Lifetimes, branching ratios, and transition probabilities in Co II

S. Salih and J. E. Lawler
University of Wisconsin, Madison, Wisconsin 53706

W. Whaling*
Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125
(Received 24 August 1984)

The radiative lifetime of 14 levels in the z^5F, z^5D, and z^5G terms of Co II have been measured with use of time-resolved laser fluorescence spectroscopy with a Co^+-ion beam. Our lifetime values are shorter by 15—50% than earlier results from beam-foil time-of-flight measurements. The lifetimes were converted to 41 individual transition probabilities with use of branching ratios measured on spectra recorded with the 1-m Fourier-transform spectrometer at the Kitt Peak National Observatory. On average our transition probabilities agree with those of Kurucz and Peytremann; for $\Delta S=1$ transitions their calculated values are lower than our experimental results by a factor of $\sim\frac{1}{4}$.

INTRODUCTION

Orbiting observatories have overcome the wavelength limitations imposed by the Earth's atmosphere and have created a need for spectroscopic data to analyze observations at the new wavelengths. In this paper we report the first measurements by modern methods of oscillator strengths in Co II, including the 28 strongest lines in the prominent multiplets UV7, UV8, and UV9 in the 2300—2500-Å range. The oscillator strengths were measured by the reliable method of combining level lifetimes with level branching ratios. The level lifetimes were measured by direct timing of the decay of the fluorescence induced by selective laser excitation. Branching ratios were measured with the high resolution provided by the Kitt Peak 1-m Fourier-transform spectrometer, high resolution that is essential for the analysis of the rich Co I + Co II spectrum.

In the absence of reliable experimental transition probabilities for Co II, recent studies of the cobalt abundance in the sun[1] and in the supernova 1981b in NGC 4536[2] have had to use the semiempirical values of Kurucz and Peytremann[3] (KP), who have computed transition probabilities for every electric dipole transition between known levels in Co II. Until experimental values are measured for the many transitions of interest to astronomers, the KP computation will continue to serve as the only source of the necessary transition probabilities, and one would like to know how accurate the KP values are. We compare their Co II transition probabilities with our experimental values and find good agreement for the stronger transitions, poor agreement for transitions involving a spin change.

RADIATIVE LIFETIMES

Radiative lifetimes for 14 levels in the z^5F, z^5D, and z^5G terms of Co II have been measured using time-resolved laser-induced fluorescence with a slow Co^+-ion beam. Laser excitation of atoms in beams has proven to be a very reliable method of determining atomic lifetimes. Recent lifetime measurements in Nb *I* are an example; three independent sets of measurements agree within a few percent.[4–6] We expect that the same method should be equally reliable in the case of atomic ions. Selective laser excitation eliminates the cascading problem that plagues beam-foil time-of-flight lifetime measurements. The beam environment eliminates errors due to radiation trapping and collisional quenching.

Figure 1 is a schematic of the experiment. The apparatus is similar to that used by Duquette *et al.* to produce atomic beams.[4] The beam source is based on a low-pressure, large-bore, hollow-cathode discharge. The hollow cathode is used as a beam source by sealing one end of the cathode except for a 1.0-mm-diam opening. The opening is flared outward at 45° to serve as a nozzle for forming an uncollimated ion beam. The hollow cathode

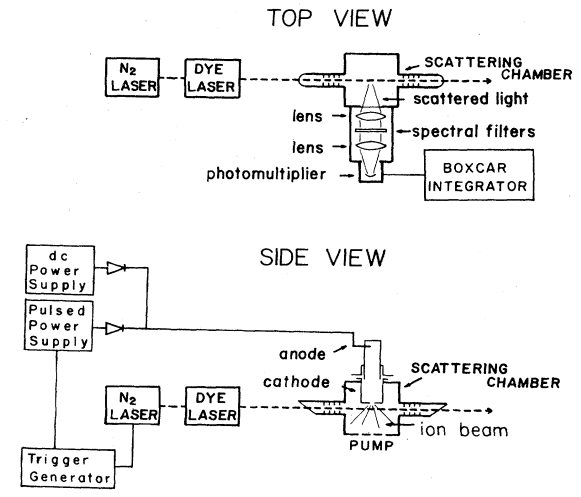

FIG. 1. Schematic diagram of the experimental arrangement used to measure the radiative lifetime of the Co^+ ions.

