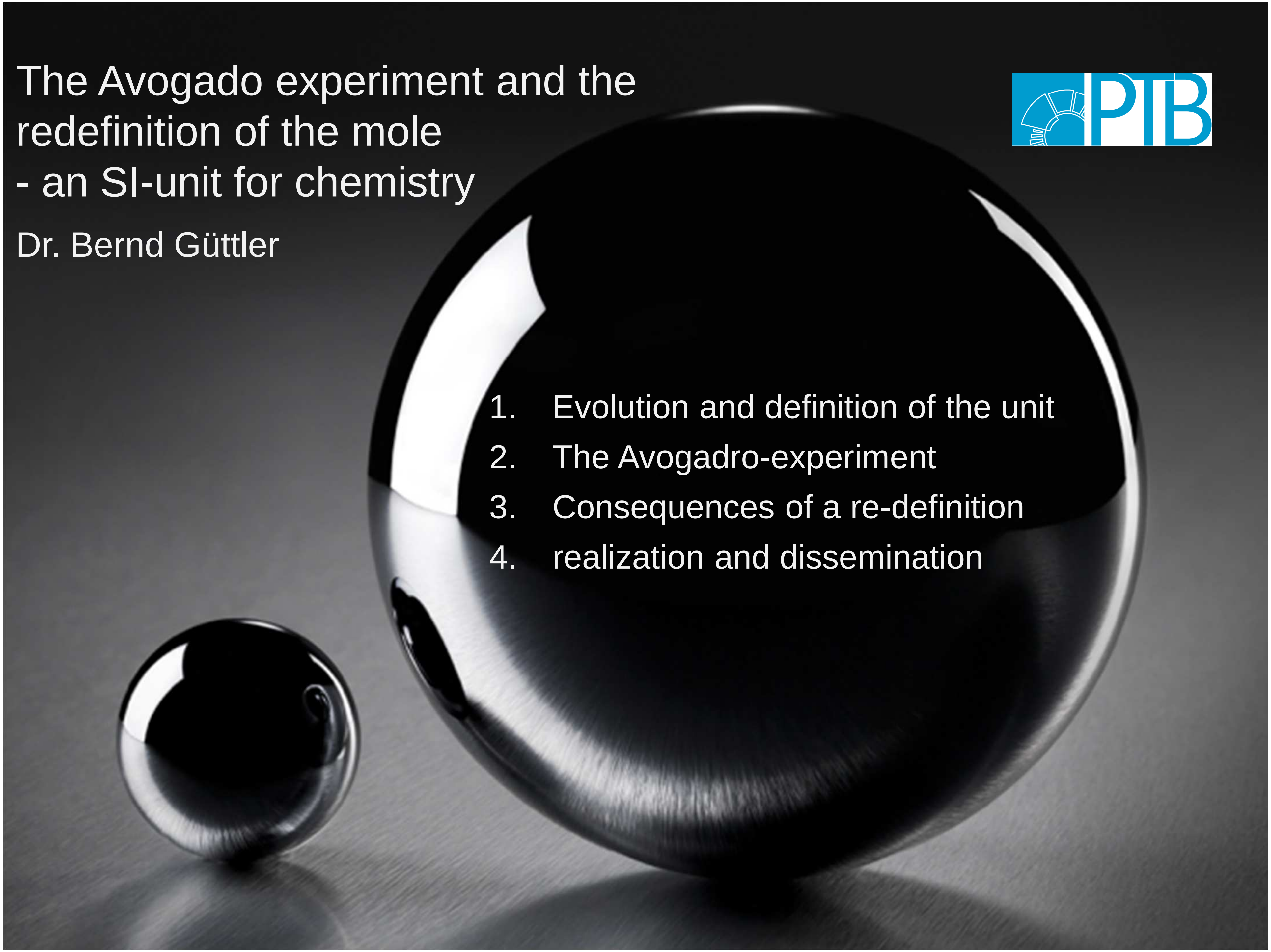
The Avogado experiment and the redefinition of the mole
- an SI-unit for chemistry

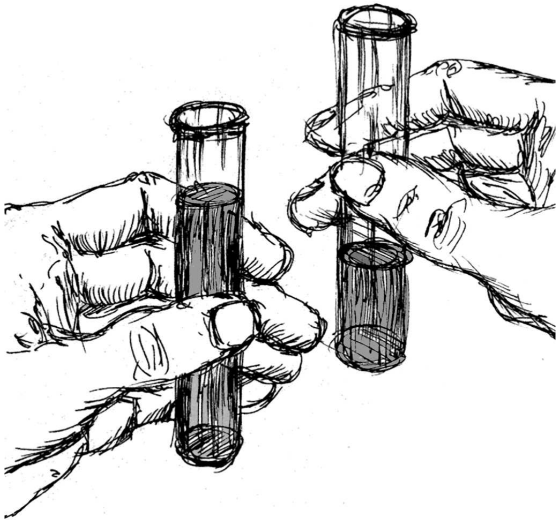
Dr. Bernd Güttler



1. Evolution and definition of the unit
2. The Avogadro-experiment
3. Consequences of a re-definition
4. realization and dissemination

The SI-unit "mole" - a description

the mole - an SI-unit for chemistry



- The "mole" is an SI-base unit for the base quantity "amount of substance".
- It corresponds to fixed number of defined particels.

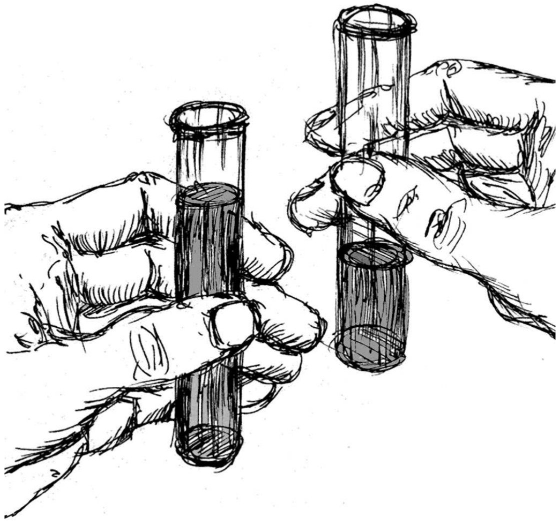
Chemical reactions occur on the basis of multiples of those smallest identifiable entities of substances (atoms or molecules).

The mole allows for a quantitative description of chemical processes in a clear and simple way.

The SI-unit "mole" - a description

the mole – an SI-unit for chemistry

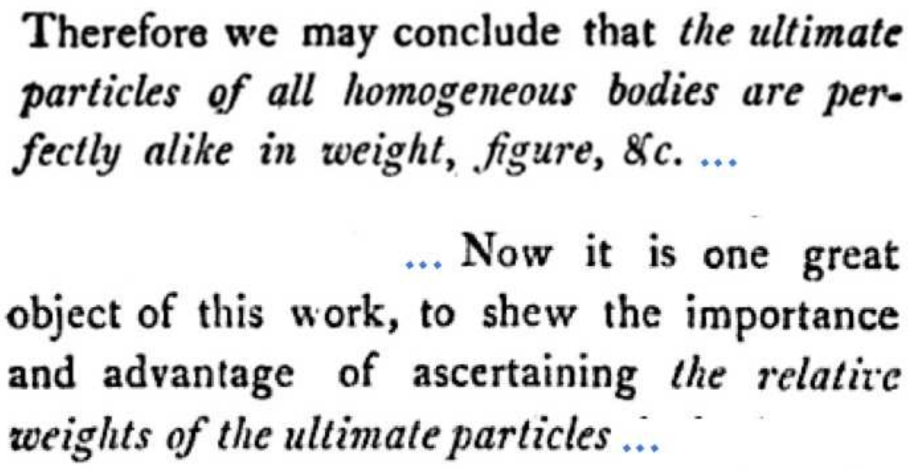
- The mole creates a link between the SI of the Metre Convention and chemistry.
- The mole allows to make quantitative measurements in chemistry traceable to the SI and internationally comparable.



The unit mole comprises for practical and historical reasons a (large) number of particles such that the unit can be easily related to other SI units such as the kilogram.

base quantity "amount of substance": Dalton's atoms

John Dalton



Therefore we may conclude that *the ultimate particles of all homogeneous bodies are perfectly alike in weight, figure, &c.* ...

... Now it is one great object of this work, to shew the importance and advantage of ascertaining *the relative weights of the ultimate particles* ...

- relation to a discrete, microscopic base quantity: "**ultimate particles**"
- every element consists of characteristic, identical and impartible particles
- the particles cannot be destroyed or created by chemical means
- elements differ with respect to their mass and volume

„A New System of Chemical Philosophy“, p. 143, Chpt. 2 „On the constitution of bodies“,
*R. Bickerstaff, Strand, London **1808***

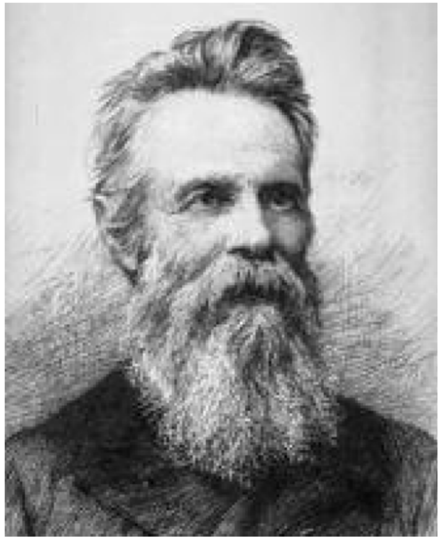
base unit mole: the number of particles

"The first hypothesis ... and obviously the only permissible one, is the assumption, that the number of molecules in all gases is the same in the same volume and that this number is always proportional to the volume...."

Amedeo Avogadro

Essay on a Manner of Determining the Relative Masses of the Elementary Molecules of Bodies, and the Proportions in Which They Enter into these Compounds
Journal de Physique, 73, 58-76 (Orig. 1811)

base unit mole: the number of particles



Joseph Lochschmidt

$$N_L = \frac{3}{4\,\pi\,\lambda\,s_0^2}$$

s_0: Loschmidt's molecular diameter

λ: mean free path

N_L = 2,686 7805 (24) · 10^{25} m^{-3}

...and as the most accurate experiments of the mean free path (of those particles) reveal a value of 170 parts of a millionth of a millimeter we finally obtain 1.17 millionth of a millimeter, i.e. the diameter of a molecule of air is about 1 millionth of a millimeter.

Zur Größe der Luftmoleküle, in: Anzeiger der Kaiserlichen Akademie der Wissenschaften Wien, Mathematisch-Naturwissenschaftliche Klasse, 2, S. 162-164, 1865

base unit mole: about the reality of atoms

Walther Nernst

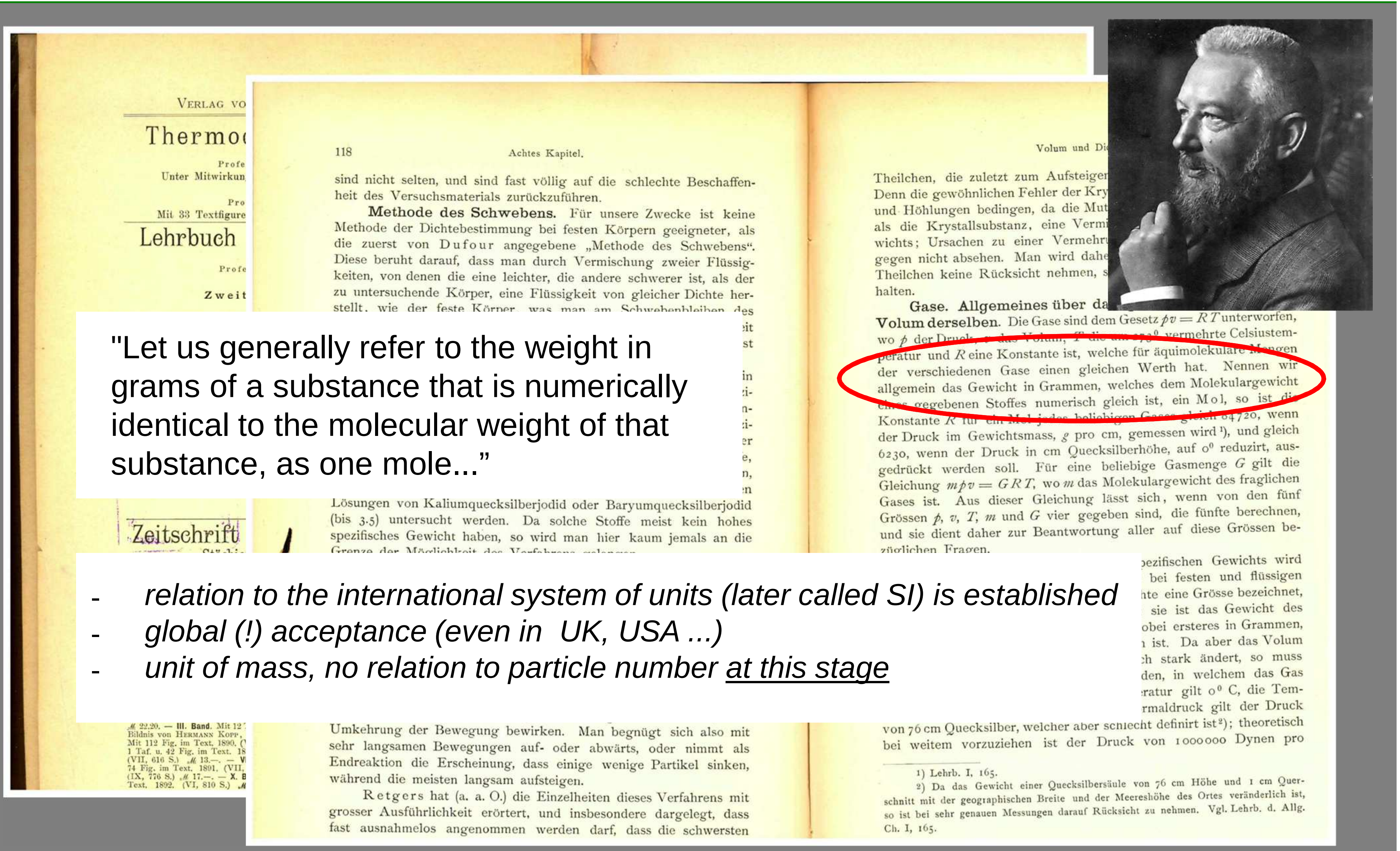
...about Avogadro's hypothesis and
Daltons "hypothesis on molecules"...

