New quantum SI units (active starting right now)

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Outline

- Proton vs. kilogram (as yesterday)
- Macroscopic quantum phenomena and electrical units
- m/h
- 4 units to change
- CODATA specials: the last determination of h, e, k, and N_A
- Silicon unit
- Kibble's watt balance
- New and old constants

- Does it really matter?
- What is next?

- Are atomic physics and QED involved?

Who deal with the units? And why?

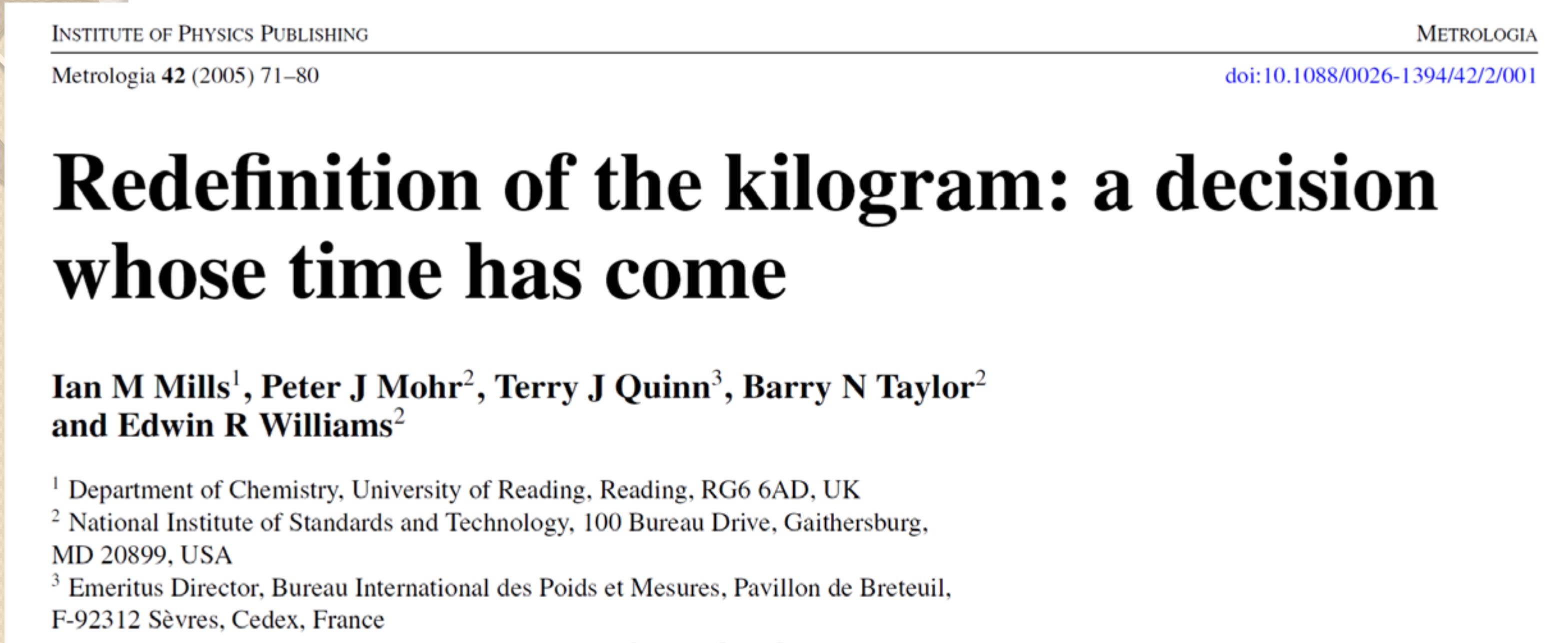
Who?

- Non-physicists.
- Many have physical education, but different priorities and responsibilities.
- Not for physicists.

Why?

- For better standards
- to facilitate better measurements of practical importance.
- Nothing to do with fundamental physics.

When did all that [re]start?



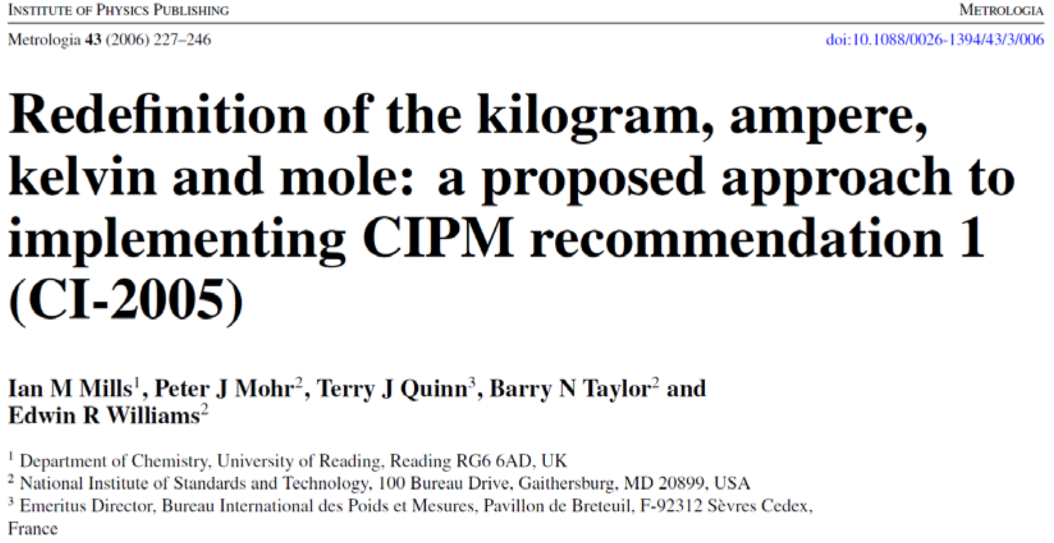
INSTITUTE OF PHYSICS PUBLISHING METROLOGIA

Metrologia **42** (2005) 71–80 doi:10.1088/0026-1394/42/2/001

Redefinition of the kilogram: a decision whose time has come

Ian M Mills[1], Peter J Mohr[2], Terry J Quinn[3], Barry N Taylor[2] and Edwin R Williams[2]

[1] Department of Chemistry, University of Reading, Reading, RG6 6AD, UK
[2] National Institute of Standards and Technology, 100 Bureau Drive, Gaithersburg, MD 20899, USA
[3] Emeritus Director, Bureau International des Poids et Mesures, Pavillon de Breteuil, F-92312 Sèvres, Cedex, France



INSTITUTE OF PHYSICS PUBLISHING METROLOGIA

Metrologia **43** (2006) 227–246 doi:10.1088/0026-1394/43/3/006

Redefinition of the kilogram, ampere, kelvin and mole: a proposed approach to implementing CIPM recommendation 1 (CI-2005)

Ian M Mills[1], Peter J Mohr[2], Terry J Quinn[3], Barry N Taylor[2] and Edwin R Williams[2]

