

University of Groningen

Compilation of Spectroscopic Data of Radium (Ra I and Ra II)

Dammalapati, U.; Jungmann, K.; Willmann, L.

Published in:
Journal of Physical and Chemical Reference Data

DOI:
[10.1063/1.4940416](https://doi.org/10.1063/1.4940416)

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2016

[Link to publication in University of Groningen/UMCG research database](#)

Citation for published version (APA):

Dammalapati, U., Jungmann, K., & Willmann, L. (2016). Compilation of Spectroscopic Data of Radium (Ra I and Ra II). *Journal of Physical and Chemical Reference Data*, 45(1), 013101-1 - 013101-14.
<https://doi.org/10.1063/1.4940416>

Copyright

Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

The publication may also be distributed here under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license. More information can be found on the University of Groningen website: <https://www.rug.nl/library/open-access/self-archiving-pure/taverne-amendment>.

Take-down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): <http://www.rug.nl/research/portal>. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.

Compilation of Spectroscopic Data of Radium (Ra I and Ra II)

U. Dammalapati, K. Jungmann, and L. Willmann

Citation: *Journal of Physical and Chemical Reference Data* **45**, 013101 (2016); doi: 10.1063/1.4940416

View online: <http://dx.doi.org/10.1063/1.4940416>

View Table of Contents: <http://scitation.aip.org/content/aip/journal/jpcrd/45/1?ver=pdfcov>

Published by the [AIP Publishing](#)

Articles you may be interested in

Determination of the binding energies of the np Rydberg states of H₂, HD, and D₂ from high-resolution spectroscopic data by multichannel quantum-defect theory

J. Chem. Phys. **140**, 104303 (2014); 10.1063/1.4866809

Towards a precise measurement of atomic parity violation in a single Ra⁺ ion

AIP Conf. Proc. **1441**, 552 (2012); 10.1063/1.3700614

The spectroscopic characterization of the methoxy radical. II. Rotationally resolved $A^{\sim} A 2 1 - X^{\sim} E 2$ electronic and $X^{\sim} E 2$ microwave spectra of the perdeuteromethoxy radical CD₃O

J. Chem. Phys. **130**, 074303 (2009); 10.1063/1.3072105

Spectroscopic Data for Neutral Francium (Fr I)

J. Phys. Chem. Ref. Data **36**, 497 (2007); 10.1063/1.2719251

Vibronic dependence of the B state lifetimes of CH₃I and CD₃I using femtosecond photoionization spectroscopy

J. Chem. Phys. **108**, 3445 (1998); 10.1063/1.475744

Compilation of Spectroscopic Data of Radium (Ra I and Ra II)

U. Dammalapati,^{a)} K. Jungmann, and L. Willmann^{b)}

Van Swinderen Institute, Faculty of Mathematics and Natural Sciences, University of Groningen, Zernikelaan 25,
 9747 AA Groningen, The Netherlands

(Received 10 December 2015; accepted 11 January 2016; published online 12 February 2016)

Energy levels, wavelengths, lifetimes, and hyperfine structure constants for the isotopes of the first and second spectra of radium, Ra I and Ra II, have been compiled. Wavelengths and wavenumbers are tabulated for ^{226}Ra and for other Ra isotopes. Isotope shifts and hyperfine structure constants of even and odd- A isotopes of neutral radium atom and singly ionized radium are included. Experimental lifetimes of the states for both neutral and ionic Ra are also added, where available. The information is beneficial for present and future experiments aimed at different physics motivations using neutral Ra and singly ionized Ra. © 2016 AIP Publishing LLC for the National Institute of Standards and Technology. [<http://dx.doi.org/10.1063/1.4940416>]

Key words: energy levels; hyperfine structure; lifetime; radium (Ra I); radium ion (Ra II); spectroscopic data; transitions; wavenumbers.

CONTENTS

1. Introduction.....	1	10. Wavelengths, wavenumbers, classification, and transition probabilities for observed lines in radium ion, $^{226}\text{Ra II}$	9
2. Ra I.....	7	11. Ritz wavelengths and uncertainty of Ritz wavelengths in $^{226}\text{Ra II}$	11
3. Ra II.....	10	12. Wavelengths, wavenumbers, and terms of isotopes of Ra II.....	12
4. Spectroscopic Data.....	13	13. Isotope shifts and hyperfine constants of the $7s\ ^2S_{1/2}$, $7p\ ^2P_{1/2}^0$, and $7p\ ^2P_{3/2}^0$ levels in Ra II....	12
Acknowledgments.....	13	14. Isotope shifts and HFS constants A and B of the $6d\ ^2D_{3/2}$ and $7p\ ^2P_{1/2}^0$ levels in Ra II.....	12
5. References.....	13	15. Isotope shifts and HFS constants A and B of the $7p\ ^2P_{3/2}^0$ and $6d\ ^2D_{3/2}$ levels in Ra II.....	13
		16. Lifetimes of energy levels in $^{212}\text{Ra II}$	13

List of Tables

1. Isotopes of radium with zero nuclear spin (I) and with nonzero nuclear spin.....	2
2. Energy levels of $^{226}\text{Ra I}$	3
3. Wavelengths, wavenumbers, classification, and transition probabilities in neutral radium (^{226}Ra), Ra I.....	5
4. Lifetimes of energy levels— $^{226}\text{Ra I}$	7
5. Isotope shifts and HFS constants A and B of $7s\ ^2S_0$ and $7s7p\ ^1P_1^0$ levels in Ra I.....	7
6. Isotope shifts and HFS constants A and B of $7s\ ^2S_0$ and $7s7p\ ^3P_1^0$ levels in Ra I.....	7
7. Isotope shifts and HFS constants A and B of the $7s7p\ ^3P_2^0$ level and the $7s6d\ ^3D_3$ level in Ra I....	8
8. Isotope shifts and HFS constants A and B of the $7s7p\ ^1P_1^0$ level and the $7s6d\ ^3D_1$ level in Ra I....	8
9. Energy levels of $^{226}\text{Ra II}$	8

1. Introduction

Radium (Ra), a radioactive element, was discovered by Curie, Curie, and Bemont in the year 1898.¹ It was extracted by chemical means from pitchblende or uraninite. About one gram (1 g) of radium is present in 7 tons of pitchblende. The activity of 1 g of ^{226}Ra was defined later as the unit of radioactivity, Curie, Ci [1 Ci = 3.7×10^{10} disintegrations per second (dis/s)]. The term *radioactivity* was introduced by Mme. Curie. Ritz in 1908 classified two series of lines of neutral radium, Ra I.² In 1911, radium was isolated by Mme. Curie and Debierne, who found it to be a brilliant white solid.³ Some energy levels and line classifications of Ra I were given by Fues in 1920.⁴ In 1922, Fowler gave classifications of some series of lines in both Ra I and singly ionized radium, Ra II.⁵ In 1933–1934, Rasmussen first measured the energy levels of singly ionized radium (Ra II)⁶ using arc discharge and of neutral radium (Ra I)⁷ using 2 mg of radiumchloride (RaCl_2) in a discharge lamp and monochromator for determining the wavelengths. Some of the

^{a)}Electronic mail: dammalapati.umakanth.a8@tohoku.ac.jp. Present address: Cyclotron and Radioisotope Center (CYRIC), Tohoku University, 6-3 Aramaki-Aza Aoba, Aoba-ku, Miyagi 980-8578, Japan.

^{b)}Electronic mail: l.willmann@rug.nl.

© 2016 AIP Publishing LLC.

TABLE 1. Isotopes of radium with zero nuclear spin (I) and with nonzero nuclear spin. The half-lives (ns-nanoseconds, μ s-microseconds, ms-milliseconds, s-seconds, m-minutes, d-days, and y-years) and nuclear spin (I) are taken from Ref. 47. The atomic weights are taken from Ref. 48

Isotope	Atomic weight ⁴⁸ u	Half-life $t_{1/2}$	Nuclear spin ¹⁹ I	Nuclear magnetic moment ⁴⁷ [μ_I/μ_N]	Electric quadrupole moment ²³ Q_s in [b] ^a
²³⁵ Ra	235.054 970(320)				
²³⁴ Ra	234.050 340(30)	30 s	0		
²³³ Ra	233.047 582(17)	30 s			
²³² Ra	232.043 475(10)	4.2 m	0		
²³¹ Ra	231.041 027(12)	104.1 s	5/2		
²³⁰ Ra	230.037 055(11)	93 m	0		
²²⁹ Ra	229.034 942(16)	4.0 m	5/2	0.5025(27)	3.09(4)
²²⁸ Ra	228.031 070 7(2.6)	5.75 y	0		
²²⁷ Ra	227.029 178 3(2.5)	42.2 m	3/2	-0.4038(24)	1.58(3)
²²⁶ Ra	226.025 410 3(2.5)	1600 y	0		
²²⁵ Ra	225.023 612(3)	14.9 d	1/2	-0.7338(15)	
²²⁴ Ra	224.020 212(2.3)	3.6319 d	0		
²²³ Ra	223.018 502 3(2.7)	11.43 d	3/2	0.2705(19)	1.254(3)
²²² Ra	222.015 375(5)	38.0 s	0		
²²¹ Ra	221.013 918(5)	28 s	5/2	-0.1799(17)	1.978(7)
²²⁰ Ra	220.011 026(9)	18 ms	0		
²¹⁹ Ra	219.010 085(9)	10 ms	7/2		
²¹⁸ Ra	218.007 141(12)	25.2 μ s	0		
²¹⁷ Ra	217.006 321(9)	1.6 μ s	9/2		
²¹⁶ Ra	216.003 533(9)	182 ns	0		
²¹⁵ Ra	215.002 720(8)	1.55 ms	9/2		
²¹⁴ Ra	214.000 100(6)	2.46 s	0		
²¹³ Ra	213.000 384(22)	2.73 m	1/2	0.6133(18)	
²¹² Ra	211.999 787(12)	13 s	0		
²¹¹ Ra	211.000 893(9)	13 s	5/2	0.8780(38)	0.48(2)
²¹⁰ Ra	210.000 494(16)	3.7 s	0		
²⁰⁹ Ra	209.001 990(50)	4.6 s	5/2	0.865(13)	0.40(2)
²⁰⁸ Ra	208.001 841(17)	1.3 s	0		
²⁰⁷ Ra	207.003 800(60)	1.35 s	3/2,5/2		
²⁰⁶ Ra	206.003 828(19)	0.24 s	0		
²⁰⁵ Ra	205.006 270(80)	210 ms	3/2		
²⁰⁴ Ra	204.006 492(16)	57 ms	0		
²⁰³ Ra	203.009 300(90)	31 ms	3/2		
²⁰² Ra	202.009 760(26)	16 ms	0		
^{201m} Ra	201.012 710(110)	1.6 ms	13/2		

^a 1 barn (b) = 10^{-24} cm².

transition terms of neutral radium measured by Rasmussen were corrected by Russell.⁸ The first compilation of energy levels for neutral and singly ionized radium was published by Moore in 1958 in atomic energy levels (AELs).⁹ After that, no updates were made to reference data on neutral and singly ionized Ra. With the advent of accelerator facilities, modern experimental methods to produce radium isotopes and to probe the atomic structure, more information is available on these spectra in the literature. At this juncture, we realized the need to update the information available on Ra atom and Ra ion and gathered it, which might be beneficial for various experiments that are in progress^{10–14} and for the future experiments^{15,16} with different physics motivations and for various fields of research.

About forty six years after Rasmussen's measurement of energy levels and wavelengths in Ra ion and Ra atom, furnace-absorption measurements of energy levels of the $7snp\ ^1P_1^0$ ($n = 13–52$) series of neutral radium in the ultraviolet region were reported by Armstrong *et al.*^{17,18} From the experimental results and applying the multichannel quantum defect theory (MQDT), values for $7snp$ ($n = 9–12$) levels were

semiempirically determined. The reported uncertainty was 0.006 cm^{-1} for wavenumbers and 0.001 \AA for wavelengths.

The first systematic measurements on a series of neutral and singly ionized radium isotopes employing the technique of collinear laser spectroscopy were conducted by the ISOLDE collaboration at CERN, Geneva.^{19–23} Radium isotopes were produced by impinging protons of energy 600 MeV on a UC₂ cloth target. These studies established nuclear spins and obtained nuclear moments from the measured hyperfine structure (HFS) and isotope shifts.

