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A Review of Oscillator Strengths for Lines of Cu I

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New determinations of oscillator strengths made by Kock and Richter provide for the first time reference standards which permit the adjustment of five previous sets of measurements to an improved scale of absolute oscillator strengths for lines of Cu I. Critical discussions of the several sets of measurements and a consistent list of values for 272 lines in the region 2024 to 8092 Å are presented.

Key words: Atomic spectra; copper; Cu I; oscillator strengths; spectral lines of Cu I.

1. Introduction

Because of its superior electrical and thermal conductivity, relatively high melting point and strength, and its purity and cheapness in commerce, copper is widely used in electrical apparatus. It frequently serves as electrode material in various kinds of arcs and electrical discharges and its spectrum is on that account frequently observed in the laboratory. A good knowledge of the various physical constants associated with its spectrum leads to understanding of the discharges themselves. Although useful in the laboratory, the spectrum of copper is not well developed in stellar atmospheres, and is at present of limited astrophysical interest. About 20 lines of Cu I are observed in the solar spectrum.

The wavelengths and energy levels of the arc spectrum of copper have been thoroughly studied and determined by Shenstone [1948] but knowledge of the oscillator strengths of the lines, which is required if excitation conditions in discharges are to be measured and understood, is rather fragmentary. The reports of measurements are scattered throughout the literature, some of the measurements (my own included) are reduced to oscillator strengths with wrong temperatures, and the quantities reported differ in each report. Nevertheless, much of this data can be evaluated, corrected to proper temperatures, adjusted to an absolute scale, and tabulated in a useful and uniform fashion.

The framework on which this data can be reformed and assembled was provided by Kock and Richter [1966] when they measured 27 Cu I lines over the wavelength range 2618 to 5782 Å and energy level range 30535 to 64472 cm^{-1}. Their data provide lines over a wide enough range of energies to correct for erroneous temperatures used in earlier papers.

2. Published Data

A summary of the data critically reviewed in this paper is given in table 1. All of these measurements were made on relative scales; some were reported on absolute scales.

There are several papers of which the results are not included in this report. The early work at Utrecht by van Lingen [1936] and van den Bold [1945] on the two resonance lines, the six strong green and yellow lines, and the two infrared lines is now mainly of historical interest. Dickerman and Deuel [1964] have measured 12 lines in the blue region with a high-current free-burning arc in argon. Their results show serious and unsystematic disagreement with those of Kock and Richter and others. Riemann [1964] measured the six green and yellow lines and the two strong resonance lines in a wall-stabilized arc.

Ostroumenko and Rossikhin [1965] measured nine resonance lines between 2165 and 3274 Å in absorption with a furnace. Their value for the line at 2225 is an order of magnitude too low when compared with that of Slavenas [1966], who measured the same lines by the hook method. The same lines were also measured by Lvov [1970] using the method of atomic absorption in a flame. His value for the line at 2441 is an order of magnitude too high compared to the measurements of the other authors. With those two exceptions, the three sets of data are in good agreement.

An interesting paper by Vujnovic, Ivezic, and Tonejc-Mejaski [1968] included a few calculations according to Bates and Damgaard's coulomb approximation, which were in good agreement with Kock and Richter's experimental results. This prompted us to make further calculations of that kind, which are reported in section 4.

TABLE 1. *Published data on intensities and oscillator strengths in the first spectrum of copper* (Cu I)

Reference	Date	No. of lines	Wavelength range	Energy level range	Type of experiment	Quantity reported
			Å	cm^{-1}		
Allen	1932	27	4069–5641	62,403–64,472	Arc in air	$I\lambda^4$
Allen and Asaad	1957	133	3247–5432	30,535–75,263	Arc in air	log *gf*
Meggers, Corliss, and Scribner	1961	46	2024–8092	30,535–71,291	Arc in air	I
Corliss	1963	180	2626–7154	30,535–79,116	Arc in air	I
Slavenas	1966	9	2165–3274	30,535–46,173	Furnace	*f*
Corliss	1967	13	2024–2441	40,944–58,691	Arc in air	I
Kock and Richter	1968	27	2618–5782	30,535–64,472	Stabilized arc in Ar	A, log *gf*

2.1. Kock and Richter [1968]

These authors have made the first comprehensive set of measurements of oscillator strengths for lines of Cu I in a light source operating under LTE conditions at accurately specified temperatures and electron densities. The plasma temperatures were determined from the absolute intensity of Ar I lines that have accurately known transition probabilities. The light source was of the wall-stabilized arc design originally developed at the University of Kiel by Maecker [1956]. A great deal of study has been devoted to methods of accurate temperature determination in this arc, both in Germany and in the United States. See, e.g., W. L. Wiese [1968]. The temperature determinations of other experiments discussed subsequently in this review are decidedly inferior and some are now known to be seriously in error.

