TOWARDS A NEW DEFINITION OF THE KELVIN: WAYS TO GO

Joachim Fischer, Bernd Fellmuth, Joachim Seidel, Wolfgang Buck

Physikalisch-Technische Bundesanstalt (PTB), Berlin, Germany

ABSTRACT

The present definition of the kelvin links the unit of temperature with a material property. It would be more consistent with the current approaches to other base units to fix the value of the Boltzmann constant *k*, instead. For this purpose, *k* must first be determined with distinctly lower uncertainty. This paper considers experimental methods having potential to contribute to the determination of *k*.

1. INTRODUCTION

The unit of temperature *T*, the kelvin is presently defined by the temperature of the triple point of water (TPW). Thus, the kelvin is linked to a material property. Instead, it would be advantageous to proceed in the same way as with other units: to relate the unit to a fundamental constant and fix its value. By this no temperature value and no measurement method would be favoured. For the kelvin, the corresponding constant is the Boltzmann constant *k,* because temperature always appears as thermal energy *kT* in fundamental laws of physics.

To ensure that such a redefinition would maintain the uncertainty currently achieved for the realisation of the temperature unit ($u = 3 \cdot 10^{-7}$ at the TPW, see chapter 2), *k* must be known with similar uncertainty. At present its uncertainty is still about one order of magnitude higher. Therefore, *k* has to be determined with distinctly lower uncertainty. The CODATA value of *k* is based on the acoustic gas thermometer (AGT) at the National Institute of Standards and Technology (NIST), the primary thermometer [1] with the smallest uncertainty obtained up to now at the TPW. A study recently completed at PTB shows that another variant of the gas thermometer, the dielectric-constant gas thermometer (DCGT) operated with helium, is promising for further reducing the uncertainty as required – in particular, because the polarisability of the helium atom can now be calculated very precisely by quantum mechanics. PTB is on the way to further improve this technique.

Noise thermometry played an important role in establishing the Provisional Low Temperature Scale PLTS-2000 and corroborated the thermodynamic basis of the low temperature part of the ITS-90. In combination with a Josephson voltage standard, noise thermometry could be developed to be competitive at higher temperatures to contribute to a new value of *k*.

Spectral radiation measurements on the basis of Planck´s radiation law, even if they are not expected to reach comparably small uncertainties, will support the redefinition of the kelvin. With this method at the National Physical Laboratory (NPL), NIST, and PTB considerable progress has been achieved in recent years. Spectral radiation measurements are considered to be the only method which is capable of disseminating the temperature scale based on the new definition directly to the users − especially at high temperatures. Another primary thermometer applicable for determining *k* is based on the Stefan-Boltzmann law and measures the total radiation without spectral selection. This method has been developed at NPL and a project proposal of NPL anticipates that the new absolute radiation thermometer of NPL can be operated with sufficiently small uncertainty and contribute to an improved value of the Boltzmann constant as well.

Very recently Université Paris Nord in cooperation with the French BNM-INM/CNAM has started a project to investigate the feasibility to determine k with a spectroscopic method. It is proposed to measure the Doppler broadening of rotational and vibration modes of ammonia gas by a frequency-stabilised CO_2 laser. The above mentioned methods are reviewed in chapters 3 to 6.

2. UNITS AND FUNDAMENTAL CONSTANTS

It took 100 years until the proposal by William Thomson, the later Lord Kelvin of Largs, namely to define the unit of temperature by the interval between absolute zero and a further fixed point, was finally adopted in substance by the 10th CGPM in 1954 [2]. In 1967 the symbol °K was replaced by K. In the meantime big efforts have been made, partly initiated by practical needs for accuracy and reliability of measurement and partly favoured by the discovery of new physical effects, to replace artefacts and prototypes in the definition of the SI base units and to relate the units to fundamental constants considered to be invariant in space and time. In most cases the fundamental constants used had to be determined more precisely than known before within the existing system of units, and then have been given a fixed value by convention.

