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RADIATIVE LIFETIMES AND ULTRAVIOLET BRANCHING FRACTIONS FOR RESONANCE LINES OF Co II

K. L. MULLMAN, J. C. COOPER, AND J. E. LAWLER
Department of Physics, University of Wisconsin-Madison, Madison, WI 53706
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ABSTRACT

Radiative lifetime measurements are combined with experimental branching fraction measurements to give 28 absolute oscillator strengths for ultraviolet lines of Co II. The radiative lifetimes are determined by laser-induced fluorescence measurements, and the branching fractions are measured using a high-resolution grating spectrometer and an optically thin hollow cathode discharge. The oscillator strengths establish the absolute scale for relative absorption oscillator strength measurements made with the high-sensitivity absorption spectroscopy experiment at the University of Wisconsin.

Subject headings: atomic data — ISM: abundances — ISM: atoms — methods: laboratory — ultraviolet: general

1. INTRODUCTION

Accurate oscillator strengths are required in order to determine absolute abundances and other physical parameters from observational data. It has been stated (Leckrone et al. 1993) that "there is a critical need for a global improvement in the oscillator strengths of UV transitions of ... Co II." UV Co II transitions have been detected toward a number of OB-type stars as well as in high-redshift "damped Lyα" absorption systems toward quasi-stellar objects (Shull 1993). Since Co II has a lower cosmic abundance than prominent interstellar species such as Fe II or Si II, Co II transitions can be used to obtain accurate iron group abundances along lines of sight for which many absorption lines of these other species are saturated (Shull 1993). In addition, cobalt is usually depleted in the ISM because of dust formation, which makes its absorption lines even weaker than its cosmic abundance would suggest. This depletion makes cobalt observations valuable in studies of dust depletion patterns in interstellar diffuse clouds as well.

The UV lines that are of most interest in studies of the interstellar medium (ISM), namely, resonance lines (lines connected to the ground state), also serve as reference lines for the high-sensitivity absorption spectroscopy experiment at the University of Wisconsin. The absorption experiment measures relative oscillator strengths for lines originating from a common lower level (Mullman, Sakai, & Lawler 1997). Usually, a vacuum ultraviolet (VUV) transition is measured relative to a UV transition above 200 nm. These branching fraction and radiative lifetime measurements provide an accurate absolute scale for oscillator strength measurements below 200 nm.

The most widely applicable and reliable method for measuring oscillator strengths of lines above 200 nm combines branching fraction measurements with radiative lifetime determinations. We measure branching fractions with a high-resolution spectrometer and an optically thin hollow cathode discharge. Radiative lifetimes are determined for all levels in the $z\,^3G^o$, $z\,^3F^o$, and $z\,^3D^o$ terms using laser-induced fluorescence. We report branching fraction measurements for all significant branches of the $z\,^3G^o$ ($J = 5, 4$) and the $z\,^3F^o$ ($J = 4, 3, 2$) levels of Co II. These measurements are combined with radiative lifetime measurements of the same upper levels to give 28 absolute UV oscillator strengths for Co II.

2. BRANCHING FRACTIONS

The spectrometer used in this study is a 3 m focal length vacuum echelle grating spectrometer. Because the spectrometer operates in high order, 22d–29th in this experiment, a premonochromator is used as an order sorter. An uncoated, back-thinned, boron-doped, deep UV sensitive CCD detector array is used with the spectrometer. The CCD chip is from Scientific Imaging Technologies; the camera head, electronics, and software are all from Princeton Instruments. The spectrometer system achieves a resolving power of 350,000.

The emission source is a water-cooled, open-ended, double-sided hollow cathode discharge. The cathode is 1 cm in inner diameter and 10 cm long. Emission from the Co II levels is optimized with a 2.4 torr Ne fill, and discharge currents from 80 to 700 mA are used in this study. The hollow cathode discharge system uses essentially all metal seals that allow a stable operation with a static gas fill. The Co II transitions are identified by comparing the emission from the hollow cathode discharge with published line lists for Co I and Co II (Iglesias 1979; Russell, King, & Moore 1940).

