Realization of the kilogram using ^{28}Si-enriched spheres at the National Metrology Institute of Japan, NMIJ

Naoki KURAMOTO, Yuya KANO, Yuichi OTA, Kazuaki FUJITA, Lulu ZHANG, Yasushi AZUMA, Sho OKUBO and Hajime INABA
National Metrology Institute of Japan (NMIJ)

- Redefinition of the kilogram in 2019
  - International Porotype of the Kilogram → Planck constant *h*
    → Realization of the kilogram using any physical phenomenon that links *h* to mass.
- Realization of the kilogram in order to establish the primary mass standard at NMIJ by the X-Ray Crystal Density (XRCD) method
  - Principle
  - 1 kg ^{28}Si-enriched spheres
  - International Avogadro Coordination (IAC)
- International comparison of kg realizations CCM.M-K8.2024

1 kg ^{28}Si-enriched spheres

Effect of the redefinition of the kilogram on the primary mass standards of National Metrology Institutes

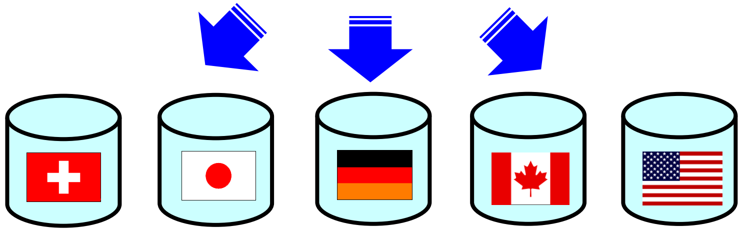
Before the redefinition (1889 - 2019)

International Prototype of the Kilogram

The kilogram was realized by this weight.

→ Its mass was exactly 1 kg.

BIPM (France, Sèvres)



METAS NMIJ PTB NRC NIST

- The masses of the primary mass standards of National Metrology Institutes (NMIs) were determined by mass comparison using an electronic balance at BIPM.

After the redefinition (2019 -)

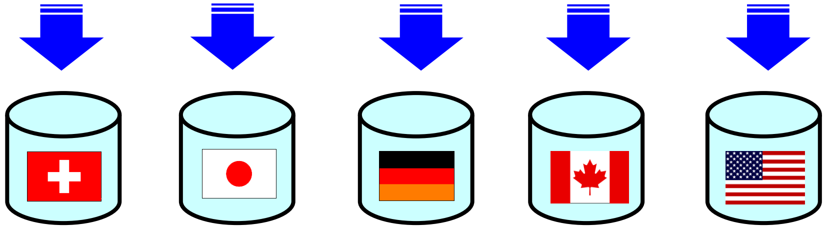
Planck constant *h*

We cannot touch or see this physical constant.

→ We have to produce mass standards from *h*.

