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INTERNATIONAL REPORT

Practical realization of the definition of the metre, including recommended radiations of other optical frequency standards (2001)

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Foreword

In 1983, at the time of the adoption of the present definition of the metre by the 17th General Conference on Weights and Measures (CGPM), the International Committee for Weights and Measures (CIPM) drew up recommendations for the practical realization of the definition. These have formerly been referred to as the *mise en pratique* of the definition of the metre. It was understood that the practical realization would, from time to time, be updated to take account of new measurements and improvements in techniques of laser stabilization.

In 1992 the CIPM, acting on the advice of the then Consultative Committee for the Definition of the Metre (CCDM), adopted a revision of the *mise en pratique* in its Recommendation 3 (CI-1992). The text was published in *Metrologia* (1993/94 **30** 523–41).

In 1997 a second revised version of the practical realization of the definition of the metre was adopted by the CIPM in its Recommendation 1 (CI-1997). The text was published in *Metrologia* (1999 **36** 211–44).

In 2001, the CIPM again adopted a revised version of the practical realization of the metre and this time included recommended frequencies for other optical frequency standards. The text of this Recommendation (Recommendation 1 (CI-2002)) is given here*. In addition, a revised list of recommended radiations, and an appendix containing the source data used in estimating the wavelengths, frequencies and uncertainties of the recommended radiations are given. In adopting the revised practical realization, the CIPM acknowledged the considerable effort put into its preparation by the Consultative Committee for Length (CCL) through its Working Group on the *mise en pratique* that included representatives of national metrology institutes and the BIPM. A significant part of the work was related to the estimation of the uncertainties of the values given in the list of recommended radiations and the CIPM drew attention to this as an example of the importance of making proper estimates of uncertainty in reporting the results of all metrological work.

* The French version of this Recommendation, which is the official one, will be published along with the English version in the Report of the 91st Meeting of the CIPM (2002).

Revision of the practical realization of the definition of the metre

Recommendation 1 (CI-2002)

The Comité International des Poids et Mesures,

recalling

- that in 1983 the 17th Conférence Générale des Poids et Mesures (CGPM) adopted a new definition of the metre;
- that in the same year the CGPM invited the CIPM
  - to draw up instructions for the practical realization of the metre,
  - to choose radiations which can be recommended as standards of wavelength for the interferometric measurement of length and draw up instructions for their use,
  - to pursue studies undertaken to improve these standards and in due course to extend or revise these instructions;
- that in response to this invitation the CIPM adopted Recommendation 1 (CI-1983) (*mise en pratique* of the definition of the metre) to the effect:
  - that the metre should be realized by one of the following methods:
    (a) by means of the length l of the path travelled in vacuum by a plane electromagnetic wave

in a time t; this length is obtained from the measured time t, using the relation $l = c_0 \cdot t$ and the value of the speed of light in vacuum $c_0 = 299\,792\,458\ \mathrm{m\,s^{-1}}$,

(b) by means of the wavelength in vacuum λ of a plane electromagnetic wave of frequency f; this wavelength is obtained from the measured frequency f using the relation $\lambda = c_0/f$ and the value of the speed of light in vacuum $c_0 = 299\,792\,458\ \mathrm{m\,s^{-1}}$,

(c) by means of one of the radiations from the list below, whose stated wavelength in vacuum or whose stated frequency can be used with the uncertainty shown, provided that the given specifications and accepted good practice are followed;

- that in all cases any necessary corrections be applied to take account of actual conditions such as diffraction, gravitation or imperfection in the vacuum;
- that in the context of general relativity, the metre is considered a unit of proper length. Its definition, therefore, applies only within a spatial extent sufficiently small so that the effects of the non-uniformity of the gravitational field can be ignored. In this case, the effects to be taken into account are those of special relativity only. The local methods for the realization of the metre recommended in (b) and (c) provide the proper metre but not necessarily that given in (a). Method (a) should therefore be restricted to lengths l which are sufficiently short for the effects predicted by general relativity to be negligible with respect to the uncertainties of realization. For advice on the interpretation of measurements in which this is not the case, see the report of the Consultative Committee for Time and Frequency (CCTF) working group on the application of general relativity to metrology [1].

- that the CIPM had already recommended a list of radiations for this purpose;

recalling also that in 1992 and in 1997 the CIPM revised the practical realization of the definition of the metre;

considering

- that science and technology continue to demand improved accuracy in the realization of the metre;
- that since 1997 work in national laboratories, in the BIPM and elsewhere has identified new radiations and methods for their realization which lead to lower uncertainties;
- that there is an increasing move towards optical frequencies for time-related activities, and that there continues to be a general widening of the scope of application of the recommended radiations of the *mise en pratique* to cover not only dimensional metrology and the realization of the metre, but also high-resolution spectroscopy, atomic and molecular physics, fundamental constants and telecommunication;
- that a number of new frequency values with reduced uncertainties for radiations of high-stability cold atom and ion standards already listed in the *recommended radiations* list are now available, that the frequencies of radiations of several new cold atom and ion species have also recently been measured, and that new improved values with substantially reduced uncertainties for a number of optical frequency standards based on gas cells have been determined, including the wavelength region of interest to optical telecommunications;
- that new femtosecond comb techniques have clear significance for relating the frequency of high-stability optical frequency standards to that of the frequency standard realizing the SI second, that these techniques represent a convenient measurement technique for providing traceability to the SI and that comb technology also can provide frequency sources as well as a measurement technique;

recognizes

- comb techniques as timely and appropriate, and recommends further research to fully investigate the capability of the techniques;

welcomes

- validations now being made of comb techniques by comparison with other frequency chain techniques;

urges

- national metrology institutes and other laboratories to pursue the comb technique to the highest level of accuracy achievable and also to seek simplicity so as to encourage widespread application;

recommends

- that the list of recommended radiations given by the CIPM in 1997 (Recommendation 1 (CI-1997)) be replaced by the list of radiations given below, including
  - updated frequency values for cold Ca atom, H atom and the trapped Sr^+ ion;
  - frequency values for new cold ion species including trapped Hg^+ ion, trapped In^+ ion and trapped Yb^+ ion;
  - updated frequency values for Rb-stabilized lasers, I_2-stabilized Nd : YAG and He–Ne lasers, CH_4-stabilized He–Ne lasers and OsO_4-stabilized CO_2 lasers at 10 μm;
  - frequency values for standards relevant to the optical communication bands, including Rb- and C_2H_2-stabilized lasers;
- that a more encompassing title for the *mise en pratique*, such as *Recommended radiations for the realization of the definition of the metre and other optical frequency standards* should be applied [action already taken].

CIPM list of approved radiations for the practical realization of the metre, 2002: frequencies and vacuum wavelengths

This list replaces those published in *BIPM Proc.-Verb. Com. Int. Poids et Mesures* 1983 **51** 25–8, 1992 **60** 141–4, 1997 **65** 61–71 and *Metrologia* 1984 **19** 165–6, 1993/94 **30** 523–41, 1999 **36** 211–44.

In this list, the values of the frequency f and of the vacuum wavelength λ should be related exactly by the relation $\lambda f = c_0$, with $c_0 = 299\,792\,458\ \mathrm{m\,s^{-1}}$ but the values of λ are rounded.

The data and analysis used for the compilation of this list are set out in the associated Appendix 1: source data for the list of recommended radiations, 2001.

It should be noted that for several of the listed radiations, few independent values are available, so the estimated uncertainties may not reflect all sources of variability.

Each of the listed radiations can be replaced, without degrading the accuracy, by a radiation corresponding to another component of the same transition or by another radiation, when the frequency difference is known with sufficient accuracy. Such radiations are listed in Appendix 2: absolute frequency of the other transitions related to those adopted as recommended and frequency intervals between transitions and hyperfine components.

It should be also noted that to achieve the uncertainties given here it is not sufficient just to meet the specifications for the listed parameters. In addition, it is necessary to follow the best good practice concerning methods of stabilization as described in numerous scientific and technical publications. References to appropriate articles, illustrating accepted good practice for a particular radiation, may be obtained by application to a member laboratory of the CCL[1] or to the BIPM.

1. Recommended radiations of stabilized lasers

1.1. Absorbing ion $^{115}In^+$, $5s^2\ ^1S_0$–$5s5p\ ^3P_0$ transition.

The values $f = 1\,267\,402\,452\,899.92$ kHz
$\lambda = 236\,540\,853.549\,75$ fm

are associated with a relative standard uncertainty of 3.6×10^{-13}.

1.2. Absorbing atom ^1H, 1S–2S two-photon transition.

The values $f = 1\,233\,030\,706\,593.55$ kHz
$\lambda = 243\,134\,624.626\,04$ fm

with a relative standard uncertainty of 2.0×10^{-13} apply to the laser frequency stabilized to the two-photon transition in a cold hydrogen beam, corrected to zero laser power, and for atoms which are effectively stationary, i.e. the values are corrected for second-order Doppler shift.

1.3. Absorbing ion $^{199}Hg^+$, $5d^{10}6s\ ^2S_{1/2}$ $(F = 0)$–$5d^9 6s^2\ ^2D_{5/2}$ $(F = 2)$ $\Delta m_F = 0$ transition.

The values $f = 1\,064\,721\,609\,899\,143$ Hz
$\lambda = 281\,568\,867.591\,969$ fm

with a relative standard uncertainty of 1.9×10^{-14} are corrected for the second-order Zeeman shift.

1.4. Absorbing ion $^{171}Yb^+$, $6s\ ^2S_{1/2}$ $(F = 0,\ m_F = 0)$–$5d\ ^2D_{3/2}$ $(F = 2,\ m_F = 0)$ transition.

The values $f = 688\,358\,979\,309\,312$ Hz
$\lambda = 435\,517\,610.739\,69$ fm

are associated with a relative standard uncertainty of 2.9×10^{-14}.

[1] At its 1997 Meeting, the CIPM changed the name of the CCDM to that of CCL.

1.5. Absorbing ion $^{171}Yb^+$, $^2S_{1/2}$ $(F = 0,\ m_F = 0)$–$^2F_{7/2}$ $(F = 3,\ m_F = 0)$ transition.

The values $f = 642\,121\,496\,772.6$ kHz
$\lambda = 466\,878\,090.061$ fm

with a relative standard uncertainty of 4.0×10^{-12} are corrected for the AC Stark shift and second-order Zeeman shift.

1.6. Absorbing molecule $^{127}I_2$, a_{10} component, R(56) 32-0 transition[2].

The values $f = 563\,260\,223\,513$ kHz
$\lambda = 532\,245\,036.104$ fm

with a relative standard uncertainty of 8.9×10^{-12} apply to the radiation of a frequency-doubled Nd : YAG laser, stabilized with an iodine cell external to the laser, having a cold-finger temperature of −15 °C.

1.7. Absorbing molecule $^{127}I_2$, a_{16}, or f, component, R(127) 11-5 transition.

The values $f = 473\,612\,353\,604$ kHz
$\lambda = 632\,991\,212.58$ fm

with a relative standard uncertainty of 2.1×10^{-11} apply to the radiation of a He–Ne laser with an internal iodine cell, stabilized using the third harmonic detection technique, subject to the conditions:

- cell-wall temperature (25 ± 5) °C[3];
- cold-finger temperature (15.0 ± 0.2) °C;
- frequency modulation width, peak-to-peak, (6.0 ± 0.3) MHz;
- one-way intracavity beam power (i.e. the output power divided by the transmittance of the output mirror) (10 ± 5) mW for an absolute value of the power shift coefficient $\leqslant 1.0$ kHz mW^{-1}.

These conditions are by themselves insufficient to ensure that the stated standard uncertainty will be achieved. It is also necessary for the optical and electronic control systems to be operating with the appropriate technical performance. The iodine cell may also be operated under relaxed conditions, leading to the larger uncertainty specified in Appendix 1.

1.8. Absorbing atom ^{40}Ca, $^1S_0$–$^3P_1$; $\Delta m_J = 0$ transition.

The values $f = 455\,986\,240\,494\,150$ Hz
$\lambda = 657\,459\,439.291\,67$ fm

with a relative standard uncertainty of 1.1×10^{-13} apply to the radiation of a laser stabilized to Ca atoms. The values correspond to the mean frequency of the two recoil-split components for atoms which are effectively stationary, i.e. the values are corrected for the second-order Doppler shift.

[2] All transitions in I_2 refer to the $B\,^3\Pi_{0+u}$–$X\,^1\Sigma_g^+$ system from now on.

[3] For the specification of operating conditions, such as temperature, modulation width and laser power, the symbols ± refer to a tolerance, not an uncertainty.

1.9. Absorbing ion $^{88}Sr^+$, $5\,^2S_{1/2}$–$4^2D_{5/2}$ transition.

The values $f = 444\,779\,044\,095.5$ kHz
$\lambda = 674\,025\,590.8631$ fm

with a relative standard uncertainty of 7.9×10^{-13} apply to the radiation of a laser stabilized to the transition observed with a trapped and cooled strontium ion. The values correspond to the centre of the Zeeman multiplet.

1.10. Absorbing atom ^{85}Rb, $5S_{1/2}(F_g = 3)$–$5D_{5/2}$ $(F_e = 5)$ two-photon transition.

The values $f = 385\,285\,142\,375$ kHz
$\lambda = 778\,105\,421.23$ fm

with a relative standard uncertainty of 1.3×10^{-11} apply to the radiation of a laser stabilized to the centre of the two-photon transition. The values apply to a rubidium cell at a temperature below 100 °C and are corrected to zero laser power.

1.11. Absorbing molecule $^{13}C_2H_2$, P(16) $(\nu_1 + \nu_3)$ transition.

The values $f = 194\,369\,569.4$ MHz
$\lambda = 1\,542\,383\,712$ fm

with a provisional relative standard uncertainty of 5.2×10^{-10} apply to the radiation of a laser stabilized with an external $^{13}C_2H_2$ cell at a pressure range from 1.3 Pa to 5.3 Pa.

1.12. Absorbing molecule CH_4, $F_2^{(2)}$ component, P(7) ν_3 transition.

1.12.1. The values $f = 88\,376\,181\,600.18$ kHz
$\lambda = 3\,392\,231\,397.327$ fm

with a relative standard uncertainty of 3×10^{-12} apply to the radiation of a He–Ne laser stabilized to the central component, (7–6) transition, of the resolved hyperfine-structure triplet. The values correspond to the mean frequency of the two recoil-split components for molecules which are effectively stationary, i.e. the values are corrected for second-order Doppler shift.

1.12.2. The values $f = 88\,376\,181\,600.5$ kHz
$\lambda = 3\,392\,231\,397.31$ fm

with a relative standard uncertainty of 2.3×10^{-11} apply to the radiation of a He–Ne laser stabilized to the centre of the unresolved hyperfine-structure of a methane cell, within or external to the laser, held at room temperature and subject to the following conditions:

- methane pressure $\leqslant 3$ Pa;
- mean one-way intracavity surface power density (i.e. the output power density divided by the transmittance of the output mirror) $\leqslant 10^4$ W m^{-2};
- radius of wavefront curvature $\geqslant 1$ m;
- inequality of power between counter-propagating waves $\leqslant 5\%$;
- servo-referenced to a detector placed at the output facing the laser tube.

