Radiative lifetimes in Co I

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New radiative-lifetime measurements based on time-resolved laser-induced fluorescence are reported for 133 odd-parity and 2 even-parity levels of Co I, ranging in energy from 28 300 to 59 400 cm^{-1}. Our lifetimes agree with earlier, but much less extensive, lifetime measurements based on laser-induced fluorescence. Satisfactory agreement is also found with the critical compilation of atomic transition probabilities from the U.S. National Bureau of Standards [J. Phys. Chem. Ref. Data **17,** Suppl 4 (1988)]. Our measurements provide a reliable absolute normalization for a much more comprehensive determination of Co I atomic transition probabilities.

1. INTRODUCTION

A combination of techniques from laser spectroscopy and Fourier-transform spectroscopy is rapidly improving the database of atomic transition probabilities. Recent studies, of Y I and Y II,[1] of Sc I and Sc II,[2] and of Fe I,[3] demonstrate the power of this approach. Laser-induced fluorescence (LIF) from atoms and ions in a beam is used to measure accurate (±5%) radiative lifetimes. These lifetimes provide the normalization required for converting branching fractions, as measured with a Fourier transform spectrometer, into absolute transition probabilities. Transition probability data of quite high quality (uncertainty <10%) are produced efficiently with this approach.

There is a need for the most comprehensive possible database of transition probabilities for the high-abundance iron-group elements, including cobalt, which dominate stellar photospheric spectra. Although sufficient transition probability data are available to let one determine abundances of the iron-group elements, the available data are often inadequate to let one perform a reliable spectral synthesis. Spectral synthesis enables an astronomer to subtract away the many lines from the high-abundance iron-group elements and detect lines from lower-abundance elements. Butcher's study,[4] in which he measured thorium abundance in a selected set of stars to determine the age of the Galaxy, is an example. The measurement of thorium abundances enables one to determine the ages of stars by using a method analogous to radiocarbon dating of terrestrial organic material. We cite this study as one example of what can be learned with modern large-aperture telescopes and detector arrays. It is interesting to note that the work on thorium abundances was hampered by the lack of an accurate Co I transition probability.[5]

We report new radiative-lifetime measurements performed by time-resolved LIF for 133 odd-parity and 2 even parity levels of Co I, ranging in energy from 28 300 to 59 400 cm^{-1}. Our lifetimes, accurate to ±5% (or ±0.2 ns for the shortest lifetimes), are in generally good agreement with earlier, but much less extensive, LIF lifetime measurements and with lifetimes derived by the summing of transition probabilities from a recent critical compilation.[5–8] The lifetimes reported here provide a reliable absolute normalization for a planned series of measurements of a much more extensive set of Co I transition probabilities.

2. EXPERIMENT

O'Brian *et al.*[3] recently described the apparatus used in this experiment. A hollow-cathode discharge source is used to produce a slow beam of cobalt atoms, which are excited by a pulsed dye laser. The resulting fluorescence decay is detected and analyzed to yield a radiative lifetime. A complete description will not be given here, but some of the important experimental details are included below in the context of a discussion of potential systematic errors.

3. RANDOM AND SYSTEMATIC UNCERTAINTIES

A conservative estimate of the total random and systematic uncertainty in our lifetimes is the larger of ±5% or ±0.2 ns. The signal from the photomultiplier (PMT) in this experiment is recorded and averaged with a Tektronix SCD1000 transient waveform digitizer, which has an analog bandwidth of 1 GHz and a sampling rate as high as 200 GHz. The leading edge of the signal from the PMT and the first 5 ns after the peak are discarded in our analysis of the LIF, so that a deconvolution of the fluorescence signal and the laser pulse is unnecessary. The signal is analyzed by a least-squares fit to a single exponential decay. Each reported lifetime is an average of more than 12,000 individual fluorescence decay curves, each of which represents as many as 10^4 photons. The statistical uncertainty is less than 0.5% (1 standard deviation) when signals are strong.

The lifetime experiment has a dynamic range from 2 ns to 2 μs. The finite electronic bandwidth of the detection apparatus ultimately limits the experiment at the short end of the range, and error that is due to atoms that escape from the observation region before radiating is the limiting factor at the long end of the range.

