Precision measurement of relative oscillator strengths — V. Comparison of oscillator strengths of Fe i transitions from levels $a^5 F_{1-5} (0.86-1.01 \text{ eV})$ and those from $a^5 D_{0-4} (0.00-0.12 \text{ eV})$

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Summary. A photoelectric pyrometer has been built and used to measure the temperature of the Oxford spectroscopic furnace on the International Practical Temperature Scale 1968 to an accuracy of ± 1 K (3 $\sigma$). Measurements have been made of the relative oscillator strengths of Fe i absorption lines originating from energy levels separated by about 1 eV. These measures have an accuracy of about 0.5 per cent and are intended to link existing measures made at Oxford from levels $a^5 F_{1-5} (0.86-1.01 \text{ eV})$ to measures made from levels $a^5 D_{0-4} (0.00-0.12 \text{ eV})$.

1 The purpose of the measurements

Other papers in this series have been concerned with the precise* measurement of relative oscillator strengths of Fe i lines having closely similar excitation potentials. Thus, Paper IV (Blackwell et al. 1979a) deals with the 0 eV (0.00–0.12 eV) group of lines and Paper VI (Blackwell, Petford & Shallis 1979b) with the 1 eV (0.86–1.01 eV) group. To link these two groups of lines using the Oxford technique requires a precise measurement of temperature because the ratio of the populations of the lower levels is calculated from the Boltzmann relation. A relative error $\Delta T/T$ in the measurement of temperature leads to an error in the relative number density of excited atoms of $\Delta N/N = 1.2 \times 10^4 \times E/T \times \Delta T/T$ (Blackwell & Collins 1972), where $E$ is the difference in excitation of the lower levels in volts. We seek an accuracy of 0.5 per cent in the linkage of the two groups, separated by about 1 eV, to match the accuracy of the relative oscillator strengths in each group; this requires an accuracy in temperature of 1.24 K at 1600 K. Such an accuracy is not commonly attainable at the present time. Indeed, a decade ago it was unattainable, and it is now possible only because of recent developments in photoelectric pyrometry and high-stability lamps in national standards laboratories. In this work we try to attain at least this accuracy,

* Accuracies of relative oscillator strengths are quoted as standard errors for a set of 40 measurements. The accuracy of temperature measurement is quoted as the 99 per cent confidence level (3 $\sigma$).
bearing in mind that we shall be making many comparisons between groups of lines having different excitation potentials in the future, and that the bridging of larger excitation potentials will require a correspondingly higher accuracy.

2 Thermodynamic temperatures and their realization

Thermodynamic temperatures are closely approximated by the International Practical Temperature Scale 1968 (IPTS—68), which was ratified by the 15th General Conference on Weights and Measures in 1975 May. The defining points of this scale are quoted by Quinn (1975). The highest defining fixed point is the freezing point of gold, \( T_{Au} \), 1337.58 K. On the IPTS—68, temperatures above the gold point are measured from the ratio of the spectral radiance \( L(\lambda, T) \) at the unknown temperature to that \( L(\lambda, T_{Au}) \) at the gold point, making use of the Planck radiation law

\[
L(\lambda, T) = \frac{2hc^2n^2\lambda^5}{\exp\left(\frac{c^2}{n\lambda T}\right) - 1}
\]

in which \( c = 0.014388 \text{m.K} \) (The Royal Society 1975), \( \lambda \) is the wavelength measured in air and the refractive index of air, \( n = 1.00029 \). The difference between the value obtained and the true thermodynamic temperature is dependent (apart from experimental errors) on the correctness of the specified values for \( c \) and \( T_{Au} \). The errors in these are not known, but that in \( c \) is unlikely to be significant. Recent work (see, e.g. Bedford & Ma 1976) suggest that the gold point is close to the correct thermodynamic value, within 0.2—0.3 K almost certainly. The error \( \Delta T_{Au} \) in the gold point propagates at higher temperatures according to

\[
\Delta T = \left(\frac{T}{T_{Au}}\right)^2 \Delta T_{Au}.
\]

The temperature scale up to 1973 K has been realized at Oxford by use of a high-stability vacuum standard lamp (Lee et al. 1972), with water-cooled base, calibrated at the National Physical Laboratory. The reproducibility between national laboratories of the IPTS—6 scale above the gold point, using these high-stability lamps, has been tested through comparison of measures made by the four standards laboratories: the National Bureau of Standards, Washington, the National Physical Laboratory, Teddington, the National Standards Laboratory, Australia and the Physikalisch-Technische Bundesanstalt, Germany. Measurements at these laboratories agreed to within a few tenths of a degree up to 1973 (Lee et al. 1972). A later comparison has been made of the scales between 1300 and 2000 as realized at NPL and PTB, showing an average difference over the eight points measured of 0.04 K. These comparisons show that the high-stability lamp is a suitable standard source for our purposes. The accuracy of calibration of the lamp used at Oxford is \( \pm 0.9 \text{ K} \) (3 \( \sigma \) at 1900 K. After use at Oxford the lamp was recalibrated at NPL, when it was found that there was no significant change in its calibration. The temperature measurements at Oxford have been made using the specially constructed photoelectric pyrometer described in the next section.