In the last decade, there has been renewed interest in radium element (radium atom as well as ion) from both theoretical and experimental physicists. From theoretical calculations, radium atom is proposed as a promising candidate for searches of a permanent electric dipole moment in an atomic system.^{24–30} The reasons are large polarizability due to the near degeneracy of the opposite parity $7s7p\ ^3P_1^0$ and $7s6d\ ^3D_2$ levels; some isotopes of radium have nuclear octupole deformation and high atomic number ($Z = 88$). Singly ionized radium ion is proposed as a promising candidate for atomic parity violation experiments and as an atomic clock.^{31–33}

TABLE 2. Energy levels of ²²⁶Ra I

Configuration	Term	J	Level (cm ⁻¹)	Uncertainty (cm ⁻¹)	Level LOPT (cm ⁻¹)	Uncertainty LOPT (cm ⁻¹)	Level reference
7s ²	¹ S	0	0.0000		0.0000	0.0	
7s7p	³ P ⁰	0	13 078.44		13 078.40	0.04	9
	³ P ⁰	1	13 999.357	0.001	13 999.3569	0.0010	41
	³ P ⁰	2	16 688.54		16 688.54	0.04	9
7s6d	³ D	1	13 715.85		13 715.779	0.020	9
	³ D	2	13 993.97		13 993.94	0.04	9
	³ D	3	14 707.35		14 707.286	0.050	9
7s6d	¹ D	2	17 081.45		17 081.313	0.060	9
7s7p	¹ P ⁰	1	20 715.6142	0.0005	20 715.6142	0.0005	12
7s8s	³ S	1	26 754.05		26 754.015	0.030	9
7s8s	¹ S	0					
6d7p	³ F ⁰	2	28 038.05		28 038.00	0.04	9
	³ F ⁰	3	30 117.78		30 117.72	0.06	9
	³ F ⁰	4	32 367.78		32 367.70	0.08	9
6d7p	¹ D ⁰	2	30 918.14		30 918.01	0.07	9
7s8p	³ P ⁰	0	31 085.88		31 085.80	0.15	9
	³ P ⁰	1	31 563.29		31 563.40	0.13	9
	³ P ⁰	2	31 874.44		31 874.25	0.11	9
7p ² (6d ²) ⁵¹	³ P	0					9
	³ P	1	31 248.61		31 248.61	0.07	9
	³ P	2	32 941.13		32 941.20	0.03	9
7s7d	³ D	1	32 000.82		32 000.78	0.05	9
	³ D	2	31 993.41		31 993.40	0.06	9
	³ D	3	32 197.28		32 197.27	0.07	9
7p ² (7s7d), ²¹ (6d ²) ⁵¹	¹ D	2	32 214.84		32 214.76	0.06	9
6d7p	³ D ⁰	1	32 229.97		32 229.89	0.06	9
	³ D ⁰	2	32 506.59		32 506.52	0.05	9
	³ D ⁰	3	33 197.46		33 197.39	0.07	9
7s8p	¹ P ⁰	1	32 857.68		32 857.54	0.08	9
6d7p	³ P ⁰	0	33 782.41		33 782.32	0.20	9
	³ P ⁰	1	33 823.70		33 823.63	0.15	9
	³ P ⁰	2	34 382.91		34 382.83	0.08	9
7s9s	³ S	1	34 475.78		34 475.74	0.12	9
7s5f	³ F ⁰	2	35 255.65		35 255.51	0.09	9
	³ F ⁰	3	35 268.02		35 267.88	0.09	9
	³ F ⁰	4	35 294.40		35 294.32	0.10	9
7s6f	³ F ⁰	2					9
	³ F ⁰	3	37 922.26		37 922.2	0.3	9
	³ F ⁰	4	37 929.64		37 929.6	0.3	9
7s7f	³ F ⁰	2					9
	³ F ⁰	3	39 360.96		39 360.9	0.3	9
	³ F ⁰	4	39 366.98		39 366.9	0.3	9
7s8f	³ F ⁰	2	40 219.5		40 219.4	0.4	9
	³ F ⁰	3	40 219.5		40 219.5	0.4	9
	³ F ⁰	4	40 231.58		40 231.5	0.3	9
7s13p	¹ P ⁰	1	41 034.401	0.006	41 034.400	0.017	17
7s14p	¹ P ⁰	1	41 338.940	0.006	41 338.940	0.017	17
7s15p	¹ P ⁰	1	41 562.296	0.006	41 562.296	0.017	17
7s16p	¹ P ⁰	1	41 730.581	0.006	41 730.580	0.017	17
7s17p	¹ P ⁰	1	41 860.241	0.006	41 860.240	0.018	17
7s18p	¹ P ⁰	1	41 962.282	0.006	41 962.281	0.018	17
7s19p	¹ P ⁰	1	42 043.869	0.006	42 043.868	0.018	17
7s20p	¹ P ⁰	1	42 110.347	0.006	42 110.347	0.018	17
7s21p	¹ P ⁰	1	42 164.971	0.006	42 164.971	0.018	17
7s22p	¹ P ⁰	1	42 210.520	0.006	42 210.520	0.018	17
7s23p	¹ P ⁰	1	42 248.829	0.006	42 248.829	0.018	17
7s24p	¹ P ⁰	1	42 281.384	0.006	42 281.383	0.018	17
7s25p	¹ P ⁰	1	42 309.321	0.006	42 309.320	0.018	17
7s26p	¹ P ⁰	1	42 333.336	0.006	42 333.335	0.018	17
7s27p	¹ P ⁰	1	42 354.358	0.006	42 354.357	0.018	17
7s28p	¹ P ⁰	1	42 372.773	0.006	42 372.773	0.018	17
7s29p	¹ P ⁰	1	42 388.773	0.006	42 388.773	0.018	17
7s30p	¹ P ⁰	1	42 403.096	0.006	42 403.096	0.018	17
7s31p	¹ P ⁰	1	42 415.790	0.006	42 415.789	0.018	17

TABLE 2. Energy levels of ^{226}Ra I—Continued

Configuration	Term	J	Level (cm^{-1})	Uncertainty (cm^{-1})	Level LOPT (cm^{-1})	Uncertainty LOPT (cm^{-1})	Level reference
$7s32p$	$^1P^0$	1	42 427.050	0.006	42 427.050	0.018	17
$7s33p$	$^1P^0$	1	42 437.097	0.006	42 437.097	0.018	17
$7s34p$	$^1P^0$	1	42 446.203	0.006	42 446.203	0.018	17
$7s35p$	$^1P^0$	1	42 454.517	0.006	42 454.516	0.018	17
$7s36p$	$^1P^0$	1	42 461.863	0.006	42 461.863	0.018	17
$7s37p$	$^1P^0$	1	42 468.788	0.006	42 468.788	0.018	17
$7s38p$	$^1P^0$	1	42 474.918	0.006	42 474.917	0.018	17
$7s39p$	$^1P^0$	1	42 480.501	0.006	42 480.501	0.018	17
$7s40p$	$^1P^0$	1	42 485.662	0.006	42 485.662	0.018	17
$7s41p$	$^1P^0$	1	42 490.375	0.006	42 490.375	0.018	17
$7s42p$	$^1P^0$	1	42 494.765	0.006	42 494.765	0.018	17
$7s43p$	$^1P^0$	1	42 498.882	0.006	42 498.882	0.018	17
$7s44p$	$^1P^0$	1	42 502.575	0.006	42 502.575	0.018	17
$7s45p$	$^1P^0$	1	42 506.119	0.006	42 506.118	0.018	17
$7s46p$	$^1P^0$	1	42 509.289	0.006	42 509.288	0.018	17
$7s47p$	$^1P^0$	1	42 512.260	0.006	42 512.260	0.018	17
$7s48p$	$^1P^0$	1	42 515.131	0.006	42 515.131	0.018	17
$7s49p$	$^1P^0$	1	42 517.803	0.006	42 517.803	0.018	17
$7s50p$	$^1P^0$	1	42 520.126	0.006	42 520.125	0.018	17
$7s51p$	$^1P^0$	1	42 522.424	0.006	42 522.423	0.018	17
$7s52p$	$^1P^0$	1	42 524.473	0.006	42 524.473	0.018	17
Ra II	Limit		42 573.36	0.02			17
$(6p^6 7s^2 S_{1/2})$							

In this context, short lived radioactive isotopes were produced at the TRI μ P facility, University of Groningen, The Netherlands.³⁴ Radium isotopes were produced by the method of inverse reaction kinematics using $^{206,204}\text{Pb}$ beams hitting a rotating carbon target.^{35,36} Precision laser spectroscopy of radium ions was performed in a radio frequency quadrupole (RFQ) trap.^{13,37–39}

At the University of Groningen, The Netherlands, with ^{229}Th (10 μCi) placed in an oven, ^{225}Ra neutral atomic beam was produced. Employing this thermal beam of Ra atoms, the absolute frequency of the strong electric dipole $7s^2\ ^1S_0-7s7p\ ^1P^0_1$ transition and weaker intercombination $7s^2\ ^1S_0-7s7p\ ^3P^0_1$ transition were reported with reference to a femtosecond optical frequency comb.^{12,40} The uncertainty reported was $0.000\ 06\ \text{cm}^{-1}$ and $0.000\ 13\ \text{cm}^{-1}$, respectively.

At Argonne National Laboratory (ANL), USA, electrochemically separated neutral radium isotopes, $^{225,226}\text{Ra}$ placed in an oven were used for a laser cooling and trapping experiment.¹⁰ Further, optical dipole trapping of ^{226}Ra ¹¹ and measurement of lifetimes of $7s7p\ ^3P^0_1$, $7s6d\ ^3D_1$, and $7s6d\ ^1D_2$ states were reported by the ANL group.^{10,41,42} Very recently, using cold atoms, the first measurement of the atomic dipole moment of ^{225}Ra was reported by the same group.¹⁴

In this compilation, energy levels, wavelengths, wavenumbers, transition probabilities, lifetimes, and other spectral data have been reviewed. The most accurate information has been assembled from the available experimental and theoretical data and is presented in Tables 1–16. The uncertainty of each value, as given by the original authors, is indicated in the tables. In the line tables (Tables 3 and 10), the wavelengths and their uncertainties are reported in units of angstroms. For lines between 2000 \AA and 15 000 \AA air wavelengths and for lines below 2000 \AA vacuum wavelengths are given. The

index of refraction is determined by the three-term formula [Eq. (3)] of Peck and Reeder.⁴³ The wavenumber of each transition is given in reciprocal centimeters and its uncertainty is also given wherever applicable. The lower and upper level columns indicate the classification given for the transition. The Ritz wavelengths and their uncertainties calculated using the level optimization code, LOPT (Ref. 44) are also given. The calculated transition probabilities (A_{ik}) are given in units of inverse seconds. Their accuracy range is also given in a separate column. For singly ionized Ra, uncertainty is given for theoretical transition rates by Sahoo *et al.*³² (Table 10).

The energy level tables (Tables 2 and 9) contain the configuration, term, and J values of each energy level, using LS coupling to describe the configurations. In addition to that, energy uncertainty, energy level values, and their uncertainty from the LOPT code are also given. For visual clarity, only the first member of the term has the configuration written out similar to the notation used by Curry.⁴⁵ The level value and its uncertainty are given in reciprocal centimeters.