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[2] National Institute of Standards and Technology, 100 Bureau Drive, Gaithersburg, MD 20899, USA
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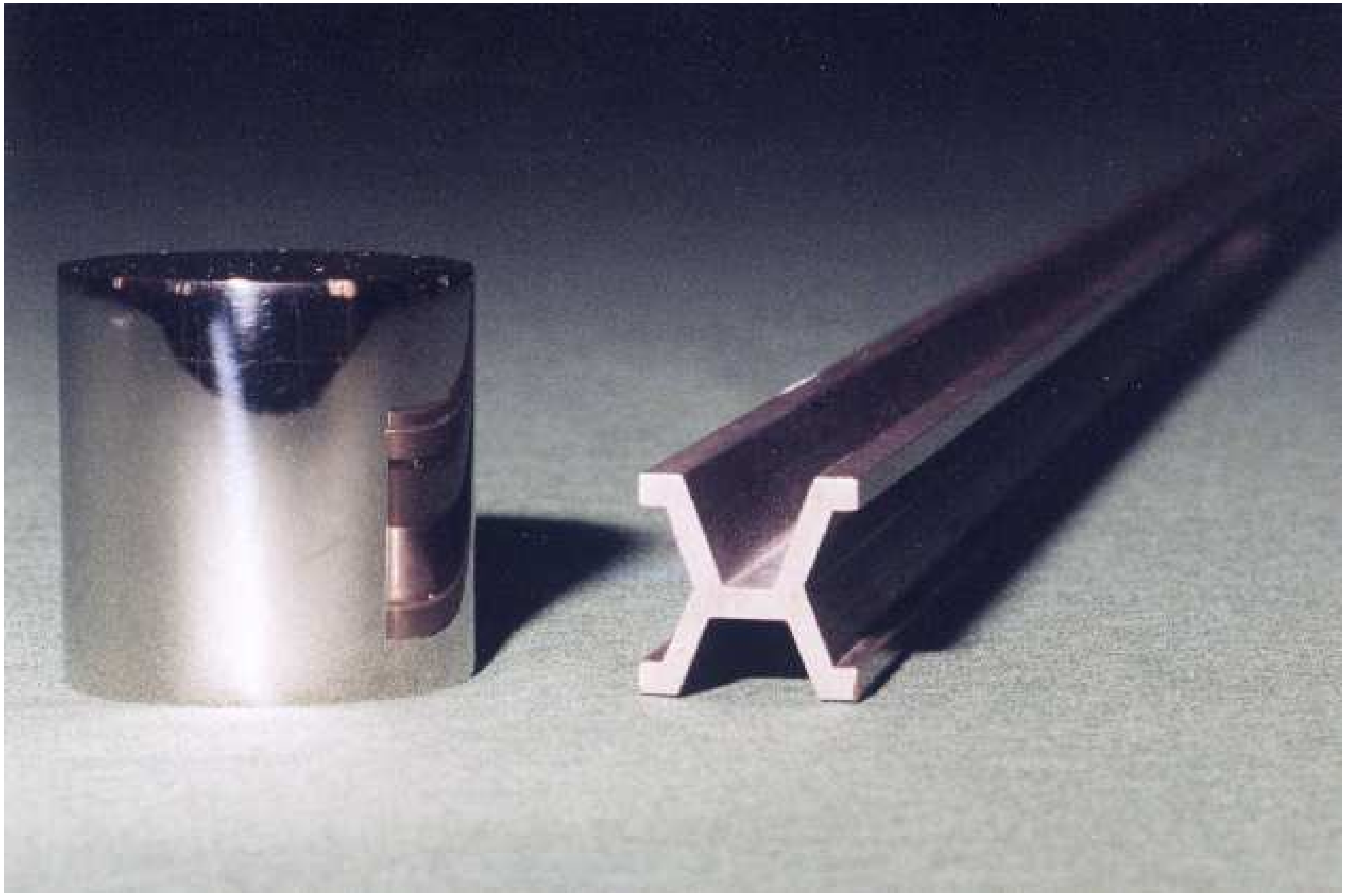
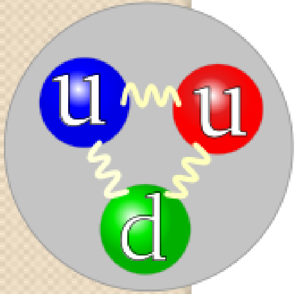
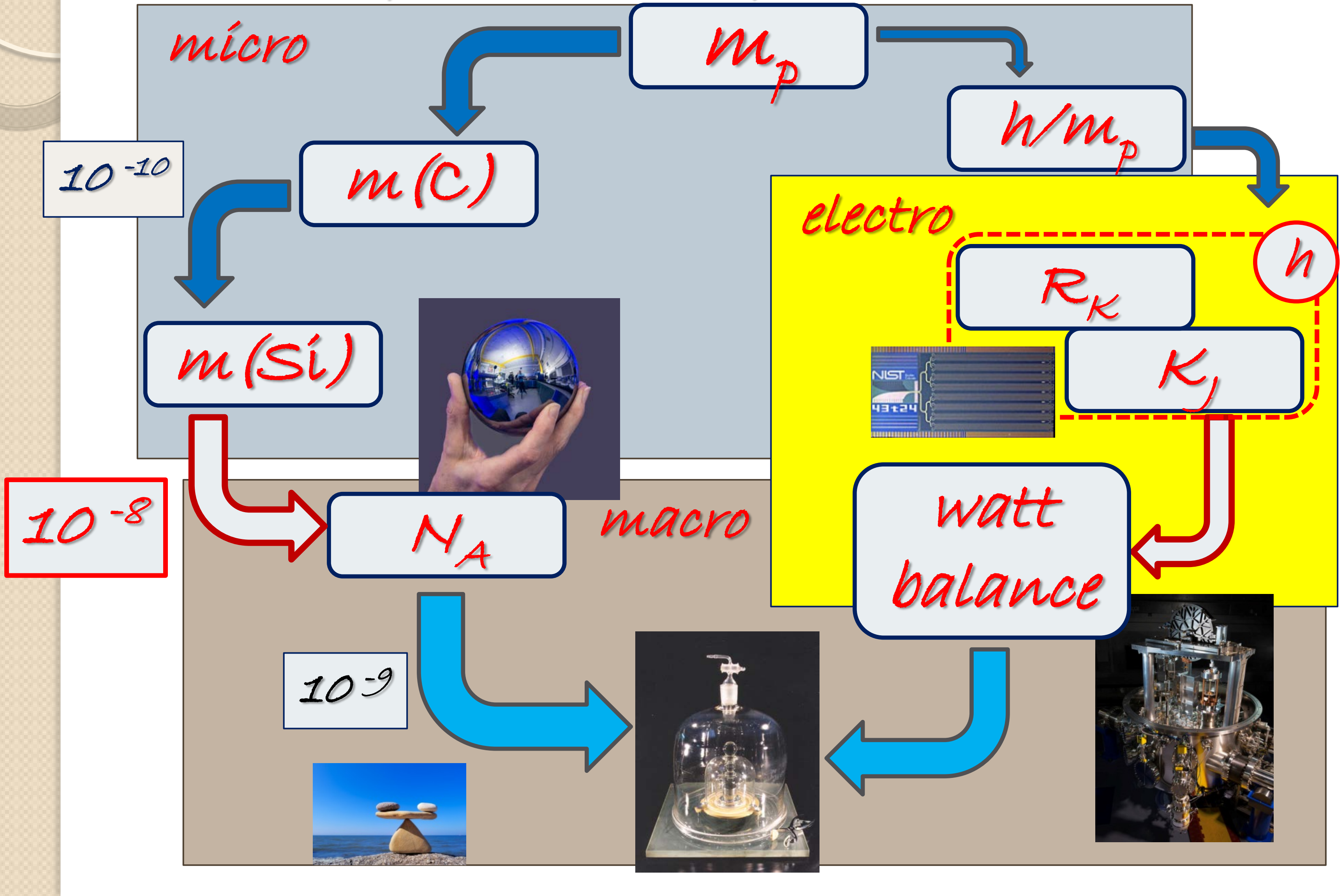
A proton vs. the kilogram (a yesterday's slide)





Proton mass and the kilogram:

microscopic, macroscopic and electrical



micro

m_p

h/m_p

$m(C)$

10^{-10}

$m(Si)$

10^{-8}

N_A

macro

electro

h

R_K

K_J

watt balance

10^{-9}

Macroscopic quantum phenomena and quantum electrical standards

ac Josephson effect

- volt standard in the terms of the Josephson constant

$K_J = 2e/h$

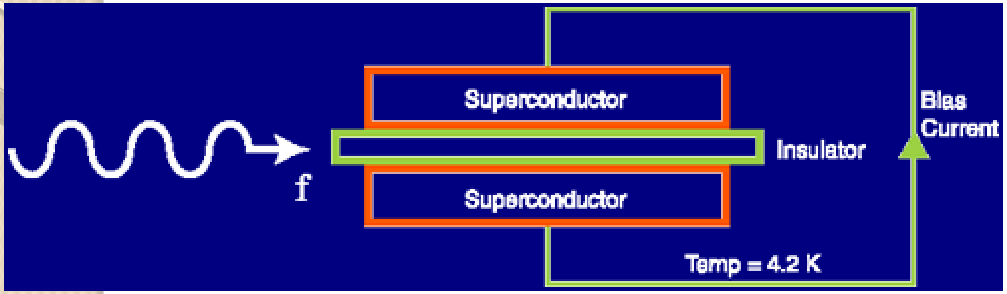
quantum Hall effect

- ohm standard in the terms of the von Klitzing constant

$R_K = h/e^2$

- The measures of those kinds are sufficient for the maintainance.
- As for the reproduction, we had to determine the values of two fundamental constants: K_J and R_K.
- These constants are fundamental and might be determined through various phenomena.

ac Josephson effect and quantum volt standard



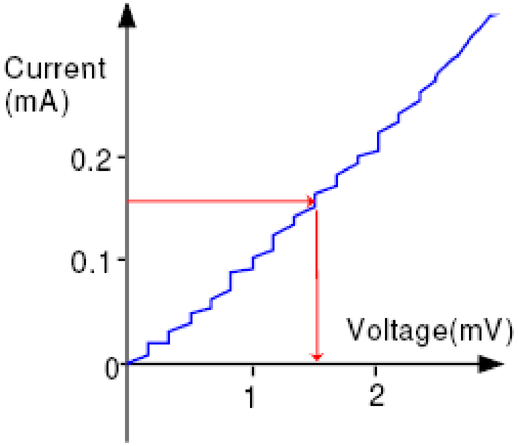
Irradiation with microwave:

- Cooper pairs synchronize with radiation
- Voltage steps appear

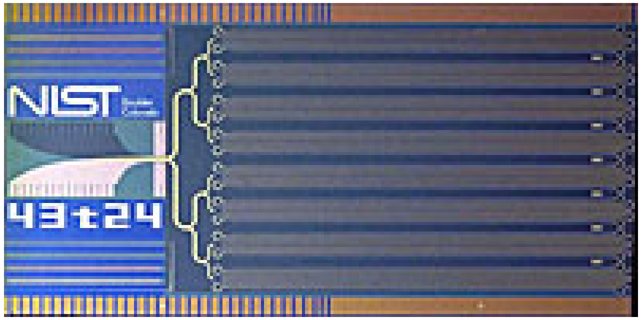
$$\boxed{V_n = n\frac{h}{2e}f}$$

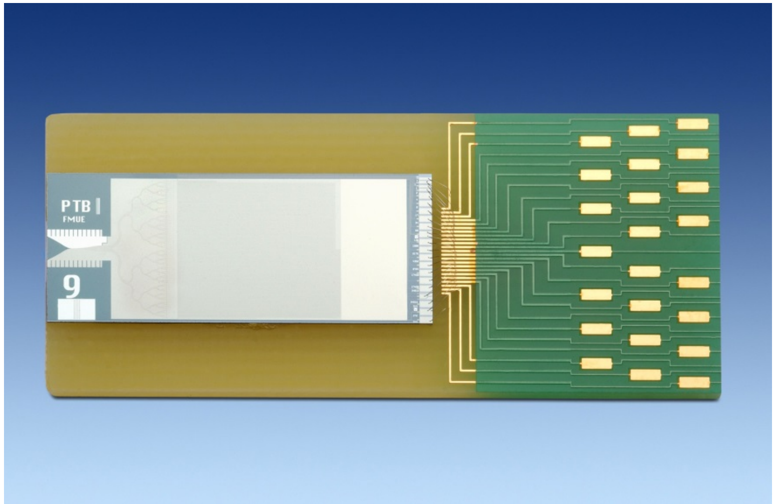
Shapiro step, 1963

V_1 ~ 145 µV @ 70 GHz

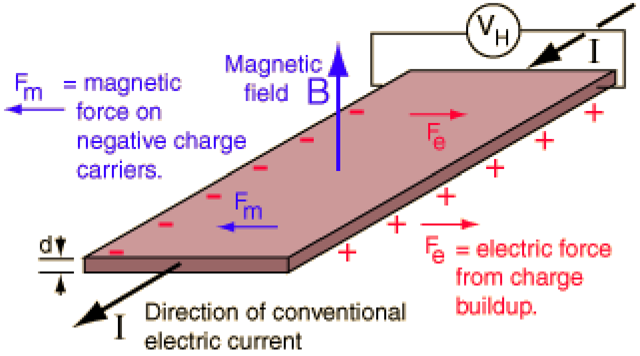


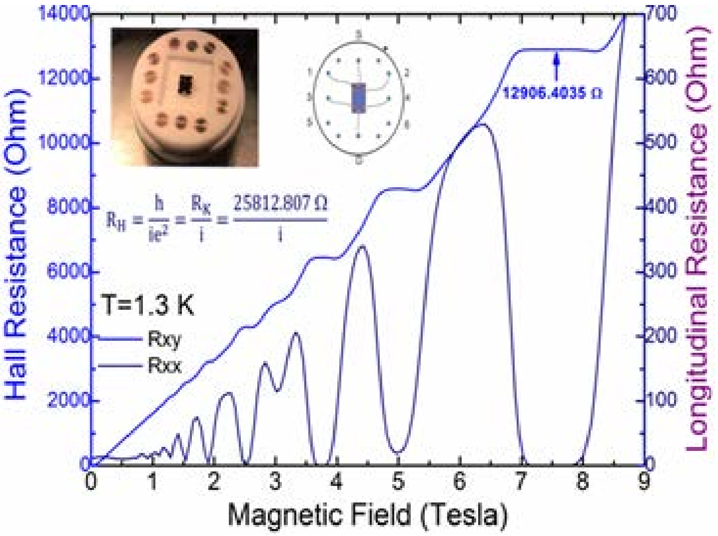
$$K_J = \frac{2e}{h}$$





Quantum Hall Effect and quantum ohm standard





Steps:

$$R_n = R_K/n$$

Atomic masses in frequency units: measuring m/h

- A back door for h
- Recoil spectroscopy
  - caesium (Berkley)
  - rubidium (LKB)
- Needs now lengthy theoretical expressions
- Energy conservation
- Recoil

