CODATA TGFC 2019 Meeting

9:30 a.m. Monday, 7 October 2019

BIPM

Agenda items

1. Opening of the meeting and introductions

2. Review of the agenda
   Document TGFC/19-01 in meeting ‘2019_Oct’

3. Review of 2018 TGFC meeting minutes
   Document TGFC/18-03 in meeting ‘2018_July (Paris)’

4. 2018 Least squares adjustment – 1st in Revised SI NIST

- The SI base units s, m, kg, C, K, and mol are now exact in terms of $\Delta\nu_{Cs}$, c, h, e, k, and N_A.

- This implies that μ_0 and ε_0 are no longer exact. In fact,

$$\mu_0 = \frac{4\pi\alpha\hbar}{e^2 c}$$

$\mu_0 = 4\pi\ 10^{-7}$ x 1.000 000 000 55(15)

- Molar masses of particles are now

For particle *p* the molar mass is $N_A\, A_r(p)\frac{m_e}{A_r(e)}$ kg/mol rather than $10^{-3}A_r(p)$ kg/mol

- Many named constants are now exact

Josephson and von Klitzing constants, molar gas constant, Stefan-Boltzmann constant

4. 2018 Least squares adjustment – 1st in Revised SI

- Change in adjusted variables:
  - Planck and molar gas constants h and R no longer used
  - Introduced muonic-Deuterium and muonic-Hydrogen Lamb shift variables

- Many constant exact:

Electromagnetic

- speed of light in vacuum, c
- Planck constant, h
- elementary charge, e
- magnetic flux quantum, Φ_0
- conductance quantum, G_0
- Josephson constant, K_J
- von Klitzing constant, R_K

Physicochemical

- Avogadro constant, N_A
- Boltzmann constant, k
- molar Planck constant, $N_\mathrm{A}h$
- molar gas constant, R
- Faraday constant, F
- molar volume of ideal gas, V_m
- Loschmidt constant, n_0
- Stefan-Boltzmann constant, σ
- radiation constants, $c_{1\mathrm{L}}$, c_1, c_1
- Wien displacement law constants b, b'

4. a. Gravitational constant

- Two 2018 results from Huazhong University of Science and Technology (HUST)

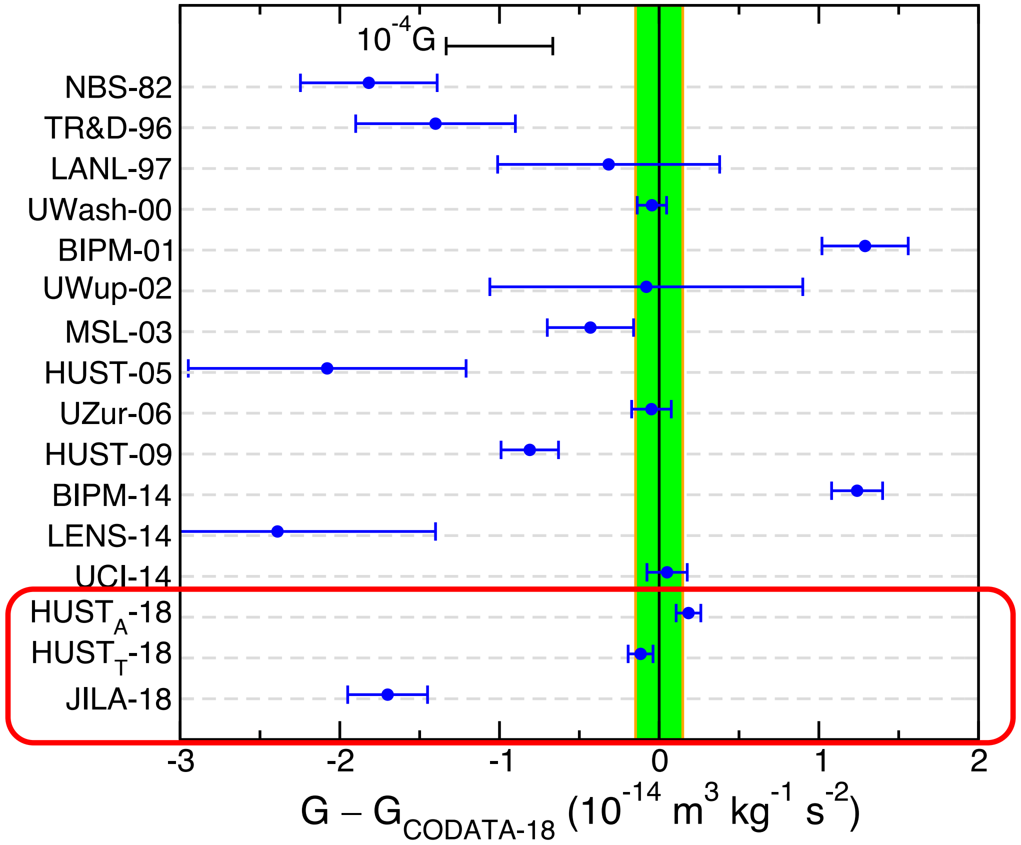
  Q. Li *et al.*, Nature **560**, 582 (2018).

- Reanalysis of the 2010 JILA value.

  slight shift and doubled uncertainty

- The new G value has 2.2 x 10^{-5} relative uncertainty.