The relative response of the spectrometer system is calibrated as a function of wavelength using a NIST calibrated argon mini–arc lamp (Bridges & Ott 1977) and verified using the Aladdin storage ring at the Synchrotron Radiation Center at the University of Wisconsin. The argon mini–arc lamp is calibrated as a secondary standard of spectral irradiance and should not be imaged onto the spectrometer entrance slit. This means that the spectrometer grating and mirrors are only partially illuminated during a calibration run. To avoid any potential error from this effect, we vary the position of the calibration lamp in a plane perpendicular to the optical axis of the system and find no variations in the performance of the system. Uncertainties in the branching ratios because of their reproducibility and high signal-to-noise ratios range from $\sim$1% to 6%. Uncertainties in the branching ratios due to the radiometric calibration using the standard lamps range from $\sim$1% to 8%. These uncertainties are combined in quadrature to yield total uncertainties on our branching ratios ranging from $\sim$1% to 10%. Branching ratios are converted to branching fractions by forcing the ratios to sum to unity. This conversion tends to redistribute uncer-

tainty away from the strong lines and toward the weaker lines from each upper level.

Scattered or stray light in the spectrometer presents a potential systematic error for the radiometric calibration. The stray light level is determined by measuring the photon flux between orders of the 3 m spectrometer. We checked the validity of this approach by measuring line absorption in Hg I at 254 nm. When the column density of Hg I becomes large, light passing through the Hg absorption cell at line center is completely absorbed. Measuring the light level at line center under conditions of complete absorption gives an independent measurement of stray light inside the spectrometer. The error in our radiometric calibration as a result of stray light inside the spectrometer is verified to be $\leq 1\%$.

Each ratio in this study is measured using at least three different current settings for the hollow cathode discharge. This verifies that the lines are not blended and that the discharge is operating under optically thin conditions. The emission source is largely stable over time, but small variations in the signal levels are seen. To correct for this, we alternately measure lines from the same upper level and average the results. This ensures that any fluctuations in the emission from the hollow cathode discharge are averaged out.

3. LIFETIMES

The radiative lifetimes in this study are measured using laser-induced fluorescence (LIF) on a slow beam of Co^+. A tunable laser selectively excites the ions from the ground level or from a metastable level to the level of interest. After the laser pulse, the fluorescence of the spontaneous decay is observed over time, and from this an exponential lifetime is extracted. This method is recognized as an accurate and broadly applicable way of measuring lifetimes.

Our atomic/ionic beam source is a large-bore hollow cathode discharge with a cobalt-lined cathode. A schematic of the apparatus is available in O'Brian et al. (1991). Bombardment of the cathode by ions sputters material from the cathode that flows through a small hole in the bottom of the cathode into a low-pressure (2×10^{-4} torr) scattering chamber. This material forms a weakly collimated beam of Ar, Ar^+, Co, Co^+ in both ground and metastable levels with trace amounts of Fe and Fe^+. Typical operating conditions for the discharge are 0.25 torr of argon buffer gas and 10 mA direct current with a 10 A (peak current), 10 μs wide (FWHM) current pulse applied at 50 Hz to increase sputtering efficiency. The laser light tuned to the transition of interest crosses the atomic beam at a right angle in the scattering chamber. An f/1 optical system of unity magnification whose axis is at right angles to both beams collects the fluorescence radiation and images it onto the photocathode of an RCA 1P28A photomultiplier tube (PMT). This is a side-window PMT with a 1.9 ns rise time.

The tunable dye laser is a two-stage laser constructed in our laboratory. Two cells containing laser dye in organic solvent are transversely pumped by a focused beam from an N_2 laser (337 nm). The beam is pulsed at 50 Hz, synchronized with the atomic beam source current pulse. It has a roughly Gaussian profile with a width of 5 ns (FWHM), a peak power of 700 kW, and an average power of 165 mW. The first cell serves as the oscillator cavity and is flanked by a wedged, uncoated window that serves as the output mirror and a prismatic beam expander ($\times 81$) followed by a diffraction grating in a pressure chamber. Coarse tuning of the laser is achieved by varying the grating angle, and fine tuning is achieved by varying the gas pressure in the chamber. The second cell amplifies and refines the dye laser beam. This dye laser pulse has a similar time profile to the pump laser pulse, but much lower power. Through the use of various dyes and either a β-barium borate or potassium dihydrogen phosphate doubling crystal, the system is continuously tunable from 205 to 700 nm. This study required only a small range of wavelengths between 230 and 265 nm. The dye laser bandwidth is 0.3 cm^{-1} (0.2 cm^{-1}) when run with (without) a frequency doubling crystal.

