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CALCULATIONS OF OSCILLATOR STRENGTHS AND LIFETIMES OF CuI, AgI AND AuI USING COULOMB APPROXIMATION

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Abstract

Oscillator strengths and lifetimes of all energy levels of CuI, AgI and AuI were calculated using the Coulomb approximation (for the first time), and then compared with available data.

Introduction

Single-valence electron atoma are an important class of atoms. Their oscillator strengths are their fundamental properties. The oscillator strengths of the spectral lines of most atoms are not known with sufficient accuracy due to experimental difficulties. The results of most measuring techniques are subject to large uncertainty due to uncertainties in vapor pressure data (1,2). A quick and simple method seems to be the Coulomb approximation of Bates and Damgaard (3). This theoretical calculation reveals some interesting properties which are generally in accordance with both experimental and detailed theoretical results. Knowing the oscillator strengths one can easily calculate the transition probabilites of the spectral lines and hence, the lifetimes of the energy levels of most atoms.

Theory

The oscillator strength F_{if} is related to the matrix elements of the dipole moment of the radiating electron. This quantity (in SI units) is expressed as (4)

$$F_{if}=\frac{2m\omega}{3\hbar g_i} \text{ if } x\frac{S_{if}}{e^2} \tag{1}$$

where m and e are the electron's mass and charge, $\hbar$, is the Plank's Constant divided by 2π, g_i is the statistical weight of the initial state, ω_{if} is the angular frequency of the absorbed or emitted radiation, and finally S_{if} is the line strength. Similar expression is given for the transition probability (4)

$$A_{fi} = \frac{e^2\,\omega^3_{fi}}{3\hbar\,\pi\,\varepsilon_0\,C^3} \times \frac{S_{if}}{g_f} \tag{2}$$

The subscripts i and f refer to the initial and final state, of the atom. The line strength S is given by where $\underset{\sim}{\varepsilon}$ is the

$$S_{if} = S_{fi} = \Sigma_{m_i\, m_f} \; |\langle im_i \mid \underset{\sim}{\varepsilon}.\underset{\sim}{D} \mid f_{mf}\rangle|^2 \tag{3}$$

polarization unit vector of light and $\underset{\sim}{D}$ is the dipole moment of the excited atom. The atomic wave function of the initial and final states are denoted by $|im_i\rangle$ and $fm_f\rangle$ respectively.

In order to calculate the oscillator strength or transition probability, one needs to know the atomic wave function. To simplify the problem, we consider transitions which do not involve equivalent electrons, and use L-S coupling as an approximation.

We rewrite equation (3) in a somewhat different form by using the components of vectors ε and D in their spherical bases

$$\underset{\sim}{\varepsilon}\cdot\underset{\sim}{D}=\Sigma_{q=-1}^{q=1}(-1)^q\,\varepsilon_{-q}D_q \tag{4}$$

Using (3), L-S coupling, and (4) we obtain

$$S\equiv S_{fi} = S_{if} = \Sigma_{q=-1}^{+1}\Sigma_{mm'}|\langle n'L's'j'm'|\,(-1)\,q\,\varepsilon_q\,D_q|nLsjm\rangle|^2 \tag{5}$$

where primed and unprimed symbols denote the lower and upper levels, respectively. Using the fact that $\varepsilon_q^2 = 1$ for $q= 0, \pm 1$ and that D_q is the q-component of a spherical tensor of rank 1 i, e $D_q = T_{lq}$ equation (5) reduces to

$$S=\Sigma_{q=-1}^{+i}\Sigma_{mm'}|\langle n'L's'j'm'|D_q\,|nLsjm\rangle|^2 \tag{6}$$

By the use of Rose's book notation (5), equation (6) can be written in uncoupled representation as

$$S=\Sigma_{q=-1}^{+1}\Sigma_{mm'}(2j+1)(2L'+1)\,W^2(Ljl'j';Sl)\times C^2(jlj',\ mqm')\,\delta_{SS'}\,|\langle n'L'|\;|D|\;|nL\rangle|^2 \tag{7}$$

Where W and C are the Racah and Clebsch-Gordan coefficients, respectively. The term $|\langle n'L'\|D\|nL\rangle|$ is called the reduced matrix element. The kronocker delta forbids spin-flip transitions. Knowing that the Clebsch-Gordan coefficients vanish unless $m'=m+q$ and using equations (3.7), (4.34),(4.35), (5.14) of the above mentioned reference, with a little calculation one obtains

$$S=e^2(2j+1)(2J'+1)(2L+1)\,W^2(Lj\,L'j',Sl)\,C^2(L1L',\ 000)\ x\int_0^\infty R^{\star}_{n'L'L''}R_{nL}\,rdr^2 \tag{8}$$