and the scattering chamber are at ground potential. Argon, the sputtering gas, flows continuously into the hollow-cathode discharge. A 6-in. diffusion pump evacuates the scattering chamber. The scattering chamber is sealed from the hollow-cathode discharge, except for the nozzle, and is maintained at a much lower pressure than the discharge. The argon pressure in the discharge is typically 0.3 Torr, while the pressure in the scattering chamber is approximately 10^{-4} Torr.

The most significant change in the ion source from that used for neutral atoms is the addition of a pulsed power supply.[7] The pulsed supply delivers a 5-μsec-duration, 16-A current pulse which produces a burst of metal ions from the source. The discharge current is maintained at 40 mA between pulses by the dc supply.

The ion beam is crossed by a pulsed dye-laser beam 1 cm from the nozzle. The dye laser is pumped by a pulsed N_2 laser. The dye laser produces a pulse of 3-nsec duration (full width at half maximum) with a 0.2-cm^{-1} bandwidth and a peak power of up to 40 kW. A KB5 (potassium pentaborate, Cleveland Crystal, Inc.) crystal frequency doubler extends the dye-laser tuning range to 2170 Å in the ultraviolet. The fluorescence is detected along an axis orthogonal to the atomic beam and laser beam. In order to minimize scattered light, several sets of light baffles are arranged along the laser-beam axis inside the Brewster windows that pass the laser beam into and out of the scattering chamber. Fluorescence from the scattering chamber is focused on the photomultiplier by two lenses comprising an $f/1$ system.

The experiment includes a trigger generator to provide an adjustable delay between the current pulse to the hollow cathode and the laser pulse. The optimum delay of 16 μsec is an average time of flight of the Co^+ ions. Levels with lifetimes less than 10 nsec are studied in this experiment. The average ion velocity of 6×10^4 cm/sec, determined by the time of flight, indicates that the ions move less than 6 μm before radiating and no ions leave the 5-mm-long observation region before radiating.

Each radiative lifetime reported in the first column of Table I represents an average of approximately ten decay curves. The standard deviation of the distribution is typically 5% or less. The overall uncertainty is ±0.2 nsec for the Co II radiative lifetimes. Collisional quenching is not a problem in this experiment because the scattering chamber pressure is 10^{-4} Torr of argon. Radiation trapping is avoided because the ion beam is optically thin. The most likely source of systematic error is the finite bandwidth of the detection apparatus.

The detection system is composed of a photomultiplier, a delay cable, and a boxcar averager. The bias resistors of the 1P28A photomultiplier are bypassed with capacitors to insure good linearity at large peak currents; small damping resistors are included to reduce ringing. All components are wired for low inductance and fast response. The delay cable is necessary for synchronization of electronic components; it has a risetime of 0.1 nsec. The window width of the Princeton Applied Research PAR-163/165 boxcar integrator is 75 psec.

The finite bandwidth of the total detection system was tested by measuring known lifetimes. We expect systematic error from the finite bandwidth to be $<10\%$, and we need to test our apparatus by measuring lifetimes in the 3-nsec range that are known to a few percent. Two levels in neutral He meet these requirements. The lifetimes of the 3^1P and 4^1P levels of He are 1.73 nsec (1%) and 3.92 nsec (3%).[8] These levels are excited (and detected) using visible or near-uv transitions from (and to) the 2^1S metastable level. They decay primarily by vuv transitions to the ground level of He. Our beam source is capable of producing an intense burst of He metastables.