- With an expansion factor of 3.9

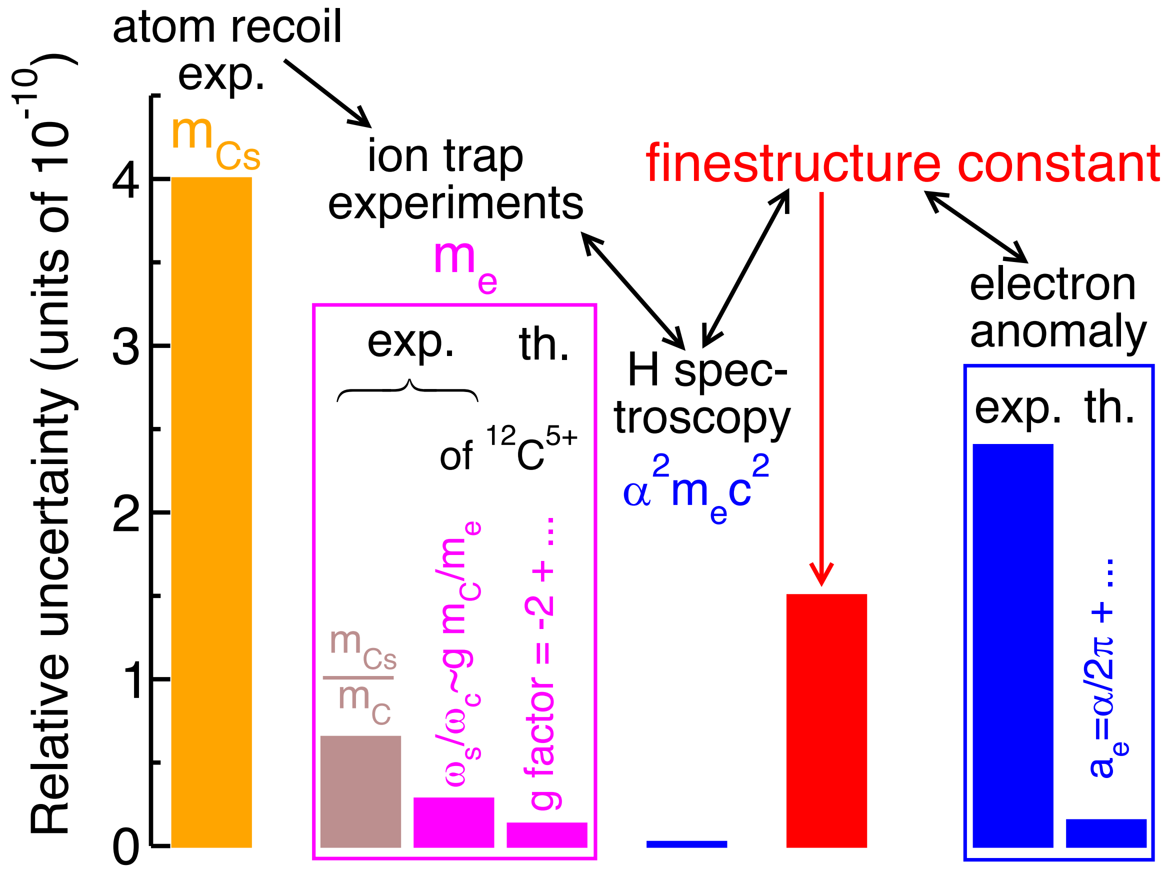


4. b. Fine structure constant

NIST

- The fine structure constant α is determined from two types of measurements
  - Anomaly (g-2) of the free electron
    - ✓ No new experiments
    - ✓ Theory, a power series in α, has improved (far more accurate than experiment).

      Again hadronic vacuum-polarization corrections, but curiously first-principle QCD(!) calculations are as accurate as a determination extracted from e^--e^+ collisions.
  - Atomic recoil measurements of laser-cooled alkali-metal atoms
    - ✓ In the revised SI these are measurements of atomic mass in kg.
    - ✓ Parker *et al*. Science **360**, 191 (2018) from Berkeley using atomic Cesium.



