Spectroscopic Data for Neutral Francium (Fr I)

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Energy levels and hyperfine structure constants have been compiled for the sixteen longest lived isotopes of francium ($Z=87$). For most isotopes with atomic weights in the range 199 $\leq A \leq 232$ the only measurements made are for the $7s\ ^2S_{1/2}$ and $7p\ ^2P^{\circ}_{1/2,3/2}$ levels. Additional energy-level data are available for ^{210}Fr, ^{212}Fr, and ^{221}Fr. Wavelengths with classifications and transition probabilities are tabulated for ^{212}Fr. In addition, the ionization energy is included for isotopes for which a sufficient number of levels have been measured, ^{212}Fr and ^{221}Fr. *© 2007 by the U.S. Secretary of Commerce on behalf of the United States. All rights reserved.* [DOI: 10.1063/1.2719251]

Key words: Francium; energy levels; atomic spectra; wavelengths; wave numbers; wavelength tables; hyperfine structure.

CONTENTS

List of Tables

1. Introduction

Although the existence of francium and some of its chemical properties were predicted as early as 1870 by Mendeleev, the element was not actually observed until 1939, when Marguerite Perey of the Curie Institute in Paris discovered a decay product of ^{227}Ac with the chemical properties of an alkali metal. Later she named the element Francium after her native country. The isotope she observed, $^{223}_{87}$Fr, is the longest-lived isotope, with a half-life of 21.8 min, and is the only one occurring naturally. However, according to the 86th Edition of the *CRC Handbook*,[1] 36 isotopes are recognized, with atomic weights in the range $199 \leq A \leq 232$. Most have half-lives of a few seconds or less; those with longer half-lives include those in Table 1 (the magnetic moments are given as the ratio to the nuclear magneton, which is $5.050\,783\,43(43)\times10^{-27}$ J T^{-1}).

Francium is the most unstable of the first 101 elements and its short half-life has made it difficult to measure its physical properties. Like all alkalis it is very reactive and electropositive and also has a low ionization energy. It has an atomic number of 87 and a melting point just above room temperature (27.2 °C). There are few practical uses for francium. However, it is of considerable spectroscopic interest because, as the heaviest alkali metal, it is an excellent candidate for parity non-conservation measurements. Theoretical investigation of the transition amplitude for the parity-non-conserving $7s-8s$ transition has been done by Dzuba *et*

TABLE 1. Isotopes of francium

Isotope	Atomic weight[a]	Half-life[a] (min)	Spin[a]	Nuclear magnetic moment[b] (μ/μN)
^{207}Fr	206.996 9	0.247	9/2	+3.89(9)
^{208}Fr	207.997 13	0.985	7	−4.75(10)
^{209}Fr	208.995 92	0.833	9/2	+3.95(8)
^{210}Fr	209.996 40	3.2	6	+4.40(9)
^{211}Fr	210.995 53	3.10	9/2	+4.00(8)
^{212}Fr	211.996 18	20.	5	+4.62(9)
^{213}Fr	212.996 17	0.577	9/2	+4.02(8)
^{220}Fr	220.012 313	0.457	1	−0.67(1)
^{221}Fr	221.014 25	4.8	5/2	+1.58(3)
^{222}Fr	222.017 54	14.3	2	+0.63(1)
^{223}Fr	223.019 731	21.8	3/2	+1.17(2)
^{224}Fr	224.023 23	3.0	1	+0.40(1)
^{225}Fr	225.025 61	3.9	3/2	+1.07(2)
^{226}Fr	226.029 3	0.82	1	+0.071(2)
^{227}Fr	227.031 8	2.48	1/2	+1.50(3)
^{228}Fr	228.035 7	0.65	2	−0.76(2)
^{229}Fr	229.038 4	0.83		

[a] See the CRC Handbook.[1]
[b] See Ekström *et al.*[9,10]

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TABLE 2. Isotopic spectral data for the $7s$ and $7p$ levels

	$7s\ ^2S_{1/2}$	$7p\ ^2P^{\circ}_{1/2}$		$7p\ ^2P^{\circ}_{3/2}$		
Atomic mass	HFS A (MHz)	Isotopic frequency shift (MHz)	HFS A (MHz)	Isotopic frequency shift (MHz)	HFS A (MHz)	HFS B (MHz)
207	8 484(1)			5 239(4)	90.7(6)	−42(13)
208	6 650.7(8)		874.8(3)	5 003(3)	72.4(5)	1(10)
209	8 606.7(9)		1127.9(2)	3 133(2)	93.3(5)	−62(5)
210	7 195.1(4)		946.3(2)	2603(1)	78.0(2)	51(4)
211	8 713.9(8)		1142.1(2)	901(3)	94.9(3)	−51(7)
212	9 064.2(2)	0	1187(7)	0	97.2(1)	−26.0(2)
213	8 757.4(19)		1150(8)	−1 641.0(2)	95.3(3)	−36.0(5)
220	−6 549.2(12)			−20 806.8(5)	−73.2(5)	−126.8(5)
221	6 209.9(10)	−22452(1)	808(12)	−23 570.0(2)	65.5(6)	−264.0(8)
222	3 070(3)			−26 262(3)	33(1)	133(9)
223	7 654(2)			−27 922(2)	83.3(9)	308(3)
224	3 876(1)			−30 891(1)	42.1(7)	136(1)
225	6 980(8)			−32 297(6)	77(3)	346(13)
226	699(4)			−34 401(1)	7(1)	−356(4)
227	20 458(4)			−38 352(2)	316(2)	
228	−3 731(4)			−40 077(5)	−41(2)	627(12)

al.[2] and the tie-in between isotope shifts and parity nonconservation analysis has been discussed by Dzuba *et al.*[3]

For this compilation of spectral data the literature has been reviewed and lists of the most accurate information have been assembled. The uncertainty for each value, as given by the original authors, is indicated in the tables; however, for some values the authors do not estimate the uncertainty, so we are unable to include that information. In the table of wavelengths, the wavelengths and their uncertainties are reported in units of ångströms. As all lines are between 2000 and 10 000 Å, air wavelengths are given, with the index of refraction determined by the three-term formula Peck and Reeder.[4] The wave number of each transition is reported in reciprocal centimeters and its uncertainty can be determined from that of the wavelength. The calculated transition probabilities (A_{ki}) are given in units of inverse seconds. No estimate for their uncertainty was given by the authors. The lower level and upper level columns indicate the classification given for the transition.

