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Interferometric measurements of $^{130}Te_2$ reference frequencies for $1S$-$2S$ transitions in hydrogenlike atoms

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The frequencies of five Doppler-free $^{130}Te_2$ transitions at 486 and 488 nm have been measured interferometrically with reference to an iodine-stabilized 633-nm He-Ne laser. These frequencies are useful as transfer standards for $1S$-$2S$ transitions in deuterium, hydrogen, positronium, and muonium. A comprehensive study of the reproducibility of such tellurium reference standards has been made. Under the conditions specified, the frequencies of components d_4, b_2, b_1, e_3, and i_3 in tellurium were found to be 613 881 149.1, 616 513 894.9, 616 678 855.8, 616 803 544.7, and 616 806 134.5 MHz, respectively. The overall standard deviation of frequency measurements on FM saturated tellurium spectra was 0.47 MHz across several cells, with 0.18 MHz day-to-day reproducibility for each cell. A comparison has also been made between the results reported here and our earlier measurements on tellurium [J. R. M. Barr, J. M. Girkin, A. I. Ferguson, G. P. Barwood, P. Gill, W. R. C. Rowley, and R. C. Thompson, Opt. Commun. **54**, 217 (1985)].

INTRODUCTION

There has been significant interest in recent years in establishing reference frequency standards near 486 nm using Doppler-free saturated spectra in molecular tellurium vapor.[1,2] Such spectra can be used to provide suitable transfer standards for the absolute frequency measurement of narrow-linewidth $1S$-$2S$ transitions in hydrogenlike atoms.[3-5] A knowledge of the $1S$-$2S$ frequency to a high precision in hydrogen and similar species such as deuterium, positronium, and muonium can lead to improved determinations of the Rydberg constant or the ground-state Lamb shift, for example, and direct experimental tests of QED.

A number of interferometric frequency measurements of specific saturated spectra in tellurium vapor near 486 nm have already been made. Original measurements[1] were of Doppler-free spectra close to one-half of the $1S$-$2S$ (243-nm) two-photon transitions in hydrogen and deuterium. Subsequently, measurements of a tellurium component near the $1S$-$2S$ 486-nm two-photon positronium transition,[6] and a further component near one-half of the muonium $1S$-$2S$ (244-nm) two-photon frequency,[7] were achieved, but relative to the original measurements.[1] Some discrepancies were evident from comparison of all these results,[2,8] both in frequency values and the stated conditions relevant to some measurements. Recently, new independent interferometric measurements were made at the appropriate tellurium components relevant to the hydrogen, deuterium, and positronium transitions.[9] These results were in good agreement with earlier measurements that used the same tellurium cell and oven arrangement.[4,6]

Against this background, it was expected that potential problems existed relating to the cell-to-cell tellurium frequency reproducibility, and between different methods of determining the true cold point and hence the vapor pressure within the cell. The Southampton cell-oven system[10] used in our original measurements had no sidearm to provide independently controllable vapor pressures, and thermocouples were used to monitor cell-wall temperatures. Subsequent workers have adopted a linear absorption criterion to verify the vapor pressure.[2]

The study reported here was undertaken in order to provide a more wide-ranging assessment of tellurium frequency standards. New and independent frequency measurements of FM saturated tellurium spectra relevant to the $1S$-$2S$ transitions in hydrogen, deuterium, positronium, and muonium are reported. The investigation involved a study of six tellurium cells, all purchased from the same manufacturer,[11] together with further measurements of the original cell in its original oven. The new cells all had a 50-mm sidearm, to provide a cold point to control the vapor pressure, and were housed in newly designed ovens. The oven design, described more fully below, provided better thermal insulation and temperature control than the original system. Particular notice has been paid to the assessment of day-to-day reproducibility using a particular cell, cell-to-cell variations, and the equivalence between different methods for monitoring conditions. Various potential sources of frequency shift have been investigated, and the results on the original cell are reassessed in the light of new data. Finally, the frequency measurements reported here are compared with those of other workers.

OBSERVATION OF DOPPLER-FREE TELLURIUM SPECTRA

Tellurium Doppler-limited absorption spectra have been observed and catalogued for wavelengths between 420 and 540 nm.[12] The commercially available cell is filled with isotopically pure ^{130}Te, providing a simpler set of spectroscopic lines than would natural tellurium, which is comprised of eight isotopes. The spectrum of tellurium is, however, still complicated because transitions to two electronic [$A(O_u^+)$ and $B(O_u^+)$] states are allowed from the ground state.[13]

The cw laser used to interrogate the tellurium lines was a Coumarin-102 standing-wave dye laser (Coherent 599-21). Approximately 15 mW single-mode output was produced with fresh dye, when pumped with 1.3 W violet output from a Coherent K-3 krypton laser. As the dye degraded, the krypton-laser power had to be increased to 3 W to maintain 15 mW dye laser output.