Unfortunately, we cannot avoid radiation trapping for He transitions to the ground level. This is not surprising since He is the carrier gas and not a minor constituent of the discharge as is the case for sputtered metal atoms and ions. The theory of radiation trapping indicates that the observed lifetime should increase linearly with the ground-state atom density over a limited range of density.[9] We use a linear extrapolation of the data in Fig. 2 to determine a "vacuum" lifetime for the 3^1P and 4^1P levels of He. The vacuum lifetimes agree very well with the known He lifetimes. The linear extrapolation is appropriate in the case of the 4^1P level. The linear extrapolation is somewhat less satisfactory in the case of the 3^1P level because (1) the slope determined in the linear least-squares fit of the 3^1P data is 30% larger than the slope determined for the 4^1P data (theory indicates it should be 9% larger), and (2) the effect of radiation trapping when mea-

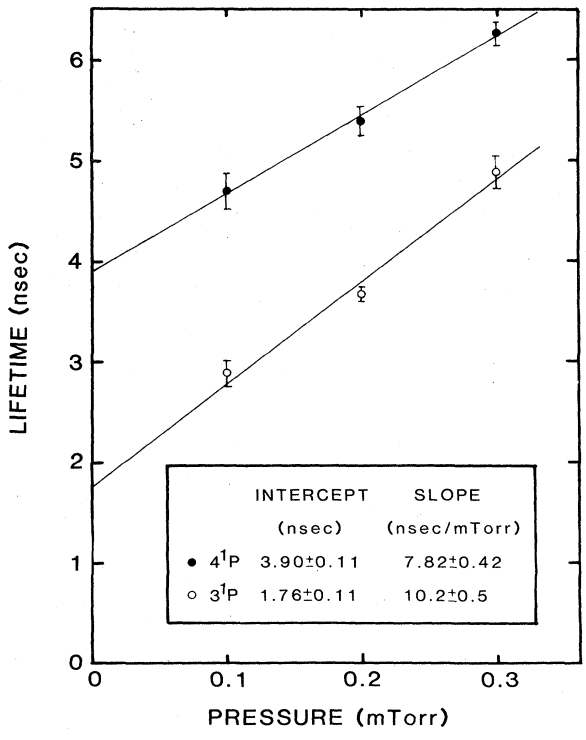

FIG. 2. Data used to test the effect of radiation trapping on the measured lifetime of the He I 3^1P and 4^1P levels.

TABLE I. Radiative lifetimes, branching ratios, and transition probabilities measured in this experiment. The wavelengths are calculated from the energy levels of Ref. 14. Our estimate of the uncertainty (standard error) of an experimental value appears in parentheses after the value.