1.13. Absorbing molecule OsO_4, transition in coincidence with the $^{12}C^{16}O_2$, R(10) (00^01)–(10^00) laser line.

The values $f = 29\,054\,057\,446\,579$ Hz
$\lambda = 10\,318\,436\,884.460$ fm

with a relative standard uncertainty of 1.4×10^{-13} apply to the radiation of a CO_2 laser stabilized with an external OsO_4 cell at a pressure below 0.2 Pa. This laser line is selected due to its reduced sensitivity to pressure shifts and other effects, in comparison with the previously selected R(12) laser line.

2. Recommended values for radiations of spectral lamps and other sources

2.1. ^{86}Kr spectral lamp radiation, $5d_5$–$2p_{10}$ transition.

The values $\lambda = 605\,780\,210.3$ fm

with a relative expanded uncertainty $U = 3.9 \times 10^{-9}$, where $U = ku_c$ $(k = 3)$, applies to the radiation emitted by a discharge lamp. The radiation of ^{86}Kr is obtained by means of a hot-cathode discharge lamp containing ^{86}Kr, of a purity not less than 99%, in sufficient quantity to assure the presence of solid krypton at a temperature of 64 K, this lamp having a capillary with an inner diameter from 2 mm to 4 mm and a wall thickness of about 1 mm.

It is estimated that the wavelength of the radiation emitted by the positive column is equal, to within 1 part in 10^8, to the wavelength corresponding to the transition between the unperturbed levels, when the following conditions are satisfied:

- the capillary is observed end-on from the side closest to the anode;
- the lower part of the lamp, including the capillary, is immersed in a cold bath maintained at a temperature within one degree of the triple point of nitrogen;
- the current density in the capillary is (0.3 ± 0.1) A cm^{-2}.

2.2. ^{86}Kr, ^{198}Hg and ^{114}Cd spectral lamp radiations.

Vacuum wavelengths, λ, for ^{86}Kr, ^{198}Hg and ^{114}Cd transitions.

Atom	Transition	λ/pm
^{86}Kr	$2p_9$–$5d'_4$	645 807.20
^{86}Kr	$2p_8$–$5d_4$	642 280.06
^{86}Kr	$1s_3$–$3p_{10}$	565 112.86
^{86}Kr	$1s_4$–$3p_8$	450 361.62
^{198}Hg	6^1P_1–6^1D_2	579 226.83
^{198}Hg	6^1P_1–6^3D_2	577 119.83
^{198}Hg	6^3P_2–7^3S_1	546 227.05
^{198}Hg	6^3P_1–7^3S_1	435 956.24
^{114}Cd	5^1P_1–5^1D_2	644 024.80
^{114}Cd	5^3P_2–6^3S_1	508 723.79
^{114}Cd	5^3P_1–6^3S_1	480 125.21
^{114}Cd	5^3P_0–6^3S_1	467 945.81

For ^{86}Kr, the above values with a relative expanded uncertainty $U = 2 \times 10^{-8}$, where $U = ku_c$ $(k = 3)$, apply to radiations emitted by a lamp operated under conditions similar to those specified in section 2.1.

For ^{198}Hg, the above values with a relative expanded uncertainty $U = 5 \times 10^{-8}$, where $U = ku_c$ $(k = 3)$, apply to radiations emitted by a discharge lamp when the following conditions are met:

- the radiations are produced using a discharge lamp without electrodes containing ^{198}Hg, of a purity not less than 98%, and argon at a pressure from 0.5 mm Hg to 1.0 mm Hg (66 Pa to 133 Pa);
- the internal diameter of the capillary of the lamp is about 5 mm, and the radiation is observed transversely;
- the lamp is excited by a high-frequency field at a moderate power and is maintained at a temperature less than 10 °C;
- it is preferred that the volume of the lamp be greater than 20 cm^3.

For ^{114}Cd, the above values with a relative expanded uncertainty $U = 7 \times 10^{-8}$, where $U = ku_c$ ($k = 3$), apply to radiations emitted by a discharge lamp under the following conditions:

- the radiations are generated using a discharge lamp without electrodes, containing ^{114}Cd of a purity not less than 95%, and argon at a pressure of about 1 mm Hg (133 Pa) at ambient temperature;
- the internal diameter of the capillary of the lamp is about 5 mm, and the radiation is observed transversely;
- the lamp is excited by a high-frequency field at a moderate power and is maintained at a temperature such that the green line is not reversed.

2.3. Absorbing molecule $^{127}I_2$, a_3 component, P(13) 43-0 transition.

The values $f = 582\,490\,603.38$ MHz
$\lambda = 514\,673\,466.4$ fm

with a relative standard uncertainty of 2.5×10^{-10} apply to the radiation of an Ar^+ laser stabilized with an iodine cell external to the laser, having a cold-finger temperature of (−5 ± 2) °C.

2.4. Absorbing molecule $^{127}I_2$, a_9 component, R(12) 26-0 transition.

The values $f = 551\,579\,482.97$ MHz
$\lambda = 543\,516\,333.1$ fm

with a relative standard uncertainty of 2.5×10^{-10} apply to the radiation of a frequency stabilized He–Ne laser with an external iodine cell having a cold-finger temperature of (0 ± 2) °C.

2.5. Absorbing molecule $^{127}I_2$, a_1 component, P(62) 17-1 transition.

The values $f = 520\,206\,808.4$ MHz
$\lambda = 576\,294\,760.4$ fm

with a relative standard uncertainty of 4×10^{-10} apply to the radiation of a dye laser (or frequency-doubled He–Ne laser) stabilized with an iodine cell, within or external to the laser, having a cold-finger temperature of (6 ± 2) °C.

2.6. Absorbing molecule $^{127}I_2$, a_7 component, R(47) 9-2 transition.

The values $f = 489\,880\,354.9$ MHz
$\lambda = 611\,970\,770.0$ fm

with a relative standard uncertainty of 3×10^{-10} apply to the radiation of a He–Ne laser stabilized with an iodine cell, within or external to the laser, having a cold-finger temperature of (−5 ± 2) °C.

2.7. Absorbing molecule $^{127}I_2$, a_9 component, P(10) 8-5 transition.

The values $f = 468\,218\,332.4$ MHz
$\lambda = 640\,283\,468.7$ fm

with a relative standard uncertainty of 4.5×10^{-10} apply to the radiation of a He–Ne laser stabilized with an internal iodine cell having a cold-finger temperature of (16 ± 1) °C and a frequency modulation width, peak-to-peak, of (6 ± 1) MHz.

APPENDIX 1

Source data for the list of recommended radiations, 2001

This appendix has been derived from data presented at the 10th Meeting of the CCL 2001, those of 1982 published in Appendix M4 of the report of the 7th Meeting of the CCDM 1982, of 1992 published in Appendix M2 of the report of the 8th Meeting of the CCDM 1992, and of 1997 published in Appendix M2 of the report of the 9th Meeting of the CCDM 1997 [2]. The source data having numbers in square brackets refer to the reference list at the end of this document. The source data having other types of indication refer to subsequent sections in this document. There have been a number of additional high-accuracy frequency comb measurements since the CCL 2001. Where appropriate, a comment in footnote is added within the body of the same data.

Values of frequency (and wavelength) may be influenced by certain experimental conditions such as the pressure and the purity of the absorbing medium, the power transported by the beam through the medium and beam geometry, as well as other effects originating outside the laser itself and related to the servo-system. The magnitude of these influences remains compatible with the limits indicated by the uncertainty (one standard deviation) provided that the conditions of operation lie within the domain of the ensemble of those of the measurements referred to below.

The frequency values and uncertainties adopted by the 10th Meeting of the CCL have been rounded in accordance with good metrological practice, bearing in mind the limited number of absolute measurements of a particular radiation in many cases, and broadly in agreement with consistency guidelines drawn up in [3].

It should be noted that the 2001 revision of the recommended frequency and uncertainty of the 633 nm radiation resulted in a correction of many of the other recommended iodine-stabilized laser source radiations. The component of the recommended radiation of 633 nm and near-lying components are denoted by letters, while all other hyperfine components are denoted by letters having a subscript specified by a number, according to [4]. The combined standard and relative uncertainties are denoted by u_c and u_c/y, respectively, according to [5].

1. Recommended radiations of stabilized lasers

1.1. Absorbing ion $^{115}In^+$, $5s^2\ ^1S_0$–$5s5p\ ^3P_0$ transition, $\lambda \approx 236$ nm.

Adopted value:

$f = 1\,267\,402\,452\,899.92\ (46)$ kHz $\quad u_c/y = 3.6 \times 10^{-13}$.

For which:

$\lambda = 236\,540\,853.549\,75\ (9)$ fm $\quad u_c/y = 3.6 \times 10^{-13}$,

calculated from

f/kHz	u_c/y	Source data
1 267 402 452 899.92	1.8×10^{-13}	[6]

With this value, based on one single determination, the CCL considered it prudent to double the relative standard uncertainty giving 3.6×10^{-13}.

1.2. Absorbing atom ^{1}H, 1S–2S two-photon transition, $\lambda \approx 243$ nm.

Adopted value:

$f = 1\,233\,030\,706\,593.55\ (25)$ kHz $\quad u_c/y = 2.0 \times 10^{-13}$.

For which:

$\lambda = 243\,134\,624.626\,04\ (5)$ fm $\quad u_c/y = 2.0 \times 10^{-13}$,

calculated from

$(f_{(1S-2S)}/2)$/kHz	u_c/y	Source data
1 233 030 706 593.67	3.4×10^{-13}	1.2-1
1 233 030 706 593.55	1.9×10^{-14}	1.2-2
Weighted mean $f = 1\,233\,030\,706\,593.55$ kHz		

The CCL considered it prudent to attribute a standard uncertainty of 2.0×10^{-13}.

Source data

1.2-1 Udem *et al* [7, 8] give the value of the frequency of the two-photon transition as

$f_{(1S-2S)} = 2\,466\,061\,413\,187.34$ kHz
$u_c/y = 3.4 \times 10^{-13}$.

For a single-photon, one calculates

$f_{(1S-2S)}/2 = 1\,233\,030\,706\,593.67$ kHz
$u_c/y = 3.4 \times 10^{-13}$.

1.2-2 Niering *et al* [9] give the value of the frequency of the two-photon transition as

$f_{(1S-2S)} = 2\,466\,061\,413\,187.103$ kHz
$u_c/y = 1.9 \times 10^{-14}$.

For a single-photon, one calculates

$f_{(1S-2S)}/2 = 1\,233\,030\,706\,593.551$ kHz
$u_c/y = 1.9 \times 10^{-14}$.

1.3. Absorbing ion $^{199}Hg^{+}$, $5d^{10}6s\ ^{2}S_{1/2}$ ($F = 0$)–$5d^{9}6s^{2}\ ^{2}D_{5/2}$ ($F = 2$) $\Delta m_F = 0$ transition, $\lambda \approx 282$ nm.

Adopted value:

$f = 1\,064\,721\,609\,899\,143\ (20)$ Hz $\quad u_c/y = 1.9 \times 10^{-14}$.

For which:

$\lambda = 281\,568\,867.591\,969\ (5)$ fm $\quad u_c/y = 1.9 \times 10^{-14}$,

calculated from

f/Hz	u_c/y	Source data
1 064 721 609 899 143	9.4×10^{-15}	[10]
1 064 721 609 899 120	2.3×10^{-13}	[11]
Weighted mean $f = 1\,064\,721\,609\,899\,143$ Hz		

With this value, based on only two separate determinations, the CCL considered it prudent to adopt a standard uncertainty in frequency of 20 Hz, corresponding to a relative standard uncertainty of 1.9×10^{-14}.

1.4. Absorbing ion $^{171}Yb^{+}$, 6s $^{2}S_{1/2}$ ($F = 0$, $m_F = 0$)–5d $^{2}D_{3/2}$ ($F = 2$, $m_F = 0$) transition, $\lambda \approx 436$ nm.

Adopted value:

$f = 688\,358\,979\,309\,312\ (20)$ Hz $\quad u_c/y = 2.9 \times 10^{-14}$.

For which:

$\lambda = 435\,517\,610.739\,69\ (1)$ fm $\quad u_c/y = 2.9 \times 10^{-14}$,

calculated from

f/Hz	u_c/y	Source data
688 358 979 309 312	8.7×10^{-15}	[12]

With this value, based on only one determination, the CCL considered it prudent to adopt a relative standard uncertainty equal to three times the reported uncertainty of 6 Hz giving 20 Hz, corresponding to a relative standard uncertainty of 2.9×10^{-14}.

1.5. Absorbing ion $^{171}Yb^{+}$, $^{2}S_{1/2}$ ($F = 0$, $m_F = 0$)–$^{2}F_{7/2}$ ($F = 3$, $m_F = 0$) transition, $\lambda \approx 467$ nm.

Adopted value:

$f = 642\,121\,496\,772.6\ (2.6)$ kHz $\quad u_c/y = 4.0 \times 10^{-12}$.

For which:

$\lambda = 466\,878\,090.061\ (2)$ fm $\quad u_c/y = 4.0 \times 10^{-12}$,

calculated from

f/kHz	u_c/y	Source data
642 121 496 772.6	2.0×10^{-12}	[13]

With this value, based on only one determination, the CCL considered it prudent to double the reported uncertainty, giving a relative uncertainty of 4.0×10^{-12} [4].

1.6. Absorbing molecule $^{127}I_2$, a_{10} component, R(56) 32-0 transition, $\lambda \approx 532$ nm.

Adopted value:

$f = 563\,260\,223\,513\ (5)$ kHz $\quad u_c/y = 8.9 \times 10^{-12}$.

For which:

$\lambda = 532\,245\,036.104\ (5)$ fm $\quad u_c/y = 8.9 \times 10^{-12}$,

[4] A more precise measurement made after the CCL 2001 has confirmed the adopted uncertainty [14].

calculated from

f/kHz	u_c/y	Source data
563 260 223 515.0	9.2×10^{-12}	1.6-1
563 260 223 514.5	8.9×10^{-12}	[15, 16]
563 260 223 510.1	5×10^{-13}	[17]
Unweighted mean $f = 563\,260\,223\,513.2$ kHz		

The standard uncertainty calculated from the dispersion of the four values is 2.4 kHz. Taking into account the frequency dependence on the cell quality and other effects, the CCL preferred to adopt a standard uncertainty of 5 kHz, corresponding to a relative standard uncertainty of 8.9×10^{-12}.