2018 adjustment

4. b. and 4. g. g factor of bound electron

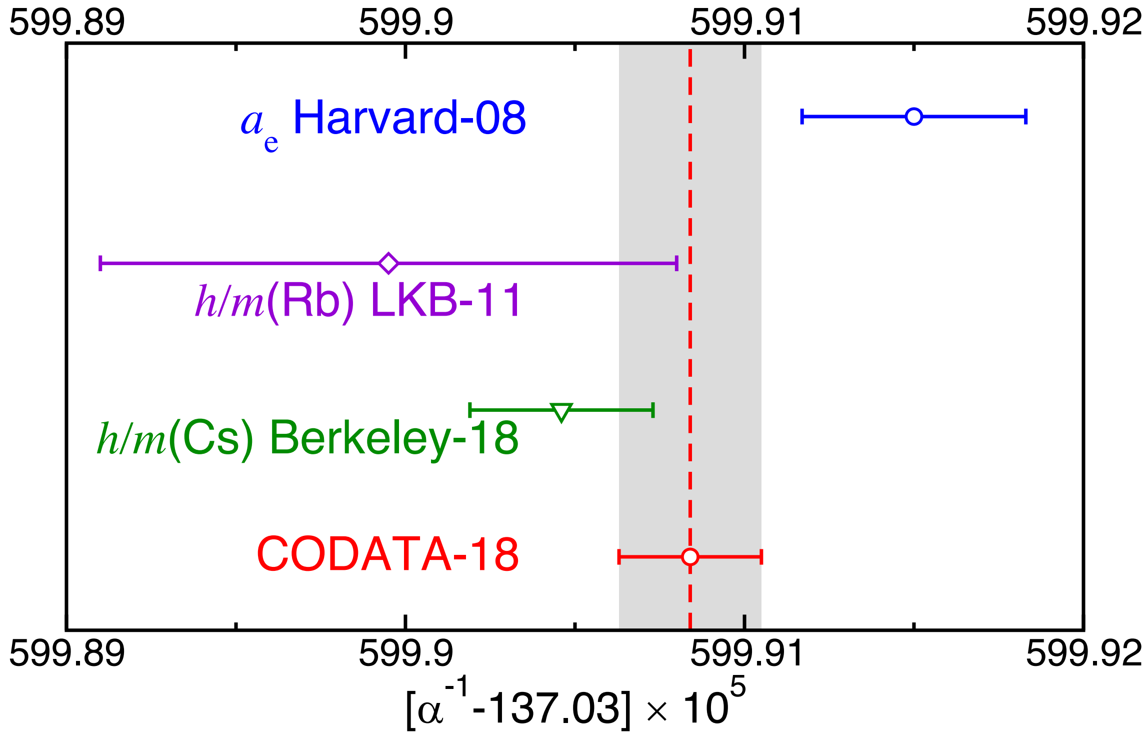
NIST

- The α evaluation via recoil measurements requires knowledge of the bound state g factor of the electron in hydrogenic C^{5+} as well as (to a lesser degree) Si^{13+}

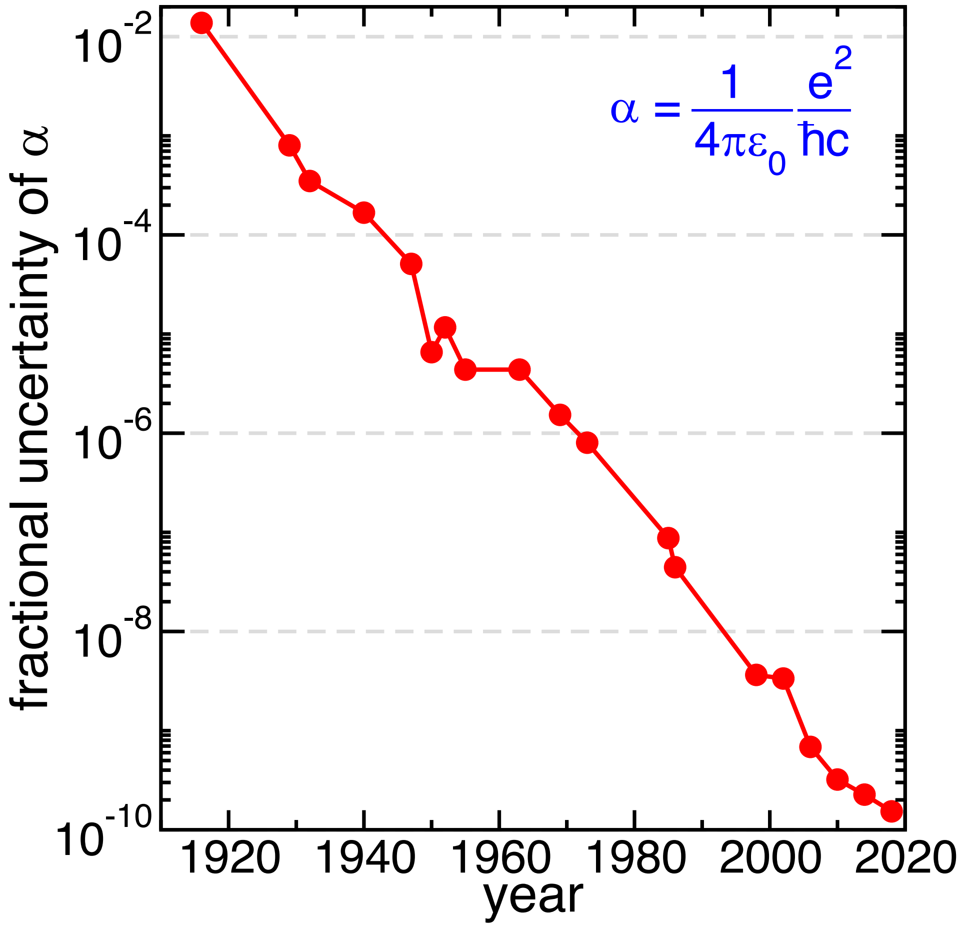
- This is most-accurately done theoretically. We included updates by
  - Czarnecki and Szafron, PRA 94 060501 (2016); light-by-light corrections of $O(\alpha^2(Z\alpha)^4)$
  - Yerokhin and Harman, PRA 95, 060501 (2017); one-loop self-energy of $O(\alpha(Z\alpha)^5)$
  - Karshenboim and Ivanov, PRA 97, 022506 (2018); higher-order nuclear size
  - Updated values for nuclear charge radii; Atomic Data and nuclear Data tables (2013).

4. b. Fine structure constant

- α as individually obtained by the three best measurements to date.