Kock and Richter included among the 27 lines they measured the three lines which depopulate the $4p\ ^2P_{3/2}$ upper level of the strong resonance line at 3247 Å. The lifetime of this level has been recently determined by three independent experiments; Levin and Budick [1966], Ney [1966] and Cunningham and Link [1967]. The value 7.1 ns is within the uncertainty of all three measurements and has been adopted by Kock and Richter to put their relative values on an absolute scale. The data reported in this review have been adjusted to their scale.

Kock and Richter's data are listed in table 3 in the column headed KR. A typographical error in their value for the line at 4480.35 Å has been corrected. The values they gave for the two strong lines near 8000 Å they calculated with Bates and Damgaard's coulomb approximation.

2.2. Allen [1932]

The first quantitative intensity measurements in Cu I were made in 1932 by C. W. Allen at Canberra in the course of a study of the behavior of the relative intensity of the sharp and diffuse lines arising from the $5s\ ^4D$ term which lies above the first ionization potential of Cu I. The $^4D_{5/2}$ and $^4D_{3/2}$ levels are broad and decay mainly by autoionization. Allen measured the relative intensities of all 27 lines of the $4p\ ^4P^\circ - 5s\ ^4D$, $4p\ ^4F^\circ - 5s\ ^4D$, and $4p\ ^4D^\circ - 5s\ ^4D$ multiplets at various currents from 1 to 19 A in a free-burning copper arc in air at atmospheric pressure. He found that the broad lines increased in intensity relative to the sharp ones as the current was increased but that the ratio reached a constant value for currents above 12 A. These limiting relative intensities were in fair agreement with Russell's multiplet sum rules. At small currents (or at low electron densities) the broad lines disappear.

Of the 27 lines in these three multiplets, 8 have been measured by Kock and Richter. A least squares fit of a straight line to the plot log $I\lambda^3/gf$(KR) versus E (upper) for these eight transitions provided the relationship by which oscillator strengths were calculated from Allen's intensities. The standard deviation of the points from the fitted line was [1] 0.18 dex (±50 percent). These results are listed in table 3 in the column headed CWA.

2.3. Meggers, Corliss, and Scribner [1961]

In order to provide quantitative intensity data on a uniform scale for thousands of spectral lines of the metallic elements, Meggers, Corliss, and Scribner at NBS diluted each of 70 elements to the extent of one atom of each element in 1000 atoms of copper and observed the spectra radiated from a 10-A free-burning arc in air between electrodes of the copper. To observe the corresponding data for copper, silver was used as the electrode material. The intensities of the copper lines in the silver arc were brought onto the same scale as the lines of the other elements by including atoms of Au and Zn in the silver electrodes. At the time that the work was done, no method of calibrating the intensity scale below 2500 Å was available. Subsequently, Corliss [1967] applied a calibration to the lines below 2500 Å.

Of the 27 Cu I lines reported by Kock and Richter, 20 are found in these NBS Intensity Tables. To correlate the two sets of data we have plotted as open circles in figure 1, log $(I\lambda^3)_{MCS}/gf_{KR}$ versus upper energy level for 18 of the lines. The two strong resonance lines at 3247 and 3274 Å have been omitted because of the possibility of systematic error in their intensity. They do not, however, deviate markedly from the least squares fitted line in the figure. The standard deviation of all the points in figure 1 from the line is 0.22 dex (±66%). Values of log *gf* were calculated from the intensities of the 46 Cu I lines in the NBS Intensity Tables by using the line in figure 1. They are reported in the column headed MCS in table 3.

[1] 0.18 dex = $10^{0.18}$.

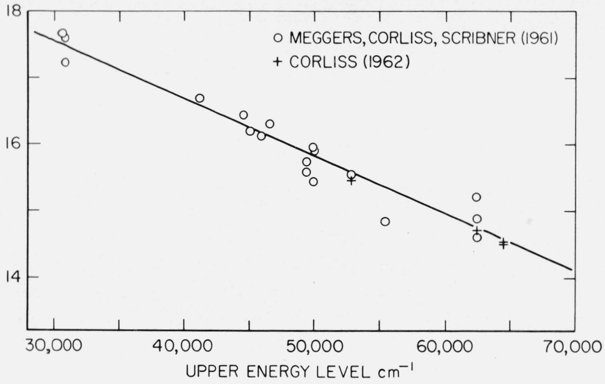

FIGURE 1. *Log ratio of intensity of copper lines in 10-ampere arcs times λ^3 to Kock and Richter's* gf*-values versus upper energy level.*

Open circles are for copper diluted 1/1000 in silver and crosses are for pure copper electrodes. Intensities from the silver arc have been multiplied by 1000.