Other $^{127}I_2$ absorbing transitions close to this transition may also be used by making reference to the following frequency differences, using the a_{10} component of the R(56) 32-0 transition as a reference, see also section 1.6-2:

Line no	Transition x	Comp. y	$f_{xy} = [f(y,x) - f(a_{10}$, R(56) 32-0)]/kHz: f_{xy}	u_c/kHz
1111	P(53) 32-0	a_1	2 599 708.0	5.0
1110	R(56) 32-0	a_{10}	0.0	—
1109	P(83) 33-0	a_{21}	−15 682 075.2	5.0
	R(134) 36-0	a_1	−17 173 681.7	5.0
1108	R(106) 34-0	a_1	−30 434 763.4	5.0
1107	R(86) 33-0	a_1	−32 190 406.0	5.0
1106	P(119) 35-0	a_1	−36 840 163.0	5.0
1105	P(54) 32-0	a_1	−47 588 897.1	5.0
1104	R(57) 32-0	a_1	−50 946 884.7	5.0
1103	P(132) 36-0	a_1	−73 517 088.1	5.0
1101	R(145) 37-0	a_1	−84 992 177.6	5.0
	R(122) 35-0	a_1	−90 981 724.1	5.0
1100	P(84) 33-0	a_1	−95 929 863.0	5.0
1099	P(104) 34-0	a_1	−98 069 775.0	5.0
	P(55) 32-0	a_1	−98 766 591.0	5.0
1098	R(58) 32-0	a_1	−102 159 978.2	5.0
1097	R(87) 33-0	a_1	−111 935 173.1	5.0

where $f(y,x)$ represents the frequency of the transition denoted y, x and $f(a_{10}$, R(56) 32-0) the frequency of the reference transition. The CCL preferred to assign an uncertainty of 5 kHz to all listed frequency differences, regarding the possible influence of the quality of the iodine cell, background slopes and the small number of data for each frequency difference available.

Source data

1.6-1 Holzwarth *et al* [18] give

$$f_{a10} = 563\,260\,223\,508.7\ \text{kHz} \qquad u_c = 5.2\ \text{kHz}$$

at a cold-finger temperature of −5 °C (iodine pressure = 2.46 Pa)[5].

Nevsky *et al* [19] give

$$f_{a10} = 563\,260\,223\,507.8\ \text{kHz} \qquad u_c/y = 2.0 \times 10^{-12}$$

at a cold-finger temperature of − 5 °C (iodine pressure = 2.46 Pa).

These two measurements have been carried out with the same iodine cell. Therefore, the CCL decided to consider the arithmetic mean of these two data, i.e.

$$f_{a10} = (563\,260\,223\,508.7 + 563\,260\,223\,507.8)/2$$
$$= 563\,260\,223\,508.25\ \text{kHz}.$$

For a reference temperature of −15 °C (iodine pressure = 0.83 Pa), using a pressure dependence of $-4.2\ \text{kHz Pa}^{-1}$ [19], a correction of +6.8 kHz has to be applied, giving

$$f_{a10} = 563\,260\,223\,515.0\ \text{kHz} \qquad u_c/y = 9.2 \times 10^{-12}.$$

1.6-2 The values given in table *A* have been obtained for the frequency differences between several $^{127}I_2$ absorbing transitions and the R(56) 32-0 transition, at an iodine cold-finger temperature of −15 °C (iodine pressure = 0.83 Pa).

1.7. Absorbing molecule $^{127}I_2$, a_{16}, or f, component, R(127) 11-5 transition, $\lambda \approx 633$ nm.

Adopted value:

$$f = 473\,612\,353\,604\ (10)\ \text{kHz} \qquad u_c/y = 2.1 \times 10^{-11}.$$

For which:

$$\lambda = 632\,991\,212.579\ (13)\ \text{fm} \qquad u_c/y = 2.1 \times 10^{-11},$$

caclulated from

$(f_{BIPM4} - f_{CIPM97})$/kHz	u_c/y	Source data
8.2	4.0×10^{-12}	[23, 24]
7.4	3.0×10^{-12}	[23, 25]
4.2	1.4×10^{-11}	1.7-1
8.2	5.3×10^{-12}	[13]
Unweighted mean $(f_{BIPM4} - f_{CIPM97}) = 7.0$ kHz		

The source data are all given in respect to the BIPM4 laser standard frequency. The relative standard uncertainty includes the uncertainty in the absolute frequency measurement and the uncertainty obtained by comparing the different frequency standards with the BIPM4 standard. The CCL proposed that the recommended radiation for the R(127) 11-5 transition, using 633 nm He–Ne lasers, no longer correspond to the a_{13}, or i, component, but is replaced by the a_{16}, or f, component, which was decided by the CIPM 2002.

The CCL adopted a correction of the previous recommended frequency by +7 kHz, giving the frequency of the f component to be 473 612 353 604 kHz. The CCL also revised the coefficient of the tolerated one-way intracavity beam power influencing the average uncertainty of beat-frequency measurements between two stabilized lasers. This results in a combined uncertainty of $u_c = 10$ kHz, corresponding to a relative uncertainty of $u_c/y = 2.1 \times 10^{-11}$, see section 1.7-2. The grouped laser comparisons from national laboratories undertaken by the BIPM (1993–2000) confirm that the choice of a relative standard uncertainty of 2.1×10^{-11} is valid [26–34]. This series of comparison is a key comparison BIPM.L-K10 and is reported on the BIPM web-site http://www.bipm.org/kcdb.

[5] For the iodine cold-finger temperature to iodine pressure conversion the formula derived by Gillespie and Fraser [20] has been used from now and here on.

Table A.

Line no	Transition x	Comp. y	$[f(y,x) - f(a_{10}, R(56)\ 32\text{-}0)]$/kHz					
			[21]	[22]	[18]	[19]	Unw. mean	u/kHz
1111	P(53) 32-0	a_1	2 599 708.0	2 599 708.0			2 599 708.0	0.0
1110	R(56) 32-0	a_{10}	0.0	0.0	0.0		0.0	0.0
1109	P(83) 33-0	a_{21}	−15 682 074.1	−15 682 076.2			−15 682 075.2	1.5
	R(134) 36-0	a_1	−17 173 680.4	−17 173 682.9			−17 173 681.7	1.8
1108	R(106) 34-0	a_1	−30 434 761.5	−30 434 765.2			−30 434 763.4	2.6
1107	R(86) 33-0	a_1	−32 190 404.0	−32 190 408.0			−32 190 406.0	2.8
1106	P(119) 35-0	a_1	−36 840 161.5	−36 840 164.4			−36 840 163.0	2.1
1105	P(54) 32-0	a_1	−47 588 892.5	−47 588 898.2	−47 588 899.8	−47 588 898.0	−47 588 897.1	3.2
1104	R(57) 32-0	a_1	−50 946 880.4	−50 946 886.4	−50 946 887.2		−50 946 884.7	3.7
1103	P(132) 36-0	a_1		−73 517 088.1				
1101	R(145) 37-0	a_1		−84 992 177.6				
	R(122) 35-0	a_1		−90 981 724.1				
1100	P(84) 33-0	a_1		−95 929 863.0				
1099	P(104) 34-0	a_1		−98 069 775.0				
	P(55) 32-0	a_1		−98 766 590.0	−98 766 591.9		−98 766 591.0	1.4
1098	R(58) 32-0	a_1		−102 159 977.4	−102 159 979.0		−102 159 978.2	1.2
1097	R(87) 33-0	a_1		−111 935 173.1				

For applications where relaxed tolerances, and the resultant wider uncertainty range are acceptable, a laser operated under the conditions recommended in 1983 [35, 36] would lead to a standard uncertainty of about 50 kHz (or a relative standard uncertainty of 1×10^{-10}).

Source data

1.7-1 Sugiyama *et al* [17] give

$$f_f = 473\,612\,353\,604.3\ \text{kHz}, \qquad u_c = 1.7\ \text{kHz}$$

as the frequency of the NRLM-P1 laser standard.

This value indicates that

$$f_f = f_{\text{CIPM97}} + f_{\text{corr}}, \qquad \text{where } f_{\text{corr}} = 7.3\ \text{kHz}.$$

In a comparison with the BIPM4 laser standard [34], they obtained

$$f_f - f_{\text{BIPM4}} = 3.1\ \text{kHz} \qquad u_c = 6.4\ \text{kHz}.$$

Assuming that this frequency has been maintained since, one obtains

$$(f_{\text{BIPM4}} - f_{\text{CIPM97}}) = 4.2\ \text{kHz}, \qquad u_c = 6.6\ \text{kHz}.$$

1.7-2 The uncertainties resulting from variations in operational parameters are listed in table *B*.

1.8. Absorbing atom ^{40}Ca, $^1S_0$–$^3P_1$; $\Delta m_J = 0$ transition, $\lambda \approx 657$ nm.

Adopted value:

$$f = 455\,986\,240\,494\,150\ (50)\ \text{Hz} \qquad u_c/y = 1.1 \times 10^{-13}.$$

For which:

$$\lambda = 657\,459\,439.291\,67\ (7)\ \text{fm} \qquad u_c/y = 1.1 \times 10^{-13},$$

calculated from

f/kHz	u_c/y	Source data
455 986 240 494.158	5.7×10^{-14}	[10, 37]
455 986 240 494.149	3.5×10^{-14}	[38, 39]
455 986 240 494.13	2.5×10^{-13}	[40]
Weighted mean f = 455 986 240 494 151 Hz		

The CCL considered it prudent to assume an estimated standard uncertainty of 50 Hz, corresponding to a relative standard uncertainty of 1.1×10^{-13} .

1.9. Absorbing ion ^{88}Sr$^+$, $5^2S_{1/2}$–$4^2D_{5/2}$ transition, $\lambda \approx 674$ nm.

Adopted value:

$$f = 444\,779\,044\,095.5\ (4)\ \text{kHz} \qquad u_c/y = 7.9 \times 10^{-13}.$$

For which:

$$\lambda = 674\,025\,590.8631\ (5)\ \text{fm} \qquad u_c/y = 7.9 \times 10^{-13},$$

calculated from

f/kHz	u_c/y	Source data
444 779 044 095.4	4.5×10^{-13}	[41]
444 779 044 095.6	6.7×10^{-13}	[13]
Unweighted mean f = 444 779 044 095.5 kHz		

Regarding the improvement of the standard uncertainty of the measurements since the last CCL in 1997, other available values having relative standard uncertainties higher than 2×10^{-11} have not been used. The CCL considered it prudent to adopt an uncertainty of 0.35 kHz, corresponding to a relative standard uncertainty of 7.9×10^{-13} [6].

[6] A more precise measurement made after the CCL 2001 has confirmed the adopted uncertainty [42].

Table B.

Parameter	Recommended value	Tolerance	Coefficient	u/kHz
Iodine cell				
Cell-wall temperature	25 °C	5 °C	0.5 kHz/°C	2.5
Cold-finger temperature	15 °C	0.2 °C	−15 kHz/°C	3.0
Iodine purity				5.0
Frequency modulation width peak-to-peak	6 MHz	0.3 MHz	−10 kHz/MHz	3.0
One-way intracavity beam power	10 mW	5 mW	⩽1.0 kHz/mW	5.0
Beat-frequency measurements between two lasers				5.0
		Combined standard uncertainty u_c = 10.0 kHz		

1.10. Absorbing atom ^{85}Rb, $5S_{1/2}$ ($F_g = 3$)–$5D_{5/2}$ ($F_e = 5$) two-photon transition, $\lambda \approx 778$ nm.

Adopted value:

$$f = 385\,285\,142\,375\ (5)\ \text{kHz} \qquad u_c/y = 1.3 \times 10^{-11}.$$

For which:

$$\lambda = 778\,105\,421.23\ (1)\ \text{fm} \qquad u_c/y = 1.3 \times 10^{-11},$$

calculated from

$f_{5S_{1/2}\ (F=3)–5D_{5/2}\ (F=5)}/2$/kHz	u_c/y	Source data
385 285 142 378.3	5.2×10^{-12}	[43]
385 285 142 373.8	3.4×10^{-12}	[44]
385 285 142 372.3	1.4×10^{-11}	1.10-1
Weighted mean f = 385 285 142 375.0 kHz		

applies to the single-photon laser frequency of the two-photon transition. The CCL decided to attribute a standard uncertainty of 5 kHz, corresponding to a relative standard uncertainty of 1.3×10^{-11} [7].

1.10-1 Bernard *et al* [46] give

$$f\{^{87}\text{Rb}, 5\text{S}_{1/2}\ (\text{F}_g = 2)–5\text{D}_{5/2}\ (\text{F}_e = 4)\}/2 = 385\,284\,566\,370.4\ \text{kHz}$$
$$u_c/y = 5.2 \times 10^{-12}.$$

From [131] cited in table 30,

$$f\{^{87}\text{Rb}, 5\text{S}_{1/2}(\text{F}_g = 2)–5\text{D}_{5/2}(\text{F}_e = 4)\}/2$$
$$-f\{^{85}\text{Rb}, 5\text{S}_{1/2}(\text{F}_g = 3)–5\text{D}_{5/2}(\text{F}_e = 5)\}/2 = -576\,002\ \text{kHz} \qquad u_c/y = 1.3 \times 10^{-11},$$

one obtains

$$f\{^{85}\text{Rb}, 5\text{S}_{1/2}\ (\text{F}_g = 3)–5\text{D}_{5/2}\ (\text{F}_e = 5)\}/2 = 385\,285\,142\,371.40 \qquad u_c/y = 1.4 \times 10^{-11}.$$

1.11. Absorbing molecule $^{13}C_2H_2$, P(16) ($\nu_1 + \nu_3$) transition, $\lambda \approx 1.54\ \mu$m.

Adopted value:

$$f = 194\,369\,569.4\ (1)\ \text{MHz} \qquad u_c/y = 5.2 \times 10^{-10}.$$

For which:

$$\lambda = 1\,542\,383\,712\ (1)\ \text{fm} \qquad u_c/y = 5.2 \times 10^{-10},$$

calculated from

f/MHz	u_c/y	Source data
194 369 569.385	6.2×10^{-11}	[17]
194 369 569.38	6.2×10^{-10}	[47]
Unweighted mean f = 194 369 569.38 MHz		

with a provisional standard uncertainty of 0.1 MHz, corresponding to a relative standard uncertainty of 5.2×10^{-10}.

1.12. Absorbing molecule CH_4, $F_2^{(2)}$ component, P(7) ν_3 transition, $\lambda \approx 3.39\ \mu$m.

1.12.1 Resolved hyperfine structure

Adopted value:

$$f = 88\,376\,181\,600.18\ (27)\ \text{kHz} \quad u_c/y = 3 \times 10^{-12}.$$

For which:

$$\lambda = 3392\,231\,397.327\ (10)\ \text{fm} \quad u_c/y = 3 \times 10^{-12},$$

calculated from

x/kHz	Laser	Frequency chain	Year	Source data
600.29	LPI	PTB	1991	[48]
599.9	LPI	VNIIFTRI	1985–1986	[49]
600.11	LPI	VNIIFTRI	1989–1992	[49]
600.18	PTB	VNIIFTRI	1989	[49]
600.16	PTB	PTB	1992	[50]
600.44	ILP	ILP	1988–1991	[51]
Unweighted mean f = 88 376 181 600.18 kHz				

where $f = (88\,376\,181\,000 + x)$ kHz.

Other available values having uncertainties larger than 200 Hz have not been used. The relative standard uncertainty of one measurement was estimated to be 2.9×10^{-12} using the maximum deviation from the mean and rounded to 3×10^{-12}.