$\sim f^2/(Mc^2/h)$

- Rydberg constant and α

$$\begin{aligned} R_\infty &= \frac{e^4 m_e}{8\epsilon_0^2 h^3 c} \\ &= \frac{c}{2}\,\boxed{\alpha^2}\,\boxed{\frac{m_e}{h}} \end{aligned}$$

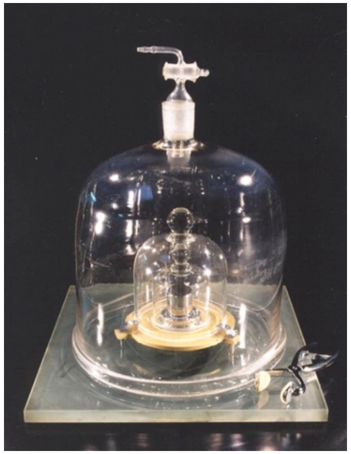
International system of units, SI

- 6 base physical units
  - second
  - metre

- 4 base physical units to change
  - kilogram
  - ampere
  - kelvin
  - mole

4 base physical units to change: yesterday's definition

- kilogram (mass of IPK)



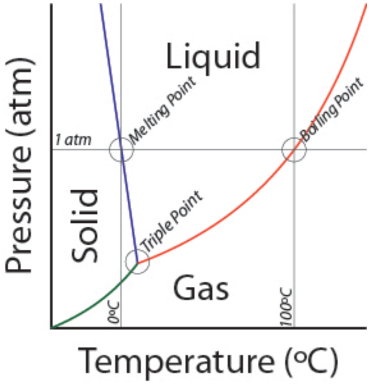
The physical mass of IPK may change, but not its value of 1 kg (exactly).

- ampere

$\mu_0 = 4\pi \times 10^{-7}$ N/A^2 (exactly)

- kelvin

$T_{triple} = 273.16$ K (exactly)

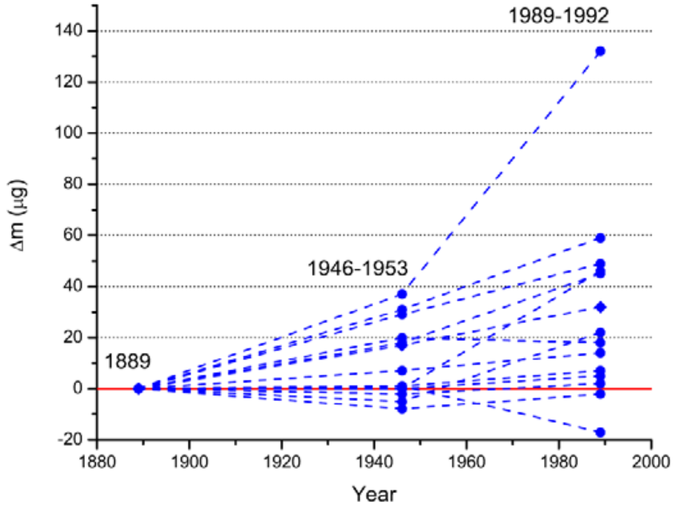


- mole

molar mass of carbon
$M(^{12}C) = 12$ g/mol
(exactly)

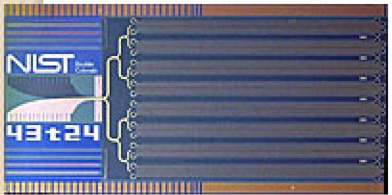
4 base physical units to change: what was wrong with them

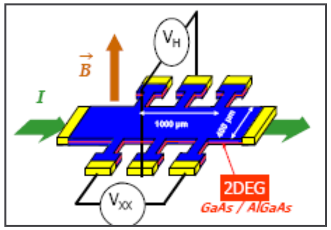
- kilogram



- ampere

hard to access ohm and volt





- kelvin
  - isotopic composition of water
  - used seldom (ITS-90 instead)
- mole
  - molar mass of a pure carbon is a fiction,
  - but that is not a problem

4 base physical units to change: today's definition

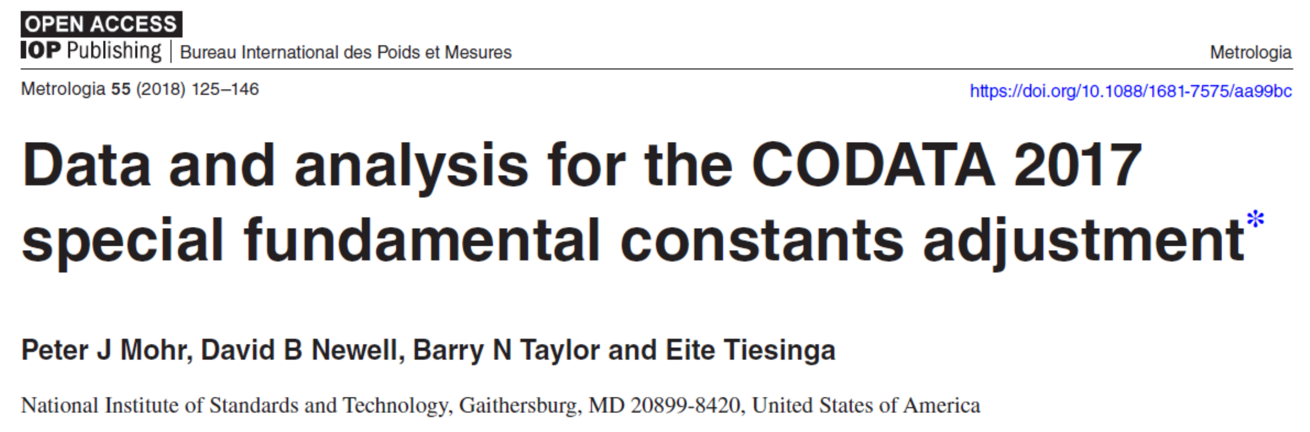
- kilogram
    - value of the Planck constant h
- ampere
    - value of the elementary charge e
- kelvin
    - value of the Boltzmann constant k
- mole
    - value of the Avogadro constant N_A

4 base physical units to change: today's definition

- kilogram
  - value of the Planck constant h
- ampere
  - value of the elementary charge e
- kelvin
  - value of the Boltzmann constant k
- mole
  - value of the Avogadro constant N_A

Continuity: the new values of the constants and the old ones should be consistent within their uncertainty. That would mean that the realized units, old and new, are consistent as well.

Special CODATA adjustment of fundamental constants 2017



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Data and analysis for the CODATA 2017 special fundamental constants adjustment*

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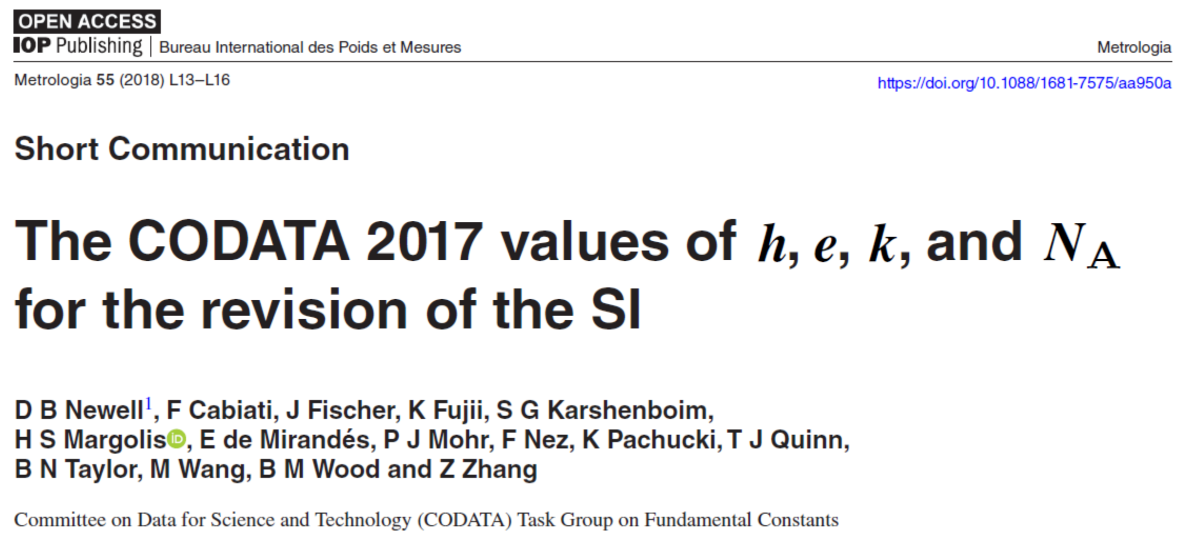