The energy level tables contain the configuration, term, and *J* values of each energy level, using *LS* coupling to describe the configurations. For visual clarity, only the first member of the term has the configuration written out. The level value and its uncertainty are given in the customary reciprocal centimeters. (As reported in Mohr and Taylor,[5] the reciprocal centimeter is related to the SI unit for energy, the joule, by $1\ \mathrm{cm}^{-1} = 1.986\,445\,61(34) \times 10^{-23}$ J). All hyperfine structure constants and isotope shifts are given in units of megahertz with the uncertainty in the last digit given in parentheses following the value. As is customary, the hyperfine splitting constant, A, is the magnetic dipole coefficient, whereas *B* is the electric quadrupole coefficient. The level reference and hyperfine reference refer to the source of the energy level value and hyperfine splitting constants, respectively.

2. Spectroscopic Data

Ground state:
$1s^22s^22p^63s^23p^63d^{10}4s^24p^64d^{10}4f^{14}5s^25p^65d^{10}6s^26p^67s\ ^2S_{1/2}$

Ionization energies:

^{212}Fr – 32 848.872(9) cm^{-1};   4.072 740 6(11) eV
^{221}Fr – 32 848.0(3) cm^{-1};   4.072 63(4) eV

TABLE 3. Isotopic spectral data for the $8p$ levels

	$8p\ ^2P^{\circ}_{1/2}$	$8p\ ^2P^{\circ}_{3/2}$		
Atomic mass	HFS A (MHz)	Isotopic frequency shift (MHz)	HFS A (MHz)	HFS B (MHz)
212	373.0(1)	0	32.8(1)	−7.7(9)
213		−1 615.0(3)	31.6(1)	−7.0(25)
220		−20 564.0(7)	−23.3(1)	41.4(14)
221		−23 298.0(8)	22.4(1)	−85.7(8)

Observing a sufficient quantity of francium to perform spectroscopic observations has been extremely difficult and the particular isotope produced depends on the technique utilized. The first spectral line reported was the D_2 resonance line observed at the European Organization of Nuclear Research (CERN) by Liberman *et al.*[6] The francium produced at CERN, using bombardment of a uranium target by protons, is predominantly ^{212}Fr, but isotopes from $A=207$ to 228 have been observed by Coc *et al.*,[7,8] Ekström *et al.*,[9,10] and Liberman *et al.*[11] The hyperfine splitting constants for the $7s$ and $7p$ levels of these isotopes are summarized in Table 2 along with the isotopic shifts of the frequencies of the transition to the ground state. The shifts in frequency are measured with respect to the corresponding transitions in ^{212}Fr ($\delta\nu=\nu_{\mathrm{isotope}}-\nu_{212}$). Thus a positive shift means that the level is farther from the ground state that the corresponding ^{212}Fr level.

Isotope shifts for the $7p\ ^2P^\circ_{3/2}$ levels and hyperfine splitting constant for them and the $7s\ ^2S_{1/2}$ levels are taken from Coc *et al.*[7,8] and Duong *et al.*[12] The A values of the $7p\ ^2P^\circ_{1/2}$ levels of the isotopes from 208 to 212 were measured by Grossman *et al.*[13] and the isotope shift for the $7p\ ^2P^\circ_{1/2}$ in ^{221}Fr was reported in Bauche *et al.*[14] Duong *et al.*[12] measured the isotope shifts and hyperfine structure constants for the $8p\ ^2\mathrm{P}^\circ$ levels listed in Table 3.

More extensive research using the ^{212}Fr produced by the CERN facilities has resulted in the measurement of the ns levels for $10\leq n\leq 22$ and the nd levels for $8\leq n\leq 20$ by Arnold *et al.*[15,16] Values for the $7p$ and $8p$ levels have been determined by Bauche *et al.*[14] and Duong *et al.*,[12] respectively. More recently, Biémont *et al.*[17] augmented the experimental data by using the Ritz formula to predict all missing ns, np, and nd levels up to $n=30$. They also calculated the transition probabilities, which are listed in Table 4. The wavelengths given in Table 4 are calculated from the energy levels given in Table 5, as compiled in Biémont *et al.*;[17] however, the $9s$ level value reported here is calculated from their Ritz formula because the value given in Table 2 of Biémont *et al.*[17] is actually from a ^{210}Fr measurement. The ionization energy for ^{212}Fr and many of the hyperfine splitting constants were determined by Arnold *et al.*[16] Splitting constants for the $7s$, $7p$, and $8p$ levels were determined by Duong *et al.*[12]