Table 1 shows that the relation of units to fundamental constants has already been realised in the definition of the second and the metre via the hyperfine transition of ^{133}Cs and the speed of light in vacuum c_0 [1]. By fixing the values of the Josephson and von Klitzing constants, K_J and R_K, respectively, the ampere can be traced back to them by Ohm's law. In order to achieve direct traceability to the elementary charge e many attempts are under way throughout the world to exploit macroscopic quantum effects such as single electron tunnelling or surface waves transport. In order to replace the kilogram prototype and to find an atomic basis for the mole, different approaches are pursued by fixing the Avogadro constant N_A, the Planck constant h, the atomic mass unit (e.g. m_{Au}) or the magnetic flux quantum Φ_0. The candela is linked to a power measurement under special spectral and geometrical conditions and therefore finally based on electrical or mechanical measurements.

Table 1: SI base units, realisation uncertainties (order of magnitude), and their relation to fundamental constants (FCs)

SI Base unit	Definition	Uncertainty [1]	Related FC	Prospected FCs
kilogram	1889	10^{-8}		h, N_A, m_{Au}, Φ_0
ampere	1948	10^{-7}		e
second	1967	10^{-14}	^{133}Cs	
kelvin	**1967**	$\mathbf{10^{-7}}$		$\boldsymbol{k}$
mole	1971	10^{-7}		N_A
candela	1979	10^{-4}		
metre	1983	10^{-11}	c_0	

Concerning temperature the second fixed point of the definition of the kelvin, the TPW, links this unit to the property of a special substance and hands it over to unpredictable changes in space and time. This situation is clearly demonstrated e. g. by two recent comparisons of TPW cells. During a EUROMET comparison [3] only half of the 27 investigated cells agreed with the circulated sample within ±50 µK ($\pm 1.8 \cdot 10^{-7}$). Two cells deviated even by more than 200 µK and were excluded from the further analysis. In contradiction to [3], a study performed in the National Research Council of Canada of also 27 different cells [4] reports an indication of a long-term drift of 4 µK per year preferably explained by the solution of minerals and silicon from the walls of the glass container. Nine cells had to be ruled out for contamination reasons with excess air or some other strange behaviour. In addition isotope effects have been reported to influence the triple point temperature by some 10 µK at least or often much more [5]. Therefore, despite of the small uncertainty of correctly working cells of some 10^{-7}, tracing the kelvin to energy measurements based on mechanical units and fixing the value of k, after having reduced its uncertainty by an order of magnitude, would considerably improve the reliability of the kelvin definition.

3. GAS THERMOMETRY

All three modern kinds of gas thermometry, constant-volume gas thermometry (CVGT), AGT, and DCGT, have been and/or will be used for determining k via primary thermometry at the TPW. They are based on different simple relations between the properties of an ideal gas and T (see Figure 1). Though many gases exhibit a nearly ideal behaviour at and above the TPW, the small departures from the ideal behaviour must be carefully considered in view of the desired level of accuracy. This is done by measuring the relevant property in dependence on the density. Then, the ideal behaviour is deduced by fitting an appropriate virial expansion to the measured isotherm and extrapolating to zero density. Table 2 illustrates that the three kinds have quite different error sources (cf. [2, 6]). Two general facts should be emphasised. First, AGT and DCGT are based upon the variation with T of an intensive property of the gas (speed of sound c and dielectric constant ε, respectively), whereas primary CVGT requires a knowledge of the number n of moles of gas present in the gas bulb. Second, the dependence of c on the pressure p is a second-order (2^{nd}o) effect.