The $^{130}Te_2$ cell was 75 mm long, 25 mm in diameter, and had a 50-mm sidearm. It was heated in an oven designed at the National Physical Laboratory (NPL) and shown in Fig. 1. Three heaters were provided, each with a separate temperature control circuit using a type-*K* thermocouple for feedback control. The heaters were wound noninductively to prevent any perturbation to the transitions from ac magnetic fields. It had previously been observed that some $^{130}Te_2$ lines were susceptible to Zeeman shifts,[1] although not those actually used for the frequency determination. Two of the three heaters controlled the wall temperature and the third controlled the sidearm temperature. A precalibrated fourth thermocouple (type *R*) was also attached to the sidearm as a monitor and, during initial tests, agreed with the feedback thermocouple to within ±1 °C. The type-*K* thermocouples had a stated accuracy over the temperature range used of ±2 °C. Thermal insulation was provided by a filling of expanded mica between the heaters and outer stainless-steel housing. This outer housing was water cooled to a temperature close to ambient to ensure that the heaters did not cause air convection around the cell and hence perturb the pointing stability of the laser beams. Finally, the oven was purged with argon, partly to protect the heaters from oxidation and partly for safety reasons, in the case of tellurium cell breakage. Two such ovens were constructed. In both systems it was observed that there was a minimum temperature difference necessary between the cell wall and sidearm to ensure that the cell cold point was located in the sidearm. If this temperature difference was too small, then tellurium condensate was observed to form in the center of the cell windows. In one oven, this was observed to occur for temperature differences of less than 13 °C and in the other oven, less than 29 °C. All the results reported here were therefore obtained with a 30 °C temperature difference to guarantee that the vapor pressure was controlled by the sidearm temperature.

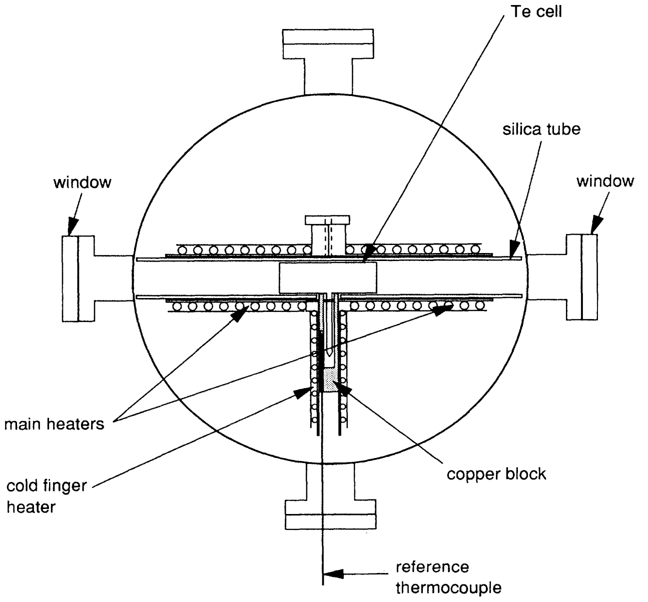

FIG. 1 Oven arrangement used for control of the tellurium cell-wall and cold-point temperatures. The outer housing, shown as a circular cross section, is of stainless steel. The space between this and the heater is filled with expanded mica, to provide thermal insulation.

Tellurium Doppler-free spectra were observed relevant to the four 1*S*-2*S* transition frequencies in deuterium, hydrogen, positronium, and muonium. The apparatus for observing these spectra is shown in Fig. 2. In order to achieve the best signal-to-noise ratio for these spectra, it was decided to observe them by fast frequency modulation (FM) techniques.[14,15] This technique has been already demonstrated in the observation of saturated iodine spectra, observed with dye[16] or He-Ne lasers.[17,18] The technique has been reported previously for dye laser stabilization to tellurium,[4] but without published details of the FM tellurium spectra. FM spectroscopy is a particularly powerful technique when used with dye lasers, since it allows signal recovery at frequencies above those where intensity noise is prevalent (i.e., less than a few MHz). FM techniques provide detection sensitivities close to the shot-noise limit.

As shown in Fig. 2, the dye laser output is split into a saturating beam and a weaker probe beam, which counterpropagate in the tellurium cell. Futher pickoff beams are provided for a commercial wavemeter[19] and a 1-m etalon is used for the precision interferometric frequency measurements, as described later. The saturating beam is frequency shifted by 40 MHz by an acousto-optic modulator (AOM) and chopped at 1 kHz. The retardation plate and polarizing beam splitter (PBS) are used to make the saturating beam cross polarized with respect to the probe beam. The purpose of this, together with the acousto-optic modulator, is to provide optical isolation between the saturation experiment and the laser. Interference effects caused by spurious scattering from various optical components would otherwise cause a background signal on the observed spectra. It was found that polarization or an acousto-optic modulator alone were insufficient to provide adequate isolation. The probe beam was phase modulated with an electro-optic modulator (EOM), driven from an oscillator via a power amplifier and coupled into the modulator via a resonant coil. The probe signal was detected by an avalanche photodiode (APD), amplified and demodulated in the double balanced mixer (DBM). The use of cross-polarized probe and saturating beams also allowed the use of the polarized beam splitter to pick off all the probe beam for the detector. Care was taken to ensure that the avalanche gain was sufficient for the signal-to-noise ratio in the detection system to be photon noise limited.