- The latest value of α has a fractional uncertainty of 1.5 x 10^{-10}



4. d. Masses of light nuclei

- Masses of the (n)eutron, (p)roton, (t)riton, (h)elion, and α particle
  - neutron mass in atomic mass units,
  - neutral hydrogen mass in atomic mass units,
  - neutral ^{4}He mass in atomic mass units,

  } from the Atomic Mass Evaluation of 2016

  - cyclotron frequency ratio $\omega_c(^{12}C^{6+})/\omega_c(p)$ from Heiße *et al*. (2017)
  - cyclotron frequency ratio $\omega_c(HD^+)/\omega_c(^3He^+)$ from Hamzeloui *et al*. (2017)

  - cyclotron frequency ratio $\omega_c(d)/\omega_c(^{12}C^{6+})$ from Zafonte and Van Dyck Jr. (2015)
  - cyclotron frequency ratio $\omega_c(t)/\omega_c(^3He^+)$ from Myers *et al*. (2015)

  and relevant electron ionization energies from NIST's Atomic Spectroscopy database + a collaborative spectroscopy effort on HD (Sprecher *et al*., JCP **133**, 111102 (2010)).

- We used expansion factor of 1.7 for $A_r(H)$ and $\omega_c(^{12}C^{6+})/\omega_c(p)$.

4. e. Magnetic Moment ratios

NIST

- We are responsible for the magnetic moments of the leptons and light nuclei.

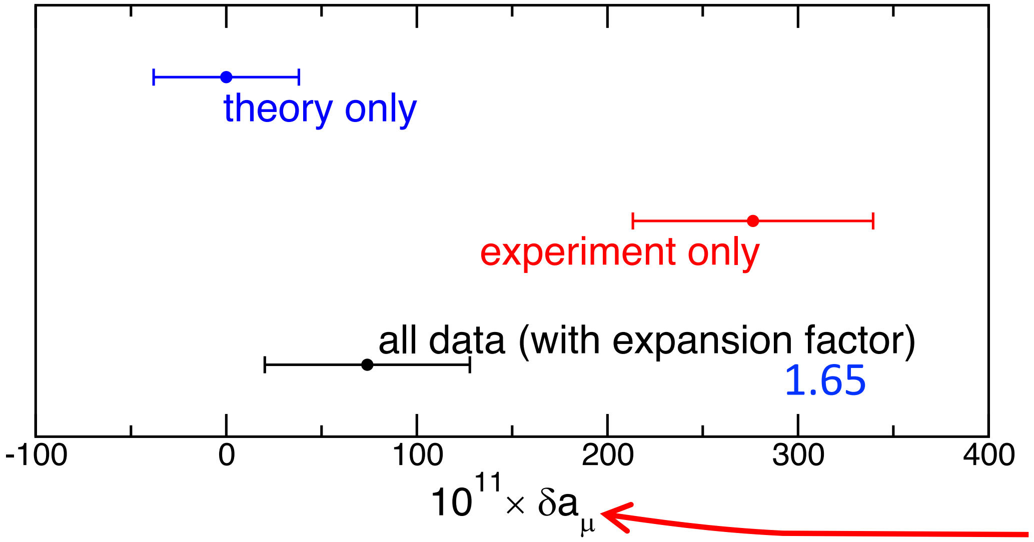
- Measurement of the proton magnetic moment by Schneider *et al*. Science **358**, 1081 (2017).

- Improved theoretical values for shielding factors σ_{dp} and σ_{tp}, binding corrections of the magnetic moment of d and t in HD and HT, from Puchalski *et al*. Phys. Rev. A 92, 020501 (2015).

- We reanalyzed 2012 measurements by Neronov and Seregin on the magn. moment of the deuteron in HD. We now include it (with expanded uncertainties).

4. f. Muon magnetic moment

- Both theory and (a single) experiment exist to determine the magnetic moment or more precisely the anomaly of the muon, a_μ.



- The two evaluations are inconsistent.
- In the previous meeting of this task group, it was decided to only use the experimental value in our 2018 adjustment.

- We have updated our codes regarding the free muon (and electron) anomaly
  - In the last two years hadronic corrections have been improved by several research groups

4. Muon mass

- The mass of the muon is best determined from the hyperfine splitting of the ground state of the muonium (μ^+-e^-) with no magnetic field applied

$$\Delta\nu \propto R_\infty \alpha^2 \frac{m_e}{m_\mu}$$

- Last experiments (which are done in a strong B-field) were performed in 1999.

- In this adjustment the theoretical value of a hadronic correction has been added.

Shelyuto, Karshenboim, and Eidelman, Phys. Rev. D **97**, 053001 (2018)

4. h. Muonic hydrogen and deuterium

- For the first time we include the experimental measurements of the 2s to 2p transition frequency (Lamb shift) for muonic hydrogen and deuterium.

  We use A. Antognini, et al., Science **339**, 417 (2013) for μ-H
  R. Pohl, *et al.*, Science **353**, 669 (2016) for μ-D.

