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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

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]

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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

TABLE 1. Isotopes of radium with zero nuclear spin (I) and with nonzero nuclear spin. The half-lives (ns-nanoseconds, μs-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] $[\mu_I/\mu_N]$	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 μs	0		
^{217}Ra	217.006 321(9)	1.6 μs	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} cm^2.

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 Å 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 UC_2 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 ^{226}Ra I

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

In this context, short lived radioactive isotopes were produced at the TRIµP facility, University of Groningen, The Netherlands.[34] Radium isotopes were produced by the method of inverse reaction kinematics using ^{206,204}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 $7s^2\,{}^1S_0$–$7s7p\,{}^1P_1^0$ transition and weaker intercombination $7s^2\,{}^1S_0$–$7s7p\,{}^3P_1$ transition were reported with reference to a femtosecond optical frequency comb.[12,40] The uncertainty reported was 0.000 06 cm^{-1} and 0.000 13 cm^{-1}, respectively.

At Argonne National Laboratory (ANL), USA, electro-chemically separated neutral radium isotopes, ^{225,226}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 $7s7p\,{}^3P_1^0$, $7s6d\,{}^3D_1$, 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 Å and 15 000 Å air wavelengths and for lines below 2000 Å 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 cm^{-1} = 1.239 841 973 9(76) × 10^{-4} eV. The reciprocal centimeter is related to the SI unit for energy, the joule, in the following way: 1 cm^{-1} is equivalent to 1.986 445 824 (24) × 10^{-23} 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 (^{226}Ra), Ra I