Thus, the oscillator strength (1) and transition probability (2) can be written as

$$F_{if} = \frac{2m\omega}{3\hbar}(2j+1)(2L+1)\,W^2(Lj\;L'j',\,Sl)\,C^2(L1L',\,000)\;x\;\left|\int_0^\infty R^*_{n'L'}R_{nL}\,r\,dr\right|^2 \tag{9}$$

and

$$A_{fi} = \frac{e^4\,\omega^3}{3\,\pi\,\varepsilon_0\,\hbar c^3}(2j'+1)(2L+1)\,W^2(Lj\;L'j',\,Sl)\times C^2(L1L';\,000)\times\left|\int_0^\infty R^*_{n'L'}R_{nL}\,r\,dr\right|^2 \tag{10}$$

respectively. In equations (1) and (2) $g_i = 2j'+1$, $g_f = 2j+1$, and $\omega_{if} = \omega_{fi} = \omega$ have been used.

In principle, all the factors in equation (9) and (10) can be calculated exactly except the radial integral part which needs to be evaluated approximately.

The Schrodinger equation for one electron atom with no spin and the central potential V (r) is given by:

$$\frac{d^2}{dr^2}R_{nL} + \left(-\frac{2m}{\hbar^2}V(r) + \frac{2m}{\hbar^2}E_n - \frac{L(L+1)}{r^2}\right)R_{nL}(r) = 0 \tag{11}$$

putting $\hbar = 1$, m 1, $2V(r) = -V(r)$, and $\varepsilon_n = -2E_n$ we have

$$\frac{d^2}{dr^2}R_{nL} + \left(V(r) - \frac{L(L+1)}{r^2} - \varepsilon_n\right)R_{nL}(r) = 0 \tag{12}$$

One needs to solve this equation for $R_{nL}(r)$ which satisfies the boundary conditions as $r \longrightarrow o$, $r \longrightarrow \infty$ and is normalized to unity.

For a hydrogen atom V (r) is the Coulomb potential and the energy parameter ϵ_n is the ionization energy expressed as:

$$\varepsilon_n = \frac{1}{n^2} \tag{13}$$

where n is an integer. For other single valance atoms, however, one usually defines an effective total quantum number n^* which is not necessarily an integer. By analogy we may put:

$$\varepsilon_{n^*} = \frac{1}{n^{*2}} \tag{14}$$

Using Thomas-Fermi function (6), one observes that the main part of radial wave function is far outside of the atomic core. Since the potential is Coulombic outside the core, Bates and Damgaard proposed to use a solution of hydrogenic Schrodinger equation with the energy parameter given by experiment and such that it still converges at $r \longrightarrow \infty$. Such a function can not generally converge at the origin, and, furthermore, does not have the right number of nodes. In calculating the matrix element of the electric dipole moment, however, such faults are not disadvantageous, since the contribution from the origin and near the origin for heavy atoms is negligible. Normalization of such functions is difficult, Bates and Damgaard take an approximate normalization factor.

To obtain the potential function for a complex atom, a central potential is assumed and it is further assumed that the major contribution to integral $\int_0^\infty R_{n'L'}\,r\,R_{nL}\,dr$ comes from the regions of moderate and large radial distances. Bates and Damgaard used the above approximation and showed that in order to evaluate the wave-function for many electron atoms it is sufficient to replace V by its asymptotic form, $\frac{Q}{r}$, where Q is the excess charge on the nucleus when the active electron is removed.

With this approximation equation (12) reduces to

$$\frac{d^2}{dr^2}R + \left(\frac{Q}{r} - \frac{L(L+1)}{r^2} - \varepsilon\right)R = 0 \tag{15}$$

The solution to equation (15), with boundary condition R $(r \longrightarrow \infty) \longrightarrow 0$, is the confluent hypergeometric function $W_{n^*,L+\frac{1}{2}}(2r/n^*)$, the expansion of which in a power series is (7)

$$W(2r/n^*) = \exp(-r/n^*)\,(2r/n^*)^{n^*}\sum_{t=0}^{\infty} A_t\,r^{-t} \tag{16}$$

Where A_0 is one and A_t is given by the following recursion formula

$$A_t = A_{t-1}\,\frac{n^*}{2t}\left(L(L+1) - (n^*-t)(n^*-t+1)\right) \tag{17}$$

The normalized wave function is obtained as

$$R_{n^*L} = \left(n^*\,\Gamma(n^*+L+1)\,\Gamma(n^*-L)/Q\right)^{1/2} W_{n^*L+1/2} \tag{18}$$

This series expansion of R_{n^*L} does not terminate for non-integer n^*.