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Short Communication

The CODATA 2017 values of h, e, k, and N_A for the revision of the SI

**D B Newell[1], F Cabiati, J Fischer, K Fujii, S G Karshenboim,
H S Margolis, E de Mirandés, P J Mohr, F Nez, K Pachucki, T J Quinn,
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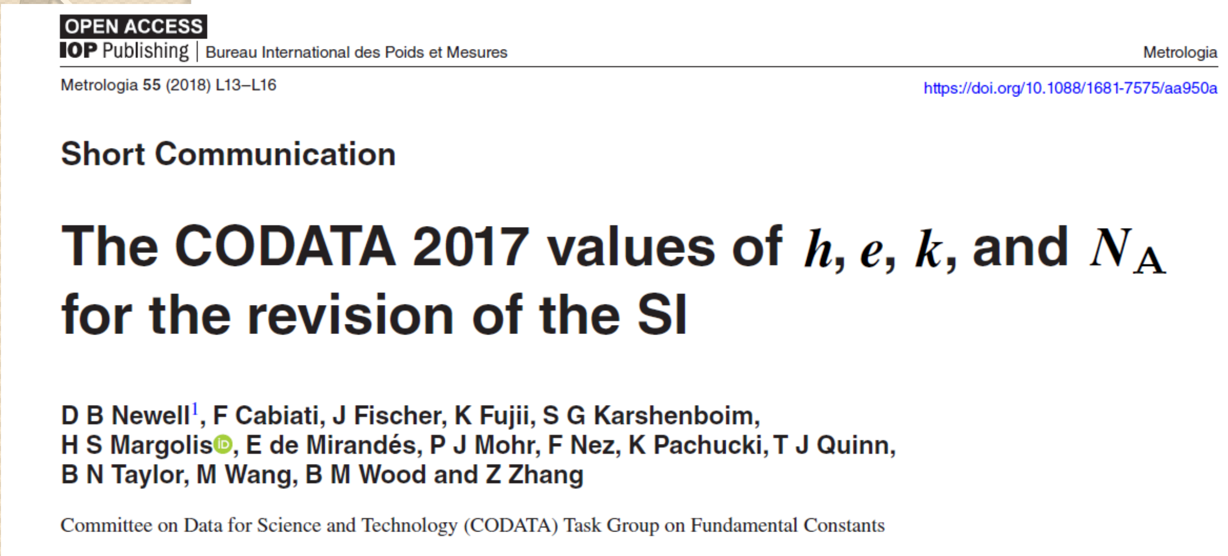
Committee on Data for Science and Technology (CODATA) Task Group on Fundamental Constants

Special CODATA adjustment of fundamental constants 2017



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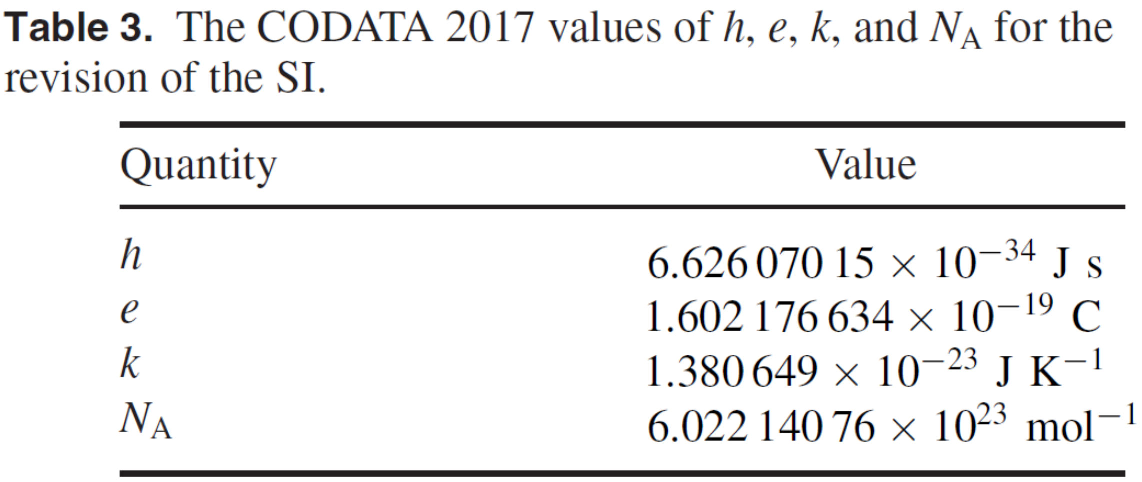
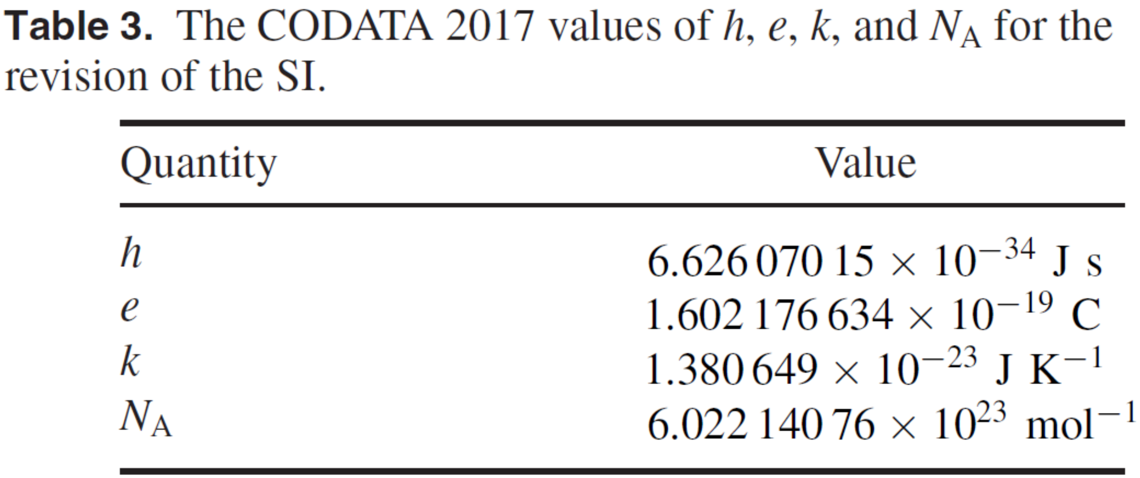


Table 3. The CODATA 2017 values of h, e, k, and N_A for the revision of the SI.

Quantity	Value
h	$6.626\,070\,15 \times 10^{-34}$ J s
e	$1.602\,176\,634 \times 10^{-19}$ C
k	$1.380\,649 \times 10^{-23}$ J K^{-1}
N_A	$6.022\,140\,76 \times 10^{23}$ mol^{-1}

The [really] last determination of h, e, k, and N_A (in yesterday's SI)



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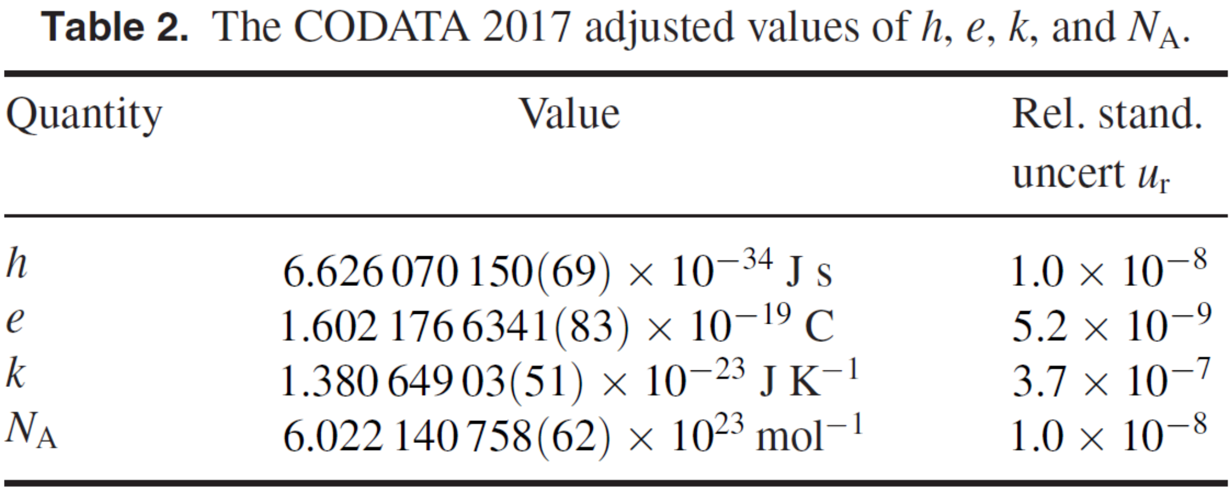


Table 2. The CODATA 2017 adjusted values of h, e, k, and N_A.

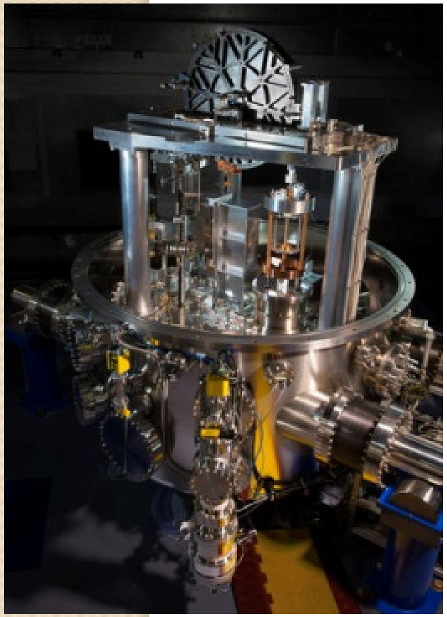
Quantity	Value	Rel. stand. uncert u_r
h	$6.626\,070\,150(69) \times 10^{-34}$ J s	1.0×10^{-8}
e	$1.602\,176\,6341(83) \times 10^{-19}$ C	5.2×10^{-9}
k	$1.380\,649\,03(51) \times 10^{-23}$ J K^{-1}	3.7×10^{-7}
N_A	$6.022\,140\,758(62) \times 10^{23}$ mol^{-1}	1.0×10^{-8}

4 base physical units to change: determination of h (in yesterday's kg)

Methods:

- Kibble watt balance
- enriched perfect silicon crystal

- Results



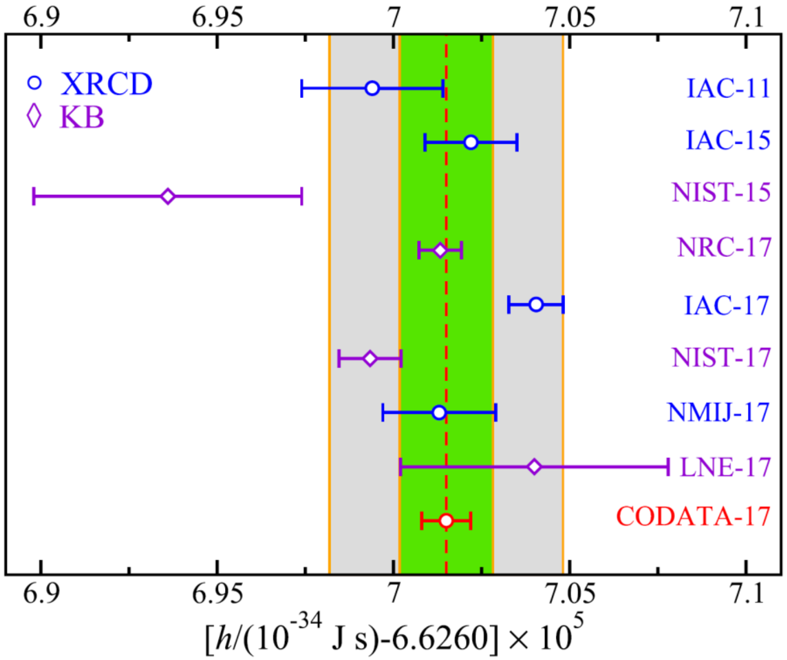


Figure 1. Values of the Planck constant h inferred from the input data in table 1 and the CODATA 2017 value in chronological order from top to bottom. The inner green band is ±20 parts in 10^9 and the outer grey band is ±50 parts in 10^9. KB: Kibble balance; XRCD: x-ray-crystal-density.