TABLE 4. Spectral lines of ^{212}Fr I

λ_{air} (Å)	Uncertainty (Å)	σ (cm^{-1})	A_{ki} (s^{-1})	Lower level	Upper level
3086.287	0.005	32 391.99	8.00E+3	$7s\ ^2\mathrm{S}_{1/2}$	$20p\ ^2\mathrm{P}^\circ_{3/2}$
3086.843	0.005	32 386.15	8.01E+3	$7s\ ^2\mathrm{S}_{1/2}$	$20p\ ^2\mathrm{P}^\circ_{1/2}$
3092.514	0.005	32 326.77	1.00E+4	$7s\ ^2\mathrm{S}_{1/2}$	$19p\ ^2\mathrm{P}^\circ_{3/2}$
3093.197	0.005	32 319.63	9.82E+3	$7s\ ^2\mathrm{S}_{1/2}$	$19p\ ^2\mathrm{P}^\circ_{1/2}$
3100.211	0.005	32 246.51	1.23E+4	$7s\ ^2\mathrm{S}_{1/2}$	$18p\ ^2\mathrm{P}^\circ_{3/2}$
3101.063	0.005	32 237.65	1.23E+4	$7s\ ^2\mathrm{S}_{1/2}$	$18p\ ^2\mathrm{P}^\circ_{1/2}$
3109.885	0.005	32 146.20	1.57E+4	$7s\ ^2\mathrm{S}_{1/2}$	$17p\ ^2\mathrm{P}^\circ_{3/2}$
3110.966	0.005	32 135.03	1.57E+4	$7s\ ^2\mathrm{S}_{1/2}$	$17p\ ^2\mathrm{P}^\circ_{1/2}$
3122.284	0.005	32 018.55	2.10E+4	$7s\ ^2\mathrm{S}_{1/2}$	$16p\ ^2\mathrm{P}^\circ_{3/2}$
3123.684	0.005	32 004.20	2.11E+4	$7s\ ^2\mathrm{S}_{1/2}$	$16p\ ^2\mathrm{P}^\circ_{1/2}$
3138.547	0.005	31 852.65	2.81E+4	$7s\ ^2\mathrm{S}_{1/2}$	$15p\ ^2\mathrm{P}^\circ_{3/2}$
3140.409	0.005	31 833.76	2.81E+4	$7s\ ^2\mathrm{S}_{1/2}$	$15p\ ^2\mathrm{P}^\circ_{1/2}$
3160.492	0.005	31 631.49	4.00E+4	$7s\ ^2\mathrm{S}_{1/2}$	$14p\ ^2\mathrm{P}^\circ_{3/2}$
3163.046	0.005	31 605.95	3.91E+4	$7s\ ^2\mathrm{S}_{1/2}$	$14p\ ^2\mathrm{P}^\circ_{1/2}$
3191.165	0.005	31 327.46	5.81E+4	$7s\ ^2\mathrm{S}_{1/2}$	$13p\ ^2\mathrm{P}^\circ_{3/2}$
3194.810	0.005	31 291.72	5.81E+4	$7s\ ^2\mathrm{S}_{1/2}$	$13p\ ^2\mathrm{P}^\circ_{1/2}$
3236.029	0.005	30 893.16	9.16E+4	$7s\ ^2\mathrm{S}_{1/2}$	$12p\ ^2\mathrm{P}^\circ_{3/2}$
3241.504	0.005	30 840.98	9.15E+4	$7s\ ^2\mathrm{S}_{1/2}$	$12p\ ^2\mathrm{P}^\circ_{1/2}$
3305.752	0.005	30 241.60	1.56E+5	$7s\ ^2\mathrm{S}_{1/2}$	$11p\ ^2\mathrm{P}^\circ_{3/2}$
3314.578	0.006	30 161.07	1.56E+5	$7s\ ^2\mathrm{S}_{1/2}$	$11p\ ^2\mathrm{P}^\circ_{1/2}$
3423.900	0.006	29 198.09	3.04E+5	$7s\ ^2\mathrm{S}_{1/2}$	$10p\ ^2\mathrm{P}^\circ_{3/2}$
3439.675	0.006	29 064.18	3.02E+5	$7s\ ^2\mathrm{S}_{1/2}$	$10p\ ^2\mathrm{P}^\circ_{1/2}$
3653.102	0.007	27 366.20	7.52E+5	$7s\ ^2\mathrm{S}_{1/2}$	$9p\ ^2\mathrm{P}^\circ_{3/2}$
3686.510	0.007	27 118.21	7.24E+5	$7s\ ^2\mathrm{S}_{1/2}$	$9p\ ^2\mathrm{P}^\circ_{1/2}$
4225.655	0.009	23 658.31	2.82E+6	$7s\ ^2\mathrm{S}_{1/2}$	$8p\ ^2\mathrm{P}^\circ_{3/2}$
4325.361	0.009	23 112.96	2.64E+6	$7s\ ^2\mathrm{S}_{1/2}$	$8p\ ^2\mathrm{P}^\circ_{1/2}$
4946.157	0.002	20 212.074	1.67E+5	$7p\ ^2\mathrm{P}^\circ_{1/2}$	$20d\ ^2\mathrm{D}_{3/2}$
4959.144	0.002	20 159.143	2.00E+5	$7p\ ^2\mathrm{P}^\circ_{1/2}$	$19d\ ^2\mathrm{D}_{3/2}$
4969.031	0.002	20 119.035	4.57E+4	$7p\ ^2\mathrm{P}^\circ_{1/2}$	$20s\ ^2\mathrm{S}_{1/2}$
4974.988	0.002	20 094.945	2.39E+5	$7p\ ^2\mathrm{P}^\circ_{1/2}$	$18d\ ^2\mathrm{D}_{3/2}$
4987.192	0.002	20 045.771	5.59E+4	$7p\ ^2\mathrm{P}^\circ_{1/2}$	$19s\ ^2\mathrm{S}_{1/2}$
4994.600	0.002	20 016.040	2.98E+5	$7p\ ^2\mathrm{P}^\circ_{1/2}$	$17d\ ^2\mathrm{D}_{3/2}$
5009.918	0.002	19 954.842	6.97E+4	$7p\ ^2\mathrm{P}^\circ_{1/2}$	$18s\ ^2\mathrm{S}_{1/2}$