- Similarly, we include the theoretical evaluation of this transition frequency. We do so as

$$\Delta E_{\mathrm{L}} = \mathcal{E}_0 + \mathcal{E}_2\, r^2 + \delta$$

treats uncertainty of theory

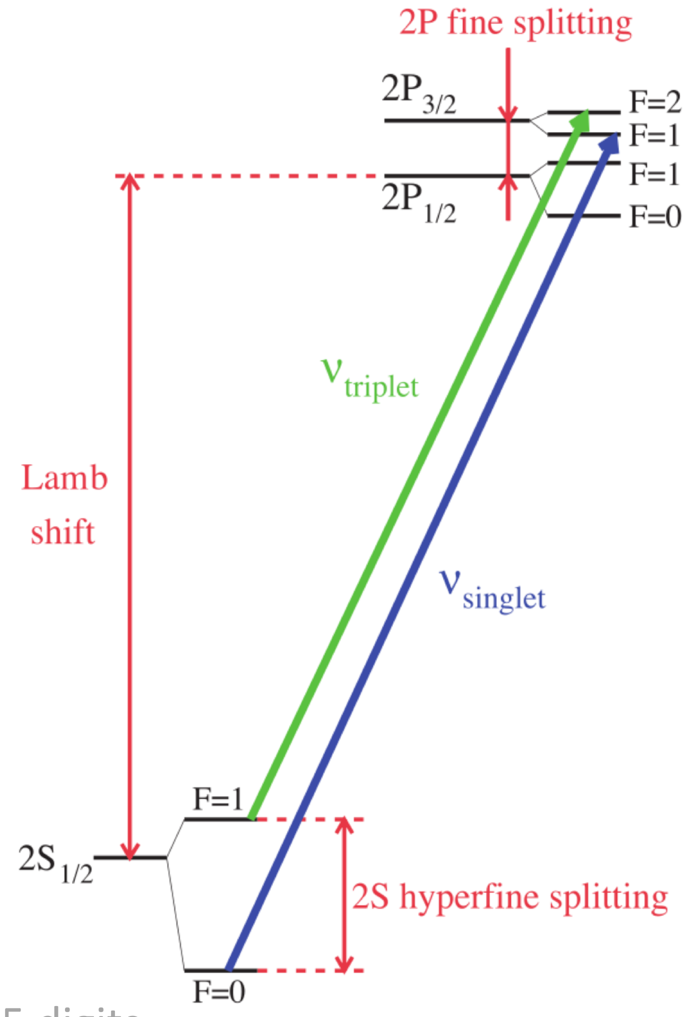
p or d charge radius

Sufficient known from (QED & nuclear) theory

Theory mostly given in the same publications.

$\mathcal{E}_0 \propto \frac{m_\mu}{m_e} E_{\mathrm{h}} \alpha^3$ known to 5 digits

- Data constrains the proton radius



4. h. Hydrogen spectroscopy

- Short hand for the determination of the Rydberg constant R_∞ or, equivalently, the Hartree energy E_h
  - This also gives the electron mass, since $E_\mathrm{h} = 2hcR_\infty = \alpha^2 m_\mathrm{e} c^2$
- New measurements
  - Beyer *et al.* (Garching) Science 358, 79 (2017); 2S-4P transition
  - Fleurbaey et al.(LKB & LNE-SYRTE), PRL 120, 183001 (2018); 1S-3S transition
  - Bezginov et al. (Toronto), Science 365, 1007 (2019); 2S-2P Lamb shift

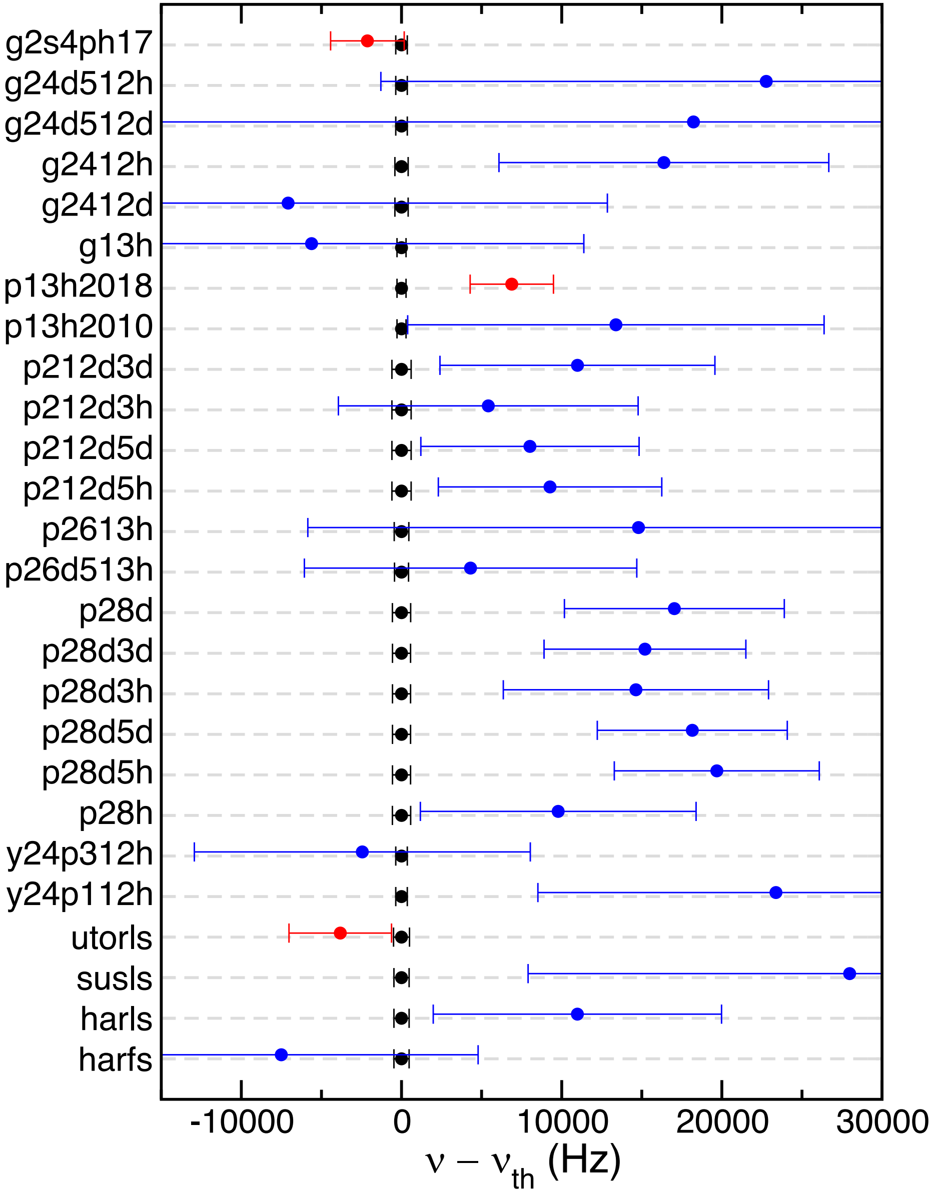
    Requires 2^{nd} order hyperfine
- New theory additions
  - Styled on a review by Yerokhin, Pachucki, Patkos, Ann. Phys. 531, 1800324 (2019).

