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Towards the next evaluation of the fundamental physical constants†

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The note discusses the experimental data likely to be considered in the forthcoming evaluation of the 'best' values of the fundamental physical constants by Cohen and Taylor, and the implications for the realization of the ampere.

As far as is known, the accurately measured fundamental physical constants show no significant variation with time when expressed in terms of dimensionless quantities. The situation is rather more complicated when the experimental values are expressed in SI units, and increasingly reflects our inability to realize the definitions of the SI units with adequate precision. From some points of view this is a happy state of affairs for it allows us to reframe our definitions of the SI units in terms of the fundamental constants: as with the new definition of the metre (Petley 1983), or the use of the Josephson effect value of $2e/h$, E_J, to maintain the volt.

The CODATA task group on fundamental constants, of which the author is a member, has been considering the experimental data that will probably be included in the forthcoming evaluation by Cohen and Taylor. In this consideration, it is quickly apparent that the accuracy of K (the ratio of the maintained ampere to the 'absolute' ampere of the SI definition), has become of increasing importance since the 1969 review by Taylor, Parker and Langenberg. Thus the estimates of the values of such constants as the elementary charge, e, the electron mass m_e, the proton mass m_p, and the Planck constant h, all depend critically on the value of $K(e)$ or K^2 (the remainder). A further limitation is provided by the measurements of the fine structure constant α.

Cohen (1981) has shown that the crucial experiments can be displayed graphically as a Birge–Bond diagram by expressing them in terms of more accurately determined constants (such as the Rydberg constant, μ'_p/μ_B, E_J, c, and the ratio of the maintained ohm to absolute SI ohm, $\bar{R}$), and two unknowns: K and the fine structure constant α. This simplification is partly allowed by the improved precision of the direct measurements of m_p/m_e by the ion-trap technique developed at the University of Washington (Van Dycke & Schwinberg 1981). Their result is in any case in good agreement with other direct measurements (see review by Wineland *et al.* 1983), and with the indirect measurements of μ'_p/μ_N of earlier times (Mamyrin *et al.* 1972; Petley & Morris 1974), combined with the Phillips *et al.* (1975) value of μ'_p/μ_B. The Rydberg constant provides an important auxiliary constant and the most accurate of the new generation of laser spectroscopy measurements is that of Amin *et al.* (1981). This has an accuracy comparable with the reproducibility of the krypton-86 realization of the metre and is in reasonable agreement with the measurements of lesser precision by Goldsmith *et al.* (1978) and Petley *et al.* (1980).

The present results are displayed in figure 1, with K and $\alpha^{-1}K$ as horizontal and vertical

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† This paper is an amplified version of a contribution to the discussion, invited by the chairman, following Professor Smith's paper.

axes, and a range of values for the coordinates of only a few parts per million. Ideally all of the experimental measurements should be consistent with a unique value of α^{-1} and K, within the assigned uncertainties. On this plot measurements of the silver Faraday F (N.B.S.: Bower & Davis 1980), and the gyromagnetic ratio of the proton in a strong magnetic field, γ'_p(high) (N.P.L.: Kibble & Hunt 1979; N.I.M.–P.R.C.: Chiao *et al.* 1980; Wang 1981) determine $\alpha^{-1}K$, and generate a horizontal line.