Ionization energies are given in units of cm^{-1} and electronvolts (eV). Conversion factor from cm^{-1} to eV was taken from the 2014 CODATA adjustment of fundamental constants:⁴⁶ $1\ \text{cm}^{-1} = 1.239\ 841\ 973\ 9(76) \times 10^{-4}\ \text{eV}$. The reciprocal centimeter is related to the SI unit for energy, the joule, in the following way: $1\ \text{cm}^{-1}$ is equivalent to $1.986\ 445\ 824\ (24) \times 10^{-23}\ \text{J}$.⁴⁶

The HFS constants and isotope shifts are given in Tables 5–15, in units of megahertz (MHz) with the uncertainty in the last digit given in parentheses following the value. All uncertainties given in this paper are on the level of one standard deviation. The hyperfine splitting constant, A , is the magnetic dipole coefficient, whereas B is the electric quadrupole coefficient. The references for energy levels and

TABLE 3. Wavelengths, wavenumbers, classification, and transition probabilities in neutral radium (²²⁶Ra), Ra I

Intensity	Observed $\lambda_{air}/\text{\AA}$	Uncertainty	Observation σ/cm^{-1}	Lower level	Upper level	Line reference(s)	Ritz $\lambda/\text{\AA}$	Uncertainty	A_{ik}/s^{-1}	References
		observation $\lambda_{air}/\text{\AA}$						Ritz $\lambda/\text{\AA}$		
	2350.8675	0.0010	42524.473	$7s^2\ ^1S_0$	$7s52p\ ^1P^0_1$	17				
	2350.9808	0.0010	42522.423	$7s^2\ ^1S_0$	$7s51p\ ^1P^0_1$	17				
	2351.1079	0.0010	42520.125	$7s^2\ ^1S_0$	$7s50p\ ^1P^0_1$	17				
	2351.2363	0.0010	42517.803	$7s^2\ ^1S_0$	$7s49p\ ^1P^0_1$	17				
	2351.3841	0.0010	42515.131	$7s^2\ ^1S_0$	$7s48p\ ^1P^0_1$	17				
	2351.5429	0.0010	42512.260	$7s^2\ ^1S_0$	$7s47p\ ^1P^0_1$	17				
	2351.7073	0.0010	42509.288	$7s^2\ ^1S_0$	$7s46p\ ^1P^0_1$	17				
	2351.8827	0.0010	42506.118	$7s^2\ ^1S_0$	$7s45p\ ^1P^0_1$	17				
	2352.0788	0.0010	42502.575	$7s^2\ ^1S_0$	$7s44p\ ^1P^0_1$	17				
	2352.2832	0.0010	42498.882	$7s^2\ ^1S_0$	$7s43p\ ^1P^0_1$	17				
	2352.5111	0.0010	42494.765	$7s^2\ ^1S_0$	$7s42p\ ^1P^0_1$	17				
	2352.7542	0.0010	42490.375	$7s^2\ ^1S_0$	$7s41p\ ^1P^0_1$	17				
	2353.0152	0.0010	42485.662	$7s^2\ ^1S_0$	$7s40p\ ^1P^0_1$	17				
	2353.3011	0.0010	42480.501	$7s^2\ ^1S_0$	$7s39p\ ^1P^0_1$	17				
	2353.6105	0.0010	42474.917	$7s^2\ ^1S_0$	$7s38p\ ^1P^0_1$	17				
	2353.9502	0.0010	42468.788	$7s^2\ ^1S_0$	$7s37p\ ^1P^0_1$	17				
	2354.3341	0.0010	42461.863	$7s^2\ ^1S_0$	$7s36p\ ^1P^0_1$	17				
	2354.7416	0.0010	42454.516	$7s^2\ ^1S_0$	$7s35p\ ^1P^0_1$	17				
	2355.2028	0.0010	42446.203	$7s^2\ ^1S_0$	$7s34p\ ^1P^0_1$	17				
	2355.7082	0.0010	42437.097	$7s^2\ ^1S_0$	$7s33p\ ^1P^0_1$	17				
	2356.2661	0.0010	42427.050	$7s^2\ ^1S_0$	$7s32p\ ^1P^0_1$	17				
	2356.8917	0.0010	42415.789	$7s^2\ ^1S_0$	$7s31p\ ^1P^0_1$	17				
	2357.5973	0.0010	42403.096	$7s^2\ ^1S_0$	$7s30p\ ^1P^0_1$	17				
	2358.3940	0.0010	42388.773	$7s^2\ ^1S_0$	$7s29p\ ^1P^0_1$	17				
	2359.2846	0.0010	42372.773	$7s^2\ ^1S_0$	$7s28p\ ^1P^0_1$	17				
	2360.3105	0.0010	42354.357	$7s^2\ ^1S_0$	$7s27p\ ^1P^0_1$	17				
	2361.4827	0.0010	42333.335	$7s^2\ ^1S_0$	$7s26p\ ^1P^0_1$	17				
	2362.8232	0.0010	42309.320	$7s^2\ ^1S_0$	$7s25p\ ^1P^0_1$	17				
	2364.3845	0.0010	42281.383	$7s^2\ ^1S_0$	$7s24p\ ^1P^0_1$	17				
	2366.2065	0.0010	42248.829	$7s^2\ ^1S_0$	$7s23p\ ^1P^0_1$	17				
	2368.3542	0.0010	42210.520	$7s^2\ ^1S_0$	$7s22p\ ^1P^0_1$	17				
	2370.9128	0.0010	42164.971	$7s^2\ ^1S_0$	$7s21p\ ^1P^0_1$	17				
	2373.9885	0.0010	42110.347	$7s^2\ ^1S_0$	$7s20p\ ^1P^0_1$	17				
	2377.7425	0.0010	42043.868	$7s^2\ ^1S_0$	$7s19p\ ^1P^0_1$	17				
	2382.3659	0.0010	41962.281	$7s^2\ ^1S_0$	$7s18p\ ^1P^0_1$	17				
	2388.1738	0.0010	41860.240	$7s^2\ ^1S_0$	$7s17p\ ^1P^0_1$	17				
	2395.5946	0.0010	41730.580	$7s^2\ ^1S_0$	$7s16p\ ^1P^0_1$	17				
	2405.2950	0.0010	41562.296	$7s^2\ ^1S_0$	$7s15p\ ^1P^0_1$	17				
	2418.2919	0.0010	41338.940	$7s^2\ ^1S_0$	$7s14p\ ^1P^0_1$	17				
	2436.2408	0.0010	41034.400	$7s^2\ ^1S_0$	$7s13p\ ^1P^0_1$	17				
2	2955.65	0.05	33823.6	$7s^2\ ^1S_0$	$6d7p\ ^3P^0_1$	8	2955.649	0.012		
			32857.68	$7s^2\ ^1S_0$	$7s8p\ ^1P^0_1$	9	3042.557	0.008		
5	3101.80	0.05	32230.0	$7s^2\ ^1S_0$	$6d7p\ ^3D^0_1$	7, 8	3101.810	0.005		
3	3771.57	0.05	26506.66			7				
1	3772.00	0.05	26503.6	$7s6d\ ^3D_1$	$7s8f\ ^3F^0_2$	7				
1	3812.00	0.05	26225.5	$7s6d\ ^3D_2$	$7s8f\ ^3F^0_3$	7				
1	3916.74	0.05	25524.2	$7s6d\ ^3D_3$	$7s8f\ ^3F^0_4$	7				
1	3941.02	0.05	25367.0	$7s6d\ ^3D_2$	$7s7f\ ^3F^0_3$	7				
1	4010.30	0.05	24928.77			7				
1	4054.07	0.05	24659.6	$7s6d\ ^3D_3$	$7s7f\ ^3F^0_4$	7				
4	4177.98	0.05	23928.3	$7s6d\ ^3D_2$	$7s6f\ ^3F^0_3$	7				
3	4265.12	0.05	23439.43			7				
4	4305.00	0.05	23222.3	$7s6d\ ^3D_3$	$7s6f\ ^3F^0_4$	7				
2	4366.30	0.05	22896.27			7				
2	4426.35	0.05	22585.65			7				
1	4444.47	0.05	22493.57			7				
8	4641.290	0.020	21539.70	$7s6d\ ^3D_1$	$7s5f\ ^3F^0_2$	7	4641.284	0.019		
1	4672.19	0.05	21397.25	$7s7p\ ^3P^0_0$	$7s9s\ ^3S_1$	7	4672.17	0.03		
8	4699.280	0.020	21273.90	$7s6d\ ^3D_2$	$7s5f\ ^3F^0_3$	7	4699.272	0.018		
2	4701.97	0.05	21261.73	$7s6d\ ^3D_2$	$7s5f\ ^3F^0_2$	7	4702.006	0.020		
2	4740.07	0.05	21090.86			7				
3	4803.11	0.05	20814.04			7				
100	4825.92806	0.00012	20715.6142	$7s^2\ ^1S_0$	$7s7p\ ^1P^0_1$	7, 12	4825.92805	0.0012	1.80×10^8	53
3	4837.27	0.05	20667.04	$7s6d\ ^3D_1$	$6d7p\ ^3P^0_2$	7	4837.268	0.017		

TABLE 3. Wavelengths, wavenumbers, classification, and transition probabilities in neutral radium (^{226}Ra), Ra I—Continued