1.12.2 Unresolved hyperfine structure

Adopted value:

$$f = 88\,376\,181\,600.5\ (2.0)\ \text{kHz}$$
$$u_c/y = 2.3 \times 10^{-11}.$$

For which:

$$\lambda = 3392\,231\,397.31\ (8)\ \text{fm} \quad u_c/y = 2.3 \times 10^{-11},$$

[7] A recent measurement made after the CCL 2001 has confirmed one of the data [45].

calculated from

x/kHz	Frequency source	Frequency chain	Year	Source data
600.9	Stationary device	ILP	1983	[51–54]
601.48	Portable laser 2	NRC	1985	[55, 56]
599.33	Portable laser 3	NRC	1986–1991	[55, 56]
596.82	Portable laser 1	AIST	1988–1990	[56]
601.52	CH_4 beam	PTB	1987–1989	[56–58]
601.77	Portable laser M101	VNIIFTRI	1985–1992	[49, 56]
600.12	Portable laser P1	VNIIFTRI	1985–1988	[49, 56]
598.5	Portable laser PL	VNIIFTRI	1986	[49]
600.96	Portable laser B.3	BIPM	1985–1992	[56]
601.33	Portable laser VB	BIPM	1988–1991	[56]
600.3	Portable laser VNIBI	BIPM	1991	[56, 59]
Unweighted mean f = 88 376 181 600.46 kHz				

where $f_{CH_4} = (88\,376\,181\,000 + x)$ kHz.

The standard deviation of one determination is 1.7 kHz. This is equivalent to a relative uncertainty of 1.9×10^{-11}, increased by the CCL to 2.3×10^{-11} to give an uncertainty of 2 kHz.

1.13. Absorbing molecule OsO_4, transition in coincidence with the $^{12}C^{16}O_2$, R(10) (00^01)-(10^00) laser line, $\lambda \approx 10\,\mu m$.

Adopted value:

$f = 29\,054\,057\,446\,579$ (20) Hz $\quad u_c/y = 6.9 \times 10^{-13}$.

For which:

$\lambda = 10\,318\,436\,884.460$ (7) fm $\quad u_c/y = 6.9 \times 10^{-13}$,

calculated from

f/Hz	u_c/y	Source data
29 054 057 446 579	1.4×10^{-13}	[60]

With this value, based on measurements made over more than one year, but determined by one single laboratory, the CCL considered it prudent to adopt a standard uncertainty given for standard conditions [61] of 20 Hz, i.e. five times the reported measured uncertainty of 4 Hz, giving a relative standard uncertainty of 6.9×10^{-13}.

This value is linked to the earlier recommended transition, R(12) (00^01)-(10^00) laser line in $^{12}C^{16}O_2$, resonant with OsO_4 [62–65].

2. Recommended values for radiations of spectral lamps and other sources

2.1. ^{86}Kr spectral lamp radiation, $5d_5$–$2p_{10}$ transition, $\lambda \approx 605$ nm.

Adopted value:

$f = 494\,886\,516.4$ (6) MHz $\quad u_c/y = 1.3 \times 10^{-9}$.

For which:

$\lambda = 605\,780\,210.3$ (1) fm $\quad u_c/y = 1.3 \times 10^{-9}$,

calculated from

f/kHz	u_c/y	Source data
494 886 516 422 kHz	1.3×10^{-9}	2.1-1

Source data

2.1-1 The CCDM 1982 [36, 66] gives

$f_{Kr}/f_i = 1.044\,919\,242\,05 \quad u_c/y = 1.3 \times 10^{-9}$,

using the recommended operation conditions [67].

Using the recommended value of f_f (section 1.7 and table 20), where

$f_i = 473\,612\,214\,712$ kHz $\quad u_c/y = 2.2 \times 10^{-11}$,

one obtains

$f_{Kr} = 494\,886\,516\,422$ kHz $\quad u_c/y = 1.3 \times 10^{-9}$.

2.2. ^{86}Kr, ^{198}Hg and ^{114}Cd spectral lamp radiations. The recommended wavelengths are those recommended by the CIPM in 1963 [68, 69].

2.3. Absorbing molecule $^{127}I_2$, a_3 component, P(13) 43-0 transition, $\lambda \approx 515$ nm.

Adopted value:

$f = 582\,490\,603.38$ (15) MHz $\quad u_c/y = 2.5 \times 10^{-10}$.

For which:

$\lambda = 514\,673\,466.42$ (13) fm $\quad u_c/y = 2.5 \times 10^{-10}$,

calculated from

f/kHz	u_c/y	Source data
582 490 603 222	2.9×10^{-10}	2.3-1
582 490 603 218	1.0×10^{-10}	2.3-2
582 490 603 433	7.3×10^{-11}	[70]
582 490 603 483	7.3×10^{-11}	[71]
582 490 603 447	8.3×10^{-11}	[72]
582 490 603 490	8.3×10^{-11}	[73]
Unweighted mean f = 582 490 603 382 kHz		

The relative standard uncertainty calculated from the dispersion of the six values is 2.2×10^{-10}, which the CCL preferred to round up to 2.5×10^{-10}.

Source data

Using the recommended value of f_f (section 1.7 and table 20), where

$f_i = 473\,612\,214\,712$ kHz $\quad u_c/y = 2.2 \times 10^{-11}$,

the following values for f_{a3} are obtained from measured wavelength ratios:

f_i/f_{a3}	u_c/y	f_{a3}/kHz	u_c/y	Ref.
0.813 081 296 23	2.9×10^{-10}	582 490 603 222	2.5×10^{-10}	2.3-1
0.813 081 296 24	1×10^{-10}	582 490 603 218	1.0×10^{-10}	2.3-2
0.813 081 295 94	7×10^{-11}	582 490 603 433	7.3×10^{-11}	[70]
0.813 081 295 87	7×10^{-11}	582 490 603 483	7.3×10^{-11}	[71]
0.813 081 295 92	8×10^{-11}	582 490 603 447	8.3×10^{-11}	[72]
0.813 081 295 86	8×10^{-11}	582 490 603 490	8.3×10^{-11}	[73]

Other available values having relative uncertainties higher than 3.0×10^{-10} have not been used.

2.3-1 Reference [74] gives

$$\lambda_{a3}/\lambda_d = 0.813\,081\,579\,7 \qquad u_c/y = 2.5 \times 10^{-10}.$$

Using the recommended value of f_f (section 1.7 and table 20), where

$$f_i = 473\,612\,214\,712\,\text{kHz}$$

and where

$$f_d = 473\,612\,379\,828\,\text{kHz},$$

one calculates

$$f_i/f_{a3} = 0.813\,081\,296\,23 \qquad u_c/y = 2.9 \times 10^{-10}.$$

2.3-2 Reference [75] gives

$$f_{a3}/f_i = 1.229\,889\,316\,88 \qquad u_c/y = 1.0 \times 10^{-10}.$$

one calculates

$$f_i/f_{a3} = 0.813\,081\,296\,22 \qquad u_c/y = 1.0 \times 10^{-10}.$$

2.4. Absorbing molecule $^{127}I_2$, a_9 component, R(12) 26-0 transition, $\lambda \approx 543$ nm.

Adopted value:

$$f = 551\,579\,482.97\ (14)\ \text{MHz} \qquad u_c/y = 2.5 \times 10^{-10}.$$

For which:

$$\lambda = 543\,516\,333.1\ (1)\ \text{fm} \qquad u_c/y = 2.5 \times 10^{-10},$$

calculated from

f/kHz	u_c/y	Source data
551 579 483 037	8.3×10^{-11}	2.4-1
551 579 482 908	13×10^{-11}	2.4-2
Unweighted mean f = 551 579 482 973 kHz		

With this mean based on only two determinations, linked by the same reference frequency, the CCL considered it prudent to assume an estimated relative standard uncertainty of 2.5×10^{-10} closely equivalent to the difference between the two values.

Source data

2.4-1 Bönsch *et al* [73] give

$$\lambda_{a9}/\lambda_i = 0.858\,647\,265\,30 \qquad u_c/y = 8 \times 10^{-11}.$$

Using the recommended value of f_f (section 1.7 and table 20), where

$$f_i = 473\,612\,214\,712\,\text{kHz} \qquad u_c/y = 2.2 \times 10^{-11},$$

one calculates

$$f_{a9} = 551\,579\,483\,045\,\text{kHz} \quad u_c/y = 8.3 \times 10^{-11}$$

at a cold-finger temperature of $-10\,^\circ$C (iodine pressure = 1.4 Pa). For a reference temperature of 0 °C (iodine pressure = 4.1 Pa), a correction of −8 kHz has to be applied to this value with the pressure dependence of $-3.0\,\text{kHz}\,\text{Pa}^{-1}$ [76], giving

$$f_{a9} = 551\,579\,483\,037\,\text{kHz} \qquad u_c/y = 8.3 \times 10^{-11}.$$

2.4-2 Reference [77] gives

$$f_{b10}/f_i = 1.164\,624\,021\,92 \qquad u_c/y = 12 \times 10^{-11}.$$

Using the recommended value of f_f (section 1.7 and table 20), where

$$f_i = 473\,612\,214\,712\,\text{kHz} \qquad u_c/y = 2.2 \times 10^{-11},$$

one calculates

$$f_{b10} = 551\,580\,162\,328\,\text{kHz} \qquad u_c/y = 12.2 \times 10^{-11}$$

at a cold-finger temperature of 0 °C (iodine pressure = 4.1 Pa). From the measured value (table 37)

$$f_{b10} - f_{a9} = 679\,420\,\text{kHz} \qquad u_c = 15\,\text{kHz},$$

one obtains

$$f_{a9} = 551\,579\,482\,908\,\text{kHz} \qquad u_c/y = 12.5 \times 10^{-11}.$$

2.5. Absorbing molecule $^{127}I_2$, a_1 component, P(62) 17-1 transition, $\lambda \approx 576$ nm.

Adopted value:

$$f = 520\,206\,808.4\ (2)\ \text{MHz} \qquad u_c/y = 4 \times 10^{-10}.$$

For which:

$$\lambda = 576\,294\,760.4\ (2)\ \text{fm} \qquad u_c/y = 4 \times 10^{-10},$$

calculated from

f/kHz	u_c/y	Source data
520 206 808 491	1.5×10^{-10}	2.5-1
520 206 808 280	1×10^{-10}	2.5-2
Unweighted mean f = 520 206 808 388 kHz		

With this mean based on only two determinations, the CCL considered it prudent to assume an estimated relative standard uncertainty of 4×10^{-10}, closely equivalent to the difference between the two values.

Source data

2.5-1 Reference [78] gives

$$f_{a1} = 520\,206\,808\,547\,\text{kHz} \qquad u_c/y = 1.5 \times 10^{-10},$$

reduced by 12 kHz at the request of the NBS delegate at the CCDM meeting in 1982 [36, 66]. This value has been multiplied by the ratio (88 376 181 600.5/ 88 376 181 608) to account for the 1992 reference value of the methane frequency (section 1.12.2) giving:

$$f_{a1} = 520\,206\,808\,491\,\text{kHz} \qquad u_c/y = 1.5 \times 10^{-10}.$$

2.5-2 Barwood *et al* [79] give

$$f_{a1}/f_i = 1.098\,381\,317\,29 \qquad u_c/y = 1 \times 10^{-10}.$$

Using the recommended value of f_f (section 1.7 and table 20), where

$$f_i = 473\,612\,214\,712\,\text{kHz} \qquad u_c/y = 2.2 \times 10^{-11},$$

one calculates

$$f_{a1} = 520\,206\,808\,280\,\text{kHz} \qquad u_c/y = 1 \times 10^{-10}.$$

2.6. *Absorbing molecule $^{127}I_2$, a_7 component, R(47) 9-2 transition, $\lambda \approx 612$ nm.*

Adopted value:

$$f = 489\,880\,354.93(15)\,\text{MHz} \qquad u_c/y = 3.0 \times 10^{-10}.$$

For which:

$$\lambda = 611\,970\,769.97(18)\,\text{fm} \qquad u_c/y = 3.0 \times 10^{-10},$$

calculated from

f/kHz	u_c/y	Source data
489 880 354 979	1×10^{-10}	2.6-1
489 880 354 728	2.1×10^{-10}	2.6-2
489 880 355 026	8.3×10^{-11}	2.6-3
489 880 355 062	3.0×10^{-10}	2.6-4
489 880 358 850	8.5×10^{-11}	2.6-5
Unweighted mean f = 489 880 354 929 kHz		

Other available values having relative uncertainties higher than 3.0×10^{-10} have not been used. The relative standard uncertainty calculated from the dispersion of the six values is 2.8×10^{-10} , which the CCL preferred to round up to 3.0×10^{-10}.

Source data

2.6-1 Reference [75] gives

$$f_{a7}/f_i = 1.034\,349\,072\,43 \qquad u_c/y = 1 \times 10^{-10}.$$

Using the recommended value of f_f (section 1.7 and table 20), where

$$f_i = 473\,612\,214\,712\,\text{kHz} \qquad u_c/y = 2.2 \times 10^{-11},$$

one calculates

$$f_{a7} = 489\,880\,354\,979\,\text{kHz} \qquad u_c/y = 1 \times 10^{-10}.$$

2.6-2 Reference [74] gives

$$f_{a7}/f_i = 1.034\,349\,071\,90 \qquad u_c/y = 2.1 \times 10^{-10}.$$

Using the recommended value of f_f (section 1.7 and table 20), where

$$f_i = 473\,612\,214\,712\,\text{kHz} \qquad u_c/y = 2.2 \times 10^{-11},$$

one calculates

$$f_{a7} = 489\,880\,354\,728\,\text{kHz} \qquad u_c/y = 2.1 \times 10^{-10}.$$

2.6-3 Bönsch *et al* [72] give

$$\lambda_{b15}/\lambda_i = 0.966\,791\,921\,43 \qquad u_c/y = 8 \times 10^{-11}.$$

Using the recommended value of f_f (section 1.7 and table 20), where

$$f_i = 473\,612\,214\,712\,\text{kHz} \qquad u_c/y = 2.2 \times 10^{-11},$$

one calculates

$$f_{b15} = 489\,880\,194\,708\,\text{kHz} \qquad u_c/y = 8.3 \times 10^{-11}.$$

From the measured value (table 40)

$$f_{b15} - f_{a7} = -160\,318\,\text{kHz} \qquad u_c = 3\,\text{kHz},$$

one calculates

$$f_{a7} = 489\,880\,355\,026\,\text{kHz} \qquad u_c/y = 8.3 \times 10^{-11}.$$

2.6-4 Vitushkin *et al* [80] give

$$\lambda_d/\lambda_{a7} = 1.034\,348\,712 \qquad u_c/y = 3 \times 10^{-10}.$$

Using the recommended value of f_f (section 1.7 and table 20), where

$$f_d = 473\,612\,379\,828\,\text{kHz} \qquad u_c/y = 2.2 \times 10^{-11},$$

one calculates

$$f_{a7} = 489\,880\,355\,062\,\text{kHz} \qquad u_c/y = 3.0 \times 10^{-10}.$$

2.6-5 Himbert *et al* [81] give

$$f_{a13} = 489\,880\,604\,541\,\text{kHz} \qquad u_c = 88\,\text{kHz}.$$

This value is a result of the frequency ratio f_{a13}/f_e, to which the recommended value adopted by the CIPM in 1983 [35, 36] was applied, i.e. $f_i = 473\,612\,214.8$ MHz. Knowing the frequency difference (table 20)

$$f_e - f_i = 152\,255\,\text{kHz} \qquad u_c = 5\,\text{kHz},$$

one obtains

$$f_e = 473\,612\,367\,055\,\text{kHz},$$

and hence

$$f_{a13}/f_e = 1.034\,349\,267 \qquad u_c/y = 8 \times 10^{-11}.$$

Using the recommended value of f_f (section 1.7 and table 20), where

$$f_e = 473\,612\,366\,967\,\text{kHz} \qquad u_c/y = 2.2 \times 10^{-11},$$

one calculates

$$f_{a13} = 489\,880\,604\,450 \qquad u_c/y = 8.3 \times 10^{-11}.$$

Knowing the frequency difference (table 39)

$$f_{a7} - f_{a13} = -249\,600\,\text{kHz} \qquad u_c = 10\,\text{kHz},$$

one obtains

$$f_{a7} = 489\,880\,354\,850 \qquad u_c/y = 8.5 \times 10^{-11}.$$

2.7. Absorbing molecule $^{127}I_2$, a_9 component, P(10) 8-5 transition, $\lambda \approx 640$ nm.

Adopted value:

$$f = 468\,218\,332.4\ (2)\ \text{MHz} \qquad u_c/y = 4.5 \times 10^{-10}.$$

For which:

$$\lambda = 640\,283\,468.7\ (3)\ fm \qquad u_c/y = 4.5 \times 10^{-10},$$

calculated from

f/kHz	u_c/y	Source data
468 218 332 419	1.0×10^{-10}	2.7-1
468 218 332 310	1.2×10^{-10}	2.7-2
468 218 332 069	4.6×10^{-10}	2.7-3
Weighted mean f = 468 218 332 366 kHz		

Given the small number of determinations, the CCL considered it prudent to assume a relative standard uncertainty of 4.5×10^{-10}.