- Realization of the kilogram

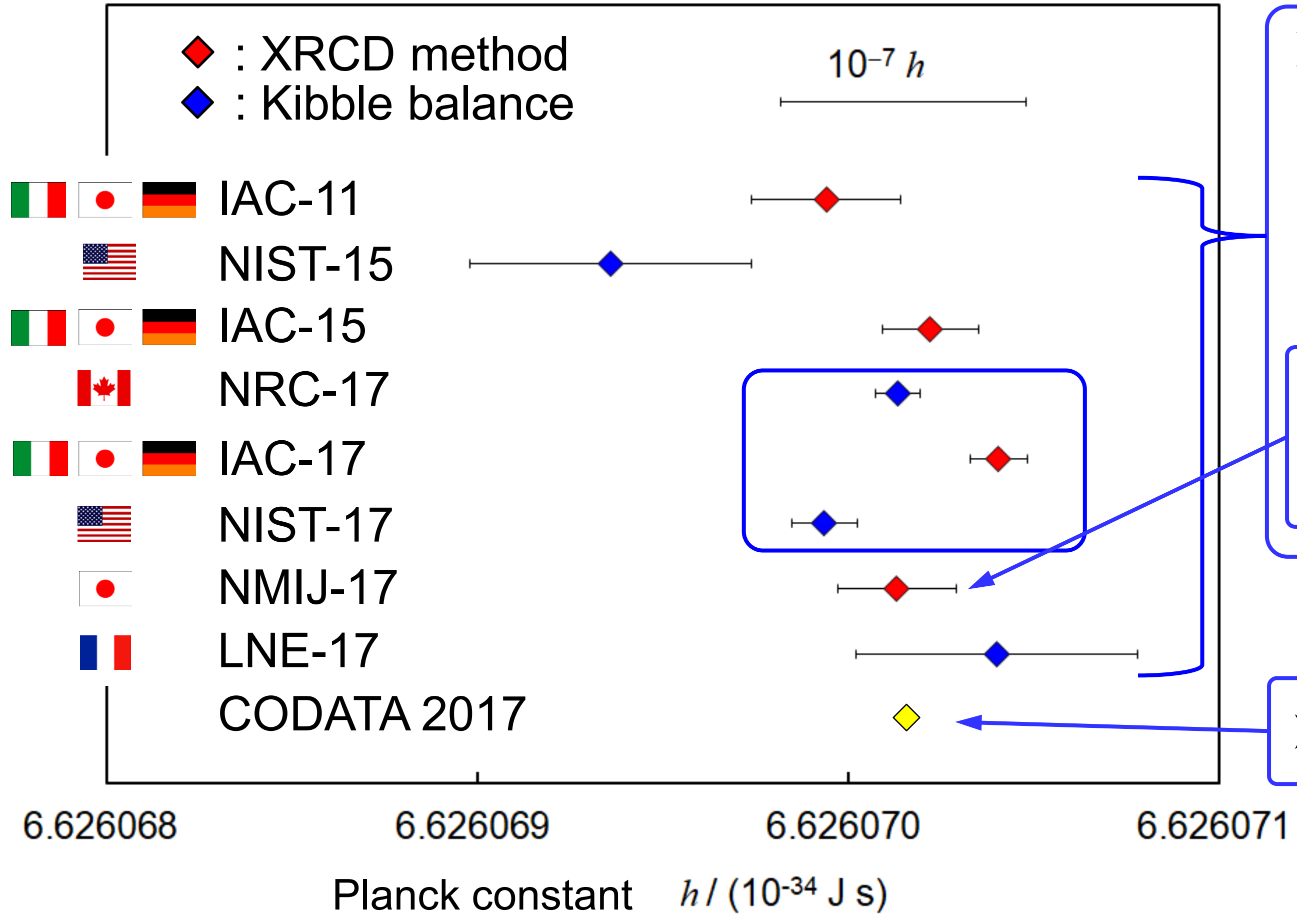
METAS NMIJ PTB NRC NIST



Individual realization

- In principle, NMIs can realize the kilogram individually by their own methods to set the primary mass standards.
  → Individual realization
- But this scheme has not been implemented yet.

Individual realization has not been implemented yet. Why?



- 8 values of the Planck constant measured by NMIs before the redefinition
  - Traceable to the primary mass standards of NMIs

NMIJ-17
- N. Kuramoto *et al.*, *etrologia*, **54**, 716 (2017)

- Planck constant in the present definition

- Some measured values of the Planck constant are inconsistent.
  → If NMIs realize the kilogram from the Planck constant individually under these conditions, their primary mass standards may not be consistent with each other.
  → International comparison to check the consistency of kg realizations

International comparison of the kg realizations, CCM.M-K8.2024

Step 1:

Participants individually realized the kilogram by their own methods.

→ Determination of the masses of their own 1 kg weights as transfer standards

Step 2:

BIPM measured the masses of the transfer standards with traceability to the International Prototype of the Kilogram.