3 The photoelectric pyrometer and its use

The design of the pyrometer follows closely that used by the National Physical Laboratory (Coates 1975). The test object in the furnace, and the standard lamp, are focused in turn to a pinhole aperture using an off-axis ellipsoidal mirror, and the light then passes through a
interference filter on to a cooled EMI type 9558 photomultiplier. The output of the photomultiplier is measured using a photon counting system, and neutral filters in the optical path reduce the count rate to about $10^3$ s$^{-1}$, with a dead-time of 120 ns. Both the dead-time and the transmission of the neutral filters have been found by measuring the count rate with the various filters placed successively in the beam, using a range of radiation fluxes on the photomultiplier. The pinhole has a diameter of 0.266 mm, corresponding to a target size at the furnace of 0.98 mm. The interference filter has a bandwidth of 0.1 nm centred on a wavelength of 661.95 nm. These parameters have been chosen so that the bandpass is free of any absorption lines formed in the furnace which would affect the measurement of temperature. The lamp has been calibrated at a wavelength of 662.6 nm, measured in air, and a correction, of the order of 0.2 K over our temperature range, has been made to allow for the difference between this wavelength and the one used at Oxford. The correction arises from the change in emissivity of tungsten between the two wavelengths.

The furnace temperature has been measured by sighting the pyrometer on to carbon blocks placed at known positions along the furnace tube. To avoid the need for a correction for emissivity, these blocks have been drilled with cavities 40 mm deep and 3 mm in diameter. Calculations of the emissivity of a cavity have been considered by Bedford (1972). The deviation from unity of the effective emissivity, $1 - \varepsilon$, of the cavity used by us as a function of the assumed surface reflectivity of carbon is plotted in Fig. 1, which shows that any surface reflectivity less than 0.25 is suitable for our purpose. To avoid contamination of the carbon surface by iron carbide we have not charged the furnace with iron, as we usually do, but have made use of the naturally occurring iron impurity in the carbon tube. The temperature that we wish to measure is that of the equilibrium radiation in the tube, and a simple argument shows that the blocks deviate from this temperature by only small amounts. Consider a block at the centre of the tube, which is of length $2L$ and radius $r$, and is at a temperature $T$. The block is heated by radiation from the inside walls, which occupy a solid angle $4\pi[1 - (T^2/2L^2)]$, and it emits radiation into a solid angle $4\pi$. Hence it will take up a temperature $T - \Delta T$, where $4\pi T^4[1 - (T^2/2L^2)] = 4\pi (T - \Delta T)^4$ and $\Delta T/T = \frac{1}{8}(T/L)^3$. For the furnace, $r = 25$ mm and $L = 610$ mm, so $\Delta T/T = 2.1 \times 10^{-4}$, i.e. $\Delta T = 0.42$ K at 2000 K. The appropriate correction has been made. In addition, the temperature distribution along the tube has been measured using a series of blocks. A correction for the effect of the furnace window has been avoided by placing an identical window in an equivalent position in the path of the light from the standard lamp. A correction has also

![Figure 1. Deviation from unity of the effective emissivity, $1 - \varepsilon$, of furnace cavity as a function of the assumed reflectivity of carbon.](image)
been made for the effect of small-angle scattering in the optical train of the pyrometer. This is necessary because of the different geometry of the surroundings to the target area in furnace and lamp; for the lamp, the pyrometer is directed at a small area on a strip, whereas for the furnace it is directed at the same area on an extended surface. The effect has been investigated by the method discussed by Coates & Andrews (1978). Tests have shown that no correction for any polarization of the light from the standard lamp is necessary. Finally, a small correction has been made for the difference in size between the target area of the NPL pyrometer and the Oxford pyrometer. This correction arises from the variation in surface brightness of the lamp filament between its centre and edge.

These corrections amount to a total of about 2 K, which is known with an accuracy of ±0.3 K (3σ). The temperature of the standard lamp was set close to the temperature of the furnace so that errors of photometry are negligibly small. We estimate that the final error in temperature measurement is not significantly different from the uncertainty in the temperature calibration of the standard lamp, i.e. ±0.9 K. When the furnace has stabilized, we have found that its temperature usually remains constant to within 0.5 K over a period of several hours.

4 Results

We have used the furnace and pyrometer to link the oscillator strengths of the 0 and 1 eV groups of lines. The scheme of measurement is shown in Fig. 2; these particular comparisons have been chosen so that the measured equivalent widths of the pairs of lines are closely

![Figure 2. Measured linkages (Δ log gf) between 0 and 1 eV blocks of Fe I lines.](image)

similar. Measured and relaxed values for the comparisons are shown in Table 1, which shows that the change on relaxation is 0.46 per cent (0.0020 dex). We express the final result by relating the value of $\log g f(358.120)$ to that of $\log g f(371.994)$: from Paper IV, $\log g f(371.994) - \log g f(367.992) = 1.1685$; from the present results, $\log g f(358.120) - \log g f(367.992) = 2.0042$, hence, $\log g f(358.120) - \log g f(371.994) = 0.8357$. The standard error of the final comparison $\log g f(358.120)/\log g f(371.994)$ is ±0.0020 dex (0.46 per cent), determined almost entirely by photometric errors.
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Table 1. Measured and relaxed values of log $gf$ for pairs of Fe I lines, with residuals.

<table>
<thead>
<tr>
<th>From</th>
<th>To</th>
<th>Measured $\Delta \log gf$</th>
<th>Relaxed $\Delta \log gf$</th>
<th>Residual</th>
</tr>
</thead>
<tbody>
<tr>
<td>$367.992$</td>
<td>$358.120$</td>
<td>$2.0062$</td>
<td>$2.0042$</td>
<td>$+0.0020$</td>
</tr>
<tr>
<td>$437.593$</td>
<td>$368.746$</td>
<td>$2.1959$</td>
<td>$2.1979$</td>
<td>$-0.0020$</td>
</tr>
</tbody>
</table>

This result will be used in a succeeding paper to place the relative data for the 1 eV group on an absolute basis, and the general technique will in future be used at Oxford for bridging large gaps in excitation potential.

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**References**