Short communication

A summary of the Planck constant measurements using a watt balance with a superconducting solenoid at NIST

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Abstract

Researchers at the National Institute of Standards and Technology have been using a watt balance, NIST-3, to measure the Planck constant \( h \) for over ten years. Two recently published values disagree by more than one standard uncertainty. The motivation for the present short communication is twofold. First, we correct the latest published number to take into account a recently discovered systematic error in mass dissemination at the Bureau International des Poids et Mesures. Second, we provide guidance on how to combine the two numbers into one final result. In order to adequately reflect the discrepancy, we added an additional systematic uncertainty to the published uncertainty budgets. The final value of \( h \) measured with NIST-3 is \( h = 6.626069 (36) \times 10^{-34} \) J s. This result is \( 77(57) \times 10^{-9} \) fractionally higher than \( h_{90} \). Each number in parentheses gives the value of the standard uncertainty in the last two digits of the respective value and \( h_{90} \) is the conventional value of the Planck constant given by \( h_{90} = 4/(K_{J90}^2 R_{K90}) \), where \( K_{J90} \) and \( R_{K90} \) denote the conventional values of the Josephson and von Klitzing constants, respectively.

Keywords: Planck constant, electronic kilogram, watt balance

(Some figures may appear in colour only in the online journal)

1. Introduction

Researchers at the National Institute of Standards and Technology (NIST) have published two results for the Planck constant \( h \) in 2007 [1] and \( h_{14} \) in 2014 [2] using the same apparatus, the third generation of the NIST watt balance, referred to as NIST-3. The published values are

\[
h_{07} = 6.626 \, 068 \, 91 (24) \times 10^{-34} \text{ J s}, \quad \text{or} \quad \frac{h_{07}}{h_{90}} - 1 = 8 \, (36) \times 10^{-9},
\]

\[
h_{14} = 6.626 \, 069 \, 79 (30) \times 10^{-34} \text{ J s}, \quad \text{or} \quad \frac{h_{14}}{h_{90}} - 1 = 141 \, (45) \times 10^{-9},
\]

respectively. Each number in parentheses gives the value of the standard uncertainty \( (k = 1) \) in the last two digits of
Figure 1. The mass of the platinum-iridium prototype No. 85 (K85). The circles represent calibrations that were performed at the time of the experiment, either by the BIPM mass department (solid) or the NIST mass and force group (open). The diagonal crosses represent values that were calculated from measurements obtained by the NIST mass and force group by subtracting a correction. The correction is 0 µg before December 2010 and 35 µg after December 2010. The upright crosses represent the current best estimate of the mass of K85 relative to the IPK.

The mass of the platinum-iridium prototype No. 85 (K85). The circles represent calibrations that were performed at the time of the experiment, either by the BIPM mass department (solid) or the NIST mass and force group (open). The diagonal crosses represent values that were calculated from measurements obtained by the NIST mass and force group by subtracting a correction. The correction is 0 µg before December 2010 and 35 µg after December 2010. The upright crosses represent the current best estimate of the mass of K85 relative to the IPK.

Before we discuss the two measurements, we note that the 2014 result must be adjusted due to an offset in the SI unit of mass disseminated by the Bureau International des Poids et Mesures (BIPM). During the extraordinary comparison [3] of the international prototype of the kilogram (IPK) at the BIPM, it was found that the mass unit as maintained by the BIPM is 35 µg larger than the mass of IPK.

All measurements of the Planck constant discussed here were performed with the NIST platinum-iridium prototype No. 85, known as K85. Figure 1 shows the calibration history of K85. The first calibration certificate for K85 was issued by the BIPM in November 2003. Shortly after being put in service with NIST-3, the mass of this prototype drifted upwards with a rate of approximately 5 µg per year. At the time of the NIST-3 experiment, this drift was taken into account in the calculations of the published values of h. In 2010, the United States shifted its mass scale by 45 µg kg⁻¹, because it was found during a routine calibration of the US national standard prototype K20 that the BIPM mass scale and the US mass scale differed by 45 µg kg⁻¹ [5]. At the end of 2011, K85 was sent for calibration to the BIPM, where it was washed two times. The measurements of the mass of K85 performed by the NIST mass and force group and the BIPM in 2012 and 2013 are in agreement within uncertainties. A constant value for the mass of K85 of 1 kg = 738.3 µg was used to calibrate all NIST-3 measurements made in 2012 and 2013.