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Table 1. Comparison of Precision Lifetime Measurements with Lifetimes Measured in this Experiment

Spectrum	Upper Level	Lifetime[a] (ns)	Lifetime (ns) This study	Difference (%)
Be I	$2s2p\ ^1P_1^\circ$	1.85(4)[b]	1.86	+0.5%
Fe II	$3d^6(^5D)4p\ z^4D_{5/2}^\circ$	3.10(8)[c]	3.06	−1.3%
Fe II	$3d^6(^5D)4p\ z^6F_{11/2}^\circ$	3.19(4)[d]	3.17	−0.6%
Fe II	$3d^6(^5D)4p\ z^6D_{9/2}^\circ$	3.70(6)[d]	3.66	−1.1%
Cu I	$4p\ ^2P_{3/2}^\circ$	7.17(6)[e]	6.93	−3.3%
Cu I	$4p\ ^2P_{1/2}^\circ$	7.27(6)[e]	7.11	−2.2%
He I	$3p\ ^3P^\circ$	94.7(9)[f]	95.1	+0.4%

[a]The number in parentheses after the lifetime in column three is the stated uncertainty in the last digit of the reported lifetimes.
[b]Ref. 12.
[c]Ref. 13.
[d]Ref. 14.
[e]Ref. 15.
[f]Ref. 11.

The base of the 1P28A PMT is wired for low overall inductance to maintain the full electronic bandwidth of the tube. The base includes bypass capacitors to provide good linearity to 10 mA of peak anode current and includes damping resistors to reduce ringing.[9] The electronic bandwidth of the detection system was previously tested by measurement of the lifetimes of the $3\ ^1P_1^\circ$ and $4\ ^1P_1^\circ$ levels of He I, which are known to ±1% from sophisticated calculations.[10,11] In the present experiment we test the apparatus for lifetimes of less than 10 ns by observing levels in Be I, Fe II, and Cu I, whose lifetimes are accurately known from theory or from high-accuracy measurements.[12–15] We also measure the lifetime of the $3\ ^3P^\circ$ level of He I as a test of the experiment in the 100-ns range.[11] The results of these measurements are given in Table 1. Our lifetimes for these levels lie within 3.3% of the calibration points. We note that our result for the Be I $2s2p\ ^1P_1^\circ$ lifetime of 1.86 ns is an average of lifetimes measured with two different cabling configurations between the PMT and the transient digitizer. At a lifetime of 20 ns our result for the $w\ ^4D_{3/2}^\circ$ level of Co I agrees with a previously published measurement made in this laboratory with different instrumentation.[5] We make cross-checks between 30 and 100 ns by comparing our transient digitizer results for selected Co I levels with lifetimes obtained by use of a boxcar averager (PAR Model 162/165), which in turn is tested on the $3\ ^3P^\circ$ He I level. In all cases we find that these results agree to within 3%.

Optimum fluorescence detection for levels with lifetimes ≤100 ns is achieved with the intersection of the laser and atomic beams imaged onto the PMT cathode. Two lenses forming an $f/1$ system with unity magnification are used. The fluorescence light is roughly collimated between the two lenses, and there is a provision for inserting interference filters and dye filters between the lenses. Occasionally branching ratios are favorable for observing fluorescence at a wavelength much different from the laser wavelength, in which case filters are used to block scattered laser light and isolate the LIF.

Imaging the intersection of the laser and the atomic beams directly onto the PMT cathode is not optimum for longer-lived levels, because this arrangement can lead to a systematic error in long lifetimes caused by atomic motion. The image of the radiating atoms moves across the photocathode, which has a position-dependent response. In addition, the solid angle of the fluorescence collection system is weakly dependent on position. These systematic effects were studied in detail during earlier experiments with the same apparatus,[16] and techniques have been developed for minimizing possible errors. One of the techniques is to defocus the image of the atomic beam on the photocathode (which results in a reduction in the fluorescence signal). The second technique, which is necessary for measuring lifetimes near 2 μs, involves time-of-flight selection of slow atoms. Since all the cobalt levels studied here have lifetimes less than 150 ns, only the former technique is used.