2.4. Corliss [1962b]

To reduce the observations of Meggers, Corliss, and Scribner to a true scale of relative intensities, numerous lines of Cu I were selected to serve as reference standards of intensity. The relative power radiated by these lines was measured by comparison with a ribbon filament lamp and with a calibrated hydrogen continuum. The measurements were made by the methods of heterochromatic photographic photometry and are described in the NBS Tables. From 2 to 24 determinations were made on each of 207 lines of Cu I. The average number of determinations per line was 9 and the standard deviation of an individual determination is about 3 percent. The results for 180 lines were reported by Corliss [1962], who also calculated *gf*-values from the intensities using an arc temperature of 5100 K and a normalization function from Corliss and Bozman [1962]. Huber and Tobey [1968] and subsequently others have shown that this normalization function should in fact be a constant. Since this function changed more than two orders of magnitude between 50000 and 75000 cm^{-1} and since Cu I is peculiar among the metallic atoms in that most of its lines originate at those high energies, Corliss' derived *gf*-values for Cu I are seriously in error.

The work of Kock and Richter provides an opportunity for an accurate reduction of Corliss' intensities to oscillator strengths. The intensity scale of the NBS Tables should be identical with that of Corliss [1962b] except for a factor 1000 arising from the dilution. The intensities from MCS were therefore multiplied by 1000 before plotting in figure 1. Four lines from Corliss' [1962b] list that are also in Kock and Richter are plotted as crosses in figure 1. It is remarkable that these four points fall accurately on the least squares line. We have, therefore, calculated *gf*-values from Corliss' [1962b] intensities with the same relationship used for MCS. Several lines reported by Corliss which arise from broad levels as noted by Shenstone are now omitted. The remaining 163 lines are found in table 3 in the column headed C.

2.5. Allen and Asaad [1957]

Allen and Asaad at the University of London Observatory measured oscillator strengths for numerous spectra by the method of dilution in copper electrodes, and in the course of their work they also measured oscillator strengths for about 130 Cu I lines. A few of the stronger lines were affected by self-absorption, but the remaining measurements seem to be of good quality. Unfortunately, the measurements were reduced with an arc temperature of 4300 K which was based primarily on oscillator strengths measured by R. B. King in an absorption furnace. It now seems, v. Garz and Kock [1969], that these early values are subject to systematic errors dependent on excitation potential. This same source of error affected the subsequent work of Corliss [1962a], who determined the temperature of his copper arc with numerous sets of furnace *f*-values. He derived a temperature of 5100 K, but the present comparison with the data of Kock and Richter in figure 1 shows that the correct value is more nearly 7000 K.

With this in mind, a readjustment of Allen and Asaad's results to the temperature scale of Kock and Richter has been made. There are 10 lines in common to the two lists, but eight of these arise from the $5s\,^4D$ term. To make a readjustment to the new temperature scale, a wider range of energy levels is required. It is preferable, therefore, to adjust Allen and Asaad's values with 63 lines in common with Corliss' list. These span a range of 35000 cm^{-1} and provide a useful relationship for removing Allen and Asaad's systematic error. A linear least squares fit was made to a plot of log (AA/C) versus upper energy level. The standard deviation of the residuals is 0.11 dex ($\pm 30\%$). The corrected values are listed in table 3 in the column headed AA.

2.6. Slavenas [1966]

Slavenas measured relative oscillator strengths for nine resonance lines of Cu I by the hook method, using a vacuum furnace for his absorption cell. His values have been adjusted to the absolute scale adopted by Kock and Richter for the lines at 3247 and 3274 Å and are reported in the column headed S in table 3.

3. Absolute Scale

A thorough summary of recent determinations of absolute values for Cu I 3247 Å is given by Bell and Tubbs [1970]. Inspection of the 11 values determined since 1957 in their table 1 leaves little doubt that at present the best *f*-value for 3247 Å is 0.43 corresponding to log $gf = -0.07$. This is in excellent agreement with the value -0.05 adopted by Kock and Richter.

4. Coulomb Approximation

The success of Kock and Richter and of Vujnovic, Ivezic, and Tonejc-Mejaski in calculating good values for several Cu I lines by the method of Bates and Damgaard [1949] prompted me to apply that method to

19 of the lines measured by Kock and Richter. The results are given in table 2 and compared with the measured values. It is seen that, with the exception of the three lines involving the metastable $3d^9 4s^2\ ^2D$ term, the two sets of values show some agreement.