Source data

2.7-1 Bennet and Mills-Baker [82] give

$$\lambda_{a9} = 640.283\,468\,6\,\text{nm}.$$

From this paper the ratio f_{a9}/f_i is calculated as

$$f_{a9}/f_i = 0.988\,611\,184\,191 \qquad u_c/y = 1 \times 10^{-10}.$$

Using the recommended value of f_f (section 1.7 and table 20), where

$$f_i = 473\,612\,214\,712\,\text{kHz} \qquad u_c/y = 2.2 \times 10^{-11},$$

one calculates

$$f_{a9} = 468\,218\,332\,434\,\text{kHz} \qquad u_c/y = 1.0 \times 10^{-10}$$

at a cold-finger temperature of 14.3 °C (iodine pressure = 16 Pa) and a modulation width of 7 MHz. For a reference temperature of 16 °C (iodine pressure = 18.9 Pa) and a modulation width of 6 MHz, corrections of −23 kHz and +8 kHz has to be applied to this value assuming a pressure dependence of $-7.8\,\text{kHz Pa}^{-1}$ and a modulation dependence of $-7.6\,\text{kHz MHz}^{-1}$, similar to that reported in [83], giving

$$f_{a9} = 468\,218\,332\,419\,\text{kHz} \qquad u_c/y = 1.0 \times 10^{-10}.$$

2.7-2 Zhao *et al* [83, 84] give

$$\lambda_{a9} = 640.283\,4688\,\text{nm} \quad 3 \times (u_c/y) = 1.1 \times 10^{-9}.$$

Bönsch *et al* [73] give

$$\lambda_i/\lambda_{a9} = 0.988\,611\,183\,86 \qquad u_c/y = 12 \times 10^{-11}.$$

Using the recommended value of f_f (section 1.7 and table 20), where

$$f_i = 473\,612\,214\,712\,\text{kHz} \qquad u_c/y = 2.2 \times 10^{-11},$$

one calculates

$$f_{a9} = 468\,218\,332\,277\,\text{kHz} \qquad u_c/y = 1.2 \times 10^{-10}$$

at a cold-finger temperature of 18 °C (iodine pressure = 22.6 Pa) and a modulation width of 6.5 MHz. For a reference temperature of 16 °C (iodine pressure = 18.9 Pa) and a modulation width of 6 MHz, corrections of +29 kHz and +4 kHz have to be applied to this value knowing a pressure dependence of $-7.8\,\text{kHz Pa}^{-1}$ and a modulation dependence of $-7.6\,\text{kHz MHz}^{-1}$, giving

$$f_{a9} = 468\,218\,332\,310\,\text{kHz} \qquad u_c/y = 1.2 \times 10^{-10}.$$

2.7-3 Reference [59, 85]

$$\lambda_{a9}(17\,^\circ\text{C})/\lambda_e(20\,^\circ\text{C}) = 1.011\,520\,341\,04$$
$$u_c/y = 4.6 \times 10^{-10}.$$

Using the recommended value of f_f (section 1.7 and table 20), where

$$f_e = 473\,612\,366\,967\,\text{kHz} \qquad u_c/y = 2.2 \times 10^{-11},$$

one calculates

$$f_{a9} = 468\,218\,332\,055\,\text{kHz} \qquad u_c/y = 4.6 \times 10^{-10}$$

at a cold-finger temperature of 17 °C (iodine pressure = 20.7 Pa). For a reference temperature of 16 °C (iodine pressure = 18.9 Pa), a correction of +14 kHz has to be applied to this value, assuming a pressure dependence of $-7.8\,\text{kHz Pa}^{-1}$ similar to that reported in [83], giving

$$f_{a9} = 468\,218\,332\,069\,\text{kHz} \qquad u_c/y = 4.6 \times 10^{-10}.$$

APPENDIX 2

Absolute frequency of the other transitions related to those adopted as recommended and frequency intervals between transitions and hyperfine components

These tables replace those published

in *BIPM Com. Cons. Déf. Mètre* 1982 **7** M65–M75 and *Metrologia* 1984 **19** 170–178;
in *BIPM Com. Cons. Déf. Mètre* 1992 **8** M51–M61 and *Metrologia* 1993/94 **30** 523–541; and
in *BIPM Com. Cons. Déf. Mètre* 1997 **9** 133–152 and *Metrologia* 1999 **36** 226–242.

The notation for the transitions and the components is that used in the source references. The values adopted for the frequency intervals are the weighted means of the values given in the references.

For the uncertainties, account has been taken of:

– the uncertainties given by the authors;
– the spread in the different determinations of a single component;
– the effect of any perturbing components;
– the difference between the calculated and the measured values.

In the tables, u_c represents the estimated combined standard uncertainty (1 σ).

All transitions in molecular iodine refer to the B–X system.

When a two-photon transition is listed, the listed frequency indicates the one-photon laser frequency.

Table 1.

λ ≈ 778 nm ^{1}H 2S–8S and 2S–8D two-photon transitions		
Transition	[f(2S–8S/D)/2]/MHz	u_c/MHz
$2S_{1/2}$–$8D_{5/2}$	385 324 780.793	0.005
$2S_{1/2}$–$8D_{3/2}$	385 324 752.227	0.007
$2S_{1/2}$–$8S_{1/2}$	385 324 675.008	0.008

Ref. [86].

Table 2.

λ ≈ 778 nm ^{2}H 2S–8S and 2S–8D two-photon transitions		
Transition	[f(2S–8S/D)/2]/MHz	u_c/MHz
$2S_{1/2}$–$8D_{5/2}$	385 429 626.426	0.004
$2S_{1/2}$–$8D_{3/2}$	385 429 597.852	0.004
$2S_{1/2}$–$8S_{1/2}$	385 429 520.626	0.005

Ref. [86].

Table 3.

λ ≈ 532 nm $^{127}I_2$ R(87) 33-0 (no 1097)					
a_n	[$f(a_n) - f(a_1)$]/MHz	u_c/MHz	a_n	[$f(a_n) - f(a_1)$]/MHz	u_c/MHz
a_1	0	—	a_{12}	582.6721	0.0020
a_2	51.5768	0.0020	a_{13}	622.8375	0.0020
a_3	101.4407	0.0020	a_{14}	663.9140	0.0020
a_4	282.4331	0.0020	a_{15}	730.3226	0.0020
a_5	332.2313	0.0020	a_{16}	752.4797	0.0020
a_6	342.2223	0.0020	a_{17}	778.0522	0.0020
a_7	390.3168	0.0020	a_{18}	799.4548	0.0020
a_8	445.6559	0.0020	a_{19}	893.1211	0.0020
a_9	462.0620	0.0020	a_{20}	907.5209	0.0020
a_{10}	497.5450	0.0020	a_{21}	923.5991	0.0020
a_{11}	511.9546	0.0020			
Frequency referenced to	a_{10}, R(56) 32-0, $^{127}I_2$: f = 563 260 223 513 kHz [2]				
	$f(a_1$, R(87) 33-0$) - f(a_{10}$, R(56) 32-0$) = -111\,935\,173$ (5) kHz [2]				

Ref. [87].

Table 4.

λ ≈ 532 nm $^{127}I_2$ R(58) 32-0 (no 1098)					
a_n	[$f(a_n) - f(a_1)$]/MHz	u_c/MHz	a_n	[$f(a_n) - f(a_1)$]/MHz	u_c/MHz
a_1	0	—	a_{10}	571.5686	0.0020
a_2	259.1938	0.0020	a_{11}	697.9347	0.0020
a_5	311.8933	0.0020	a_{12}	702.8370	0.0020
a_6	401.3702	0.0020	a_{13}	726.0151	0.0020
a_7	416.7177	0.0020	a_{14}	732.3220	0.0020
a_8	439.9735	0.0020	a_{15}	857.9730	0.0020
a_9	455.4891	0.0020			
Frequency referenced to	a_{10}, R(56) 32-0, $^{127}I_2$: f = 563 260 223 513 kHz [2]				
	$f(a_1$, R(58) 32-0$) - f(a_{10}$, R(56) 32-0$) = -102\,159\,978$ (5) kHz [2]				

Ref. [88].

Table 5.

	λ ≈ 532 nm $^{127}I_2$ P(55) 32-0				
a_n	$[f(a_n) - f(a_1)]$/MHz	u_c/MHz	a_n	$[f(a_n) - f(a_1)]$/MHz	u_c/MHz
a_1	0	—	a_{13}	609.4478	0.0020
a_2	37.8987	0.0020	a_{14}	648.9064	0.0020
a_3	73.8521	0.0020	a_{15}	714.0690	0.0020
a_4	272.2124	0.0020	a_{16}	739.8350	0.0020
a_7	373.1260	0.0020	a_{17}	763.0081	0.0020
a_8	437.4166	0.0020	a_{18}	788.2234	0.0020
a_9	455.3851	0.0020	a_{19}	879.7357	0.0020
a_{10}	477.0210	0.0020	a_{20}	893.4676	0.0020
a_{11}	490.5588	0.0020	a_{21}	910.3088	0.0020
a_{12}	573.0377	0.0020			

Frequency referenced to a_{10}, R(56) 32-0, $^{127}I_2$: $f = 563\,260\,223\,513$ kHz [2]
$f(a_1$, P(55) 32-0$) - f(a_{10}$, R(56) 32-0$) = -98\,766\,591$ (5) kHz [2]

Ref. [88].

Table 6.

	λ ≈ 532 nm $^{127}I_2$ P(104) 34-0 (no 1099)				
a_n	$[f(a_n) - f(a_1)]$/MHz	u_c/MHz	a_n	$[f(a_n) - f(a_1)]$/MHz	u_c/MHz
a_1	0	—	a_9	466.6137	0.0020
a_2	238.8227	0.0020	a_{10}	570.8323	0.0020
a_3	277.4934	0.0020	a_{11}	688.5193	0.0020
a_4	293.3463	0.0020	a_{12}	699.1488	0.0020
a_5	331.4333	0.0020	a_{13}	727.8544	0.0020
a_6	389.0585	0.0020	a_{14}	739.2895	0.0020
a_7	405.6376	0.0020	a_{15}	856.7001	0.0020
a_8	450.2193	0.0020			0.0020

Frequency referenced to a_{10}, R(56) 32-0, $^{127}I_2$: $f = 563\,260\,223\,513$ kHz [2]
$f(a_1$, P(104) 34-0$) - f(a_{10}$, R(56) 32-0$) = -98\,069\,775$ (5) kHz [2]

Ref. [88].

Table 7.

	λ ≈ 532 nm $^{127}I_2$ P(84) 33-0 (no 1100)				
a_n	$[f(a_n) - f(a_1)]$/MHz	u_c/MHz	a_n	$[f(a_n) - f(a_1)]$/MHz	u_c/MHz
a_1	0	—	a_9	459.8476	0.0020
a_2	249.8445	0.0020	a_{10}	571.2806	0.0020
a_3	281.2957	0.0020	a_{11}	694.0020	0.0020
a_4	290.0304	0.0020	a_{12}	701.7501	0.0020
a_5	320.9041	0.0020	a_{13}	726.3808	0.0020
a_6	396.5400	0.0020	a_{14}	735.0562	0.0020
a_7	411.5392	0.0020	a_{15}	857.4151	0.0020
a_8	444.9362	0.0020			

Frequency referenced to a_{10}, R(56) 32-0, $^{127}I_2$: $f = 563\,260\,223\,513$ kHz [2]
$f(a_1$, P(84) 33-0$) - f(a_{10}$, R(56) 32-0$) = -95\,929\,863$ (5) kHz [2]

Ref. [89].

Table 8.

	λ ≈ 532 nm $^{127}I_2$ R(122) 35-0				
a_n	$[f(a_n) - f(a_1)]$/MHz	u_c/MHz	a_n	$[f(a_n) - f(a_1)]$/MHz	u_c/MHz
a_1	0	—	a_9	475.9553	0.0020
a_2	224.7302	0.0020	a_{10}	570.3004	0.0020
a_3	273.2394	0.0020	a_{11}	681.2572	0.0020
a_4	297.0396	0.0020	a_{12}	695.4307	0.0020
a_5	344.9343	0.0020	a_{13}	730.2395	0.0020
a_6	378.8637	0.0020	a_{14}	745.1865	0.0020
a_7	398.2113	0.0020	a_{15}	855.9386	0.0020
a_8	456.8479	0.0020			

Frequency referenced to a_{10}, R(56) 32-0, $^{127}I_2$: $f = 563\,260\,223\,513$ kHz [2]
$f(a_1$, R(122) 35-0$) - f(a_{10}$, R(56) 32-0$) = -90\,981\,724$ (5) kHz [2]

Ref. [89].