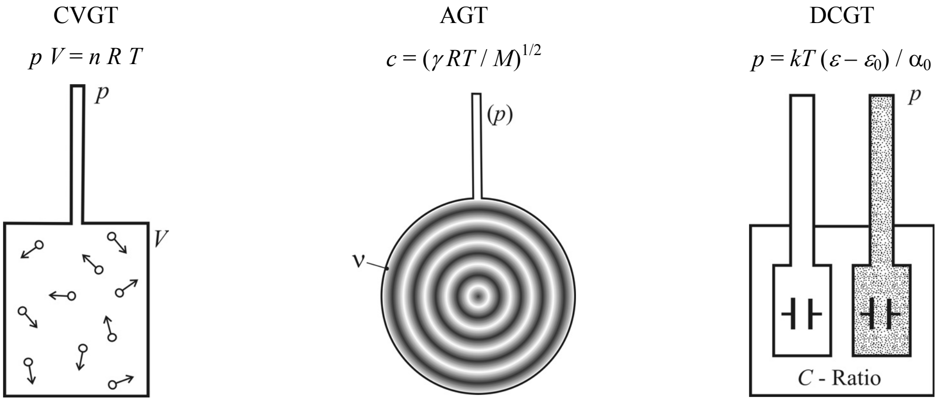

Figure 1: Principles of CVGT, AGT, and DCGT (for the symbols cf. Table 2)

Table 2: Errors in gas thermometry: Quantities to be measured and necessary corrections (κ_{eff} effective compressibility, B second density virial coefficient, $\gamma = C_p/C_V$ ratio of specific heat capacities at constant pressure and constant volume, TMPD thermomolecular pressure difference, ε_0 electric constant)

Error source	CVGT	AGT	DCGT	Error source	CVGT	AGT	DCGT
Pressure p	⊗ (1^{st}o)	⊗ (2^{nd}o)	⊗ (1^{st}o)	Dead space $\neq T$	⊗		
Aerostatic head	⊗		⊗	Capacitance C			⊗
TMPD	⊗			Temperature T	⊗	⊗	⊗
Bulb volume V	⊗	⊗		Frequency ν		⊗	
T expansion	⊗	⊗		Extrapolation	⊗	⊗	⊗
p dilatation	⊗ (V)	⊗ (V)	⊗ (κ_{eff})	Gas constant R	⊗	⊗	⊗
Amount of gas n	⊗			Molar mass M	⊗	⊗	
Impurities	⊗ (B)	⊗ (M/γ)	⊗ (ε)	Polarisability α_0			⊗
Sorption	⊗ (n)		⊗ (layers)	Ratio γ		⊗	

3.1. Constant-volume gas thermometry

CVGT [2, 6−8] is based on the equation of state of the ideal gas (see Figure 1). Considering the practical difficulties in determining the number n of moles of gas present in the gas bulb, all recent primary CVGT experiments have been performed by measuring relative isotherms, i.e. by determining the amount of gas using a reference volume at a known temperature, measuring the pressure, and solving an appropriate virial expansion. The existent historical measurements of the molar gas constant $R = kN_A$ applying conventional true pressure-volume isotherm thermometry have been carefully analysed in [9]. The conclusion was that a number of systematic effects had been overlooked. This concerns especially effects related to gas sorption, to the measurement of the gas-bulb volume, and to the pressure dilatation of the bulb. A ”plausible” uncertainty budget has been established considering all known effects that could not be completely evaluated later. A ”plausible” uncertainty of order of 10^{-5} has been obtained combining all uncertainty components in quadrature. In view of the many influencing factors and the conflicting demands e.g. concerning the parameters of the gas bulb, it seems at present not possible to reach an essentially smaller level of uncertainty.

3.2. Acoustic gas thermometry

AGT utilises the relation between the speed of sound c of a gas and the thermodynamic temperature. The relation for an unbounded ideal gas is shown in Figure 1. Two methods have been used to measure the speed of sound [2, 10]. In older works, a fixed-frequency, variable-path, cylindrical acoustic interferometer was used. Nowadays, variable-frequency, fixed-path spherical resonators are preferred. Their figure of merit is about an order of magnitude higher than that of cylindrical resonators. Furthermore, boundary layer effects and the problems due to the excitation of different modes are essentially smaller.