TABLE 2. *Values of log gf from the coulomb approximation (CA) compared with measured values (KR).*

Wave-length	Configurations and Terms				CA	KR
3247.54	$3d^{10}(^1S)4s$	$^2S_{1/2}-$	$3d^{10}(^1S)4p$	$^2P^\circ_{3/2}$	−0.01	−0.05
3273.96		$^2S_{1/2}-$		$^2P^\circ_{1/2}$	−0.32	−0.35
2961.16	$3d^9 4s^2$	$^2D_{5/2}-$	$3d^9 4s(^3D)4p$	$^2F^\circ_{7/2}$	0.09	−1.40
3063.41		$^2D_{3/2}-$		$^2P^\circ_{3/2}$	−1.08	−2.06
2824.37		$^2D_{5/2}-$		$^2D^\circ_{5/2}$	0.14	−1.25
5218.20	$3d^{10}(^1S)4p$	$^2P^\circ_{3/2}-$	$3d^{10}(^1S)4d$	$^2D_{5/2}$	0.30	0.27
5220.07		$^2P^\circ_{3/2}-$		$^2D_{3/2}$	−0.65	−0.61
5153.23		$^2P^\circ_{1/2}-$		$^2D_{3/2}$	0.04	−0.01
4530.78	$3d^{10}(^1S)4p$	$^2P^\circ_{3/2}-$	$3d^{10}(^1S)6s$	$^2S_{1/2}$	−1.38	−1.28
4480.35		$^2P^\circ_{3/2}-$		$^2S_{1/2}$	−1.68	−1.74
4062.64	$3d^{10}(^1S)4p$	$^2P^\circ_{3/2}-$	$3d^{10}(^1S)5d$	$^2D_{5/2}$	−0.35	−0.50
4022.63		$^2P^\circ_{1/2}-$		$^2D_{3/2}$	−0.61	−0.73
4275.11	$3d^9 4s(^3D)4p$	$^4P^\circ_{5/2}-$	$3d^9 4s(^3D)5s$	$^4D_{7/2}$	−0.35	−0.12
4248.96		$^4P^\circ_{1/2}-$		$^4D_{1/2}$	−1.04	−0.99
4651.12	$3d^9 4s(^3D)4p$	$^4F^\circ_{9/2}-$	$3d^9 4s(^3D)5s$	$^4D_{7/2}$	−0.18	−0.01
4704.59		$^4F^\circ_{7/2}-$		$^4D_{7/2}$	−1.11	−0.83
4586.97		$^4F^\circ_{7/2}-$		$^4D_{5/2}$	−0.38	−0.22
4539.70		$^4F^\circ_{5/2}-$		$^4D_{3/2}$	−0.51	−0.69
4509.37		$^4F^\circ_{3/2}-$		$^4D_{1/2}$	−0.69	0.77

5. Results

The results of this review are tabulated in table 3. The wavelengths, estimated intensities and energy levels of the lines are taken from Shenstone [1948]. In the intensity column, R indicates lines easily reversed or self-absorbed in the arc and H, HH, or HHH indicates the degree of broadening depending on the nature of the upper levels. The next five columns contain the various sets of data reduced to the scale of Kock and Richter as discussed in section 2. The last column gives a value which, in my judgment, is the best. In many cases it is the only value, in some cases it is Kock and Richter's value, in some cases the mean value, and in a few cases a weighted mean.

The uncertainty assigned by Kock and Richter to their results lies between 12 and 20 percent. The comparisons made in section 2 of this paper suggest that the uncertainty of the remaining values cannot be less than 30 to 66 percent.

TABLE 3. *Values of log gf for lines of* Cu I.