The theory of the technique of FM spectroscopy has been fully described elsewhere.[14–16] Purely phase-

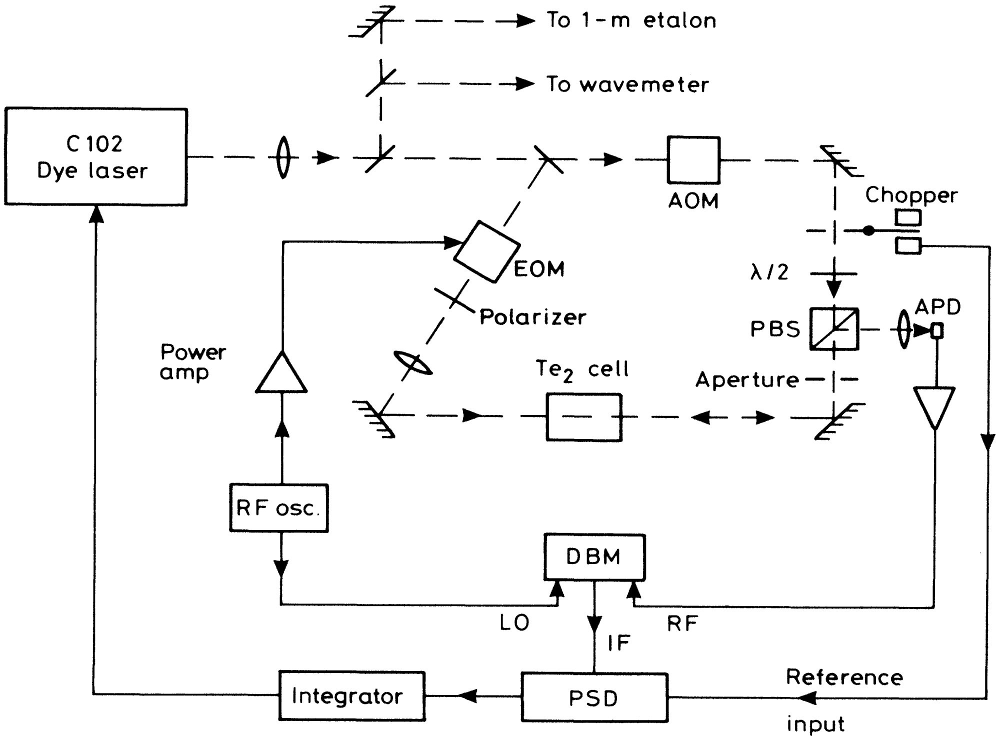

FIG. 2. Experimental arrangement for dye-laser stabilization to saturated spectra in tellurium.

modulated light should contain no associated amplitude modulation and so no output signal is then observed from the DBM. However, when the laser is tuned close to line center, the presence of the tellurium causes an imbalance in the amplitude or phase relationships of the modulation sidebands. This produces an rf beat signal at the detector which is demodulated to give a strong dc signal from the intermediate frequency (IF) output port of the DBM. The relative rf phase between the DBM local oscillator (LO) and "rf" inputs determines the shape of the observed discriminant. For frequency-stabilization purposes, a dispersion-type shape is necessary and this condition was obtained by adjusting the length of cable to the LO input to the DBM. The Doppler-free components recovered in this manner were then superimposed upon a Doppler-limited background. The phase-sensitive detector (PSD) was used to recover the signals on a flat background in a manner similar to that reported for iodine.[16]

The Doppler-free spectra for the four groups of tellurium lines under investigation obtained in the manner described above are shown in Figs. 3 and 4. These spectra were obtained with a cell-wall temperature of 550 °C and a cold point of 520 °C. The lines are labeled in the manner of previous publications[1,6,7] and the suffixes 1 to 4 refer to the spectral regions relevant to deuterium, hydrogen, positronium, and muonium, respectively. These spectra were obtained with a phase-modulation drive frequency of 47 MHz and a modulation index of 0.4. Better signal-to-noise ratios were projected for higher drive frequencies (i.e., several times the broad tellurium linewidth). Although spectra were obtained with an 87-MHz modulation frequency, the signal-to-noise ratio was actually better at 47 MHz, although the reason for this is

