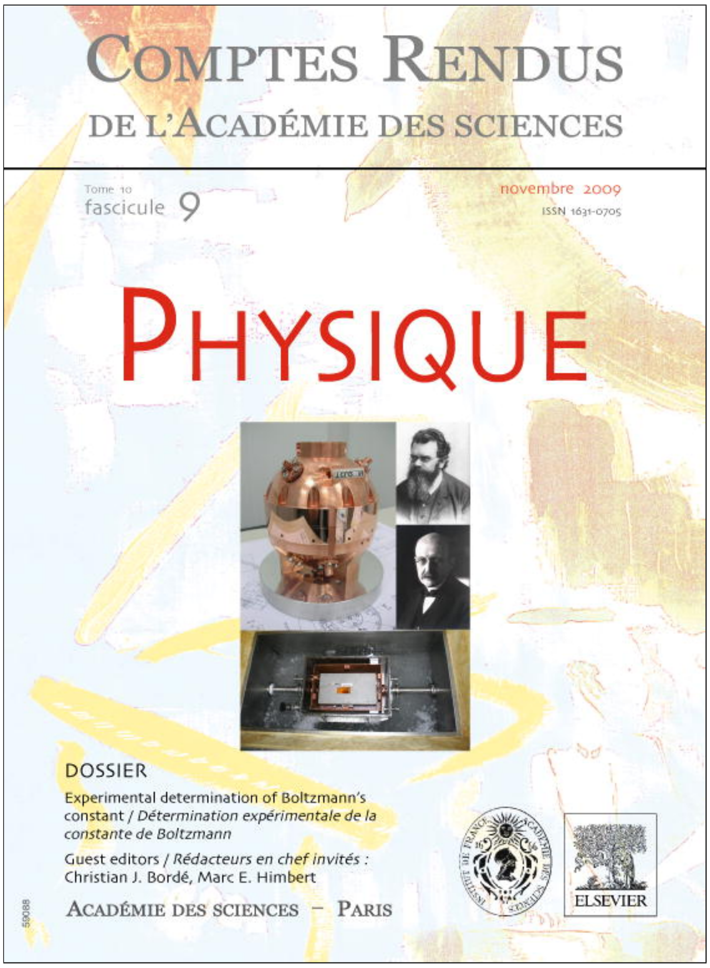
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COMPTES RENDUS PHYSIQUE

Experimental determination of Boltzmann's constant

Foreword: Progress in the experimental determination of Boltzmann's constant

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This special issue is entirely devoted to the experimental determination of Boltzmann's constant k (also frequently noted k_B to avoid the confusion with an electromagnetic wave vector modulus). Named after Ludwig Boltzmann, Austrian physicist of the XIXth century [1844–1906], this fundamental constant acts as a conversion factor from thermodynamic temperature to energy. More precisely, it has been introduced in statistical physics to link the entropy of a macroscopic system at thermodynamic equilibrium to the probability of occurrence of this state, taking into account all possible microscopic situations. The famous relation $S = k \log W$ engraved on Boltzmann's tombstone was never expressed by Boltzmann himself with a specific constant, but this was initiated later by Planck, when he derived his black-body radiation law. This constant has therefore the same dimension as entropy and the dimensionless quantity S/k is Shannon's information entropy [1]. Indeed, k is sometimes considered as the quantum of information [2].

Whatever the physical principles involved in the experiment, any measurement of k requires a refined control of the thermodynamic temperature and the materialisation of references of the temperature. Since metrologists are presently attempting to redefine base units of the SI (the international system of units) using fundamental physical constants [3], there is currently a great interest for new, accurate determinations of k, which could link the thermodynamic temperature unit (the kelvin) to the quantum of thermal energy and to statistical thermodynamics. The present definition of the unit "kelvin" assigns a fixed value to the temperature of the triple point of water. It is based on a constant of nature, assumed to be uniform and sustainable, as it is the case for the definition of the second based on the period of a transition in atomic caesium. However, the practical realization of the unit still requires a kind of artifact. One has to build cells where the triple point of water can be obtained and, indeed, the precise international recommendations for doing this have evolved over time. A new definition involving a fixed numerical value of k would also have the advantage of being directly applicable to any primary measurement method of the thermodynamic temperature, such as pyrometry. However, to obtain the full benefit from such a new definition, it is first necessary to obtain a sufficiently low relative uncertainty on the value of the Boltzmann constant, typically of the order of 10^{-6} and, of course, an international consensus on the numerical value.