Intensity	Observed λ_{air}/Å	Uncertainty observation λ_{air}/Å	Observation σ/cm^{-1}	Lower level	Upper level	Line reference(s)	Ritz λ/Å	Uncertainty Ritz λ/Å	A_{ik}/s^{-1}	References
	2 350.867 5	0.001 0	42 524.473	$7s^2\,{}^1S_0$	$7s52p\,{}^1P^0_1$	17				
	2 350.980 8	0.001 0	42 522.423	$7s^2\,{}^1S_0$	$7s51p\,{}^1P^0_1$	17				
	2 351.107 9	0.001 0	42 520.125	$7s^2\,{}^1S_0$	$7s50p\,{}^1P^0_1$	17				
	2 351.236 3	0.001 0	42 517.803	$7s^2\,{}^1S_0$	$7s49p\,{}^1P^0_1$	17				
	2 351.384 1	0.001 0	42 515.131	$7s^2\,{}^1S_0$	$7s48p\,{}^1P^0_1$	17				
	2 351.542 9	0.001 0	42 512.260	$7s^2\,{}^1S_0$	$7s47p\,{}^1P^0_1$	17				
	2 351.707 3	0.001 0	42 509.288	$7s^2\,{}^1S_0$	$7s46p\,{}^1P^0_1$	17				
	2 351.882 7	0.001 0	42 506.118	$7s^2\,{}^1S_0$	$7s45p\,{}^1P^0_1$	17				
	2 352.078 8	0.001 0	42 502.575	$7s^2\,{}^1S_0$	$7s44p\,{}^1P^0_1$	17				
	2 352.283 2	0.001 0	42 498.882	$7s^2\,{}^1S_0$	$7s43p\,{}^1P^0_1$	17				
	2 352.511 1	0.001 0	42 494.765	$7s^2\,{}^1S_0$	$7s42p\,{}^1P^0_1$	17				
	2 352.754 2	0.001 0	42 490.375	$7s^2\,{}^1S_0$	$7s41p\,{}^1P^0_1$	17				
	2 353.015 2	0.001 0	42 485.662	$7s^2\,{}^1S_0$	$7s40p\,{}^1P^0_1$	17				
	2 353.301 1	0.001 0	42 480.501	$7s^2\,{}^1S_0$	$7s39p\,{}^1P^0_1$	17				
	2 353.610 5	0.001 0	42 474.917	$7s^2\,{}^1S_0$	$7s38p\,{}^1P^0_1$	17				
	2 353.950 2	0.001 0	42 468.788	$7s^2\,{}^1S_0$	$7s37p\,{}^1P^0_1$	17				
	2 354.334 1	0.001 0	42 461.863	$7s^2\,{}^1S_0$	$7s36p\,{}^1P^0_1$	17				
	2 354.741 6	0.001 0	42 454.516	$7s^2\,{}^1S_0$	$7s35p\,{}^1P^0_1$	17				
	2 355.202 8	0.001 0	42 446.203	$7s^2\,{}^1S_0$	$7s34p\,{}^1P^0_1$	17				
	2 355.708 2	0.001 0	42 437.097	$7s^2\,{}^1S_0$	$7s33p\,{}^1P^0_1$	17				
	2 356.266 1	0.001 0	42 427.050	$7s^2\,{}^1S_0$	$7s32p\,{}^1P^0_1$	17				
	2 356.891 7	0.001 0	42 415.789	$7s^2\,{}^1S_0$	$7s31p\,{}^1P^0_1$	17				
	2 357.597 3	0.001 0	42 403.096	$7s^2\,{}^1S_0$	$7s30p\,{}^1P^0_1$	17				
	2 358.394 0	0.001 0	42 388.773	$7s^2\,{}^1S_0$	$7s29p\,{}^1P^0_1$	17				
	2 359.284 6	0.001 0	42 372.773	$7s^2\,{}^1S_0$	$7s28p\,{}^1P^0_1$	17				
	2 360.310 5	0.001 0	42 354.357	$7s^2\,{}^1S_0$	$7s27p\,{}^1P^0_1$	17				
	2 361.482 7	0.001 0	42 333.335	$7s^2\,{}^1S_0$	$7s26p\,{}^1P^0_1$	17				
	2 362.823 2	0.001 0	42 309.320	$7s^2\,{}^1S_0$	$7s25p\,{}^1P^0_1$	17				
	2 364.384 5	0.001 0	42 281.383	$7s^2\,{}^1S_0$	$7s24p\,{}^1P^0_1$	17				
	2 366.206 5	0.001 0	42 248.829	$7s^2\,{}^1S_0$	$7s23p\,{}^1P^0_1$	17				
	2 368.354 2	0.001 0	42 210.520	$7s^2\,{}^1S_0$	$7s22p\,{}^1P^0_1$	17				
	2 370.912 8	0.001 0	42 164.971	$7s^2\,{}^1S_0$	$7s21p\,{}^1P^0_1$	17				
	2 373.988 5	0.001 0	42 110.347	$7s^2\,{}^1S_0$	$7s20p\,{}^1P^0_1$	17				
	2 377.742 5	0.001 0	42 043.868	$7s^2\,{}^1S_0$	$7s19p\,{}^1P^0_1$	17				
	2 382.365 9	0.001 0	41 962.281	$7s^2\,{}^1S_0$	$7s18p\,{}^1P^0_1$	17				
	2 388.173 8	0.001 0	41 860.240	$7s^2\,{}^1S_0$	$7s17p\,{}^1P^0_1$	17				
	2 395.594 6	0.001 0	41 730.580	$7s^2\,{}^1S_0$	$7s16p\,{}^1P^0_1$	17				
	2 405.295 0	0.001 0	41 562.296	$7s^2\,{}^1S_0$	$7s15p\,{}^1P^0_1$	17				
	2 418.291 9	0.001 0	41 338.940	$7s^2\,{}^1S_0$	$7s14p\,{}^1P^0_1$	17				
	2 436.240 8	0.001 0	41 034.400	$7s^2\,{}^1S_0$	$7s13p\,{}^1P^0_1$	17				
2	2 955.65	0.05	33 823.6	$7s^2\,{}^1S_0$	$6d7p\,{}^3P^0_0$	8	2 955.649	0.012		
			32 857.68	$7s^2\,{}^1S_0$	$7s8p\,{}^1P^0_1$	9	3 042.557	0.008		
5	3 101.80	0.05	32 230.0	$7s^2\,{}^1S_0$	$6d7p\,{}^3D^0_1$	7, 8	3 101.810	0.005		
3	3 771.57	0.05	26 506.66			7				
1	3 772.00	0.05	26 503.6	$7s6d\,{}^3D_1$	$7s8f\,{}^3F^0_2$	7				
1	3 812.00	0.05	26 225.5	$7s6d\,{}^3D_2$	$7s8f\,{}^3F^0_3$	7				
1	3 916.74	0.05	25 524.2	$7s6d\,{}^3D_3$	$7s8f\,{}^3F^0_4$	7				
1	3 941.02	0.05	25 367.0	$7s6d\,{}^3D_2$	$7s7f\,{}^3F^0_3$	7				
1	4 010.30	0.05	24 928.77			7				
1	4 054.07	0.05	24 659.6	$7s6d\,{}^3D_3$	$7s7f\,{}^3F^0_4$	7				
4	4 177.98	0.05	23 928.3	$7s6d\,{}^3D_2$	$7s6f\,{}^3F^0_3$	7				
3	4 265.12	0.05	23 439.43			7				
4	4 305.00	0.05	23 222.3	$7s6d\,{}^3D_3$	$7s6f\,{}^3F^0_4$	7				
2	4 366.30	0.05	22 896.27			7				
2	4 426.35	0.05	22 585.65			7				
1	4 444.47	0.05	22 493.57			7				
8	4 641.290	0.020	21 539.70	$7s6d\,{}^3D_1$	$7s5f\,{}^3F^0_2$	7	4 641.284	0.019		
1	4 672.19	0.05	21 397.25	$7s7p\,{}^3P^0_0$	$7s9s\,{}^3S_1$	7	4 672.17	0.03		
8	4 699.280	0.020	21 273.90	$7s6d\,{}^3D_2$	$7s5f\,{}^3F^0_3$	7	4 699.272	0.018		
2	4 701.97	0.05	21 261.73	$7s6d\,{}^3D_2$	$7s5f\,{}^3F^0_2$	7	4 702.006	0.020		
2	4 740.07	0.05	21 090.86			7				
3	4 803.11	0.05	20 814.04			7				
100	4 825.928 06	0.000 12	20 715.6142	$7s^2\,{}^1S_0$	$7s7p\,{}^1P^0_1$	7, 12	4 825.928 05	0.0012	1.80×10^8	53
3	4 837.27	0.05	20 667.04	$7s6d\,{}^3D_1$	$6d7p\,{}^3P^0_2$	7	4 837.268	0.017		