Another approximation has been used in evaluating the normalized wave function (6). From equations (16), (17), (18), and after some manipulation one may obtain.

$$R_{nL} = \sum_{p=0} C(n^*,L)\,Q^{1/2}\,(Qr)^{n^*-p}\exp(-Qr\,|\,n^*) \tag{19}$$

where coefficients $C(n^*, L)$ are given by

$$C(n^*,L) = y(L)\cdot Q^{L-1/2}\,(2/n^*)^{n^*}A(L) \tag{20}$$

and

$$y(L) \equiv Q^{1/2}\left(n^*\left(\Gamma(n^*+L+1)\,\Gamma(n^*-2)\right)^{1/2}\right)^{-1}$$

$$A(L) \equiv A_t$$

When a similar expression obtained for the lower state and equation (19) are used we find

$$\int_0^\infty R_{n'L'}R_{nL}\,r\,dr = \frac{1}{Q}\sum_{p,p'=0}\int_0^\infty C_{p'}(n'^*,L')\,C_p(n^*,L)\;x\;(Qr)^{n'^*+n^*+1-p-p'}\exp\left[-Qr\left((n'^*+n^*)/(n'^*n^*)\right)\right]dr$$

$$= \frac{1}{Q}\sum_{p,p'=0}C_{p'}(n'^*,L')\,C_p(n^*,L)\left[n^*n^{1*}/(n^*+n^{1*})\right]^{n^*+n^{1*}+2-p-p^1}\times\Gamma(n^*+n^{1*}+2-p-p^1) \tag{21}$$

Now, the radial integral is in a calculable form provided that Γ-functions can be determined. The Γ-functions are determined (8) from.

$$\Gamma(z) = 1/\left(\sum_{k=1}^{\infty} C_k z^k\right), \tag{22}$$

where the coefficients C_k are tabulated in the above mentioned reference.

Numerical Calculations

Now all the factors in equations (9) and (10) are in calculable form. A computer program originally developed by P. Tsederis in Professor W. Happer's laboratory at Columbia University was used to evaluate the noble metal oscillator strengths, transition probabilities, and hence the lifetimes of the states. The values for the energy levels were taken from C. E. Moore's book (9).

Tables 1, 2, and 3, list, for example, the calculated oscillator strengths and wavelengths for given initial and final states of AgI, AuI, and CuI, respectively. Since the complete list of these data take quite a large space only part of them are given here.The complete list of these data can be obtained by request from the author.

The lifetime of each state for the above elements was calculated using transition probabilities. The results for these elements are listed in tables 4, 5, and 6 respectively. Double precision has been used throughout the computer program. The wavelengths and lifetimes are given only to two decimal places.

Discussion of the Results

A number of transition probabilities which are calculated by Pitchler (10) for AgI and CuI using this method are listed in column four of the tables 7 and 8 respectively, for comparison. The rest of the columns are taken from the same reference and list the corresponding experimental values. The agreement of present calculated transition probabilities with those of Pitchler is clearly seen.We should emphasis that our wavelengths are slightly larger than those given by Pitchler, but do not make any significant change to the values of oscillator strengths or transition probabilities.

A number of lifetimes of AgI and CuI are also listed in table 9. Column three shows the results of the present work. The rest of the columns list experimental values. Relatively good agreement between these results exist.

Summary

We have given a complete and comprehensive theoretical description of the Coulomb approximation. A computer program based on this theory has been written. With the help of this computer program the oscillator strengths and lifetimes of all available energy levels of CuI, AgI and AuI are calculated. To the best of our knowledge these data are given for the first time. These results have been compared, whenever available, with the corresponding theoretical and experimental results. In general, good agreement between them exist.