4 base physical units to change: determination of e (in yesterday's A)

- Relation between e and h
- Relation between α, ε_0, e, and h

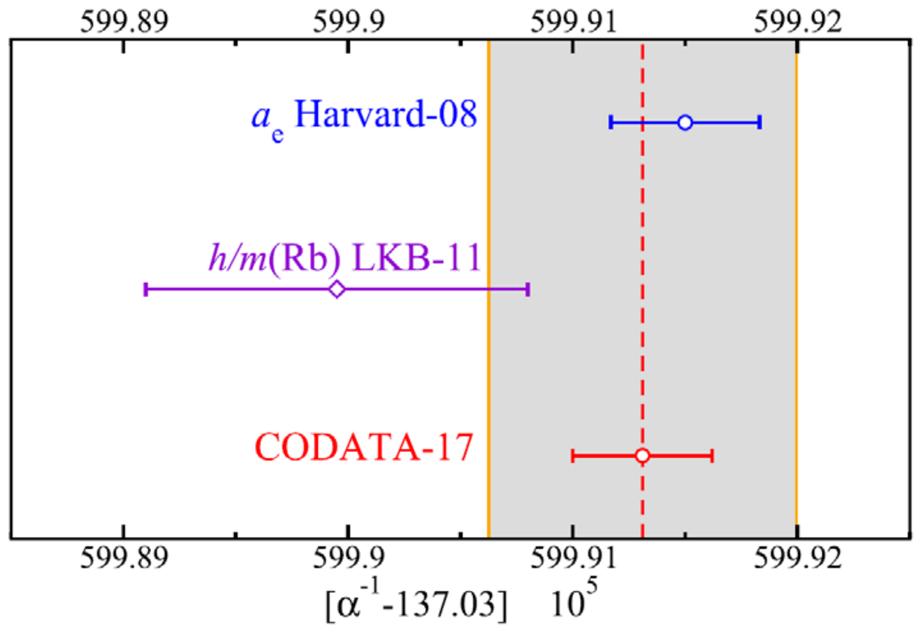


Figure 1. Comparison of input data *B*21 (HarvU-08) and *B*39 (LKB-11) through their inferred values of α (see table 9). Both *B*21 and *B*39 have the same value as in the 2010 and 2014 adjustments and are essentially the sole determinants of the recommended value of α in each. The grey band is ±5 parts in 10^{10}.

$$\begin{aligned}\alpha &= \frac{e^2}{4\pi\epsilon_0\hbar c}\\ &= \frac{1}{2\epsilon_0 c}\cdot e^2\cdot\frac{1}{h}\end{aligned}$$

4 base physical units to change: determination of k (in yesterday's K)

Methods

- Acoustic Gas Thermometry
- Dielectric Constant Gas Thermometry
- Johnson Noise Thermometry

- Results

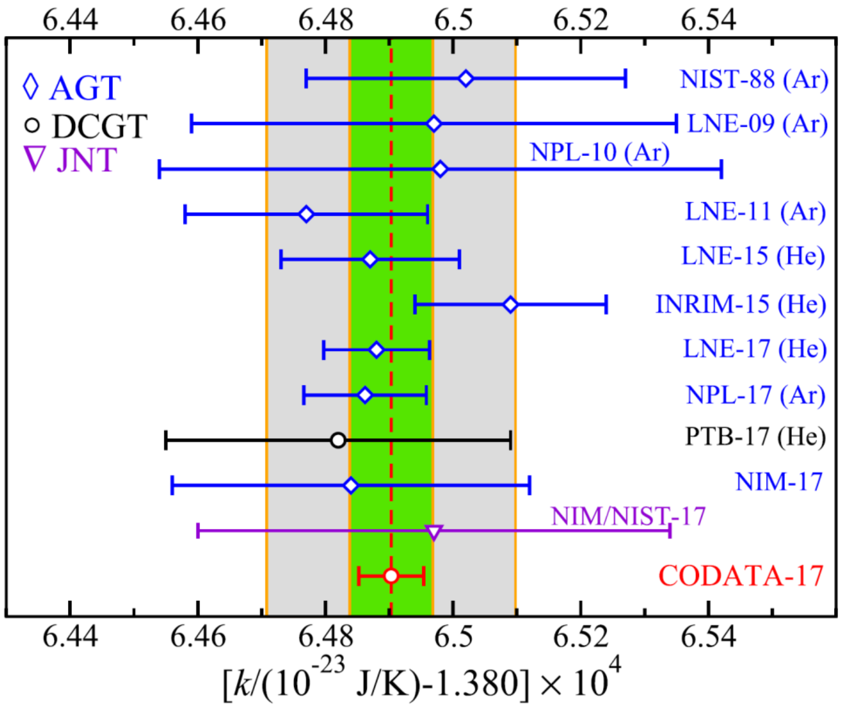
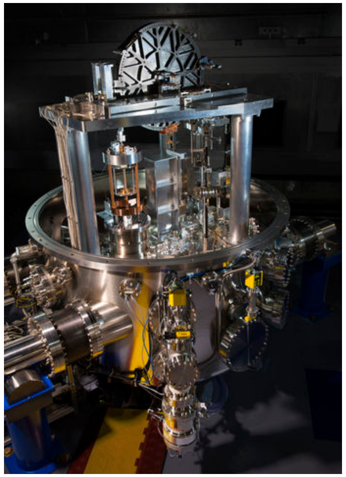


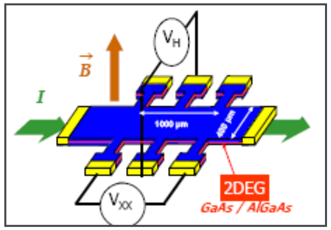
Figure 2. Values of the Boltzmann constant k inferred from the key input data in table 1 and the CODATA 2017 value in chronological order from top to bottom. The inner green band is ± 5 parts in 10^7 and the outer grey band is ± 15 parts in 10^7. AGT: acoustic gas thermometry; DCGT: dielectric constant gas thermometry; JNT: Johnson noise thermometry.

The kilogram and ampere: today's definitions & reproduction

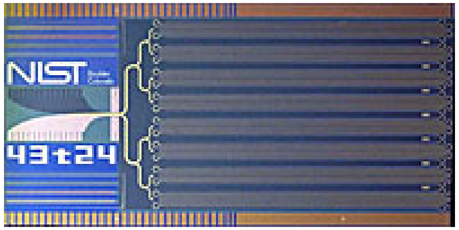
- The kilogram and ampere will be defined with adopted values of h and e.
- The realization of the kilogram will be based on Kibble watt balance or silicon crystal.



- The ohm is on the base of QHE and h/e^2.



- The volt is on base of ac JE and $2e/h$.



- The ampere is from the Ohm law.

Silicon crystal, atomic masses, and determination of h (in yesterday's kg)

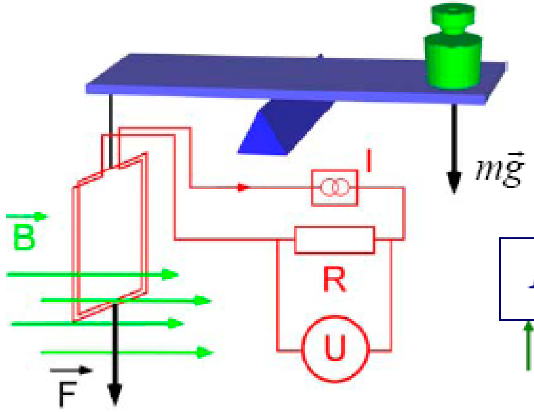
- Relation between h, α, R_∞, and the atomic masses [in atomic units and kilograms]

$$m(\mathrm{Si}) = A_r(\mathrm{Si})/A_r(e) \times m_e/h \times h$$

$$\begin{aligned} R_\infty &= \frac{e^4 m_e}{8\epsilon_0^2 h^3 c} \\ &= \frac{c}{2}\,\alpha^2\,\frac{m_e}{h} \end{aligned}$$

Kibble's watt balance and determination of h (in yesterday's kg)

WB Principle (1): static phase / weighing mode

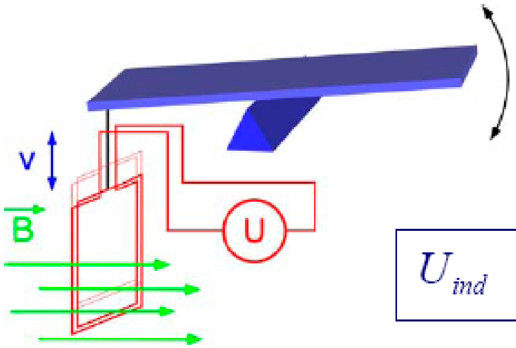


$$\boxed{I\cdot\int d\ell\times B = mg}$$

$$\uparrow$$

$$I = \frac{U_j}{R}$$ (QHE & JVS)

WB Principle (2): dynamic phase / velocity mode



$$\boxed{U_{ind} = v\cdot\int d\ell\times B}$$

WB Principle (3): combination of modes

$$G(B,\ell) = \underbrace{\frac{mg}{I}}_{\text{static}} \overset{\text{Only if } G_m = G_e}{\downarrow \atop =} \underbrace{\frac{U}{v}}_{\text{dynamic}} \Rightarrow \boxed{UI = m\,g\,v}$$

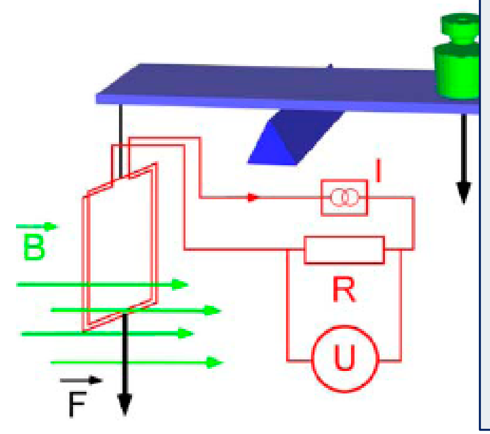
electrical power ↗ mechanical power ↖

B. Jeanneret, Les Houches, 2007

Kibble's watt balance and determination of h (in yesterday's kg)

The watt balance is a comparator for the force, energy or power. It compare the mechanical ones, linked to the kilogram, to the electric ones, linked to the maintained electrical units, whatever they are.