of course, there is no proof for this hypothesis as there is also no proof for the hypothesis about molecules in general but it seems very likely because it can explain the validity of the third law on gases* in a very simple way. The numerous successes that were observed by its consistent application are all witnesses in its favour;

Nernst, W.: Theoretische Chemie vom Standpunkte der Avogadro’schen Regel und der Thermodynamik, (1893), S. 31, Stuttgart: Enke Verlag

*law on multiple proportions

Definition of the mole



VERLAG VO

Thermo

Profe
Unter Mitwirkun

Pro
Mit 33 Textfigure

Lehrbuch

Profe

Zweit

Zeitschrift

ℳ 22.20. — III. Band. Mit 12
Bildnis von HERMANN KOPP,
Mit 112 Fig. im Text. 1890. (
1 Taf. u. 42 Fig. im Text. 18
(VII, 616 S.) ℳ 13.—. — V
74 Fig. im Text. 1891. (VII,
(IX, 776 S.) ℳ 17.—. — X. B
Text. 1892. (VI, 810 S.) ℳ

118 Achtes Kapitel.

sind nicht selten, und sind fast völlig auf die schlechte Beschaffenheit des Versuchsmaterials zurückzuführen.

Methode des Schwebens. Für unsere Zwecke ist keine Methode der Dichtebestimmung bei festen Körpern geeigneter, als die zuerst von Dufour angegebene „Methode des Schwebens“. Diese beruht darauf, dass man durch Vermischung zweier Flüssigkeiten, von denen die eine leichter, die andere schwerer ist, als der zu untersuchende Körper, eine Flüssigkeit von gleicher Dichte herstellt, wie der feste Körper, was man am Schwebenbleiben des

Lösungen von Kaliumquecksilberjodid oder Baryumquecksilberjodid (bis 3.5) untersucht werden. Da solche Stoffe meist kein hohes spezifisches Gewicht haben, so wird man hier kaum jemals an die Grenze der Möglichkeit des Verfahrens gelangen.

Umkehrung der Bewegung bewirken. Man begnügt sich also mit sehr langsamen Bewegungen auf- oder abwärts, oder nimmt als Endreaktion die Erscheinung, dass einige wenige Partikel sinken, während die meisten langsam aufsteigen.

Retgers hat (a. a. O.) die Einzelheiten dieses Verfahrens mit grosser Ausführlichkeit erörtert, und insbesondere dargelegt, dass fast ausnahmelos angenommen werden darf, dass die schwersten

Volum und Di

Theilchen, die zuletzt zum Aufsteiger
Denn die gewöhnlichen Fehler der Kry
und Höhlungen bedingen, da die Mut
als die Krystallsubstanz, eine Vermi
wichts; Ursachen zu einer Vermehru
gegen nicht absehen. Man wird dahe
Theilchen keine Rücksicht nehmen, s
halten.

Gase. Allgemeines über da
Volum derselben. Die Gase sind dem Gesetz $pv = RT$ unterworfen, wo p der Druck, v das Volum, T die um 273° vermehrte Celsiustemperatur und R eine Konstante ist, welche für äquimolekulare Mengen der verschiedenen Gase einen gleichen Werth hat. Nennen wir allgemein das Gewicht in Grammen, welches dem Molekulargewicht eines gegebenen Stoffes numerisch gleich ist, ein Mol, so ist die Konstante R für ein Mol jedes beliebigen Gases gleich 84720, wenn der Druck im Gewichtsmass, g pro cm, gemessen wird[1]), und gleich 6230, wenn der Druck in cm Quecksilberhöhe, auf 0° reduzirt, ausgedrückt werden soll. Für eine beliebige Gasmenge G gilt die Gleichung $mpv = GRT$, wo m das Molekulargewicht des fraglichen Gases ist. Aus dieser Gleichung lässt sich, wenn von den fünf Grössen p, v, T, m und G vier gegeben sind, die fünfte berechnen, und sie dient daher zur Beantwortung aller auf diese Grössen bezüglichen Fragen.

pezifischen Gewichts wird
bei festen und flüssigen
hte eine Grösse bezeichnet,
sie ist das Gewicht des
obei ersteres in Grammen,
ı ist. Da aber das Volum
ch stark ändert, so muss
den, in welchem das Gas
ratur gilt 0° C, die Tem-
rmaldruck gilt der Druck
von 76 cm Quecksilber, welcher aber schlecht definirt ist[2]); theoretisch bei weitem vorzuziehen ist der Druck von 1000000 Dynen pro

---

1) Lehrb. I, 165.

2) Da das Gewicht einer Quecksilbersäule von 76 cm Höhe und 1 cm Querschnitt mit der geographischen Breite und der Meereshöhe des Ortes veränderlich ist, so ist bei sehr genauen Messungen darauf Rücksicht zu nehmen. Vgl. Lehrb. d. Allg. Ch. I, 165.

"Let us generally refer to the weight in grams of a substance that is numerically identical to the molecular weight of that substance, as one mole...”

- *relation to the international system of units (later called SI) is established*
- *global (!) acceptance (even in UK, USA ...)*
- *unit of mass, no relation to particle number* ***<u>at this stage</u>***

Definition of the mole

"Let us generally refer to the weight in grams of a substance that is numerically identical to the molecular weight of that substance, as one mole..."

The mole, mol, is the unit of amount of substance of a specified elementary entity, which may be an atom, molecule, ion, electron, any other particle or a specified group of such particles;
its magnitude is set by fixing the numerical value of the Avogadro constant to be equal to exactly 6.022 141X$\cdot 10^{23}$ when it is expressed in the unit mol^{-1}.

Ostwald 1893

?

proposed definition

Definition of the mole

"Let us generally refer to the weight in grams of a substance that is numerically identical to the molecular weight of that substance, as one mole...”

Ostwald 1893

$$M(\mathrm{X}) = A_r(\mathrm{X}) \times M_u$$

$$n(X) = M_\mathrm{X}/M(\mathrm{X})$$

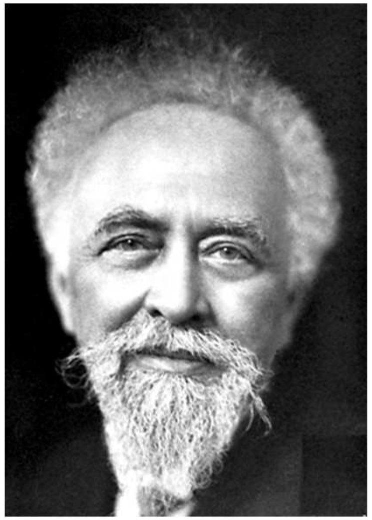
$M(\mathrm{X})$	molar mass of X
$\mathrm{A_r}(\mathrm{X})$	Σ rel. atomic masses (dimension less) of X
M_u	molar mass constant (10^{-3} kg/mol)
M_x	mass of X

Molecules per mole: Avogadro's Constant

Albert Einstein

$$N_A = (1/\langle x^2 \rangle)(RT/3\pi \eta r)$$

η viscosity
r particle radius
x average displacement



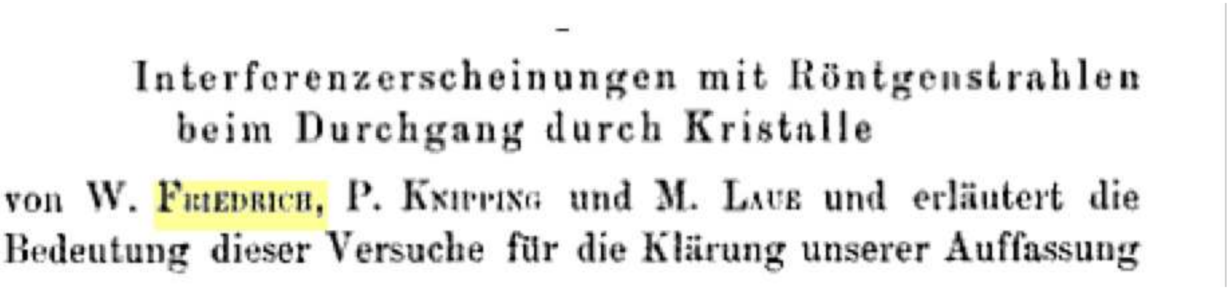
Jean Perrin

"Any two gram-molecules always contain the same number of molecules. This invariable number N is a universal constant which may appropriatly be designated Avogadro's constant."

Perrin. J.: Brownian Motion and Molecular Reality
aus: Annales de Chimie et de Physique 18, 1-114 (1909)

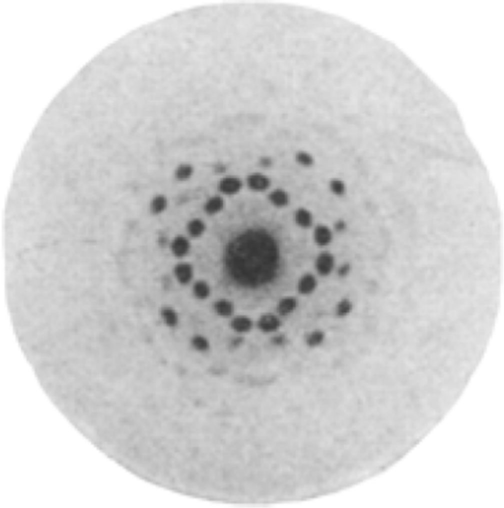
Basiseinheit "Mol": Über die Realität der Atome

Max von Laue



Interferenzerscheinungen mit Röntgenstrahlen beim Durchgang durch Kristalle

von W. Friedrich, P. Knipping und M. Laue und erläutert die Bedeutung dieser Versuche für die Klärung unserer Auffassung



Sitzungsberichte der Mathematisch-Naturwissenschaftlichen Klasse der Königl. Bayerischen Akademie der Wissenschaften zu München S. 303 (1912)

dual interpretation and base quantity "Stoffmenge":

8. Mit den Bezeichnungen „Mol“ und „Äquivalent“ verbundene Begriffe und Einheiten

Ulrich Stille

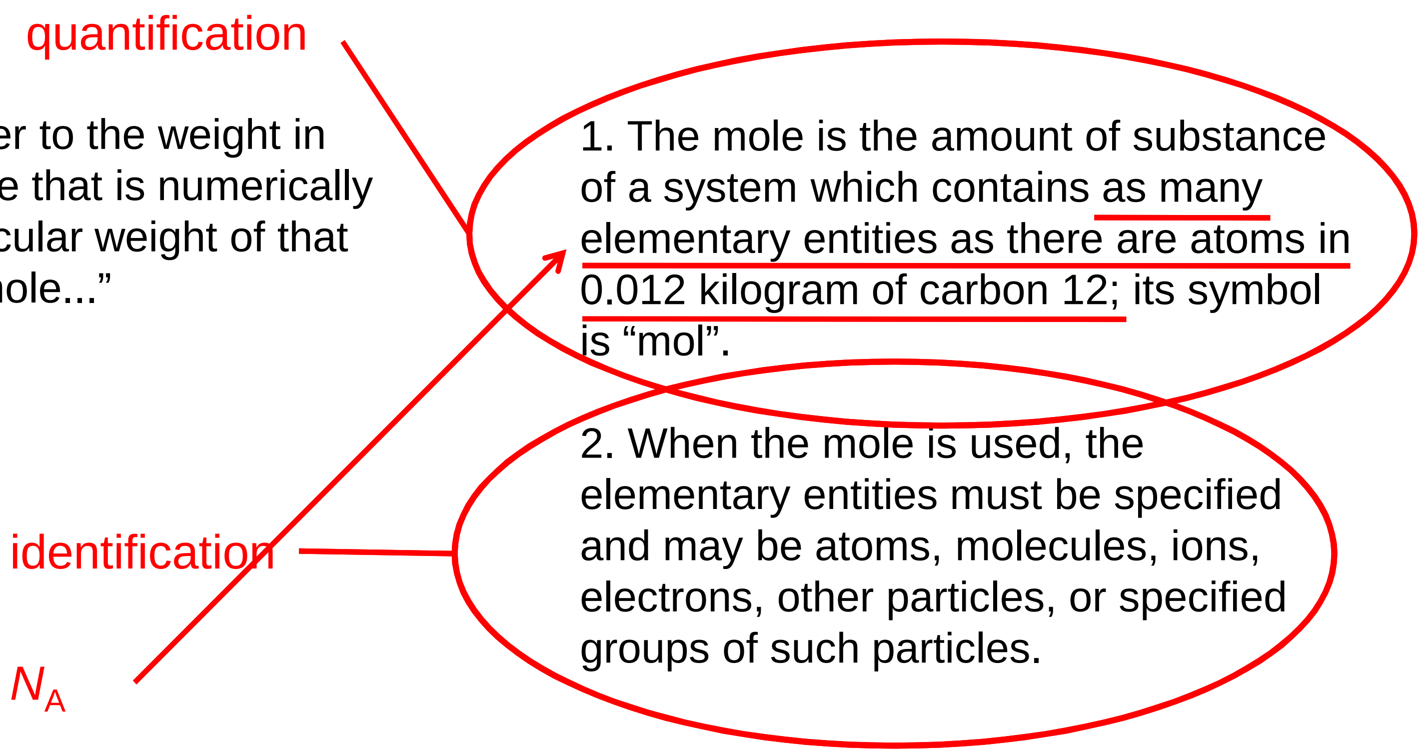
"First of all it (the mole) is understood as a chemical mass unit in accordance with **Ostwald's view of a continuum** and has an individual value for each type of molecule.