The photomultiplier tube (PMT) signal is delivered by coaxial cable to a Tektronix SCD 1000 transient digitizer, a state-of-the-art waveform digitizer with 11 bit voltage resolution and 5 ps time resolution. The digitized signal from the PMT is downloaded to a computer for curve fitting. The PMT signal has two components: a roughly Gaussian pulse as a result of scattered light while the laser is on and an exponential decay curve from the fluorescence, which is the component of interest. The PMT signal is digitized over a time window of 2–3 lifetimes, starting a minimum of 6 ns past the peak fluorescence, so the scattered background is gone. Each recorded trace is the average of 640 decay curves. Each lifetime is measured 5 times and, if possible, another 5 times on a second time window. Where possible, the lifetime is also rechecked on a second transition from the same level to ensure that the lines are properly identified and unblended. Thus, each lifetime reported from this study is based on about 10,000 individual decay curves.

The analysis must avoid or correct for a number of potential systematic errors. At very short lifetimes, such as those in this study, the bandwidth of the electronics is the dominant systematic effect. The bandwidth limits the precision of the measurements to ± 0.2 ns and prevents us from measuring lifetimes significantly shorter than ~ 2 ns. Our primary means of addressing this systematic error is to use reference lifetimes known from theory and accurate LIF experiments on fast beams as a test of the experiment. For this study, the following reference lifetimes were measured: Be I $2s2p\ ^1P^o_1$, $\tau = 1.80(4)$ ns (Weiss 1995); Fe II $z\ ^6F^o_{11/2}$, $\tau = 3.19(4)$ ns (Biemont et al. 1991); Fe II $z\ ^6D^o_{9/2}$, $\tau = 3.70(6)$ ns (Biemont et al. 1991); Yb II $4f^{13}(^2F^o_{7/2})\ 6s6p(^1P^o_1)\ J = 3.5$ $E_u = 59090.13$ cm^{-1}, $\tau = 2.31(10)$ ns (Pinnington, Berends, & Ji 1994); and Yb II $4f^{13}(^2F^o_{7/2})\ 6s6p(^1P^o_1)\ J = 4.5$ $E_u = 57765.32$ cm^{-1}, $\tau = 2.87(11)$ ns (Pinnington et al. 1994).

Errors from the precession of polarized atoms in a magnetic field (Zeeman quantum beats) are addressed by using three pairs of coils to cancel the geomagnetic field to within 0.02 G. Cascades through lower levels are not a concern for our measurements in Co II because of the structure of Co^+ energy levels. The Co^+ ion has only even parity energy levels up to ~ 44000 cm^{-1} and odd parity levels between 44000 and ~ 53000 cm^{-1}. Thus, there are no multistep decay chains allowed from the levels we are studying.

4. RESULTS

The branching fractions measured in this work are listed in Table 1. The number in parenthesis after each measurement is the uncertainty in the last digit(s). The energy levels in the table are from Sugar & Corliss (1985). Air wavelengths are from Iglesias (1979). Improved Co II energy levels and wavelengths will soon be submitted for pub-