Using a spherical resonator, the most accurate determination of the gas constant is described in [10]. The achieved standard uncertainty has been estimated to be $1.8 \cdot 10^{-6}$ [11]. The main uncertainty components of this determination arose from the necessary linking to the temperature of the TPW, the extrapolation to zero pressure and the determination of the volume of the resonator. Advanced systems for primary thermometry are discussed in [12−14]. A relative uncertainty of order of 10^{-6} seems to be at present achievable for relative measurements near to the temperature of the TPW. A very recent approach is the development of quasi-spherical resonators for AGT [15]. The quasi-spherical shape retains the advantages of spherical resonators while simplifying the determination of the resonator’s thermal expansion using microwave resonances.

3.3. Dielectric-constant gas thermometry

The basic idea of DCGT is to replace the density in the state equation of a gas by the dielectric constant ε. For an ideal gas, this yields the simple relation between the pressure p and ε given in Figure 1, where ε_0 is the exactly known electric constant and α_0 the static electric dipole polarisability of a gas atom. The measurement of DCGT isotherms yields A_ε/R and thus $k = (R/A_\varepsilon)\,\alpha_0/(3\,\varepsilon_0)$, where A_ε is the molar polarisability. As AGT, DCGT avoids the troublesome density determination of the conventional gas thermometry. In addition, the pressure sensing tubes can be of any convenient size and the thermometric gas can be moved in or out the bulb without the need to allow for the amount of the gas involved. Absolute DCGT requires knowing α_0 with the necessary accuracy. Nowadays this condition is fulfilled for helium, which has become a model substance for evaluating the accuracy of ab initio calculations of thermophysical properties. Recent progress has decreased the uncertainty of the ab initio value of α_0 well below one part in 10^6 [16, 17].

Up to now, DCGT using cylindrical capacitors for determining ε has been performed by two groups in the range from about 3 K to 27 K [18, 19]. The obtained relative uncertainties are of order of 10^{-5}. The deficiency of the conventional cylindrical capacitors used is the fact that the whole length of the capacitor plates influences the effective compressibility κ_{eff}. For the system described in [19], this deficiency caused a dominant uncertainty component together with the measurement of pressure and capacitance changes. An evaluation of the results obtained so far considering especially the state-of-the-art level of accuracy of the measurement of pressure and capacitance shows that DCGT has potential for both decreased uncertainty and increased application range, at least up to the TPW. Using the same cylindrical capacitors as in [19], the uncertainty of the determination of k at the TPW would be also in the order of magnitude of 10^{-5}. But it seems to be possible in the next few years to decrease the uncertainty at least by an order of magnitude by optimising the capacitor design and measuring κ_{eff} in situ [20]. This will allow to determine k with an uncertainty which is comparable with that obtained with AGT, see above. Further progress depends essentially on the developments in p and C measurements. A new proposal is to apply quasi-spherical resonators for DCGT [21]. But as for AGT, the achievable level of accuracy still has to be checked.

4. NOISE THERMOMETRY

The noise thermometer is based on the temperature dependence of the mean square noise voltage $\langle U^2 \rangle$ developed in a resistor. Nyquist derived Eq. (1) from thermodynamic calculations [22] valid for frequencies $\nu \ll k\,T/h$, where R is a frequency-independent resistance and $\Delta\nu$ the bandwidth. From the statistical nature of the measured quantity, long measuring times arise. One of the main problems is the accurate measurement of the very small noise voltages avoiding extraneous sources of noise and maintaining a constant bandwidth and gain of the amplifiers. For details see [2, 23, 24].

$$<U^2> = 4\,k\,T\,R\,\Delta\nu \tag{1}$$

In the past, except for the low temperature range, the uncertainties of noise thermometry were not comparable to those of gas-based techniques due to limitations from the non-ideal performance of electronic detection systems. The most successful technique to date is the switched input digital correlator pioneered by Brixy *et al.* [25, 26]. A relative uncertainty of $2 \cdot 10^{-5}$ (k=1) at the zinc fixed point has been estimated. In this method the source voltage is fed via two separate pairs of leads to two identical amplifiers whose output signals are multiplied together, squared, and time-averaged. The correlator is implemented by digitising the signals from the two channels (see Figure 2a) and carrying out the multiplication and averaging function of the correlator by software. This eliminates the amplifier and transmission line noise superimposed on the thermal noise signal since the respective noise voltages are completely uncorrelated. On the other hand, the respective source resistance noise voltages are perfectly correlated and so will in principle yield $<U^2>$ without error.