The other understanding of the "**Mole**" is that of **a number of atoms or molecules**, that is comprised in a mole. (We will call it mole number.)“

When you intend to find a more precise wording, for example by introducing a base quantity **"Stoffmenge"** (amount of substance) it can be considered as the numerical value of the amount of substance."

Stille U.: Messen und Rechnen in der Physik, Vieweg & Sohn S. 117f. (1955)

Definition of the mole



quantification

"Let us generally refer to the weight in grams of a substance that is numerically identical to the molecular weight of that substance, as one mole..."

1. The mole is the amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kilogram of carbon 12; its symbol is “mol”.

identification

2. When the mole is used, the elementary entities must be specified and may be atoms, molecules, ions, electrons, other particles, or specified groups of such particles.

N_A

Ostwald 1893

current definition (1971)

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current definition (1971)

$$M(\mathrm{X}) = A_r(\mathrm{X}) \text{ x } M_u$$

$$M(\mathrm{X}) = m(\mathrm{X}) \text{ x } N_A$$

$m(\mathrm{X})$	$A_\mathrm{r}(\mathrm{X})\, m_\mathrm{u}$
m_u	$m(^{12}\mathrm{C})/12$
N_A	Avogadro constant

now: $u(M_\mathrm{u}) = 0$
$u(N_\mathrm{A}) = 2 \text{ x } 10^{-8}$

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current definition (1971)

- In the new SI all 7 base units will be defined by constants of nature (SI reference constants),
- the respective SI reference constants will have exact numerical values,
- the new SI is expected to be more stable since there are no artefacts involved.

demands for redefinition

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proposed definition

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$$M(\mathrm{X}) = A_r(\mathrm{X}) \times M_u$$

$$M(\mathrm{X}) = m(\mathrm{X}) \times N_A$$

$$n(\mathrm{X}) = M_\mathrm{x}/M(\mathrm{X})$$

$$n(\mathrm{X}) = N(\mathrm{X})/N_A$$

$N(\mathrm{X})$ number of particles X

proposed definition

then: $u(M_\mathrm{u}) \leq 4 \times 10^{-9}$

$\boldsymbol{u(N_\mathrm{A}) = 0}$

mise en pratique of the mole

A *mise en pratique* for the definition of a unit is a set of instructions that allows the definition to be realized in practice at the highest level. The *mise en pratique* should describe the primary realizations based on top-level primary methods.

CCU would like to see some homogeneity in their content.

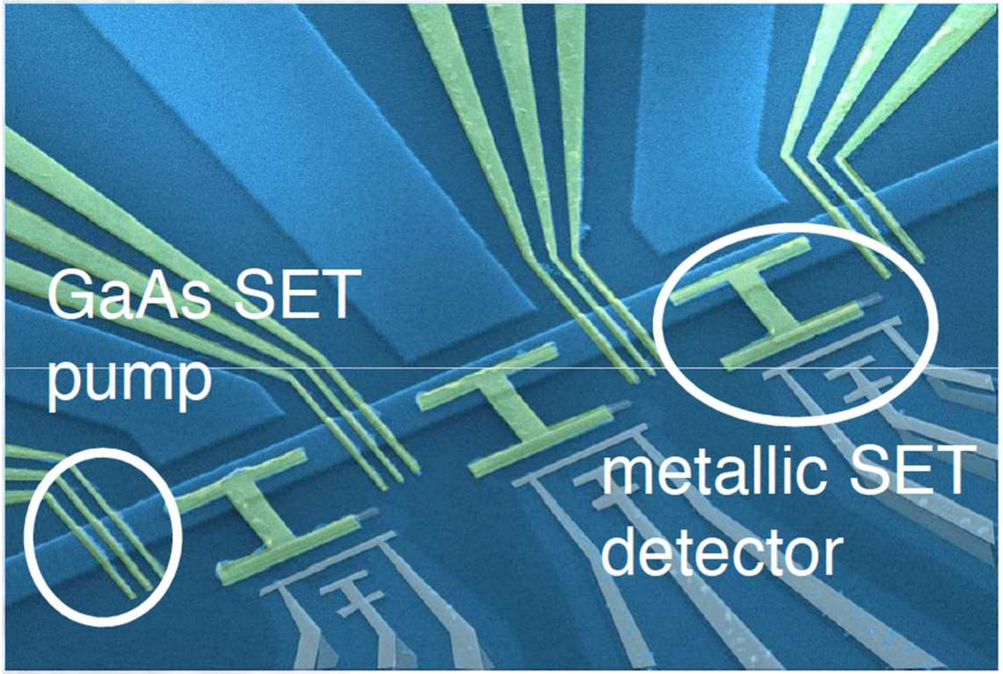
(report of the 97th meeting of the CIPM (2008)).

mise en pratique of the mole

The mole can be realized by counting N_A electrons in a conductor line with a SET device.

$$n_{el} = \langle N_{el} \rangle / N_A$$

"One Ampere is realized by measuring the current created by the charge of 2.66046X x 10^{-5} mol_{el}/s passing through a SET turnstile device."



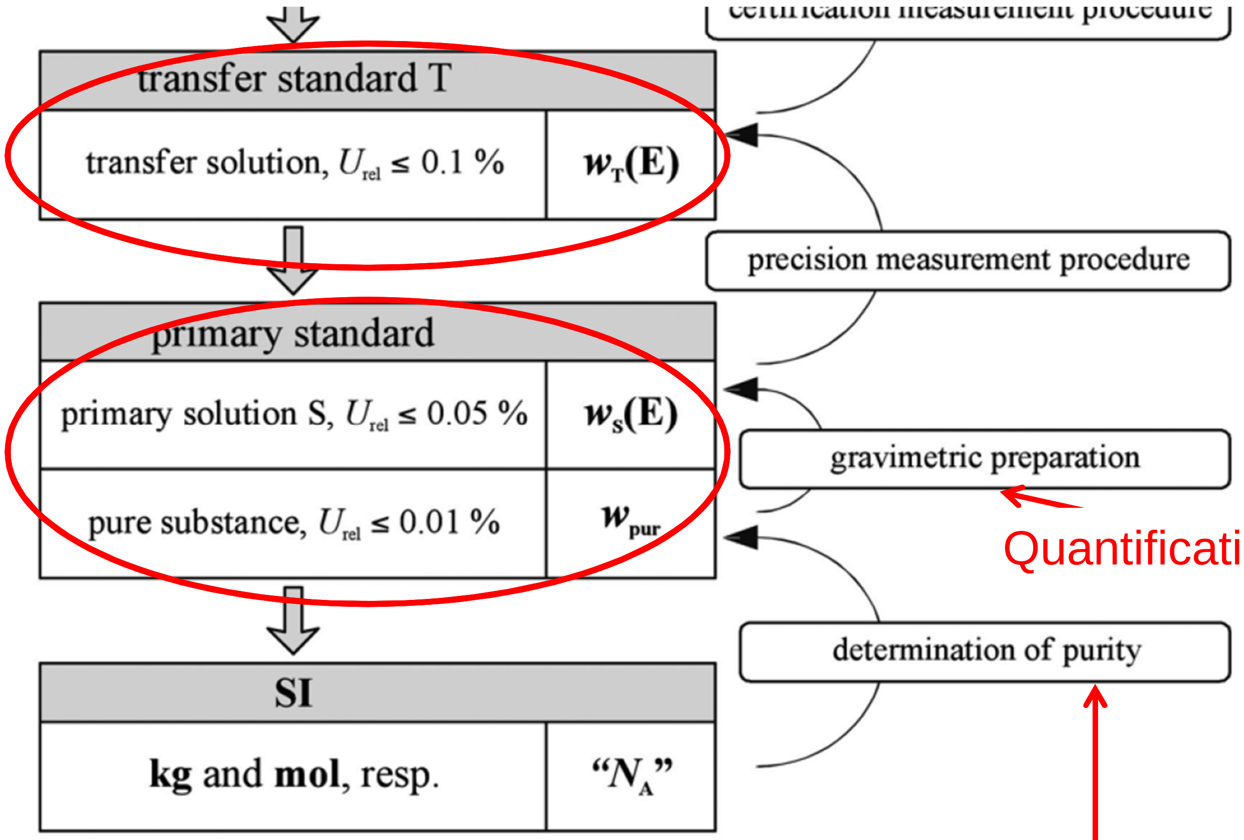
A semiconductor single-electron-tunneling (SET) pump.

$$I = \langle N_{el} \rangle ef$$

S. P. Giblin et al. Nature Communications 3.930
DOI 10.1038 ncomms 1935
from: U. Siegner, PTB

mise en pratique of the mole

Traceability



certification measurement procedure

transfer standard T

transfer solution, $U_{rel} \leq 0.1\ \%$ | $w_T(E)$

precision measurement procedure

primary standard

primary solution S, $U_{rel} \leq 0.05\ \%$ | $w_S(E)$

gravimetric preparation

pure substance, $U_{rel} \leq 0.01\ \%$ | w_{pur}

determination of purity

SI

kg and **mol**, resp. | "N_A"

primary level

transfer standard

$$c(X) = \frac{n(X)}{V_{sol}}$$

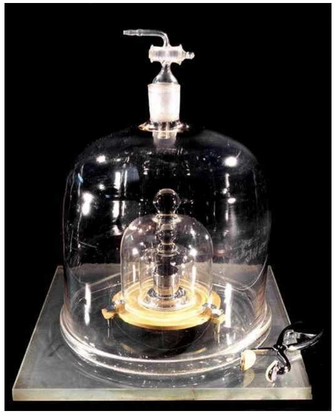
primary standard

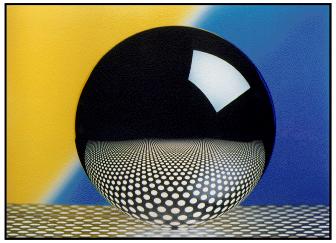
Quantification

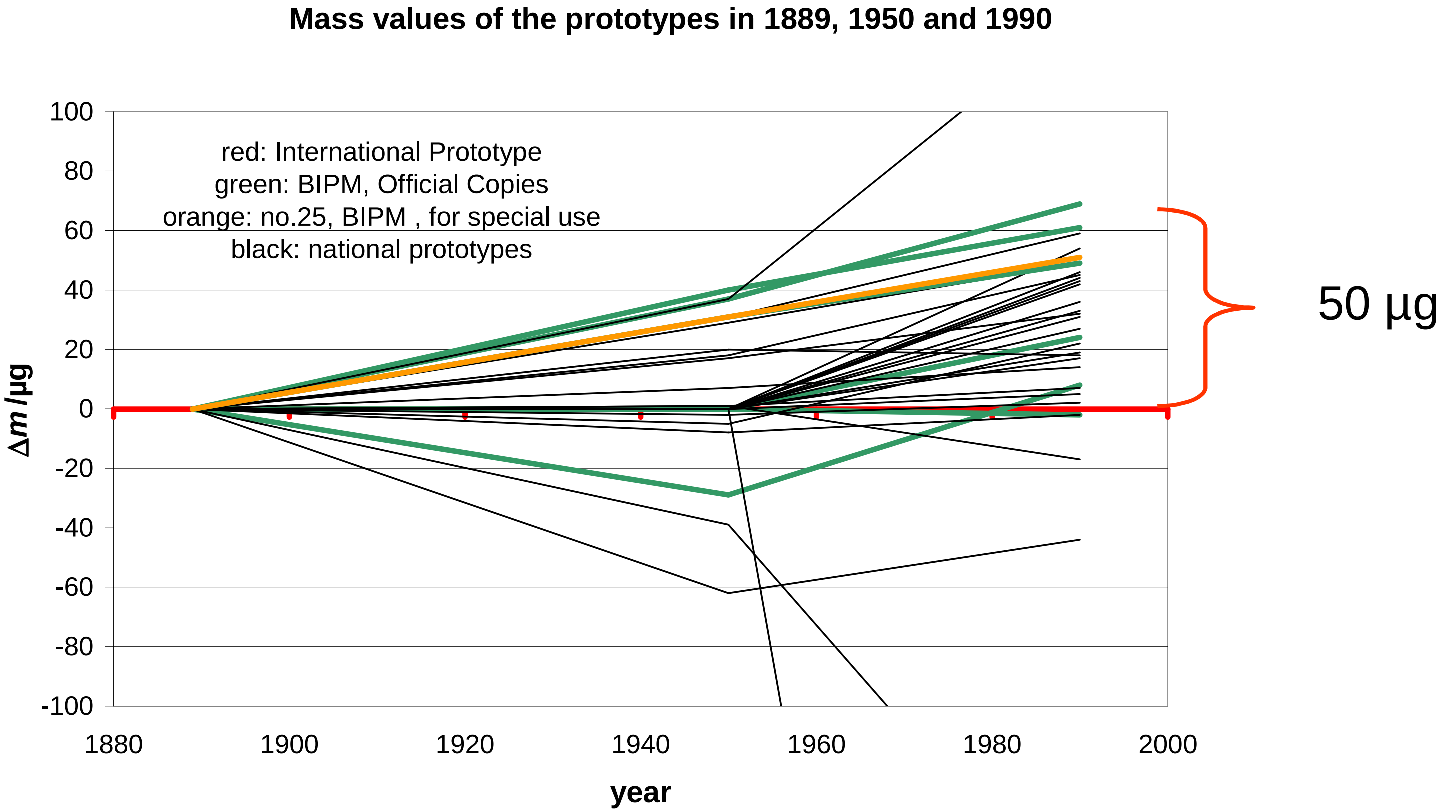
$$n(X) = \frac{M_X}{M(X)} R(X)$$

Identification

the kilogram artefact problem







$$N_A = \frac{8 \cdot M \cdot V_{\text{sphere}}}{m \cdot a^3}$$

© Güttler

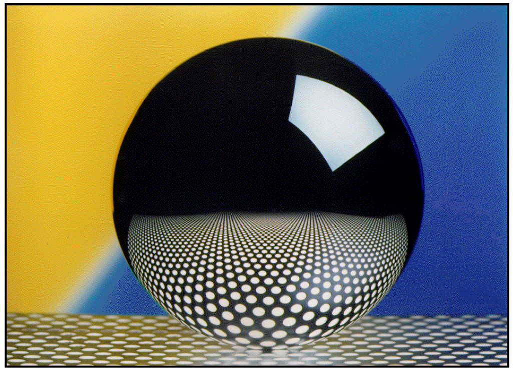
precondition for new defintion

Measurement challenge:

$u(N_A)$ or $u(h)$ ≤ present situation

- Three measurement results of N_A or h available
- one of them should have a rel. stand. uncertainty of $2\cdot 10^{-8}$ and
- two should have a rel. standard uncertainty of $5\cdot 10^{-8}$

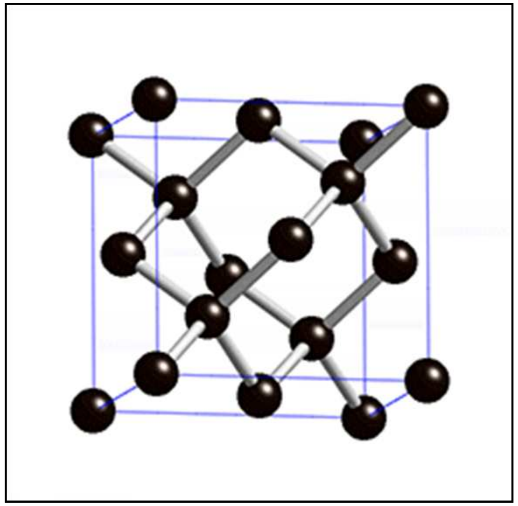
Avogadro's constant via Bragg's relationship



$N = V_{\mathrm{Sphere}} / V_{\mathrm{Atom}}$

$n = N / N_A = m / M$

$N_A = (M / m)\,(V_{\mathrm{Sphere}} / V_{\mathrm{Atom}})$



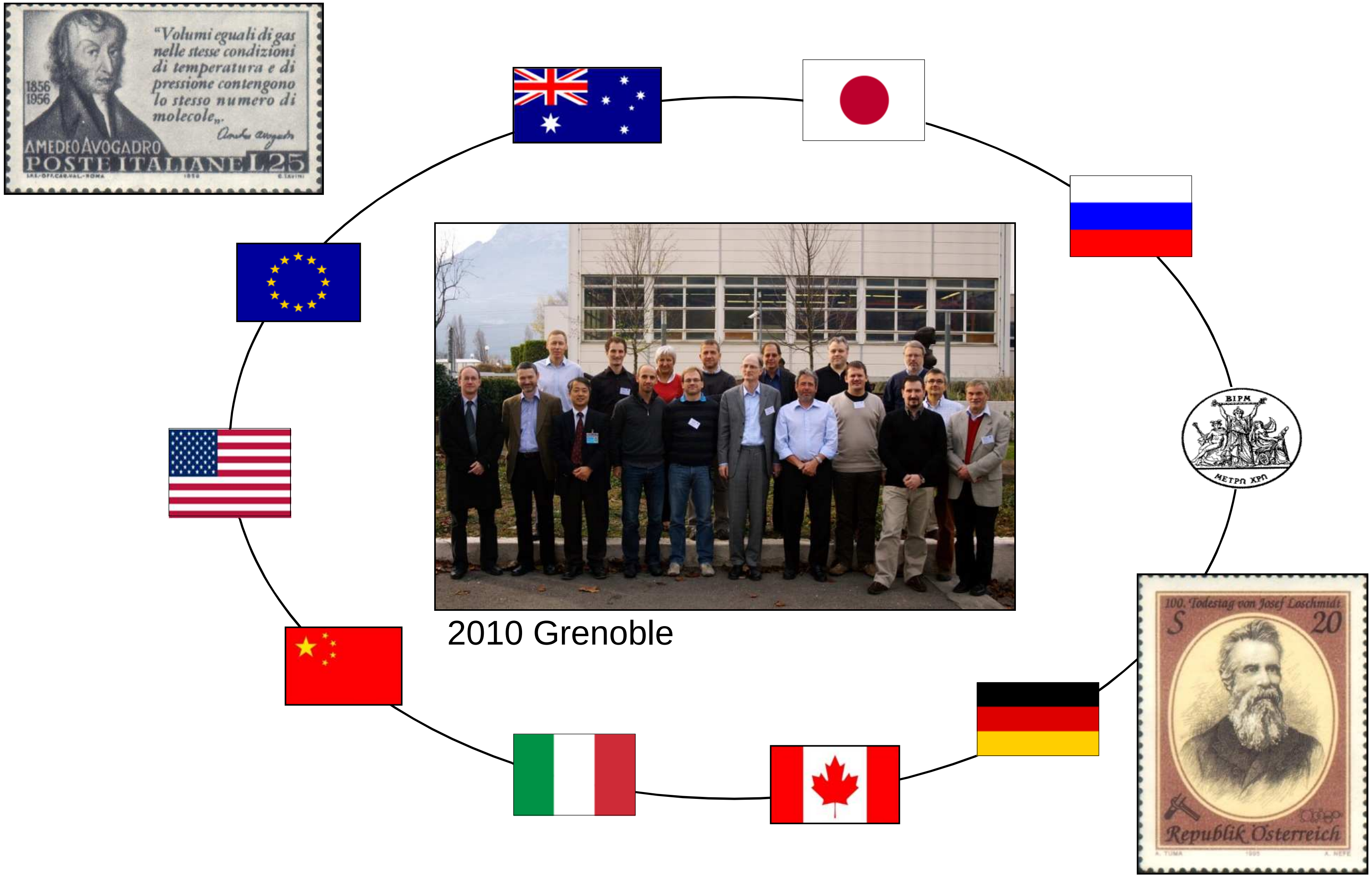
$$\boxed{N_A = \frac{8 \cdot M \cdot V_{\mathrm{sphere}}}{m \cdot a^3}}$$

$$N_A h = \frac{c A_r(e) M_u \alpha^2}{2 R_\infty}$$

http://www.msm.cam.ac.uk/phase-trans/2003/MP1.crystals/MP1.crystals.html

see J. Stenger & E.O. Göbel, Metrologia 49 (2012), L25–L27

International Avogadro Coordination (IAC)
CCM Working Group on the Avogadro Constant (WGAC)



2010 Grenoble

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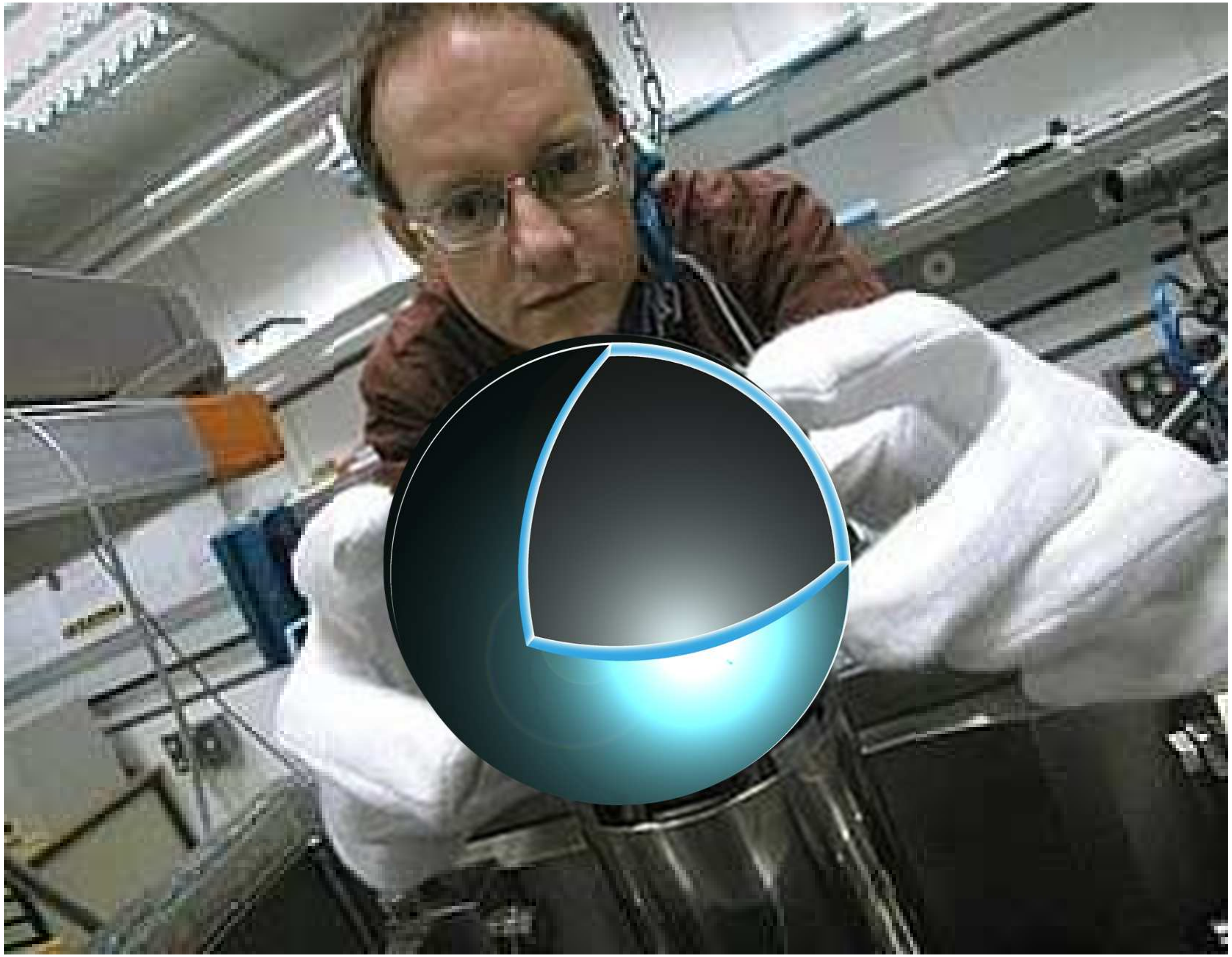
measurement of the Avogadro constant via Bragg's relation



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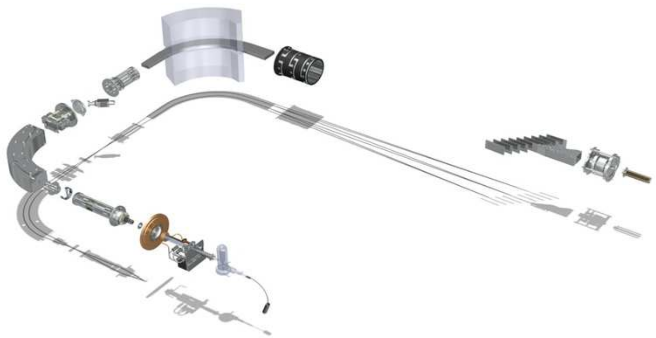
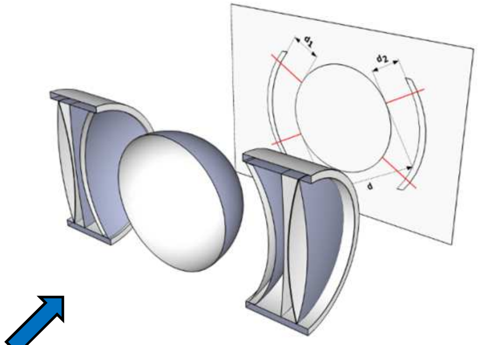
International Avogadro Coordination



Multicollector ICPMS

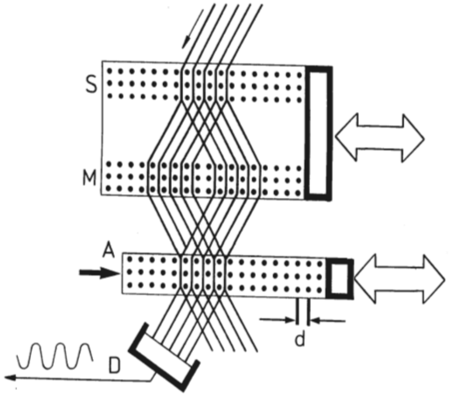
Optical sphere interferometer



$$N_A = \frac{8 \cdot \underline{M} \cdot \underline{V_{\text{sphere}}}}{\underline{m_{\text{sphere}}} \cdot \underline{a}^3}$$