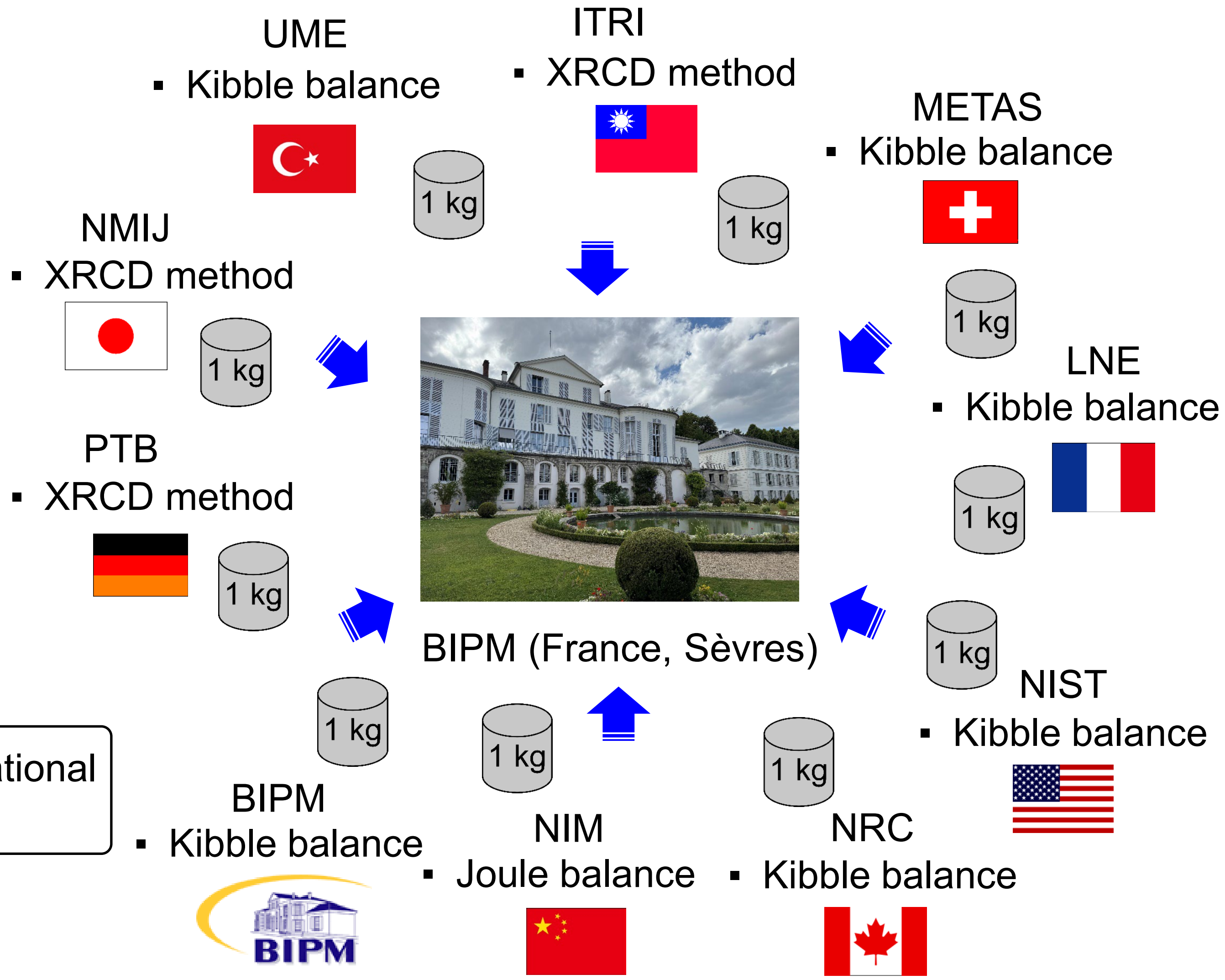
Step 3:

BIPM calculated Δm for each transfer standard.