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

Intensity	Observed λ_{air}/Å	Uncertainty observation λ_{air}/Å	Observation σ/cm^{-1}	Lower level	Upper level	Line reference(s)	Ritz λ/Å	Uncertainty Ritz λ/Å	A_{ik}/s^{-1}	References
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	$7s7p\ ^3P_1^0$	$7p^2\ ^3P_2$	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	$7s6d\ ^3D_1$	$6d7p\ ^3D_1^0$	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	$7s7p\ ^3P_1^0$	$7s7d\ ^3D_1$	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	$7s6d\ ^3D_2$	$7s8p\ ^3P_0^0$	7, 8	5 591.192	0.024		
5	5 601.50	0.05	17 847.41	$7s6d\ ^3D_1$	$7s8p\ ^3P_0^0$	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	$7s6d\ ^3D_1$	$7s8p\ ^3P_1^0$	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	$7s6d\ ^3D_2$	$6d7p\ ^3F_3^0$	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	$7s7p\ ^3P_2^0$	$7s7d\ ^3D_1$	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	$7s6d\ ^3D_1$	$6d7p\ ^3F_2^0$	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 λ_{air}/Å	Uncertainty observation λ_{air}/Å	Observation σ/cm^{-1}	Lower level	Upper level	Line reference(s)	Ritz λ/Å	Uncertainty Ritz λ/Å	A_{ik}/s^{-1}	References
1	7 836.09	0.05	12 757.96			7				
20	7 838.120	0.020	12 754.65	$7s7p\ ^3P_1^0$	$7s8s\ ^3S_1$	7	7 838.116	0.018	2.10×10^7	53
2	7 877.08	0.05	12 691.57			7				
3	7 896.43	0.05	12 660.47			7				
3	8 005.13	0.05	12 488.56			7				
2	8 019.25	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

		$7s7p\ ^1P_1^0$			
Atomic mass	$7s^2\ ^1S_0$	Isotopic frequency shift (MHz)	HFS A (MHz)	HFS B (MHz)	References
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}Ra isotopes.

Table 2 presents the energy levels of ^{226}Ra. They are taken from Moore 1958 compilation[9] and other sources where improved experimental values are available. Moore's compilation is mainly based on the measurements of Rasmussen[6] 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 ±0.006 cm^{-1} given by Armstrong et al. for wavenumbers is not correct as the uncertainty 0.001 Å 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

		$7s7p\ ^3P_1^0$			
Atomic mass	$7s^2\ ^1S_0$	Isotopic frequency shift (MHz)	HFS A (MHz)	HFS B (MHz)	References
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

| | $7s7p\ ^3P_2^0$ | | $7s7d\ ^3D_3$ | | | |
| | HFS | HFS | Isotopic frequency | HFS | HFS | |
Atomic mass	A (MHz)	B (MHz)	shift (MHz)	A (MHz)	B (MHz)	References
212			−887(4)			21
214			0			21
221	278.6(0.9)	1103.8(3.9)	7 001(7)	213.3(0.6)	117.8(4.4)	21
222			7 781(4)			21
223	699.6(3.3)	688.5(4.0)	8 762(6)	535.6(4.6)	73.9(3.0)	21
224			9 481(5)			21
226			11 102(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