Upper level [energy, lifetime]	Lower level	λ (Å)	Branching ratio (%)	Transition probability (s^{-1}) This work	KP[a]	CB[b]
$z^5F_5^o$	a^5F_5	2388.92	97.3(2)	$[2.8(2)]\times10^8$	3.60×10^8	25×10^8
[45 197.78 K,	a^5F_4	2428.29	2.6(1)	$[7.4(5)]\times10^6$	1.00×10^7	1.3×10^8
3.5(2) ns]	b^3F_4	2825.24	0.6(1)	$[1.7(3)]\times10^6$	4.08×10^5	
$z^5F_4^o$	a^5F_5	2378.63	66(1)	$[1.9(1)]\times10^8$	1.85×10^8	18×10^8
[45 378.85 K,	a^5F_4	2417.65	29.6(6)	$[8.5(5)]\times10^7$	1.67×10^8	13×10^8
3.5(2) ns]	a^5F_3	2449.16	2.5(1)	$[7.1(6)]\times10^6$	1.55×10^7	1.2×10^8
	b^3F_4	2810.86	0.50(7)	$[1.4(2)]\times10^6$	7.11×10^5	
	a^5P_3	3621.22	0.9(2)	$[2.6(6)]\times10^6$	8.17×10^5	
$z^5F_3^o$	a^5F_4	2383.45	67.7(5)	$[1.8(1)]\times10^8$	2.02×10^8	25×10^8
[45 972.17 K,	a^5F_3	2414.06	26.7(5)	$[7.2(4)]\times10^7$	1.42×10^8	10×10^8
3.7(2) ns]	a^5F_2	2436.98	5.0(3)	$[1.4(1)]\times10^7$	2.60×10^7	1.8×10^8
	b^3F_3	2834.94	0.38(7)	$[1.0(2)]\times10^6$	4.30×10^5	
$z^5D_4^o$	a^5F_5	2326.47	26.0(8)	$[7.9(5)]\times10^7$	1.89×10^8	4.9×10^8
[46 320.96 K,	a^5F_4	2363.79	69(1)	$[2.1(1)]\times10^8$	1.83×10^8	18×10^8
3.3(2) ns]	a^5F_3	2393.90	3.3(3)	$[1.0(1)]\times10^7$	6.63×10^6	3.1×10^8
	b^3F_3	2807.18	0.26(5)	$[8(2)]\times10^5$	1.71×10^5	
	a^5P_3	3501.72	2(1)	$[6(3)]\times10^6$	5.14×10^6	
$z^5F_2^o$	a^5F_3	2386.36	Blend with λ2386.38 m		1.95×10^8	23×10^8
[46 452.82 K,	a^5F_2	2408.75	$(c^3P_1\text{-}z^1D_2^o)$		1.38×10^8	9.4×10^8
3.0(2) ns]	a^5F_1	2423.62			3.36×10^7	4.2×10^8
$z^5F_1^o$	a^5F_2	2389.54	50(3)	$[1.5(2)]\times10^8$	1.70×10^8	30×10^8
[46 786.53 K,	a^5F_1	2404.17	50(3)	$[1.5(2)]\times10^8$	1.97×10^8	21×10^8
3.4(2) ns]						
$z^5D_3^o$	a^5F_4	2324.31	26.6(5)	$[7.8(5)]\times10^7$	1.68×10^8	7.6×10^8
[47 039.27 K,	a^5F_3	2353.41	65.8(7)	$[1.9(1)]\times10^8$	1.97×10^8	
3.4(2) ns]	a^5F_2	2375.19	4.4(2)	$[1.3(1)]\times10^7$	1.07×10^7	2.9×10^8
	a^5P_3	3415.77	0.5(3)	$[1.5(8)]\times10^6$	2.25×10^6	
	a^5P_2	3446.38	1.5(3)	$[4(1)]\times10^6$	4.11×10^6	
$z^5G_6^o$	a^5F_5	2286.16	100	$[3.3(2)]\times10^8$	4.30×10^8	13×10^8
[47 078.74 K,						
3.0(2) ns]						
$z^5G_5^o$	a^5F_5	2272.35	1(1)	$[3(3)]\times10^6$	1.05×10^7	
[47 345.94 K,	a^5F_4	2307.86	82(3)	$[2.6(2)]\times10^8$	3.86×10^8	15×10^8
3.2(2) ns]	b^3F_4	2663.53	17(3)	$[5.3(9)]\times10^7$	1.35×10^7	5.9×10^8
$z^5D_2^o$	a^5F_3	2326.13	Blend with λ2326.11		1.70×10^8	12×10^8
[47 537.48 K,	a^5F_2	2347.40	$(a^3G_5\text{-}y^3G_5^o)$		1.92×10^8	18×10^8
3.3(2) ns]	a^5F_1	2361.52			1.23×10^7	2.4×10^8
	b^3F_3	2714.45			2.50×10^4	
	a^5P_1	3423.83			2.38×10^6	
$z^5G_4^o$	a^5F_4	2283.52	5.9(6)	$[2.0(2)]\times10^7$	2.41×10^7	1.3×10^8
[47 807.58 K,	a^5F_3	2311.60	85(2)	$[2.8(2)]\times10^8$	3.82×10^8	14×10^8
3.0(2) ns]	b^3F_3	2694.68	9(2)	$[3.0(5)]\times10^7$	6.90×10^6	3.0×10^8

TABLE I. (*Continued*).