Mass based on the individual realization by a participant	Δm ⇔	Mass based of the International Prototype of the Kilogram

Realization by NMIJ ⇔ Consistent ⇔ Realization by PTB

Δm_{NMIJ} ⇔ Consistent ⇔ Δm_{PTB}



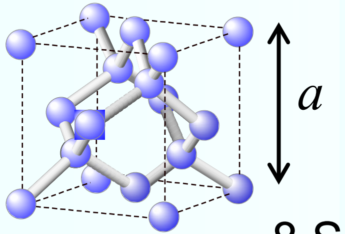
CCM.M-K8.2024

- 10 Participants

X-Ray Crystal Density method

Counting of Si atoms in a Si sphere

Si sphere



Unit cell

8 Si atoms

m_{sphere} : almost 1 kg

a : Lattice constant → Volume of unit cell, a^3

V_S : Volume of Si sphere

Number of unit cells in Si sphere

$$N = 8 \times \frac{V_S}{a^3}$$

Number of Si atoms in unit cell

N : Number of Si atoms in Si sphere

$$\frac{m(\text{Si})}{m(\text{e})} = \frac{A_r(\text{Si})}{A_r(\text{e})}$$

$m(\text{Si})$: Mass of a single Si atom

$m(\text{e})$: Mass of a single electron

$A_r(\text{Si})$: Relative atomic mass of Si

$A_r(\text{e})$: Relative atomic mass of electron

$$m(\text{e}) = 2hR_\infty / (c\alpha^2)$$

h : Planck constant

R_∞ : Rydberg constant

α : Fine-structure constant

c : Speed of light in vacuum

$$m_{\text{sphere}} = Nm(\text{Si}) = \frac{2hR_\infty}{c\alpha^2} \frac{A_r(\text{Si})}{A_r(\text{e})} \frac{8V_S}{a^3}$$

Electron mass | Mass ratio | Number of Si atoms

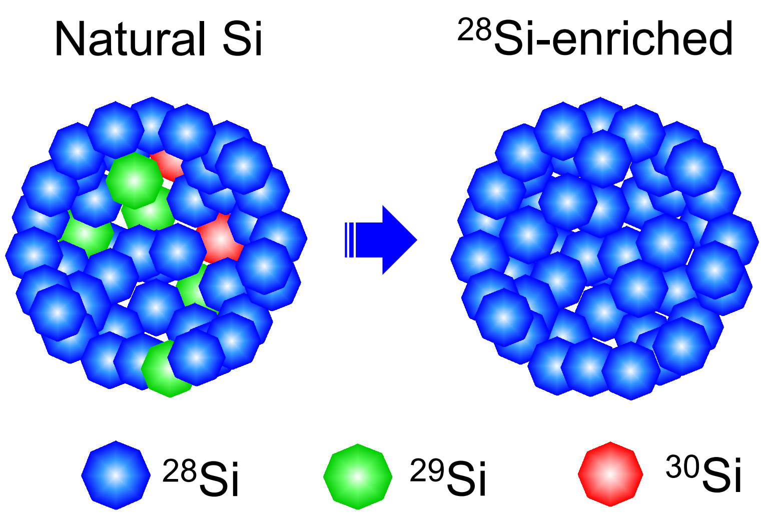
Mass comparison using a balance

Transfer standard

- 1 kg Platinum/Iridium weight

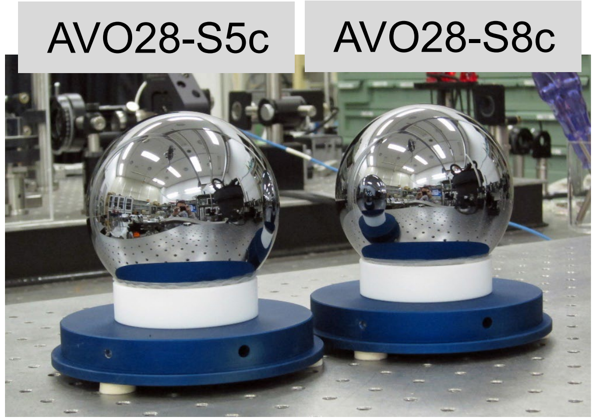
^{28}Si-enriched crystal

	Natural Si	^{28}Si-enriched
^{28}Si	92 %	99.9958 %
^{29}Si	5 %	0.0041 %
^{30}Si	3 %	0.0001 %
$u_r(A_r(\mathrm{Si}))$	1×10^{-7}	1×10^{-8}