Wave-length	Intensity Estimate	Energy Levels	KR	S	MCS	C	AA	Best
Å		cm^{-1}						
2024.335	200R	0–49383			−0.48			−0.48
2138.533	500R	11203–57949			−0.17			−0.17
2165.093	1300R	0–46173		−0.77	−0.92			−0.84
2178.944	1600R	0–45879		−0.57	−0.83			−0.70
2181.720	1700R	0–45821		−0.77	−1.00			−0.89
2199.583	1700R	11203–56651			−0.12			−0.12
2199.752	1300R	13245–58691			−0.04			−0.04
2214.581	1600R	11203–56344			−0.38			−0.38
2225.697	2100R	0–44916		−1.10	−1.48			−1.29
2227.775	1600R	13245–58119			0.03			0.03
2230.084	2500R	11203–56030			−0.06			−0.06
2244.265	2300R	0–44544		−2.05				−2.05
2293.842	2500R	11203–54784			−0.77			−0.77
2441.637	1000R	0–40944		−2.35	−2.53			−2.44
2492.146	2000R	0–40114		−1.91	−1.87			−1.89
2618.366	2500R	11203–49383	−0.90		−0.92			−0.90
2626.678	10H	40944–79003				−1.10		−1.10
2630.001	20H	39019–77031				−1.05		−1.05
2634.933	30H	39019–76959				−1.01		−1.01
2645.303	20H	40114–77905				−1.47		−1.47
2649.840	30H	40114–77841				−1.31		−1.31
2766.371	2500R	13245–49383	−1.36		−1.55			−1.36
2824.370	1250R	11203–46598	−1.25		−0.98			−1.25
2846.478	15	40944–76064				−1.97		−1.97
2858.225	50H	39019–73995				−1.18		−1.18
2858.734	200	11203–46173				−3.48		−3.48
2882.934	1500	11203–45879			−2.02			−2.02
2890.84	50H	44406–78988				−1.06		−1.06
2891.64	30H	44544–79116				−1.11		−1.11
2931.699	10H	40944–75044				−2.16		−2.16
2933.060	20	39019–73103				−1.90		−1.90
2961.165	2500R	11203–44963	−1.40		−1.38			−1.40
2978.295	30H	43514–77080				−0.92		−0.92
2979.380	25H	43514–77068				−0.99		−0.99
2997.364	2000	13245–46598			−2.00			−2.00
2998.384	150	11203–44544				−3.84		−3.84
3010.838	2000	11203–44406			−1.95			−1.95
3012.005	250	40114–73305				−1.11		−1.11
3014.848	30H	41153–74313				−1.49		−1.49
3021.544	300H	40909–73995				−0.97		−0.97
3022.608	300H	39019–72093				−1.16		−1.16
3030.258	10H	40114–73105				−1.69		−1.69
3036.101	2500	13245–46173			−1.84			−1.84
3044.028	20H	41153–73995				−1.67		−1.67
3052.554	15H	41563–74313				−1.98		−1.98
3063.411	2500	13245–45879	−2.06		−2.03			−2.06
3068.906	15	13245–45821				−4.26		−4.26
3073.798	1400	11203–43726				−2.88		−2.88
3088.132	125	40944–73316				−1.13		−1.13
3093.989	1500	11203–43514			−2.44			−2.44

TABLE 3. *Values of log gf for lines of* Cu I.—Continued

Wave-length	Intensity Estimate	Energy Levels	KR	S	MCS	C	AA	Best
Å		cm^{-1}						
3099.928	1250	39019–71268				−0.53		−0.53
3113.482	50	39019–71128				−1.57		−1.57
3120.435	50H	40114–72151				−1.48		−1.48
3126.109	1400H	39019–70998				−0.35		−0.35
3128.701	650H	40114–72067				−0.71		−0.71
3140.312	400H	39019–70853				−0.99		−0.99
3142.444	750H	40114–71927				−0.57		−0.57
3146.821	450H	40114–71883				−0.83		−0.83
3148.333	3	41563–73316				−1.98		−1.98
3149.508	30	41563–73305				−1.61		−1.61
3156.629	450	13245–44916				−3.27		−3.27
3160.047	25	41563–73199				−1.59		−1.59
3169.681	500H	41563–73103				−0.69		−0.69
3171.663	5H	44544–76064				−1.66		−1.66
3194.099	1500	13245–44544	−2.02		−1.80			−2.02
3208.231	1400	13245–44406			−2.31			−2.31
3223.435	400H	42302–73316				−0.89		−0.89
3224.664	450H	42302–73305				−0.80		−0.80
3231.178	650H	41153–72093				−0.63		−0.63
3233.899	450H	41153–72067				−1.11		−1.11
3235.713	650H	42302–73199				−0.38		−0.38
3243.164	1500H	41153–71979				−0.15		−0.15
3247.540	10000R	0–30784	−0.05	−0.05	−0.22			−0.05
3268.278	650H	41563–72151				−0.67		−0.67
3273.957	10000R	0–30535	−0.35	−0.36	−0.53			−0.35
3279.815	2000	13245–43726			−2.14			−2.14
3282.716	1400H	41563–72017				−0.27		−0.27
3290.541	1500H	40909–71291				−0.19		−0.19
3292.393	125H	41563–71927				−1.25		−1.25
3292.827	650	11203–41563				−3.22		−3.22
3307.948	2500H	40909–71131			0.64			0.64
3317.218	750	41153–71291				−0.49		−0.49
3319.682	150	41153–71268				−0.68	−0.64	−0.66
3329.636	225	41153–71178				−1.05	−1.04	−1.04
3335.215	400	41153–71128				−1.04	−1.02	−1.03
3337.845	1500	11203–41153	−2.29		−2.10		−2.68	−2.29
3349.279	450H	42302–72151				−0.73	−0.52	−0.62
3354.474	60HH	42302–72104					−0.96	−0.96
3365.342	750H	41153–70860				−0.54	−0.56	−0.55
3375.672	30H	41563–71178				−1.52	−1.42	−1.47
3381.421	200H	41563–71128				−0.86	−0.62	−0.74
3384.80	15H	41563–71098					−1.47	−1.47
3392.016	8H	43726–73199				−1.87		−1.87
3396.324	10H	41563–70998				−1.79	−1.98	−1.88
3413.343	200H	45821–75109				−0.92		−0.92
3420.166	8H	45879–75109					−1.48	−1.48
3433.972	3H	30535–59647					−3.30	−3.30
3436.543	5H	46173–75263					−1.41	−1.41
3440.507	250	13245–42302				−3.60		−3.60
3457.850	750	11203–40114				−3.31	−3.50	−3.40