Upper level [energy, lifetime]	Lower level	λ (Å)	Branching ratio (%)	Transition probability (s^{-1}) This work	KP[a]	CB[b]
$z^5D^o_1$	a^5F_2	2330.36	45(1)	$[1.32(9)]\times10^8$	2.02×10^8	16×10^8
[47 848.89 K,	a^5F_1	2344.27	52(2)	$[1.5(1)]\times10^8$	1.73×10^8	21×10^8
3.4(2) ns]	a^5P_2	3352.80	1.0(3)	$[2.9(9)]\times10^6$	2.15×10^6	
	a^5P_1	3387.70	2.1(5)	$[6(2)]\times10^6$	5.90×10^6	
$z^5G^o_3$	a^5F_3	2293.38	10.3(4)	$[3.3(3)]\times10^7$	3.96×10^7	2.4×10^8
[48 151.07 K,	a^5F_2	2314.06	87(1)	$[2.8(2)]\times10^8$	3.63×10^8	19×10^8
3.1(2) ns]	b^3F_2	2714.44	2.4(5)	$[8(2)]\times10^6$	1.29×10^6	
$z^5G^o_2$	a^5F_2	2301.40	12.2(5)	$[3.8(3)]\times10^7$	4.91×10^7	
[48 388.62 K,	a^5F_1	2314.97	87(1)	$[2.7(2)]\times10^8$	3.60×10^8	23×10^8
3.2(2) ns]	b^3F_2	2697.04	0.9(5)	$[3(2)]\times10^6$	2.97×10^5	

[a]R. L. Kurucz and M. Peytremann, *Smithsonian Special Report No. 362,* Smithsonian Astrophysical Observatory, Cambridge, Mass., 1975 (unpublished).

[b]C. H. Corliss and W. R. Bozman, *NBS Monograph No. 53* (1962).

sured as a percentage of the vacuum lifetime is larger for the 3^1P level than for the 4^1P level. Although we have reservations about using a linear extrapolation of the He 3^1P data, the essential conclusion from the He data is that our detection apparatus has sufficient bandwidth to measure lifetimes as short as 3 nsec. All of the Co II lifetimes reported in this paper are 3 nsec or longer.

BRANCHING RATIOS

Branching ratios were measured on spectra recorded with the 1-m Fourier-transform spectrometer[10] (FTS) at the Kitt Peak National Observatory, with the FTS parameters set to provide a theoretical resolution of 8.7×10^5. The minimum linewidth observed was 0.15 K FWHM, but the typical Co line profile was much wider because of incompletely resolved hyperfine structure (HFS).

The spectral source was a water-cooled hollow-cathode discharge in a Co cathode cavity 8-mm i.d. by 32-mm long. High-purity neon or a 10:1 Ne:Ar mixture at 3 Torr was used to sustain the discharge of 800 or 400 mA in recording various spectra.

As a test for self-absorption in the source, the relative intensity of two lines, one weak and one strong, both emitted from the same upper level, were compared in spectra recorded at different power levels. As in our earlier investigations of Co I, no evidence of self-absorption was found in even the strongest spectra, in striking contrast to the source behavior with the other transition metals that we have studied.