TABLE 4. Spectral lines of ^{212}Fr I—Continued

λ_{air} (Å)	Uncertainty (Å)	σ (cm^{-1})	A_{ki} (s^{-1})	Lower level	Upper level
5019.293	0.002	19 917.570	3.81E+5	$7p\ ^2P^\circ_{1/2}$	$16d\ ^2D_{3/2}$
5038.896	0.002	19 840.083	8.88E+4	$7p\ ^2P^\circ_{1/2}$	$17s\ ^2S_{1/2}$
5051.011	0.002	19 792.500	4.84E+5	$7p\ ^2P^\circ_{1/2}$	$15d\ ^2D_{3/2}$
5076.691	0.002	19 692.380	1.15E+5	$7p\ ^2P^\circ_{1/2}$	$16s\ ^2S_{1/2}$
5092.753	0.002	19 630.273	6.28E+5	$7p\ ^2P^\circ_{1/2}$	$14d\ ^2D_{3/2}$
5127.362	0.002	19 497.773	1.56E+5	$7p\ ^2P^\circ_{1/2}$	$15s\ ^2S_{1/2}$
5149.331	0.002	19 414.591	8.48E+5	$7p\ ^2P^\circ_{1/2}$	$13d\ ^2D_{3/2}$
5197.664	0.002	19 234.056	2.14E+5	$7p\ ^2P^\circ_{1/2}$	$14s\ ^2S_{1/2}$
5228.917	0.002	19 119.097	1.19E+6	$7p\ ^2P^\circ_{1/2}$	$12d\ ^2D_{3/2}$
5299.592	0.002	18 864.130	3.05E+5	$7p\ ^2P^\circ_{1/2}$	$13s\ ^2S_{1/2}$
5346.417	0.002	18 698.916	1.76E+6	$7p\ ^2P^\circ_{1/2}$	$11d\ ^2D_{3/2}$
5396.176	0.002	18 526.490	1.55E+5	$7p\ ^2P^\circ_{3/2}$	$20d\ ^2D_{5/2}$
5396.469	0.002	18 525.485	2.62E+4	$7p\ ^2P^\circ_{3/2}$	$20d\ ^2D_{3/2}$
5411.578	0.002	18 473.763	1.86E+5	$7p\ ^2P^\circ_{3/2}$	$19d\ ^2D_{5/2}$
5411.932	0.002	18 472.554	3.13E+4	$7p\ ^2P^\circ_{3/2}$	$19d\ ^2D_{3/2}$
5423.708	0.002	18 432.446	6.99E+4	$7p\ ^2P^\circ_{3/2}$	$20s\ ^2S_{1/2}$
5430.372	0.002	18 409.829	6.66E+5	$7p\ ^2P^\circ_{3/2}$	$18d\ ^2D_{5/2}$
5430.806	0.002	18 408.356	3.73E+4	$7p\ ^2P^\circ_{3/2}$	$18d\ ^2D_{3/2}$
5445.352	0.002	18 359.182	8.73E+4	$7p\ ^2P^\circ_{3/2}$	$19s\ ^2S_{1/2}$
5453.642	0.002	18 331.277	2.77E+5	$7p\ ^2P^\circ_{3/2}$	$17d\ ^2D_{5/2}$
5454.185	0.002	18 329.451	4.55E+4	$7p\ ^2P^\circ_{3/2}$	$17d\ ^2D_{3/2}$
5456.375	0.002	18 322.095	4.56E+5	$7p\ ^2P^\circ_{1/2}$	$12s\ ^2S_{1/2}$
5472.457	0.002	18 268.253	1.06E+5	$7p\ ^2P^\circ_{3/2}$	$18s\ ^2S_{1/2}$
5482.954	0.002	18 233.276	3.45E+5	$7p\ ^2P^\circ_{3/2}$	$16d\ ^2D_{5/2}$
5483.645	0.002	18 230.981	5.80E+4	$7p\ ^2P^\circ_{3/2}$	$16d\ ^2D_{3/2}$
5507.052	0.002	18 153.494	1.35E+5	$7p\ ^2P^\circ_{3/2}$	$17s\ ^2S_{1/2}$
5520.637	0.002	18 108.823	4.48E+5	$7p\ ^2P^\circ_{3/2}$	$15d\ ^2D_{5/2}$
5521.524	0.002	18 105.911	7.37E+4	$7p\ ^2P^\circ_{3/2}$	$15d\ ^2D_{3/2}$
5531.716	0.002	18 072.553	2.67E+6	$7p\ ^2P^\circ_{1/2}$	$10d\ ^2D_{3/2}$
5552.227	0.002	18 005.791	1.75E+5	$7p\ ^2P^\circ_{3/2}$	$16s\ ^2S_{1/2}$
5570.255	0.002	17 947.516	1.74E+6	$7p\ ^2P^\circ_{3/2}$	$14d\ ^2D_{5/2}$
5571.444	0.002	17 943.684	9.77E+4	$7p\ ^2P^\circ_{3/2}$	$14d\ ^2D_{3/2}$
5612.892	0.002	17 811.184	2.37E+5	$7p\ ^2P^\circ_{3/2}$	$15s\ ^2S_{1/2}$
5637.589	0.002	17 733.157	2.35E+6	$7p\ ^2P^\circ_{3/2}$	$13d\ ^2D_{5/2}$
5639.228	0.002	17 728.002	1.32E+5	$7p\ ^2P^\circ_{3/2}$	$13d\ ^2D_{3/2}$
5697.247	0.002	17 547.467	3.25E+5	$7p\ ^2P^\circ_{3/2}$	$14s\ ^2S_{1/2}$
5718.746	0.002	17 481.500	7.38E+5	$7p\ ^2P^\circ_{1/2}$	$11s\ ^2S_{1/2}$
5732.468	0.002	17 439.657	1.09E+6	$7p\ ^2P^\circ_{3/2}$	$12d\ ^2D_{5/2}$
5734.818	0.002	17 432.508	1.80E+5	$7p\ ^2P^\circ_{3/2}$	$12d\ ^2D_{3/2}$
5819.941	0.002	17 177.541	4.60E+5	$7p\ ^2P^\circ_{3/2}$	$13s\ ^2S_{1/2}$
5853.491	0.002	17 079.088	4.44E+6	$7p\ ^2P^\circ_{1/2}$	$9d\ ^2D_{3/2}$
5872.900	0.002	17 022.645	1.58E+6	$7p\ ^2P^\circ_{3/2}$	$11d\ ^2D_{5/2}$
5876.462	0.002	17 012.327	2.65E+5	$7p\ ^2P^\circ_{3/2}$	$11d\ ^2D_{3/2}$
6009.574	0.002	16 635.506	6.84E+5	$7p\ ^2P^\circ_{3/2}$	$13s\ ^2S_{1/2}$
6095.276	0.002	16 401.607	3.56E+6	$7p\ ^2P^\circ_{3/2}$	$10d\ ^2D_{5/2}$
6101.095	0.002	16 385.964	3.99E+5	$7p\ ^2P^\circ_{3/2}$	$10d\ ^2D_{3/2}$
6185.60	0.02	16 162.12	7.93E+2	$6d\ ^2D_{3/2}$	$20p\ ^2P^\circ_{3/2}$
6187.83	0.02	16 156.28	7.94E+3	$6d\ ^2D_{3/2}$	$20p\ ^2P^\circ_{1/2}$
6210.66	0.02	16 096.90	9.90E+2	$6d\ ^2D_{3/2}$	$19p\ ^2P^\circ_{3/2}$
6213.41	0.02	16 089.76	9.91E+3	$6d\ ^2D_{3/2}$	$19p\ ^2P^\circ_{1/2}$
6219.813	0.002	16 073.208	1.33E+6	$7p\ ^2P^\circ_{1/2}$	$10s\ ^2S_{1/2}$
6241.78	0.02	16 016.64	1.23E+3	$6d\ ^2D_{3/2}$	$18p\ ^2P^\circ_{3/2}$
6245.24	0.02	16 007.78	1.21E+4	$6d\ ^2D_{3/2}$	$18p\ ^2P^\circ_{1/2}$
6263.01	0.02	15 962.35	6.89E+3	$6d\ ^2D_{5/2}$	$20p\ ^2P^\circ_{3/2}$
6281.12	0.02	15 916.33	1.53E+3	$6d\ ^2D_{3/2}$	$17p\ ^2P^\circ_{3/2}$
6285.53	0.02	15 905.16	1.54E+4	$6d\ ^2D_{3/2}$	$17p\ ^2P^\circ_{1/2}$
6288.70	0.02	15 897.13	8.60E+3	$6d\ ^2D_{5/2}$	$19p\ ^2P^\circ_{3/2}$
6320.62	0.02	15 816.87	1.05E+4	$6d\ ^2D_{5/2}$	$18p\ ^2P^\circ_{3/2}$