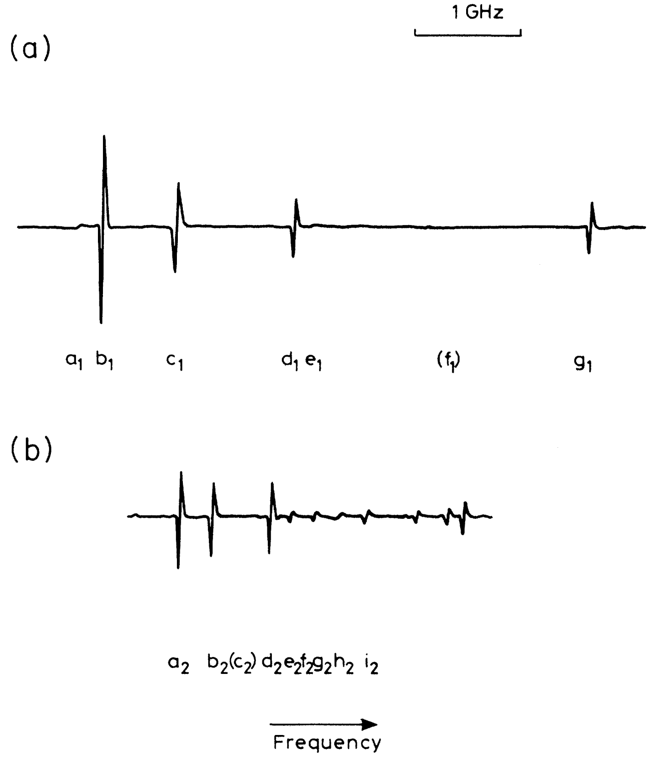

FIG. 3. Doppler-free FM spectra in $^{130}Te_2$ close to the frequency equal to a quarter of the $1S$-$2S$ transition frequency in (i) deuterium and (ii) hydrogen. The modulation frequency is 47 MHz. Component c_2 is broad and so was too small to be observed at this modulation frequency. Component e_2 lies in the high-frequency wing of d_2.

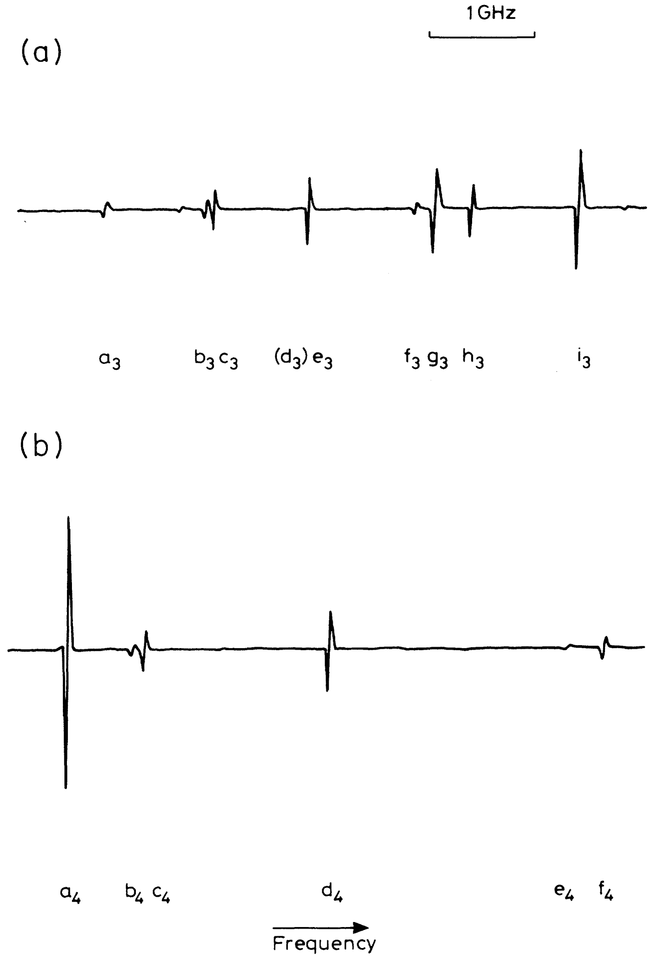

FIG. 4. Doppler-free FM spectra in ${}^{130}Te_2$ close to the frequency equal to (i) a half of the $1S$-$2S$ transition frequency in positronium and (ii) a quarter of the $1S$-$2S$ transition frequency in muonium. The modulation frequency is 47 MHz.

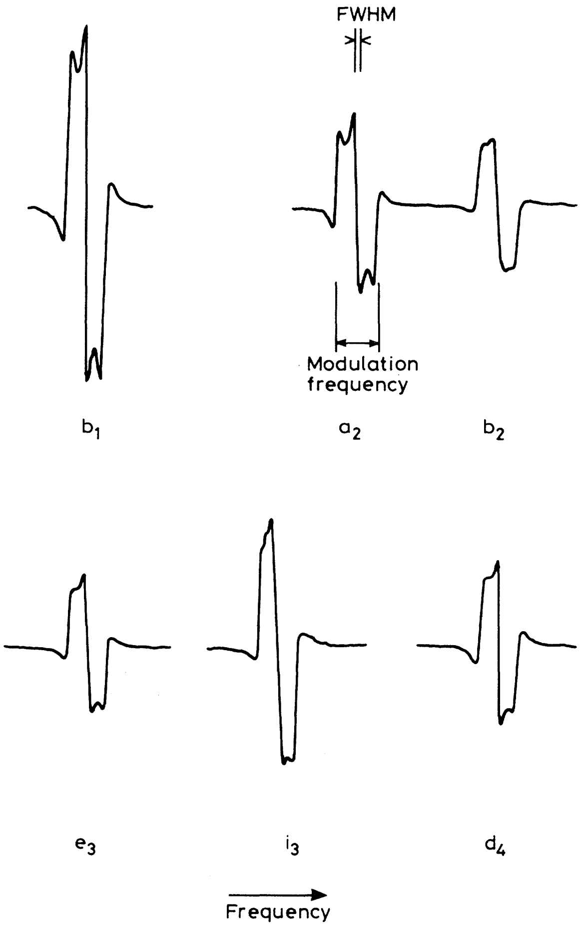

FIG. 5. Selection of scans over various Doppler-free tellurium spectra with a 87-MHz modulation frequency. The wide variety of linewidths and the small asymmetries obtained are illustrated in this figure.

not clear. For this drive frequency, a maximum signal-to-noise ratio of 200 was obtained on line b_1 for a PSD time constant of 0.1 s. On this line, the residual background noise corresponds to a frequency uncertainty in the lock position of ±30 kHz.

