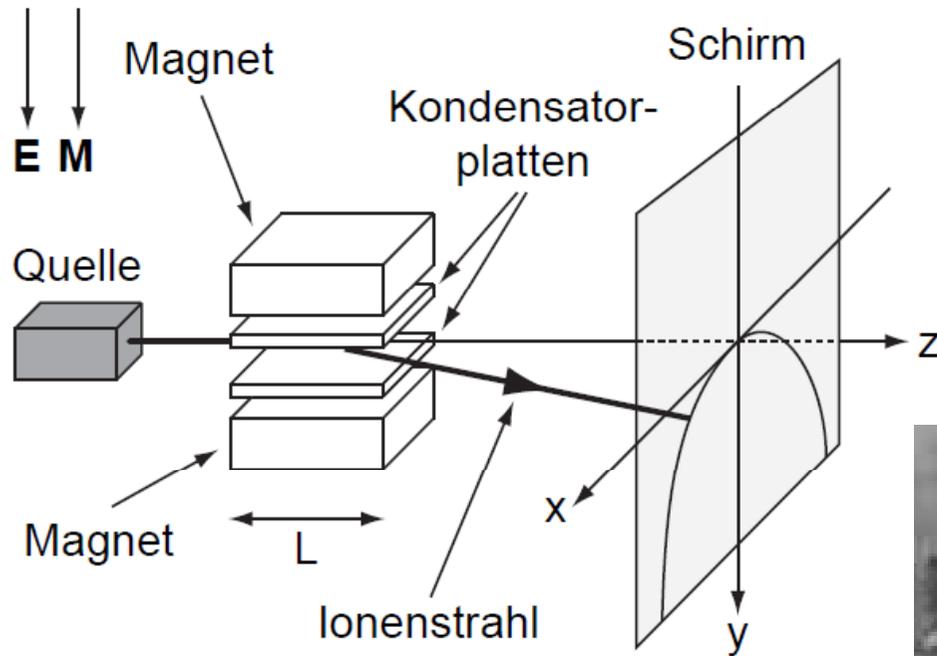
Kugel aus  $^{28}\text{Si}$

Das “rundeste” Objekt der Welt:

- Durchmesser 93.6 mm
- Variation über die Kugel: 50 nm
- Vermessung der Kugel mit Laserinterferometrie ( $\pm 0.6 \text{ nm}$ ),  
Gitterkonstante aus Röntgenbeugungsexperimenten

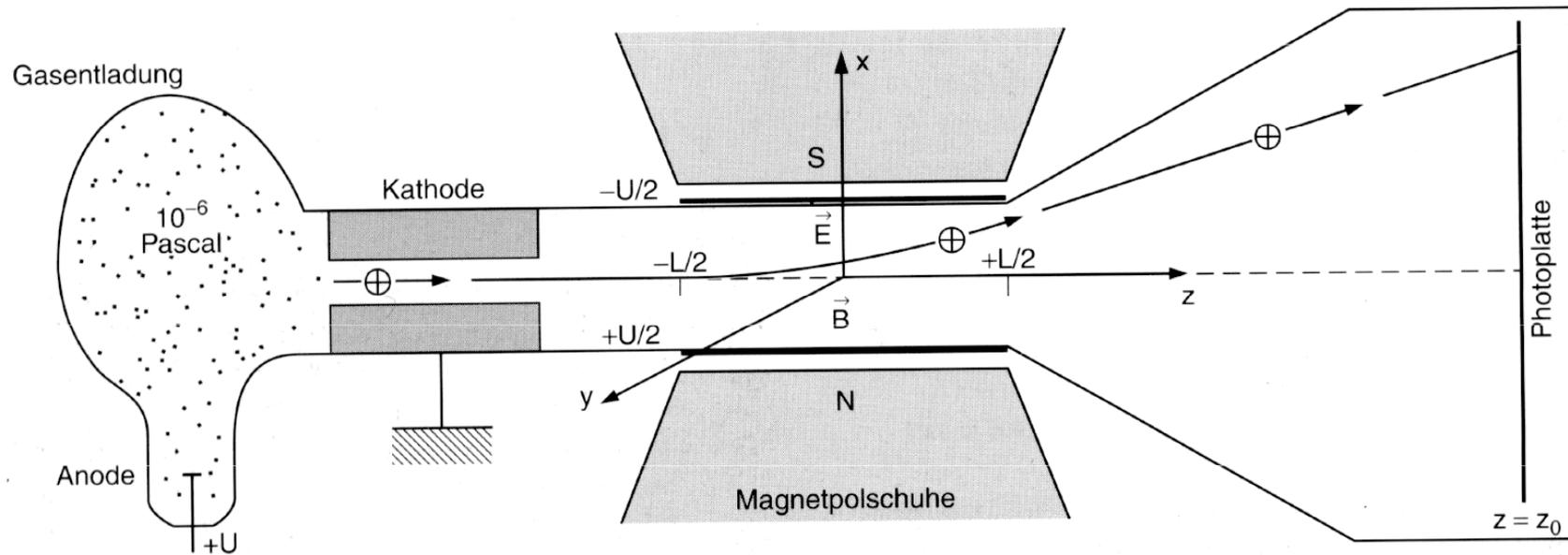
# Massenbestimmung Thomson

Schönenberger group [www.nanoelectronics.ch](http://www.nanoelectronics.ch)