- ^{28}Si, ^{29}Si, ^{30}Si → Mean relative atomic mass A_r(Si)
  - $A_r(\mathrm{Si}) = x_{28} A_r(^{28}\mathrm{Si}) + x_{29} A_r(^{29}\mathrm{Si}) + x_{30} A_r(^{30}\mathrm{Si})$
  - x_i : Isotopic abundance of ^{i}Si
- Target of the accuracy to establish primary mass standard : 10^{-8} order
- ^{28}Si-enriched crystal is essential for the realization to set the primary mass standard.
- AVO28 crystal
  - Prepared by International Avogadro Coordination (IAC)

AVO28



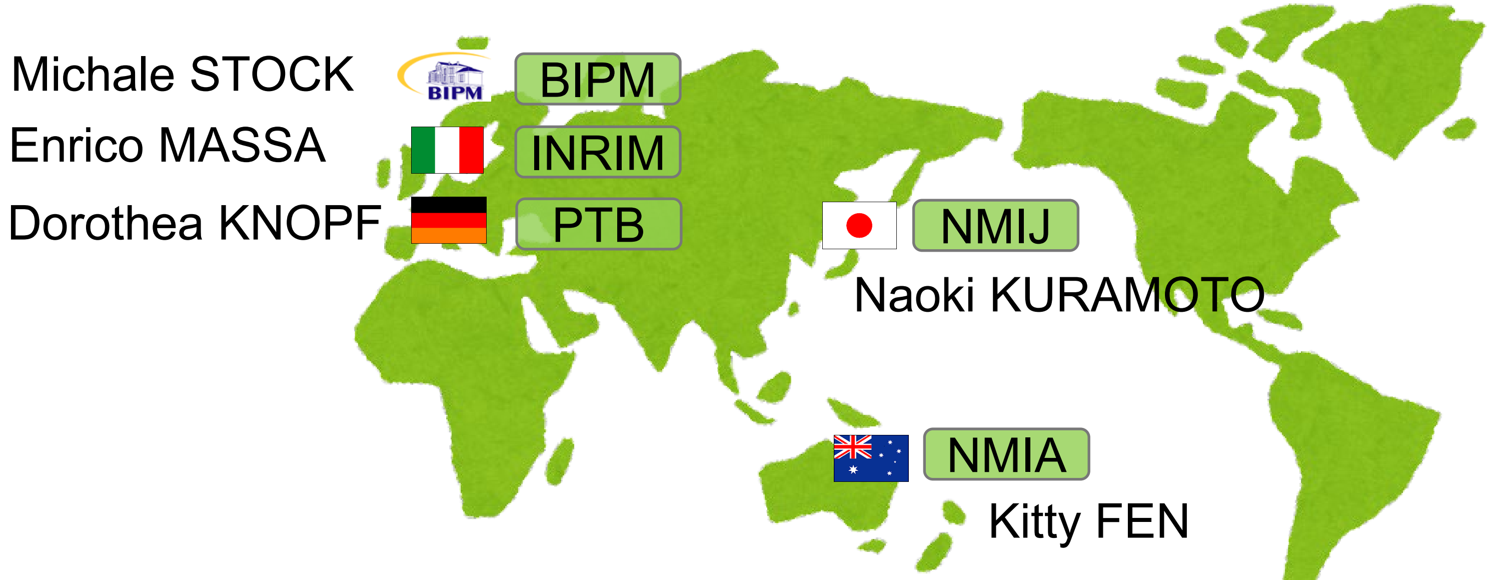
1 kg ^{28}Si-enriched spheres

International Avogadro Coordination (IAC)

- Start : 2004
- Members : BIPM, IMGC(IT), IRMM(EU), NML(AU), NMIJ(JP), NPL(UK), PTB(DE)
- Target : Accurate measurement of the Planck constant and the Avogadro constant for the redefinition of the kilogram
  → Preparation of ^{28}Si-enriched crystal (AVO28)