Mass comparator

Surface layer :	XRR, XRF, XPS, opt. ellipsometry
Impurities:	IR, NAA



X-Ray Interferometer

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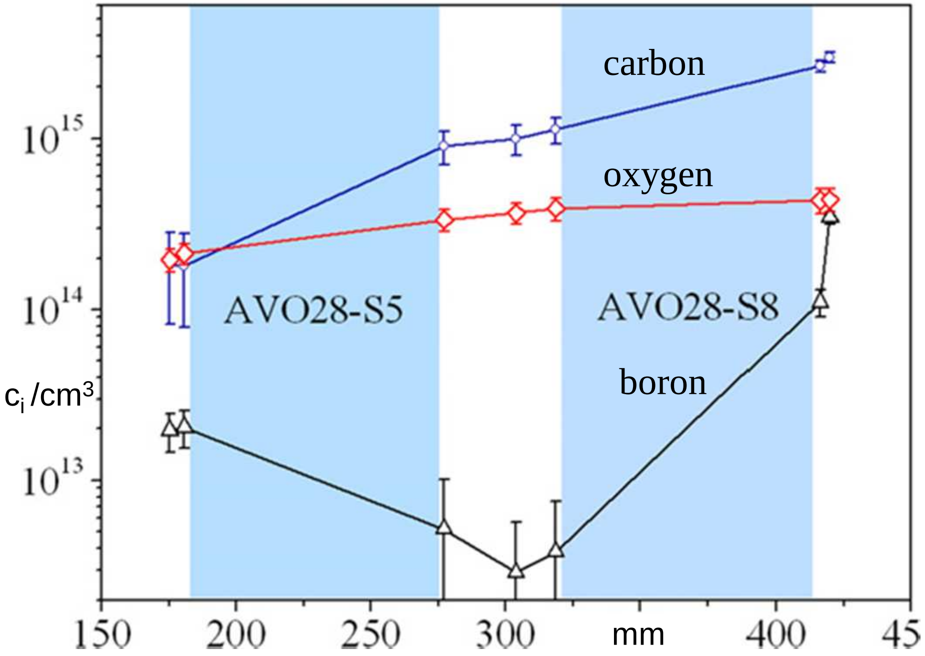
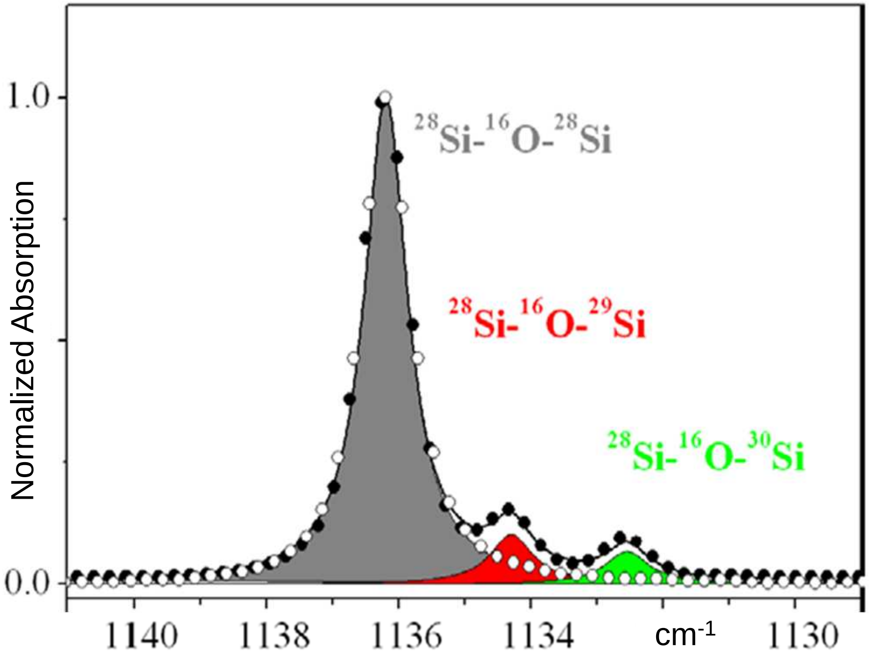
measurement uncertainty $N_{A:}$ impurities



Major impurities by infrared absorption spectroscopy

contribution to $u(N_A)_{rel}$: << 1×10^{-9}

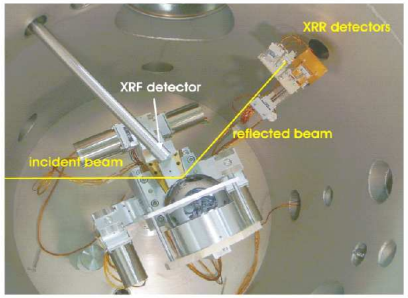


Infrared absorption spectra of oxygen in Si at 7K

The three dominant vibrational modes of oxygen (coloured) in natural Si (full circles). For comparison the measured spectra of ‘Si28’ (open circles).

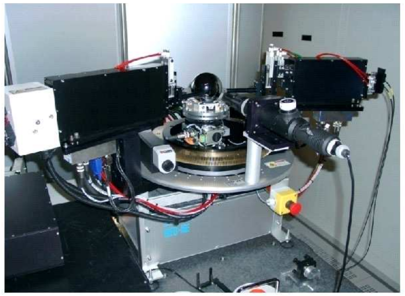
© Güttler

Surface passivation layer (silicon oxide)

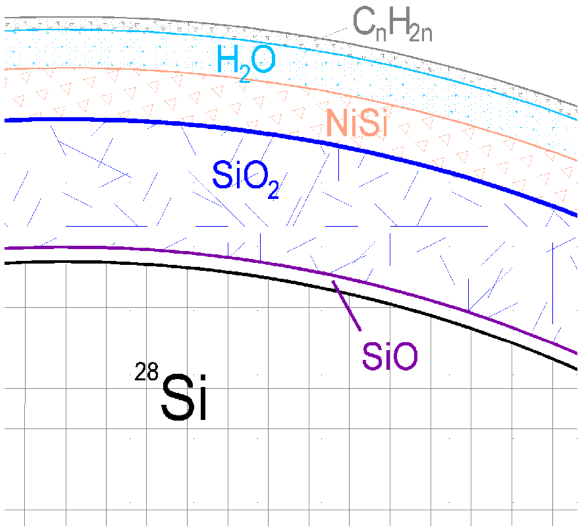


X-ray reflectometry (BESSY)

X-ray spectroscopy (METAS)



Spectral ellipsometry (PTB, NMIJ)



sphere	d_{SL}	m_{SL}
S5	2,88(33) nm	222,1 (14,5) µg
S8	2,69(32) nm	213,6 (14,4) µg

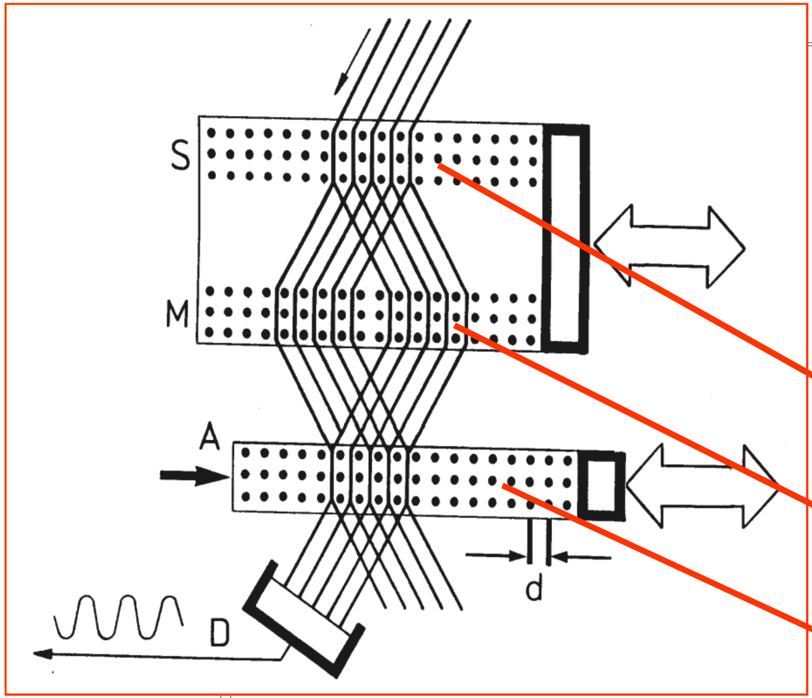
relevant parameters:

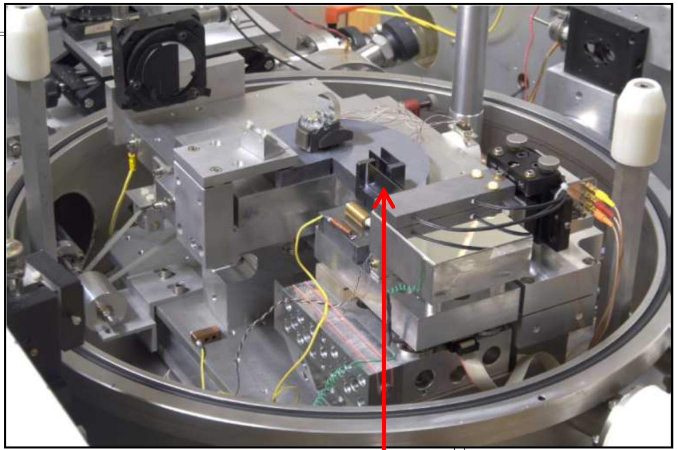
- Optical constants
- Contamination
- Surface quality

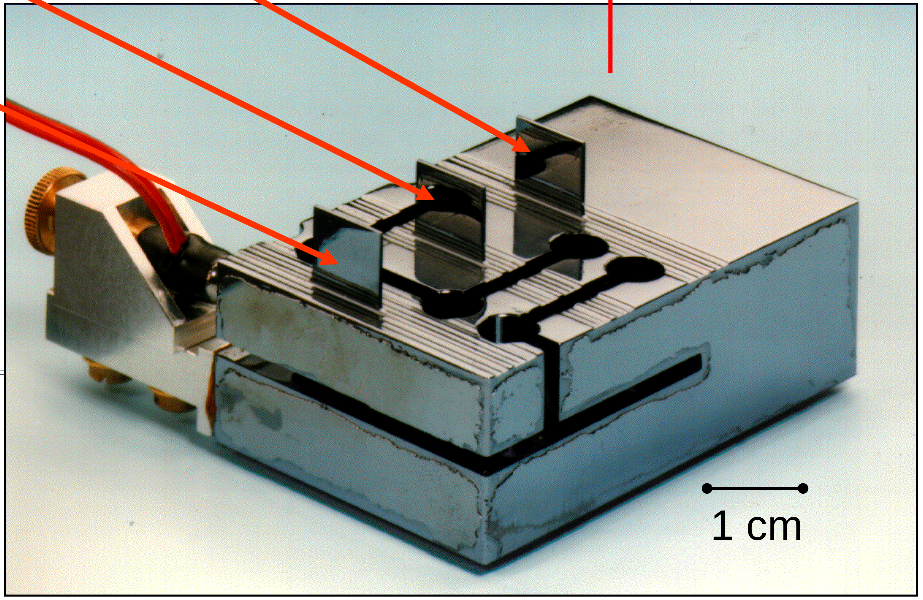
Total uncertainty: 0,3 nm
14 µg

© Güttler

INRIM X-ray interferometer

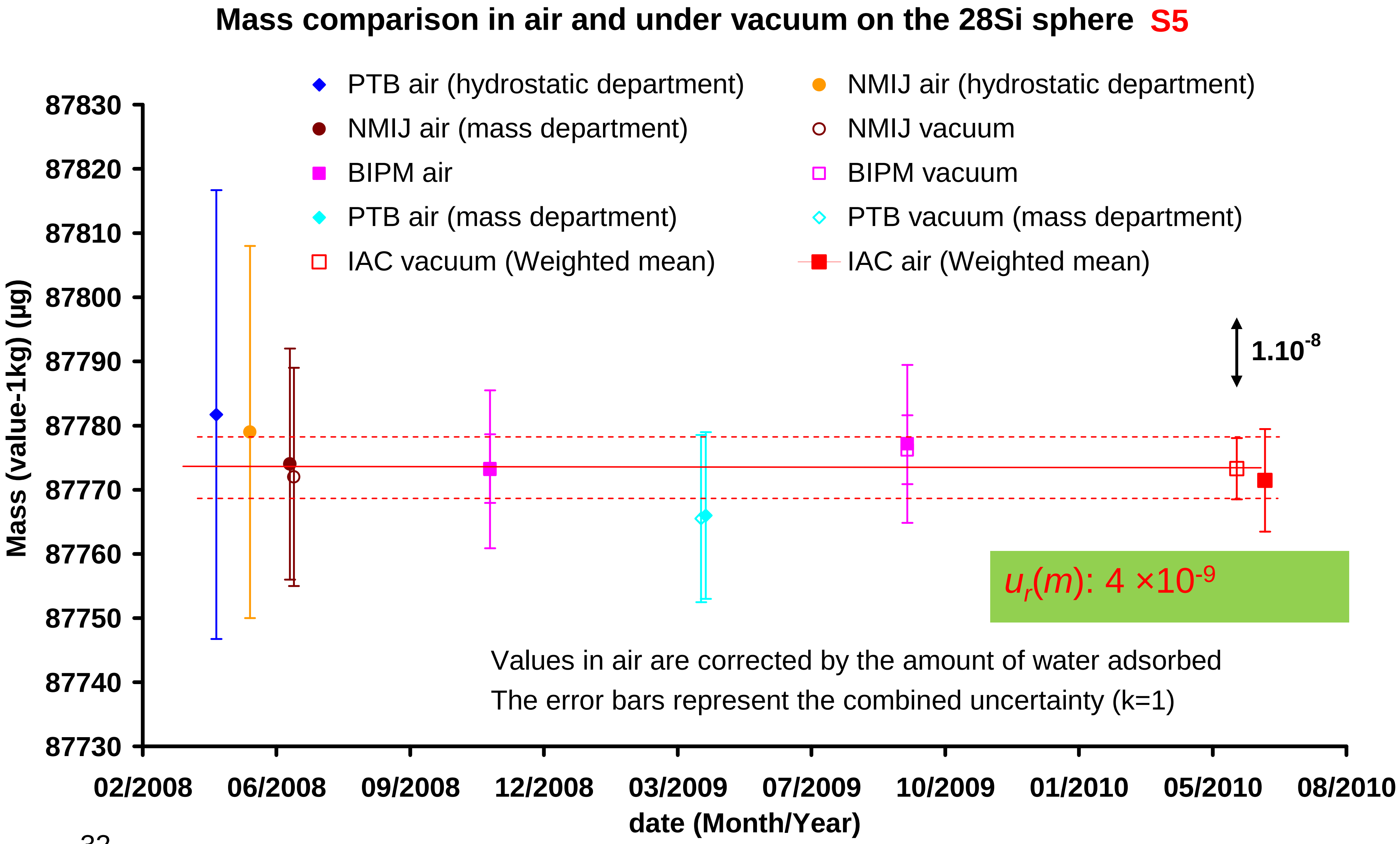






Combined optical and x-ray interferometry

mass comparison



$u_r(m)$: 4 ×10^{-9}

Values in air are corrected by the amount of water adsorbed

The error bars represent the combined uncertainty (k=1)