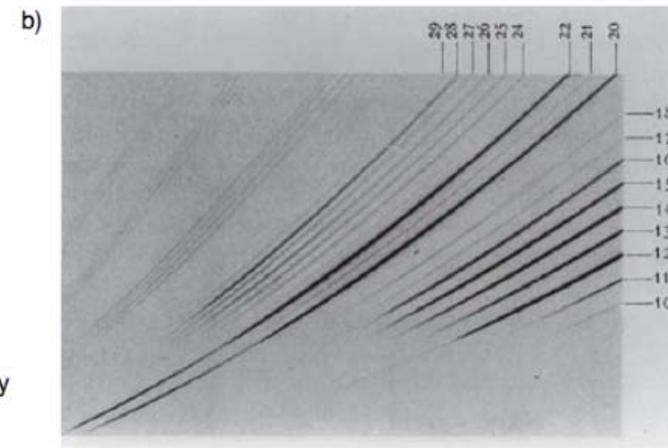
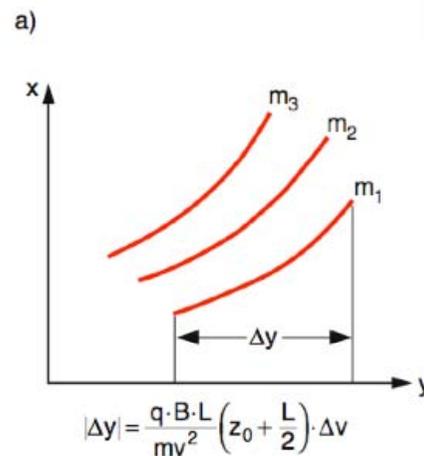
# Massenspektrometer nach Thomson

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Demtröder, Abb. 2.64

- E- und B-Feld parallel
- E-Feld: Energiefilter
- B-Feld: Impulsfilter

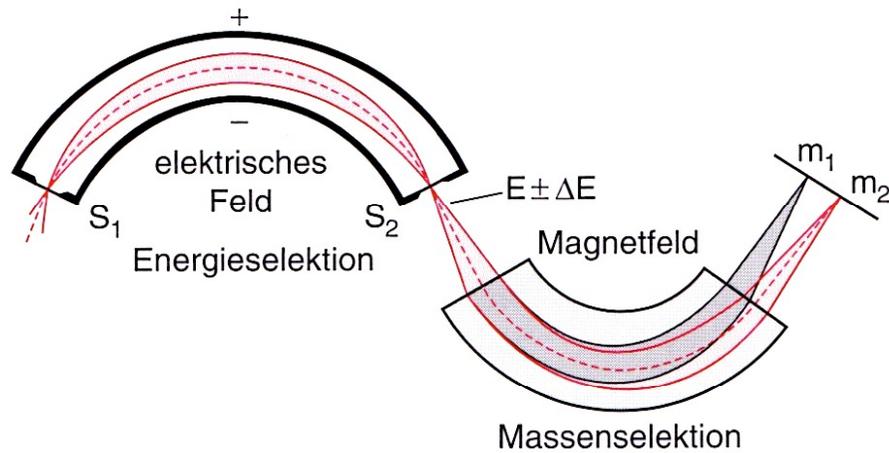


# Moderne Massenspektrometer

Schönenberger group [www.nanoelectronics.ch](http://www.nanoelectronics.ch)