    Also rewrite of nuclear size corr.

  But acknowledge results by

  - Yerokhin and Shabaev, PRL 115, 233002 (2015); nuclear polarization
  - Czarnecki and Szafron, PRA 94 060501 (2016); two-photon, light-by-light corrections
  - Karshenboim and Ivanov, PRA 98, 022522 (2018); logarithmic two- and three-photon contr.

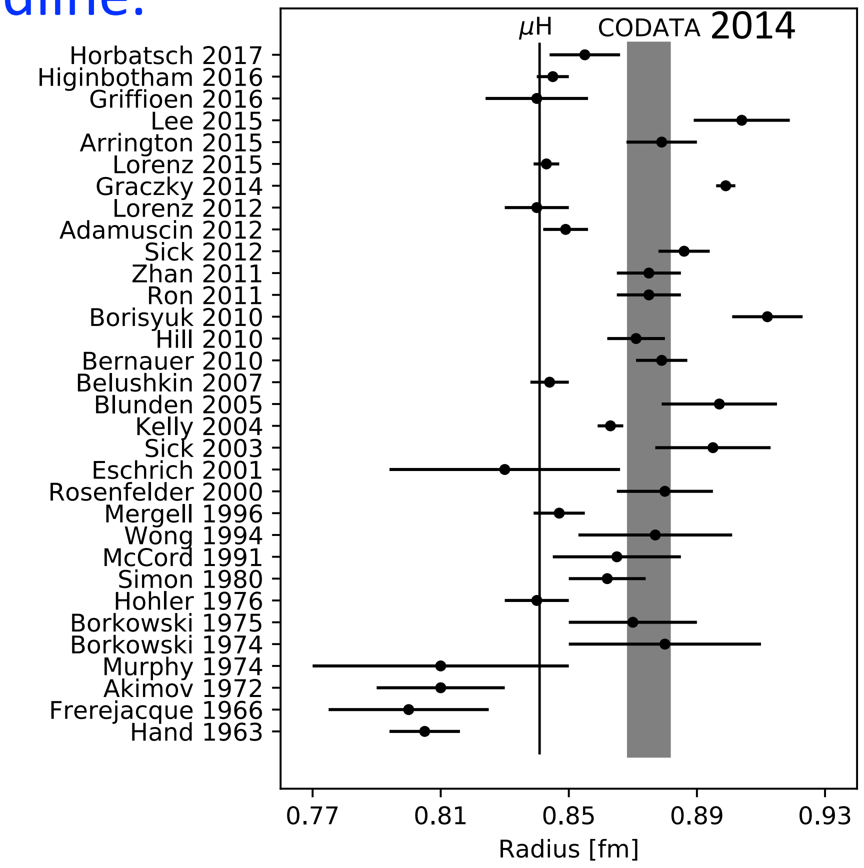
4. h. Hydrogen spectroscopy



4. h. Electron-proton scattering

- Extraction of an accurate proton radius.
- A fair number of articles appeared giving reanalyses of experimental e-p scattering data just before our December 2018 deadline.