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

TABLE 9. Energy levels of ^{226}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		66 838.72	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 supported 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, ^{226}Ra II

Intensity[61]	Observation λ/Å	Uncertainty observation λ/Å	Observation σ/cm⁻¹	Uncertainty observation σ/cm⁻¹	Lower level	Upper level	Line reference[62]	A_{ik}/s⁻¹	Acc.[63]	References
5	1 888.70	0.20	52 946		$6d\ ^2D_{5/2}$	$7f\ ^2F^0_{7/2}$	6HQ			
8	1 908.70	0.20	52 392		$7s\ ^2S_{1/2}$	$8p\ ^2P^0_{3/2}$	6HQ	1.75×10^7	B	32
4	1 972.60	0.20	50 695		$7p\ ^2P^0_{1/2}$	$10d\ ^2D_{3/2}$	6HQ			
2	1 976.00	0.20	50 607		$7s\ ^2S_{1/2}$	$8p\ ^2P^0_{1/2}$	6HQ			
2	2 006.40	0.20	49 824		$7p\ ^2P^0_{1/2}$	$11s\ ^2S_{1/2}$	6HQ			
3	2 012.75	0.10	49 667		$6d\ ^2D_{5/2}$	$9p\ ^2P^0_{3/2}$	6HQ			
2	2 070.60	0.20	48 280		$7p\ ^2P^0_{3/2}$	$11d\ ^2D_{5/2}$	6HQ			
4	2 107.60	0.20	47 432		$6d\ ^2D_{3/2}$	$6f\ ^2F^0_{5/2}$	6Q	2.67×10^7	B	32
5	2 131.00	0.20	46 912		$7p\ ^2P^0_{1/2}$	$9d\ ^2D_{3/2}$	6Q			
10	2 169.90	0.20	46 071		$6d\ ^2D_{5/2}$	$6f\ ^2F^0_{7/2}$	6Q			
4	2 177.30	0.20	45 914		$7p\ ^2P^0_{3/2}$	$10d\ ^2D_{5/2}$	6Q			
1	2 181.10	0.20	45 834		$7p\ ^2P^0_{3/2}$	$10d\ ^2D_{3/2}$	6Q			
2	2 197.80	0.20	45 486		$7p\ ^2P^0_{1/2}$	$10s\ ^2S_{1/2}$	6Q			
3	2 223.30	0.20	44 964		$7p\ ^2P^0_{3/2}$	$11s\ ^2S_{1/2}$	6Q			
8	2 369.730	0.020	42 186.0		$7p\ ^2P^0_{3/2}$	$9d\ ^2D_{5/2}$	6Q			
3	2 377.100	0.020	42 055.2		$7p\ ^2P^0_{3/2}$	$9d\ ^2D_{3/2}$	6Q			
8	2 460.55	0.03	40 629.0		$7p\ ^2P^0_{3/2}$	$10s\ ^2S_{1/2}$	6Q			
10	2 475.50	0.03	40 383.7		$7p\ ^2P^0_{1/2}$	$8d\ ^2D_{3/2}$	6Q			
4	2 480.11	0.03	40 308.6		$6d\ ^2D_{3/2}$	$8p\ ^2P^0_{3/2}$	6Q	7.5×10^5	C	32
8	2 586.61	0.03	38 649.1		$6d\ ^2D_{5/2}$	$8p\ ^2P^0_{3/2}$	6Q			
2	2 595.15	0.03	38 521.9		$6d\ ^2D_{3/2}$	$8p\ ^2P^0_{1/2}$	6Q			
10	2 643.73	0.03	37 814.1		$7p\ ^2P^0_{1/2}$	$9s\ ^2S_{1/2}$	6Q			
20	2 708.960	0.020	36 903.6		$6d\ ^2D_{3/2}$	$5f\ ^2F^0_{5/2}$	6G	3.70×10^8	A	32
10p (Mg II)	2 795.21	0.07	35 764.9		$7p\ ^2P^0_{3/2}$	$8d\ ^2D_{5/2}$	6Q			
30	2 813.760	0.020	35 529.2		$6d\ ^2D_{5/2}$	$5f\ ^2F^0_{7/2}$	6G			
6	2 836.460	0.020	35 244.85		$6d\ ^2D_{5/2}$	$5f\ ^2F^0_{5/2}$	6G			
10	3 033.44	0.04	32 956.3		$7p\ ^2P^0_{3/2}$	$9s\ ^2S_{1/2}$	6Q			
2	3 423.10	0.20	29 204.9		$5f\ ^2F^0_{5/2}$	$11g\ ^2G_{7/2,9/2}$	6Q			