We avoid possible error from the distortion of the fluorescence decay curve by Zeeman quantum beats by zeroing the magnetic field in the LIF experiments to within ±0.02 G. Collisional quenching is not important at the background pressure of 10^{-4} Torr of argon, and radiation trapping is absent in the atomic beam. Tests such as throttling the diffusion pump and varying the atomic beam intensity in the LIF experiment confirm that collisional quenching and radiation trapping are not a source of error.

In principle the fluorescence decay curve could also be distorted by hyperfine quantum beats, but we see no evidence of this in our data. Our apparatus is not sensitive to these beats for several reasons. The absence of a polarizer in and the large solid angle of the fluorescence collection system reduce the amplitude of any possible hyperfine quantum beats. Furthermore, the non-Rydberg levels of cobalt and other transition metals generally have large hyperfine structure. Guthohrlein and Keller report hyperfine A coefficients for some levels in the $(3d + 4s)^8\ 4p$ configuration studied here.[17] These hyperfine A coefficients range from 0.3 to 1.4 GHz, and they typically result in beat frequencies in the gigahertz range and higher. The electronic bandwidth of our detection system is not large enough to resolve such beats. Lower-frequency beats, if present, would be readily identified from the nonexponential character of the decay curve or a significant discrepancy between apparent lifetimes determined with different digitizer sweep durations. Fluorescence traces are always recorded and analyzed with at least two different time sweeps.

Repopulation of the level under study by radiative cascade from higher levels is not a problem because of the highly selective laser excitation. Emission from lowerlying levels that are populated by radiative cascade from the upper level under study can be tested for and blocked with filters. Effects of this cascade fluorescence are observed (and eliminated with filters) for a few odd-parity levels above 50 000 cm^{-1}, including the $u\,^2F^\circ_{7/2}$, $w\,^2G^\circ_{9/2}$, and $30^\circ_{5/2}$ levels. These levels have significant branches in the infrared. On the basis of all these tests of the experiment, we conclude that a conservative estimate of the total random and systematic uncertainty in our reported lifetimes is the larger of ±5% or 0.2 ns.

4. RESULTS

Table 2 is a list of our lifetime measurements. The number in parentheses following each entry in columns six and seven is the uncertainty in the last digit of the entry. Configuration and term assignments, along with level energies, are from Ref. 18. Laser wavelengths used to excite the levels are also listed. The wavelengths, with a few exceptions, are from Ref. 19. Whenever possible more than one transition is used to excite a level.

Table 2. Radiative Lifetimes in Co I[a]