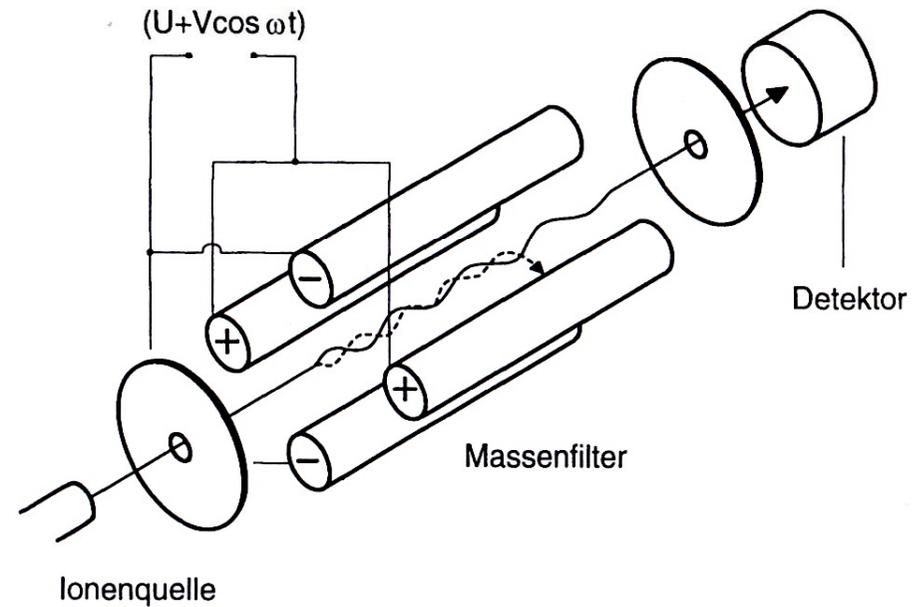


## Geschwindigkeits- und Richtungsfokussierung



Demtröder, Abb. 2.68

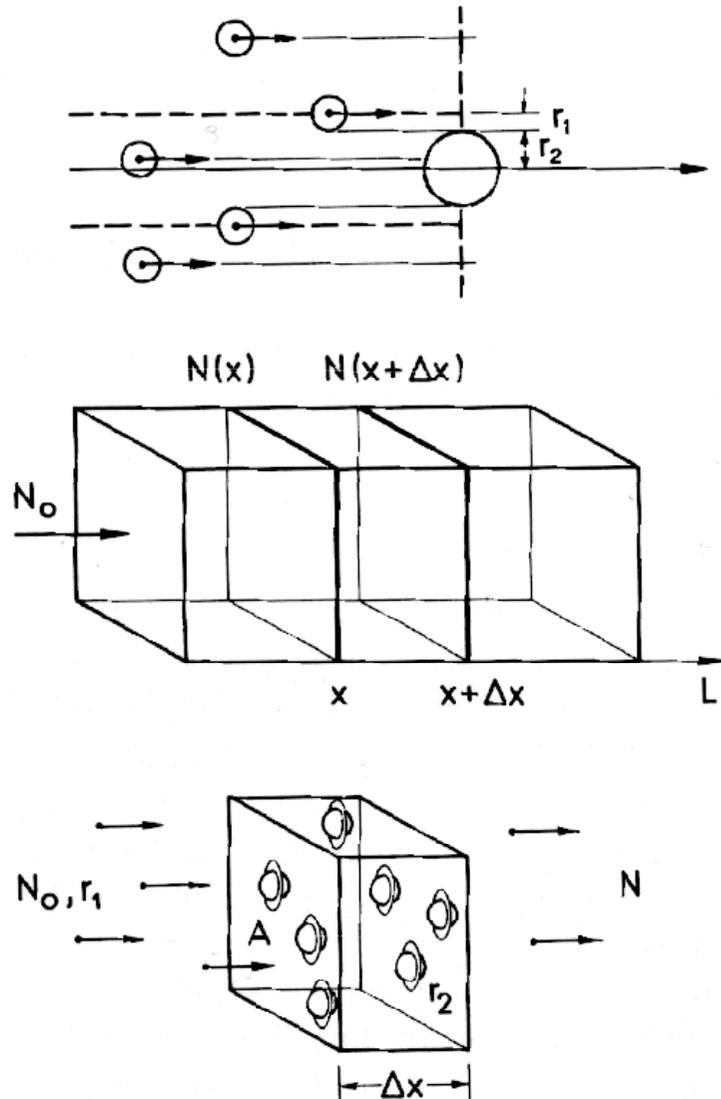
## Quadrupol-Massenspektrometer



Haken-Wolf, Abb. 3.7

# Wirkungsquerschnitt

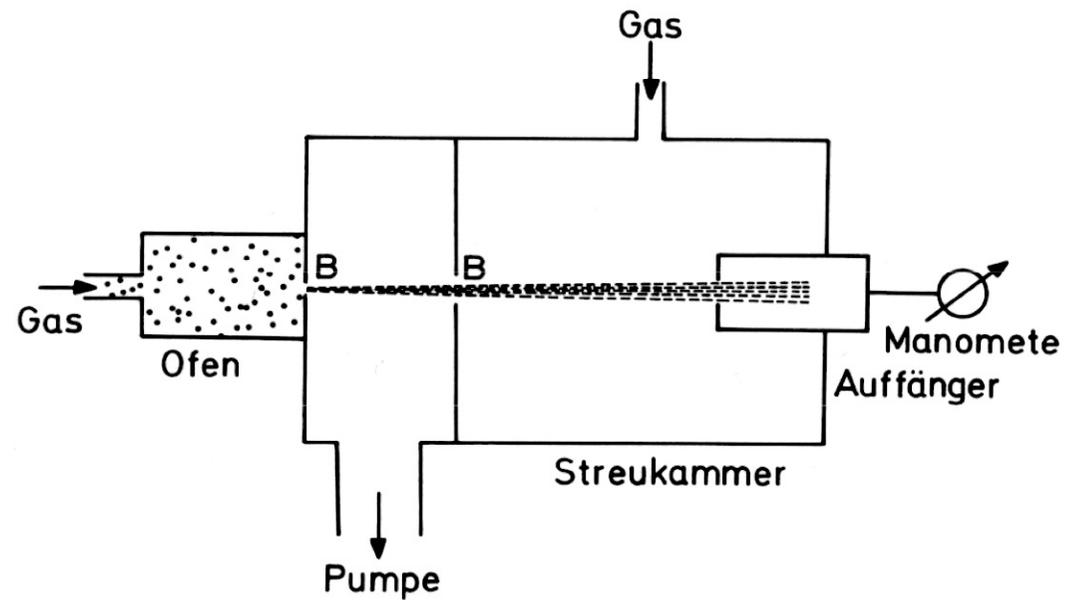
Schönenberger group [www.nanoelectronics.ch](http://www.nanoelectronics.ch)