2	3 456.20	0.20	28 925.2		$5f\ ^2F^0_{7/2}$	$11g\ ^2G_{7/2,9/2}$	6Q			
2	3 514.80	0.20	28 443.0		$5f\ ^2F^0_{5/2}$	$10g\ ^2G_{7/2,9/2}$	6Q			
2	3 550.20	0.20	28 159.4		$5f\ ^2F^0_{7/2}$	$10g\ ^2G_{7/2,9/2}$	6Q			
100	3 649.550	0.020	27 392.83		$7p\ ^2P^0_{1/2}$	$7d\ ^2D_{3/2}$	6G			
3	3 686.160	0.020	27 120.78		$5f\ ^2F^0_{7/2}$	$9g\ ^2G_{7/2,9/2}$	6P			
200	3 814.421 9	0.0003	26 208.8538	0.0021	$7s\ ^2S_{1/2}$	$7p\ ^2P^0_{3/2}$	6G, 13	1.880×10^8	A	32
5p (Cl II)	3 851.90	0.05	25 953.9		$5f\ ^2F^0_{5/2}$	$8g\ ^2G_{7/2,9/2}$	6P			
5	3 894.55	0.03	25 669.63		$5f\ ^2F^0_{7/2}$	$8g\ ^2G_{7/2,9/2}$	6P			
8	4 194.09	0.03	23 836.36		$5f\ ^2F^0_{5/2}$	$7g\ ^2G_{7/2,9/2}$	6P			
2	4 195.56	0.03	23 828.01		$8p\ ^2P^0_{1/2}$	$11d\ ^2D_{3/2}$	6P			
1	4 220.24	0.03	23 688.66		$8p\ ^2P^0_{3/2}$	$12d\ ^2D_{5/2}$	6P			
8	4 244.72	0.04	23 552.05		$5f\ ^2F^0_{7/2}$	$7g\ ^2G_{7/2,9/2}$	6P			
100p (H I)	4 340.64	0.07	23 031.6		$7p\ ^2P^0_{3/2}$	$7d\ ^2D_{5/2}$	6P			
20	4 436.270	0.020	22 535.13		$7p\ ^2P^0_{3/2}$	$7d\ ^2D_{3/2}$	6G			
30	4 533.110	0.020	22 053.73		$7p\ ^2P^0_{1/2}$	$8s\ ^2S_{1/2}$	6G			
3	4 663.52	0.05	21 437.03		$8p\ ^2P^0_{1/2}$	$10d\ ^2D_{3/2}$	6P			
100	4 682.239 40	0.000 17	21 351.3259	0.0008	$7s\ ^2S_{1/2}$	$7p\ ^2P^0_{1/2}$	6G, 13	1.061×10^8	A	32
10	4 859.41	0.05	20 572.88		$5f\ ^2F^0_{5/2}$	$6g\ ^2G_{7/2,9/2}$	6P			
10	4 927.53	0.05	20 288.48		$5f\ ^2F^0_{7/2}$	$6g\ ^2G_{7/2,9/2}$	6P			
3	4 997.26	0.05	20 005.39		$8s\ ^2S_{1/2}$	$9p\ ^2P^0_{3/2}$	6P			
3	5 066.57	0.05	19 731.72		$8p\ ^2P^0_{3/2}$	$10d\ ^2D_{5/2}$	6P			
1	5 323.09	0.06	18 780.86		$8p\ ^2P^0_{3/2}$	$11s\ ^2S_{1/2}$	6P			
3	5 623.43	0.07	17 777.81		$7d\ ^2D_{3/2}$	$7f\ ^2F^0_{5/2}$	6P			
6	5 661.73	0.07	17 657.55		$8p\ ^2P^0_{1/2}$	$9d\ ^2D_{3/2}$	6P			
4	5 728.83	0.07	17 450.73		$7d\ ^2D_{5/2}$	$7f\ ^2F^0_{7/2}$	6P			
20	5 813.630	0.020	17 196.19		$7p\ ^2P^0_{3/2}$	$8s\ ^2S_{1/2}$	6G			
1	6 158.73	0.08	16 232.62		$8p\ ^2P^0_{1/2}$	$10s\ ^2S_{1/2}$	6P			
4	6 247.16	0.08	16 002.85		$8p\ ^2P^0_{3/2}$	$9d\ ^2D_{5/2}$	6P			
1	6 298.56	0.08	15 872.26		$8p\ ^2P^0_{3/2}$	$9d\ ^2D_{3/2}$	6P			
10	6 593.340	0.020	15 162.63		$5f\ ^2F^0_{5/2}$	$5g\ ^2G_{7/2,9/2}$	6G			
10	6 719.320	0.020	14 878.35		$5f\ ^2F^0_{7/2}$	$5g\ ^2G_{7/2,9/2}$	6G			
1	6 920.11	0.10	14 446.65		$8p\ ^2P^0_{3/2}$	$10s\ ^2S_{1/2}$	6P			
5	7 078.02	0.10	14 124.35		$6d\ ^2D_{3/2}$	$7p\ ^2P^0_{3/2}$	6G	3.39×10^6	B	32