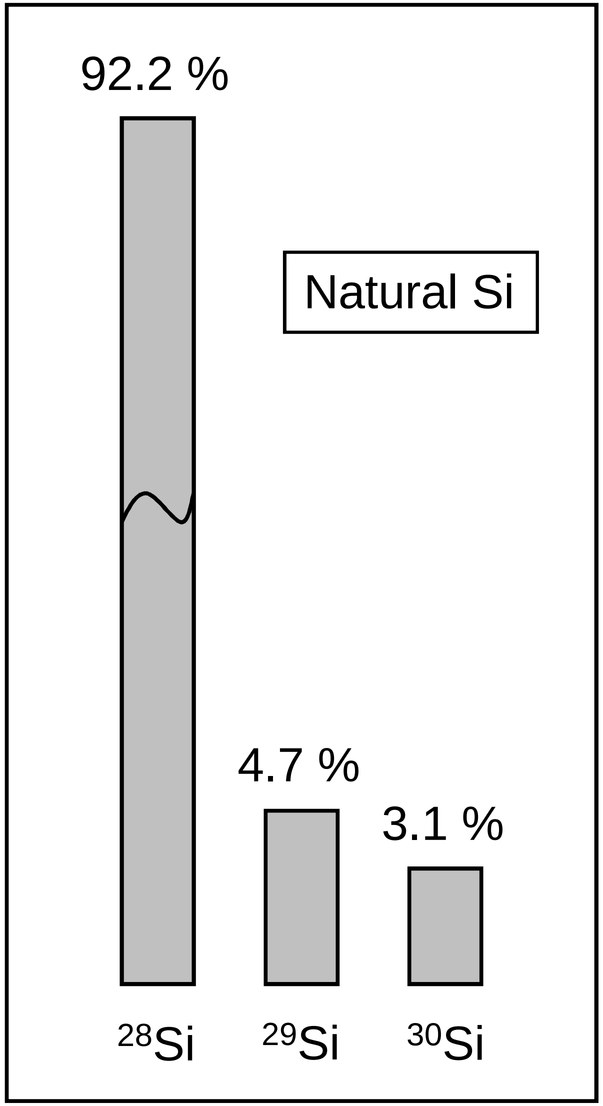
© Güttler

determination of the molar mass of silicon

- three isotopes: ^{28}Si, ^{29}Si, ^{30}Si
- amount fractions x ↔ isotope ratios R
- Challenge: Target uncertainty of $u_{M,\mathrm{rel}} \leq 1 \cdot 10^{-8}$

$$M(\mathrm{Si}) = \sum_{i=28}^{30} \left[x\left({}^{i}\mathrm{Si}\right) \cdot M\left({}^{i}\mathrm{Si}\right) \right] \qquad x\left({}^{i}\mathrm{Si}\right) = \frac{R_i}{\sum_{j=28}^{30} R_j}$$

Measurement challenge I

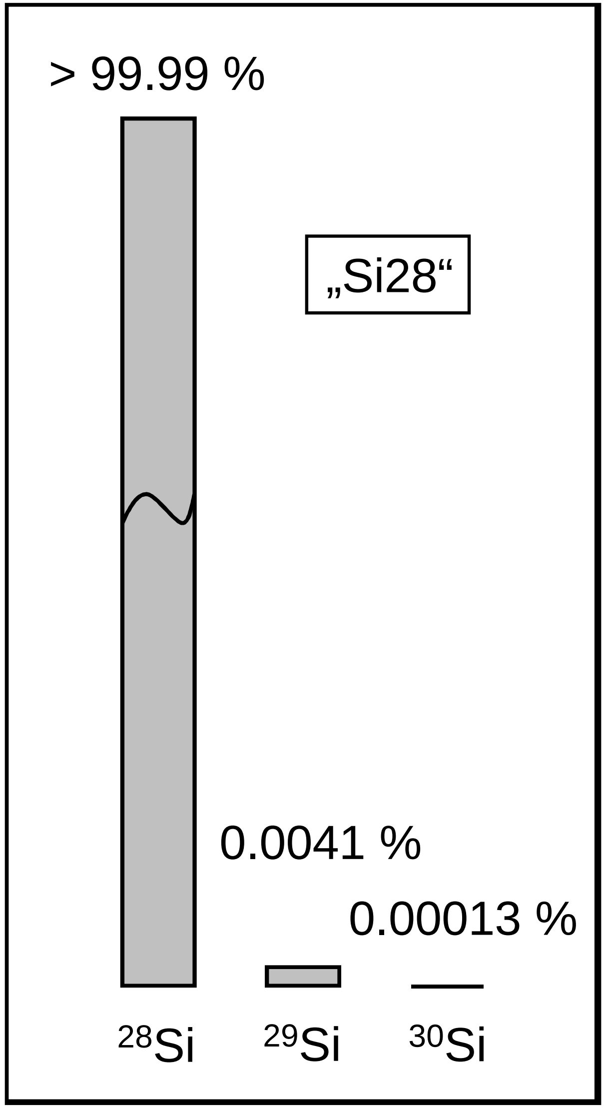


Isotopic ratios

	nat. Si	
R **28/28**	**1**	
R **29/28**	**$5.0 \cdot 10^{-2}$**	
R **30/28**	**$3.4 \cdot 10^{-2}$**	

$U < 10^{-7}$

Measurement challenge II

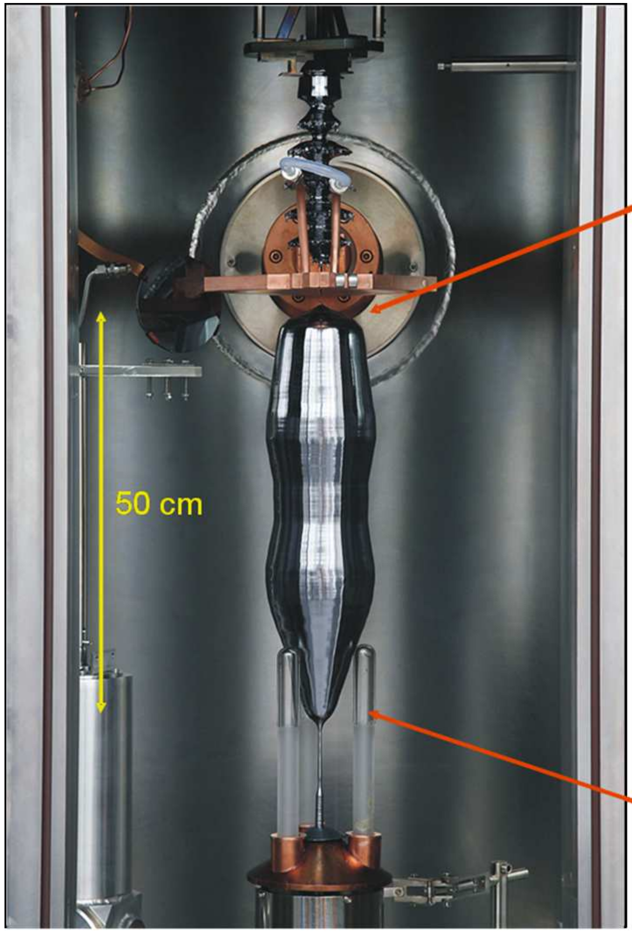


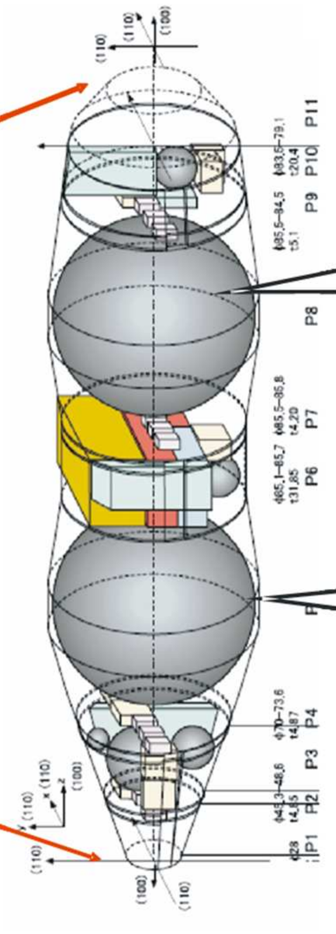
Isotopic ratios

	nat. Si	
$R_{28/28}$	**1**	
$R_{29/28}$	**$5.0 \cdot 10^{-2}$**	
$R_{30/28}$	**$3.4 \cdot 10^{-2}$**	

$U < 10^{-7}$ $U \approx 10^{-3}$

Material for the N_A measurement





Isotopically enriched Si(28) material

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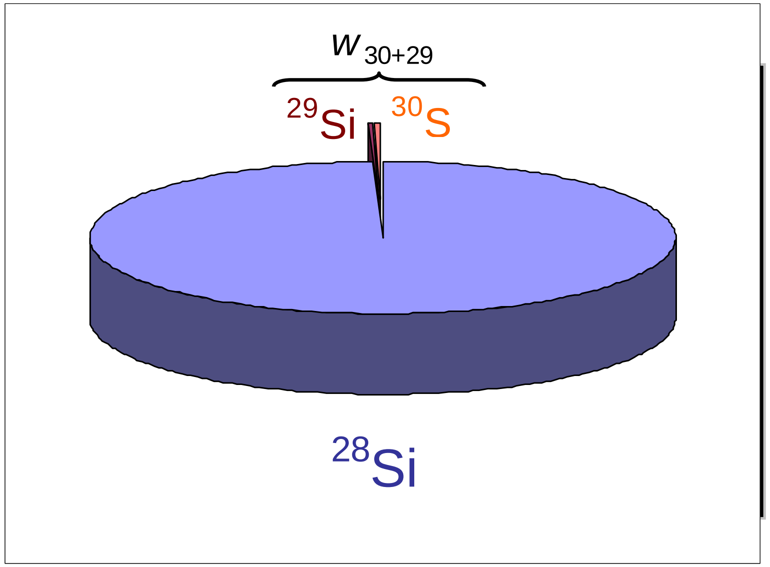
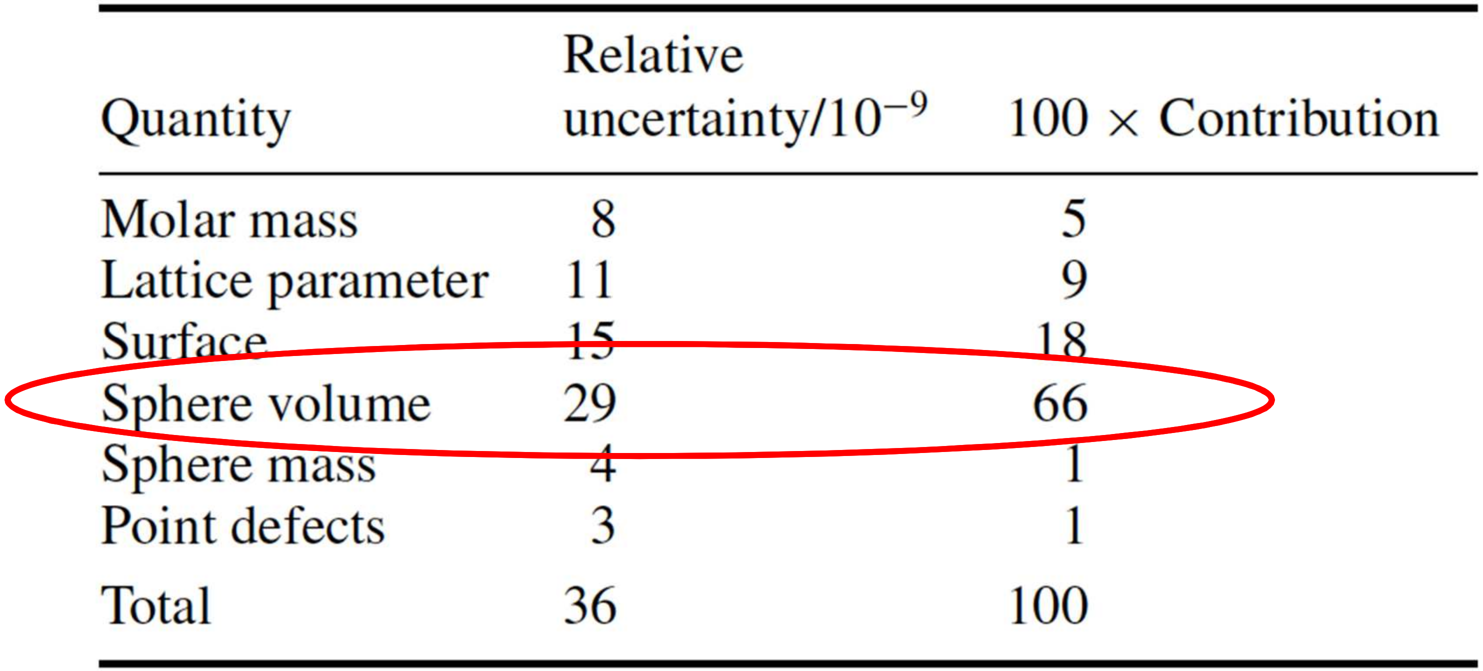
the "virtuell element" concept