Intensity	Observed $\lambda_{air}/\text{\AA}$	Uncertainty		Lower level	Upper level	Line reference(s)	Ritz $\lambda/\text{\AA}$	Uncertainty		References
		observation $\lambda_{air}/\text{\AA}$	Observation σ/cm^{-1}					Ritz $\lambda/\text{\AA}$	A_{ik}/s^{-1}	
10	4 856.070	0.020	20 587.03	$7s6d^3D_3$	$7s5f^3F_4^0$	7				
2	4 862.27	0.05	20 560.78	$7s6d^3D_3$	$7s5f^3F_3^0$	7	4 862.314	0.021		
3	4 882.28	0.05	20 476.52	$7s7p^3P_1^0$	$7s9s^3S_1$	7	4 882.31	0.03		
4	4 903.24	0.05	20 388.98	$7s6d^3D_2$	$6d7p^3P_2^0$	7	4 903.263	0.017		
5	4 971.77	0.05	20 107.95	$7s6d^3D_1$	$6d7p^3P_1^0$	7, 8	4 971.79	0.03		
4	4 982.03	0.05	20 066.54	$7s6d^3D_1$	$6d7p^3P_0^0$	7, 8				
5	5 041.56	0.05	19 829.60	$7s6d^3D_2$	$6d7p^3P_1^0$	7, 8	5 041.54	0.04		
6	5 081.030	0.020	19 675.56	$7s6d^3D_3$	$6d7p^3P_2^0$	7	5 081.035	0.017		
10	5 097.56	0.05	19 611.78			7				
10	5 205.930	0.020	19 203.52	$7s6d^3D_2$	$6d7p^3D_3^0$	7	5 205.948	0.015		
4	5 263.96	0.05	18 991.83			7				
2	5 277.91	0.05	18 941.62	$7s7p^3P_0^0$	$7p^2^3P_2$	7	5 277.849	0.008		
10	5 283.280	0.020	18 922.37	$7s7p^3P_0^0$	$7s7d^3D_1$	7	5 283.277	0.014		
10	5 320.290	0.020	18 790.74	$7s6d^3D_1$	$6d7p^3D_2^0$	7	5 320.290	0.014		
10	5 399.800	0.020	18 514.06	$7s6d^3D_1$	$6d7p^3D_0^0$	7	5 399.784	0.014		
20	5 400.230	0.020	18 512.58	$7s6d^3D_2$	$6d7p^3D_2^0$	7	5 400.231	0.013		
20	5 406.810	0.020	18 490.05	$7s6d^3D_3$	$6d7p^3D_3^0$	7	5 406.795	0.016		
8	5 482.130	0.020	18 236.02	$7s6d^3D_2$	$6d7p^3D_1^0$	7	5 482.150	0.015		
4	5 488.32	0.05	18 215.45	$7s7p^3P_1^0$	$7p^2^1D_2$	7	5 488.334	0.017		
2	5 497.83	0.05	18 183.95			7				
10	5 501.980	0.020	18 170.23	$7s7p^3P_0^0$	$7p^2^3P_1$	7	5 501.985	0.018		
4	5 505.50	0.05	18 158.61	$7s6d^3D_1$	$7s8p^3P_2^0$	7, 8	5 505.542	0.024		
3	5 544.25	0.05	18 031.71			7				
10	5 553.570	0.020	18 001.44	$7s7p^3P_0^0$	$7s7d^3D_1$	7	5 553.574	0.015		
20	5 555.850	0.020	17 994.05	$7s7p^3P_1^0$	$7s7d^3D_2$	7	5 555.852	0.018		
2	5 591.15	0.05	17 880.44	$7s6d^3D_2$	$7s8p^3P_2^0$	7, 8	5 591.192	0.024		
5	5 601.50	0.05	17 847.41	$7s6d^3D_1$	$7s8p^3P_1^0$	7	5 601.43	0.03		
10	5 616.660	0.020	17 799.23	$7s6d^3D_3$	$6d7p^3D_2^0$	7	5 616.660	0.015		
3	5 620.47	0.05	17 787.17	$7s7p^3P_2^0$	$7s9s^3S_1$	7	5 620.46	0.04		
50	5 660.810	0.020	17 660.42	$7s6d^3D_3$	$6d7p^3F_4^0$	7			4.30×10^7	53
3	5 690.16	0.05	17 569.32	$7s6d^3D_2$	$7s8p^3P_1^0$	7	5 690.12	0.03		
4	5 755.45	0.05	17 370.02	$7s6d^3D_1$	$7s8p^3P_0^0$	7, 8				
5	5 778.28	0.05	17 301.39	$7s6d^1D_2$	$6d7p^3P_2^0$	7	5 778.24	0.03		
5	5 795.78	0.05	17 249.16	$7s7p^3P_1^0$	$7p^2^3P_1$	7	5 795.745	0.023		
5	5 811.58	0.05	17 202.26	$7s6d^3D_1$	$6d7p^1D_2^0$	7	5 811.588	0.021	4.00×10^6	53
3	5 823.49	0.05	17 167.07	$7s6d^3D_3$	$7s8p^3P_2^0$	7, 8	5 823.53	0.03		
2	5 907.20	0.05	16 923.80	$7s6d^3D_2$	$6d7p^1D_2^0$	7	5 907.107	0.021	5.50×10^4	53
2	5 957.17	0.05	16 781.86			7				
5	5 957.67	0.05	16 780.45			7				
3	6 151.19	0.05	16 252.52	$7s7p^3P_2^0$	$7p^2^3P_2$	7	6 151.137	0.019		
5	6 167.03	0.05	16 210.77	$7s6d^3D_3$	$6d7p^1D_2^0$	7	6 167.049	0.024	1.50×10^7	53
30	6 200.300	0.020	16 123.79	$7s6d^3D_2$	$6d7p^3F_2^0$	7	6 200.304	0.016	2.50×10^7	53
10	6 336.900	0.020	15 776.22	$7s6d^1D_2$	$7s8p^1P_1^0$	7				
3	6 438.90	0.05	15 526.31	$7s7p^3P_2^0$	$7p^2^1D_2$	7	6 438.94	0.03		
20	6 446.200	0.020	15 508.73	$7s7p^3P_2^0$	$7s7d^3D_3$	7				
2	6 474.47	0.05	15 441.02			7				
20	6 487.320	0.020	15 410.43	$7s6d^3D_3$	$6d7p^3F_3^0$	7	6 487.317	0.017	9.90×10^6	53
2	6 528.92	0.05	15 312.24	$7s7p^3P_0^0$	$7s7d^3D_1$	7	6 528.92	0.02		
3	6 532.08	0.05	15 304.83	$7s7p^3P_2^0$	$7s7d^3D_2$	7	6 532.07	0.03		
3	6 545.93	0.05	15 272.46			7				
4	6 585.41	0.05	15 180.90			7				
3	6 599.47	0.05	15 148.55	$7s6d^1D_2$	$6d7p^3D_1^0$	7	6 599.46	0.03		
2	6 645.95	0.05	15 042.61			7				
2	6 653.33	0.05	15 025.92			7				
4	6 758.20	0.05	14 792.76	$7s6d^1D_2$	$7s8p^3P_2^0$	7, 8	6 758.12	0.04		
3	6 903.10	0.05	14 482.25	$7s6d^1D_2$	$7s8p^3P_1^0$	7	6 903.18	0.04		
20	6 980.220	0.020	14 322.25	$7s6d^3D_1$	$6d7p^3F_0^0$	7	6 980.232	0.017	1.70×10^7	53
20	7 118.500	0.020	14 044.03	$7s6d^3D_2$	$6d7p^3F_2^0$	7	7 118.486	0.017	9.80×10^6	53
50	7 141.2167	0.0005	13 999.3569	$7s^2^1S_0$	$7s7p^3P_1^0$	7, 41	7 141.2167	0.0005	2.37×10^6	41 ⁶⁰
20	7 225.160	0.020	13 836.71	$7s6d^1D_2$	$6d7p^1D_2^0$	7	7 225.167	0.019	3.50×10^7	53
10	7 310.270	0.020	13 675.62	$7s7p^3P_0^0$	$7s8s^3S_1$	7	7 310.271	0.018	8.50×10^6	53
1	7 468.21	0.05	13 386.41			7				
2	7 499.87	0.05	13 329.90			7				
2	7 565.49	0.05	13 214.31			7				

TABLE 3. Wavelengths, wavenumbers, classification, and transition probabilities in neutral radium (^{226}Ra), Ra I—Continued

Intensity	Observed $\lambda_{air}/\text{\AA}$	Uncertainty observation $\lambda_{air}/\text{\AA}$	Observation σ/cm^{-1}	Lower level	Upper level	Line reference(s)	Ritz $\lambda/\text{\AA}$	Uncertainty		References
								Ritz $\lambda/\text{\AA}$	A_{ik}/s^{-1}	
1	7836.09	0.05	12 757.96			7				
20	7838.120	0.020	12 754.65	$7s7p\ ^3P_1^0$	$7s8s\ ^3S_1$	7	7 838.116	0.018	2.10×10^7	53
2	7877.08	0.05	12 691.57			7				
3	7896.43	0.05	12 660.47			7				
3	8005.13	0.05	12 488.56			7				
2	8019.25	0.05	12 466.58			7				
6	8 177.310	0.020	12 225.60	$7s7p\ ^1P_1^0$	$7p^2\ ^3P_2$	7	8 177.319	0.019		
3	8 248.70	0.05	12 119.79			7				
3	8 269.03	0.05	12 090.00			7				
5	8 335.07	0.05	11 994.21			7				
4	8 693.94	0.05	11 499.11	$7s7p\ ^1P_1^0$	$7p^2\ ^1D_2$	7	8 693.91	0.04		
2	9 094.80	0.05	10 992.28			7				
5	9 932.21	0.05	10 065.49	$7s7p\ ^3P_2^0$	$7s8s\ ^3S_1$	7	9 932.23	0.04	2.50×10^7	53
	14 282.14	0.04	6 999.84	$7s6d\ ^3D_1$	$7s7p\ ^1P_1^0$	10	14 286.05	0.04	4.40×10^4	53

 TABLE 4. Lifetimes of energy levels— ^{226}Ra I

Level	$7s7p\ ^3P_1^0$	$7s6d\ ^1D_2$	$7s6d\ ^3D_1$
Lifetime	422(20) ns	385(45) μs	510(60) μs
Reference	41	42	10

 TABLE 5. Isotope shifts and HFS constants A and B of $7s^2\ ^1S_0$ and $7s7p\ ^1P_1^0$ levels in Ra I

Atomic mass	$7s^2\ ^1S_0$	$7s7p\ ^1P_1^0$		References	
		Isotopic frequency shift (MHz)	HFS A (MHz)		HFS B (MHz)
208		8 485(8)		21	
209		8 313(8)	-656.5(1.2)	135.0(5.0)	21
210		6 003(6)			21
211		5 522(4)	-668.4(0.9)	162.0(4.0)	21
212		3 256(3)			21
213		2 167(3)	-2314.8(2.5)		21
214	0	0			21
220		-21 904(8)			21
221		-25 945(8)	136.3(0.8)	669.6(3.0)	21
222		-28 827(8)			21
223		-32 453(9)	-344.5(0.9)	421.5(1.6)	21
224		-35 123(9)			21
225		-38 888(10)	2796.5(2.5)		21
226		-41 124(11)			21
227		-43 937(12)	512.5(2.3)	531.0(5.0)	21
228		-46 950(12)			21
229		-50 066(15)	-382.7(1.4)	1042.0(5.0)	21
230		-53 634(15)			21
232		-59 585(17)			21

HFS splitting and isotope shifts are given to the source of the energy level value and hyperfine splitting constants, respectively.

2. Ra I

In Table 1, radium isotopes, atomic weights, half-lives, nuclear spins, nuclear magnetic moments, and electric quadrupole moments are given. Up to now, 35 radium isotopes have been discovered excluding the isomers of $^{203m}, ^{205m}, ^{207m}, ^{213m}\text{Ra}$ isotopes.

Table 2 presents the energy levels of ^{226}Ra . They are taken from Moore 1958 compilation⁹ and other sources where improved experimental values are available. Moore's compilation is mainly based on the measurements of Rasmussen⁶ and corrections made to them by Russell.⁸ In addition to the compilation of Moore, we have added the energy levels of ^{226}Ra in the UV region from the absorption measurements of Armstrong *et al.*¹⁷ However, the uncertainty $\pm 0.006\text{ cm}^{-1}$ given by Armstrong *et al.* for wavenumbers is not correct as the uncertainty 0.001 \AA in their wavelengths corresponds to the wavenumber uncertainty of 0.018 cm^{-1} . This is brought to the notice of the authors by Kramida.⁴⁹ The updated uncertainties of the wavenumbers are given in Table 2. We have not included the semiempirical values given in the work of Armstrong *et al.*¹⁷ for $7s9p-7s12p$ energy levels. Improved values of the $7s7p\ ^1P_1^0$ level from Santra *et al.*,¹² $7s7p\ ^3P_1^0$ level from Scielzo *et al.*,⁴¹ and $7s6d\ ^3D_1$ level from Guest *et al.*¹⁰ are also given.

 TABLE 6. Isotope shifts and HFS constants A and B of $7s^2\ ^1S_0$ and $7s7p\ ^3P_1^0$ levels in Ra I

Atomic mass	$7s^2\ ^1S_0$	$7s7p\ ^3P_1^0$		References	
		Isotopic frequency shift (MHz)	HFS A (MHz)		HFS B (MHz)
212		3 303(5)			21
214	0	0			21
221			-475.8(1.4)	-747.6(2.6)	21
222		-29 253(9)			21
223		-32 934(10)	1202.1(0.6)	-470.2(1.2)	21
224		-35 644(11)			21
225		-39 465(12)	-9793.9(4.3)		21
226		-41 733(12)			21

TABLE 7. Isotope shifts and HFS constants A and B of the $7s7p\ ^3P_2^0$ level and the $7s7d\ ^3D_3$ level in Ra I

Atomic mass	$7s7p\ ^3P_2^0$		$7s7d\ ^3D_3$			References
	HFS A (MHz)	HFS B (MHz)	Isotopic frequency shift (MHz)	HFS A (MHz)	HFS B (MHz)	
212			-887(4)			21
214			0			21
221	278.6(0.9)	1103.8(3.9)	7001(7)	213.3(0.6)	117.8(4.4)	21
222			7781(4)			21
223	699.6(3.3)	688.5(4.0)	8762(6)	535.6(4.6)	73.9(3.0)	21
224			9481(5)			21
226			11102(6)			21

TABLE 8. Isotope shifts and HFS constants A and B of the $7s7p\ ^1P_1^0$ level and the $7s6d\ ^3D_1$ level in Ra I

Atomic mass	$7s7p\ ^1P_1^0$		$7s6d\ ^3D_1$			References
	HFS A (MHz)	HFS B (MHz)	Isotopic frequency shift (MHz)	HFS A (MHz)	HFS B (MHz)	
225	2797.3 (1.5)		540.2 (2.0)	4687.7 (1.5)		10
226			0			10