TABLE 4. Spectral lines of ^{212}Fr I—Continued

λ_{air} (Å)	Uncertainty (Å)	σ (cm^{-1})	A_{ki} (s^{-1})	Lower level	Upper level
6329.403	0.003	15 794.911	1.10E+6	$7p\ ^2P^\circ_{3/2}$	$11s\ ^2S_{1/2}$
6331.90	0.02	15 788.68	1.99E+3	$6d\ ^2D_{3/2}$	$16p\ ^2P^\circ_{3/2}$
6337.66	0.02	15 774.33	1.99E+4	$6d\ ^2D_{3/2}$	$16p\ ^2P^\circ_{1/2}$
6360.96	0.02	15 716.56	1.33E+4	$6d\ ^2D_{5/2}$	$17p\ ^2P^\circ_{3/2}$
6399.14	0.02	15 622.78	2.63E+3	$6d\ ^2D_{3/2}$	$15p\ ^2P^\circ_{3/2}$
6406.89	0.02	15 603.89	2.63E+4	$6d\ ^2D_{3/2}$	$15p\ ^2P^\circ_{1/2}$
6413.04	0.02	15 588.91	1.73E+4	$6d\ ^2D_{5/2}$	$16\mathrm{p}\ ^2P^\circ_{3/2}$
6482.03	0.02	15 423.01	2.28E+4	$6d\ ^2D_{5/2}$	$15p\ ^2P^\circ_{3/2}$
6484.210	0.003	15 417.819	3.91E+6	$7p\ ^2P^\circ_{3/2}$	$9d\ ^2D_{5/2}$
6491.03	0.02	15 401.62	3.61E+3	$6d\ ^2D_{3/2}$	$14p\ ^2P^\circ_{3/2}$
6494.876	0.003	15 392.499	6.41E+5	$7p\ ^2P^\circ_{3/2}$	$9d\ ^2D_{3/2}$
6501.81	0.02	15 376.08	3.52E+4	$6d\ ^2D_{3/2}$	$14p\ ^2P^\circ_{1/2}$
6507.242	0.003	15 363.248	8.04E+6	$7p\ ^2P^\circ_{1/2}$	$8d\ ^2D_{3/2}$
6576.33	0.02	15 201.85	3.06E+4	$6d\ ^2D_{5/2}$	$14p\ ^2P^\circ_{3/2}$
6621.74	0.03	15 097.59	5.01E+3	$6d\ ^2D_{3/2}$	$13p\ ^2P^\circ_{3/2}$
6637.46	0.03	15 061.85	5.00E+4	$6d\ ^2D_{3/2}$	$13p\ ^2P^\circ_{1/2}$
6710.54	0.03	14 897.82	4.35E+4	$6d\ ^2D_{5/2}$	$13p\ ^2P^\circ_{3/2}$
6817.87	0.03	14 663.29	7.49E+3	$6d\ ^2D_{3/2}$	$12p\ ^2P^\circ_{3/2}$
6842.22	0.03	14 611.11	7.46E+4	$6d\ ^2D_{3/2}$	$12\mathrm{p}\ ^2P^\circ_{1/2}$
6912.04	0.03	14 463.52	6.50E+4	$6d\ ^2D_{5/2}$	$12p\ ^2P^\circ_{3/2}$
6948.987	0.003	14 386.619	1.90E+6	$7p\ ^2P^\circ_{3/2}$	$10s\ ^2S_{1/2}$
7134.91	0.03	14 011.73	1.16E+4	$6d\ ^2D_{3/2}$	$11p\ ^2P^\circ_{3/2}$
7176.16	0.03	13 931.20	1.15E+5	$6d\ ^2D_{3/2}$	$11p\ ^2P^\circ_{1/2}$
7179.866	0.001	13 923.998	4.78E+7	$7s\ ^2S_{1/2}$	$7p\ ^2P^\circ_{3/2}$
7238.11	0.03	13 811.96	1.01E+5	$6d\ ^2D_{5/2}$	$11p\ ^2P^\circ_{3/2}$
7285.892	0.004	13 721.375	6.93E+6	$7p\ ^2P^\circ_{3/2}$	$8d\ ^2D_{5/2}$
7309.713	0.004	13 676.659	1.13E+6	$7p\ ^2P^\circ_{3/2}$	$8d\ ^2D_{3/2}$
7441.98	0.04	13 433.59	2.75E+6	$7p\ ^2P^\circ_{1/2}$	$9s\ ^2S_{1/2}$
7709.04	0.04	12 968.22	1.99E+4	$6d\ ^2D_{3/2}$	$10p\ ^2P^\circ_{3/2}$
7789.47	0.04	12 834.31	1.95E+5	$6d\ ^2D_{3/2}$	$10p\ ^2P^\circ_{1/2}$
7829.65	0.04	12 768.45	1.72E+5	$6d\ ^2D_{5/2}$	$10p\ ^2P^\circ_{3/2}$
7901.71	0.04	12 652.01	6.55E+3	$8s\ ^2S_{1/2}$	$20p\ ^2P^\circ_{3/2}$
7905.36	0.04	12 646.17	6.56E+3	$8s\ ^2S_{1/2}$	$20p\ ^2P^\circ_{1/2}$
7942.65	0.04	12 586.79	7.98E+3	$8s\ ^2S_{1/2}$	$19p\ ^2P^\circ_{3/2}$
7947.16	0.04	12 579.65	7.99E+3	$8s\ ^2S_{1/2}$	$19p\ ^2P^\circ_{1/2}$
7993.62	0.04	12 506.53	9.92E+3	$8s\ ^2S_{1/2}$	$18p\ ^2P^\circ_{3/2}$
7999.29	0.04	12 497.67	9.93E+3	$8s\ ^2S_{1/2}$	$18p\ ^2P^\circ_{1/2}$
8058.26	0.04	12 406.22	1.29E+4	$8s\ ^2S_{1/2}$	$17p\ ^2P^\circ_{3/2}$
8065.52	0.04	12 395.05	1.29E+4	$8s\ ^2S_{1/2}$	$17p\ ^2P^\circ_{1/2}$
8142.03	0.04	12 278.57	1.70E+4	$8s\ ^2S_{1/2}$	$16p\ ^2P^\circ_{3/2}$
8151.56	0.04	12 264.22	1.66E+4	$8s\ ^2S_{1/2}$	$16p\ ^2P^\circ_{1/2}$
8169.418	0.002	12 237.409	3.22E+7	$7s\ ^2S_{1/2}$	$7p\ ^2P^\circ_{1/2}$
8253.55	0.04	12 112.67	2.28E+4	$8s\ ^2S_{1/2}$	$15p\ ^2P^\circ_{3/2}$
8266.44	0.04	12 093.78	2.28E+4	$8s\ ^2S_{1/2}$	$15p\ ^2P^\circ_{1/2}$
8326.45	0.02	12 006.62	1.66E+7	$7p\ ^2P^\circ_{1/2}$	$7d\ ^2D_{3/2}$
8407.05	0.04	11 891.51	3.18E+4	$8s\ ^2S_{1/2}$	$14p\ ^2P^\circ_{3/2}$
8425.15	0.04	11 865.97	3.17E+4	$8s\ ^2S_{1/2}$	$14p\ ^2P^\circ_{1/2}$
8510.47	0.04	11 747.00	3.66E+6	$7p\ ^2P^\circ_{3/2}$	$9s\ ^2S_{1/2}$
8627.63	0.04	11 587.48	4.68E+4	$8s\ ^2S_{1/2}$	$13p\ ^2P^\circ_{3/2}$
8654.33	0.04	11 551.74	4.66E+4	$8s\ ^2S_{1/2}$	$13p\ ^2P^\circ_{1/2}$
8963.59	0.05	11 153.18	7.53E+4	$8s\ ^2S_{1/2}$	$12p\ ^2P^\circ_{3/2}$
8977.15	0.05	11 136.33	3.85E+4	$6d\ ^2D_{3/2}$	$9p\ ^2P^\circ_{3/2}$
9005.72	0.05	11 101.00	7.31E+4	$8s\ ^2S_{1/2}$	$12p\ ^2P^\circ_{1/2}$
9141.13	0.05	10 936.56	3.31E+5	$6d\ ^2D_{5/2}$	$9p\ ^2P^\circ_{3/2}$
9181.62	0.05	10 888.34	3.61E+5	$6d\ ^2D_{3/2}$	$9p\ ^2P^\circ_{1/2}$
9519.73	0.05	10 501.62	1.30E+5	$8s\ ^2S_{1/2}$	$11p\ ^2P^\circ_{3/2}$
9593.29	0.05	10 421.09	1.29E+5	$8s\ ^2S_{1/2}$	$11p\ ^2P^\circ_{1/2}$
9604.50	0.03	10 408.93	1.29E+7	$7p\ ^2P^\circ_{3/2}$	$7d\ ^2D_{5/2}$

