

MEP 2003

IODINE ($\lambda \approx 633$ nm)

Absorbing molecule $^{127}\text{I}_2$, a_{16} or f component, R(127) 11-5 transition ⁽¹⁾

1. CIPM recommended values

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 $(25 \pm 5)^\circ\text{C}$ ⁽²⁾;
- cold-finger temperature $(15.0 \pm 0.2)^\circ\text{C}$;
- 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 ≤ 1.0 kHz/mW.

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 section 2 below.

2. Source data

Adopted value: $f = 473\,612\,353\,604$ (10) kHz $u_c/y = 2.1 \times 10^{-11}$
for which:
 $\lambda = 632\,991\,212.579$ (13) fm $u_c/y = 2.1 \times 10^{-11}$

calculated from

f / kHz	u_c/y	source data
8.2	4.0×10^{-12}	[1, 2]
7.4	3.0×10^{-12}	[1, 3]
4.2	1.4×10^{-11}	See section 2.1
8.2	5.3×10^{-12}	[5]
Unweighted mean:	$(f_{\text{BIPM4}} - f_{\text{CIPM97}}) = 7.0$ kHz	

The source data are all given with 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 2001.

⁽¹⁾ All transitions in I_2 refer to the $\text{B}^3\Pi_{0_u^+} - \text{X}^1\Sigma_g^+$ system.

⁽²⁾ For the specification of operating conditions, such as temperature, modulation width and laser power, the symbols $\pm$ refer to a tolerance, not an uncertainty.

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 2-2. 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 [6–14]. This series of comparisons is a key comparison BIPM.L-K10 and is reported on the BIPM website <http://www.bipm.org/kcdb>.

For applications where relaxed tolerances, and the resultant wider uncertainty range are acceptable, a laser operated under the conditions recommended in 1983 [15, 16] would lead to a standard uncertainty of about 50 kHz (or a relative standard uncertainty of 1×10^{-10}).

Source data

2.1 Sugiyama et al. [14] give

$f_f = 473\,612\,353\,604.3$ kHz $u_c = 1.7$ kHz as the frequency of the NRLM-P1 laser standard.

This value indicates that $f_f = f_{\text{CIPM97}} + f_{\text{corr}}$ where $f_{\text{corr}} = 7.3$ kHz.

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

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

Assuming that this frequency has been maintained since, one obtains

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

2.2 The uncertainties resulting from variations in operational parameters are listed below.

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				

3. 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. Long., 2001, **10**, 168-173 and Metrologia, 2003, **40**, 121-123.

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 (1σ).

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

Table 1

$\lambda \approx 633\text{ nm } ^{127}\text{I}_2\text{ R(127) 11-5}$							
a_n	x	$[f(a_n)-f(a_{16})]/\text{MHz}$	u_c/MHz	a_n	x	$[f(a_n)-f(a_{16})]/\text{MHz}$	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, $^{127}\text{I}_2$: $f = 473\,612\,353\,604\text{ kHz}$							[17]
Ref. [18–29]							

Table 2 $\lambda \approx 633 \text{ nm } ^{127}\text{I}_2 \text{ P(33) 6-3}$

b_n	x	$[f(b_n)-f(b_{21})]/\text{MHz}$	u_c/MHz	b_n	x	$[f(b_n)-f(b_{21})]/\text{MHz}$	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		$a_{16} \text{ (f), R(127) 11-5, }^{127}\text{I}_2: f= 473\,612\,353\,604 \text{ kHz}$				[17]	
		$f(b_{21}, \text{P(33) 6-3})-f(a_{16}, \text{R(127) 11-5})=-532.42 \text{ (2) MHz}$				[30]	
Ref. [25, 30–34]							

Table 3 $\lambda \approx 633 \text{ nm } ^{129}\text{I}_2 \text{ P(54) 8-4}$

a_n	x	$[f(a_n)-f(a_{28})]/\text{MHz}$	u_c/MHz	a_n	x	$[f(a_n)-f(a_{28})]/\text{MHz}$	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 7	0.5
a_{11}	q'	-298.2	1	a_{25}	n_1		-55.6 see m ₈ table 7
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, $^{127}\text{I}_2$: $f=473\,612\,353\,604\text{ kHz}$ [17]							
$f(a_{28}, \text{P(54) 8-4}) - f(a_{16}, \text{R(127) 11-5 } \{^{127}\text{I}_2\}) = -42.99\text{ (4) MHz}$ [35–36]							

Table 4 $\lambda \approx 633 \text{ nm } ^{129}\text{I}_2 \text{ P}(69) 12\text{-}6$

b_n	x	$[f(b_n) - f(a_{28})] / \text{MHz}$	u_c / MHz	b_n	x	$[f(b_n) - f(a_{28})] / \text{MHz}$	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 7	0.05	b_{25}	l'	560.94	0.05
b_6	q''	264.84 see m ₂₉ table 7	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 $a_{16} (f), R(127) 11\text{-}5, ^{127}\text{I}_2: f = 473\,612\,353\,604 \text{ kHz}$ [17]
 $f(a_{28}, P(54) 8\text{-}4) - f(a_{16}, R(127) 11\text{-}5 \{^{127}\text{I}_2\}) = -42.99 (4) \text{ MHz}$ [35–36]

Ref. [38, 41–43]

Table 5 $\lambda \approx 633 \text{ nm } ^{129}\text{I}_2 \text{ R}(60) 8\text{-}4$

d_n	x	$[f(d_n) - f(a_{28})] / \text{MHz}$	u_c / MHz	d_n	x	$[f(d_n) - f(a_{28})] / \text{MHz}$	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 $a_{16} (f), R(127) 11\text{-}5, ^{127}\text{I}_2: f = 473\,612\,353\,604 \text{ kHz}$ [17]
 $f(a_{28}, P(54) 8\text{-}4) - f(a_{16}, R(127) 11\text{-}5 \{^{127}\text{I}_2\}) = -42.99 (4) \text{ MHz}$ [35–36]

Ref. [38]

Table 6

$\lambda \approx 633 \text{ nm } ^{129}\text{I}_2 \text{ P(33) 6-3}$							
e_n	x	$[f(e_n) - f(e_2)]/\text{MHz}$	u_c/MHz	e_n	x	$[f(e_n) - f(e_2)]/\text{MHz}$	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 $a_{16}(\text{f}), \text{R}(127) 11-5, ^{127}\text{I}_2: f = 473\,612\,353\,604 \text{ kHz}$						[17]	
$f(e_2, \text{P(33) 6-3}) - f(a_{16}, \text{R(127) 11-5 } \{^{127}\text{I}_2\}) = 849.4 (2) \text{ MHz}$						[45-46]	
Ref. [38, 43, 45, 47]							

Table 7

$\lambda \approx 633 \text{ nm}$ $^{127}\text{I}^{129}\text{I}$ P(33) 6-3

m_n	$[f(m_n) - f(a_{28})]/\text{MHz}$	u_c/MHz	m_n	$[f(m_n) - f(a_{28})]/\text{MHz}$	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 4	0.10
m_4 j'	-207	2	m_{29} q''	264.84, see b ₆ table 4	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 3	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			

Frequency referenced to a_{16} (f), R(127) 11-5, $^{127}\text{I}_2$: $f = 473\,612\,353\,604 \text{ kHz}$ [17]
 $f(a_{28}, \text{P}(54) \text{ 8-4}) - f(a_{16}, \text{R}(127) \text{ 11-5 } \{^{127}\text{I}_2\}) = -42.99 \text{ (4) MHz}$ [35-36]

Ref. [38, 44, 41-43]

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