Haken-Wolf, Abb. 2.4

$$\sigma = \pi(r_1 + r_2)^2$$

$$N(x) = N_0 e^{-x\sigma n}$$



Haken-Wolf, Abb. 2.6

# Röntgenbeugung

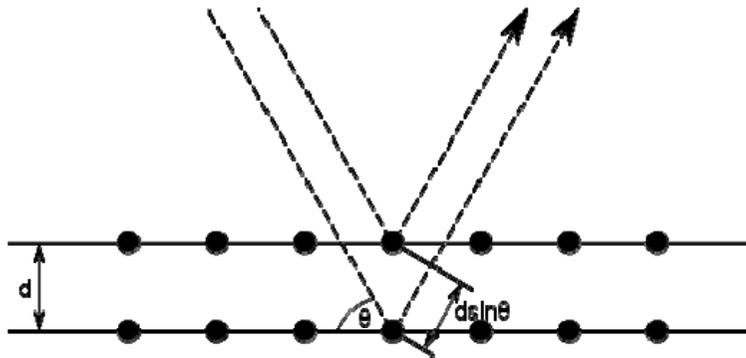
Schönenberger group [www.nanoelectronics.ch](http://www.nanoelectronics.ch)



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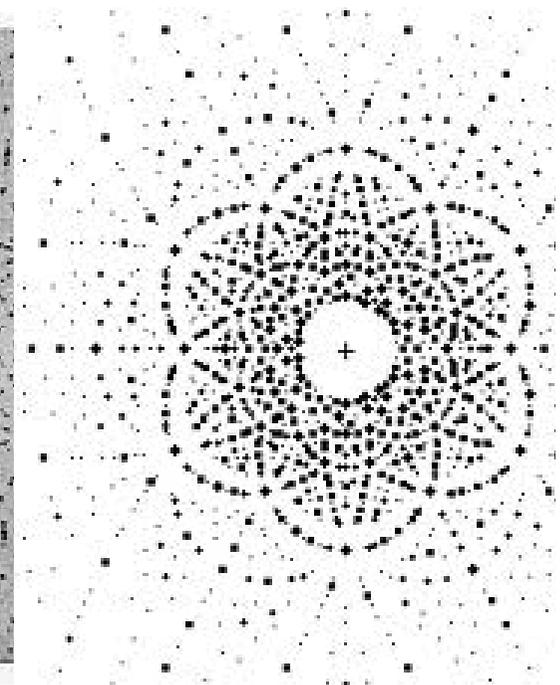
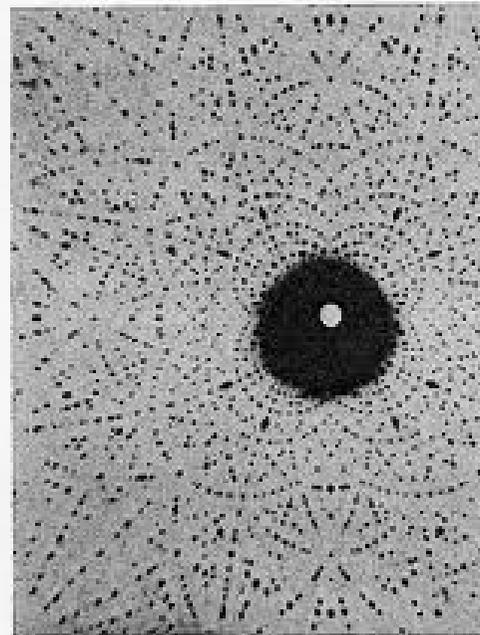
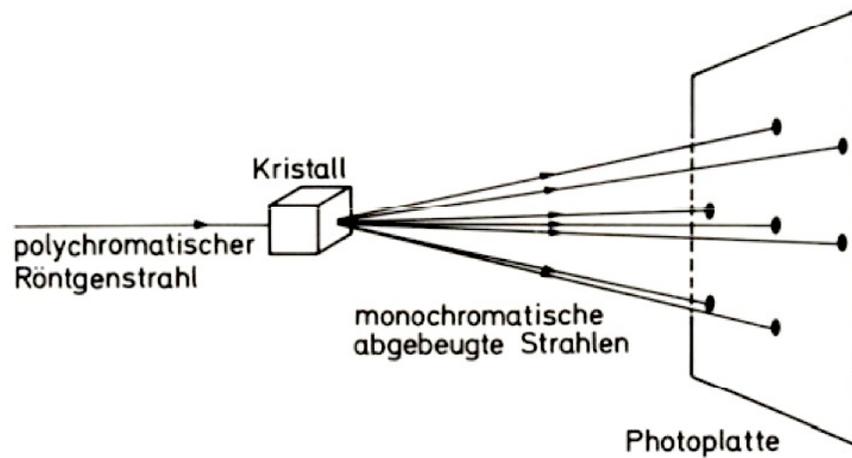
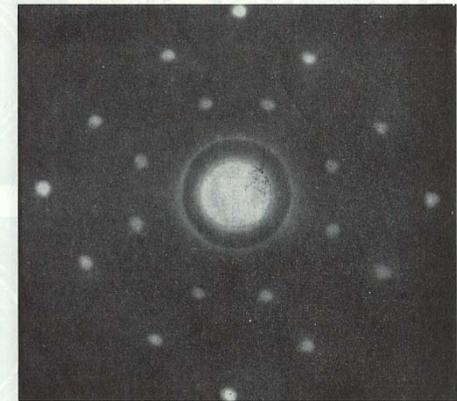
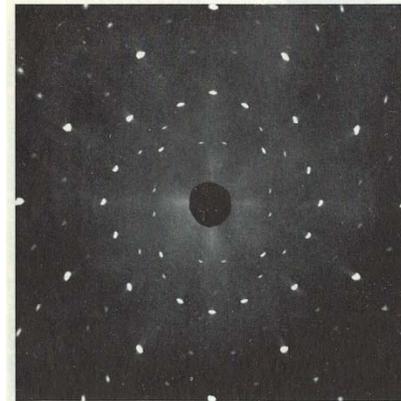