TABLE 9. Energy levels of $^{226}\text{Ra II}$

Configuration	Term	J	Level (cm^{-1})	Uncertainty (cm^{-1})	Level LOPT (cm^{-1})	Uncertainty 1 LOPT (cm^{-1})	Uncertainty 2 LOPT (cm^{-1})	Level reference
7s	2S	1/2	0.000		0.000	0.0007	0	
6d	2D	3/2	12 084.2721		12 084.2721	0.0006	0.0010	9
	2D	5/2	13 742.99		13 742.99	0.03	0.03	9
7p	$^2P^0$	1/2	21 351.3259	0.0008	21 351.3259	0.0005	0.0008	9, 13
	$^2P^0$	3/2	26 208.8538	0.0021	26 208.8538	0.0021	0.0021	9, 13
8s	2S	1/2	43 405.05		43 405.05	0.05	0.05	9
7d	2D	3/2	48 744.04		48 744.04	0.10	0.08	9
	2D	5/2	49 240.45		49 240.45	0.18	0.4	9
5f	$^2F^0$	5/2	48 987.86		48 987.86	0.04	0.15	9
	$^2F^0$	7/2	49 272.14		49 272.14	0.04	0.16	9
8p	$^2P^0$	1/2	50 606.29		50 606.29	0.16	0.22	9
	$^2P^0$	3/2	52 392.02		52 392.02	0.10	0.19	9
9s	2S	1/2	59 165.3		59 165.3	0.3	0.3	9
6f	$^2F^0$	5/2	59 517		59 517	5	5	9
	$^2F^0$	7/2	59 814		59 814	4	4	9
8d	2D	3/2	61 735.0		61 735.0	0.5	0.5	9
	2D	5/2	61 973.8		61 973.8	0.9	0.9	9
9p	$^2P^0$	3/2	63 410.43		63 410.43	0.20	0.21	9
5g	2G	7/2,9/2	64 150.49		64 150.49	0.03	0.15	9
7f	$^2F^0$	5/2	66 521.85		66 521.85	0.22	0.24	9
	$^2F^0$	7/2	66 691.18		66 691.18	0.21	0.4	9
10s	2S	1/2	66 837.88		66 837.88	0.18	0.22	9
9d	2D	3/2	68 264.07		68 264.07	0.19	0.21	9
	2D	5/2	68 394.87		68 394.87	0.18	0.23	9
6g	2G	7/2,9/2	69 560.68		69 560.68	0.15	0.21	9
11s	2S	1/2	71 172.88		71 172.88	0.21	0.3	9
10d	2D	3/2	72 043.33		72 043.33	0.23	0.3	9
	2D	5/2	72 123.74		72 123.74	0.19	0.3	9
7g	2G	7/2,9/2	72 824.21		72 824.21	0.14	0.20	9
11d	2D	3/2	74 434.30		74 434.30	0.17	0.3	9
	2D	5/2	74 489		74 489	5	5	9
8g	2G	7/2,9/2	74 941.76		74 941.76	0.17	0.23	9
12d	2D	5/2	76 080.68		76 080.68	0.17	0.3	9
9g	2G	7/2,9/2	76 392.92		76 392.92	0.15	0.21	9
10g	2G	7/2,9/2	77 431.2		77 431.2	1.2	1.1	9
11g	2G	7/2,9/2	78 195.1		78 195.1	2.0	1.2	9

Furthermore, the measurements of Rasmussen and Armstrong *et al.* are attributed to the ^{226}Ra isotope due to its natural abundance and long half-life compared to the other Ra isotopes. Also, the high probability that Rasmussen used ^{226}Ra is sup-

ported by the fact that the knowledge of isotopes was not available at that time as the first isotope of an element observed and reported by Urey *et al.* in 1932 was deuterium.⁵⁰ Furthermore, the recent measurements from the Argonne group and Gronin-

TABLE 10. Wavelengths, wavenumbers, classification, and transition probabilities for observed lines in radium ion, ²²⁶Ra II

Intensity ⁶¹	Observation $\lambda/\text{\AA}$	Uncertainty observation $\lambda/\text{\AA}$	Observation σ/cm^{-1}	Uncertainty observation σ/cm^{-1}	Lower level	Upper level	Line ref- erence 62	A_{ik}/s^{-1}	Acc. ⁶³	References
5	1888.70	0.20	52946		6d ² D _{5/2}	7f ² F _{7/2} ⁰	6HQ			
8	1908.70	0.20	52392		7s ² S _{1/2}	8p ² P _{3/2} ⁰	6HQ	1.75 × 10 ⁷	B	32
4	1972.60	0.20	50695		7p ² P _{1/2} ⁰	10d ² D _{3/2}	6HQ			
2	1976.00	0.20	50607		7s ² S _{1/2}	8p ² P _{1/2} ⁰	6HQ			
2	2006.40	0.20	49824		7p ² P _{1/2} ⁰	11s ² S _{1/2}	6HQ			
3	2012.75	0.10	49667		6d ² D _{5/2}	9p ² P _{3/2} ⁰	6HQ			
2	2070.60	0.20	48280		7p ² P _{3/2} ⁰	11d ² D _{5/2}	6HQ			
4	2107.60	0.20	47432		6d ² D _{3/2}	6f ² F _{5/2} ⁰	6Q	2.67 × 10 ⁷	B	32
5	2131.00	0.20	46912		7p ² P _{1/2} ⁰	9d ² D _{3/2}	6Q			
10	2169.90	0.20	46071		6d ² D _{5/2}	6f ² F _{7/2} ⁰	6Q			
4	2177.30	0.20	45914		7p ² P _{3/2} ⁰	10d ² D _{5/2}	6Q			
1	2181.10	0.20	45834		7p ² P _{3/2} ⁰	10d ² D _{3/2}	6Q			
2	2197.80	0.20	45486		7p ² P _{1/2} ⁰	10s ² S _{1/2}	6Q			
3	2223.30	0.20	44964		7p ² P _{3/2} ⁰	11s ² S _{1/2}	6Q			
8	2369.730	0.020	42186.0		7p ² P _{3/2} ⁰	9d ² D _{5/2}	6Q			
3	2377.100	0.020	42055.2		7p ² P _{3/2} ⁰	9d ² D _{3/2}	6Q			
8	2460.55	0.03	40629.0		7p ² P _{3/2} ⁰	10s ² S _{1/2}	6Q			
10	2475.50	0.03	40383.7		7p ² P _{1/2} ⁰	8d ² D _{3/2}	6Q			
4	2480.11	0.03	40308.6		6d ² D _{3/2}	8p ² P _{3/2} ⁰	6Q	7.5 × 10 ⁵	C	32
8	2586.61	0.03	38649.1		6d ² D _{5/2}	8p ² P _{3/2} ⁰	6Q			
2	2595.15	0.03	38521.9		6d ² D _{3/2}	8p ² P _{1/2} ⁰	6Q			
10	2643.73	0.03	37814.1		7p ² P _{1/2} ⁰	9s ² S _{1/2}	6Q			
20	2708.960	0.020	36903.6		6d ² D _{3/2}	5f ² F _{5/2} ⁰	6G	3.70 × 10 ⁸	A	32
10p (Mg II)	2795.21	0.07	35764.9		7p ² P _{3/2} ⁰	8d ² D _{5/2}	6Q			
30	2813.760	0.020	35529.2		6d ² D _{5/2}	5f ² F _{7/2} ⁰	6G			
6	2836.460	0.020	35244.85		6d ² D _{5/2}	5f ² F _{5/2} ⁰	6G			
10	3033.44	0.04	32956.3		7p ² P _{3/2} ⁰	9s ² S _{1/2}	6Q			
2	3423.10	0.20	29204.9		5f ² F _{5/2} ⁰	11g ² G _{7/2,9/2}	6Q			
2	3456.20	0.20	28925.2		5f ² F _{7/2} ⁰	11g ² G _{7/2,9/2}	6Q			
2	3514.80	0.20	28443.0		5f ² F _{5/2} ⁰	10g ² G _{7/2,9/2}	6Q			
2	3550.20	0.20	28159.4		5f ² F _{7/2} ⁰	10g ² G _{7/2,9/2}	6Q			
100	3649.550	0.020	27392.83		7p ² P _{1/2} ⁰	7d ² D _{3/2}	6G			
3	3686.160	0.020	27120.78		5f ² F _{7/2} ⁰	9g ² G _{7/2,9/2}	6P			
200	3814.4219	0.0003	26208.8538	0.0021	7s ² S _{1/2}	7p ² P _{3/2} ⁰	6G, 13	1.880 × 10 ⁸	A	32
5p (Cl II)	3851.90	0.05	25953.9		5f ² F _{5/2} ⁰	8g ² G _{7/2,9/2}	6P			
5	3894.55	0.03	25669.63		5f ² F _{7/2} ⁰	8g ² G _{7/2,9/2}	6P			
8	4194.09	0.03	23836.36		5f ² F _{5/2} ⁰	7g ² G _{7/2,9/2}	6P			
2	4195.56	0.03	23828.01		8p ² P _{1/2} ⁰	11d ² D _{3/2}	6P			
1	4220.24	0.03	23688.66		8p ² P _{3/2} ⁰	12d ² D _{5/2}	6P			
8	4244.72	0.04	23552.05		5f ² F _{7/2} ⁰	7g ² G _{7/2,9/2}	6P			
100p (H I)	4340.64	0.07	23031.6		7p ² P _{3/2} ⁰	7d ² D _{5/2}	6P			
20	4436.270	0.020	22535.13		7p ² P _{3/2} ⁰	7d ² D _{3/2}	6G			
30	4533.110	0.020	22053.73		7p ² P _{1/2} ⁰	8s ² S _{1/2}	6G			
3	4663.52	0.05	21437.03		8p ² P _{1/2} ⁰	10d ² D _{3/2}	6P			
100	4682.23940	0.00017	21351.3259	0.0008	7s ² S _{1/2}	7p ² P _{1/2} ⁰	6G, 13	1.061 × 10 ⁸	A	32
10	4859.41	0.05	20572.88		5f ² F _{5/2} ⁰	6g ² G _{7/2,9/2}	6P			
10	4927.53	0.05	20288.48		5f ² F _{7/2} ⁰	6g ² G _{7/2,9/2}	6P			
3	4997.26	0.05	20005.39		8s ² S _{1/2}	9p ² P _{3/2} ⁰	6P			
3	5066.57	0.05	19731.72		8p ² P _{3/2} ⁰	10d ² D _{5/2}	6P			
1	5323.09	0.06	18780.86		8p ² P _{3/2} ⁰	11s ² S _{1/2}	6P			
3	5623.43	0.07	17777.81		7d ² D _{3/2}	7f ² F _{5/2} ⁰	6P			
6	5661.73	0.07	17657.55		8p ² P _{1/2} ⁰	9d ² D _{3/2}	6P			
4	5728.83	0.07	17450.73		7d ² D _{5/2}	7f ² F _{7/2} ⁰	6P			
20	5813.630	0.020	17196.19		7p ² P _{3/2} ⁰	8s ² S _{1/2}	6G			
1	6158.73	0.08	16232.62		8p ² P _{1/2} ⁰	10s ² S _{1/2}	6P			
4	6247.16	0.08	16002.85		8p ² P _{3/2} ⁰	9d ² D _{5/2}	6P			
1	6298.56	0.08	15872.26		8p ² P _{3/2} ⁰	9d ² D _{3/2}	6P			
10	6593.340	0.020	15162.63		5f ² F _{5/2} ⁰	5g ² G _{7/2,9/2}	6G			
10	6719.320	0.020	14878.35		5f ² F _{7/2} ⁰	5g ² G _{7/2,9/2}	6G			
1	6920.11	0.10	14446.65		8p ² P _{3/2} ⁰	10s ² S _{1/2}	6P			
5	7078.02	0.10	14124.35		6d ² D _{3/2}	7p ² P _{3/2} ⁰	6G	3.39 × 10 ⁶	B	32

TABLE 10. Wavelengths, wavenumbers, classification, and transition probabilities for observed lines in radium ion, $^{226}\text{Ra II}$ —Continued

Intensity ⁶¹	Observation $\lambda/\text{\AA}$	Uncertainty observation $\lambda/\text{\AA}$	Observation σ/cm^{-1}	Uncertainty observation σ/cm^{-1}	Lower level	Upper level	Line ref- erence 62	A_{ik}/s^{-1}	Acc. ⁶³	References
50	8 019.700	0.020	12 465.87		$6d\ ^2D_{5/2}$	$7p\ ^2P_{3/2}^0$	6G	2.29×10^7	B	32
	10 787.9609	0.0007	9 267.0538	0.0006	$6d\ ^2D_{3/2}$	$7p\ ^2P_{1/2}^0$	13	1.06×10^7	B	32

gen group support this in addition to the ISOLDE group. The very recent measurement of the $7s6d\ ^3D_1-7s7p\ ^1P_1^0$ transition in ^{226}Ra by the Argonne group¹⁰ confirms attribution of Rasmussen's measurements to the ^{226}Ra isotope.