					Lifetime (ns)		
Configuration	Term	J	Level (cm^{-1})	Laser Wavelength in Air (nm)	This Expt.	Other LIF	Critical Compilation[b]
$3d^7(^4F)4s4p(^3P^\circ)$	$z\,^4F^\circ$	9/2	28 345.86	352.685, 402.090	68.3(34)	62.8(31)[c]	72.1
		7/2	28 777.27	357.536, 365.254	79.0(40)	75.1(38)[c]	69.8
		5/2	29 216.37	352.008, 364.766	82.3(41)	72.5(48)[c]	66.7
		3/2	29 563.17	355.059, 408.259	82.1(41)		71.1
$3d^7(^4F)4s4p(^3P^\circ)$	$z\,^4G^\circ$	11/2	28 845.22	346.579, 394.173	91.3(46)		105
		9/2	29 269.73	351.348, 397.865	106(5)		<124
		7/2	29 735.18	352.903, 399.168	108(5)		104
		5/2	30 102.96	353.336, 393.392	111(6)		102
$3d^7(^4F)4s4p(^3P^\circ)$	$z\,^4D^\circ$	7/2	29 294.52	351.043, 397.473	28.6(14)	27.2(19)[c]	<35.4
		5/2	29 948.76	350.263, 387.395	31.9(16)	31.1(28)[c]	35.3
		3/2	30 443.63	349.132, 388.187	34.1(17)		36.5
		1/2	30 742.65	345.524, 687.239	36.1(18)		34.1
$3d^7(^4F)4s4p(^3P^\circ)$	$z\,^2G^\circ$	9/2	31 699.69	362.781, 412.132	42.1(21)		<40.6
		7/2	32 733.07	395.292, 411.877	33.6(17)		<35.0
$3d^7(^4F)4s4p(^3P^\circ)$	$z\,^2F^\circ$	7/2	31 871.15	352.157, 409.239	51.1(26)		<35.0
		5/2	32 781.71	394.533, 411.053	128(6)		<102
$3d^8(^3F)4p$	$y\,^4D^\circ$	7/2	32 027.50	350.228, 358.515	10.0(5)		10.9
		5/2	32 654.50	350.631, 357.497	8.7(4)		9.8
		3/2	33 150.68	351.264, 523.021	8.4(4)		7.8
		1/2	33 449.18	352.342, 524.792	8.4(4)		10.1
$3d^8(^3F)4p$	$y\,^4G^\circ$	11/2	32 430.59	308.261, 345.351	7.4(4)	8.7(5)[c]	8.9
		9/2	32 464.73	352.982, 399.531	9.7(5)		10.9
		5/2	33 674.38	344.917, 381.106	7.4(4)	8.4(4)[d]	6.9
$3d^8(^3F)4p$	$y\,^4F^\circ$	9/2	32 841.99	340.512, 393.596	6.9(3)	7.6(4)[c]	<7.6
						7.2(2)[d]	
		3/2	34 196.21	338.816, 343.304	7.1(4)	7.5(4)[d]	6.6
$3d^8(^3F)4p$		7/2	33 173.36	350.984, 404.539	8.4(4)	8.5(3)[d]	8.5
$3d^8(^3F)4p$	$y\,^2G^\circ$	9/2	33 439.72	341.234, 384.547	8.2(4)	8.6(3)[d]	<8.9
		7/2	34 133.59	339.537, 389.407	9.6(5)	10.1(3)[d]	<9.4
$3d^7(^4F)4s4p(^3P^\circ)$	$z\,^2D^\circ$	5/2	33 462.83	384.205, 546.930	60.5(30)		<65.6
		3/2	34 352.42	303.443, 386.116	42.2(21)		34.3
$3d^8(^3F)4p$		7/2	33 466.87	340.918, 399.790	7.3(4)	7.5(2)[d]	<7.9
$3d^8(^3F)4p$		5/2	33 945.90	307.234, 346.280	6.9(3)	7.0(3)[d]	6.9
$3d^8(^3F)4p$	$y\,^2F^\circ$	7/2	35 450.56	356.937, 370.406	6.5(3)		6.0
		5/2	36 329.86	286.260, 358.719	6.6(3)		7.0
$3d^8(^3F)4p$	$y\,^2D^\circ$	5/2	36 092.44	283.392, 348.940	7.1(4)		<7.5
		3/2	36 875.13	281.859, 351.834	7.2(4)		<6.3
$3d^7(^4F)4s4p(^1P^\circ)$	$x\,^4D^\circ$	7/2	39 649.16	252.136, 257.435	3.1(2)		3.1
		5/2	40 345.95	252.897, 256.734	3.2(2)		<3.2
		3/2	40 827.77	253.596, 256.212	3.4(2)		<4.4
		1/2	41 101.80	254.425, 277.496	3.4(2)		<3.3

(*Table continued*)