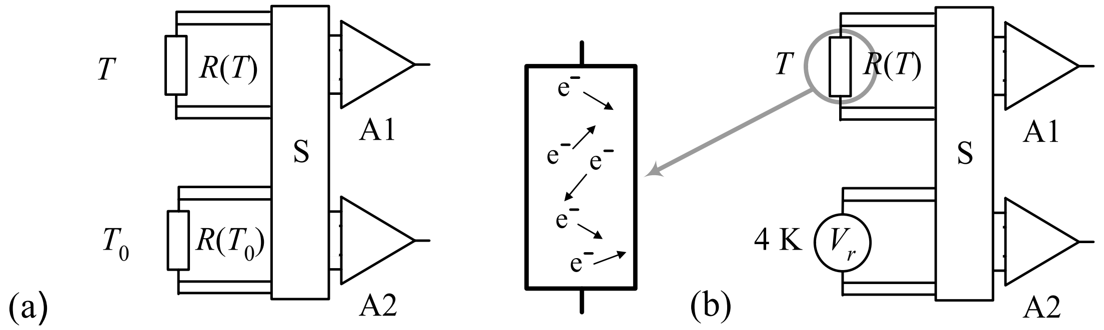

Figure 2: (a) Block diagram for the conventional relative method with switched-input noise correlator, S: switching, A1, A2: amplification and digitisation. (b) Block diagram for the new absolute method.

In use, the thermometer switches between a reference noise source at a reference temperature T_0, and the noise source at the unknown temperature T (Figure 2a). The switching removes the effects of drift in the gain and bandwidth of the amplifiers and filters requiring only measurements of resistance ratio and noise power ratio. The remaining three limiting factors are measurement time, nonlinearity, and transmission-line effects. The last error can be eliminated by operating the noise thermometer with a constant sensing resistance $R(T_0) = R(T)$. However, this condition conflicts with the condition $R(T_0)T_0 = R(T)T$ required to reject the nonlinearity. In practice, the operating frequency is limited to reduce the transmission-line error, which in turn limits the accuracy of the noise power ratio. The main drawback in noise thermometry is the measurement time: for an uncertainty of k below 10^{-5} a measuring time of about 8 weeks (bandwidth 20 kHz) is required. Even nowadays it is highly improbable that amplifiers, attenuators and other electronic units remain sufficiently stable for such a long period.

In addition, the conventional switching approach does not contain enough free parameters to resolve the conflicting requirements for matching both the sensing resistances and the noise powers. Currently, a collaboration between NIST and the Measurement Standards Laboratory of New Zealand [27] explores a new approach using the perfect quantisation of voltages from the Josephson effect. This approach keeps the proven elements of the switched correlator, but separates the roles of the temperature and voltage references. The sensing resistor in the reference arm of the comparator is replaced by an ac Josephson voltage standard V_r (Figure 2b). If the Josephson voltage standard is used to generate noise of a calculated and constant power spectral density it is not necessary to measure the noise power at the reference temperature T_0 because the definition of the kelvin is contained in the value of k. Thus, measurements at the TPW would provide a determination of k.

However, the long term goal of the project is to build a relative noise thermometer with an uncertainty of 10^{-5} over the wide temperature range 83 K to 430 K. The first step was a proof of concept at the triple points of gallium and water [28].