TABLE 4. Spectral lines of ^{212}Fr I—Continued

λ_{air} (Å)	Uncertainty (Å)	σ (cm^{-1})	A_{ki} (s^{-1})	Lower level	Upper level
9687.24	0.03	10 320.03	2.09E+6	$7p\ ^{2}\mathrm{P}^{\circ}_{3/2}$	$7d\ ^{2}\mathrm{D}_{3/2}$

TABLE 5. Energy levels of ^{212}Fr I

Configuration	Term	J	Level (cm^{-1})	Uncertainty (cm^{-1})	Level reference	Hyperfine constants		Hyperfine reference
						A (MHz)	B (MHz)	
$7s$	$^{2}\mathrm{S}$	1/2	0.000	0.002	16	9064.4(15)		12
$7p$	$^{2}\mathrm{P}^{\circ}$	1/2	12 237.409	0.002	14	1187(7)		12
		3/2	13 923.998	0.002	14	97.2(1)	−26.0(2)	12
$6d$	$^{2}\mathrm{D}$	3/2	16 229.87	0.03	17			
		5/2	16 429.64	0.03	17			
$8s$	$^{2}\mathrm{S}$	1/2	19 739.98	0.03	17			
$8p$	$^{2}\mathrm{P}^{\circ}$	1/2	23 112.960	0.005	12	373.0(1)		12
		3/2	23 658.306	0.004	12	32.8(1)	−7.7(9)	12
$7d$	$^{2}\mathrm{D}$	3/2	24 244.03	0.03	17			
		5/2	24 332.93	0.03	17			
$9s$	$^{2}\mathrm{S}$	1/2	25 671.00	0.04	17			
$9p$	$^{2}\mathrm{P}^{\circ}$	1/2	27 118.21	0.05	17			
		3/2	27 366.20	0.05	17			
$8d$	$^{2}\mathrm{D}$	3/2	27 600.657	0.007	16	13.0(6)		16
		5/2	27 645.373	0.007	16	−7.2(6)		16
$10s$	$^{2}\mathrm{S}$	1/2	28 310.617	0.006	16	401(5)		16
$10p$	$^{2}\mathrm{P}^{\circ}$	1/2	29 064.18	0.05	17			
		3/2	29 198.09	0.05	17			
$9d$	$^{2}\mathrm{D}$	3/2	29 316.497	0.007	16	7.1(7)		16
		5/2	29 341.817	0.007	16	−3.6(4)		16
$11s$	$^{2}\mathrm{S}$	1/2	29 718.909	0.006	16	225(3)		16
$11p$	$^{2}\mathrm{P}^{\circ}$	1/2	30 161.07	0.05	17			
		3/2	30 241.60	0.05	17			
$10d$	$^{2}\mathrm{D}$	3/2	30 309.962	0.006	15			
		5/2	30 325.605	0.006	15			
$12s$	$^{2}\mathrm{S}$	1/2	30 559.504	0.006	15			
$12p$	$^{2}\mathrm{P}^{\circ}$	1/2	30 840.98	0.05	17			
		3/2	30 893.16	0.05	17			
$11d$	$^{2}\mathrm{D}$	3/2	30 936.325	0.006	15			
		5/2	30 946.643	0.006	15			
$13s$	$^{2}\mathrm{S}$	1/2	31 101.539	0.006	15			
$13p$	$^{2}\mathrm{P}^{\circ}$	1/2	31 291.72	0.05	17			
		3/2	31 327.46	0.05	17			
$12d$	$^{2}\mathrm{D}$	3/2	31 356.506	0.006	15			
		5/2	31 363.655	0.006	15			
$14s$	$^{2}\mathrm{S}$	1/2	31 471.465	0.006	15			