Table 2. Continued

Configuration	Term	J	Level (cm^{-1})	Laser Wavelength in Air (nm)	Lifetime (ns) This Expt.	Lifetime (ns) Other LIF	Lifetime (ns) Critical Compilation[b]
$3d^7(^4P)4s4p(^3P°)$	$z\ ^4S°$	3/2	40 621.62	254.930, 257.573	63.3(32)		
$3d^7(^4F)4s4p(^1P°)$	$x\ ^4F°$	9/2	41 225.76	242.493, 269.585	2.5(2)		3.1
		7/2	41 918.41	238.486, 243.221	2.7(2)		3.4
		5/2	42 434.23	240.206, 246.080	2.8(2)		<3.1
		3/2	42 796.67	243.904, 265.027	2.9(2)		<3.7
$3d^7(^4F)4s4p(^1P°)$	$x\ ^4G°$	11/2	41 528.53	240.725, 262.764	2.0(2)		<2.8
		9/2	42 269.32	236.506, 262.206	2.1(2)		
		7/2	42 811.44	233.510, 241.446	2.1(2)		<2.9
		5/2	43 199.65	235.868, 239.203	2.3(2)		<2.5
$3d^8(^3P)4p$	$z\ ^4P°$	5/2	41 968.89	242.923, 354.844	15.1(8)		
		1/2	41 969.90	248.925, 381.632	19.5(10)		
		3/2	41 982.66	246.378, 248.846	16.4(8)		
$3d^7(^2G)4s4p(^3P°)$	$^4H°$	7/2	42 988.12	237.051, 253.055	114(6)		
$3d^8(^1D)4p$	$z\ ^2P°$	1/2	43 130.24	365.444, 410.474	15.2(8)		
$3d^7(^4P)4s4p(^3P°)$	$w\ ^4D°$	5/2	43 242.95	241.276, 363.944	8.6(4)		
		3/2	43 263.57	259.169, 369.336	20.6(10)	21(1)[e]	
		7/2	43 398.62	230.350, 250.452	18.6(9)		
		1/2	43 435.58	240.160, 370.746	21.0(11)		
$3d^7(^2G)4s4p(^3P°)$	$w\ ^4F°$	9/2	43 295.32	230.902, 235.336	5.6(3)		6.1
		3/2	44 555.71	233.866, 250.768	4.4(2)		
$3d^8(^1D)4p$		5/2	43 425.71	234.616, 370.882	12.3(6)		
$3d^8(^1D)4p$		3/2	43 537.71	285.005, 369.348	12.6(6)		
$3d^8(^1D)4p$	$x\ ^2F°$	7/2	43 555.22	229.522, 369.072	8.6(4)		
$3d^7(^2G)4s4p(^3P°)$		7/2	43 847.98	232.313, 369.311	5.9(3)		
$3d^8(^1D)4p$	$x\ ^2D°$	3/2	43 911.36	355.299, 364.318	11.0(6)		
		5/2	43 921.89	231.915, 364.178	10.6(5)		
$3d^7(^2G)4s4p(^3P°)$	$w\ ^4G°$	11/2	43 952.06?	227.450, 247.027	55.9(28)		<66.7
		9/2	44 183.34	226.259, 230.517	36.8(18)		
		7/2	44 394.47	229.400, 232.553	23.3(12)		
		5/2	44 568.47	228.486, 231.616	16.3(8)		
$3d^7(^2G)4s4p(^3P°)$		5/2	44 201.92	230.418, 233.600	5.4(3)		
$3d^7(^4P)4s4p(^1P°)$	$y\ ^4P°$	3/2	44 658.03	233.307, 252.563	57.5(29)		
$3d^8(^3P)4p$	$^2D°$	5/2	45 688.15	240.627, 366.216	9.0(5)		
		3/2	46 186.41	223.246, 225.271	8.6(4)		
$3d^8(^3P)4p$	$^4S°$	3/2	45 904.68	224.660, 242.559	9.4(5)		
$3d^7(^4P)4s4p(^3P°)$	$x\ ^4P°$	1/2	45 957.29	226.441, 244.535	12.6(6)		
		5/2	46 002.83	221.235, 224.165	12.2(6)		
		3/2	46 260.02	222.881, 224.898	9.3(5)		
$3d^8(^3P)4p$	$^4D°$	7/2	45 971.19	217.460, 224.325	6.1(3)		
		5/2	46 329.63	224.546, 240.083	7.1(4)		
		1/2	46 502.15	223.680, 241.319	6.9(3)		
$3d^7(^4P)4s4p(^3P°)$	$^2D°$	3/2	46 454.95	221.915, 396.100	9.9(5)		
		5/2	46 671.94	218.006, 220.851	10.5(5)		
$3d^8(^3P)4p$		3/2	46 562.87	223.376, 262.376	8.7(4)		
$3d^8(^3P)4p$		3/2	46 685.43	220.785, 222.767	8.0(4)		
$3d^7(^2P)4s4p(^3P°)$		7/2	46 872.74	213.277, 217.056, 230.397	10.4(5)		
$3d^8(^3P)4p$	$y\ ^2P°$	1/2	47 091.14	220.770, 237.936	10.7(5)		

(*Table continued*)