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Initial State	**Upper State**	**Absorption Oscillator Strength**	**Wavelength Å**
$5\ S_{1/2}$	$5\ P_{1/2}$	0.24	3383.86
	$5\ P_{3/2}$	0.51	3281.6
	$6\ P_{1/2}$	0.77×10^{-2}	2070.50
	$6\ P_{3/2}$	0.21×10^{-1}	2061.82
	$7\ P_{1/2}$	0.18×10^{-2}	1850.44
	$7\ P_{3/2}$	0.57×10^{-2}	1847.70
	$8\ P_{1/2}$	0.72×10^{-3}	1766.13
	$8\ P_{3/2}$	0.23×10^{-2}	1764.89
	$9\ P_{1/2}$	0.35×10^{-3}	1723.98
	$9\ P_{3/2}$	0.12×10^{-2}	1723.33
	$10\ P_{1/2}$	0.19×10^{-3}	1699.69
	$10\ P_{3/2}$	0.47×10^{-3}	1699.24
$5\ P_{1/2}$	$6\ S_{1/2}$	0.11	7689.89
	$5\ D_{3/2}$	0.52	5210.51
	$7\ S_{1/2}$	0.10×10^{-1}	4477.29
	$6\ D_{3/2}$	0.11	4056.61
	$11\ S_{1/2}$	0.50×10^{-3}	3380.21
	$10\ D_{3/2}$	0.88×10^{-2}	3351.55
	$12\ S_{1/2}$	0.32×10^{-3}	3330.83
	$11\ D_{3/2}$	0.61×10^{-2}	3311.35
	$12\ D_{3/2}$	0.42×10^{-2}	3283.47
$5\ P_{3/2}$	$6\ S_{1/2}$	0.12	8275.78
	$5\ D_{5/2}$	0.56×10^{-1}	5473.06
	$5\ D_{3/2}$	0.505	5467.01
	$7\ S_{1/2}$	0.10×10^{-1}	4669.78
	$6\ D_{3/2}$	0.11×10^{-1}	4214.00
	$6\ D_{5/2}$	0.10	4212.14
	$8\ S_{1/2}$	0.33×10^{-2}	3982.70
	$7\ D_{3/2}$	0.45×10^{-2}	3814.16
	$7\ D_{5/2}$	0.41×10^{-1}	3812.017
	$9\ S_{1/2}$	0.15×10^{-2}	3710.24
	$8\ D_{3/2}$	0.23×10^{-2}	3626.17
	$8\ D_{5/2}$	0.21×10^{-1}	3625.71

Table 1 - The Oscillator Strength and Wavelength of AgI

Initial State	Upper State	Absorption Oscillator Strength	Wavelength A°	Initial State	Upper State	Absorption Oscillator Strength	Wavelength A°
	$8 S_{1/2}$	0.34×10^{-2}	3941.83		$10 S_{1/2}$	0.81×10^{-3}	3570.73
	$7 D_{3/2}$	0.45×10^{-1}	3684.76		$9 D_{3/2}$	0.13×10^{-2}	3522.39
	$9 S_{1/2}$	0.15×10^{-2}	3587.69		$9 D_{5/2}$	0.12×10^{-1}	3522.12
	$8 D_{3/2}$	0.23×10^{-1}	3509.02		$11 S_{1/2}$	0.48×10^{-3}	3488.78
	$10 S_{1/2}$	0.83×10^{-3}	3457.08		$10 D_{3/2}$	0.86×10^{-3}	3458.26
	$9 D_{3/2}$	0.13×10^{-1}	3411.75		$10 D_{5/2}$	0.79×10^{-2}	3458.05
	$12 S_{1/2}$	0.31×10^{-3}	3436.20				
	$11 D_{3/2}$	0.60×10^{-3}	3415.48				
	$11 D_{5/2}$	0.54×10^{-2}	3415.44				
	$12 D_{3/2}$	0.41×10^{-3}	3385.82				
	$12 D_{5/2}$	0.37×10^{-2}	3385.82				