The area under the line profile on the transformed spectrum was integrated to obtain the observed line intensity $A(\lambda)$. The relative line intensity is then given by $I(\lambda)=A(\lambda)/\epsilon(\lambda)$, where $\epsilon(\lambda)$ is the relative detection efficiency of the spectrometer system at wavelength λ. The response function $\epsilon(\lambda)$ was measured using argon branching ratios as an internal calibration standard for wavelengths ≥2800 Å as described earlier.[11] Calibration over the range $2160\leq\lambda\leq3100$ Å was made against molecular branching ratios using the $v'=0$ and $v'=1$ vibrational sequences in the NO gamma system. These branching ratios have been measured by several authors, most recently by McGee *et al.*[12] A 10:1 by volume mixture of N_2:air was used in the discharge to excite the NO spectrum. The NO spectrum was recorded before and after the Co spectrum to check that the FTS response function remained constant. The stronger Co lines were present in the NO calibration spectrum and the ratio of Co lines from the same upper level was measured as a further check on the stability of the FTS response. Only the relative response as a function of wavelength is critical for branching-ratio measurements.

The branching ratio is defined as $R(\lambda_{ul'})=I_{ul'}/\sum I_{ul}$ where $I_{ul'}$ is the photon intensity (photons/sec) of the transition between upper level u and lower level l'. If the sum in the denominator includes all the lower levels to which the level u decays, then $R_{ul'}=A_{ul'}\tau_u$ determines the transition probability $A_{ul'}$ in terms of the measured $R_{ul'}$ and radiative lifetime τ_u.

We have taken the following precautions to see that the sum includes all the significant decay channels. Wavelengths were calculated for all electric dipole transitions with wavelength $\leq10\,000$ Å and $\Delta S<2$ from each level of known lifetime to all lower opposite-parity levels reported by Iglesias;[13] the level energies were taken from Sugar and Corliss.[14] We then searched our spectra for these predicted transitions. For wavelengths between 2300 and 10 000 Å, we were able to see branches that contributed as much as 1% to the total decay strength of a level.

The detection efficiency of the FTS falls off rapidly for wavelengths shorter than 2300 Å and we were not able to measure transitions to the ground term (a^3D) from any of our quintet levels. Iglesias[13] has observed several of these $\Delta S=1$ transitions. However, she finds that the strongest $\Delta S=1$ line (a^3F_4-$z^5G^o_5$; 2111.54 Å) contributes less than 3% to the total decay probability of the $z^5G^o_5$ level. It should be noted that the Iglesias intensities are only visual estimates.

Kurucz and Peytremann[3] have computed a transition probability for each electric dipole transition between known levels in Co II, and they find that none of the a^3D-z^5F, -z^5D, -z^5G transitions have branching ratios as large as 0.5%. On the basis of this evidence that these unseen $\Delta S=1$ transitions are weak, we have computed branching ratios on the assumption that they have zero probability. Likewise, we have relied on the Kurucz and Peytremann estimates of the probability of transitions with wavelength greater than 10000 Å to justify our neglect of ir transitions.

Blending of the broad Co lines presented considerable difficulty. The HFS splits lines into structures as wide as 1.5 K, and the rich spectrum of Co I and Co II inevitably leads to occasional blends. Interference from Ne or Ar was easily detected by examining other Ne and Ar spectra (without Co) recorded with the FTS under similar source conditions and eliminated by measuring the line on spectra recorded without the interfering gas.

When a Co II line is blended with a Co I line, the relative contribution of each can be estimated by measuring the change in intensity of other lines from the same upper levels in Co I and Co II when the source power is changed. However, a blend of two Co II lines, from levels at about the same excitation energy, cannot be resolved by this method. Thus we were unable to resolve the Co II transitions a^5F_3-$z^5D^o_2$ (2326.13 Å) and a^3G_5-$y^3G^o_5$ (2326.11 Å). The 2326 Å line is the predominant decay channel for the $z^5D^o_2$ level, and without the intensity of this line we were unable to find transition probabilities for any of the decay channels from this level.