From Higinbotham *et al.*, https://arxiv.org/abs/1812.05706



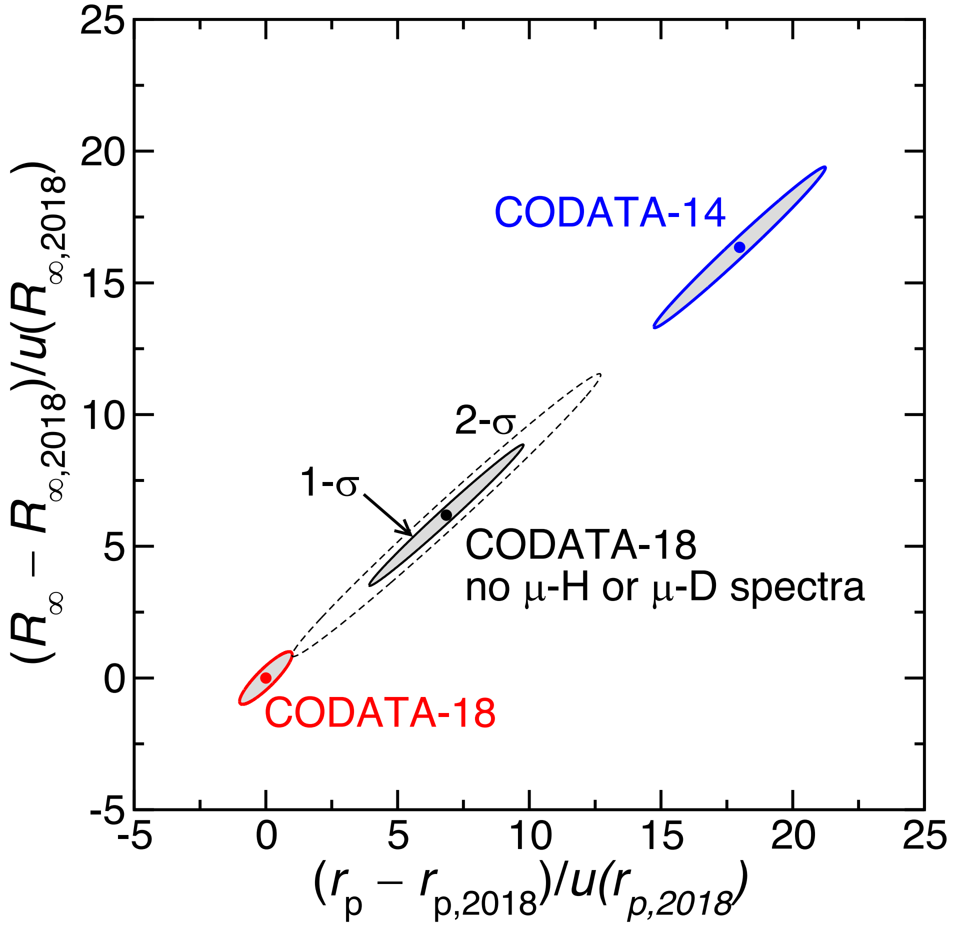
- We have assumed r_p= 0.880(20) fm based on the best of these evaluations.

The data point has little weight in our adjustment.

4. h. Proton radius puzzle

NIST

- The discrepancy between r_p obtained from muonic-H and regular H-spectroscopy has mostly been resolved.
  - With the inclusion of the muonic data the values for the Rydberg constant and proton radius are less correlated.
  - We required an expansion factor of 1.6.
  - Rydberg constant now known with relative uncertainty of 1.9×10^{-12}.
  - r_p=0.8414(19) fm.



4. Silicon Lattice constant

- In 2017 NIST published a new data point to improve the value for the lattice constant of an ideal defect-free, impurity-free, natural-abundance Silicon crystal

at T=22.5 ^{o}C and zero pressure.

4. i. Details on Least Squares

NIST

- A regular least squares procedure that treats uncertainties of and correlations among input data.
- Uncertainties in the theoretical models are included as additional data points.

Typically, determined by estimates of the first missing term in the expansion in the finestructure constant.

interpretable as an extra "experimental" data point.

Formally, we assume $Q_{th} = f(\alpha, m_e, \ldots) + \Delta Q$ with $\Delta Q = 0(\sigma)$ and add

$$\frac{\left(Q_{exp} - f(\alpha, m_e, \ldots) - \Delta Q_{th}\right)^2}{\sigma_{exp}^2} + \frac{(0 - \Delta Q_{th})^2}{\sigma^2}$$

to χ^2 with ΔQ_{th} as additional fit parameter

- No Data excluded.
- Several expansion factors have been used to treat discrepant data.