Table 1 cont

Initial State	Upper State	Absorption Oscillator Strength	Wavelength (A°)	Initial State	Upper State	Absorption Oscillator Strength	Wavelength A°
$6 S_{1/2}$	$6 P_{1/2}$	0.19	2676.73		$6 D_{3/2}$	0.47×10^{-1}	4812.94
	$6 p_{3/2}$	0.45	2428.69		$6 D^{5/2}$	0.41	4794.00
	$7 P_{1/2}$	0.10×10^{-2}	1665.75		$8 S_{1/2}$	0.10×10^{-1}	4243.02
	$7 P_{3/2}$	0.12×10^{-1}	1646.66		$7 D_{3/2}$	0.10×10^{-1}	3802.99
	$8 P_{1/2}$	0.33×10	1501.38		$7 D_{5/2}$	0.99×10^{-1}	3797.02
	$8 P_{3/2}$	0.14×10^{-2}	1494.53		$9 S_{1/2}$	0.31×10^{-2}	3635.54
					$8 D_{3/2}$	0.43×10^{-2}	3472.58
$6 P_{1/2}$	$7 S_{1/2}$	0.85×10^{-1}	5839.07		$8 D_{5/2}$	0.40×10^{-1}	3468.21
	$6 D_{3/2}$	0.34	4066.24		$10 S_{1/2}$	0.14×10	3396.39
	$8 S_{1/2}$	0.94×10^{-2}	3651.83		$9 D_{3/2}$	0.23×10^{-2}	3313.44
	$7 D_{3/2}$	0.92×10^{-1}	3321.10		$9 D_{5/2}$	0.21×10^{-1}	3310.59
	$9 S_{1/2}$	0.31×10^{-2}	3192.68		$11 S_{1/2}$	$0.78 , 10^{-3}$	3274.44
	$8 D_{3/2}$	0.39×10^{-1}	3066.31		$10 D_{3/2}$	0.13×10^{-2}	3226.89
	$10 S_{1/2}$	0.14×10^{-2}	3006.75		$10 D_{5/2}$	0.12×10^{-1}	3226.17
	$9 D_{3/2}$	0.21×10^{-1}	2941.56		$12 S_{1/2}$	0.4730×10^{-1}	3202.91
	$11 S_{1/2}$	0.77×10^{-3}	2910.79		$11 D_{3/2}$	0.86×10^{-3}	3173.01
	$10 D_{3/2}$	0.12×10^{-1}	2873.15		$11 D_{5/2}$	0.81×10^{-2}	3172.53
	$12 S_{1/2}$	0.47×10^{-3}	2854.12		$13 S_{1/2}$	0.30×10^{-3}	3157.24
	$11 D_{3/2}$	0.81×10^{-2}	2830.36		$12 D_{3/2}$	0.58×10^{-3}	3137.08
	$13 S_{1/2}$	0.31×10^{-3}	2817.80		$12 D_{5/2}$	0.55×10^{-2}	3136.71
	$12 D_{3/2}$	0.55×10^{-2}	2801.74		$14 S_{1/2}$	0.21×10^{-3}	3126.19
	$14 S_{1/2}$	0.21×10^{-3}	2793.04		$13 D_{3/2}$	0.40×10^{-3}	3111.98
	$13 D_{3/2}$	$0. 38 \times 10^{-2}$	2781.70		$13 D_{5/2}$	0.40×10^{-2}	3111.55
	$14 D_{3/2}$	0.29×10^{-2}	2766.90		$14 D_{3/2}$	0.30×10^{-3}	3093.47
$6 P_{3/2}$	$7 S_{1/2}$	0.11	7512.80		$14 D_{5/2}$	0.29×10^{-2}	3093.27

Table 2 – The Oscillator Strength and Wavelength of AuI

Initial State	Upper State	Absorption Oscillator Strength	Wavelength A	Initial State	Upper State	Absorption Oscillator Strength	Wavelength A°
$4 S_{1/2}$	$4 P_{1/2}$	0.24	3274.89		$6 P_{3/2}$	0.68×10^{-3}	1817.26
	$4 P_{3/2}$	0.49	3248.47		$7 P_{1/2}$	0.17×10^{-2}	1741.57
	$5 P_{1/2}$	0.71×10^{-2}	2024.97		$7 P_{3/2}$	0.49×10^{-2}	1725.66
	$5 P_{3/2}$	0.14×10^{-1}	2024.99		$8 P_{1/2}$	0.18×10^{-2}	1685.68
	$6 P_{1/2}$	0.14×10^{-3}	1825.34		$8 P_{3/2}$	0.24×10^{-2}	1687.04