Similarly, the transitions a^5F_3-$z^5F^o_2$ (2386.36 Å) and c^3P_1-$z^1D^o_2$ (2386.37 Å) were not resolvable. One might expect the $\Delta S=1$ transition to be much the weaker of the two and that it would contribute very little to the observed line at 2386 Å. However, we found that the profile of this line changed as the source power was changed, a clear indication of a blend. Furthermore, if one computes the population of the $z^5F^o_2$ level from $N_u=\sum I_{ul}\tau_{u'}$ and includes the observed intensity of the 2386 Å line in the sum, one finds a population much larger than that of other levels in the z^5F term. We are confident that the observed line is a blend, although the interfering transition may not be the $\Delta S=1$ transition suggested by Iglesias. We found many lines in our spectra, clearly cobalt lines from their HFS, that are not transitions between the known levels in Co I or Co II. Level information for these these two systems is sparse.

The level lifetimes, branching ratios, and transition probabilities are listed in Table I. The uncertainty assigned to the branching ratios includes a contribution from the uncertainty in the measured line area and the uncertainty in the FTS response function; the latter is the larger contribution except for the weakest transitions. The uncertainty in the transition probability includes a contribution from the uncertainty in the radiative lifetime.

COMPARISON WITH OTHER VALUES

Radiative lifetimes of several of the levels in Table I have been measured by Pinnington *et al.*[15] and by Sorensen[16] by the beam-foil time-of-flight method. Their lifetime values are longer than those reported here by 15—50%. It seems likely that the well-known difficulties with cascading, aggravated by the poor spectral resolution inherent in the spectroscopy of fast ion beams, accounts for this disagreement.

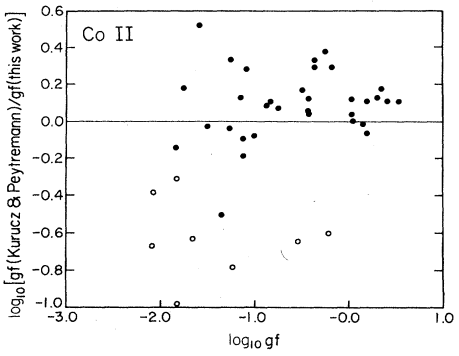

FIG. 3. Comparison of the semiempirical gf values of Kurucz and Peytremann (Ref. 3) and those measured in this experiment. The solid circles represent transitions with $\Delta S=1$.

Experimental transition probabilities in Co II have been published by Corliss and Bozman;[17] their transition probabilities are roughly a factor of 10 larger than the values in Table I. Warner[18] has published gf values for the a^5P-z^5D^o multiplet, derived from solar lines, emission intensities, and theoretical calculations; his values are a factor of ~ 10 greater than ours.

Kurucz and Peytremann[3] have found gf values for all transitions between known levels in Co II by a semiempirical calculation. Since their values are the only gf values for the great majority of Co II lines, it is of interest to see how reliable they are. In Fig. 3 we plot $\log[gf(\text{KP})/gf(\text{this work})]$ as a function of $\log[gf(\text{this work})]$. It is apparent that the average value of this ratio is near unity. For the 22 strongest lines in Table I with $A_{ul}\geq 10^8$ s^{-1}, the mean value of $\log[gf(\text{KP})/gf(\text{this work})]$ is 0.084 with a standard deviation of 0.069. This 21% discrepancy is similar to the 15—25% discrepancy that Kurucz[19] found in comparing his Fe II gf values with experiment. For weaker transitions, the agreement is not so good. Transitions to the b^3F term ($\Delta S=1$), plotted as open circles in Fig. 3, are uniformly low; for the eight transitions in Table I with $\Delta S=1$, the mean value of $\log[gf(\text{KP})/gf(\text{this work})]$ is -0.62 ± 0.22. The overall agreement between the KP transition probabilities and experiment is impressive, and we feel confident in using their values to show that the decay channels with $\lambda>10000$ Å are negligible.

Gruzdev[20] has calculated relative gf values for transitions from the levels studied here to the a^5F and b^3F terms using an intermediate coupling scheme. The relative intensity of the decay branches computed by Gruzdev agree remarkably well with the experimental values for transitions to the a^5F term. For the stronger branches ($R>25\%$), the mean value of the ratio R(Gruzdev)/R(this expt) is 1.01 with a standard deviation of 0.08.