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**Bragg-Bedingung**

$$2d \sin \theta = n\lambda$$



# Elektronenmikroskop



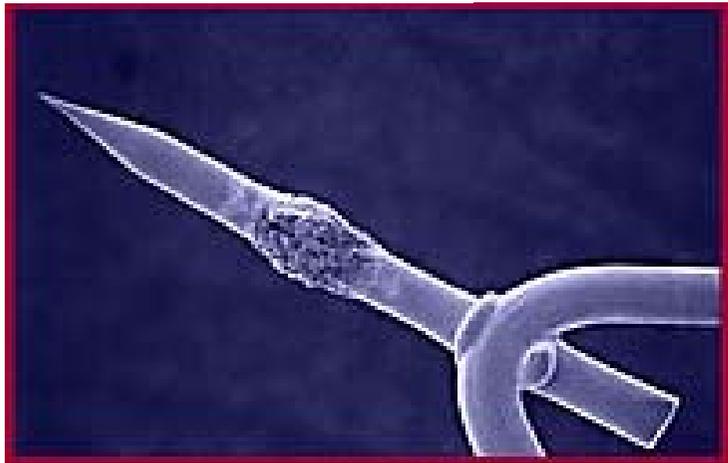
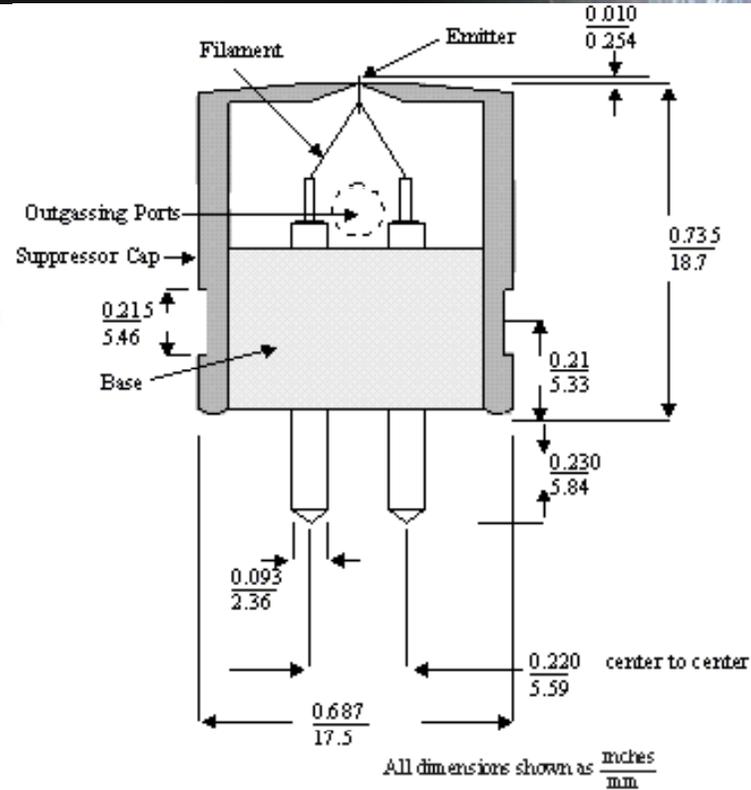
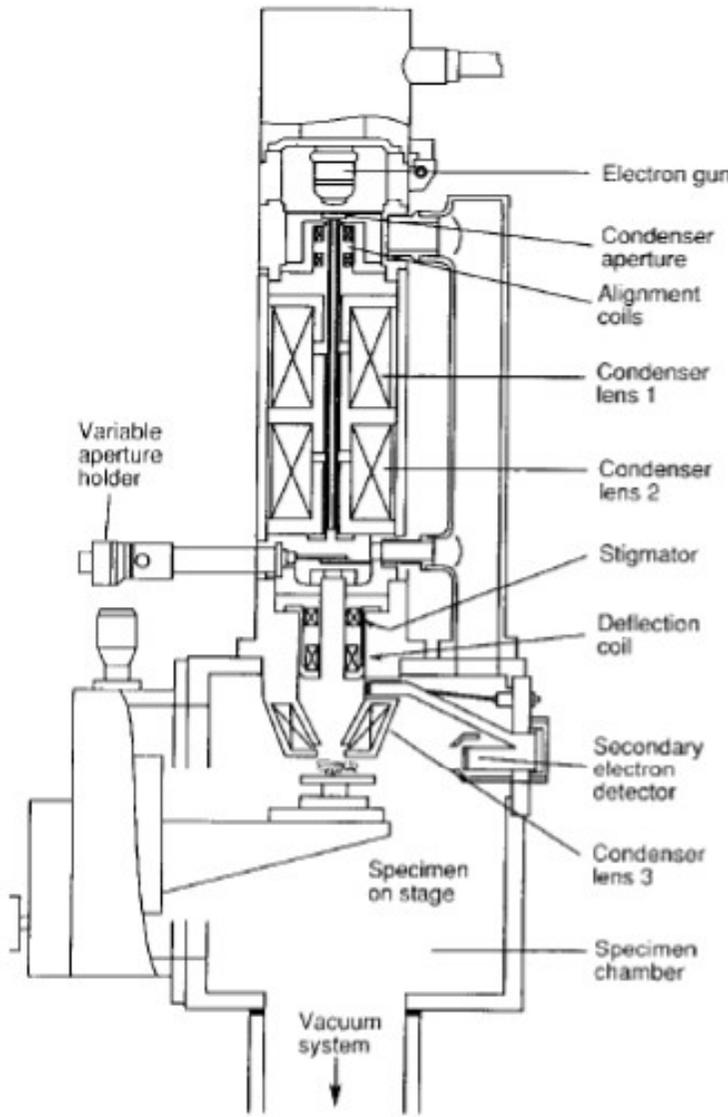
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# Elektronenmikroskop