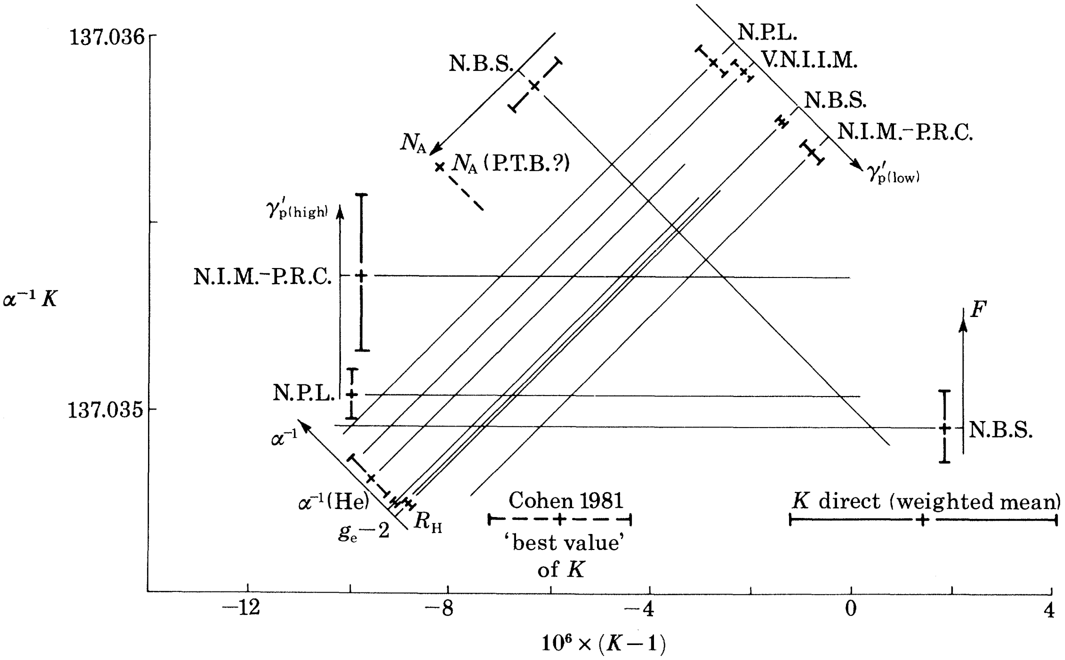

FIGURE 1. Birge–Bond display of most of the present data relating to the fine structure constant α, and ampere conversion constant K (i.e. ampere maintained at the B.I.P.M./ampere SI); each result has an associated standard deviation uncertainty and generates an appropriate line, as shown (based on the figure and data in Cohen 1981). The national metrological laboratories identified here by initials are given in full in the Appendix.

The direct realizations of the ampere K, yield a vertical line and these have been represented by the weighted mean of the available results (see Cohen & Taylor 1973; Cohen 1981). Elnekave & Fau (1981) have reported a preliminary absolute volt realization. Although their work, as with that of others (see, for example, Kibble *et al.* 1983), is not yet finally completed, the results are tending to confirm the estimates of K obtained via the fundamental constants.

The Avogadro constant, N_A(N.B.S.), has been measured by Deslattes *et al.* (see Deslattes 1980) by measuring the density and lattice parameter of very pure samples of silicon. Their measurement yields $\alpha^{-1}K^2$, defining a rectangular hyperbola on the figure. Incidentally the P.T.B. measurement of the lattice parameter of silicon, if confirmed by a corresponding value for N_A (N_A(P.T.B?): Becker *et al.* 1981) would give a value in better accord with the γ'_p(high) and Faraday measurements.

There are two remaining groups of results which essentially determine α^{-1}. The non-QED value is obtained via the measurements of the gyromagnetic ratio of the proton in a weak magnetic field, γ'_p(low). The most precise of these is that of Williams & Olsen (1979) (N.B.S.). Other measurements have been reported by Tarbeyev (1981) (V.N.I.I.M.), by Vigoureux & Dupuy (1980) (N.P.L.), and by Wang (1981) (N.I.M.–P.R.C.). The other determinations of

α^{-1} tend to involve QED, with the possible exception of the measurements of the quantized Hall resistance, R_H. The latter was first demonstrated as a measurement of α^{-1} by Klitzing *et al.* (1980). More accurate measurements by this technique have already been reported by Yamanouchi *et al.* (1981), by Tsui *et al.* (1982), and by Bliek *et al.* (1983). At present there are some discrepancies at the part per million level (possibly in the measurement process) and only one result has been shown for clarity. The most accurate estimate of the fine structure constant by a spectroscopic technique now comes from the measurements of Kponou *et al.* in helium (α^{-1}(He): Hughes 1981), as a result of improvements in the theory. The remaining, and most accurate estimate of α, is obtained from the determination of the g-factor anomaly of the free electron ($g_e - 2$) at the University of Washington by Van Dycke *et al.* (1979).

The data pertaining to the fine structure constant is reasonably consistent with the 1973 recommended value and leads to the conclusion that all continues to be well with quantum electrodynamic calculations to the *n*th decimal place. The situation regarding the best value of K shows little change since that discussed by Taylor (1976). The results are not as consistent as one would like, but they suggest that the 'best value' would be about 6 parts per million less than unity, as shown (the 1973 data was compatible with unity). There are likely to be consequent changes (*ca.* $2\sigma_{73}$) in the recommended values of many of the fundamental constants in the forthcoming evaluation (meanwhile the 1973 values should continue to be used). Of the remaining constants, the Boltzmann constant may be obtained from measurements of the gas constant (Quinn *et al.* 1976) and there is a new measurement of the gravitational constant, Luther *et al.* (1982), of precision better than 0.01 % that will supersede the 1973 recommended value. The forthcoming evaluation will be rather more sophisticated than the simplified analysis given here; thus the ratio of the maintained ohm to the absolute SI ohm is likely to be evaluated as well. Evidently, there is a strong incentive for the experimenter and theoretician to strive for improvement in the measurements, despite the fact that there is an important group of users who, quite sensibly, approximate the velocity of light as 3×10^8 m s^{-1}.

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Appendix. Explanation of abbreviations in figure 1.

N.B.S.: National Bureau of Standards, U.S.A.;
N.I.M.-P.R.C.: National Institute of Metrology, People's Republic of China;
N.P.L.: National Physical Laboratory, U.K.;
P.T.B.: Phisikalische-Technische Bundesanstalt, F.R.G.;
V.N.I.I.M.: All-Union Scientific Research Institute of Metrology (Mendeleev Institute), U.S.S.R.