Table 3 – The Oscillator Strength and Wavelength of CuI

Initial state	**Upper state**	**Absorption Oscillator Strength**	**Wavelength Å**
	$9P_{1/2}$	0.78×10^{-3}	1664.30
	$9P_{3/2}$	0.11×10^{-2}	1664.70
	$10P_{1/2}$	0.43×10^{-3}	1650.11
	$10P_{3/2}$	0.46×10^{-3}	1640.47
	$11P_{1/2}$	0.23×10^{-3}	1640.47
	$11P_{3/2}$	0.46×10^{-3}	1640.47
$4P_{1/2}$	$5S_{1/2}$	0.12	7935.31
	$4D_{3/2}$	0.51	5154.66
	$6S_{1/2}$	0.10×10^{-1}	4481.60
	$5D_{3/2}$	0.11	4023.76
	$7S_{1/2}$	0.32×10^{-2}	3826.12
	$6D_{3/2}$	0.44×10^{-1}	3655.27
	$8S_{1/2}$	0.14×10^{-2}	3567.14
	$7D_{3/2}$	0.22×10^{-1}	3482.60
	$9S_{1/2}$	0.78×10^{-3}	3434.94
	$8D_{3/2}$	0.13×10^{-1}	3386.36
	$9D_{3/2}$	0.83×10^{-2}	3326.76
	$10D_{3/2}$	0.56×10^{-2}	3287.13
$4P_{3/2}$	$5S_{1/2}$	0.12	8094.85
	$4D_{3/2}$	0.52×10^{-1}	5221.51
	$4D_{5/2}$	0.47	5219.65
	$6S_{1/2}$	0.10×10^{-1}	4532.05
	$5D_{3/2}$	0.11×10^{-1}	4064.38
	$5D_{5/2}$	0.10	4063.78
	$7S_{1/2}$	0.32×10^{-2}	3862.83
	$6D_{3/2}$	0.44×10^{-2}	3683.76
	$6D_{5/2}$	0.40×10^{-1}	3688.48
	$8S_{1/2}$	0.14×10^{-2}	3599.03
	$7D_{3/2}$	0.22×10^{-2}	3512.49
	$7D_{5/2}$	0.20×10^{-1}	3512.83
	$9S_{1/2}$	0.77×10^{-3}	3464.49
	$8D_{3/2}$	0.13×10^{-2}	3415.08
	$8D_{5/2}$	0.11×10^{-1}	3414.99
	$9D_{3/2}$	0.82×10^{-3}	3354.48
	$9D_{5/2}$	0.75×10^{-2}	3354.42
	$10D_{3/2}$	0.56×10^{-3}	3314.19
	$10D_{5/2}$	0.51×10^{-2}	3314.14
	$11D_{5/2}$	0.35×10^{-2}	3286.02
$5S_{1/2}$	$5P_{1/2}$	0.44	16010.09
	$5P_{3/2}$	0.89	16010.88
	$6P_{1/2}$	0.28×10^{-2}	8586.00
	$6P_{3/2}$	0.20×10^{-1}	8410.04
	$7P_{1/2}$	0.64×10^{-3}	7001.76
	$7P_{3/2}$	0.17×10^{-1}	6751.50
	$8P_{1/2}$	0.49×10^{-2}	6178.19
	$8P_{3/2}$	0.71×10^{-2}	6196.50
	$9P_{1/2}$	0.19×10^{-2}	5900.40
	$9P_{3/2}$	0.33×10^{-2}	5905. 48
	$10P_{1/2}$	0.10×10^{-2}	5725.83
	$10P_{3/2}$	0.19×10^{-2}	5728.09
	$11P_{1/2}$	0.64×10^{-3}	5611.42
	$11P_{3/2}$	0.12×10^{-2}	5611.42

Table 3 cont.

State	**Lifetime (n sec)**	**State**	**Lifetime (n sec)**	**State**	**Lifetime (n sec)**
$5S_{1/2}$	∞	$5F_{5/2}$	136.76	$11S_{1/2}$	538.23
$5P_{1/2}$	6.89	$5F_{7/2}$	137.53	$10D_{3/2}$	213.60
$5P_{3/2}$	6.23	$7D_{3/2}$	54.80	$10D_{5/2}$	220.35
$6S_{1/2}$	26.36	$7D_{5/2}$	56.13	$12S_{1/2}$	836.21
$6P_{1/2}$	45.54	$5G_{7/2}$	229.33	$11D_{3/2}$	301.83
$6P_{3/2}$	36.21	$5G_{9/2}$	229.33	$11D_{5/2}$	314.05
$5D_{3/2}$	12.95	$9S_{1/2}$	212.23	$12D_{3/2}$	422.21
$5D_{5/2}$	13.28	$9P_{1/2}$	564.26	$12D_{5/2}$	442.16
$7S_{1/2}$	58.40	$9P_{3/2}$	413.23		
$7P_{1/2}$	138.89	$8D_{3/2}$	91.97		
$7P_{3/2}$	104.67	$8D_{5/2}$	95.01		
$6D_{3/2}$	28.82	$6F_{5/2}$	228.30		
$6D_{5/2}$	29.70	$6F_{7/2}$	229.51		
$4F_{5/2}$	69.99	$10S_{1/2}$	349.47		
$4F_{7/2}$	70.27	$10P_{1/2}$	932.56		
$8S_{1/2}$	117.89	$10P_{3/2}$	650.80		
$8P_{1/2}$	306.06	$9D_{3/2}$	143.92		
$8P_{3/2}$	224.99	$9D_{5/2}$	148.73		