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Detailed Diagram of SEM



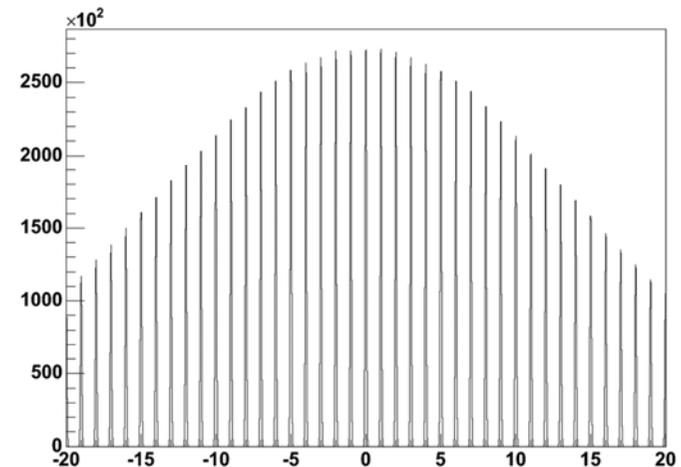
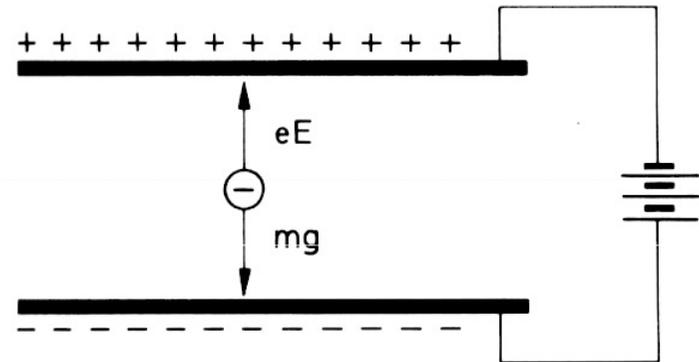
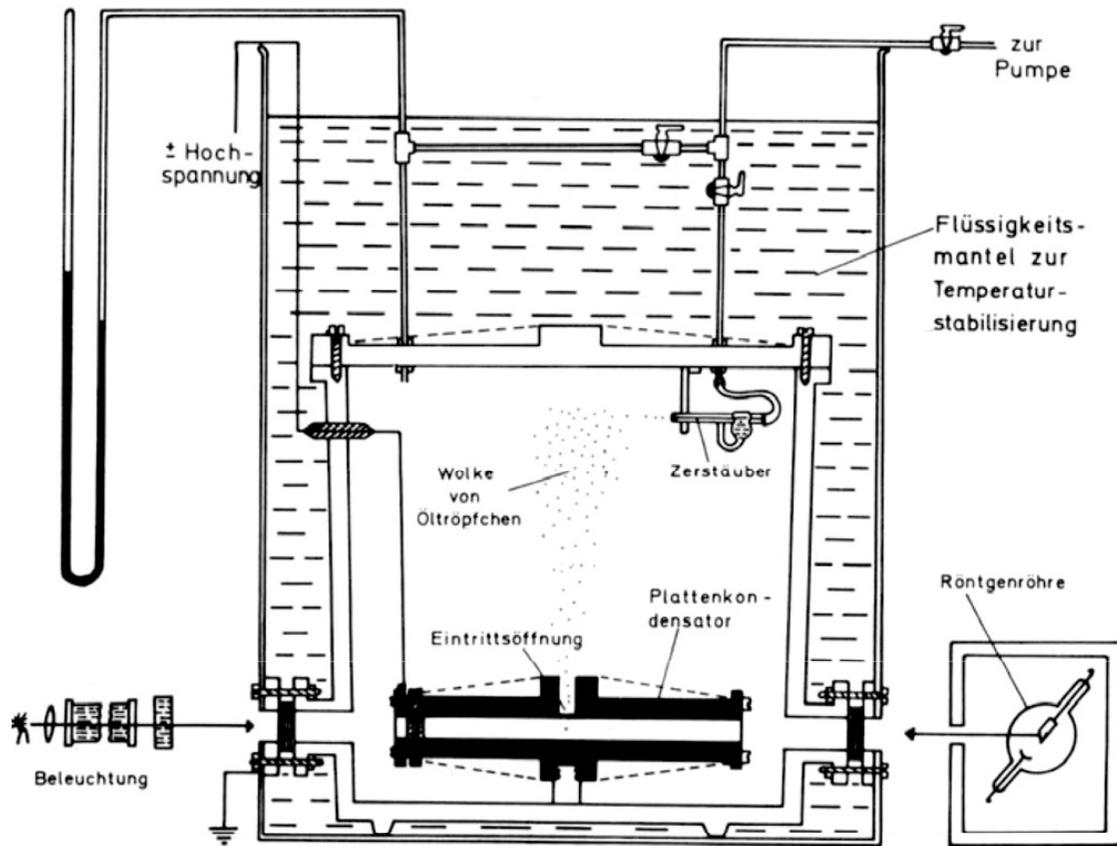
# Millikan 1911