WB Principle (1): static phase



$I = \frac{U}{R}$ (QHE & JVS)

WB Principle (3): combination of modes

Only if $G_m = G_e$

$$G(B,\ell) = \underbrace{\frac{mg}{I}}_{\text{static}} = \underbrace{\frac{U}{v}}_{\text{dynamic}} \Rightarrow \boxed{UI = m\,g\,v}$$

electrical power

mechanical power

B. Jeanneret, Les Houches, 2007

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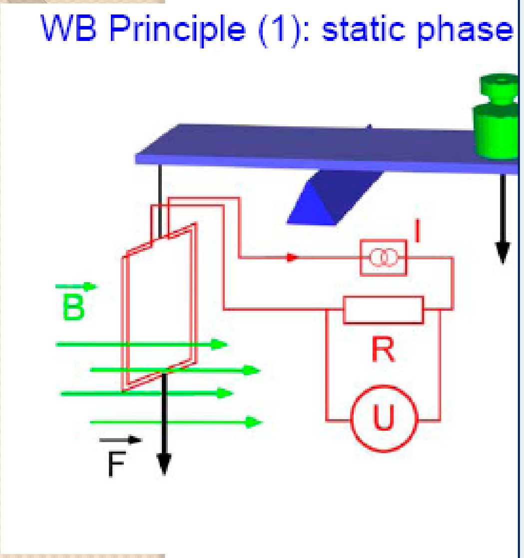

The watt balance is a comparator for the force, energy or power. It compare the mechanical ones, linked to the kilogram, to the electric ones, linked to the maintained electrical units, whatever they are.

If one uses ac JE and QHE, then …

WB Princ

$$G(B,\ell) = \underbrace{\frac{mg}{I}}_{\text{static}} = \underbrace{\frac{U}{v}}_{\text{dynamic}} \Rightarrow \boxed{UI = m\,g\,v}$$

electrical power

mechanical power

B. Jeanneret, Les Houches, 2007

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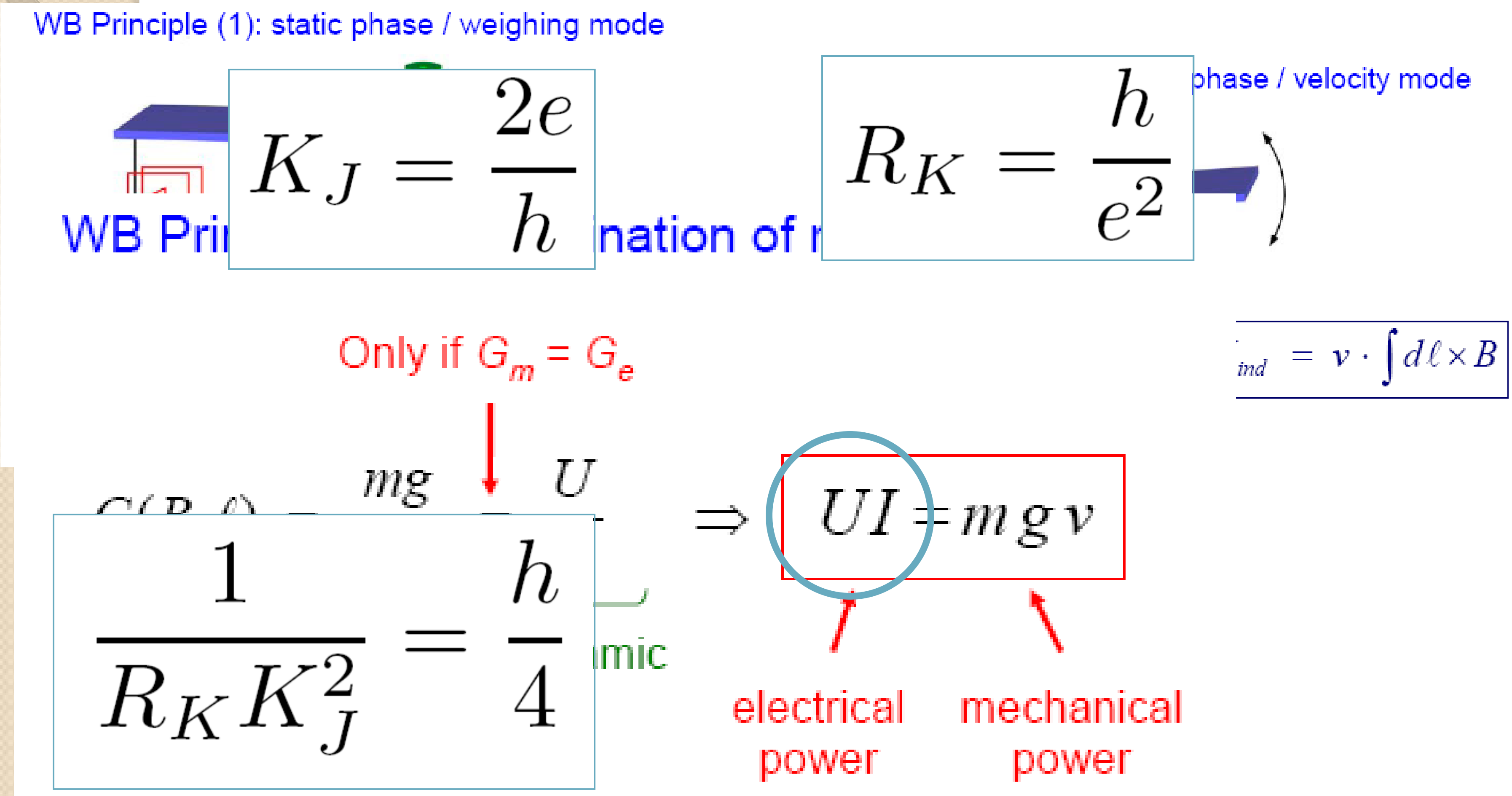

WB Principle (1): static phase / weighing mode

phase / velocity mode

WB Pri nation of r

$$K_J = \frac{2e}{h}$$

$$R_K = \frac{h}{e^2}$$

$$\mathcal{E}_{ind} = v \cdot \int d\ell \times B$$

Only if $G_m = G_e$

$$\frac{1}{R_K K_J^2} = \frac{h}{4}$$

$$\Rightarrow UI = m\,g\,v$$

electrical power

mechanical power

B. Jeanneret, Les Houches, 2007

The kilogram and ampere: today's definitions & reproduction

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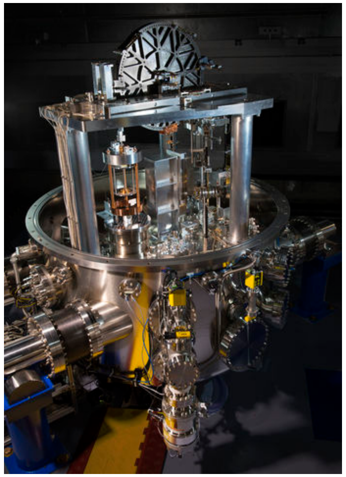
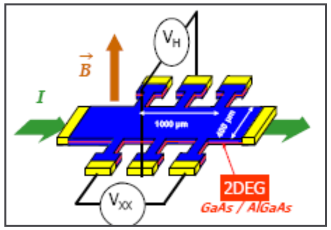
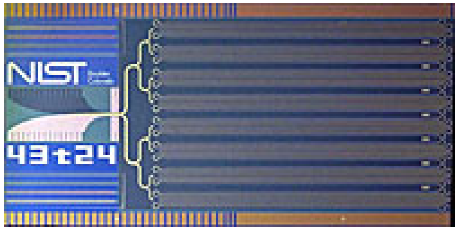
- The realization of the kilogram will be based on Kibble watt balance or silicon crystal.



- The ohm is on the base of QHE and h/e^2.



- The volt is on base of ac JE and $2e/h$.



- The ampere is from the Ohm law.