MEASUREMENT OF FEATURE LINEWIDTH AND LINEAR ABSORPTION

The dispersion line shapes for six tellurium lines, obtained for a modulation frequency of 87 MHz and 520 °C cold-point temperature, are shown in Fig. 5. These spectra display a more characteristic dispersion-shape profile than Figs. 3 and 4, due to the higher modulation frequency. Tellurium transitions display a variety of linewidths, all considerably larger than typical iodine linewidths of a few MHz.[20] Asymmetries have also been reported for tellurium lines,[9] and these may be observed in Fig. 5. The full width at half maximum (FWHM) linewidths for the lines b_1, b_2, e_3, i_3, and d_4 were 11, 18, 16, 18, and 16 MHz, respectively. Such broad linewidths indicate that we should not expect such a good reproducibility from a tellurium-stabilized laser as from one stabilized to iodine. For the b_1 line, the broadening as a function of tellurium vapor pressure was also measured and found to be 34 kHz Pa^{-1}. The linewidths measured here agree with those previously published, within experimental error, although the previously published[9] measurements were made at a slightly lower pressure. The FM spectra provide a particularly convenient method for linewidth determination, since calibration of the frequency scale is readily provided by the fact that the subsidiary zero crossings of the dispersion shape are 87 MHz apart, corresponding to the modulation frequency. Both the drive-frequency interval and the linewidth (FWHM) are indicated in Fig. 5, for one of the tellurium lines, to illustrate the measurement.

Linear absorption of the tellurium vapor has previously been used[2,6-9] as a basis for checking the effective temperature of the cold point, and hence the vapor pressure. The absorption line used is an isolated absorption about 9 GHz below the frequency of the b_2 line. It was verified that only one Doppler-free feature could be observed within the Doppler-limited profile. For a cell length l, containing N molecules per unit volume, the expected absorption is $1-\exp(-N\sigma l)$, where σ is an effective absorption cross section. To obtain this as a function of temperature, it is necessary to express N as a function of temperature.[21] There is also the possibility that the absorption may vary with wall temperature, reflecting a change in the ground-state occupancy. For a cold-point temperature of 520 °C, however, a rise in the wall temperature from 550 °C to 660 °C increased the absorption by only 5%. Figure 6 shows the measured absorption versus temperature for three particular cells. It is immediately apparent that the observed variations do not correspond to the expected theoretical dependence at high temperatures. "Break points" are observed, above which the absorption fails to reach expected values, and which vary in temperature from 505 °C to 585 °C for the six cells investigated. We suggest that this occurs because, at this break point, all the available tellurium has been vaporized. Above this temperature, the molecular density remains constant. The temperatures of 505 °C and 585 °C correspond to vapor pressures of 98 and 562 Pa. These pressures correspond to the cells containing only 0.14 and 0.7 mg of Te, respectively. Above the break point, the absorption increases only slightly, similar to the slight increase with wall temperature noted above. The absorption data below the break points for all cells have been averaged, and fitted to the absorption formula given above using at least-squares fit. The fit yields $\sigma=7.2\times 20^{-22}$ m^2, and is drawn as the solid line in Fig. 6. The root-mean-square error of the fit is 2.7%, and the cell-to-cell agreement using the two ovens at 520 °C was ±2%.