The $7p^2$ configuration of the 1D_2 term given in Moore's compilation from Rasmussen measurements was changed to the $7s7d$ configuration by the ISOLDE group²¹ based on the analysis of their experimental results. In Table 2 of neutral Ra energy level data it is shown in parentheses. For the 1D_2 term, the $6d^2$ configuration is attributed by Quinet *et al.*⁵¹ It is also shown in parentheses. Also, the $^3P_{0,1,2}$ levels assigned to the $7p^2$ configuration as given in Moore's compilation are predicted to belong to the $6d^2$ configuration by Quinet *et al.*,⁵¹ which is shown in parentheses. For the $7s8p\ ^1P_1^0$ level, Armstrong *et al.*¹⁷ restored Rasmussen's identification. Furthermore, Ginges and Dzuba in their recent theoretical work⁵² noted that their calculated value of the $7s8p\ ^1P_1$ energy level is very low compared to the values from Rasmussen's data and Moore's compilation. For example, the difference from Moore's compilation is 2155 cm^{-1} . Because of the discrepancies between the observed spectra and the contradicting interpretations of configuration terms of some energy levels and deviations from the theoretical calculations in Ra I, more experimental data are required.

In Table 3, the intensity, observed wavelengths in air, uncertainty in observed wavelengths, observed wavenumbers, lower and upper levels, classifications, Ritz wavelengths obtained with the LOPT code, uncertainties in Ritz wavelengths, and transition probabilities are given. The Ritz wavelengths are not given for lines that alone determine one of the levels involved in the transition. Some of the observed wavenumbers given in column 4 differ from the wavenumbers given in the original work of Rasmussen⁷ and Armstrong *et al.*¹⁷ The difference from the original values and the present reported values is due to the conversion formulas used by Rasmussen and Armstrong *et al.* for arriving at the wavenumbers from the measured wavelengths. Here, we have used the widely accepted formula of Peck and Reeder⁴³ to arrive at the wavenumbers. The first reference (column 7) corresponds to the transitions/lines and the second reference (column 11) to transition probabilities. We have given theoretical transition rates for some of the transitions in Ra atom calculated by Dzuba and Flambaum⁵³ and one value from the experiment.⁴¹ In column 4 of Table 3, we have given wavenumbers for the transitions from the measurements of Rasmussen⁷ and from Russell.⁸ Absorption measurements from Armstrong *et al.*¹⁷ have no information on the intensity of the observed lines. Their wavenumbers and air wavelengths with uncertainties are also given. For the $7s^2\ ^1S_0-7s7p\ ^3P_1^0$ transitions, two line references are given; the first one for the intensity and the second one for the

wavenumber. The wavenumber and the air wavelength of the $7s6d\ ^3D_1-7s7p\ ^3P_1^0$ transition measured by the ANL group are also given. The measured value is 6999.84 cm^{-1} with an uncertainty of 0.02 cm^{-1} . In columns 8 and 9, Ritz wavelengths and their uncertainties are given. These are obtained from the calculations using the LOPT code of National Institute of Standards and Technology (NIST), USA.

Theoretically calculated lifetimes and transition rates for some of the energy levels in neutral Ra have been previously reported.^{26,53,54} However, only three experimental lifetimes of states in neutral Ra atom are available and they are given in Table 4.

In Table 5, isotope shifts in frequency for the $7s^2\ ^1S_0-7s7p\ ^1P_1$ electric dipole allowed transition of 19 neutral Ra isotopes and HFS constants A and B of the $7s7p\ ^1P_1$ level for the odd isotopes are given. The isotope shifts are given with respect to the ^{214}Ra isotope.

Given in Table 6 are the isotope shifts between eight Ra isotopes for the $7s^2\ ^1S_0-7s7p\ ^3P_1$ intercombination (spin-forbidden) transition and the HFS constants A and B of the $7s7p\ ^3P_1$ level for the odd isotopes. Here again, the isotope shifts are given with respect to the ^{214}Ra isotope.

In Table 7, isotope shifts of seven Ra isotopes for the $7s7p\ ^3P_2-7s7d\ ^3D_3$ transition at 644.6 nm and the HFS constants A and B of the $7s7p\ ^3P_2$ and $7s7d\ ^3D_3$ levels for the odd isotopes are given. The isotope shifts are given with respect to the ^{214}Ra isotope similar to the other transitions.

In Table 8, the isotope shifts between ^{226}Ra and ^{225}Ra isotopes for the $7s6d\ ^3D_1-7s7p\ ^1P_1$ transition at 1428 nm and the HFS constants A and B of the $7s7p\ ^1P_1$ and $7s6d\ ^3D_1$ levels for the ^{225}Ra isotope are given.

3. Ra II

The first experimental measurements on singly ionized Ra were conducted by Rasmussen in 1933 using an arc discharge as the light source. In total, 62 lines were identified, corresponding to 43 energy levels. The energy levels are given in Table 9. In Table 9, additional information on energy levels and their uncertainties is also given, which was obtained using the LOPT code.⁴⁴ In column 6, energy level values obtained with the LOPT code are given. Two uncertainties for the energy level values estimated by LOPT code are given; uncertainty 1 (column 7) and uncertainty 2 (column 8). Uncertainty 1 is the best determined separation from other energy levels and uncertainty 2 is determined for the excitation energy. Further, some of the energy levels given in Moore's compilation⁹ are significantly improved by our level optimization, while a few were found to be much less accurate

TABLE 11. Ritz wavelengths and uncertainty of Ritz wavelengths in $^{226}\text{Ra II}$

Lower level	Upper level	Ritz $\lambda/\text{\AA}$	Uncertainty Ritz $\lambda/\text{\AA}$
$6d\ ^2D_{5/2}$	$7f\ ^2F_{7/2}^0$	1888.639	0.015
$7s\ ^2S_{1/2}$	$8p\ ^2P_{3/2}^0$	1908.688	0.007
$7p\ ^2P_{1/2}^0$	$10d\ ^2D_{3/2}$	1972.698	0.012
$7s\ ^2S_{1/2}$	$8p\ ^2P_{1/2}^0$	1976.039	0.009
$7p\ ^2P_{1/2}^0$	$11s\ ^2S_{1/2}$	2006.514	0.011
$6d\ ^2D_{5/2}$	$9p\ ^2P_{3/2}^0$	2012.741	0.008
$7p\ ^2P_{3/2}^0$	$9d\ ^2D_{3/2}$	2130.944	0.009
$7p\ ^2P_{3/2}^0$	$10d\ ^2D_{5/2}$	2177.261	0.013
$7p\ ^2P_{3/2}^0$	$10d\ ^2D_{3/2}$	2181.081	0.015
$7p\ ^2P_{1/2}^0$	$10s\ ^2S_{1/2}$	2197.725	0.011
$7p\ ^2P_{3/2}^0$	$11s\ ^2S_{1/2}$	2223.308	0.014
$7p\ ^2P_{3/2}^0$	$9d\ ^2D_{5/2}$	2369.730	0.013
$7p\ ^2P_{3/2}^0$	$9d\ ^2D_{3/2}$	2377.101	0.012
$7p\ ^2P_{3/2}^0$	$10s\ ^2S_{1/2}$	2460.499	0.013
$6d\ ^2D_{3/2}$	$8p\ ^2P_{3/2}^0$	2480.164	0.012
$6d\ ^2D_{5/2}$	$8p\ ^2P_{3/2}^0$	2586.613	0.013
$6d\ ^2D_{3/2}$	$8p\ ^2P_{1/2}^0$	2595.142	0.015
$7p\ ^2P_{1/2}^0$	$9s\ ^2S_{1/2}$	2643.737	0.021
$6d\ ^2D_{3/2}$	$5f\ ^2F_{5/2}^0$	2708.960	0.011
$6d\ ^2D_{5/2}$	$5f\ ^2F_{7/2}^0$	2813.762	0.012
$6d\ ^2D_{5/2}$	$5f\ ^2F_{5/2}^0$	2836.458	0.012
$7p\ ^2P_{3/2}^0$	$9s\ ^2S_{1/2}$	3033.42	0.03
$5f\ ^2F_{5/2}^0$	$11g\ ^2G_{7/2,9/2}$	3422.83	0.14
$5f\ ^2F_{7/2}^0$	$11g\ ^2G_{7/2,9/2}$	3456.47	0.14
$5f\ ^2F_{5/2}^0$	$10g\ ^2G_{7/2,9/2}$	3514.76	0.14
$5f\ ^2F_{7/2}^0$	$10g\ ^2G_{7/2,9/2}$	3550.24	0.14
$7p\ ^2P_{1/2}^0$	$7d\ ^2D_{3/2}$	3649.566	0.011
$7s\ ^2S_{1/2}$	$7p\ ^2P_{3/2}^0$	3814.421 9	0.0003
$5f\ ^2F_{5/2}^0$	$8g\ ^2G_{7/2,9/2}$	3851.89	0.03
$5f\ ^2F_{7/2}^0$	$8g\ ^2G_{7/2,9/2}$	3894.55	0.03
$5f\ ^2F_{5/2}^0$	$7g\ ^2G_{7/2,9/2}$	4194.091	0.024
$5f\ ^2F_{7/2}^0$	$7g\ ^2G_{7/2,9/2}$	4244.72	0.03
$7p\ ^2P_{3/2}^0$	$7d\ ^2D_{5/2}$	4340.64	0.07
$7p\ ^2P_{3/2}^0$	$7d\ ^2D_{3/2}$	4436.259	0.017
$7p\ ^2P_{1/2}^0$	$8s\ ^2S_{1/2}$	4533.111	0.010
$8p\ ^2P_{1/2}^0$	$10d\ ^2D_{3/2}$	4663.52	0.05
$7s\ ^2S_{1/2}$	$7p\ ^2P_{1/2}^0$	4682.239 40	0.000 17
$5f\ ^2F_{5/2}^0$	$6g\ ^2G_{7/2,9/2}$	4859.42	0.04
$5f\ ^2F_{7/2}^0$	$6g\ ^2G_{7/2,9/2}$	4927.52	0.04
$8s\ ^2S_{1/2}$	$9p\ ^2P_{3/2}^0$	4997.26	0.05
$8p\ ^2P_{3/2}^0$	$10d\ ^2D_{5/2}$	5066.57	0.05
$8p\ ^2P_{3/2}^0$	$11s\ ^2S_{1/2}$	5323.09	0.06
$8p\ ^2P_{1/2}^0$	$9d\ ^2D_{3/2}$	5661.65	0.06
$7d\ ^2D_{5/2}$	$7f\ ^2F_{7/2}^0$	5728.83	0.07
$7p\ ^2P_{3/2}^0$	$8s\ ^2S_{1/2}$	5813.628	0.017
$8p\ ^2P_{1/2}^0$	$10s\ ^2S_{1/2}$	6158.80	0.07
$8p\ ^2P_{3/2}^0$	$9d\ ^2D_{5/2}$	6247.16	0.07
$8p\ ^2P_{3/2}^0$	$9d\ ^2D_{3/2}$	6298.64	0.06
$5f\ ^2F_{5/2}^0$	$5g\ ^2G_{7/2,9/2}$	6593.341	0.019
$5f\ ^2F_{7/2}^0$	$5g\ ^2G_{7/2,9/2}$	6719.320	0.019
$8p\ ^2P_{3/2}^0$	$10s\ ^2S_{1/2}$	6920.09	0.08
$6d\ ^2D_{3/2}$	$7p\ ^2P_{3/2}^0$	7077.904 2	0.0011
$6d\ ^2D_{5/2}$	$7p\ ^2P_{3/2}^0$	8019.701	0.020
$6d\ ^2D_{3/2}$	$7p\ ^2P_{1/2}^0$	10787.960 9	0.0007

than implied by the number of significant figures given by Moore.

The ionization energy (IE) of Ra II has been redetermined because of the changes in the energy level values of Ra II.