TABLE 5. Energy levels of ^{212}Fr I—Continued

Configuration	Term	J	Level (cm^{-1})	Uncertainty (cm^{-1})	Level reference	Hyperfine constants		Hyperfine reference
						A (MHz)	B (MHz)	
14*p*	$^2P^\circ$	1/2	31 605.95	0.05	17			
		3/2	31 631.49	0.05	17			
13*d*	^2D	3/2	31 652.000	0.006	15			
		5/2	31 657.155	0.006	15			
15*s*	^2S	1/2	31 735.182	0.006	15			
15*p*	$^2P^\circ$	1/2	31 833.76	0.05	17			
		3/2	31 852.65	0.05	17			
14*d*	^2D	3/2	31 867.682	0.006	15			
		5/2	31 871.514	0.006	15			
16*s*	^2S	1/2	31 929.789	0.006	15			
16*p*	$^2P^\circ$	1/2	32 004.20	0.05	17			
		3/2	32 018.55	0.05	17			
15*d*	^2D	3/2	32 029.909	0.006	15			
		5/2	32 032.821	0.006	15			
17*s*	^2S	1/2	32 077.492	0.006	15			
17*p*	$^2P^\circ$	1/2	32 135.03	0.05	17			
		3/2	32 146.20	0.05	17			
16*d*	^2D	3/2	32 154.979	0.006	15			
		5/2	32 157.274	0.006	15			
18*s*	^2S	1/2	32 192.251	0.006	15			
18*p*	$^2P^\circ$	1/2	32 237.65	0.05	17			
		3/2	32 246.51	0.05	17			
17*d*	^2D	3/2	32 253.449	0.006	15			
		5/2	32 255.275	0.006	15			
19*s*	^2S	1/2	32 283.180	0.006	15			
19*p*	$^2P^\circ$	1/2	32 319.63	0.05	17			
		3/2	32 326.77	0.05	17			
18*d*	^2D	3/2	32 332.354	0.006	15			
		5/2	32 333.827	0.006	15			
20*s*	^2S	1/2	32 356.444	0.006	15			
20*p*	$^2P^\circ$	1/2	32 386.15	0.05	17			
		3/2	32 391.99	0.05	17			
19*d*	^2D	3/2	32 396.552	0.006	15			
		5/2	32 397.761	0.006	15			
21*s*	^2S	1/2	32 416.340	0.006	15			
21*p*	$^2P^\circ$	1/2	32 440.87	0.05	17			
		3/2	32 445.71	0.05	17			
20*d*	^2D	3/2	32 449.483	0.006	15			
		5/2	32 450.488	0.006	15			
22*s*	^2S	1/2	32 465.937	0.006	15			

TABLE 5. Energy levels of ^{212}Fr I—Continued

Configuration	Term	J	Level (cm^{-1})	Uncertainty (cm^{-1})	Level reference	Hyperfine constants		Hyperfine reference
						A (MHz)	B (MHz)	
22*p*	$^2P^\circ$	1/2	32 486.43	0.05	17			
		3/2	32 490.48	0.05	17			
21*d*	^2D	3/2	32 493.64	0.03	17			
		5/2	32 494.48	0.03	17			
23*s*	^2S	1/2	32 507.47	0.03	17			
23*p*	$^2P^\circ$	1/2	32 524.76	0.05	17			
		3/2	32 528.19	0.05	17			
22*d*	^2D	3/2	32 530.86	0.03	17			
		5/2	32 431.57	0.03	17			
24*s*	^2S	1/2	32 542.59	0.03	17			
24*p*	$^2P^\circ$	1/2	32 557.32	0.05	17			
		3/2	32 560.25	0.05	17			
23*d*	^2D	3/2	32 562.52	0.03	17			
		5/2	32 563.13	0.03	17			
25*s*	^2S	1/2	32 572.56	0.03	17			
25*p*	$^2P^\circ$	1/2	32 585.20	0.05	17			
		3/2	32 587.72	0.05	17			
24*d*	^2D	3/2	32 589.68	0.03	17			
		5/2	32 590.20	0.03	17			
26*s*	^2S	1/2	32 598.34	0.03	17			
26*p*	$^2P^\circ$	1/2	32 609.27	0.05	17			
		3/2	32 611.45	0.05	17			
25*d*	^2D	3/2	32 613.15	0.03	17			
		5/2	32 613.60	0.03	17			
27*s*	^2S	1/2	32 620.67	0.03	17			
27*p*	$^2P^\circ$	1/2	32 630.19	0.05	17			
		3/2	32 632.09	0.05	17			
26*d*	^2D	3/2	32 633.57	0.03	17			
		5/2	32 633.97	0.03	17			
28*s*	^2S	1/2	32 640.14	0.03	17			
28*p*	$^2P^\circ$	1/2	32 648.48	0.05	17			
		3/2	32 650.15	0.05	17			
27*d*	^2D	3/2	32 651.44	0.03	17			
		5/2	32 651.79	0.03	17			
29*s*	^2S	1/2	32 657.22	0.03	17			
29*p*	$^2P^\circ$	1/2	32 664.57	0.05	17			
		3/2	32 666.04	0.05	17			
28*d*	^2D	3/2	32 667.18	0.03	17			
		5/2	32 667.49	0.03	17			
30*s*	^2S	1/2	32 672.29	0.03	17			