TABLE 3. *Values of log gf for lines of* Cu I.—Continued

Wave-length	Intensity Estimate	Energy Levels	KR	S	MCS	C	AA	Best
Å		cm^{-1}						
3459.428	25H	44406–73305				−1.44	−1.48	−1.46
3463.499	5HH	30784–59647					−2.65	−2.65
3472.141	200H	44406–73199				−1.08	−1.02	−1.05
3474.578	5	44544–73316				−1.78	−1.94	−1.86
3475.999	750H	44544–73305				−0.42		−0.42
3481.614	5	30535–59249					−1.67	−1.67
3483.761	1250H	44406–73103				−0.27		−0.27
3487.566	60H	46598–75263					−1.21	−1.21
3488.858	100H	44544–73199				−1.22	−1.24	−1.23
3498.063	125H	43514–72093				−1.25	−1.22	−1.24
3500.324	50H	44544–73105				−1.28		−1.28
3507.407	5H	43514–72017				−1.67	−0.94	−1.67
3512.121	650H	43514–71979				−0.48		−0.48
3517.039	100H	43726–72151				−1.25	−1.42	−1.34
3520.031	500	44916–73316				−0.54		−0.54
3524.231	1250	43726–72093				−0.31		−0.31
3527.482	500	43726–72067				−0.65	−0.71	−0.68
3530.383	2000	13245–41563				−2.60	−2.67	−2.64
3533.746	500	43726–72017				−0.66	−0.57	−0.62
3544.963	125H	43726–71927				−1.11	−1.12	−1.12
3546.433	15H	44916–73105				−1.52	−1.54	−1.53
3566.131	5HH	30535–58568					−2.31	−2.31
3594.023	30	11203–39019				−4.22	−4.31	−4.26
3599.132	1400	43514–71291			0.40			0.40
3602.032	1400	43514–71268			0.40		−0.38	0.40
3609.295	200	13245–40944				−3.84		−3.84
3610.809	200	44406–72093				−1.03	−1.04	−1.04
3613.761	600	43514–71178				−0.62	−0.62	−0.62
3614.218	200	44406–72067				−0.96	−1.04	−1.00
3620.352	225	43514–71128				−1.06	−1.15	−1.10
3621.245	600	44544–72151				−0.61	−0.62	−0.62
3624.236	100	43514–71098					−1.12	−1.12
3627.32	125HH	44544–72104					−0.68	−0.68
3629.771	10	43726–71268				−1.77		−1.77
3632.558	50	44406–71927					−1.23	−1.23
3635.916	250	45821–73316				−0.78	−0.77	−0.78
3641.693	50	43726–71178				−1.23	−1.30	−1.26
3645.232	250	45879–73305				−0.94	−1.00	−0.97
3648.383	125	43726–71128				−1.29	−1.40	−1.35
3650.855	5	44544–71927					−1.66	−1.66
3652.34	100H	43726–71098					−0.58	−0.58
3655.859	600H	43514–70860				−0.78	−0.92	−0.85
3656.785	125H	44544–71883				−1.13	−1.24	−1.18
3659.353	125H	45879–73199				−1.03	−1.11	−1.07
3665.735	125H	43726–70998				−1.31	−1.43	−1.37
3671.953	100H	45879–73105				−1.12	−1.14	−1.13
3687.438	400	30784–57895					−0.82	−0.82
3695.358	8H	44963–72017				−1.65	−2.03	−1.65
3699.097	10H	46173–73199				−1.55	−1.72	−1.64

TABLE 3. *Values of log gf for lines of* Cu I.