Such that all input data have residuals less than two

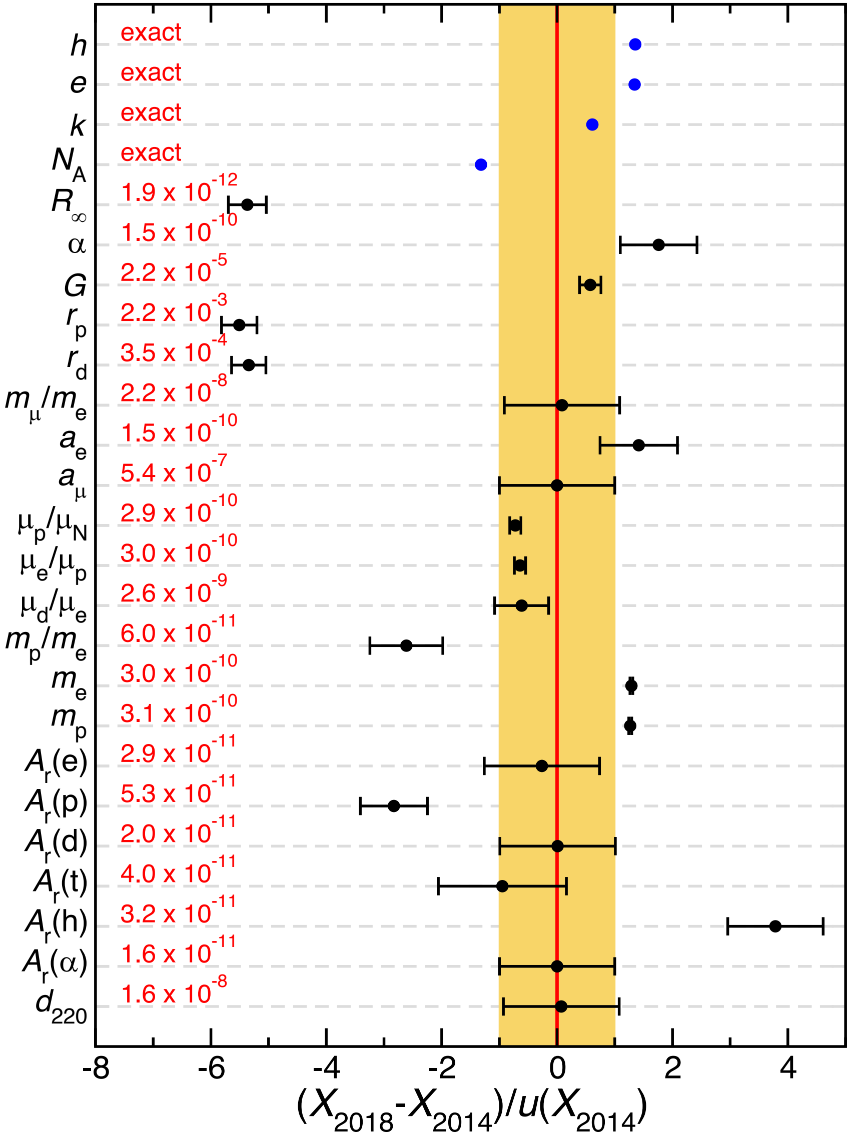
Request

- Please feel free to shoot us an email whenever you are aware of a relevant publication. (eite.tiesinga@nist.gov)

4. i. Comparison 2014 and 2018

NIST

- Finally,



5. Publication of the 2018 Adjustment

NIST

- The 2018 database has become available on 20 May, 2019.
  - http://physics.nist.gov/constants
- Writeup is expected spring 2020.

6. Other topics – CCU agenda items

- Discussion on the definition of the term ‘unit’
- Discussion on angles and dimensionless quantities
- Discussion on the SI in the digital world
- Discussion on the possible extension of the available range of SI prefixes

6. Other topics – CCU agenda items

NIST

- Discussion on the definition of the term 'unit'

Draft 9th edition of the SI Brochure:

The value *Q* of a quantity is expressed by the product of a number {*Q*} and a unit [*Q*]:
$Q = \{Q\}[Q]$.
The unit is simply a particular example of the value of a quantity, defined by convention, which is used as a reference and the number is the ratio of the value of the quantity to the unit."

8th edition of the SI Brochure:

"The value of a quantity is generally expressed as the product of a number and a unit. The unit is simply a particular example of the quantity concerned which is used as a reference, and the number is the ratio of the value of the quantity to the unit."

2018 CODATA TGFC meeting, vote was taken and the result was that the wording of the 8th edition of the SI Brochure was preferred (7 for the 8th edition version, 1 for the draft 9th edition version, 3 abstain). It was generally agreed that the 8th edition is easier to understand and that changing from the 8th edition version should be discussed at a CCU meeting.

6. Other topics – CCU agenda items

- Discussion on angles and dimensionless quantities

2018 TGFC values and units posted May 20, 2019:

- Planck constant* with units Hz and rad/s :

$h = 6.626\ 070\ 15 \times 10^{-34}$ J Hz^{-1}

$\hbar = 1.054\ 571\ ...\times 10^{-34}$ J s ⟷ (rad = 1 is implied)

* The energy of a photon with frequency ν expressed in unit Hz is

$$E = h\nu \text{ in unit J.}$$

Unitary time evolution of the state of this photon is given by

$$\exp[i^{Et}/_{\hbar}]|\varphi\rangle,$$

where $|\varphi\rangle$ is the photon state at time t = 0 and time is expressed in unit s. The ratio $^{Et}/_{\hbar}$ is a phase.

6. Other topics – CCU agenda items

- Discussion on angles and dimensionless quantities

2018 TGFC values and units posted May 20, 2019:

- Full description of other units, e. g.

Rydberg constant

$$R_\infty = 10\ 973\ 731.568\ 160(21)\ [\mathrm{m}^{-1}]^\dagger$$

Compton wavelength

$$\lambda_\mathrm{C} = 2.426\ 310\ 238\ 67(73) \times 10^{-12}\ [\mathrm{m}]^\dagger$$

† The full description of m^{-1} is cycles or periods per meter and that of m is meter per cycle (m/cycle). The scientific community is aware of the implied use of these units. It traces back to the conventions for phase and angle and the use of unit Hz versus cycles/s. No solution has been agreed upon.

6. Other topics – CCU agenda items

- Discussion on the SI in the digital world
  - machine-interpretable artifacts derived from the SI Brochure and similar references?

6. Other topics – CCU agenda items

NIST

- Discussion on the possible extension of the available range of SI prefixes - CCU/19-10_03

Submultiple	Name	Symbol	Etymology
10^{-27}	ronto	r	Greek & Latin, derived from ‘ennea’ and ‘novem’, suggesting 9 (ninth power of 10^3)
10^{-30}	quecto	q	Latin, derived from ‘decem’, suggesting 10 (tenth power of 10^3)

Multiple	Name	Symbol	Etymology
10^{27}	ronna	R	Greek & Latin, derived from ‘ennea’ and ‘novem’, suggesting 9 (ninth power of 10^3)
10^{30}	quecca	Q	Latin, derived from ‘decem’, suggesting 10 (tenth power of 10^3)

Table 1. Suggested names, symbols and derivations of SI prefixes for 10^{-27}, 10^{-30}, 10^{27} and 10^{30}.

Agenda items

7. Other topics?

8. Task Group administration
   - Upcoming workshops to endorse
   - Membership

9. Date and location of the next Task Group meeting

10. Adjournment