In practice, only a few physical principles can be applied to set up an experiment aiming at the determination of k. In most cases, one has to link a macroscopic observable to the microscopic thermal motion of particles at the thermodynamic equilibrium. The equation of state of an ideal gas gives directly access to the gas constant R, and thus to k. The velocity of sound in gases relies on how mechanical waves can propagate in the medium, thanks

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to the collisions between molecules, which also depend on their thermal motion. The static or dynamic orientation of the electric (or magnetic) dipoles of polarisable molecules in an electric (or magnetic) field result in a balance between the driving process by the field and the thermal dispersion of the observable quantity. Dielectric constant measurements and refractive index measurements are thus linked to k. The electrical noise in a conducting device relies on the thermal motion of the charge carriers in the medium. The shape of the spectral line observed by probing the absorption of atoms or molecules in a gas can be deduced from their individual velocity distribution, thanks to the Doppler effect. Finally the spectral distribution of the radiation emitted by a black body, according to Planck's law, also involves the Boltzmann constant.

The most accurate determination of the Boltzmann constant, up to now, has been performed by Moldover et al. at NIST (USA) more than 20 years ago, with an accuracy in the 2×10^{-6} range [4], using an acoustic method in a gas. The first article of this special issue is a review of the progress in such experimental determinations. It is completed by the paper of Pitre et al. describing recent advances achieved in France using the acoustic resonance measurements in quasi-spherical resonators. These experiments are measurements of the gas constant R and give a determination of k if the Avogadro constant N_A is known. They mainly rely on the thermophysical properties of helium, which can be computed ab initio, as is recalled in the paper by Mehl.

In the same way, electrical properties of helium such as the electrical dipole polarisability, have been accurately modelled. This gives access to the determination of k (also through a measurement of R) described in Fellmuth et al., where the equation of state of the gas is expressed in terms of the dielectric constant.

A promising way to have a direct experimental access to k is the spectroscopic analysis of the line shape for atomic or molecular transitions obtained from gases in the Doppler regime. Several experiments are described in this issue for molecular lines in the infrared range of the electromagnetic spectrum (Djerroud et al., Yamada et al., Castrillo et al.). A general description of the different processes contributing to the line shape is detailed in the paper by Bordé. These experiments derive the Boltzmann constant k from the de Broglie–Compton frequency mc^2/h of the atomic species known from atomic interferometry measurements and from accurate ion trap measurements of atomic mass ratios. So, this is an experimental determination of the ratio between k and the Planck constant h.

Finally, the concept of the electrical Johnson-noise thermometer has been revisited. In the experiment described by Benz et al., the voltage is calibrated using quantum references, giving again access, after frequency measurements, to the k/h ratio.

One should emphasize the interest of a direct link to frequency measurements. Indeed most of the base quantities of the SI will be measured in the future through the use of the fixed values of fundamental constants combined with a frequency measurement. Since in the future SI it is very likely that Planck's constant will be fixed, the combination k/h leads to a direct connection between the unit of temperature and the unit of time. This also underlines the analogy between the action in quantum mechanics – for which the conjugate variable of the energy is the time – and the entropy in statistical physics – for which the conjugate variable of the energy is the inverse of the temperature [3]. The h/k ratio is the natural combination which appears in statistical quantum mechanics e.g. in complex time.

Some other experimental attempts to determine k are not covered by this special issue, such as refractive index measurements at NIST, a radiometry experiment at NPL, and other acoustic experiments in several laboratories. Nevertheless, most of the physical methods under progress are described in the issue. Some of them should lead, in the near future, to accurate determinations in the 1×10^{-6} relative uncertainty range. It is certainly highly desirable that at least two different methods agree at that level. Such a perspective would open the way, in the forthcoming years, to a new definition of the kelvin, the unit of thermodynamical temperature, in terms of a fixed numerical value for the Boltzmann constant.

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