Schönenberger group [www.nanoelectronics.ch](http://www.nanoelectronics.ch)



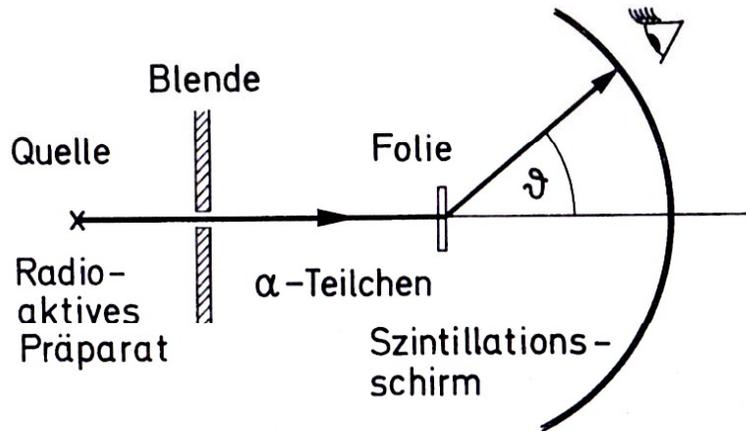
## Bestimmung der Elementarladung

$$e = 1.602 \times 10^{-19} \text{ C}$$



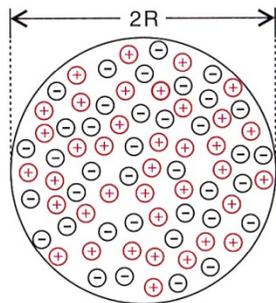
# Rutherfordstreuung

Schönenberger group [www.nanoelectronics.ch](http://www.nanoelectronics.ch)

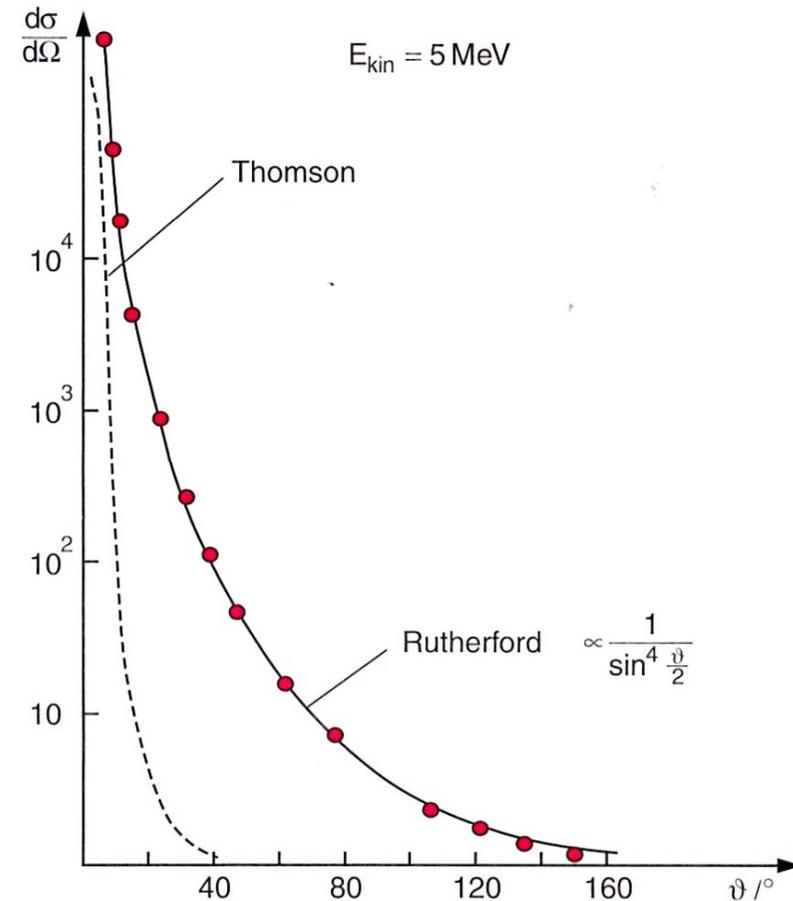
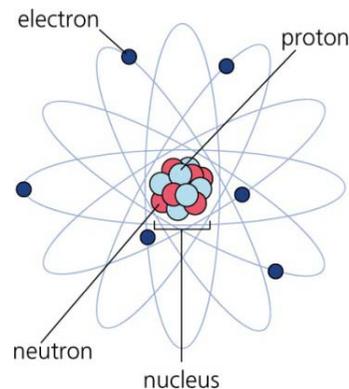