- ^{29}Si and ^{30}Si treated like a virtual two-isotop-element impurity in the isotopically enriched Si (28) matrix
- Measurement of the mass fraction w_{30+29} by IDMS



$$w_{30+29} = w_{\mathrm{imp}} = \frac{m_{29} + m_{30}}{m_{28}+m_{29}+m_{30}} = \frac{m_{\mathrm{imp}}}{m_{28}+m_{\mathrm{imp}}}$$

uncertainty budget for N_A using AVO28-S5

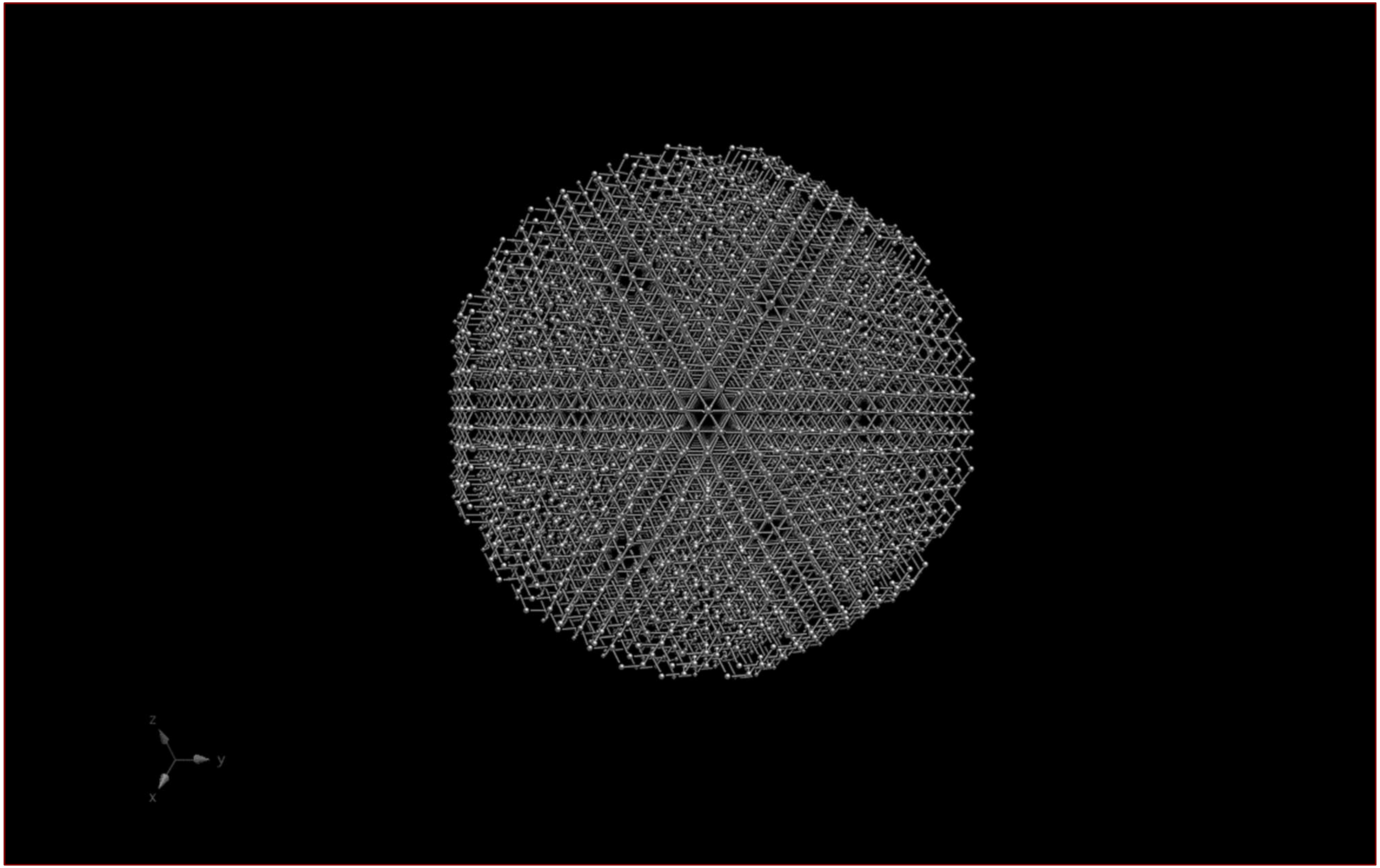


Quantity	Relative uncertainty/10^{-9}	$100 \times$ Contribution
Molar mass	8	5
Lattice parameter	11	9
Surface	15	18
Sphere volume	29	66
Sphere mass	4	1
Point defects	3	1
Total	36	100

Der prozentuale Anteil der gesamten Messunsicherheit sind die relevanten Varianzanteile an der Gesamtvarianz- Die größten Beiträge zur Messunsicherheit liefern die Oberflächencharakterisierung und die Volumenbestimmung.

aus: B Andreas et al., Metrologia, 48 (2011) S1–S13

interferometric volume determination



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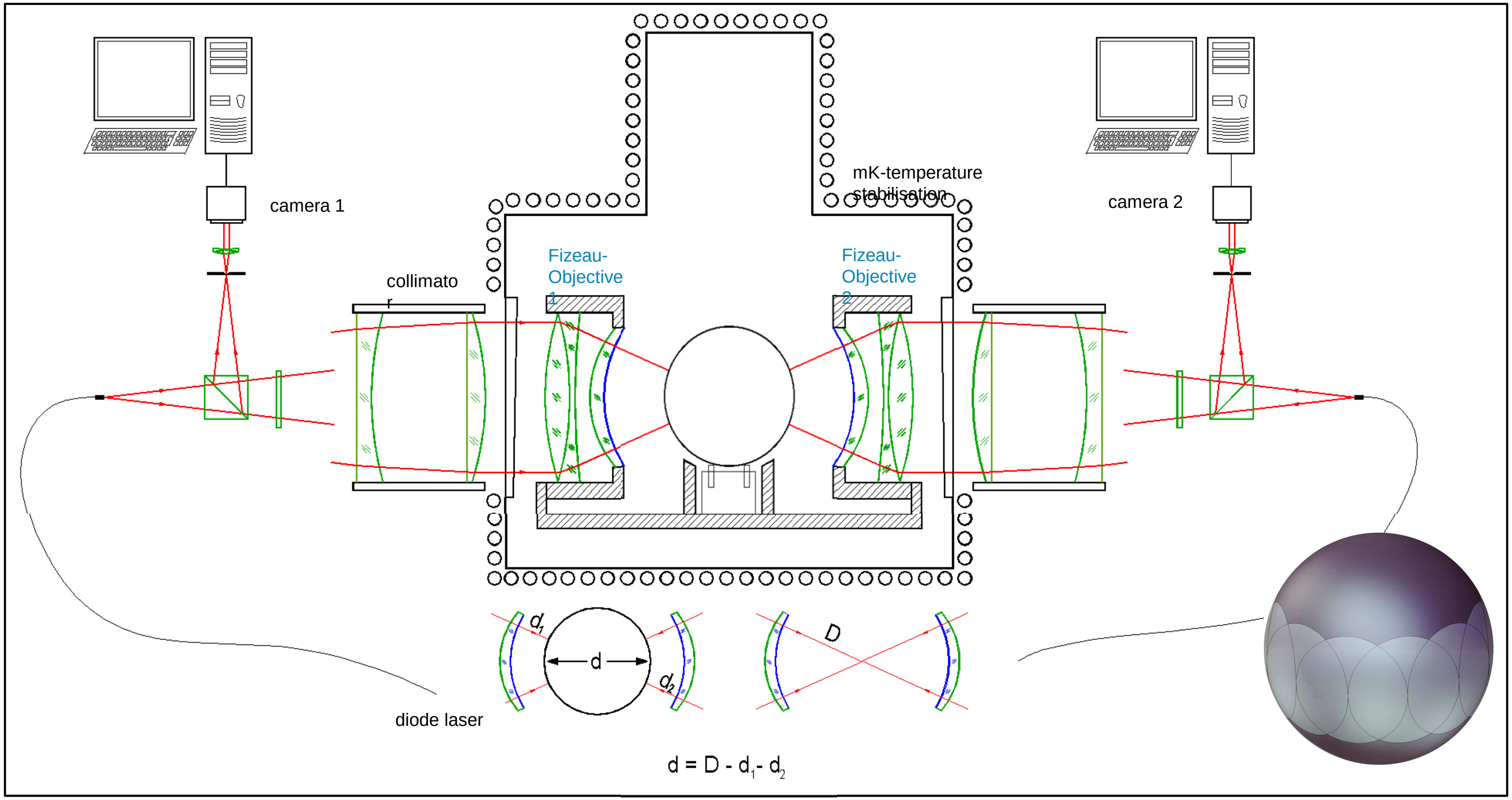
interferometric volume determination



thousands of diameters are measured simultaneously

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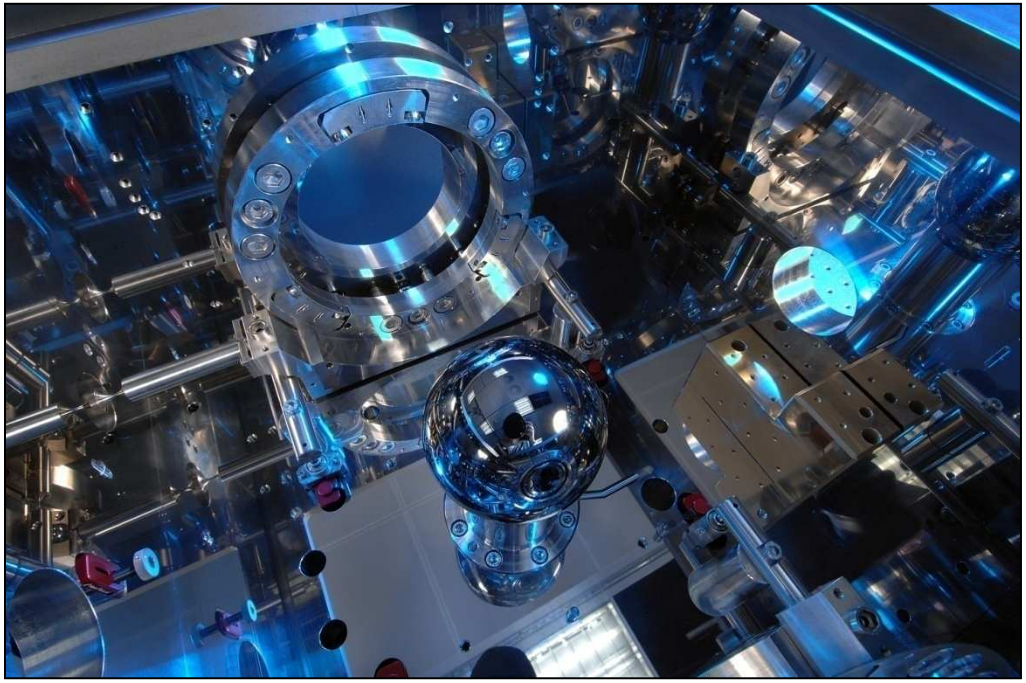
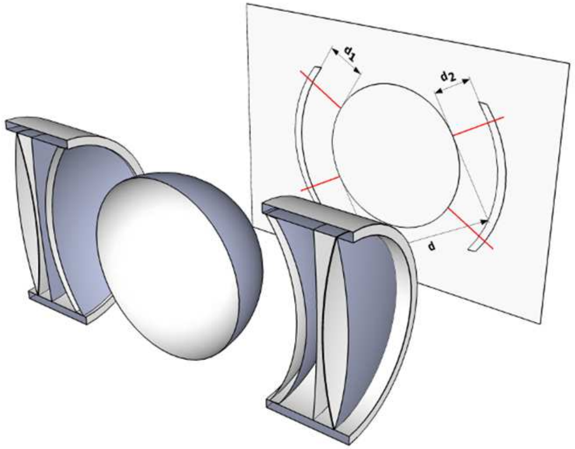
interferometric volume determination

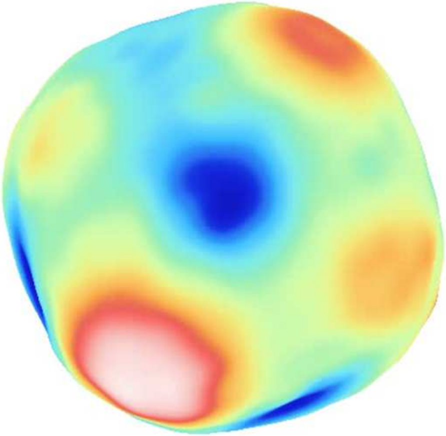


PTB‘s sphere interferometer enables complete topographies of spheres, $n_{diameter} \approx 600\,000$.