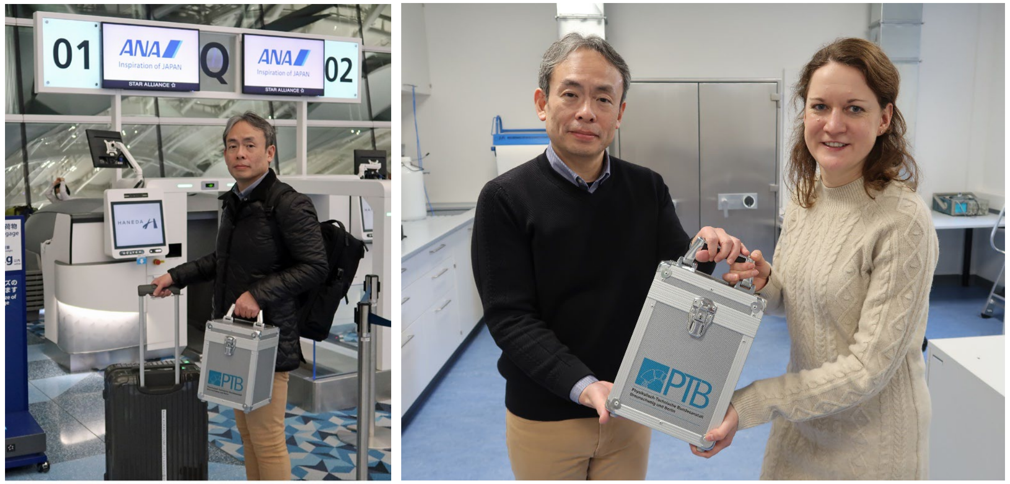
⬇

- Target from 2019 :
  - International cooperation for the realization of the kilogram using AVO28



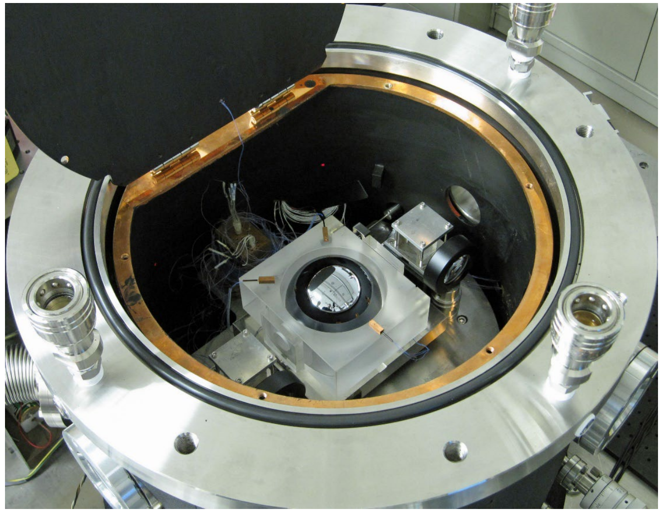
Present members and coordinators of IAC

Danila Eppers (PTB)



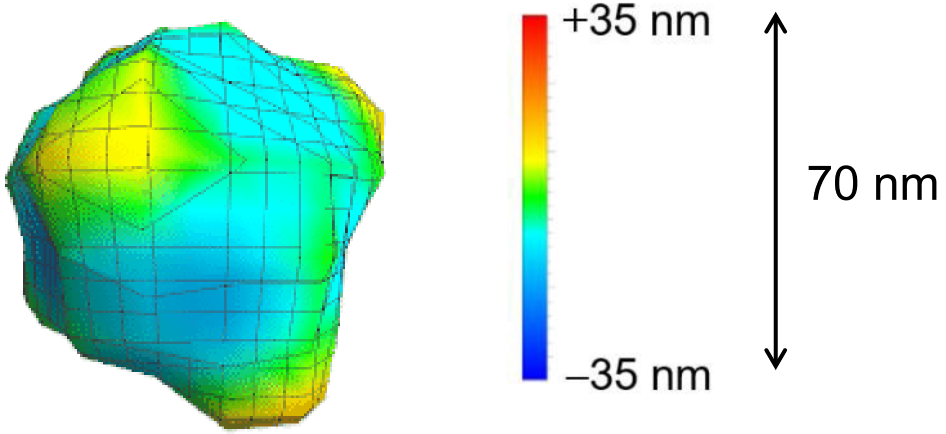
Transportation of a ^{28}Si-enriched sphere from NMIJ (Japan) to PTB (Germany) for research cooperation in 2023