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

Intensity[61]	Observation $\lambda/\text{Å}$	Uncertainty observation $\lambda/\text{Å}$	Observation σ/cm^{-1}	Uncertainty observation σ/cm^{-1}	Lower level	Upper level	Line reference 62	A_{ik}/s^{-1}	Acc.[63]	References
50	8 019.700	0.020	12 465.87		$6d\ ^2D_{5/2}$	$7p\ ^2P^0_{3/2}$	6G	2.29×10^7	B	32
	10 787.960 9	0.0007	9 267.0538	0.0006	$6d\ ^2D_{3/2}$	$7p\ ^2P^0_{1/2}$	13	1.06×10^7	B	32

gen group support this in addition to the ISOLDE group. The very recent measurement of the $7s6d\ ^3D_1$–$7s7p\ ^1P^0_1$ transition in ^{226}Ra by the Argonne group[10] 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 group[21] 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 $7s8p\ ^1P^0_1$ level, Armstrong et al.[17] restored Rasmussen's identification. Furthermore, Ginges and Dzuba in their recent theoretical work[52] 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 Rasmussen[7] 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 Reeder[43] 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 Flambaum[53] and one value from the experiment.[41] In column 4 of Table 3, we have given wavenumbers for the transitions from the measurements of Rasmussen[7] 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 $7s^2\ ^1S_0$–$7s7p\ ^{3,1}P^0_1$ 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 $7s6d\ ^3D_1$–$7s7p\ ^3P^0_1$ 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 compilation[9] 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}Ra II