In 2014, during the extraordinary mass comparison, it was discovered that the mass unit as maintained by the BIPM is 35 µg kg⁻¹ larger than the mass scale set by the IPK. It is believed that the difference between the mass unit as maintained by the BIPM and the IPK has accumulated between 2000 and 2014. Calibrations made at the BIPM before 2000 are therefore deemed good calibrations with respect to the IPK [3]. But, calibration certificates issued by the BIPM after 2000 have to be corrected to be consistent with the international definition of the kilogram. According to a numerical model made by the BIPM, the calibration value assigned to K85 by the BIPM in 2003 must be decreased by approximately 4 µg and the one assigned in 2012 by approximately 35 µg [4]. The latter correction largely erases the adjustment made to the US mass scale in 2010.

After K85 had arrived at NIST at the end of 2003, it was measured against the national prototype, K20, by the NIST mass and force group. The national prototype, as well as the national check standard, K4, have been calibrated at the BIPM in 1999. At this time the mass unit as maintained by the BIPM was still synchronized to the IPK. Hence, it is believed that the calibration values determined by the NIST mass and force group for K85 from 2004 through the end of 2011 are accurate representations of the mass of K85 with respect to the mass of the IPK. The h measurements taken during this time do not need to be corrected [6].

In 2011, the mass and force group shifted its mass scale to be consistent with the mass scale given by the mass unit as maintained by the BIPM, which, as we now know, was different than the mass unit given by the IPK. Hence, all data taken with NIST-3 in 2012 and 2013 used a value for K85 that was tied to the mass scale as maintained by the BIPM, which was about 35 µg different from the mass of the IPK at that time. Therefore, the measured value for h₄₂ needs to be corrected down relatively by 35 × 10⁻⁹. This yields

\[
\frac{h_{14corr}}{h_{90}} = 1 = 106 (45) \times 10^{-9}.
\]

In summary, the time dependent shape of the correction to the NIST h values is a step function rather than a smooth interpolation. The relative correction that must be applied to the published h values is 0 × 10⁻⁹ for data taken before December 2011 and −35 × 10⁻⁹ for data taken thereafter.

The relative difference between the values of \( h_{90} \) and \( h_{14corr} \) is 98 × 10⁻⁹. All data obtained with NIST-3 using K85 are shown in figure 2. The data points after January 2012 are corrected by the 35 × 10⁻⁹ as discussed above. The lower panel shows the data grouped in daily data runs. The data can be divided into three epochs. The upper panel shows the values obtained by taking the mean of the data in each epoch. The error bars indicate the statistical standard deviation of the data. The mean value and the statistical standard deviation for each epoch are also given in table 1.

The average value of the data in the first epoch is slightly larger than the value published in [1]. This is due to the fact that...
After more than fifteen years of experience with this apparatus, we believe that our best measurement of $\hbar$ is obtained from the unweighted average of the values obtained in the three epochs listed in table 1. This average is $\hbar/\hbar_0 - 1 = 77 \times 10^{-9}$.

Despite all our experience, we acknowledge that we do not understand the cause of the approximately $70 \times 10^{-9}$ relative shift. This lack of understanding must be reflected in the uncertainty assigned to the final value. We assign half of the observed shift, $35 \times 10^{-9}$, as an additional relative uncertainty component to account for a possible unexplained systematic effect in the measurements. By adding this type B component in quadrature to the relative uncertainty published in [2], a combined relative standard uncertainty of $57 \times 10^{-9}$ is obtained.

The final value for the Planck constant obtained with NIST-3 in ten years of measurement is

$$h_{\text{NIST-3}} = 6.626\,069\,36\,(37) \times 10^{-34} \text{ J s, or}$$

$$\frac{h_{\text{NIST-3}}}{\hbar_0} - 1 = 77\,(57) \times 10^{-9}.$$

A previous version of the NIST watt balance (NIST-2) was used to determine a value of the Planck constant in a measurement campaign lasting four months in 1998 [7, 8]. The result

$$h_{\text{NIST-2}} = 6.626\,068\,91\,(58) \times 10^{-34} \text{ J s, or}$$

$$\frac{h_{\text{NIST-2}}}{\hbar_0} - 1 = 8\,(87) \times 10^{-9}$$

was obtained using two gold masses with a combined mass of 1 kg. Hence, the value $h_{\text{NIST-2}}$ is independent of the mass changes discussed above and there is no need to modify this value or its uncertainty. Based on the previous estimate [9] of 0.14 for the correlation coefficient between $h_{\text{NIST-2}}$ and $h_{\text{NIST-3}}$, we estimate

$$r(h_{\text{NIST-3}}, h_{\text{NIST-2}}) = 0.09$$

to be an upper limit for the correlation coefficient between $h_{\text{NIST-3}}$ and $h_{\text{NIST-2}}$.

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