Table 9.

a_n	$[f(a_n) - f(a_1)]$/MHz	u_c/MHz	a_n	$[f(a_n) - f(a_1)]$/MHz	u_c/MHz
$\lambda \approx 532$ nm $^{127}I_2$ R(145) 37-0 (no 1101)					
a_1	0	—	a_{12}	608.2166	0.0020
a_2	111.3681	0.0020	a_{13}	680.6255	0.0020
a_3	220.5695	0.0020	a_{14}	752.7967	0.0020
a_4	298.7582	0.0020	a_{15}	769.5347	0.0020
a_5	376.9445	0.0020	a_{16}	799.1414	0.0020
a_6	414.9517	0.0020	a_{17}	846.4138	0.0020
a_7	469.8127	0.0020	a_{18}	874.8758	0.0020
a_8	491.2288	0.0020	a_{19}	940.0615	0.0020
a_9	495.5179	0.0020	a_{20}	964.5342	0.0020
a_{10}	580.7013	0.0020	a_{21}	990.2893	0.0020
a_{11}	605.3833	0.0020			
Frequency referenced to	a_{10}, R(56) 32-0, $^{127}I_2$: $f = 563\,260\,223\,513$ kHz [2]				
	$f(a_1$, R(145) 37-0) $- f(a_{10}$, R(56) 32-0) $= -84\,992\,178$ (5) kHz [2]				

Ref. [87].

Table 10.

a_n	$[f(a_n) - f(a_1)]$/MHz	u_c/MHz	a_n	$[f(a_n) - f(a_1)]$/MHz	u_c/MHz
$\lambda \approx 532$ nm $^{127}I_2$ P(132) 36-0 (no 1103)					
a_1	0	—	a_9	482.3956	0.0020
a_2	215.0115	0.0020	a_{10}	569.8339	0.0020
a_3	270.3841	0.0020	a_{11}	676.1016	0.0020
a_4	299.4166	0.0020	a_{12}	692.6715	0.0020
a_5	354.1318	0.0020	a_{13}	731.8283	0.0020
a_6	371.6729	0.0020	a_{14}	749.1808	0.0020
a_7	393.0781	0.0020	a_{15}	855.2633	0.0020
a_8	461.2856	0.0020			
Frequency referenced to	a_{10}, R(56) 32-0, $^{127}I_2$: $f = 563\,260\,223\,513$ kHz [2]				
	$f(a_1$, P(132) 36-0) $- f(a_{10}$, R(56) 32-0) $= -73\,517\,088$ (5) kHz [2]				

Ref. [87].

Table 11.

a_n	$[f(a_n) - f(a_1)]$/MHz	u_c/MHz	a_n	$[f(a_n) - f(a_1)]$/MHz	u_c/MHz
$\lambda \approx 532$ nm $^{127}I_2$ R(57) 32-0 (no 1104)					
a_1	0	—	a_{13}	610.925	0.001
a_2	39.372	0.001	a_{14}	650.805	0.001
a_3	76.828	0.001	a_{15}	715.550	0.001
a_4	273.042	0.001	a_{16}	741.175	0.001
a_7	375.284	0.001	a_{17}	764.716	0.001
a_8	438.243	0.001	a_{18}	789.777	0.001
a_9	456.183	0.001	a_{19}	881.116	0.001
a_{10}	479.201	0.001	a_{20}	895.016	0.001
a_{11}	492.915	0.001	a_{21}	911.901	0.001
a_{12}	573.917	0.001			
Frequency referenced to	a_{10}, R(56) 32-0, $^{127}I_2$: $f = 563\,260\,223\,513$ kHz [2]				
	$f(a_1$, R(57) 32-0) $- f(a_{10}$, R(56) 32-0) $= -50\,946\,885$ (5) kHz [2]				

Ref. [21, 90].

Table 12.

$\lambda \approx 532$ nm $^{127}I_2$ P(54) 32-0 (no 1105)					
a_n	$[f(a_n) - f(a_1)]$/MHz	u_c/MHz	a_n	$[f(a_n) - f(a_1)]$/MHz	u_c/MHz
a_1	0	—	a_9	454.563	0.001
a_2	260.992	0.001	a_{10}	571.536	0.001
a_3	285.008	0.001	a_{11}	698.614	0.001
a_4	286.726	0.001	a_{12}	702.935	0.001
a_5	310.066	0.001	a_{13}	725.834	0.001
a_6	402.249	0.001	a_{14}	731.688	0.001
a_8	417.668	0.001	a_{15}	857.961	0.001
a_8	438.919	0.001			

Frequency referenced to a_{10}, R(56) 32-0, $^{127}I_2$: $f = 563\,260\,223\,513$ kHz [2]
$f(a_1, \text{P(54) 32-0}) - f(a_{10}, \text{R(56) 32-0}) = -47\,588\,897\,(5)$ kHz [2]

Ref. [21, 90].

Table 13.

$\lambda \approx 532$ nm $^{127}I_2$ P(119) 35-0 (no 1106)					
a_n	$[f(a_n) - f(a_1)]$/MHz	u_c/MHz	a_n	$[f(a_n) - f(a_1)]$/MHz	u_c/MHz
a_1	0	—	a_{13}	645.617	0.002
a_2	75.277	0.002	a_{14}	697.723	0.002
a_3	148.701	0.002	a_{15}	747.389	0.003
a_4	290.376	0.003	a_{16}	771.197	0.003
a_5	349.310	0.002	a_{17}	804.769	0.003
a_6	371.567	0.002	a_{18}	827.641	0.003
a_9	474.953	0.004	a_{19}	912.125	0.002
a_{10}	530.727	0.002	a_{20}	930.053	0.002
a_{11}	548.787	0.002	a_{21}	949.288	0.003

Frequency referenced to a_{10}, R(56) 32-0, $^{127}I_2$: $f = 563\,260\,223\,513$ kHz [2]
$f(a_1, \text{P(119) 35-0}) - f(a_{10}, \text{R(56) 32-0}) = -36\,840\,163\,(5)$ kHz [2]

Ref. [91, 92].

Table 14.

$\lambda \approx 532$ nm $^{127}I_2$ R(86) 33-0 (no 1107)					
a_n	$[f(a_n) - f(a_1)]$/MHz	u_c/MHz	a_n	$[f(a_n) - f(a_1)]$/MHz	u_c/MHz
a_1	0	—	a_9	460.973	0.002
a_2	248.206	0.002	a_{10}	571.262	0.002
a_3	280.802	0.002	a_{11}	693.205	0.002
a_4	290.502	0.002	a_{12}	701.377	0.002
a_5	322.524	0.002	a_{13}	726.710	0.002
a_6	395.386	0.002	a_{14}	735.795	0.002
a_7	410.696	0.002	a_{15}	857.383	0.002
a_8	445.759	0.002			

Frequency referenced to a_{10}, R(56) 32-0, $^{127}I_2$: $f = 563\,260\,223\,513$ kHz [2]
$f(a_1, \text{R(86) 33-0}) - f(a_{10}, \text{R(56) 32-0}) = -32\,190\,406\,(5)$ kHz [2]

Ref. [92, 93].

Table 15.

$\lambda \approx 532$ nm $^{127}I_2$ R(106) 34-0 (no 1108)					
a_n	$[f(a_n) - f(a_1)]$/MHz	u_c/MHz	a_n	$[f(a_n) - f(a_1)]$/MHz	u_c/MHz
a_1	0	—	a_9	467.984	0.002
a_2	236.870	0.002	a_{10}	570.799	0.002
a_3	276.941	0.002	a_{11}	687.539	0.002
a_4	293.861	0.002	a_{12}	698.663	0.002
a_5	333.350	0.002	a_{13}	728.261	0.002
a_6	387.636	0.002	a_{14}	740.185	0.002
a_7	404.635	0.002	a_{15}	856.675	0.002
a_8	451.175	0.002			

Frequency referenced to a_{10}, R(56) 32-0, $^{127}I_2$: $f = 563\,260\,223\,513$ kHz [2]
$f(a_1, \text{R(106) 34-0}) - f(a_{10}, \text{R(56) 32-0}) = -30\,434\,763\,(5)$ kHz [2]

Ref. [92–94].

Table 16.

λ ≈ 532 nm $^{127}I_2$ R(134) 36-0					
a_n	$[f(a_n) - f(a_1)]$/MHz	u_c/MHz	a_n	$[f(a_n) - f(a_1)]$/MHz	u_c/MHz
a_1	0	—	a_8	462.603	0.009
a_2	212.287	0.007	a_9	484.342	0.007
a_3	269.634	0.022	a_{11}	674.703	0.009
a_4	300.097	0.011	a_{12}	691.951	0.008
a_5	356.801	0.008	a_{13}	732.405	0.008
a_6	369.644	0.008	a_{14}	750.434	0.009
a_7	391.684	0.009			
Frequency referenced to	a_{10}, R(56) 32-0, $^{127}I_2$: $f = 563\,260\,223\,513$ kHz [2]				
	$f(a_1$, R(134) 36-0) $- f(a_{10}$, R(56) 32-0) $= -17\,173\,682$ (5) kHz [2]				

Ref. [92, 93].

Table 17.

λ ≈ 532 nm $^{127}I_2$ P(83) 33-0 (no 1109)					
a_n	$[f(a_n) - f(a_1)]$/MHz	u_c/MHz	a_n	$[f(a_n) - f(a_1)]$/MHz	u_c/MHz
a_1	0	—	a_{11}	507.533	0.004
a_2	48.789	0.004	a_{13}	620.065	0.004
a_3	95.839	0.008	a_{14}	659.930	0.004
a_4	281.343	0.010	a_{15}	728.070	0.004
a_5	330.230	0.004	a_{16}	750.131	0.004
a_6	338.673	0.004	a_{17}	774.805	0.004
a_7	385.830	0.004	a_{18}	796.125	0.004
a_8	444.365	0.006	a_{19}	890.709	0.005
a_9	460.503	0.004	a_{20}	904.712	0.005
a_{10}	493.533	0.006	a_{21}	920.475	0.004
Frequency referenced to	a_{10}, R(56) 32-0, $^{127}I_2$: $f = 563\,260\,223\,513$ kHz [2]				
	$f(a_{21}$, P(83) 33-0) $- f(a_{10}$, R(56) 32-0) $= -15\,682\,075$ (5) kHz [2]				

Ref. [92, 93].

Table 18.

λ ≈ 532 nm $^{127}I_2$ R(56) 32-0 (no 1110)					
a_n	$[f(a_n) - f(a_{10})]$/MHz	u_c/MHz	a_n	$[f(a_n) - f(a_{10})]$/MHz	u_c/MHz
a_1	−571.542	0.0015	a_{10}	0	—
a_2	−311.844	0.0015	a_{11}	126.513	0.0015
a_5	−260.176	0.0015	a_{12}	131.212	0.0015
a_6	−170.064	0.0015	a_{13}	154.488	0.0015
a_7	−154.548	0.0015	a_{14}	160.665	0.0015
a_8	−131.916	0.0015	a_{15}	286.412	0.0015
a_9	−116.199	0.0015			
Frequency referenced to	a_{10}, R(56) 32-0, $^{127}I_2$: $f = 563\,260\,223\,513$ kHz [2]				

Ref. [92, 93, 95–100].

Table 19.

λ ≈ 532 nm $^{127}I_2$ P(53) 32-0 (no 1111)					
a_n	$[f(a_n) - f(a_1)]$/MHz	u_c/MHz	a_n	$[f(a_n) - f(a_1)]$/MHz	u_c/MHz
a_1	0	—	a_{17}	762.623	0.006
a_2	37.530	0.006	a_{18}	788.431	0.008
a_3	73.060	0.007	a_{19}	879.110	0.006
a_4	271.326	0.016	a_{20}	892.953	0.009
a_{15}	712.935	0.012	a_{21}	910.093	0.006
a_{16}	739.274	0.008			
Frequency referenced to	a_{10}, R(56) 32-0, $^{127}I_2$: $f = 563\,260\,223\,513$ kHz [2]				
	$f(a_1$, P(53) 32-0) $- f(a_{10}$, R(56) 32-0) $= 2\,599\,708$ (5) kHz [2]				

Ref. [92, 93].

Table 20.

		λ ≈ 633 nm $^{127}I_2$ R(127) 11-5					
a_n	x	$[f(a_n) - f(a_{16})]$/MHz	u_c/MHz	a_n	x	$[f(a_n) - f(a_{16})]$/MHz	u_c/MHz
a_2	t	−721.8	0.5	a_{12}	j	−160.457	0.005
a_3	s	−697.8	0.5	a_{13}	i	−138.892	0.005
a_4	r	−459.62	0.01	a_{14}	h	−116.953	0.005
a_5	q	−431.58	0.05	a_{15}	g	−13.198	0.005
a_6	p	−429.18	0.05	a_{16}	f	0	—
a_7	o	−402.09	0.01	a_{17}	e	13.363	0.005
a_8	n	−301.706	0.005	a_{18}	d	26.224	0.005
a_9	m	−292.693	0.005	a_{19}	c	144.114	0.005
a_{10}	l	−276.886	0.005	a_{20}	b	152.208	0.005
a_{11}	k	−268.842	0.005	a_{21}	a	161.039	0.005
Frequency referenced to		a_{16} (f), R(127) 11-5, $^{127}I_2$: f = 473 612 353 604 kHz [2]					

Ref. [101–112].

Table 21.

		λ ≈ 633 nm $^{127}I_2$ P(33) 6-3					
b_n	x	$[f(b_n) - f(b_{21})]$/MHz	u_c/MHz	b_n	x	$[f(b_n) - f(b_{21})]$/MHz	u_c/MHz
b_1	u	−922.571	0.008	b_{12}	j	−347.354	0.007
b_2	t	−895.064	0.008	b_{13}	i	−310.30	0.01
b_3	s	−869.67	0.01	b_{14}	h	−263.588	0.009
b_4	r	−660.50	0.02	b_{15}	g	−214.53	0.02
b_5	q	−610.697	0.008	b_{16}	f	−179.312	0.005
b_6	p	−593.996	0.008	b_{17}	e	−153.942	0.005
b_7	o	−547.40	0.02	b_{18}	d	−118.228	0.007
b_8	n	−487.074	0.009	b_{19}	c	−36.73	0.01
b_9	m	−461.30	0.03	b_{20}	b	−21.980	0.007
b_{10}	l	−453.21	0.03	b_{21}	a	0	—
b_{11}	k	−439.01	0.01				
Frequency referenced to		a_{16} (f), R(127) 11-5, $^{127}I_2$: f = 473 612 353 604 kHz [2] $f(b_{21}$, P(33) 6-3) − $f(a_{16}$, R(127) 11-5) = −532.42 (2) MHz [113]					

Ref. [108, 113–117].

Table 22.