Determination of fundamental constants (in past & present)

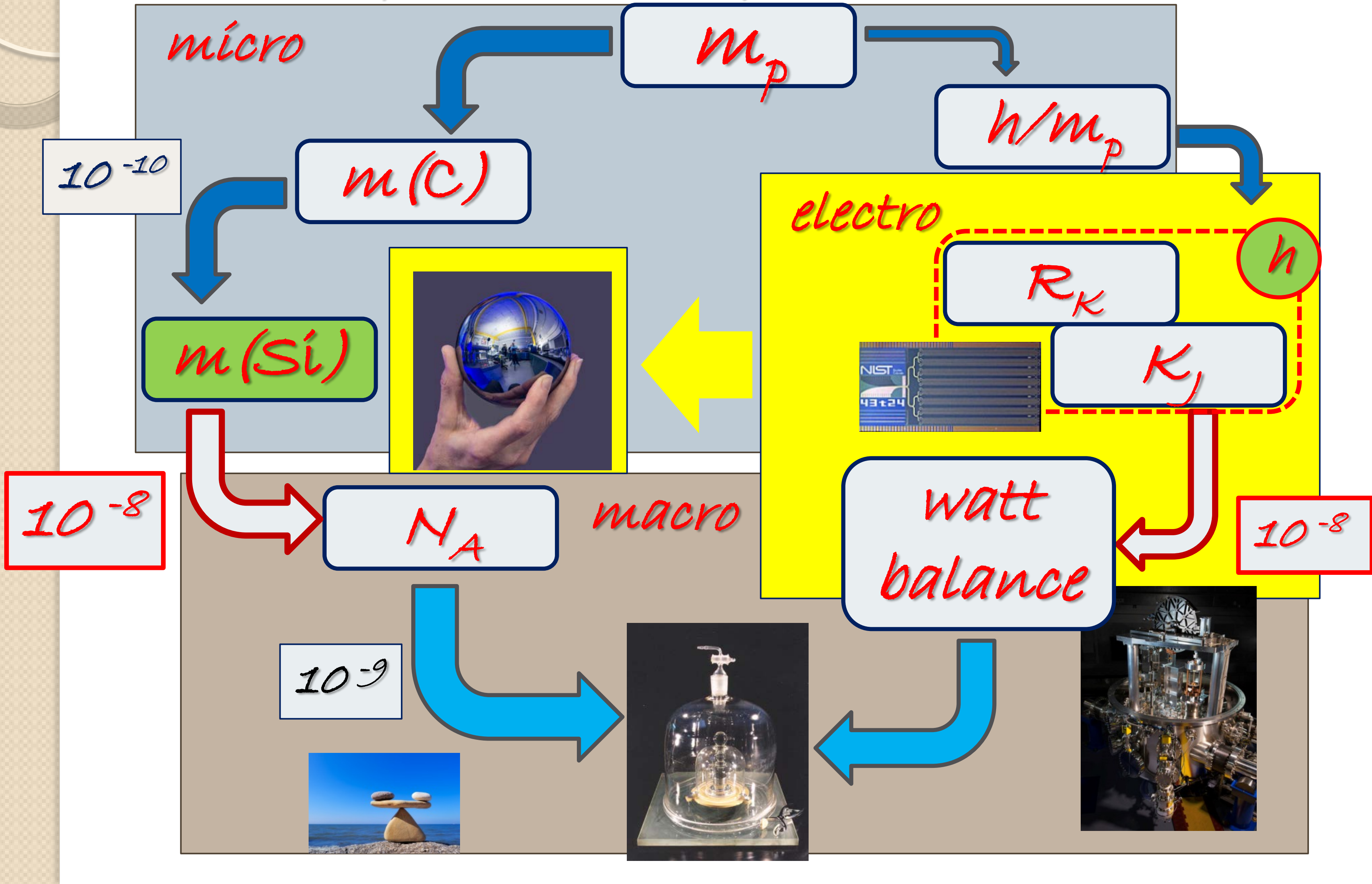
Yesterday:

- measurable
  - e
  - h
  - k
  - N_A
- exact
  - ε_0
  - $M(^{12}C)$
  - T_{triple}

Today:

- measurable
  - ε_0
  - $M(^{12}C)$
  - T_{triple}
- exact
  - e
  - h
  - k
  - N_A

Proton mass and the kilogram:
microscopic, macroscopic and electrical



micro

m_p

h/m_p

10^{-10}

$m(C)$

electro

h

R_K

K_J

$m(Si)$

10^{-8}

N_A

macro

watt balance

10^{-8}

10^{-9}

Does it matter: electron-Volt?

Photons

- energy expressed in eV
- while measured through frequency and wave length

The today's conversion factor from eV to Hz and m^{-1} is known exactly (cf. 5×10^{-9}).

Note:

- the former conversion factor was inaccurate and `time-dependent' because of progress in the field.
- `Old' results need corrections but for the last time.

Does it matter: electron-Volt?

Photons

- energy expressed in eV
- while measured through frequency and wave length

The today's conversion factor from eV to Hz and m^{-1} is known

Note:

- the former conversion factor was inaccurate and `time-dependent' because of progress in the field.
- `Old' results need corrections but for

$$hcR_\infty = 13.605\,693\,122\,994(26)\ \text{eV}\ [1.9 \times 10^{-12}]$$

Does it matter: electron-Volt?

Atomic and nuclear masses;

mass excesses (nuclear binding energy)

- The today's conversion factor from eV/c^2 to u is known with essentially higher accuracy than ever.

Note:

- the former conversion factor was inaccurate and `time-dependent'.
- `Old' results need corrections but afterwards the conversion will have accuracy ~ 5×10^{-10} (cf. 5×10^{-9}) .

Does it matter: electron-Volt?

Atomic and nuclear masses;

mass excesses (nuclear binding energy)

- The today's conversion factor from eV/c^2 to u is known with

Note:

- the former conversion factor was inaccurate and `time-dependent'.
- `Old' results need corrections but afterwards the conversion will have

$m_e = 0.510\,998\,950\,00(15)$ MeV/c^2 [3.0 X 10^{-10}]

Do we need quantum electrodynamics for new SI?

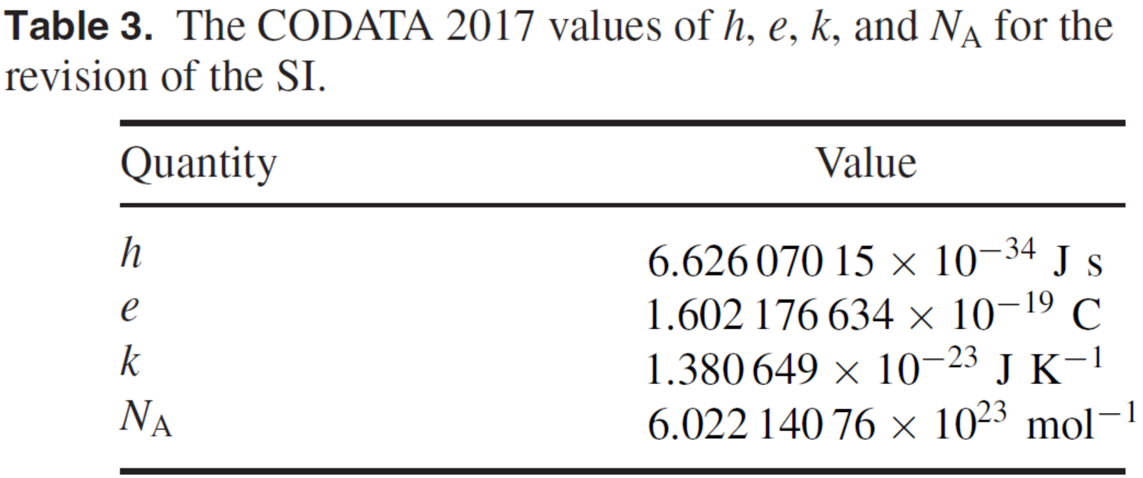


Table 3. The CODATA 2017 values of h, e, k, and N_A for the revision of the SI.

Quantity	Value
h	$6.626\,070\,15 \times 10^{-34}$ J s
e	$1.602\,176\,634 \times 10^{-19}$ C
k	$1.380\,649 \times 10^{-23}$ J K^{-1}
N_A	$6.022\,140\,76 \times 10^{23}$ mol^{-1}

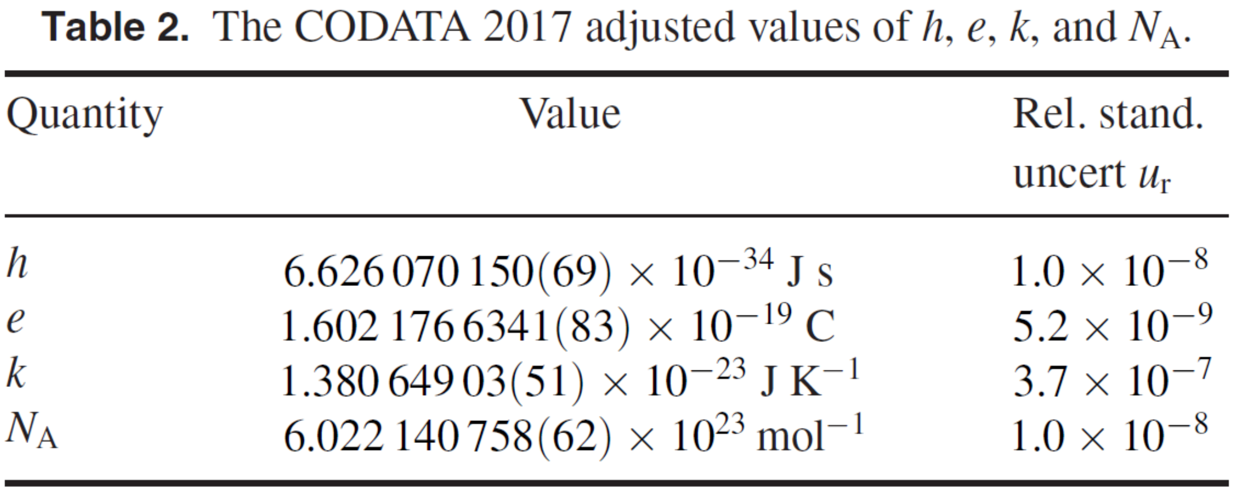
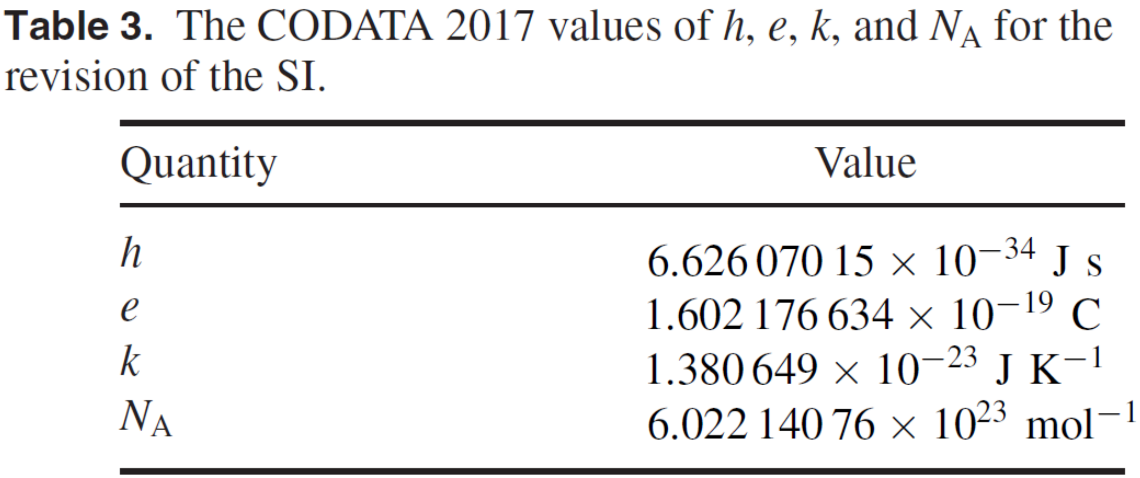


Table 2. The CODATA 2017 adjusted values of h, e, k, and N_A.