The series used to determine the IE is $ng\ ^2G$ with $n = 5-11$, five members of which ($n = 5-9$) have been determined with uncertainties about 0.2 cm^{-1} . Using this series, two values of IE have been obtained; one by fitting a polarization formula

TABLE 12. Wavelengths, wavenumbers, and terms of isotopes of Ra II

Atomic mass	$\lambda_{air}/\text{\AA}$	σ/cm^{-1}	Uncertainty (cm^{-1})	Lower level	Upper level	References
212	3 814.096 2	26 211.0916	0.0021	$7s\ ^2S_{1/2}$	$7p\ ^2P_{3/2}^0$	13
	4 681.782 73	21 353.4085	0.0005	$7s\ ^2S_{1/2}$	$7p\ ^2P_{1/2}^0$	13
	7 078.071 4	14 124.2481	0.0018	$6d\ ^2D_{3/2}$	$7p\ ^2P_{3/2}^0$	13
	10 788.530	9 266.5650	0.0004	$6d\ ^2D_{3/2}$	$7p\ ^2P_{1/2}^0$	13
213	4 681.793 96	21 353.3573	0.0004	$7s\ ^2S_{1/2}$	$7p\ ^2P_{1/2}^0$	13
	7 078.082 2 (F=2-F=1)	14 124.2264	0.0017	$6d\ ^2D_{3/2}$	$7p\ ^2P_{3/2}^0$	13
	10 788.517 6	9 266.5756	0.0005	$6d\ ^2D_{3/2}$	$7p\ ^2P_{1/2}^0$	13
214	3 814.120 14	26 210.9273	0.0017	$7s\ ^2S_{1/2}$	$7p\ ^2P_{3/2}^0$	13
	4 681.816 26	21 353.2556	0.0005	$7s\ ^2S_{1/2}$	$7p\ ^2P_{1/2}^0$	13
	7 078.059 9	14 124.2709	0.0014	$6d\ ^2D_{3/2}$	$7p\ ^2P_{3/2}^0$	13
	10 788.490 2	9 266.5992	0.0004	$6d\ ^2D_{3/2}$	$7p\ ^2P_{1/2}^0$	13
225	4 682.216 42	21 351.4307	0.0008	$7s\ ^2S_{1/2}$	$7p\ ^2P_{1/2}^0$	13
	10 787.989 2	9 267.0295	0.0006	$6d\ ^2D_{3/2}$	$7p\ ^2P_{1/2}^0$	13
226	10 787.960 9	9 267.0538	0.0006	$6d\ ^2D_{3/2}$	$7p\ ^2P_{1/2}^0$	13

TABLE 13. Isotope shifts and hyperfine constants of the $7s\ ^2S_{1/2}$, $7p\ ^2P_{1/2}^0$, and $7p\ ^2P_{3/2}^0$ levels in Ra II

Atomic mass	$7s\ ^2S_{1/2}$	$7p\ ^2P_{1/2}^0$		$7p\ ^2P_{3/2}^0$			Reference(s)
	HFS A (MHz)	Isotopic frequency shift (MHz)	HFS A (MHz)	Isotopic frequency shift (MHz) ^a	HFS A (MHz) ^a	HFS B (MHz) ^a	
208		11 950(8)					21
209							21
210		8 449(6)					21
211	6 624.8(1.0)	7 770(4)	1 299.7(0.8)				21
212		4 583(3)		4 937(2)			23
213	22 920.0(6.0)	3 049(3)	4 525.0(5.0)				21
214		0		0			
220		-30 808(14)					21
221	-1 348.6(1.8) ^a	-36 496(14)	-266.3(1.5)	-3 9222(18)	-22.4(9)	1 364.2(5.1)	21, 23
222		-40 552(14)		-4 3572(14)			21
223	3 404.0(1.9) ^a	-45 657(16)	667.1(2.1)	-49 050(18)	56.5(8)	864.8(1.9)	21, 23
224		-49 411(16)		-53 076(21)			21
225	-27 731(13) ^a	-54 710(18)	-5446.0(7.0)	-58 776(22)	-466.4(4.6)		21, 23
226		-57 852(18)		-62 159(21)			21
227	-5 063.5(3.1)	-61 811(19)	-996.2(2.3)				21
228		-66 050(20)					21
229	3 789.7(2.3)	-70 432(22)	743.9(1.2)				21
230		-75 456(23)					21
232							

^aFrom reference 23.TABLE 14. Isotope shifts and HFS constants A and B of the $6d\ ^2D_{3/2}$ and $7p\ ^2P_{1/2}^0$ levels in Ra II

Atomic mass	$6d\ ^2D_{3/2}$		$7p\ ^2P_{1/2}^0$		Reference(s)
	HFS A (MHz)	HFS B (MHz)	Isotopic frequency shift (MHz)	HFS A (MHz)	
209	148(10) ^a	104(38) ^a	2645(56) ^b	1276(20) ^c	37, 38, 39
210			1884(16)		39
211	151(2) ^a	103(6) ^a	1755(14) ^b	1299.7(0.8) ^d	38, 39, 21
212			1025(12)		39
213	528(5) ^c		707(14) ^b	4525(5) ^d	37, 39, 21
214			0		

^aReference 38.^bReference 39.^cReference 37.^dReference 21.

and another by fitting a Ritz-type quantum defect formula as given in references.^{55,56} The results of these two determinations are $81\,842.6(5)\text{ cm}^{-1}$ and $81\,842.5(5)\text{ cm}^{-1}$ resulting in an average of $81\,842.5(5)\text{ cm}^{-1}$. One can also use the series $ns\ ^2S_{1/2}$ ($n = 7-11$), $nd\ ^2D_{3/2}$ ($n = 6-11$), and $nd\ ^2D_{5/2}$ ($n = 6-12$) to determine IE. However, the IE limit values have larger scatter and uncertainties. Thus, the recommended IE value is $81\,842.5(5)\text{ cm}^{-1}$, which agrees with Rasmussen's value of $81\,842.31\text{ cm}^{-1}$ (as given by Moore) within the uncertainty.

In Table 10, intensity, observed wavelengths of the transitions, uncertainty of the observed wavelengths, observed wavenumbers, uncertainty of the observed wavenumbers, the corresponding lower and upper levels, line reference (column 8), transition rates, uncertainty of the transition rates, and the reference for the transition rates (column 11) are given. Theoretical estimates of energy levels and dipole matrix

TABLE 15. Isotope shifts and HFS constants A and B of the $7p\ ^2P_{3/2}^0$ and $6d\ ^2D_{3/2}$ levels in Ra II

Atomic mass	$6d\ ^2D_{3/2}$		$7p\ ^2P_{3/2}^0$		Reference(s)
	HFS A (MHz)	Isotopic frequency shift (MHz)	HFS A (MHz)	HFS B (MHz)	
212	528(5)	701(50)			37, 39
213		453(34)			37
214		0			

elements for singly ionized Ra have been reported.^{32,51,57,58} Here, we present the transition rates from Sahoo *et al.*³² as the uncertainty was given for the calculated values. In the intensity (column 1), “p” means “perturbed by.” The corresponding perturbing species are given in parentheses. In the line reference (column 8) “6” corresponds to the reference for the transition/line and the letter codes for the spectrometer used in the measurement have the following meaning: HQ - Hilger Quartz, Q - Quartz prism, P - Glass prism and G-Grating (used in the red region). The Ritz wavelengths and their uncertainties for Ra II are given in Table 11. These values were calculated with the LOPT code.⁴⁴ For wavelengths less than 2000 Å, vacuum wavelengths are given and for wavelengths greater than 2000 Å air wavelengths are given. The uncertainty of the given wavelengths mentioned in Ref. 6 is 0.1 Å to 0.02 Å between 3600 and 7000 Å and 0.1 Å between 1880 and 2200 Å.⁴⁴ In the red and near-infrared wavelength regions, i.e., 7000 Å to 10 000 Å, the uncertainty is 0.01 Å. Some of the observed wavenumbers given in column 4 differ from the wavenumbers given in the original work of Rasmussen.⁶ The difference from the original values and the present reported values is due to the conversion formula used by Rasmussen for arriving at the wavenumbers from the measured wavelengths. Here, we have used the three-term formula of Peck and Reeder⁴³ to arrive at the wavenumbers.

In Table 12, improved values of wavelengths in air, wavenumbers, and uncertainty in wavenumbers are given for ^{212,213,214,225,226}Ra isotopes for the $7s\ ^2S_{1/2}$ – $7s7p\ ^2P_{1/2,3/2}^0$ and $6d\ ^2D_{3/2}$ – $7s7p\ ^2P_{1/2,3/2}^0$ transitions. The wavenumbers are derived from the absolute frequency measurements of the corresponding transitions with a reference to a femtosecond optical frequency comb. The air wavelengths are calculated using the three-term formula [Eq. (3)] from Peck and Reeder.⁴³

Table 13 gives isotope shifts of seventeen Ra isotopes for the $7s\ ^2S_{1/2}$ – $7p\ ^2P_{1/2}$ transition and of eight isotopes for the $7s\ ^2S_{1/2}$ – $7p\ ^2P_{3/2}$ transition, seven HFS constants for the $7s\ ^2S_{1/2}$ and $7p\ ^2P_{1/2}$ states, while for the $7p\ ^2P_{3/2}$ state, three magnetic dipole constants and two electric quadrupole constants measured by the ISOLDE group are given. The uncertainties are given in parentheses. The isotope shifts are given with respect to the ²¹⁴Ra isotope, which has a zero nuclear spin.

In Table 14, isotope shifts of six Ra isotopes for the $6d\ ^2D_{3/2}$ – $7p\ ^2P_{1/2}$ transition of singly ionized Ra and HFS

 TABLE 16. Lifetimes of energy levels in ²¹²Ra II

Level	$6d\ ^2D_{5/2}$
Lifetime	232(4) ms
Reference	37

constants of the $6d\ ^2D_{3/2}$ and $7p\ ^2P_{1/2}$ states measured at the University of Groningen are given.

Table 15 consists of isotope shifts of the ^{212,213}Ra isotopes with respect to ²¹⁴Ra for the $6d\ ^2D_{3/2}$ – $7p\ ^2P_{3/2}$ transition and HFS of the $6d\ ^2D_{3/2}$ state. There is only one experimental measurement of lifetime of a state in singly ionized Ra. It is for the $6d\ ^2D_{5/2}$ state in ²¹²Ra with the lifetime of 232(4) ms (Table 16). Although theoretical calculations are available for the lifetimes of different states in the literature,^{32,57–59} we have not included them in this compilation.

4. Spectroscopic Data

Ground state and configuration:

Ra I— $1s^2\ 2s^22p^6\ 3s^23p^63d^{10}\ 4s^24p^64d^{10}4f^{14}5s^25p^65d^{10}6s^26p^6\ 7s^2\ ^1S_0$

Ra II— $1s^2\ 2s^22p^6\ 3s^23p^63d^{10}\ 4s^24p^64d^{10}4f^{14}5s^25p^65d^{10}6s^26p^6\ 7s\ ^2S_{1/2}$

Ionization energies:

Ra I—42 573.36(2) cm⁻¹; 5.278 423 9(25) eV (Ref. 17)

Ra II—81 842.5(5) cm⁻¹; 10.147 18(6) eV

Acknowledgments

The authors gratefully acknowledge Alexander Kramida, Atomic Spectroscopy Group, National Institute of Standards and Technology (NIST), USA for generously providing his calculations of ionization energy, LOPT code, and other information. One of the authors U.D. acknowledges kind help from Arun K. Thazathveetil, Department of Chemistry, North-Western University, Evanston, USA, S. Knoop, Vrije Universiteit, Amsterdam, The Netherlands, Lotje Wansbeek, The Netherlands and B. Santra, Technische Universität Kaiserslautern, Germany.

5. References

- ¹P. Curie, M. Curie, and G. Bemont, C. R. Acad. Sci. **127**, 1215 (1898).
- ²W. Ritz, Phys. Z. **9**, 521 (1908).
- ³D. R. Lide, *CRC Handbook of Chemistry and Physics*, 88th ed. (CRC Press, Boca Raton, FL, 2007).
- ⁴E. Fues, *Ann. Phys.* **368**, 1 (1920).
- ⁵A. Fowler, *Report on Series in Line Spectra* (Fleetway Press, London, 1922).
- ⁶E. Rasmussen, *Z. Phys.* **86**, 24 (1933).
- ⁷E. Rasmussen, *Z. Phys.* **87**, 607 (1934).
- ⁸H. N. Russell, *Phys. Rev.* **46**, 989 (1934).
- ⁹C. E. Moore, “Atomic energy levels,” NBS Circular No. 467 (U.S. Government Printing Office, Washington, DC, 1958), pp. 231 and 232.
- ¹⁰J. R. Guest, N. D. Scielzo, I. Ahmad, K. Bailey, J. P. Greene, R. J. Holt, Z.-T. Lu, T. P. O’Connor, and D. H. Potterveld, *Phys. Rev. Lett.* **98**, 093001 (2007).