		λ ≈ 633 nm $^{129}I_2$ P(54) 8-4					
a_n	x	$[f(a_n) - f(a_{28})]$/MHz	u_c/MHz	a_n	x	$[f(a_n) - f(a_{28})]$/MHz	u_c/MHz
a_2	z′	−449	2	a_{16}	i′	−197.73	0.08
a_3	y′	−443	2	a_{17}	h′	−193.23	0.08
a_4	x′	−434	2	a_{18}	g′	−182.74	0.03
a_5	w′	−429	2	a_{19}	f′	−162.61	0.05
a_6	v′	−360.9	1	a_{20}	e′	−155.72	0.05
a_7	u′	−345.1	1	a_{21}	d′	−138.66	0.05
a_8	t′	−340.8	1	a_{22}	c′	−130.46	0.05
a_9	s′	−325.4	1	a_{23}	a′	−98.22	0.03
a_{10}	r′	−307.0	1	a_{24}	n_2	−55.6, see m_8 table 26	0.5
a_{11}	q′	−298.2	1	a_{25}	n_1	−55.6, see m_8 table 26	0.5
a_{12}	p′	−293.1	1	a_{26}	m_2	−43.08	0.03
a_{13}	o′	−289.7	1	a_{27}	m_1	−41.24	0.05
a_{14}	n′	−282.7	1	a_{28}	k	0	—
a_{15}	j′	−206.1	0.2				
Frequency referenced to		a_{16} (f), R(127) 11-5, $^{127}I_2$: f = 473 612 353 604 kHz [2] $f(a_{28}$, P(54) 8-4) − $f(a_{16}$, R(127) 11-5 $\{^{127}I_2\}$) = −42.99 (4) MHz [118, 119]					

Ref. [118–126].

Table 23.

		$\lambda \approx 633$ nm $^{129}I_2$ P(69) 12-6					
b_n	x	$[f(b_n) - f(a_{28})]$/MHz	u_c/MHz	b_n	x	$[f(b_n) - f(a_{28})]$/MHz	u_c/MHz
b_1	b'''	99.12	0.05	b_{21}	q'	507.66	0.10
b_2	a'''	116.08	0.05	b_{22}	o'	532.65	0.10
b_3	z''	132.05	0.05	b_{23}	n'	536.59	0.10
b_4	s''	234.54	0.05	b_{24}	m'	545.06	0.05
b_5	r''	256.90, see m_{28} table 26	0.05	b_{25}	l'	560.94	0.05
b_6	q''	264.84, see m_{29} table 26	0.05	b_{26}	k'	566.19	0.05
b_7	p''	288.06	0.05	b_{27}	j'	586.27	0.03
b_8	k''	337.75	0.1	b_{28}	i'	601.78	0.03
b_9	i''_1 |	358.8	0.5	b_{29}	h'	620.85	0.03
b_{10}	i''_2 |	358.8	0.5	b_{30}	g'	632.42	0.03
b_{11}	f''	373.80	0.05	b_{31}	f'	644.09	0.03
b_{12}	d''	387.24	0.05	b_{32}	e'	655.47	0.03
b_{13}	c''	395.3	0.2	b_{33}	d'	666.81	0.10
b_{14}	b''	402.45	0.05	b_{34}	c'	692.45	0.10
b_{15}	a''	407	4	b_{35}	b'	697.96	0.10
b_{16}	z'	412.37	0.05	b_{36}	a'	705.43	0.10
b_{17}	y'	417	4				

Frequency referenced to a_{16} (f), R(127) 11-5, $^{127}I_2$: $f = 473\,612\,353\,604$ kHz [2]
$f(a_{28}$, P(54) 8-4$) - f(a_{16}$, R(127) 11-5 $\{^{127}I_2\}) = -42.99$ (4) MHz [118, 119]

Ref. [121, 124, 126].

Table 24.

		$\lambda \approx 633$ nm $^{129}I_2$ R(60) 8-4					
d_n	x	$[f(d_n) - f(a_{28})]$/MHz	u_c/MHz	d_n	x	$[f(d_n) - f(a_{28})]$/MHz	u_c/MHz
d_{23}	A′	−555	5	d_{26}	M |	−499	2
d_{24}	N |	−511	2	d_{27}	M |	−499	2
d_{25}	N |	−511	2	d_{28}	K	−456	2

Frequency referenced to a_{16} (f), R(127) 11-5, $^{127}I_2$: $f = 473\,612\,353\,604$ kHz [2]
$f(a_{28}$, P(54) 8-4$) - f(a_{16}$, R(127) 11-5 $\{^{127}I_2\}) = -42.99$ (4) MHz [118, 119]

Ref. [121].

Table 25.

		$\lambda \approx 633$ nm $^{129}I_2$ P(33) 6-3					
e_n	x	$[f(e_n) - f(e_2)]$/MHz	u_c/MHz	e_n	x	$[f(e_n) - f(e_2)]$/MHz	u_c/MHz
e_1	A	−19.82	0.05	e_{10}	J	249	2
e_2	B	0	—	e_{11}	K	260	2
e_3	C	17.83	0.03	e_{12}	L	269	3
e_4	D	102.58	0.05	e_{13}	M	273	4
e_5	E	141	2	e_{14}	N	287	4
e_6	F	157	2	e_{15}	O	293	5
e_7	G	191	2	e_{16}	P	295	5
e_8	H	208	2	e_{17}	Q	306	6
e_9	I	239	2				

Frequency referenced to a_{16} (f), R(127) 11-5, $^{127}I_2$: $f = 473\,612\,353\,604$ kHz [2]
$f(e_2$, P(33) 6-3$) - f(a_{16}$, R(127) 11-5 $\{^{127}I_2\}) = 849.4$ (2) MHz [127, 128]

Ref. [121, 126, 127, 129].

Table 26.

λ ≈ 633 nm $^{127}I^{129}I$ P(33) 6-3

m_n		$[f(m_n) - f(a_{28})]$/MHz	u_c/MHz	m_n		$[f(m_n) - f(a_{28})]$/MHz	u_c/MHz
m_1	m′	−254	3	m_{26}	u″	212.80	0.05
m_2	l′	−233.71	0.10	m_{27}	t″	219.43	0.05
m_3	k′	−226.14	0.10	m_{28}	r″	256.90, see b_5 table 23	0.10
m_4	j′	−207	2	m_{29}	q″	264.84, see b_6 table 23	0.05
m_5	b′	−117.79	0.10	m_{30}	o″	299.22	0.05
m_6	p	−87.83	0.15	m_{31}	n″	312.43	0.05
m_7	o	−78.2	0.5	m_{32}	m″	324.52	0.03
m_8	n	−56, see a_{24} and a_{25} table 22	1	m_{33}	l″	333.14	0.03
m_9	l	−17.55	0.05	m_{34}	k''_2	337.7	0.5
m_{10}	j	12.04	0.03	m_{35}	k''_1	337.7	0.5
m_{11}	i	15.60	0.03	m_{36}	j″	345.05	0.05
m_{12}	h	33.16	0.03	m_{37}	h″	362.18	0.10
m_{13}	g_2	39.9	0.2	m_{38}	g″	369.78	0.03
m_{14}	g_1	41.3	0.2	m_{39}	e″	380.37	0.03
m_{15}	f	50.72	0.03	m_{40}	d″	385	4
m_{16}	e	54.06	0.10	m_{41}	x′	431	4
m_{17}	d	69.33	0.03	m_{42}	w′	445	4
m_{18}	c	75.06	0.03	m_{43}	v′	456.7	0.5
m_{19}	b	80.00	0.03	m_{44}	u′	477.17	0.05
m_{20}	a	95.00	0.03	m_{45}	t′	486.43	0.05
m_{21}	y″	160.74	0.03	m_{46}	s′	495.16	0.05
m_{22}	x″	199.52	0.03	m_{47}	r′	503.55	0.05
m_{23}	w″	205.06	0.05	m_{48}	p′	515.11	0.05
m_{24}	v''_2	207.9	0.5				
m_{25}	v''_1	207.9	0.5				

Frequencies referenced to a_{16}, R(127) 11-5, $^{127}I_2$: $f = 473\,616\,353\,604$ kHz [2]
$f(a_{28}$, P(54) 8-4) − $f(a_{16}$, R(127) 11-5 $\{^{127}I_2\}) = -42.99$ (4) MHz [118, 119]

Ref. [74, 121, 124–126].

Table 27.

λ ≈ 778 nm ^{85}Rb $5S_{1/2}$–$5D_{3/2}$ two-photon transition

F_g–F_e	$[f(5S_{1/2}\ (F_g) - 5D_{3/2}\ (F_e))/2 - f_{ref}]$/kHz	u_c/kHz
3–1	−44 462 655	7
3–2	−44 459 151	7
3–3	−44 453 175	7
3–4	−44 443 871	7
2–1	−42 944 789	7
2–2	−42 941 283	7
2–3	−42 935 308	7
2–4	−42 926 004	7

Frequency referenced to $f_{ref} = f(5S_{1/2}\ (F_g = 3) - 5D_{5/2}\ (F_e = 5))/2\ \{^{85}Rb\}$ [2]
$f_{ref} = 385\,285\,142\,375$ kHz

Ref. [130].

Table 28.

λ ≈ 778 nm ^{85}Rb $5S_{1/2}$–$5D_{5/2}$ two-photon transition

F_g–F_e	$[f(5S_{1/2}\ (F_g) - 5D_{5/2}\ (F_e))/2 - f_{ref}]$/kHz	u_c/kHz
3–5	0	—
3–4	4 718	9
3–3	9 228	9
3–2	13 031	9
3–1	15 771	14
2–4	1 522 595	9
2–3	1 527 094	9
2–2	1 530 887	9
2–1	1 533 631	11
2–0	1 535 084	26

Frequency referenced to $f_{ref} = f(5S_{1/2}\ (F_g = 3) - 5D_{5/2}\ (F_e = 5))/2\ \{^{85}Rb\}$ [2]
$f_{ref} = 385\,285\,142\,375$ kHz

Ref. [130, 131[8]].

[8] Improved interval measurements are available for certain components and can be used provided appropriate consideration to uncertainties is made.

Table 29.

$\lambda \approx 778$ nm ^{87}Rb $5S_{1/2}$–$5D_{3/2}$ two-photon transition		
F_g–F_e	$[f(5S_{1/2}\ (F_g) - 5D_{3/2}\ (F_e))/2 - f_{ref}]$/kHz	u_c/kHz
2–0	−45 047 389	7
2–1	−45 040 639	7
2–2	−45 026 674	7
2–3	−45 004 563	7
1–1	−41 623 297	7
1–2	−41 609 335	7
1–3	−41 587 223	7
Frequency referenced to	$f_{ref} = f\ (5S_{1/2}\ (F_g = 3) - 5D_{5/2}\ (F_e = 5))/2$ {^{85}Rb} [2]	
	$f_{ref} = 385\,285\,142\,375$ kHz [2]	

Ref. [130].

Table 30.

$\lambda \approx 778$ nm ^{87}Rb $5S_{1/2}$–$5D_{5/2}$ two-photon transition		
F_g–F_e	$[f(5S_{1/2}\ (F_g) - 5D_{5/2}\ (F_e))/2 - f_{ref}]$/kHz	u_c/kHz
2–4	−576 001	9
2–3	−561 589	9
2–2	−550 112	9
2–1	−542 142	9
1–3	2 855 755	9
1–2	2 867 233	9
1–1	2 875 200	9
Frequency referenced to	$f_{ref} = f\,(5S_{1/2}\ (F_g = 3) - 5D_{5/2}\ (F_e = 5))/2$ {^{85}Rb} [2]	
	$f_{ref} = 385\,285\,142\,375$ kHz	

Ref. [130, 131[9]].

Table 31.

$\lambda \approx 1.54\ \mu$m $^{13}C_2H_2\,\nu_1 + \nu_3$ band					
J	f(P(J))/MHz	u_c/MHz	J	f(R(J))/MHz	u_c/MHz
30	−1 149 564.7	0.2	0	1 219 093.1	0.2
29	−1 063 105.1	0.2	1	1 284 955.8	0.2
28	−977 244.4	0.2	2	1 350 174.0	0.2
27	−892 105.5	0.2	3	1 414 736.5	0.2
26	−807 638.2	0.2	4	1 478 632.0	0.2
25	−723 847.1	0.2	5	1 541 851.4	0.2
24	−640 722.1	0.2	6	1 604 387.0	0.2
23	−558 275.9	0.2	7	1 666 233.6	0.2
22	−476 502.7	0.2	8	1 727 380.4	0.2
21	−395 403.0	0.2	9	1 787 844.3	0.2
20	−314 976.3	0.2	10	1 847 604.8	0.2
19	−235 222.8	0.2	11	1 906 665.9	0.2
18	−156 142.2	0.2	12	1 965 025.9	0.2
17	−77 734.4	0.2	13	2 022 683.7	0.2
16	0.0	—	14	2 079 635.6	0.2
15	77 062.9	0.2	15	2 135 883.2	0.2
14	153 451.2	0.2	16	2 191 422.0	0.2
13	229 165.9	0.2	17	2 246 250.5	0.2
12	304 206.5	0.2	18	2 300 366.6	0.2
11	378 572.2	0.2	19	2 353 768.0	0.2
10	452 257.0	0.2	20	2 406 452.4	0.2
9	525 279.1	0.2	21	2 458 417.6	0.2
8	597 619.6	0.2	22	2 509 661.5	0.2
7	669 287.3	0.2	23	2 560 176.5	0.2
6	740 285.1	0.2			
5	810 618.3	0.2			
4	880 294.4	0.2			
3	949 322.3	0.2			
2	1 017 710.7	0.2			
1	1 085 467.1	0.2			
Frequency referenced to	P(16)$\nu_1 + \nu_3$, $^{13}C_2H_2$: $f = 194\,369\,569.4$ MHz [2]				

Ref. [47].

[9] See footnote 8.

Table 32.