Quantity	Value	Rel. stand. uncert u_r
h	$6.626\,070\,150(69) \times 10^{-34}$ J s	1.0×10^{-8}
e	$1.602\,176\,6341(83) \times 10^{-19}$ C	5.2×10^{-9}
k	$1.380\,649\,03(51) \times 10^{-23}$ J K^{-1}	3.7×10^{-7}
N_A	$6.022\,140\,758(62) \times 10^{23}$ mol^{-1}	1.0×10^{-8}

Do we need quantum electrodynamics for new SI?



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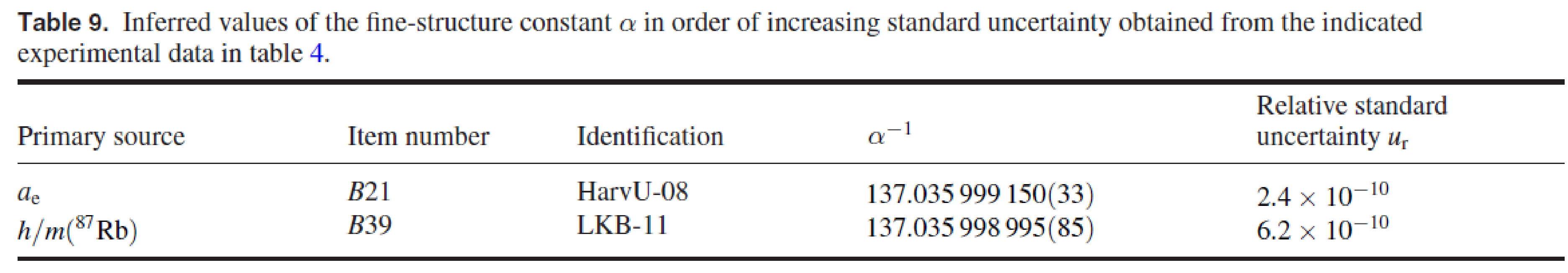
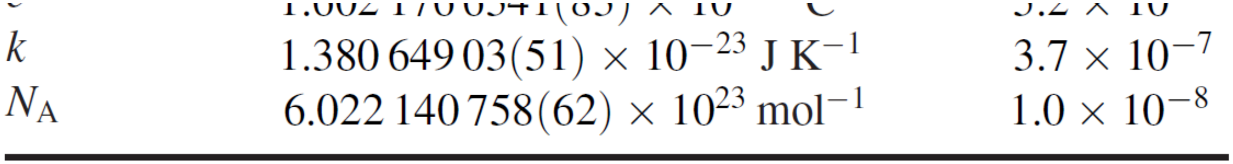


Table 9. Inferred values of the fine-structure constant α in order of increasing standard uncertainty obtained from the indicated experimental data in table 4.

Primary source	Item number	Identification	α^{-1}	Relative standard uncertainty u_r
a_e	*B*21	HarvU-08	137.035 999 150(33)	2.4×10^{-10}
$h/m(^{87}\text{Rb})$	*B*39	LKB-11	137.035 998 995(85)	6.2×10^{-10}



k	$1.380\,649\,03(51) \times 10^{-23}$ J K^{-1}	3.7×10^{-7}
N_A	$6.022\,140\,758(62) \times 10^{23}$ mol^{-1}	1.0×10^{-8}

Do we need quantum electrodynamics for new SI?

α obtained from QED is required for

- continuity of ohm, farad and ε_0;
- continuity of kg/A^2 and h/e^2;
- continuity of kg/mol and hN_A;
- continuity of kg/mol and molar masses;
- continuity of A^2/mol and e^2N_A

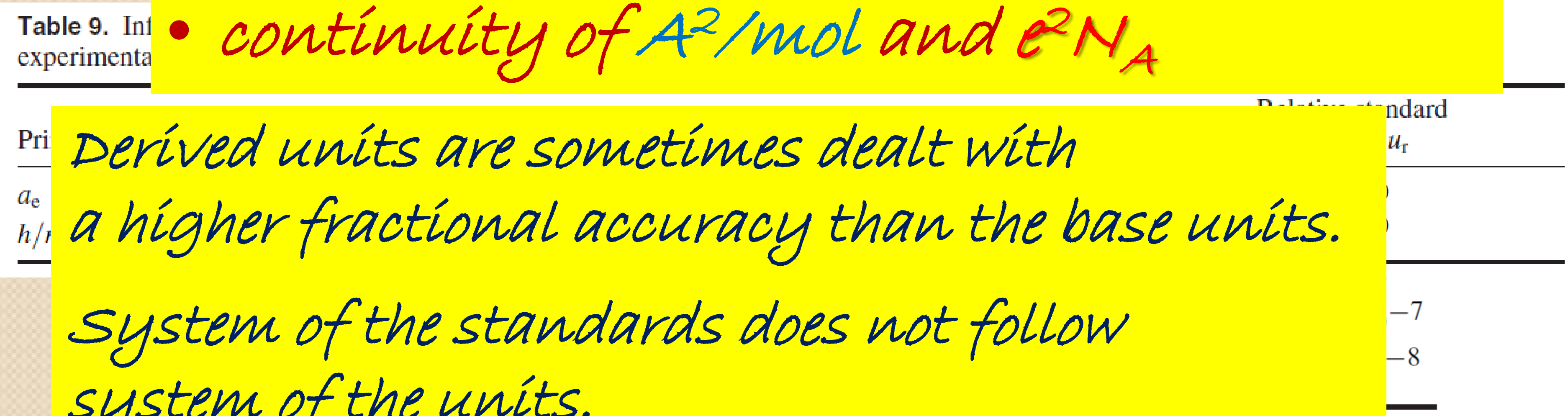


Table 9. Inf

experimenta

Pri

Relative standard

u_r

a_e

h/r

−7

−8

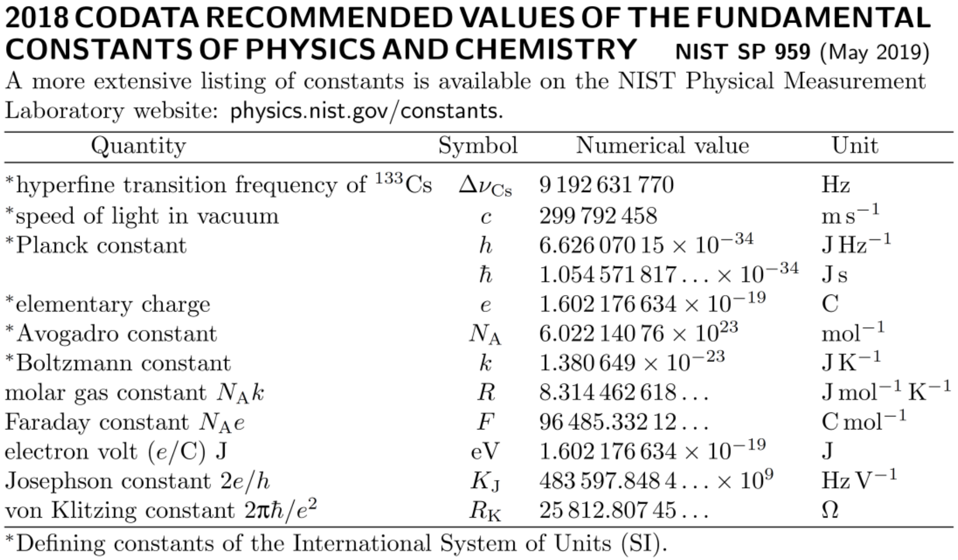
Derived units are sometimes dealt with a higher fractional accuracy than the base units.

System of the standards does not follow system of the units.


CHANGE AHEAD
EVERY THING is going to be OK

What's new?

The brand new CODATA's values in terms of brand new SI units have been available from the NIST web site.



2018 CODATA RECOMMENDED VALUES OF THE FUNDAMENTAL CONSTANTS OF PHYSICS AND CHEMISTRY **NIST SP 959** (May 2019)

A more extensive listing of constants is available on the NIST Physical Measurement Laboratory website: physics.nist.gov/constants.

Quantity	Symbol	Numerical value	Unit
*hyperfine transition frequency of ^{133}Cs	$\Delta\nu_{\mathrm{Cs}}$	$9\,192\,631\,770$	Hz
*speed of light in vacuum	c	$299\,792\,458$	$\mathrm{m\,s^{-1}}$
*Planck constant	h	$6.626\,070\,15 \times 10^{-34}$	$\mathrm{J\,Hz^{-1}}$
	$\hbar$	$1.054\,571\,817\ldots \times 10^{-34}$	$\mathrm{J\,s}$
*elementary charge	e	$1.602\,176\,634 \times 10^{-19}$	C
*Avogadro constant	N_{A}	$6.022\,140\,76 \times 10^{23}$	$\mathrm{mol^{-1}}$
*Boltzmann constant	k	$1.380\,649 \times 10^{-23}$	$\mathrm{J\,K^{-1}}$
molar gas constant $N_{\mathrm{A}}k$	R	$8.314\,462\,618\ldots$	$\mathrm{J\,mol^{-1}\,K^{-1}}$
Faraday constant $N_{\mathrm{A}}e$	F	$96\,485.332\,12\ldots$	$\mathrm{C\,mol^{-1}}$
electron volt (e/C) J	eV	$1.602\,176\,634 \times 10^{-19}$	J
Josephson constant $2e/h$	K_{J}	$483\,597.848\,4\ldots \times 10^{9}$	$\mathrm{Hz\,V^{-1}}$
von Klitzing constant $2\pi\hbar/e^2$	R_{K}	$25\,812.807\,45\ldots$	Ω

*Defining constants of the International System of Units (SI).

https://physics.nist.gov/cuu/Constants/index.html