Lower level	Upper level	Ritz $\lambda/\text{Å}$	Uncertainty Ritz $\lambda/\text{Å}$
$6d\ ^2D_{5/2}$	$7f\ ^2F^0_{7/2}$	1 888.639	0.015
$7s\ ^2S_{1/2}$	$8p\ ^2P^0_{3/2}$	1 908.688	0.007
$7p\ ^2P^0_{1/2}$	$10d\ ^2D_{3/2}$	1 972.698	0.012
$7s\ ^2S_{1/2}$	$8p\ ^2P^0_{1/2}$	1 976.039	0.009
$7p\ ^2P^0_{1/2}$	$11s\ ^2S_{1/2}$	2 006.514	0.011
$6d\ ^2D_{5/2}$	$9p\ ^2P^0_{3/2}$	2 012.741	0.008
$7p\ ^2P^0_{1/2}$	$9d\ ^2D_{3/2}$	2 130.944	0.009
$7p\ ^2P^0_{3/2}$	$10d\ ^2D_{5/2}$	2 177.261	0.013
$7p\ ^2P^0_{3/2}$	$10d\ ^2D_{3/2}$	2 181.081	0.015
$7p\ ^2P^0_{1/2}$	$10s\ ^2S_{1/2}$	2 197.725	0.011
$7p\ ^2P^0_{3/2}$	$11s\ ^2S_{1/2}$	2 223.308	0.014
$7p\ ^2P^0_{3/2}$	$9d\ ^2D_{5/2}$	2 369.730	0.013
$7p\ ^2P^0_{3/2}$	$9d\ ^2D_{3/2}$	2 377.101	0.012
$7p\ ^2P^0_{3/2}$	$10s\ ^2S_{1/2}$	2 460.499	0.013
$6d\ ^2D_{3/2}$	$8p\ ^2P^0_{3/2}$	2 480.164	0.012
$6d\ ^2D_{5/2}$	$8p\ ^2P^0_{3/2}$	2 586.613	0.013
$6d\ ^2D_{3/2}$	$8p\ ^2P^0_{1/2}$	2 595.142	0.015
$7p\ ^2P^0_{1/2}$	$9s\ ^2S_{1/2}$	2 643.737	0.021
$6d\ ^2D_{3/2}$	$5f\ ^2F^0_{5/2}$	2 708.960	0.011
$6d\ ^2D_{5/2}$	$5f\ ^2F^0_{7/2}$	2 813.762	0.012
$6d\ ^2D_{5/2}$	$5f\ ^2F^0_{5/2}$	2 836.458	0.012
$7p\ ^2P^0_{3/2}$	$9s\ ^2S_{1/2}$	3 033.42	0.03
$5f\ ^2F^0_{5/2}$	$11g\ ^2G_{7/2,9/2}$	3 422.83	0.14
$5f\ ^2F^0_{7/2}$	$11g\ ^2G_{7/2,9/2}$	3 456.47	0.14
$5f\ ^2F^0_{5/2}$	$10g\ ^2G_{7/2,9/2}$	3 514.76	0.14
$5f\ ^2F^0_{7/2}$	$10g\ ^2G_{7/2,9/2}$	3 550.24	0.14
$7p\ ^2P^0_{1/2}$	$7d\ ^2D_{3/2}$	3 649.566	0.011
$7s\ ^2S_{1/2}$	$7p\ ^2P^0_{3/2}$	3 814.421 9	0.0003
$5f\ ^2F^0_{5/2}$	$8g\ ^2G_{7/2,9/2}$	3 851.89	0.03
$5f\ ^2F^0_{7/2}$	$8g\ ^2G_{7/2,9/2}$	3 894.55	0.03
$5f\ ^2F^0_{5/2}$	$7g\ ^2G_{7/2,9/2}$	4 194.091	0.024
$5f\ ^2F^0_{7/2}$	$7g\ ^2G_{7/2,9/2}$	4 244.72	0.03
$7p\ ^2P^0_{3/2}$	$7d\ ^2D_{5/2}$	4 340.64	0.07
$7p\ ^2P^0_{3/2}$	$7d\ ^2D_{3/2}$	4 436.259	0.017
$7p\ ^2P^0_{1/2}$	$8s\ ^2S_{1/2}$	4 533.111	0.010
$8p\ ^2P^0_{1/2}$	$10d\ ^2D_{3/2}$	4 663.52	0.05
$7s\ ^2S_{1/2}$	$7p\ ^2P^0_{1/2}$	4 682.239 40	0.000 17
$5f\ ^2F^0_{5/2}$	$6g\ ^2G_{7/2,9/2}$	4 859.42	0.04
$5f\ ^2F^0_{7/2}$	$6g\ ^2G_{7/2,9/2}$	4 927.52	0.04
$8s\ ^2S_{1/2}$	$9p\ ^2P^0_{3/2}$	4 997.26	0.05
$8p\ ^2P^0_{3/2}$	$10d\ ^2D_{5/2}$	5 066.57	0.05
$8p\ ^2P^0_{3/2}$	$11s\ ^2S_{1/2}$	5 323.09	0.06
$8p\ ^2P^0_{1/2}$	$9d\ ^2D_{3/2}$	5 661.65	0.06
$7d\ ^2D_{5/2}$	$7f\ ^2F^0_{7/2}$	5 728.83	0.07
$7p\ ^2P^0_{3/2}$	$8s\ ^2S_{1/2}$	5 813.628	0.017
$8p\ ^2P^0_{1/2}$	$10s\ ^2S_{1/2}$	6 158.80	0.07
$8p\ ^2P^0_{3/2}$	$9d\ ^2D_{5/2}$	6 247.16	0.07
$8p\ ^2P^0_{3/2}$	$9d\ ^2D_{3/2}$	6 298.64	0.06
$5f\ ^2F_{5/2}$	$5g\ ^2G_{7/2,9/2}$	6 593.341	0.019
$5f\ ^2F_{7/2}$	$5g\ ^2G_{7/2,9/2}$	6 719.320	0.019
$8p\ ^2P^0_{3/2}$	$10s\ ^2S_{1/2}$	6 920.09	0.08
$6d\ ^2D_{3/2}$	$7p\ ^2P^0_{3/2}$	7 077.904 2	0.0011
$6d\ ^2D_{5/2}$	$7p\ ^2P^0_{3/2}$	8 019.701	0.020
$6d\ ^2D_{3/2}$	$7p\ ^2P^0_{1/2}$	10 787.960 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	λ_{air}/Å	σ/cm^{-1}	Uncertainty (cm^{-1})	Lower level	Upper level	References
212	3 814.096 2	26 211.0916	0.0021	$7s\ ^2S_{1/2}$	$7p\ ^2P^0_{3/2}$	13
	4 681.782 73	21 353.4085	0.0005	$7s\ ^2S_{1/2}$	$7p\ ^2P^0_{1/2}$	13
	7 078.071 4	14 124.2481	0.0018	$6d\ ^2D_{3/2}$	$7p\ ^2P^0_{3/2}$	13
	10 788.530	9 266.5650	0.0004	$6d\ ^2D_{3/2}$	$7p\ ^2P^0_{1/2}$	13
213	4 681.793 96	21 353.3573	0.0004	$7s\ ^2S_{1/2}$	$7p\ ^2P^0_{1/2}$	13
	7 078.082 2 (F=2-F=1)	14 124.2264	0.0017	$6d\ ^2D_{3/2}$	$7p\ ^2P^0_{3/2}$	13
	10 788.517 6	9 266.5756	0.0005	$6d\ ^2D_{3/2}$	$7p\ ^2P^0_{1/2}$	13
214	3 814.120 14	26 210.9273	0.0017	$7s\ ^2S_{1/2}$	$7p\ ^2P^0_{3/2}$	13
	4 681.816 26	21 353.2556	0.0005	$7s\ ^2S_{1/2}$	$7p\ ^2P^0_{1/2}$	13
	7 078.059 9	14 124.2709	0.0014	$6d\ ^2D_{3/2}$	$7p\ ^2P^0_{3/2}$	13
	10 788.490 2	9 266.5992	0.0004	$6d\ ^2D_{3/2}$	$7p\ ^2P^0_{1/2}$	13
225	4 682.216 42	21 351.4307	0.0008	$7s\ ^2S_{1/2}$	$7p\ ^2P^0_{1/2}$	13
	10 787.989 2	9 267.0295	0.0006	$6d\ ^2D_{3/2}$	$7p\ ^2P^0_{1/2}$	13
226	10 787.960 9	9 267.0538	0.0006	$6d\ ^2D_{3/2}$	$7p\ ^2P^0_{1/2}$	13