5. ABSOLUTE RADIATION THERMOMETRY

Employing absolute measurements of blackbody radiation, primary thermometry can also be based on Planck's law [29] for the spectral radiance (versus frequency ν) L_ν or the Stefan-Boltzmann law for the total (frequency-integrated) radiance L of a blackbody at temperature T:

$$L_\nu = \frac{2h}{c_0^{\,2}}\,\nu^3\left[\exp\left(\frac{h\nu}{kT}\right)-1\right]^{-1} \qquad \text{and} \qquad L = \int_0^\infty L_\nu\,\mathrm{d}\nu = \frac{\sigma}{\pi}T^4 \,. \tag{2}$$

Here, $\sigma = 2\pi^5 k^4/(15 c_0^{\,2} h^3)$ is the Stefan-Boltzmann constant.

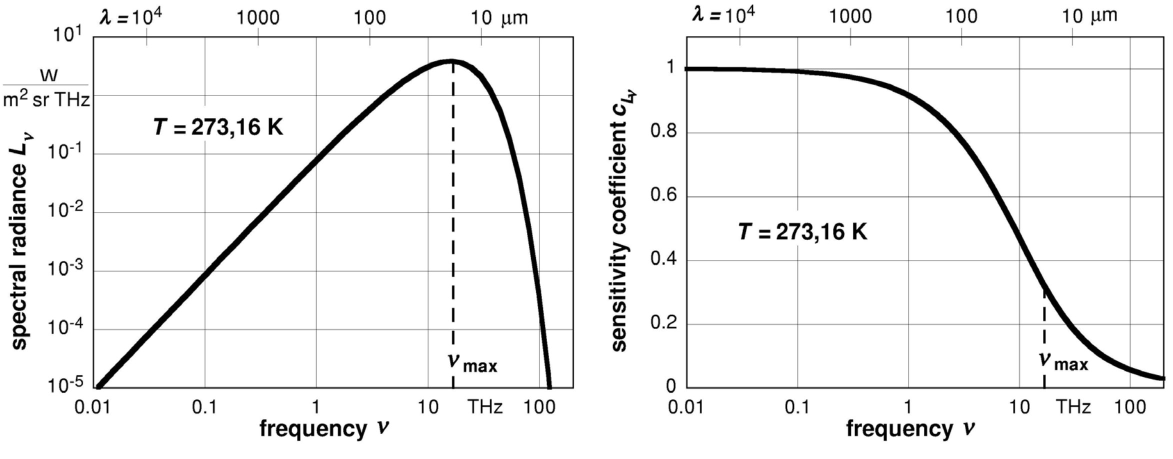

Figure 3: (a) Planck's radiation law for a perfect blackbody at the TPW temperature. (b) Sensitivity coefficient c_{L_ν} multiplying the relative uncertainty of L_ν in the expression for the relative combined uncertainty of k.

At the Physikalisch-Technische Reichsanstalt in Berlin, radiometric measurements of blackbody radiation were already performed with remarkably small uncertainties more than a century ago [see, e. g., 30] (and in fact these measurements first stimulated Planck's investigations and then supported his theoretical result). The principle of measurement is still the same today – substitution of electrical heating (bringing about the same rise in temperature) for the heating of a detector by absorbed radiation. However, the prospect of attaining measurement uncertainties well below 0.1% or even below 0.01% with an electrical substitution radiometer (ESR) opened up only in the late 1970s, when the ESR was first operated at cryogenic temperature at the NPL [31]. This ”cryogenic radiometer” was employed for a determination of the Stefan-Boltzmann constant [32] with a relative uncertainty of $1.3{\cdot}10^{-4}$. Today, such devices are routinely used to measure suitable laser radiation powers with a relative uncertainty of a few parts in 10^5 [33]. Corresponding to this progress in radiometry, “absolute” radiometric determination of high thermodynamic temperatures is now possible with an uncertainty similar to or even smaller than that of the ITS-90 fixed points (about 40 mK at the silver freezing point close to 1235 K, which result from the necessity of relating all thermodynamic temperatures to the TPW temperature) [34]. With a specialised device, its ”Absolute Radiation Detector” [35], the NPL even expects to measure L (and thus σ) at the TPW with a relative uncertainty of about 10^{-5}, which would in turn allow to determine k with a relative uncertainty of a few 10^{-6} (note that the relative uncertainty of k is essentially only one fourth of that of σ it is derived from). This would not, however, improve the uncertainty of k to some 10^{-7}, as required for a new definition of the kelvin, and such a reduction by another order of magnitude appears to be too ambitious for absolute radiation thermometry in the foreseeable future. Nevertheless, radiation thermometry would be very useful for improved dissemination of a temperature scale based on a fixed value of k, in particular at high temperatures.