TABLE 5. Energy levels of ^{212}Fr I—Continued

Configuration	Term	J	Level (cm^{-1})	Uncertainty (cm^{-1})	Level reference	Hyperfine constants A (MHz)	Hyperfine constants B (MHz)	Hyperfine reference
30*p*	^{2}P$^\circ$	1/2	32 678.80	0.05	17			
		3/2	32 680.10	0.05	17			
29*d*	^{2}D	3/2	32 681.11	0.03	17			
		5/2	32 681.39	0.03	17			
30*d*	^{2}D	3/2	32 693.50	0.03	17			
		5/2	32 693.75	0.03	17			
Fr II (^{1}S$_0$)		*Limit*	32 848.872	0.009	16			

A second approach to producing francium atoms was used by Andreev *et al.*[18,19] at the Institute of Spectroscopy of the USSR Academy of Sciences. They produced atoms of ^{221}Fr by decay of ^{229}Th, then used two-photon laser spectroscopy to measure Rydberg levels for *ns* ($23 \leq n \leq 31$) and *nd* ($22 \leq n \leq 33$). The series was combined with the measurement of the $7p\ ^2P^\circ_{3/2}$ level by Duong *et al.*[12] to give the ionization limit given in the ^{221}Fr energy level table. Hyperfine splitting constants were determined by Coc *et al.*[8] and Duong *et al.*[12] (See Table 6).

TABLE 6. Energy levels of ^{221}Fr I

Configuration	Term	*J*	Level (cm^{-1})	Uncertainty (cm^{-1})	Level reference	Hyperfine constants A (MHz)	Hyperfine constants B (MHz)	Hyperfine reference
7*s*	^{2}S	1/2	0.000	0.002	14	6209.9(10)		12
7*p*	^{2}P$^\circ$	1/2	12 236.660	0.002	14	808(12)		8
		3/2	13 923.212	0.002	12	65.5(6)	−264.0(3)	12
8*p*	^{2}P$^\circ$	3/2	23 657.529	0.002	12	22.4(1)	−85.7(8)	12
22*d*	^{2}D	3/2,5/2	32 530.34	0.18	19			
23*s*	^{2}S	1/2	32 506.57	0.23	19			
23*d*	^{2}D	3/2,5/2	32 562.08	0.19	19			
24*d*	^{2}D	3/2,5/2	32 589.16	0.12	19			
25*s*	^{2}S	1/2	32 571.5	0.3	19			
25*d*	^{2}D	3/2,5/2	32 612.49	0.08	19			
26*s*	^{2}S	1/2	32 597.5	0.2	19			
26*d*	^{2}D	3/2,5/2	32 632.93	0.09	19			
27*s*	^{2}S	1/2	32 619.68	0.13	19			
27*d*	^{2}D	3/2,5/2	32 650.87	0.09	19			
28*d*	^{2}D	3/2,5/2	32 666.57	0.10	19			
29*s*	^{2}S	1/2	32 656.28	0.10	19			
29*d*	^{2}D	3/2,5/2	32 680.53	0.13	19			
30*s*	^{2}S	1/2	32 671.26	0.13	19			
30*d*	^{2}D	3/2,5/2	32 692.84	0.16	19			
31*s*	^{2}S	1/2	32 684.95	0.18	19			
31*d*	^{2}D	3/2,5/2	32 703.83	0.15	19			

TABLE 6. Energy levels of ^{221}Fr I—Continued

Configuration	Term	J	Level (cm^{-1})	Uncertainty (cm^{-1})	Level reference	Hyperfine constants A (MHz)	B (MHz)	Hyperfine reference
32d	^{2}D	3/2,5/2	32 713.8	0.3	19			
33d	^{2}D	3/2,5/2	32 722.71	0.18	19			
Fr II (^{1}S$_0$)		*Limit*	32 848.0	0.3	19			

TABLE 7. Energy levels of ^{210}Fr I

Configuration	Term	J	Level (cm^{-1})	Uncertainty (cm^{-1})	Level reference	Hyperfine constants A (MHz)	B (MHz)	Hyperfine reference
7s	^{2}S	1/2	0.000	0.004	20	7195.1(4)		7
7p	^{2}P$^\circ$	1/2				946.3(2)		23
		3/2	13 924.085	0.002	7	78.0(2)	51(4)	7
8s	^{2}S	1/2	19 732.523	0.004	27	1577.8(11)		27
7d	^{2}D	3/2	24 244.831	0.003	24	22.3(5)		24
		5/2	24 333.298	0.003	24	−17.8(8)	64(17)	24
9s	^{2}S	1/2	25 671.021	0.006	20			

TABLE 8. Lifetimes of energy levels of ^{210}Fr I

Level	$7p\ ^2P^\circ_{1/2}$	$7p\ ^2P^\circ_{3/2}$	$7d\ ^2D_{3/2}$	$7d\ ^2D_{5/2}$	$8s\ ^2S_{1/2}$	$8p\ ^2P^\circ_{1/2}$	$8p\ ^2P^\circ_{3/2}$	$9s\ ^2S_{1/2}$
Lifetime(ns)	29.45(11)	21.02(11)	73.6(3)	68(3)	53.3(4)	149(4)	83.5(15)	107.5(9)
Reference	21	21	23	23	26	25	25	25

Scientists at the State University of New York at Stony Brook create the isotope ^{210}Fr by bombarding gold targets with highly accelerated ions of ^{18}O from a superconducting linear accelerator (Simsarian *et al.*,[20–22] Grossman *et al.*,[23,24] Aubin *et al.*,[25] and Gomez *et al.*[26]). This technique produces 10^6 Fr ions/s, but the 3.2 min half-life of this isotope necessitates rapid transport to an optical trap where the measurement takes place. Using two-photon spectroscopy, they have been able to directly observe the 8s and 9s levels, as listed in Table 7. In addition to the spectroscopic data for ^{210}Fr summarized in Table 7, the lifetimes of several levels have been measured and are presented in Table 8.

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