Table 2. Continued

Configuration	Term	J	Level (cm^{-1})	Laser Wavelength in Air (nm)	Lifetime (ns) This Expt.	Other LIF	Critical Compilation[b]
$3d^7(^2G)4s4p(^3P°)$		5/2	47 128.96	232.562, 235.561	8.2(4)		
$3d^7(^2G)4s4p(^3P°)$		7/2	47 225.11	215.407, 228.541, 235.028	9.4(5)		
$3d^7(^2P)4s4p(^3P°)$	$u\ ^4D°$	5/2	47 393.93	214.626, 217.384	11.9(6)		
		3/2	47 612.18	216.357, 218.259	9.8(5)		
	6°	7/2	47 839.15	225.378, 228.780	11.3(6)		
$3d^7(^2P)4s4p(^3P°)$		1/2	47 905.26	216.871	9.0(5)		
$3d^8(^3P)4p$		1/2	48 026.34	216.303, 232.754	6.1(3)		
$3d^7(a^2D)4s4p(^3P°)$	$t\ ^4D°$	7/2	48 217.32	226.816, 229.670	13.2(7)		
		5/2	48 443.76	209.894, 225.657, 228.481	13.1(7)		
		1/2	48 571.77	213.778, 229.836	8.8(4)		
$3d^7(^2H)4s4p(^3P°)$	$^4G°$	7/2	48 317.17	222.973, 229.145	12.3(6)		
		5/2	48 615.56?	227.588, 229.604	10.6(5)		
$3d^7(^4P)4s4p(^3P°)$	$^2P°$	3/2	48 334.37	213.028, 229.054	12.7(6)		
		1/2	48 837.72	228.438, 328.333	11.0(6)		
$3d^7(a^2D)4s4p(^3P°)$		3/2	48 546.07	213.897, 249.393	12.7(6)		
$3d^7(^2P)4s4p(^3P°)$	$x\ ^4S°$	3/2	48 753.72	226.874, 228.877	24.6(12)		
$3d^7(a^2D)4s4p(^3P°)$		5/2	48 828.87	223.712, 226.488	39.0(20)		
$3d^7(^2P)4s4p(^3P°)$		3/2	49 025.42	227.462, 246.446	14.0(7)		
$3d^7(a^2D)4s4p(^3P°)$	$^4F°$	9/2	49 197.74?	218.678, 221.881	91.2(46)		
		7/2	49 484.05	220.480, 223.175	63.2(32)		
		5/2	49 847.08	223.288, 235.751	58.8(29)		
		3/2	50 105.05	240.056, 291.197	35.7(18)		
$3d^8(^1G)4p$	$y\ ^2H°$	9/2	50 210.80	369.902, 370.224	12.1(6)		
		11/2	50 375.91	367.655	16.1(8)		
$3d^8(^1G)4p$	$u\ ^2F°$	7/2	50 578.73	231.752, 295.767	13.7(7)		
		5/2	50 712.45	236.605, 363.471	13.6(7)		
$3d^8(^1G)4p$	$w\ ^2G°$	9/2	50 593.38	215.215, 292.950	36.3(18)		
		7/2	50 611.22	292.797, 299.515	32.7(16)		
$3d^7(^2H)4s4p(^3P°)$	$^4H°$	11/2	50 703.08	363.284	36.1(18)		
		9/2	50 902.61	290.320	61.0(31)		
$3d^7(^2P)4s4p(^3P°)$	$v\ ^2P°$	3/2	50 925.11	216.220, 292.767	12.9(6)		
		1/2	50 945.47	217.941, 284.238	12.5(6)		
$3d^7(a^2D)4s4p(^3P°)$	$w\ ^4P°$	5/2	51 160.03	277.881, 282.515	18.2(9)		
		3/2	52 014.45	279.101, 283.715	14.7(7)		
		1/2	52 355.12	278.590	18.4(9)		
$3d^7(a^2D)4s4p(^3P°)$	$^2F°$	7/2	53 103.78	218.935, 278.702	14.6(7)		
$3d^7(a^2D)4s4p(^3P°)$	$u\ ^2D°$	3/2	53 074.92	224.074, 268.010, 273.111	8.4(4)		
		5/2	53 195.98	218.495, 262.997	8.6(4)		
$3d^7(^2H)4s4p(^3P°)$	$v\ ^2G°$	9/2	53 276.02	218.112, 271.599	5.6(3)		
		7/2	53 373.53	217.649, 222.585	5.8(3)		
$3d^74s(^5F)4d$	$e\ ^6G$	13/2	53 728.36?	331.948, 349.679	6.1(3)		
$3d^74s(^5F)4d$	$e\ ^6H$	15/2	53 822.08	348.537	6.3(3)		
	$v\ ^4F°$	7/2	55 314.04?	249.115	2.3(2)		