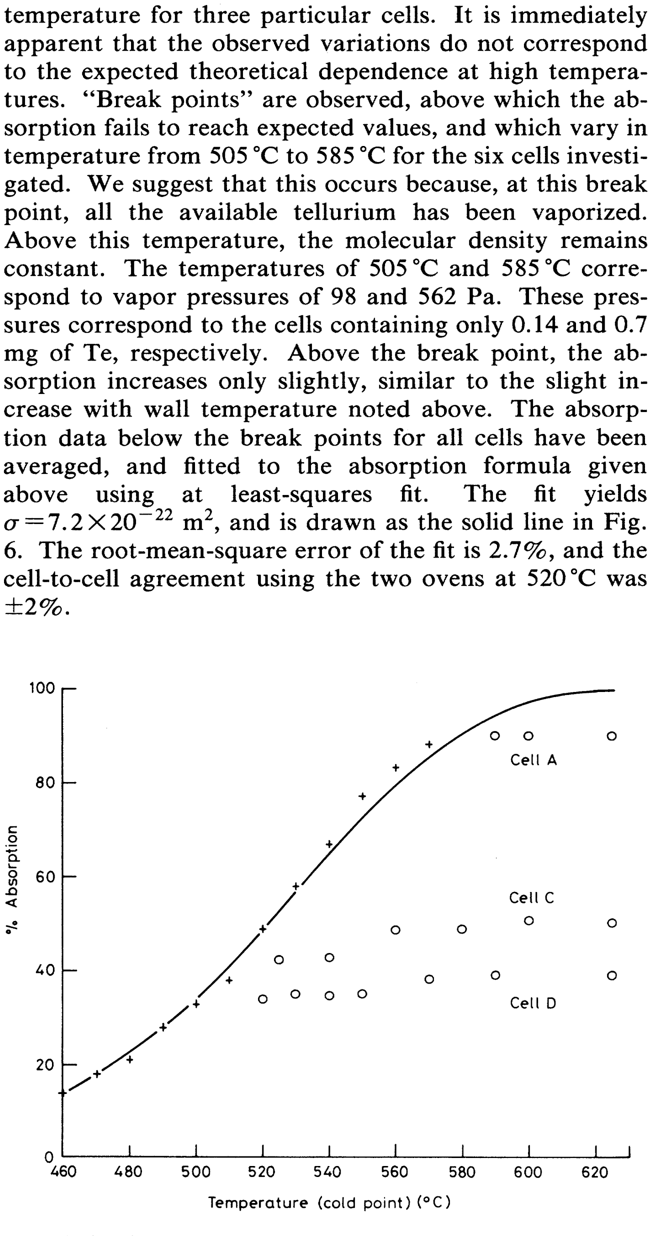

FIG. 6. Linear absorption as a function of cold-point temperature on a tellurium line 9 GHz less than the frequency of the b_2 line. The varying amounts of tellurium in three cells give rise to three different break points where the absorption no longer follows the expected (solid) line. Data above and below the break point are indicated by circles and crosses, respectively.

In previously published work,[9] the absorption at the working temperature was set to 23% and, from Fig. 6, it may be deduced that this corresponds to a temperature of 480 °C, whereas a temperature of 513 °C was recorded. This probably suggests that 513 °C was a wall temperature, and that there is a temperature difference of 33 °C between the hot and cold points, similar to our system.

LASER FREQUENCY STABILIZATION TO ^{130}Te$_2$ TRANSITIONS

In order to make measurements on the frequencies of the various tellurium transitions, the dye laser was frequency stabilized to each component in turn. The output signal from the PSD was fed via an integrator to the external input of the dye-laser control box. The acousto-optic drive frequency was +40 MHz, resulting in dye-laser stabilization at +20 MHz above line center,[16] and this offset was corrected for in the final results. The PSD reference input was obtained from the chopper frequency of ≈1 kHz. The probe beam in the tellurium cell had a beam radius $w(=1/e$ amplitude radius) of ≈ 0.17 mm, and the saturating beam radius was ≈ 0.47 mm. With the normal dye-laser operating power (P) of 15 mW, the probe and saturation powers were 0.14 and 4 mW, respectively. This corresponds to peak power densities $(=2P/\pi w^2)$ of $\approx 3.1\times 10^3$ and 12×10^3 Wm^{-2}, respectively. The tellurium cell was operated at a cold-point temperature of 520 °C, with a wall temperature of 550 °C. These conditions are the same as those used to obtain the spectra of Figs. 3 and 4.

INTERFEROMETRIC FREQUENCY MEASUREMENTS

Interferometric frequency measurements of the stabilized dye laser with respect to a 633-nm iodine-stabilized reference laser were made using an evacuated 1-m plane mirror Fabry-Pérot interferometer. A fuller description of the operation of the interferometer has been given in previous publications.[22,23] Two spacers were available, to provide free spectral ranges of 7.5 GHz and 150 MHz using the same étalon plates, which enabled the phase shift of the plates at 486 nm to be determined. The length of either spacer could be independently determined using frequency-stabilized He-Ne lasers of known frequency at 543 and 612 nm.[24] A commercial wavemeter[19] was verified to have an accuracy sufficient to determine the order number at 486 nm for the shorter étalon. The results from the shorter étalon are then sufficient to determine the order number in the blue for the longer étalon. Measurements on the shorter étalon were performed using components b_1 and i_3. Alternative sources for values of the tellurium frequencies, sufficiently accurate to determine the order number of the 1-m étalon, are found in recent publications.[1,6–9] In addition, the frequency interval between components e_3 and i_3 was determined approximately by counting the 17.5 fringes of the 1-m étalon, while scanning the dye laser between the components. The excellent agreement between all these sources provides complete assurance for the correct determination of the longer étalon order number for all five lines.

In the experimental arrangement of Fig. 2, a significant advantage over the method previously employed[1] is that the dye-laser light is unmodulated. This is essential for the proper operation of the 1-m interferometer, since modulated light broadens the fringes of the 1-m étalon causing systematic offsets. The stabilized dye-laser frequencies were determined by interferometric comparison with the 633-nm light from a He-Ne laser stabilized to component "i" of the 11-5 R(127) transition in $^{127}I_2$. A value of 473 612 214.8 MHz for the frequency of this laser has been assumed in measuring the tellurium frequencies. The laser was an NPL reference system, operated under preferred conditions.[25] It has a resettability of about 1 part in 10^{11} and its frequency is within 4 parts in 10^{11} of the mean of a number of lasers from other national standards laboratories with which it has been compared.[26]

The stabilized dye laser was frequency servocontrolled to components b_1, b_2, e_3, i_3, and d_4. Components b_1 and b_2 are those previously measured at NPL in our original determination.[1] Components e_3 and d_4 have been measured at Stanford[6,7] and so were chosen for our determination. However, component e_3 lies on a second broad feature, especially noticeable when observed by amplitude modulation techniques, and so it was decided to measure an alternative component near the positronium line. Line i_3 is a strong, relatively narrow transition, on a flat background, and therefore appeared suitable for stabilization purposes.