Volume measurement by laser interferometry



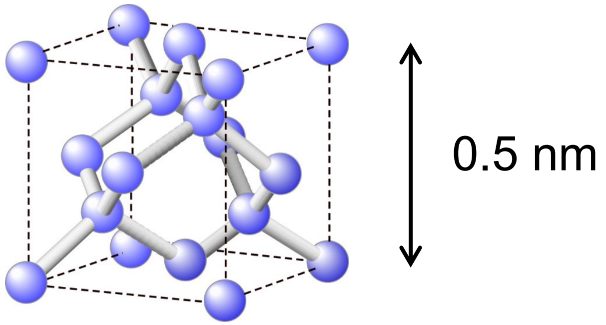
Laser interferometer for the volume measurement of 1 kg Si spheres developed at NMIJ

- Diameters in many different directions → Volume
- u(sphere diameter) = 0.6 nm
- N. Kuramoto *et al.*, *Metrologia*, **62**, 035001 (2025)



Topography of AVO28-S5c

+ Mass of surface layer, Mean relative atomic mass, Lattice constant,,,

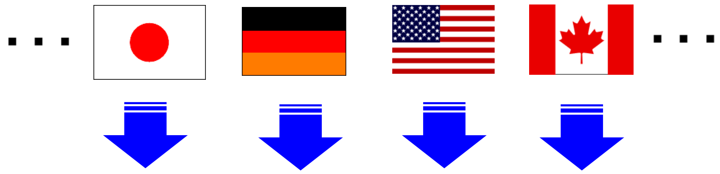


Unit cell of Si crystal

➢ $u_r(m_{sphere})$ = 2.1 × 10^{-8}, 21 μg for 1 kg

Results of CCM.M-K8.2024

Δ*m*



Mass based on the individual realization

⇕ Δ*m*

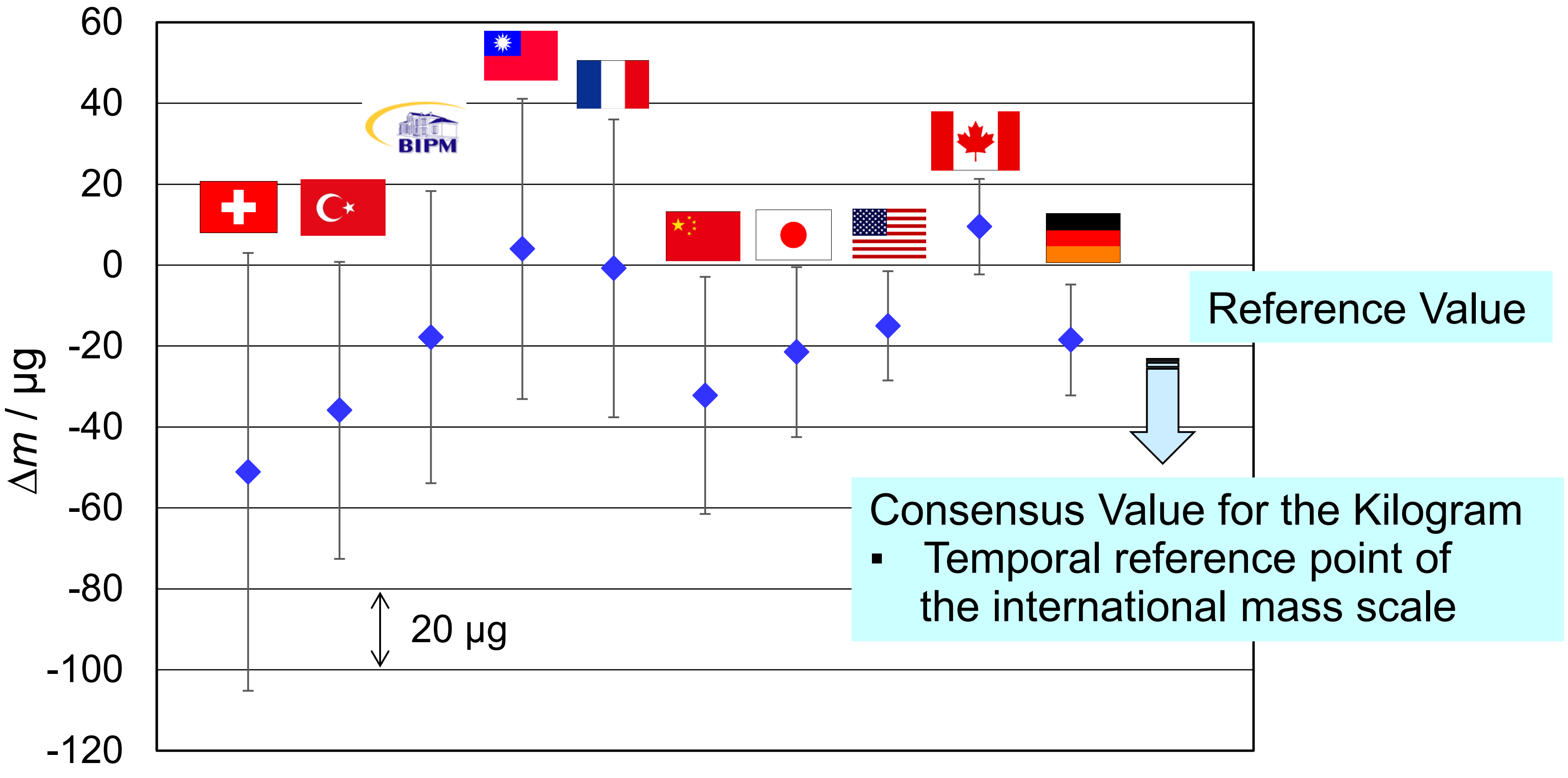
Mass based of the International Prototype of the Kilogram