Haken-Wolf, Abb. 4.7

**Thomson-Atommodell:**  
"Rosinenkuchen"



**Rutherford-Atommodell:**

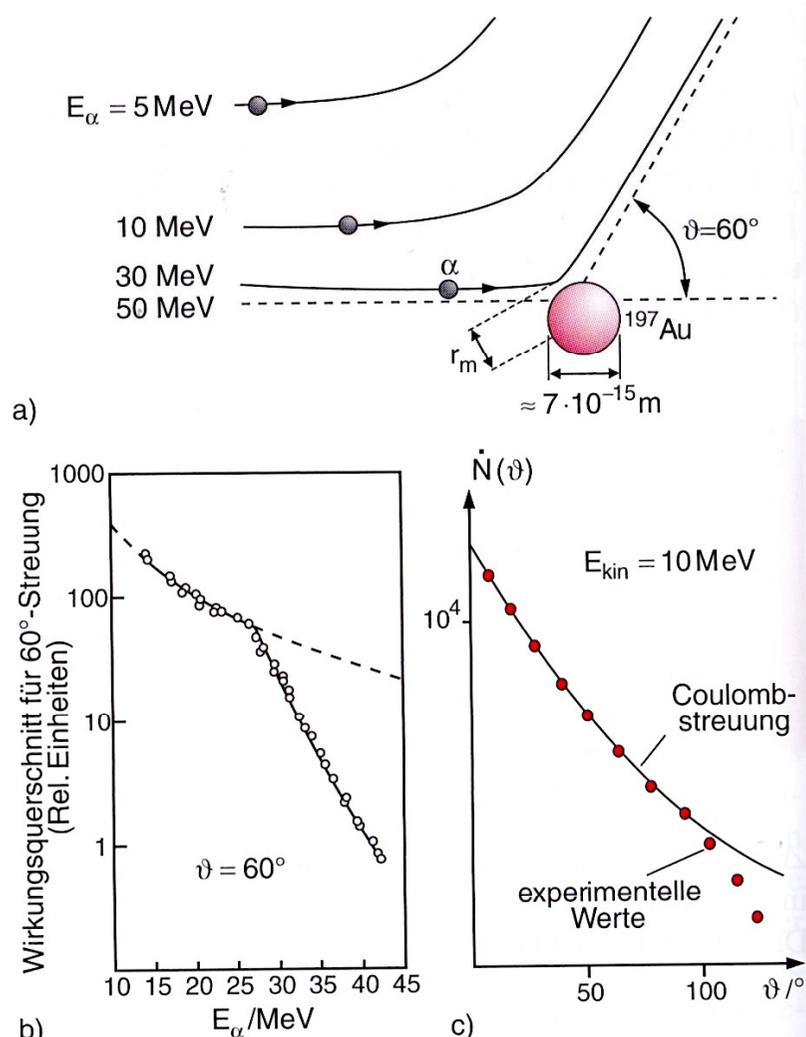


**Abb. 2.91.** Vergleich zwischen den experimentellen Ergebnissen Rutherfords (Kreise), dem berechneten Wirkungsquerschnitt für Coulombstreuung und dem Streuquerschnitt des Thomson-Modells

Demtröder, Abb. 2.91

# Rutherfordstreuung

Schönenberger group [www.nanoelectronics.ch](http://www.nanoelectronics.ch)

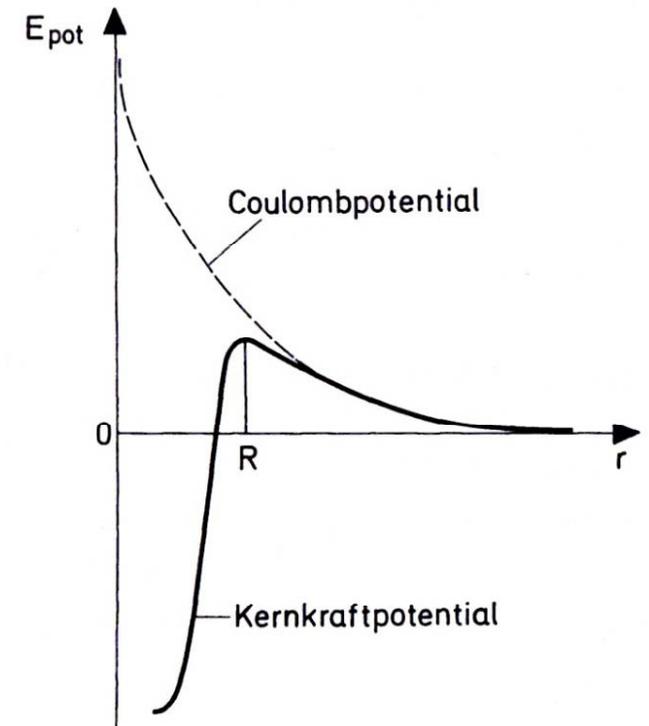


**Abb. 2.92.** (a) Bahn von an einem Goldkern gestreuten Teilchen für  $\vartheta = 60^\circ$  und verschiedene Teilchenenergien; (b) Abweichung vom Coulombstreuquerschnitt für  $\vartheta = 60^\circ$  bei höheren Energien  $E_{\text{kin}}$ ; (c) Abweichung bei fester Teilchenenergie für  $\vartheta > 100^\circ$

Demtröder, Abb. 2.92

## Kernradius aus Abweichung von Rutherford-Streuung

Abweichung von Rutherford-Formel für Coulomb-Streuung für kleine Abstände (d.h. hohe Energien/grosse Streuwinkel)



Haken-Wolf, Abb. 4.9