Frequency measurements were performed on four of the available six cells, using the 1-m étalon, the remaining two cells (labeled C and D) having too little tellurium for measurements under the chosen conditions. A total of 113 observations were made under the standard operating conditions, each observation being an 8-min average. For each of the four cells, all five tellurium components were measured on at least four different days. These measurements provided values for the day-to-day frequency reproducibility of the laser using a given cell, and also shifts attributable to the cell itself. The day-to-day reproducibility was 0.18 MHz (one standard deviation), although cell-to-cell shifts of up to 0.7 MHz were recorded for the new cells. This range is well outside that expected from the temperature uncertainty of ±2 °C. The temperature uncertainty agrees well with the ±2% reproducibility on the absorption measurements, but corresponds to a pressure uncertainty of only ±8 Pa at 520 °C, or ±70 kHz frequency change. These figures are all included in the error budget of Table I. In this table, the last five entries concern the performance of the iodine-stabilized reference laser and the tellurium-stabilized dye laser. The first five entries relate to the operation of the 1-m étalon. The entry for "prismatic imbalance" refers to the effect of a possible relative displacement between the red and blue Fabry-Pérot rings that are imaged onto the detector pinhole. Due to imperfect relative alignment of the wedge angles of the étalon plates and the windows of the vacuum vessel, which act as small-angle prisms, images in the different colors may be slightly displaced.

Within the overall reproducibility of 0.18 MHz for a particular cell, no significant shifts in frequency were observed on changing a number of operating parameters. These included the rf frequency to the electro-optic modulator (operated at 47 and 87 MHz), modulation index (using $m = 0.4$ and 0.2), and cell-wall temperature (varied from +30 °C to +60 °C above the cold point). Under the normal beam-focusing conditions, reducing the laser power to 50% of normal also produced no observable shift. However, shifts of up to 1 MHz could be observed when using tighter beam focusing. With a similar laser power to normal, these tighter focusing conditions corresponded to $w = 42$ μm (for the probe beam) and $w = 126$ μm for the saturating beam. Both beam power densities were then about 15 times that normally used. With the normal, weaker focusing, the observed frequency did not change significantly within the overall statistics, either with time or with optical realignment.

The most significant parameter affecting the optical frequency is the Te_2 vapor pressure. The effect on the b_2 line of increasing Te_2 vapor pressure is shown in Fig. 7 for cell A. It is immediately observed that there are two portions to this curve. The results of Fig. 5 suggest that all the tellurium in this particular cell is vaporized at 577 °C (480 Pa). Therefore, the true shift with pressure is the steeper curve, for $P < 480$ Pa. For $P > 480$ Pa, the gentler slope is presumably only due to ideal-gas expansion. The break-point temperature observed from pres-

TABLE I. Measurement uncertainties.

Source of uncertainty	Standard deviation ($\times 10^{-11}$)
Phase-shift determination	3
Flatness and illumination uniformity	3
Prismatic imbalance (image shear)	6
Diffraction	2
Servo errors	2
633-nm reproducibility	2
Te cell temperature (±2 °C)	12
Repeatability of results (statistical)	29
Te cell-to-cell variation	60
633 nm (relative to definition)	34
Overall total (root sum of squares)	76 (=0.47 MHz)

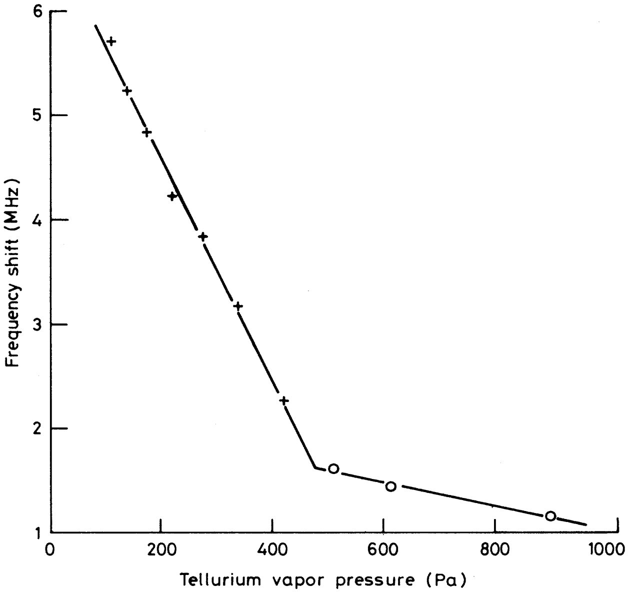

FIG. 7. Frequency shift as a function of pressure for the tellurium b_1 line. This is measured using cell A, and the break point of 480 Pa corresponds to that observed by absorption in Fig. 5. The vapor pressure is that calculated from the sidearm temperature, although, above the break point, the actual pressure should only increase as expected for a nearly ideal gas.