Wave-length	Intensity Estimate	Energy Levels	KR	CWA	MCS	C	AA	Best
Å		cm^{-1}						
3700.536	250H	44963–71979				−0.92		−0.92
3712.009	30H	46173–73105				−1.27	−1.22	−1.24
3720.771	150	13245–40114				−3.99	−4.03	−4.01
3721.666	8H	44406–71268				−1.78	−1.69	−1.74
3734.180	200H	44406–71178				−1.14	−1.11	−1.12
3741.242	450H	44406–71128				−0.89	−0.90	−0.90
3745.356	20H	44406–71098					−1.11	−1.11
3759.492	60	44406–70998				−1.30	−1.46	−1.38
3764.837	5H	44544–71098					−1.76	−1.76
3771.904	100H	46598–73103				−1.04	−0.99	−1.02
3780.045	5H	44406–70853					−1.90	−1.90
3797.245	8	44963–71291					−1.81	−1.81
3799.88	10H	44544–70853				−1.68	−1.49	−1.58
3800.502	30H	44963–71268				−1.34	−1.36	−1.35
3805.232	100H	45879–72151				−1.11		−1.11
3811.95	8HH	45879–72104					−1.39	−1.39
3813.542	10	44963–71178				−1.69	−1.63	−1.66
3817.490	5	45879–72067					−1.93	−1.93
3820.884	60	44963–71128				−1.27	−1.84	−1.27
3825.047	100H	30535–56671					−1.84	−1.84
3837.976	5	45879–71927				−1.91	−1.98	−1.94
3860.472	600	44963–70860				−0.67	−0.60	−0.64
3881.714	5	46173–71927				−1.76		−1.76
3888.40	4H	46173–71883					−1.87	−1.87
3921.267	5	46598–72093				−1.43	−1.40	−1.42
3925.274	8	46598–72067				−1.36	−1.29	−1.33
3933.027	5	46598–72017				−1.65		−1.65
3946.938	3	46598–71927				−1.88	−1.81	−1.84
3951.616	2	45879–71178				−2.30		−2.30
3964.16	5H	45879–71098					−1.70	−1.70
3975.7	5HHH	40114–65260					−1.73	−1.73
3979.954	5	45879–70998				−2.11	−2.19	−2.15
3993.692	0	45821–70853				−2.46		−2.46
3998.018	3	46173–71178				−2.13		−2.13
4003.028	15	45879–70853				−1.43	−1.45	−1.44
4010.836	8H	46173–71098					−1.93	−1.93
4015.8	10HHH	30535–55429					−2.49	−2.49
4022.629	1250	30535–55388	−0.73		−1.13			−0.73
4027.026	10	46173–70998				−1.42		−1.42
4050.617	20H	46173–70853				−1.45	−1.59	−1.52
4052.380	2	46598–71268				−1.39	−1.78	−1.78
4062.641	2000	30784–55391	−0.50					−0.50
4069.53	6HH	39019–63585		−2.59				−2.59
4073.224	20HHH	40114–64657					−1.59	−1.59
4075.572	50	46598–71128				−0.96	−1.00	−0.98
4080.534	15H	46598–71098					−1.12	−1.12
4104.218	25	40114–64472		−1.95		−1.75	−1.62	−1.77
4111.4	3HHH	40944–65260					−1.71	−1.71
4121.74	10	46598–70853				−1.55	−1.54	−1.54
4123.287	30H	43726–67971					−1.32	−1.32