TABLE 1

COMPARISON OF BRANCHING FRACTIONS MEASURED IN THIS STUDY TO OTHER RESULTS FROM THE LITERATURE

Upper Level		Lower Level			Branching Fraction		
Designation	E_u (cm^{-1})	Designation	E_l (cm^{-1})	λ_{air} (nm)	This work	Kurucz[a]	López-Urrutia[b]
$z\,^3G^o_5$	48556.16	$a\,^3F_4$	0.00	205.882	0.035(2)	0.0551	0.045(5)
		$a\,^5F_5$	3350.58	221.143	0.0273(11)	0.0140	0.030(5)
		$a\,^5F_4$	4029.00	224.513	0.195(6)	0.1228	0.23(3)
		$b\,^3F_4$	9812.96	258.032	0.743(9)	0.8077	0.70(7)
$z\,^3G^o_4$	49348.43	$a\,^3F_4$	0.00	202.576	0.067(7)	0.2295	0.07(1)
		$a\,^3F_3$	950.51	206.554	0.048(5)	0.0743	0.06(1)
		$a\,^5F_5$	3350.58	217.333	0.0079(8)	0.0043	0.012(4)
		$a\,^5F_3$	4560.81	223.208	0.041(3)	0.0058	...
		$b\,^3F_4$	9812.96	252.862	0.436(7)	0.5705	0.41(4)
		$b\,^3F_3$	10708.47	258.722	0.392(8)	0.1078	0.41(4)
$z\,^3F^o_4$	49697.81	$a\,^3F_4$	0.00	201.151	0.177(8)	0.1766	0.31(3)
		$a\,^5F_5$	3350.58	215.694	0.0038(2)	0.0006	...
		$a\,^5F_4$	4029.00	218.899	0.0037(2)	0.0056	...
		$a\,^5F_3$	4560.81	221.479	0.041(3)	0.0479	...
		$b\,^3F_4$	9812.96	250.646	0.384(4)	0.0925	0.34(3)
		$b\,^3F_3$	10708.47	256.404	0.383(5)	0.6689	0.34(3)
$z\,^3F^o_3$	50381.86	$a\,^3F_3$	950.51	202.235	0.219(18)	0.1854	0.31(3)
		$a\,^5F_2$	4950.20	220.041	0.0204(15)	0.0244	0.060(1)
		$b\,^3F_4$	9812.96	246.420	0.172(4)	0.0591	0.11(1)
		$b\,^3F_3$	10708.47	251.982	0.314(10)	0.0570	0.26(3)
		$b\,^3F_2$	11321.96	255.941	0.262(9)	0.6588	0.22(2)
		$a\,^3P_2$	13260.77	269.309	0.0024(3)	0.0047	...
$z\,^3F^o_2$	50914.51	$a\,^3F_3$	950.51	200.079	0.007(2)	0.0110	0.03(1)
		$a\,^3F_2$	1597.32	202.705	0.251(18)	0.3707	0.37(4)
		$a\,^5F_1$	5204.82	218.703	0.0076(5)	0.0111	0.010(3)
		$b\,^3F_3$	10708.47	248.644	0.183(5)	0.1128	0.15(2)
		$b\,^3F_2$	11321.96	252.497	0.527(14)	0.4723	0.43(4)
		$a\,^1D_2$	11651.48	254.616	0.0145(9)	0.0113	0.015(3)

NOTE.—Numbers in parentheses after each entry designate the uncertainty in the last digit(s).

[a] Kurucz 1988.

[b] López-Urrutia et al. 1994.

lication by Pickering et al. (1997). The table compares our results to the theoretical results of Kurucz (1988) and the experimental results of López-Urrutia et al. (1994). Our results agree well with López-Urrutia et al. (1994) for the z^3G^o levels, but we find significant differences between our results and those of López-Urrutia et al. (1994) for the $z\,^3F^o$ levels. We do not measure branching fractions for some of the weaker transitions, but these branches contribute less than 2% to the total decay of the upper level. We correct our data for the unmeasured branches using the calculations of Kurucz (1988). For example, for the $z\,^3G^o_4$ upper level, we did not measure the transition at 220.587 nm or any transition with $\lambda_{air} > 258.722$ nm. According to Kurucz (1988), these transitions account for 0.78% of the total decay from the upper level. Thus, instead of normalizing our branching fractions from that level to 1.0, we correct for the unmeasured branches and normalize to 0.9922. Therefore, the branching fractions in our table sum to slightly less than 1.0. This adjustment is a small correction to our data and generally falls within the uncertainties of our measurements.

Table 2 lists the lifetimes measured in this study. The wavelength column lists the transitions used for laser excitation to measure the lifetime of the upper level. The number in parenthesis after each measurement indicates the uncertainty in the final digit(s). The values listed from the literature were made by using the beam-foil technique. We find the best agreement with the measurements of Pinnington, Lutz, & Carriveau (1973). The average and rms difference between the lifetimes from Pinnington et al. (1973) and ours are +2.0% and 8.4%, respectively. The other beam-foil measurements yielded lifetimes that were longer than ours, probably as a result of cascade repopulation.