sure shifts agreed to within ±4 °C with that observed from absorption measurements for four of the cells. One cell (C) had a discrepancy of 15 °C between break temperatures measured in the two ways, and the sixth cell had too much tellurium to determine a break temperature by frequency-shift observations. Each of the pressure shifts for the five lines was determined at least twice, using two of the available cells. The average slopes for the temperatures below the break point were, in kHz Pa^{-1}, -9.1, -10.0, -11.3, -10.1, and -8.8 for the lines d_4, b_2, b_1, e_3, and i_3, respectively. The estimated standard error of the mean for these gradients is 0.3 kHz Pa^{-1}. In measuring pressure shifts, we have used the same reference[21] for calculating pressure from temperature as in previous work.[6-9] However, it is commented upon in one article[27] that such pressure measurements are rarely made to better than ±20%. If a new Te_2 vapor pressure determination were made, or alternative data used, we may expect this to significantly affect pressure-shift gradients. However, it is ultimately only sidearm temperature that can easily be measured, and the frequency variation with temperature will be unaffected by a vapor pressure redetermination.

Table II summarizes the measured frequencies for a sidearm temperature of 520 °C for the five components measured. The frequencies represent a mean for the four cells measured, labeled A, B, E, and F. Also shown in this table are the offsets from the mean of results measured with the four cells individually. The table shows that the pairs of cells (A,B) and (E,F) show similar offsets. These pairs were purchased at the same time, and such pairs of cells show similar character both as regards the amount of tellurium and the measured frequency. The results of Table II may be compared with fully independent measurements of the same components,[9] once a pressure correction is made to allow for the difference in cell cold-point temperatures. A cold point of 480 °C is assumed to be the true cold point, rather than the 513 °C temperature quoted,[9] as discussed previously. Once this correction is made, the mean frequencies of the results reported here are found to be higher by only $+(0.2\pm0.2)$ MHz, well within the cell-to-cell variations shown in Table II.

The results reported in this paper have allowed a reassessment of earlier measurements[1] with the original cell and oven arrangement. The frequency values for b_1 and b_2 are not statistically different from those independently measured,[9] being about 1 MHz higher, with reported standard deviations of 0.25 MHz[1] and 0.6 MHz,[9] respectively. The frequency of the b_1 line was remeasured using the FM technique, and with the original cell and oven heated to give a wall-temperature thermocouple reading close to that originally reported of 643 °C. The cell was first heated to well above this temperature to verify, from linear absorption measurements, that there was adequate tellurium available. The observed frequency was only 0.4 MHz lower than the original measurement,[1] but higher than the mean of Table II by 1.3 MHz. Thus the b_1 frequency with the original cell and recorded wall temperature, but with a substantially different frequency-stabilization technique, has been found to give values within the observed day-to-day reproducibility for a given cell. The work on the Rydberg constant that used this cell[5,8] does not therefore require a correction from the results reported here. However, our recent measurements of the optical absorption and a remeasurement of the melting point of the tellurium in that cell confirm that the coldest part of the cell was lower than reported earlier.[1] There was also no observable evidence

TABLE II. Measured tellurium frequencies (for a cell cold-point temperature of 520 °C). Individual cell shifts from the mean are also shown.

		Individual cell shifts (MHz)			
Line	Frequency (MHz)	A	B	E	F
d_4	613 881 149.1	−0.16	−0.32	+0.27	+0.21
b_2	616 513 894.9	−0.16	−0.41	+0.34	+0.22
b_1	616 678 855.8	−0.48	−0.29	+0.42	+0.35
e_3	616 803 544.7	−0.33	−0.34	+0.41	+0.26
i_3	616 806 134.5	−0.20	−0.26	+0.27	+0.19

of foreign gas broadening in this original cell. In a comparison of the b_1 linewidths in the original cell and a new cell, the linewidths agreed to within ±2 MHz.

CONCLUSION

This paper has presented the results of a detailed study into the use of tellurium vapor absorption cells as reference standards for use in the absolute frequency measurement of hydrogenlike species. The frequencies of five Doppler-free tellurium features in the blue region (486 nm–488 nm) have been measured interferometrically with respect to an iodine-stabilized 633-nm He-Ne laser. Each feature has a frequency convenient for the measurement of the $1S$-$2S$ transition in either hydrogen, deuterium, positronium, or muonium. A total of six cells within temperature-controlled oven assemblies have been studied.

The estimated standard deviation of the frequency measurements of each component is 0.47 MHz, including cell-to-cell variations. The reproducibility for day-to-day measurements on a single cell is estimated to be 0.18 MHz, for the chosen optical arrangement and FM saturation technique. The variation of frequency with tellurium vapor pressure has been measured for all cells, and also correlated with linear absorption measurements on an isolated tellurium transition. One unexpected result from these studies has suggested that the cells have varying amounts of tellurium in them. This results in different cells exhibiting break points in the pressure-shift data, and linear absorption saturation at different vapor pressures. Some cells were found to have a break point too low in temperature for use. The slope of the pressure shift for temperatures below the break point were of order $-(10\pm2)$ kHz Pa^{-1} for all components measured, in good agreement with other measurements.[9]

In conclusion, tellurium-saturated spectra within well-controlled experimental arrangements can be useful at the ±1-MHz level. This is a factor of 10 worse than for similar saturated iodine reference spectra, but consistent with the ratio of linewidths. The use of such standards to a higher level of accuracy would require a considerably wider-ranging investigation into cell contamination and other systematic effects.

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