5.1 Total radiation thermometry

Strictly, exploitation of the Stefan-Boltzmann law in order to determine k should be done with a perfectly ”black” radiation detector (inverse blackbody) with absorptivity (and emissivity) equal to 1 over the whole spectral range which contributes to the integral of L_ν, Eq. (2). (Note that still 0.1% of the total thermal radiation is emitted at wavelengths greater than about 200 µm at the TPW temperature, and still about 10^{-6} at wavelengths greater than 2 mm, see Figure 3a.) Cavity detectors of cryogenic radiometers can be designed to very nearly fulfil this condition over a wide spectral range, and absorptivity corrections can be determined with the help of Monte Carlo simulations. Nevertheless, the uncertainty of these corrections will become a hindrance if a relative uncertainty level of 10^{-5} or lower is to be reached for σ.

Moreover, without an imaging optics it is not L that is measured by a radiation detector, but rather the radiative power received. In order to have a well-defined relation of the power received by the detector to the radiance emitted by the blackbody, some ”geometrical” system of apertures has to be mounted in between the detector and the blackbody. Determination of the effects of this system is no problem in the limit of geometrical optics, if all dimensions are exactly known. However, the uncertainties connected with the determination of ”radiometric” aperture areas (and shapes) as well as corrections for diffraction and scattering by the aperture edges will also become problematic at the 10^{-5} relative uncertainty level.

Taking into account all of the uncertainties sketched above, a determination of the Stefan-Boltzmann constant with reliable relative uncertainty of 10^{-5} would certainly have to be considered a major advance of absolute radiation thermometry. Even then, however, the current definition of the kelvin would not be surpassed in terms of reproducibility.

5.2 Spectral-band-limited radiation thermometry

As compared to total radiation thermometry, this method can be set up to operate only around $\nu_{\max}$, i.e., around the maximum of radiation emission (Figure 3a), thus reaching a better signal-to-noise ratio and avoiding the problem of very-long-wavelength radiation. With a view to the propagation of uncertainty it may be even more advantageous to perform the measurement at somewhat higher frequencies, where L_ν does start to decrease sharply, but the sensitivity coefficient multiplying the relative uncertainty of L_ν in the expression for the relative combined uncertainty of k decreases also to values below 1/3, the value at $\nu_{\max}$ (Figure 3b). However, the spectral band has to be defined by some filter. The additional uncertainty of the calibration of the filter transmission (or expediently of the spectral responsivity of the whole filter radiometer, i.e., the filter-detector assembly) has to be taken into account, which cannot be lower than the uncertainty of the cryogenic radiometer used for calibration. Altogether, this results in best relative uncertainties at the 10^{-4} level for this type of radiation thermometry and measurements at temperatures of about 500 °C and above [34]. Since the uncertainty will not diminish with decreasing temperature, $5 \cdot 10^{-5}$ is presently considered a realistic estimate for the relative uncertainty of k that can be reached by measurement at the TPW. Accordingly, spectral-band-limited radiation thermometry, too, is not expected to contribute to an improvement of the present uncertainty of k.

6. SPECTRAL-LINE DOPPLER BROADENING

Another method of primary thermometry utilising radiation measurements has only recently been proposed for the purpose of determining k [36] and is presently under investigation with respect to the uncertainty that may be achieved. It is a standard means of diagnostics for high-temperature plasmas [37], but in this field of application uncertainties are at the percent level or even higher.