The radius uncertainty is 0.7 nm or 8×10^{-9}



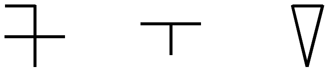
PTB‘s sphere interferometer with spherical symmetry

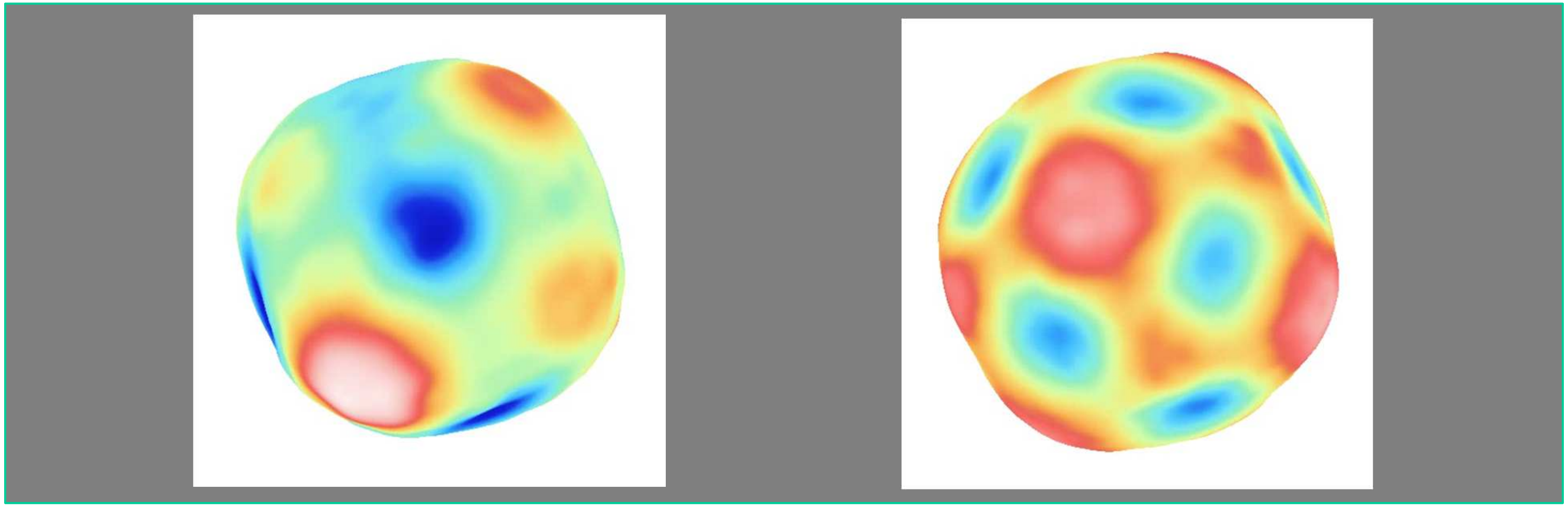


Radius topography of ^{28}Si-sphere S8. Peak to valley deviations from roundness amount to 99 nm.

© Güttler

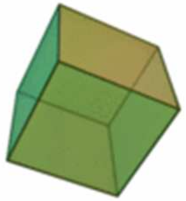
Interferometry on the ^{28}Si spheres

application of 3 marks  in a distance of 90°



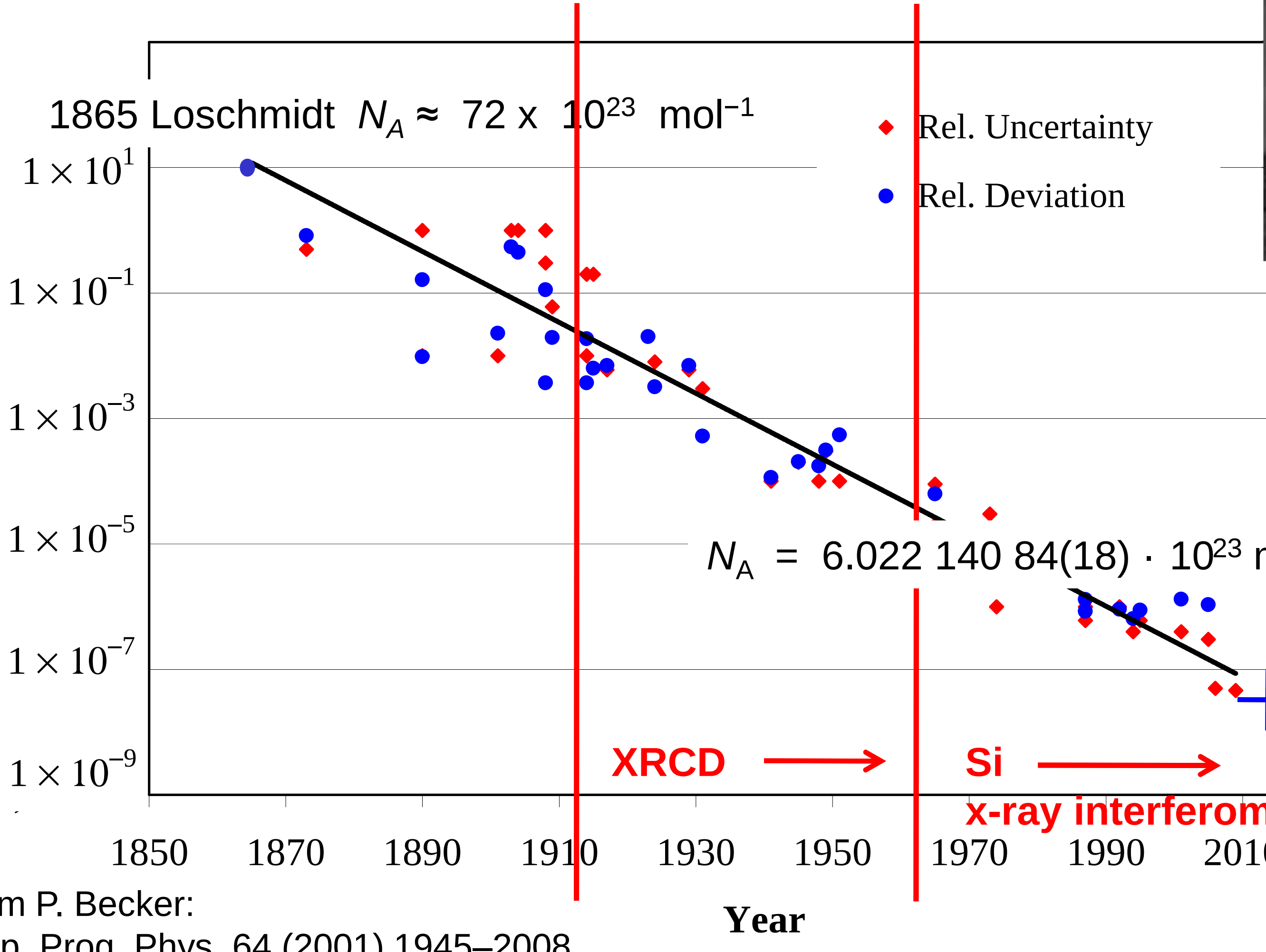
Hexaeder (Würfel)

Kuboktaeder



- working group 5.41,
  Dr. Arnold Nicolaus
- Measurement of ^{28}Si-S5

Avogadro constant: accuracy over time



Avogadro constant: Relative uncertainty and deviation from CODATA v

1865 Loschmidt $N_A \approx 72 \times 10^{23}$ mol^{-1}

N_A = 6.022 140 84(18) · 10^{23} mol^{-1} $u_\mathrm{rel} = 2 \times 10^{-8}$

XRCD →

Si →

x-ray interferometry

Max von Laue

from P. Becker:
Rep. Prog. Phys. 64 (2001) 1945–2008

mise en pratique for mole and kilogram

The kilogram, kg, is the SI unit of mass; its magnitude is set by fixing the numerical value of the Planck constant to be equal to exactly 6.626 068X $\cdot 10^{-34}$ when it is expressed in the unit s^{-1} m^2 kg, which is equal to J s

$$N = 8V_{\mathrm{sphere}} / a({}^{28}\mathrm{Si})^3$$

2.2 Realization by the X-ray-crystal-density (XRCD) method

To realize the definition of the kilogram, the mass m_s of (a ^{28}Si single crystal) sphere is... expressed in terms of the mass of a single atom

$$m_s = Nm({}^{28}Si)$$

and

$$m_s = hN[m({}^{28}Si)/h]$$

The XRCD experiment determines N; $m({}^{28}Si)/h$ is a constant of nature whose value is... known to high accuracy and h is now exactly defined.

mise en pratique: realizing the mole

2. Realization of the definition of the mole

Currently, the most accurate method of realizing the mole is by counting ^{28}Si atoms in a single crystal of Si enriched in ^{28}Si using volumetric and X-ray interferometric measurements

$$N_\mathrm{A} = \frac{8 \cdot M \cdot V_\mathrm{sphere}}{m \cdot a(^{28}\mathrm{Si})^3} \qquad (1)$$

$$N = 8V_\mathrm{sphere} / a(^{28}\mathrm{Si})^3 \qquad (2)$$

$$n = N / N_\mathrm{A} \qquad (3)$$

One mol of ^{28}Si atoms is equivalent to the number of ^{28}Si atoms that is contained in a sample of a ^{28}Si single crystal with a volume of 12.05867069 cm^3 at 20 ℃ and in vacuum. The relative standard uncertainty of this volume would be 2×10^{-8}. (Hypothetical!)

mise en pratique: example ^{28}Si in AVO28-S5

Identification step:

In case that the specified elementary entity is **^{28}Si** and the real crystal is ***not*** purely **^{28}Si** also other elementary entities (elemental impurities, i.e. C, O, B and isotope impurities, i.e. ^{29}Si, ^{30}Si) and the volume of the surface passivation layer must be considered (i.e. excluded). In the ^{28}Si enriched single crystal Si-sphere AVO28-S5 the following statements apply:

One mol of ^{28}Si atoms is equivalent to the number of ^{28}Si atoms that is contained in a sample of the AVO28-S5 single crystal sphere with a volume of 12.05918321 cm^3 at 20 ℃ and in vacuum.

The AVO28-S5 single crystal sphere contains 35.7452948469 mol of ^{28}Si atoms.

...in case of the proposed redefinition:

$$N_A h = \frac{c A_r(e) M_u \alpha^2}{2 R_\infty}$$

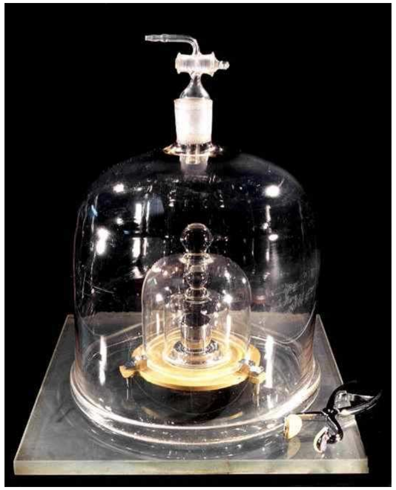
N_A	Avogadro-constant
h	*Planck-constant*
c	*speed of light*
α	*fine-structure constant*
R_∞	*Rydberg constant*
e	*elementary charge*
M_u	*molar mass constant =* $1\text{x}10^{-3}$ *kg/mol*

c, h, N_A *fixed in the definitionen of metre, kilogram and mole*
α *und* R_∞ *remain independent measurands*
$A_r(e)$, M_u *dependent variables of those measurands*

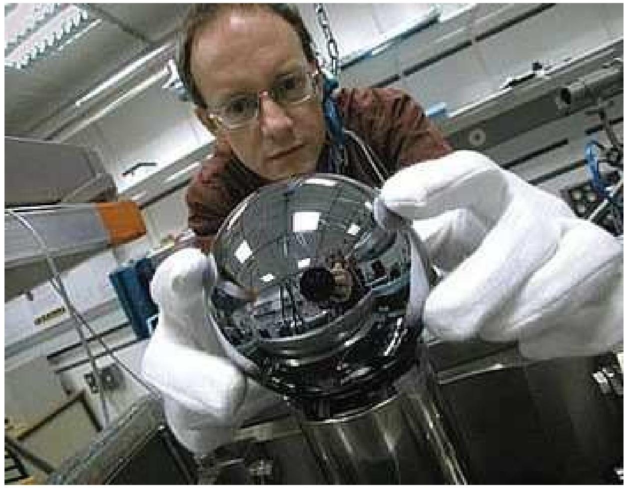
$A_r(e)$: *changes mean deviation from* $A_r(^{12}C) = 12$ *- exakt*
M_u: *changes mean deviation from* $1\text{x}10^{-3}$ *kg/mol – exakt* $(\leq 1{,}4 \text{ x } 10^{-9}$ $(k = 1))$

mise en pratique of the mole

kilogram



Mole



Planck-route

Avogadro-route

$$n(X) = \frac{N_x}{N_A}$$

primary standard

Integration of the Avogadro-project and the mise en pratique of the mole

- the most accurate realisation of the mole: the perfect implementation of a mise en pratique of the mole
- possibly the origin of the fixed value of the natural constant that accompanies the unit mole
- the only realisation of the mole that does not require the determination of a mass (i.e. is independant of the mass)
- a description that is closely linked to the mise en pratique of the kilogram so that the interelation of the units can be made easily transparent
- a perfect tool to explain the mole to the world outside of the chemical community