Reference value

1 kg determined by all participants based on the new definition

⇕ Reference value

1 kg based on the previous definition



CCM.M-K8.2024

- The consistency among all data was confirmed statistically using chi-squared test for consistency using the 95 % cut-off criterion.
- After the next international comparison in 2027, we will consider the implementation of individual realization.

Present mass traceability using the Consensus Value

Planck constant

↑

Consensus Value of the Kilogram of 2026

- Implementation : March 1, 2026
- Value : 1 kg − 12 µg
- Standard uncertainty : 20 µg

↑

International Prototype of the Kilogram

- Mass : 1 kg − 12 µg

↑

…  …

Mass traceability using the Consensus Value

NMIJ

National Prototype of the Kilogram of Japan, No. 6

↑

Japan Calibration Service System (JCSS) calibration laboratory

- 一般財団法人 日本品質保証機構
- 株式会社 島津製作所
- 株式会社 村上衡器製作所
- メトラー･トレド 株式会社
- ザルトリウス･ジャパン 株式会社
- 一般社団法人 日本計量振興協会
- 有限会社 三協インターナショナル
- ⋮
- 株式会社 エー･アンド･デイ
- 大和製衡 株式会社
- 株式会社 田中衡機工業所
- 鎌長製衡 株式会社
- 株式会社 日本製衡所
- 日本電気計器検定所
- 日東イシダ株式会社
- ⋮

↑

User

Activities of the Mass Standards Group of NMIJ

- Mission of Mass Standards Group of NMIJ : Realization and dissemination of mass and density standards in Japan
- Presentations in the poster session
  - Yuya KANO et al., High-precision mass measurement of 1 kg weights using a vacuum mass comparator system at NMIJ/AIST
  - Yohei KAYUKAWA, Reduction of calibration mass uncertainty by subdivision using silicon weights
  - Yuichi OTA et al., Development of an automated mass comparator for sub-milligram weights and evaluation of automatic sub-multiple mass calibration for the weights at NMIJ
  - Kazuaki FUJITA et al., An experimental investigation on repeatability of small mass measurements in an electrostatic force balance
  - Kanako NISHIHASHI et al., Development of high-precision solid density measurement apparatus by hydrostatic weighing at NMIJ
  - Akane SATO et al., A metrological framework for ensuring reliable weight calibration at NMIJ/AIST

Please come and check out our posters!
Thanks for your attention.