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

Atomic mass	$7s\ ^2S_{1/2}$ HFS A (MHz)	$7p\ ^2P^0_{1/2}$ Isotopic frequency shift (MHz)	$7p\ ^2P^0_{1/2}$ HFS A (MHz)	$7p\ ^2P^0_{3/2}$ Isotopic frequency shift (MHz)[a]	$7p\ ^2P^0_{3/2}$ HFS A (MHz)[a]	$7p\ ^2P^0_{3/2}$ HFS B (MHz)[a]	Reference(s)
208		11 950(8)					21
209							21
210		8 449(6)					21
211	6 624.8(1.0)	7 770(4)	1299.7(0.8)				21
212		4 583(3)		4 937(2)			23
213	22 920.0(6.0)	3 049(3)	4525.0(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)	1364.2(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							

[a]From reference 23.

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

Atomic mass	$6d\ ^2D_{3/2}$ HFS A (MHz)	$6d\ ^2D_{3/2}$ HFS B (MHz)	$7p\ ^2P^0_{1/2}$ Isotopic frequency shift (MHz)	$7p\ ^2P^0_{1/2}$ HFS A (MHz)	Reference(s)
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		

[a]Reference 38.
[b]Reference 39.
[c]Reference 37.
[d]Reference 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) cm^{-1} and 81 842.5(5) cm^{-1} resulting in an average of 81 842.5(5) 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) cm^{-1}, which agrees with Rasmussen's value of 81 842.31 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 $7p\ ^2P^0_{3/2}$ and $6d\ ^2D_{3/2}$ levels in Ra II

	$6d\ ^2D_{3/2}$	$7p\ ^2P^0_{3/2}$			
Atomic mass	HFS A (MHz)	Isotopic frequency shift (MHz)	HFS A (MHz)	HFS B (MHz)	Reference(s)
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 Reeder[43] 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 $7s\ ^2S_{1/2}$–$7s7p\ ^2P^0_{1/2,3/2}$ and $6d\ ^2D_{3/2}$–$7s7p\ ^2P^0_{1/2,3/2}$ 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 ^{214}Ra 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

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 ^{214}Ra 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 ^{212}Ra 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

5. References

TABLE 16. Lifetimes of energy levels in ^{212}Ra II

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

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[60]From experiment. Accuracy, B – uncertainty is ≤ 10%.

[61]'p' means 'perturbed by' with the perturbing species given in parentheses.

[62]Ref. 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.

[63]Accuracy, A – Uncertainty is ≤ 3%, B – uncertainty is ≤ 10%, C – uncertainty is ≤ 25% and D – uncertainty ≤ 54%.