In Table 3, we combine the branching fraction measurements with the radiative lifetime measurements to determine 28 absolute UV oscillator strengths. We have listed these in the table in terms of $\log_{10}(gf)$, where $g = 2J + 1$. The results of Kurucz (1988) and Gruzdev (1962) are theoretical; the work of Corliss & Bozman (1962) is experimental. The theoretical oscillator strengths of Gruzdev (1962) are only relative; we have normalized his results so that they agree with ours for the strongest (258.032 nm) line. As is often the case, no estimates of uncertainties on the theoretical oscillator strengths are given. A comparison of our experimental oscillator strengths to the theoretical "semiempirical" oscillator strengths from Kurucz (1988) shows very good agreement on average with somewhat more serious scatter than was observed for other Co II lines (Kurucz 1981; Salih, Lawler, & Whaling 1985). The mean and rms value of $\log_{10}[(gf_K)/(gf_{expt})]$ are +0.007 and 0.345, respectively, where gf_K is the theoretical value from Kurucz (1988) and gf_{expt} is from this work. In an earlier comparison of Kurucz (1981) Co II oscillator strengths to experimental results, Salih et al. (1985) found the most serious discordances for spin-forbidden transitions. In this comparison, the most serious discordances tend to be distributed

TABLE 2

COMPARISON OF RADIATIVE LIFETIMES MEASURED USING LIF TO VALUES FROM THE LITERATURE

Term	J	E (cm^{-1})	λ_{air}[a] (nm)	Lifetime (ns)	
				This Work	Other Values
$z\,^3G^o$.....	5	48556.16	258.032	3.6(2)	4.6(4),[b] 3.3(2),[c] 5.2(12)[d]
	4	49348.43	252.862	3.3(2)	3.4(2)[c]
	3	50036.55	254.194	3.5(2)	3.9(2),[c] 5.5(8)[d]
$z\,^3F^o$.....	4	49697.81	250.646, 256.404	2.9(2)	3.9(4)[b]
	3	50381.86	251.982, 255.941	2.9(2)	...
	2	50914.51	252.497	2.9(2)	...
$z\,^3D^o$.....	3	51512.41	239.739, 245.000	2.3(2)	...
	2	52229.92	240.766	2.3(2)	3.9(4)[b]
	1	52684.77	241.690	2.4(2)	...

NOTE.—Number in parentheses after each entry is the uncertainty in the last digit(s).
[a] Listed wavelengths designate the transitions used for laser excitation in our measurement.
[b] Sørensen 1979.
[c] Pinnington, Lutz, & Carriveau 1973.
[d] Pinnington, Lutz, & Carriveau 1974.

between allowed and forbidden transitions. A comparison of our experimental oscillator strengths to the theoretical "intermediate coupling" results of Gruzdev (1962) shows that his results grossly overestimate the strengths of some of the spin-forbidden transitions. The mean and rms values of $\log_{10}[(gf_G)/(gf_{expt})]$ are +0.45 and 1.19, respectively, where gf_G is the theoretical value from Gruzdev (1962). The same comparison limited to spin-allowed transitions results in mean and rms values of −0.037 and 0.059, respectively. Corliss & Bozman (1962) estimated their uncertainties on $\log_{10}(gf)$ values as ±0.30. It is well known that actual errors, especially for ion lines, are larger. Except for one, all of the oscillator strengths from Corliss & Bozman (1962) are more than a factor of 10 larger than our oscillator strengths. Similar errors were seen by Salih et al. (1985) for other Co II lines.

5. CONCLUSION

We present branching fraction measurements for five levels and LIF radiative lifetime measurements for nine