(*Table continued*)

Table 2. Continued

Configuration	Term	J	Level (cm^{-1})	Laser Wavelength in Air (nm)	Lifetime (ns) This Expt.	Lifetime (ns) Other LIF	Lifetime (ns) Critical Compilation[b]
	27°	5/2	55 061.49	242.257	4.1(2)		
	30°	5/2	55 508.78	239.659, 241.050	5.2(3)		
	32°	3/2	55 818.91	237.890, 241.358	2.8(2)		
	36°	7/2, 9/2	58 187.39	239.623, 244.104	2.5(2)		
	37°	5/2, 7/2	59 388.89	237.146	3.0(2)		

[a]The number in parentheses following an entry is the uncertainty in the last digit(s) of the entry. ?, See text.
[b]Ref. 8.
[c]Ref. 6.
[d]Ref. 7.
[e]Ref. 5.

This ensures that the original classification of the line is correct, that the line is unblended, and that it is correctly identified in our experiment. We classified the line at 217.941 nm and used it to excite the $v\ ^2P^{\circ}_{1/2}$ level. Even-parity levels studied in this work are excited from the $z\ ^6F^{\circ}_{11/2}$ and $z\ ^6G^{\circ}_{13/2}$ levels, which are effectively metastable odd-parity levels.

Question marks after level energies in Table 2 are from Ref. 18. The question marks denote levels that were considered possibly not real because of accidental line coincidences. Four of these five levels are confirmed to be real by our observation of a consistent lifetime from different laser excitation wavelengths.

The critical compilation of atomic transition probabilities by Fuhr *et al.*[8] reviewed research performed before 1988 on Co I transition probabilities. Thus the comparison in Table 2 is primarily between the present study and the critical compilation of Ref. 8. We also include earlier LIF measurements of lifetimes in Table 2 because they are directly comparable with our results. The average and the root-mean-squared differences between earlier LIF lifetime measurements by Marek and Vogt[6] and our lifetimes are −0.7% and 10.6%, respectively. The average and root-mean-squared differences between earlier LIF lifetime measurements by Figger *et al.*[7] and our lifetimes are +4.7% and 3.9%, respectively. The agreement within 5% on average is typical for LIF lifetime measurements, although the root-mean-squared difference of 10.6% between measurements by Marek and Vogt and our measurements is larger than is typical.

The critical compilation of atomic transition probabilities by Fuhr *et al.* includes transition probabilities for essentially all the decay channels of some selected cobalt levels.[8] Lifetimes for these selected levels are derived by summation of transition probabilities and are included in Table 2. Upper limits for a few additional lifetimes derived by summation of transition probabilities are also incuded in Table 2. The critical compilation included most (80% or 90%) of the total transition probability for decay from these additional levels. Typically the uncertainties in the transition probabilities in the critical compilation are ±25% for spectral lines from lower excited levels and range up to ±50% for lines from higher excited levels. These uncertainties are conservative. If we limit the comparison to upper levels for which the critical compilation has a complete set of transition probabilities, then the agreement between lifetimes from the critical compilation and our lifetimes is extremely good. The average and the root-mean-squared differences are +2.6% and 12.6%, respectively.

In summary, we report new radiative lifetime measurements for 135 levels in Co I. Our measurements agree with earlier but less extensive LIF measurements; they also are in good agreement with lifetimes derived by summation of transition probabilities from a recent critical compilation. Our measurements provide a reliable absolute normalization for a much more extensive set of Co I transition probabilities. D. E. Nitz is undertaking a comprehensive set of branching fraction measurements on Co I.

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