The method is based on the Doppler shift of the frequency of an electromagnetic wave in a moving frame of reference as compared to a frame at rest. As a consequence, an atomic absorption resonance frequency, which is ν_0 for an atom at rest, is shifted by $\Delta\nu = \nu_0 \boldsymbol{\beta} \cdot \boldsymbol{\kappa} / \kappa$ for an atom moving with constant velocity $\boldsymbol{v} = c_0 \boldsymbol{\beta}$ in the field of laser radiation with wave vector $\boldsymbol{\kappa}$. For a laser beam propagating through an absorption cell containing an ideal gas of such atoms or molecules with atomic mass m and uniform temperature T, the Gaussian Maxwell distribution of atomic velocities results in a Gaussian Doppler-broadened absorption line profile around the absorption frequency ν_0 which is proportional to $\exp[-(\Delta\nu/\Delta\nu_D)^2]$ with Doppler width $\Delta\nu_D = [2kT/(mc_0^2)]^{1/2} \cdot \nu_0$. It is this relation which allows to determine the value of the Boltzmann constant by spectroscopic measurement.

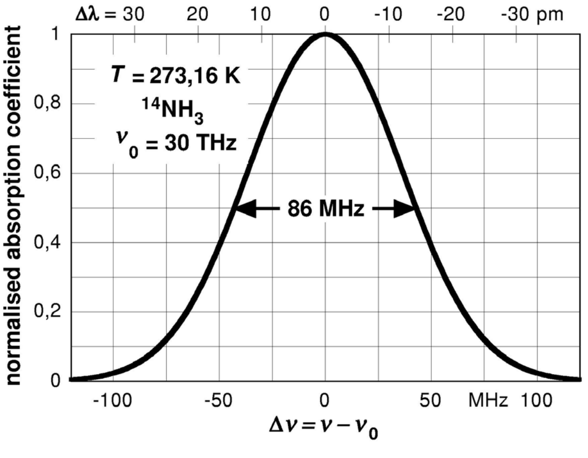

Figure 4: Doppler-broadened absorption line profile for ammonia $^{14}NH_3$ at T_{TPW} assuming a central frequency $\nu_0 = 30$ THz

In principle, the absorption profile (for an example, see Figure 4) can be measured using standard laser-spectroscopic techniques. As a main advantage compared to absolute radiation thermometry, the Doppler width can be determined by relative radiation measurements. Moreover, laser frequencies can be controlled with outstanding small uncertainties. However, at the 10^{-6} or 10^{-7} relative uncertainty level, various other sources of uncertainty will have to be investigated in detail. Apart from the quadratic Doppler effect disregarded above, these include, among others, the effects brought about by interatomic interactions, notably the additional line broadening ("pressure broadening") and the reduction of Doppler broadening caused by a finite mean free path length ("Dicke narrowing"). Because of these, measurements may have to be performed at a series of pressure values and extrapolated to pressure zero. Similarly, heating by the absorbed laser power − if it cannot be neglected at all − may require an extrapolation to vanishing laser power. Therefore, the overall uncertainty this method may provide for the Boltzmann constant is not yet known and the results of more detailed investigations remain to be seen.

7. CONCLUSIONS

Considering the aforementioned uncertainty estimates, the two methods promising at most a significant reduction of the uncertainty of k are currently DCGT and AGT. Thus, an improved value of the Boltzmann constant proposed for defining the kelvin would ideally have been determined by these two fundamentally different methods and be corroborated by other – preferably optical − measurements with larger uncertainty. Finally, a new definition of the kelvin could be as simple as "The kelvin is the change of thermodynamic temperature that results in a change of thermal energy kT by $1.38065XX \cdot 10^{-23}$ Joule".

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Address of the first Author:

Joachim Fischer, Physikalisch-Technische Bundesanstalt, Abbestrasse 2−12, 10587 Berlin, Germany,
tel. +4930 3481 473, fax +4930 3481 508, e-mail: joachim.fischer@ptb.de, website www.ptb.de