	$\lambda \approx 10.3\ \mu m\ OsO_4$							
	$^{12}C^{16}O_2$	OsO_4						
n	Laser line	Line	[Isotope]	$[f_n - f\{R(10)\}]$/kHz	u_c/kHz	$[f(OsO_4) - f(CO_2)]$/kHz	u_c/kHz
1	P(22)	P(74)A1(5)	[192]	−802 127 930.98	0.09	−12 149.5	0.2
2	P(20)	*not identified*		−747 823 325.30	0.09	9 229.6	0.2
3	P(18)	*n.i.*		−694 298 622.36	0.08	−14 992	5
4	P(18)	*n.i.*		−694 287 490.14	0.08	−3 855.2	0.1
5	P(18)	P(64)A1(2) −	[188]	−694 228 479.74	0.08	55 150	5
6	P(18)	P(64)A1(2) +	[188]	−694 222 035.30	0.08	61 594	5
7	P(16)	*n.i.*		−641 510 912.32	0.08	−43 197	5
8	P(16)	*n.i.*		−641 434 335.52	0.08	33 384.6	0.1
9	P(14)	*n.i.*		−589 380 507.62	0.08	3 219.6	0.2
10	P(12)	P(39)A1(3)	[192]	−538 005 458.32	0.08	25 330.6	0.1
11	P(12)	P(39)A1(2)	[192]	−538 005 001.14	0.08	25 782	5
12	P(10)	*n.i.*		−487 427 074.66	0.08	−18 821.1	0.1
13	P(8)	P(30)A1(1)	[188]	−437 503 817.04	0.08	11 864.7	0.1
14	P(6)	*n.i.*		−388 374 844.21	0.08	−22 003	5
15	P(4)	*n.i.*		−339 945 022.42	0.08	−25 299	5
16	P(4)	*n.i.*		−339 937 689.31	0.08	−17 966	5
17	P(4)	*n.i.*		−339 929 467.51	0.08	9 744	5
18	R(0)	Q(15)A2(2)	[188]	−222 040 746.1	2.0	−9 519.0	2
19	R(2)	*n.i.*		−176 145 049.74	0.08	9 955	5
20	R(4)	*n.i.*		−131 026 773.25	0.08	−15 760	5
21	R(6)	*n.i.*		−86 634 255.43	0.08	−33 873.0	0.1
22	R(8)	*n.i.*		−42 940 582.49	0.08	−16 145	5
23	R(8)	*n.i.*		−42 920 080	1	4 368	1
24	R(8)	*n.i.*		−42 898 034.29	0.08	26 402	5
25	R(8)	*n.i.*		−42 894 454.94	0.08	29 982	5
26	R(8)	R(26)A1(0)	[189]	−42 876 821.68	0.08	47 615	5
27	R(8)	*n.i.*		−42 876 683.60	0.08	47 753	5
28	R(8)	*n.i.*		−42 875 301.45	0.08	49 135	5
29	R(8)	*n.i.*		−42 875 199.99	0.08	49 237	5
30	R(10)	*n.i.*		0	—	−15 252.7	0.6
31	R(12)	*n.i.*		42 217 505.67	0.08	558.1	0.1
32	R(14)	*n.i.*		83 689 586.75	0.08	10 919.1	0.1
33	R(16)	R(49)A1(2)	[187]	124 411 469.06	0.08	13 237.9	0.1
34	R(18)	*n.i.*		164 349 843.53	0.08	−23 400	5
35	R(18)	*n.i.*		164 392 583.43	0.08	19 342.6	0.1
36	R(18)	*n.i.*		164 394 642.25	0.08	21 398	5
37	R(20)	R(67)	[192]	203 576 376.40	0.08	−24 706.6	0.2
38	R(22)	R(73)A1(0)	[192]	242 072 138.79	0.08	−6 788	5
39	R(22)	*n.i.*		242 088 910.50	0.08	9 986.0	0.2
40	R(24)	*n.i.*		279 818 815.98	0.09	15 102.1	0.1
41	R(26)	*n.i.*		316 756 631.74	0.09	−15 542.5	0.1

Frequencies referenced to R(10)/CO_2, OsO_4: $f = 29\,054\,057\,446\,579$ Hz [2]

Ref. [65, 132–141].

Table 33.

$\lambda \approx 515$ nm $^{127}I_2$ P(13) 43-0					
a_n	$[f(a_n) - f(a_3)]$/MHz	u_c/MHz	a_n	$[f(a_n) - f(a_3)]$/MHz	u_c/MHz
a_1	−131.770	0.001	a_{12}	435.599	0.003
a_2	−59.905	0.001	a_{13}	499.712	0.005
a_3	0	—	a_{14}	518	1
a_4	76.049	0.002	a_{15}	587.396	0.002
a_5	203.229	0.005	a_{16}	616.756	0.005
a_6	240.774	0.005	a_{17}	660.932	0.005
a_7	255.005	0.001	a_{18}	740	1
a_8	338.699	0.005	a_{19}	742	1
a_9	349.717	0.005	a_{20}	757.631	0.010
a_{10}	369	1	a_{21}	817.337	0.005
a_{11}	393.962	0.002			

Frequency referenced to a_3, P(13) 43-0, $^{127}I_2$: $f = 582\,490\,603.38$ MHz [2]

Ref. [142–145].

Table 34.

$\lambda \approx 515$ nm $^{127}I_2$ R(15) 43-0					
b_n	$[f(b_n) - f(b_1)]$/MHz	u_c/MHz	b_n	$[f(b_n) - f(b_1)]$/MHz	u_c/MHz
b_1	0	—	b_{12}	566.287	0.005
b_2	69.739	0.005	b_{13}	630.782	0.005
b_3	129.155	0.005	b_{14}	658.178	0.005
b_4	217	1	b_{15}	725.166	0.005
b_5	335.828	0.005	b_{16}	739.394	0.005
b_6	368	1	b_{17}	791.673	0.005
b_7	396.442	0.005	b_{18}	865.523	0.005
b_8	471	1	b_{19}	874.840	0.005
b_9	472	1	b_{20}	892.895	0.010
b_{10}	500.627	0.005	b_{21}	947.278	0.010
b_{11}	525.207	0.005			

Frequency referenced to a_3, P(13) 43-0, $^{127}I_2$: $f = 582\,490\,603.38$ MHz [2]
$f(a_1$, P(13) 43-0) $- f(a_3$, P(13) 43-0) $= -131.770$ (1) MHz
$f(b_1$, R(15) 43-0) $- f(a_1$, P(13) 43-0) $= 283.835$ (5) MHz [143]

Ref. [143, 144].

Table 35.

$\lambda \approx 515$ nm $^{127}I_2$ R(98) 58-1					
d_n	$[f(d_n) - f(d_6)]$/MHz	u_c/MHz	d_n	$[f(d_n) - f(d_6)]$/MHz	u_c/MHz
d_1	−413.488	0.005	d_9	225.980	0.005
d_2	−359.553	0.005	d_{10}	253	1
d_3	−194.521	0.005	d_{11}	254	1
d_4	−159.158	0.005	d_{12}	314.131	0.005
d_5	−105.769	0.005	d_{13}	426.691	0.005
d_6	0	—	d_{14}	481.574	0.005
d_7	172.200	0.005	d_{15}	510.246	0.005
d_8	200.478	0.005			

Frequency referenced to a_3, P(13) 43-0, $^{127}I_2$: $f = 582\,490\,603.38$ MHz [2]
$f(d_6$, R(98) 58-1) $- f(a_3$, P(13) 43-0) $= -2100$ (1) MHz [146]

Ref. [144, 146].

Table 36.

$\lambda \approx 543$ nm $^{127}I_2$ R(12) 26-0					
a_n	$[f(a_n) - f(a_9)]$/MHz	u_c/MHz	a_n	$[f(a_n) - f(a_9)]$/MHz	u_c/MHz
a_1	−482.82	0.02	a_9	0	—
a_2	−230.45	0.02	a_{10}	83.286	0.005
a_3	−220.69	0.03	a_{11}	193.81	0.01
a_4	−173.916	0.005	a_{12}	203.07	0.01
a_5	−168.711	0.005	a_{13}	256.19	0.01
a_6	−116.50	0.01	a_{14}	269.41	0.01
a_7	−72.962	0.005	a_{15}	373.510	0.005
a_8	−53.714	0.005			

Frequency referenced to a_9, R(12) 26-0, $^{127}I_2$: $f = 551\,579\,482.97$ MHz [2]

Ref. [147–153].

Table 37.

$\lambda \approx 543$ nm $^{127}I_2$ R(106) 28-0					
b_n	$[f(b_n) - f(a_9)]$/MHz	u_c/MHz	b_n	$[f(b_n) - f(a_9)]$/MHz	u_c/MHz
b_1	105.655	0.005	b_9	564.845	0.005
b_2	358.958	0.005	b_{10}	679.420	0.005
b_3	387.83	0.01	b_{11}	804.25	0.01
b_4	397.277	0.005	b_{12}	811.73	0.01
b_5	425.745	0.005	b_{13}	833.93	0.01
b_6	506.727	0.005	b_{14}	842.07	0.01
b_7	519.992	0.005	b_{15}	966.66	0.01
b_8	551.660	0.005			

Frequency referenced to a_9, R(12) 26-0, $^{127}I_2$: $f = 551\,579\,482.97$ MHz [2]

Ref. [147–153].

Table 38.

$\lambda \approx 576$ nm $^{127}I_2$ P(62) 17-1							
a_n	x	$[f(a_n) - f(a_1)]$/MHz	u_c/MHz	a_n	x	$[f(a_n) - f(a_1)]$/MHz	u_c/MHz
a_1	o	0	—	a_7	i	428.51	0.02
a_2	n	275.03	0.02	a_8	h	440.17	0.02
a_3	m	287.05	0.02	a_9	g	452.30	0.02
a_4	l	292.57	0.02	a_{10}	f	579.43	0.03
a_5	k	304.26	0.02	a_{15}	a	869.53	0.03
a_6	j	416.67	0.02				
Frequency referenced to a_1, P(62) 17-1, $^{127}I_2$: $f = 520\,206\,808.4$ MHz [2]							

Ref. [79, 154].

Table 39.

$\lambda \approx 612$ nm $^{127}I_2$ R(47) 9-2							
a_n	x	$[f(a_n) - f(a_7)]$/MHz	u_c/MHz	a_n	x	$[f(a_n) - f(a_7)]$/MHz	u_c/MHz
a_1	u	−357.16	0.02	a_{12}	j	219.602	0.006
a_2	t	−333.97	0.01	a_{13}	i	249.60	0.01
a_3	s	−312.46	0.02	a_{14}	h	284.30	0.01
a_4	r	−86.168	0.007	a_{15}	g	358.37	0.03
a_5	q	−47.274	0.004	a_{16}	f	384.66	0.01
a_6	p	−36.773	0.003	a_{17}	e	403.76	0.02
a_7	o	0	—	a_{18}	d	429.99	0.02
a_8	n	81.452	0.003	a_{19}	c	527.16	0.02
a_9	m	99.103	0.003	a_{20}	b	539.22	0.02
a_{10}	l	107.463	0.005	a_{21}	a	555.09	0.02
a_{11}	k	119.045	0.006				
Frequency referenced to a_7, R(47) 9-2, $^{127}I_2$: $f = 489\,880\,354.9$ MHz [2]							

Ref. [148, 155–159].

Table 40.

$\lambda \approx 612$ nm $^{127}I_2$ P(48) 11-3					
b_n	$[f(b_n) - f(a_7)]$/MHz	u_c/MHz	b_n	$[f(b_n) - f(a_7)]$/MHz	u_c/MHz
b_1	−1034.75	0.07	b_9	−579.91	0.01
b_2	−755.86	0.05	b_{10}	−452.163	0.005
b_3	−748.28	0.03	b_{11}	−316.6	0.4
b_4	−738.35	0.04	b_{12}	−315.8	0.4
b_5	−731.396	0.006	b_{13}	−297.42	0.03
b_6	−616.01	0.03	b_{14}	−294.72	0.03
b_7	−602.42	0.03	b_{15}	−160.318	0.003
b_8	−593.98	0.01			
Frequency referenced to a_7, R(47) 9-2, $^{127}I_2$: $f = 489\,880\,354.9$ MHz [2]					

Ref. [148, 155, 157–160].

Table 41.

$\lambda \approx 612$ nm $^{127}I_2$ R(48) 15-5					
c_n	$[f(c_n) - f(a_7)]$/MHz	u_c/MHz	c_n	$[f(c_n) - f(a_7)]$/MHz	u_c/MHz
c_1	−513.83	0.03	c_5	−209.96	0.03
c_2	−237.40	0.03	c_6	−97.74	0.03
c_3	−228.08	0.03	c_8	−73.92	0.03
c_4	−218.78	0.03	c_9	−59.30	0.03
Frequency referenced to a_7, R(47) 9-2, $^{127}I_2$: $f = 489\,880\,354.9$ MHz [2]					

Ref. [155].

Table 42.

		$\lambda \approx 612$ nm $^{129}I_2$ P(110) 10-2					
a_n	x	$[f(a_n) - f(a_7\{^{127}I_2\})]$/MHz	u_c/MHz	a_n	x	$[f(a_n) - f(a_7\{^{127}I_2\})]$/MHz	u_c/MHz
a_1	b′	−376.29	0.05	a_{15}	n	1.61	0.20
a_2	a′	−244.76	0.10	a_{16}	m	10.63	0.15
a_3	z	−230.79	0.20	a_{17}	l	15.82	0.20
a_4	y	−229.40	0.20	a_{18}	k	25.32	0.10
a_5	x	−216.10	0.05	a_{19}	j	49.44	0.15
a_6	w	−149.37	0.10	a_{20}	i	54.66	0.20
a_7	v	−134.68	0.10	a_{21}	h	69.02	0.10
a_8	u	−130.98	0.10	a_{22}	g	74.47	0.15
a_9	t	−116.67	0.05	a_{23}	f	110.60	0.10
a_{10}	s	−96.26	0.20	a_{24}	e	153.09	0.20
a_{11}	r	−90.70	0.20	a_{25}	d	154.70	0.20
a_{12}	q	−84.12	0.20	a_{26}	c	163.98	0.20
a_{13}	p	−77.79	0.20	a_{27}	b	166.22	0.20
a_{14}	o	−72.70	0.20	a_{28}	a	208.29	0.10
Frequency referenced to a_7, R(47) 9-2, $^{127}I_2$: $f = 489\,880\,354.9$ MHz [2]							

Ref. [161–163].

Table 43.

		$\lambda \approx 612$ nm $^{129}I_2$ R(113) 14-4					
b_n	x	$[f(b_n) - f(a_7\{^{127}I_2\})]$/MHz	u_c/MHz	b_n	x	$[f(b_n) - f(a_7\{^{127}I_2\})]$/MHz	u_c/MHz
b_{19}	r	−410.4	0.3	b_{28}	i	−289.4	0.5
b_{20}	q	−390.0	0.3	b_{29}	h	−273.1	0.3
b_{21}	p	−383.9	0.5	b_{30}	g	−255.7	0.5
b_{22}	o	−362.8	0.3	b_{31}	f	−247	5
b_{23}	n	−352.9	0.3	b_{32}	e	−237	5
b_{24}	m	−346.4	0.3	b_{33}	d	−223	5
b_{25}	l	−330.0	0.3	b_{34}	c	−198.6	0.3
b_{26}	k	−324.9	0.3	b_{35}	b	−193.1	0.3
b_{27}	j	−304.7	0.3	b_{36}	a	−187.0	0.3
Frequency referenced to a_7, R(47) 9-2, $^{127}I_2$: $f = 489\,880\,354.9$ MHz [2]							

Ref. [162, 163].

Table 44.

	$\lambda \approx 640$ nm $^{127}I_2$ P(10) 8-5				
a_n	$[f(a_n) - f(a_9)]$/MHz	u_c/MHz	a_n	$[f(a_n) - f(a_9)]$/MHz	u_c/MHz
a_1	−495.4	0.4	a_9	0	—
a_2	−241.5	0.7	a_{10}	77.84	0.03
a_3	−233.0	0.4	a_{11}	186.22	0.07
a_4	−177.8	1.3	a_{12}	199.51	0.07
a_5	−175.2	0.6	a_{13}	256.6	0.2
a_6	−130.8	0.1	a_{14}	272.75	0.07
a_7	−82.45	0.03	a_{15}	374.0	0.2
a_8	−61.85	0.14			
Frequency referenced to a_9, P(10) 8-5, $^{127}I_2$: $f = 468\,218\,332.4$ MHz [2]					

Ref. [148, 158, 164–169].

Table 45.

	$\lambda \approx 640$ nm $^{127}I_2$ R(16) 8-5	
b_n	$[f(b_n) - f(a_9)]$/MHz	u_c/MHz
b_1	62.834	0.01
b_2	329.8	0.2
b_3	335.99	0.02
Frequency referenced to a_9, P(10) 8-5, $^{127}I_2$: $f = 468\,218\,332.4$ MHz [2]		

Ref. [148, 158, 164–169].

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