Table 4 – The lifetime of each state in AgI

State	Lifetime (n sec)	State	Lifetime (n sec)	State	Lifetime (n sec)
$6\,S_{1/2}$	∞	$7\,D_{5/2}$	27.69	$12\,S_{1/2}$	525.51
$6\,P_{1/2}$	5.42	$5\,F_{7/2}$	69.85	$11\,D_{3/2}$	200.14
$6\,P_{3/2}$	3.89	$5\,F_{5/2}$	68.74	$11\,D_{5/2}$	212.17
$7\,S_{1/2}$	22.29	$9\,S_{1/2}$	92.35	$13\,S_{1/2}$	783.11
$7\,P_{1/2}$	91.31	$8\,D_{3/2}$	49.82	$12\,D_{3/2}$	285.98
$7\,P_{3/2}$	37.88	$8\,D_{5/2}$	52.15	$12\,D_{5/2}$	302.64
$6\,D_{3/2}$	11.82	$10\,S_{1/2}$	191.32	$14\,S_{1/2}$	1117.25
$6\,D_{5/2}$	12.39	$9\,D_{3/2}$	84.31	$13\,D_{3/2}$	397.78
$8\,S_{1/2}$	47.38	$9\,D_{5/2}$	89.26	$13\,D_{5/2}$	414.35
$8\,P_{1/2}$	344.77	$11\,S_{1/2}$	332.43	$14\,D_{3/2}$	525.56
$8\,P_{3/2}$	168.53	$10\,D_{3/2}$	133.81	$14\,D_{5/2}$	557.13
$7\,D_{3/2}$	26.25	$10\,D_{5/2}$	141.53		

Table 5 – The lifetime of each state in AuI

State	Lifetime (n sec)	State	Lifetime (n sec)	State	Lifetime (n sec)	State	Lifetime (n sec)
$4\,S_{1/2}$	∞	$5\,D_{5/2}$	28.91	$7\,D_{5/2}$	93.12	$10\,D_{3/2}$	314.09
$4\,P_{1/2}$	6.51	$4\,F_{5/2}$	69.67	$8\,P_{1/2}$	157.21	$10\,D_{5/2}$	308.54
$4\,P_{3/2}$	6.34	$4\,F_{7/2}$	69.77	$8\,P_{3/2}$	217.99	$11\,P_{1/2}$	1021.55
$4\,S_{1/2}$	25.79	$7\,S_{1/2}$	114.15	$9\,S_{1/2}$	357.01	$11\,P_{3/2}$	1020.50
$5\,P_{1/2}$	43.15	$7\,P_{1/2}$	180.99	$8\,D_{3/2}$	149.90	$11\,D_{5/2}$	425.61
$5\,P_{3/2}$	43.17	$7\,P_{3/2}$	116.35	$8\,D_{5/2}$	146.45		
$4\,D_{3/2}$	12.80	$6\,D_{3/2}$	55.52	$9\,P_{1/2}$	339.30		
$4\,D_{5/2}$	12.88	$6\,D_{5/2}$	55.51	$9\,P_{3/2}$	422.89		
$6\,S_{1/2}$	58.54	$5\,F_{5/2}$	135.54	$9\,D_{3/2}$	221.89		
$6\,P_{1/2}$	324.83	$5\,F_{7/2}$	135.30	$9\,D_{5/2}$	217.61		
$6\,P_{3/2}$	230.95	$8\,S_{1/2}$	208.48	$10\,P_{1/2}$	594.70		
$5\,D_{3/2}$	28.61	$7\,D_{3/2}$	96.27	$10\,P_{3/2}$	725.22		

Table 6 – The lifetime of each state in CuI

		gA ($10^8\ s^{-1}$)			
λ (Å)	Transition	Present work	P.	T.S.	C.B.
8275.78	$5p^2P^o_{3/2}-6s^2\,S_{1/2}$	0.49	0.5	0.27	2.3
7689.88	$5p^2P^o_{1/2}-6s^2\,S_{1/2}$	0.23	0.27	0.17	1.4
5473.06	$5p^2P^o_{3/2}-5d^2\,D_{3/2}$	0.49	0.52	0.46	1.6
5467.01	$5p^2P^o_{3/2}-5d^2\,D_{5/2}$	4.44	4.66	4.1	16
5210.51	$5p^2P^o_{1/2}-5d^2\,D_{1/2}$	2.54	2.68	2.48	15
4669.78	5p P – 7s S	0.12	0.14	0.22	1.4
4477.29	5p P – 7s S	0.06	0.07	0.11	1.1
4214.00	5p P – 6d D	0.16	0.18	—	—
4212.14	5p P – 6d D	1.44	1.65	1.1	2.6
4056.61	5p P – 6d D	0.88	0.97	0.6	—
3982.70	5p P – 8s S	0.055	0.062	0.062	—
3841.83	5p P – 8s S	0.030	0.034	0.034	—
3814.16	5p P – 7d D	0.082	0.09	—	—
3812.01	5p P – 7d D	0.74	0.8	0.52	—
3684.76	5p P – 7d D	0.44	0.48	0.3	—