TABLE 3

COMPARISON OF THE VALUES OF $\log_{10}(gf)$ TO OTHER RESULTS FROM THE LITERATURE

λ_{air} (nm)	Level		$\log_{10}(gf)$	
	Lower	Upper	This Work	Other Values
200.079.....	$a\,^3F_3$	$z\,^3F^o_2$	−2.15(11)	−1.684[a]
201.151.....	$a\,^3F_4$	$z\,^3F^o_4$	−0.48(3)	−0.377[a]
202.235.....	$a\,^3F_3$	$z\,^3F^o_3$	−0.49(4)	−0.439[a]
202.576.....	$a\,^3F_4$	$z\,^3G^o_4$	−0.95(5)	−0.264[a]
202.705.....	$a\,^3F_2$	$z\,^3F^o_2$	−0.57(4)	−0.291[a]
205.882.....	$a\,^3F_4$	$z\,^3G^o_5$	−1.17(4)	−0.933[a]
206.554.....	$a\,^3F_3$	$z\,^3G^o_4$	−1.07(5)	−0.846[a]
215.694.....	$a\,^5F_5$	$z\,^3F^o_4$	−2.09(4)	−2.665,[a] −0.76[c]
217.333.....	$a\,^5F_5$	$z\,^3G^o_4$	−1.81(5)	−1.846,[a] +0.84[c]
218.703.....	$a\,^5F_1$	$z\,^3F^o_2$	−2.03(4)	−1.97,[a] +0.65[c]
218.899.....	$a\,^5F_4$	$z\,^3F^o_4$	−2.08(4)	−1.801,[a] +0.84[c]
220.041.....	$a\,^5F_2$	$z\,^3F^o_3$	−1.45(4)	−1.392,[a] −0.29[c]
221.143.....	$a\,^5F_5$	$z\,^3G^o_5$	−1.21(3)	−1.378,[a] −1.86[c]
221.479.....	$a\,^5F_3$	$z\,^3F^o_4$	−1.02(4)	−0.969,[a] −1.60[c]
223.208.....	$a\,^5F_3$	$z\,^3G^o_4$	−1.08(4)	−1.89,[a] −1.35[c]
224.513.....	$a\,^5F_4$	$z\,^3G^o_5$	−0.35(3)	−0.51,[a] +0.31,[b] −0.71[c]
246.420.....	$b\,^3F_4$	$z\,^3F^o_3$	−0.42(3)	−0.655,[a] +0.65,[b] −0.52[c]
248.644.....	$b\,^3F_3$	$z\,^3F^o_2$	−0.54(3)	−0.484,[a] +0.76,[b] −0.60[c]
250.646.....	$b\,^3F_4$	$z\,^3F^o_4$	+0.05(3)	−0.467,[a] +1.45,[b] −0.04[c]
251.982.....	$b\,^3F_3$	$z\,^3F^o_3$	−0.14(3)	−0.76,[a] +1.21,[b] −0.15[c]
252.497.....	$b\,^3F_2$	$z\,^3F^o_2$	−0.06(3)	+0.005,[a] +1.25,[b] −0.04[c]
252.862.....	$b\,^3F_4$	$z\,^3G^o_4$	+0.06(3)	+0.324,[a] +1.74,[b] +0.07[c]
254.616.....	$a\,^1D_2$	$z\,^3F^o_2$	−1.61(4)	−1.61[a]
255.941.....	$b\,^3F_2$	$z\,^3F^o_3$	−0.21(3)	+0.17,[a] +1.23,[b] −0.23[c]
256.404.....	$b\,^3F_3$	$z\,^3F^o_4$	+0.07(3)	+0.303,[a] +1.31,[b] +0.06[c]
258.032.....	$b\,^3F_4$	$z\,^3G^o_5$	+0.36(2)	+0.429,[a] +1.61,[b] +0.36[c]
258.722.....	$b\,^3F_3$	$z\,^3G^o_4$	+0.03(3)	−0.489,[a] +1.29,[b] −0.08[c]
269.309.....	$a\,^3P_2$	$z\,^3F^o_3$	−2.20(5)	−1.936[a]

NOTE.—Numbers in parentheses designate the uncertainty in the last digit(s).
[a] Kurucz 1988.
[b] Corliss & Bozman 1962.
[c] Gruzdev 1962.

levels in Co II. These measurements have been combined to determine 28 absolute UV oscillator strengths. The oscillator strengths will set the absolute scale for the relative absorption measurements currently being made at the University of Wisconsin to determine VUV oscillator strengths in Co II. The measurements reported here, particularly those for the resonance lines, should be immediately useful in the interpretation of astronomical data.

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Note added in proof.—After submission of this manuscript we became aware of new theoretical *f*-values for all of the Co II lines studied in our work. The new calculations are by A. J. J. Rassen, J. C. Pickering, & P. H. M. Uylings, A&A, submitted (1997). The mean and rms values of $\log_{10}(gf_{\rm R}/gf_{\rm expt})$ are $+0.024$ and 0.07, respectively, where $gf_{\rm R}$ is the new theoretical value.