(The corresponding ratio for the Kurucz and Peytremann gf values is 1.4 ± 0.4.) For the weak transitions to the b^3F term, Gruzdev's intensity ratios are too low by a factor of $\sim\frac{1}{4}$, as are those of Kurucz and Peytremann.

Attempts to compare our measured transition probabilities with the intensity of Co II lines in the solar spectrum have been unsuccessful. From our quintet terms only the transitions to the a^5P term are seen in the sun, and these lines fall in the 3500 Å range where the solar spectrum is too crowded to allow measurement of accurate equivalent widths.

ACKNOWLEDGMENTS

This research was supported in part by National Science Foundation Grants Nos. AST-83-00948 and AST-83-17713. We are indebted to J. W. Brault and the National Solar Observatory—National Optical Astronomical Observatory (NSO-NOAO) staff for assistance with the KPFTS spectra. The National Solar Observatory is operated by Association of Universities for Research in Astronomy (AURA), Inc., under contract with the National Science Foundation.

---

*National Solar Observatory, Kitt Peak, AZ.

[1]E. Biemont, Mon. Not. R. Astron. Soc. **184**, 683 (1978).
[2]D. Branch, C. H. Lacy, M. L. McCall, P. G. Sutherland, A. Uomoto, J. C. Wheeler, and B. J. Wills, Astrophys. J. **270**, 123 (1983).
[3]R. L. Kurucz and E. Peytremann, Smithsonian Astrophysical Observatory Special Report No. 362, Cambridge, Mass., 1975 (unpublished).
[4]D. W. Duquette and J. E. Lawler, Phys. Rev. A **26**, 330 (1982).
[5]J. Rudolph and V. Helbig, Phys. Lett. **89A**, 339 (1982).
[6]M. Kwiatkowski, P. Zimmerman, E. Biemont, and N. Grevesse, Astron. Astrophys. **112**, 337 (1982).
[7]S. Salih and J. E. Lawler, Phys. Rev. A **28**, 3653 (1983).
[8]W. L. Wiese, M. W. Smith, and B. M. Glennon, Atomic Transition Probabilities, Natl. Stand. Ref. Data Ser., Natl. Bur. Stand. (U.S.) Circ. No. 4 (U.S. GPO, Washington, D.C., 1966), Vol. I, p. 9.
[9]B. P. Kibble, G. Copley, and L. Krause, Phys. Rev. **153**, 9 (1967).
[10]J. W. Brault, J. Opt. Soc. Am. **66**, 1081 (1976).
[11]B. L. Cardon, P. L. Smith, J. M. Scalo, L. Testerman, and W. Whaling, Astrophys. J. **260**, 395 (1982).
[12]T. J. McGee, J. Burris, T. J. McIlrath, and G. E. Miller, J. Quant. Spectrosc. Radiat. Transfer **29**, 333 (1983).
[13]L. Iglesias, Opt. Pura Apl. **12**, 63 (1979).
[14]J. Sugar and C. W. Corliss, J. Phys. Chem. Ref. Data **10**, 1109 (1981).
[15]E. H. Pinnington, H. O. Lutz, and G. W. Carriveau, Z. Phys. **267**, 27 (1974).
[16]G. Sorensen, J. Phys. (Paris) Colloq. **40**, C1-190 (1979).
[17]C. H. Corliss and W. R. Bozman, *Transition Probabilities, NBS Monograph 53* (GPO, Washington, D.C., 1962).
[18]B. Warner, Mon. Not. R. Astron. Soc. **138**, 229 (1968).
[19]R. L. Kurucz, Smithsonian Astrophysical Observatory Special Report No. 390, Cambridge, Mass., 1981 (unpublished).
[20]P. F. Gruzdev, Opt. Spectrosc. **13**, 169 (1962).