TABLE 3. *Values of log gf for lines of* Cu I. — Continued

Wave-length	Intensity Estimate	Energy Levels	KR	CWA	MCS	C	AA	Best
Å		cm^{-1}						
4177.758	100HH	39019–62948		−1.30			−1.05	−1.18
4230.9	5HHH	43514–67142					−1.57	−1.57
4242.26	30H	44406–67971					−1.45	−1.45
4248.956	150	40944–64472	−0.99	−1.12		−1.00	−0.92	−0.99
4259.401	150HHH	40114–63585		−1.19				−1.19
4275.107	950	39019–62403	−0.12	−0.39	−0.11		−0.37	−0.12
4328.68	20HH	41563–64657					−1.79	−1.79
4336.00	10H	44916–67971					−1.77	−1.77
4354.74	10HHH	42302–65260					−1.55	−1.55
4378.20	550HH	40114–62948		−0.62			−0.44	−0.53
4415.54	200HH	40944–63585		−1.03			−0.78	−0.90
4480.350	500	30535–52849	−1.74			−1.81	−1.53	−1.74
4507.35	200HHH	44963–67142					−0.34	−0.34
4509.374	400	42302–64472	−0.77	−0.76		−0.75	−0.68	−0.77
4525.112	40H	45879–67971					−1.25	−1.25
4530.785	800	30784–52849	−1.28		−1.20			−1.28
4539.695	800HH	41563–63585	−0.69	−0.46			−0.50	−0.69
4586.97	1300HH	41153–62948	−0.22	−0.27			−0.19	−0.22
4642.58	150HHH	43726–65260					−0.81	−0.81
4651.124	2000	40909–62403	−0.01	−0.09	0.30		0.04	−0.01
4674.72	500HH	41563–62948		−0.71			−0.56	−0.64
4697.490	350HH	42302–63585		−0.86			−0.86	−0.86
4704.594	450	41153–62403	−0.83	−0.76		−0.81	−0.60	−0.83
4767.49	75HHH	46173–67142					−0.81	−0.81
4776.22	20HH	43726–64657					−1.59	−1.59
4797.042	20	41563–62403		−2.07		−2.07		−2.07
4842.290	25H	42302–62948		−1.84			−1.68	−1.76
4866.10	75HHH	46598–67142					−0.49	−0.49
5016.611	400	44544–64472		−0.79		−0.99	−0.81	−0.86
5034.36	100HH	43726–63585					−0.86	−0.86
5076.173	100HH	44963–64657					−0.55	−0.55
5105.541	1500	11203–30784	−1.51		−1.73			−1.51
5111.913	300	44916–64472		−0.98		−1.19	−0.94	−1.04
5144.120	550H	43514–62948		−0.69			−0.64	−0.66
5153.235	2000	30535–49935	−0.01		−0.29			−0.01
5200.87	500H	43726–62948					−0.77	−0.77
5212.780	140H	44406–63585		−1.29				−1.29
5218.202	2500	30784–49942	0.27		0.40			0.27
5220.070	500	30784–49935	−0.61		−0.38			−0.61
5250.52	500HH	44544–63585		−0.75			−0.74	−0.74
5292.517	1650	43514–62403	−0.44	−0.23	0.16		−0.16	−0.44
5352.666	300	43726–62403				−1.67		−1.67
5354.95	250HH	44916–63585		−1.02			−1.09	−1.06
5360.030	200	45821–64472				−1.70		−1.70
5376.867	5	45879–64472				−2.29		−2.29
5391.62	450HH	44406–62948		−0.81			−0.69	−0.75
5432.05	250HH	44544–62948		−1.06			−0.93	−1.00
5463.138	150	46173–64472				−1.86		−1.86
5554.935	100	44406–62403		−1.48		−1.78		−1.63
5700.240	1500	13245–30784	−2.34		−2.18			−2.34

TABLE 3. *Values of log gf for lines of* Cu I.—Continued

Wave-length	Intensity Estimate	Energy Levels	KR	CWA	MCS	C	AA	Best
Å		cm^{-1}						
5732.325	75	44963–62403				−1.82		−1.82
5782.132	1500	13245–30535	−1.78		−1.59			−1.78
6223.66	4	56030–72093				−1.33		−1.33
6325.45	5	46598–62403				−2.22		−2.22
6474.20	10	56651–72093				−1.17		−1.17
6485.18	5	56651–72067				−1.34		−1.34
6506.14	0	56651–72017				−1.95		−1.95
6544.51	1	56651–71927				−1.75		−1.75
6550.98	1	56030–71291				−1.86		−1.86
6583.54	0H	58119–73305				−1.66		−1.66
6599.68	0H	56030–71178				−1.95		−1.95
6621.61	30H	56030–71128				−1.00		−1.00
6629.67	5H	58119–73199				−1.52		−1.52
6672.23	10	58119–73103				−0.91		−0.91
6741.42	100	56030–70860				−0.47		−0.47
6881.94	10	56651–71178				−1.52		−1.52
6890.90	10	57419–71927				−1.45		−1.45
6905.94	100	56651–71128				−0.78		−0.78
6968.34	5	56651–70998				−1.84		−1.84
7154.29	5	58119–72093				−1.64		−1.64
7933.130	1500	30535–43137	−0.60		−0.34			−0.47
8092.634	2000	30784–43137	−0.30		−0.02			−0.16

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