- ¹¹R. H. Parker, M. R. Dietrich, K. Bailey, J. P. Greene, R. J. Holt, M. R. Kalita, W. Korsch, Z.-T. Lu, P. Mueller, T. P. O'Connor, J. Singh, I. A. Sulai, and W. L. Trimble, *Phys. Rev. C* **86**, 065503 (2012).
- ¹²B. Santra, U. Dammalapati, A. Groot, K. Jungmann, and L. Willmann, *Phys. Rev. A* **90**, 040501(R) (2014).
- ¹³M. Nuñez Portela, E. A. Dijck, A. Mohanty, H. Bekker, J. E. van den Berg, G. S. Giri, S. Hoekstra, C. J. G. Onderwater, S. Schlessler, R. G. E. Timmermans, O. O. Versolato, L. Willmann, H. W. Wilschut, and K. Jungmann, *Appl. Phys. B* **114**, 173 (2014).
- ¹⁴R. H. Parker, M. R. Dietrich, M. R. Kalita, N. D. Lemke, K. G. Bailey, M. Bishof, J. P. Greene, R. J. Holt, W. Korsch, Z.-T. Lu, P. Mueller, T. P. O'Connor, and J. T. Singh, *Phys. Rev. Lett.* **114**, 233002 (2015).
- ¹⁵S. J. Park, Y. J. Kim, T. Shin, Y. K. Kim, and S. K. Kim, *J. Phys. B: At., Mol. Opt. Phys.* **47**, 245301 (2014).
- ¹⁶K. M. Lynch, J. Billowes, M. L. Bissell, I. Budinčević, T. E. Cocolios, T. D. Goodacre, R. P. de Groote, V. N. Fedosseev, K. T. Flangan, S. Franchoo, R. F. Garcia Ruiz, H. Heylen, T. Kron, B. A. Marsh, G. Neyens, R. E. Rossel, S. Rothe, I. Strashnov, H. H. Stroke, and K. D. A. Wendt, Proposal for collinear resonance ionization spectroscopy of radium ions INTC-P-413, CERN, 2014.
- ¹⁷J. A. Armstrong, J. J. Wynne, and F. S. Tomkins, *J. Phys. B* **13**, L133 (1980).
- ¹⁸F. S. Tomkins and B. Ercoli, *Appl. Opt.* **6**, 1299 (1967).
- ¹⁹S. A. Ahmad, W. Klempt, R. Neugart, E. W. Otten, K. Wendt, C. Ekström, and The ISOLDE Collaboration, *Phys. Lett. B* **133**, 47 (1983).
- ²⁰E. Arnold, W. Borchers, M. Carré, H. T. Duong, P. Juncar, J. Lermé, S. Liberman, W. Neu, R. Neugart, E. W. Otten, M. Pellarin, J. Pinard, G. Ulm, J. L. Vialle, K. Wendt, and The ISOLDE Collaboration, *Phys. Rev. Lett.* **59**, 771 (1987).
- ²¹K. Wendt, S. A. Ahmad, W. Klempt, R. Neugart, E. W. Otten, H. H. Stroke, and The ISOLDE Collaboration, *Z. Phys. D: At., Mol. Clusters* **4**, 227 (1987).
- ²²S. A. Ahmad, W. Klempt, R. Neugart, E. W. Otten, P.-G. Reinhard, G. Ulm, K. Wendt, and The ISOLDE Collaboration, *Nucl. Phys. A* **483**, 244 (1988).
- ²³W. Neu, R. Neugart, E. W. Otten, G. Passler, K. Wendt, B. Fricke, E. Arnold, H. J. Kluge, G. Ulm, and The ISOLDE Collaboration, *Z. Phys. D: At., Mol. Clusters* **11**, 105 (1989).
- ²⁴V. V. Flambaum, *Phys. Rev. A* **60**, R2611 (1999).
- ²⁵V. A. Dzuba, V. V. Flambaum, and J. S. M. Ginges, *Phys. Rev. A* **61**, 062509 (2000).
- ²⁶J. Bieroń, P. Indelicato, and P. Jönsson, *Eur. Phys. J.: Spec. Top.* **144**, 75 (2007).
- ²⁷J. Bieroń, G. Gaigalas, E. Gaidamauskas, S. Fritzsche, P. Indelicato, and P. Jönsson, *Phys. Rev. A* **80**, 012513 (2009).
- ²⁸J. Engel, M. Bender, J. Dobaczewski, J. H. de Jesus, and P. Olbratowski, *Phys. Rev. C* **68**, 025501 (2003).
- ²⁹J. Dobaczewski and J. Engel, *Phys. Rev. Lett.* **94**, 232502 (2005).
- ³⁰L. Radziūte, G. Gaigalas, P. Jönsson, and J. Bieroń, *Phys. Rev. A* **90**, 012528 (2014).
- ³¹L. W. Wansbeek, B. K. Sahoo, R. G. E. Timmermans, K. Jungmann, B. P. Das, and D. Mukherjee, *Phys. Rev. A* **78**, 050501(R) (2008).
- ³²B. K. Sahoo, L. W. Wansbeek, K. Jungmann, and R. G. E. Timmermans, *Phys. Rev. A* **79**, 052512 (2009).
- ³³O. O. Versolato, L. W. Wansbeek, K. Jungmann, R. G. E. Timmermans, L. Willmann, and H. W. Wilschut, *Phys. Rev. A* **83**, 043829 (2011).
- ³⁴G. P. A. Berg, O. C. Dermois, U. Dammalapati, P. Dendooven, M. N. Harakeh, K. Jungmann, C. J. G. Onderwater, A. Rogachevskiy, M. Sohani, E. Traykov, L. Willmann, and H. Wilschut, *Nucl. Instrum. Methods Phys. Res., Sect. A* **560**, 169 (2006).
- ³⁵E. Traykov, A. Rogachevskiy, M. Bosswell, U. Dammalapati, P. Dendooven, O. C. Dermois, K. Jungmann, C. J. G. Onderwater, M. Sohani, L. Willmann, H. W. Wilschut, and A. R. Young, *Nucl. Instrum. Methods Phys. Res., Sect. A* **572**, 580 (2007).
- ³⁶P. D. Shidling, G. S. Giri, D. J. van der Hoek, K. Jungmann, W. Kruithof, C. J. G. Onderwater, M. Sohani, O. O. Versolato, L. Willmann, and H. W. Wilschut, *Nucl. Instrum. Methods Phys. Res., Sect. A* **606**, 305 (2009).
- ³⁷O. O. Versolato, G. S. Giri, L. W. Wansbeek, J. E. van den Berg, D. J. van der Hoek, K. Jungmann, W. L. Kruithof, C. J. G. Onderwater, B. K. Sahoo, B. Santra, P. D. Shidling, R. G. E. Timmermans, L. Willman, and H. W. Wilschut, *Phys. Rev. A* **82**, 010501(R) (2010).
- ³⁸O. O. Versolato, G. S. Giri, J. van den Berg, O. Böll, U. Dammalapati, D. J. van der Hoek, S. Hoekstra, K. Jungmann, W. L. Kruithof, S. Müller, M. Nuñez Portela, C. J. G. Onderwater, B. Santra, R. G. E. Timmermans, L. W. Wansbeek, L. Willmann, and H. W. Wilschut, *Phys. Lett. A* **375**, 3130 (2011).
- ³⁹G. S. Giri, O. O. Versolato, J. van de Berg, O. Böll, U. Dammalapati, D. J. van der Hoek, K. Jungmann, W. L. Kruithof, S. Müller, M. Nuñez Portela, C. J. G. Onderwater, B. Santra, R. G. E. Timmermans, L. W. Wansbeek, L. Willmann, and H. W. Wilschut, *Phys. Rev. A* **84**, 020503(R) (2011).
- ⁴⁰B. Santra, "Precision spectroscopy of neutral radium: Towards searches for permanent electric dipole moments," Ph.D. thesis, University of Groningen, 2012.
- ⁴¹N. D. Scielzo, J. R. Guest, E. C. Schulte, I. Ahmad, K. Bailey, D. L. Bowers, R. J. Holt, Z.-T. Lu, T. P. O'Connor, and D. H. Potterveld, *Phys. Rev. A* **73**, 010501(R) (2006).
- ⁴²W. L. Trimble, I. A. Sulai, I. Ahmad, K. Bailey, B. Graner, J. P. Greene, R. J. Holt, W. Korsch, Z.-T. Lu, P. Mueller, and T. P. O'Connor, *Phys. Rev. A* **80**, 054501 (2009).
- ⁴³E. R. Peck and K. Reeder, *J. Opt. Soc. Am.* **62**, 958 (1972).
- ⁴⁴A. E. Kramida, *Comput. Phys. Commun.* **182**, 419 (2011).
- ⁴⁵J. J. Curry, *J. Phys. Chem. Ref. Data* **33**, 725 (2004).
- ⁴⁶P. J. Mohr, B. N. Taylor, and B. B. Newell, The 2014 CODATA recommended values of the fundamental physical constants, web version 7.0, National Institute of Standards and Technology, Gaithersburg, MD 20899, 2015, <http://physics.nist.gov/constants>.
- ⁴⁷J. K. Tuli, *Nuclear Wallet Cards* (Nuclear Data Center, USA, 2011).
- ⁴⁸M. Wang, G. Audi, A. H. Wapstra, F. G. Kondev, M. MacCormick, X. Xu, and B. Pfeiffer, *Chin. Phys. C* **36**, 1603 (2012).
- ⁴⁹A. Kramida (private communication).
- ⁵⁰H. C. Urey, F. G. Brickwedde, and G. M. Murphy, *Phys. Rev.* **40**, 1 (1932).
- ⁵¹P. Quinet, C. Argante, V. Fivet, C. Terranova, A. V. Yushchenko, and È. Biémont, *Astron. Astrophys.* **474**, 307 (2007).
- ⁵²J. S. M. Ginges and V. A. Dzuba, *Phys. Rev. A* **91**, 042505 (2015).
- ⁵³V. A. Dzuba and V. V. Flambaum, *J. Phys. B: At., Mol. Opt. Phys.* **40**, 227 (2007).
- ⁵⁴J. Bieroń, C. F. Fischer, S. Fritzsche, and K. Pachucki, *J. Phys. B: At., Mol. Opt. Phys.* **37**, L305 (2004).
- ⁵⁵C. Sansonetti (private communication).
- ⁵⁶A. Kramida, *Fusion Sci. Technol.* **63**, 313 (2013).
- ⁵⁷V. A. Dzuba, V. V. Flambaum, and J. S. M. Ginges, *Phys. Rev. A* **63**, 062101 (2001).
- ⁵⁸R. Pal, D. Jiang, M. S. Safronova, and U. I. Safronova, *Phys. Rev. A* **79**, 062505 (2009).
- ⁵⁹B. K. Sahoo, B. P. Das, R. K. Chaudhuri, D. Mukherjee, R. G. Timmermans, and K. Jungmann, *Phys. Rev. A* **76**, 040504(R) (2007).
- ⁶⁰From experiment. Accuracy, B – uncertainty is $\leq 10\%$.
- ⁶¹'p' means 'perturbed by' with the perturbing species given in parentheses.
- ⁶²Ref. 6 is the reference for the line. HQ - Hilger Quartz, Q - Quartz prism, P - Glass prism and G - Grating (used in the red region) are the letter codes of the spectrometer used. See text for details of Table 10.
- ⁶³Accuracy, A – Uncertainty is $\leq 3\%$, B – uncertainty is $\leq 10\%$, C – uncertainty is $\leq 25\%$ and D – uncertainty is $\leq 54\%$.