Table 7 – Transition probabilities of Ag I spectral lines

λ (A°)	Transition	Present work	P.	T.S.	C.B.
3710.24	5p P - 9s S	0.028	0.032	0.03	—
3587.69	5p P - 9s S	0.015	0.018	0.015	—
3626.17	5p P - 8d D	0.041	0.05	—	—
3625.71	5p P - 8d D	0.43	0.45	0.25	—
3509.02	5p P - 8d D	0.24	0.27	0.13	—

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T.S. Terpstra and Smit (11)
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Table 7 cont.

λ (A°)	Transition	gA ($10^{8}s^{-1}$) Present work	P.	K.R.	C.B.
8094.85	$4p^2P^o_{3/2}$ $-5s^2\,S_{1/2}$	0.48	0.51	—	2.6
7935.31	$4p^2P^o_{1/2}$ $-5s^2\,S_{1/2}$	0.25	0.27	—	1.3
5221.51	$4p^2P^o_{3/2}$ $-4d^2\,D_{3/2}$	0.50	0.54	0.6	0.95
5219.65	$4p^2P^o_{3/2}$ $-4d^2\,D_{5/2}$	4.58	4.83	4.5	5.8
5154.66	$4p^2P^o_{1/2}$ $-4d^2\,D_{3/2}$	2.55	2.69	2.4	4.7
4532.05	4 p P - 6 s S	0.13	0.14	0.17	0.65
4481.60	4 p P - 6 s S	0.06	0.07	0.06	—
4064.38	4 p P - 5 d D	0.17	0.2	—	—
4063.78	4 p P - 5 d D	1.61	1.77	1.26	—
4023.76	4 p P - 5 d D	0.9	1.0	0.76	0.77
3862.83	4 p P - 7 s S	0.057	0.062	—	—
3826. 12	4 p P - 7 s S	0. 027	0.032	—	—
3688. 76	4 p P - 6 d D	0.086	0.095	—	—
3688.48	4 p P - 6 d D	0.78	0.86	—	—
3655.27	4 p P - 6 d D	0.44	0.48	—	—
3599.03	4 p P - 8 s S	0.028	0.031	—	—
3567.14	4 p P - 8 s S	0.015	0.016	—	—
3512.99	4 p P - 7 d D	0.043	0.05	—	—
3512.83	4 p P - 7 d D	0.43	0.49	—	—
3482.60	4 p P - 7 d D	0.24	0.28	—	—

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K.R. Kock and Richtler (12)
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Table 8 Transition probabilities of Cu I spectral lines

Element	State	Present work T (n sec)	Phase shift	Level crossings	Atomic beam	Hook	Absorption tube
Cu	$4p^2P^o$	*	7.2±0.3[a]	7.2±0.7[b] 7.0[c]	—	5.0±0.8[c]	6.5±1.0[c]

Table 9 – Lifetimes of State of AgI and CuI

Element	**State**	**Present work T (n sec)**	**Phase shift**	**Level crossings**	**Atomic beam**	**Hook**	**Absorption tube**
Ag	$5^2P_{3/2}$	6.23	6.7±0.4[a]	6.7[c]	7.2±0.7[f] 7.3±0.4[g]	6.4±0.7[h]	7.0±0.8[I]
Ag	$5\ P_{1/2}$	6.89	7.5±0.4[a]	7.56±0.22[j]	8.0±0.8[f]	7±0.8[h]	8.78±1[I]

* Two lifetimes have been calculated for the state of CuI. The lifetimes for $^2P_{1/2}$ and $^2P_{3/2}$ are 6.51 n sec and 6.34 n sec respectively. In no experimental report that we know of have these lines been resolved.

a Cunningham PT Link J K (13)
b Levin L A Budick B (14)
c Bucka **et al** (15)
d Ostrovskii Y" I Penkin N P (16)
e King R B Stockbarger DC (17)
f Lawrence **et al** (18)
g Selter KP Kunze HJ (19)
h Penkin NP **et al** (20)
I Moise NL (21)
j Soltanolkotabi M Gupta R (22)

Table 9 cont.