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LIFETIMES AND OSCILLATOR STRENGTHS FOR ULTRAVIOLET TRANSITIONS IN SINGLY IONIZED COPPER

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ABSTRACT

High-quality oscillator strengths are needed to convert the amount of interstellar absorption into an accurate abundance from data acquired with the *Hubble Space Telescope* and the *Far Ultraviolet Spectroscopic Explorer*. In order to help clarify the appropriate values to use for ultraviolet transitions in Cu II, we report lifetimes from our beam-foil experiments. The Cu II results for the 1358.773 Å line ($3d^{10}\,{}^1S_0$–$3d^9 4p\,{}^1P^{\rm o}_1$) provide further evidence for a short lifetime for the upper level of interest. Additional results for transitions that can repopulate this upper level indicate that the data are not affected by cascades. Our measured lifetime, the most precisely determined to date, is in excellent agreement with the most recent experimental results and is consistent with theoretical values. When combined with the theoretical branching fractions of Donnelly et al. and Dong & Fritzsche, we obtain a value of 0.273 ± 0.028 for the oscillator strength, which is in very good agreement with the theoretical results of Donnelly et al. and the most recent recommended value given by Morton.

Key words: atomic data – ISM: abundances – ISM: atoms – methods: laboratory – ultraviolet: ISM

1. INTRODUCTION

Analysis of ultraviolet absorption from ions in the interstellar medium (ISM) gives us information on the makeup of interstellar clouds, the abundance of elements, and the production of elements in our Galaxy. Accurate gas-phase abundances can be determined from a combination of high-quality astronomical data and secure oscillator strengths. The percentage of the element that is incorporated into grains is then inferred through comparison of the observed gas-phase abundance in all ionization stages to the solar system abundance.

Previous studies of the interstellar abundance of copper (Jenkins et al. 1986; Cartledge et al. 2006) relied on atomic oscillator strengths compiled by Morton and colleagues (Morton & Smith 1973; Morton 1991; Morton 2003). For the principal line of interest, the $3d^{10}\,{}^1S_0$–$3d^9 4p\,{}^1P^{\rm o}_1$ transition in Cu II at 1358.773 Å, there is a significant spread in experimental (Curtis et al. 1976; Kono & Hattori 1982; Pinnington et al. 1997) and theoretical (Theodosiou 1986; Loginov 1993; Pinnington et al. 1997; Donnelly et al. 1999; Biémont et al. 2000; Dong & Fritzsche 2005) lifetimes and the associated oscillator strengths. To help clarify the situation, we conducted a new set of measurements based on beam-foil spectroscopy.

In the following sections, the details of the experiment are discussed. In Section 2, the experimental setup and techniques used to acquire and analyze data are described. In Section 3, we present our results and compare our lifetimes and derived oscillator strength for the primary transition to previously reported measurements and calculations. This is followed by a brief discussion (Section 4) of the results and their implications for the determination of the abundance of Cu in the ISM.

2. EXPERIMENTAL DETAILS

Here, we briefly describe the Toledo Heavy Ion Accelerator and how the data are acquired; further details can be found in Haar et al. (1993). The accelerator is a Danfysik Model 1080 mass separator and ion accelerator with a Danfysik Model 911A ion source attached. The 911A ion source is a hollow cathode design that is capable of generating ions from gaseous, liquid, or solid source materials. The mass-separating magnet allows for an isotopically pure beam to be passed from the ion source to the acceleration column. Once the ions are accelerated with the desired voltage, they are steered into the foil chamber. The foil chamber contains a carriage that is precisely moveable parallel and antiparallel to the path of the ion beam. The carriage has an attached rotating wheel, which can hold up to 23 foil holders. Just after the foil holders is the optical monitor (OM), a fiber optic bundle mounted just below the path of the beam. The signal from this fiber optic bundle is connected to an ultraviolet sensitive (solar blind) photomultiplier tube (PMT). The OM signal is used to normalize the data against the total light output. A Faraday cup (FC) is fixed to the back of the foil chamber and can be used as a second means of data normalization.

Attached to the side of the foil chamber is the entrance slit to a 1 m, $f/10.4$ normal incidence, Acton vacuum monochromator (model VM-521-SG). Light enters the monochromator through a narrow entrance slit and is dispersed by a grating. Two gratings were used for the experiments on Cu II: one blazed at 800 Å with 2400 lines $\rm mm^{-1}$ and the other blazed at 1600 Å with 1200 lines $\rm mm^{-1}$. The dispersed light then passes through the exit slits and is collected by one of two detectors. A Galileo Channeltron is used for the shortest wavelengths, and a Hamamatsu R7154 PMT records spectra near 2000 Å. The signals from the detector are then passed through a preamplifier, an amplifier, and a discriminator to data collection electronics. The signals pass through a Jorway Model 73A Camac Crate controller and are finally stored and displayed on a data acquisition computer.

Lifetime measurements are made by fixing the grating to disperse a particular wavelength and by moving the foil carriage in discrete steps with respect to the entrance slit. Since the distance downstream is known and the postfoil velocity of the beam can be calculated, the postfoil time can be determined. The typical maximum distance from the foil that is measured in these experiments is about 25 mm set by the size of the chamber.

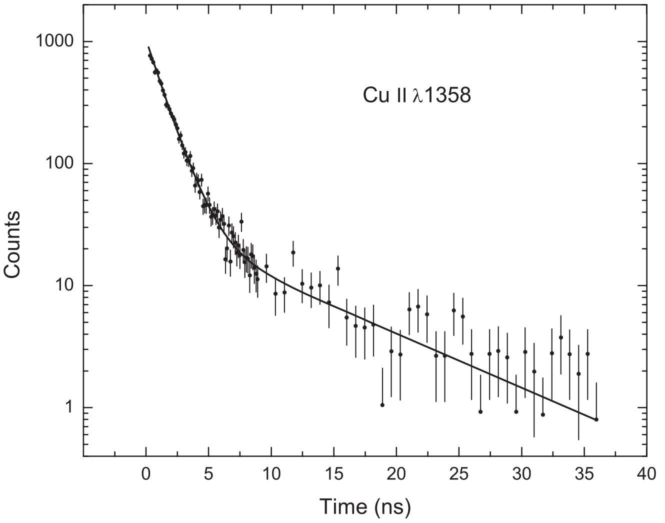

Figure 1. Decay curve with two exponential fit of Cu II line at 1358 Å at 170 keV in the forward direction. The postfoil beam velocity at this energy was 0.7002 mm ns^{-1}, establishing the time since excitation for a given foil position. The foil was moved relative to the monochromator entrance slit in increments of 0.1 mm until it was displaced to 5 mm; then the increments were increased to 0.5 mm.

In order to account for systematic errors, three different types of lifetime measurements are taken: forward lifetime measurements, reverse lifetime measurements at the same energy, and forward lifetime measurements at a significantly different energy. The forward lifetime measurements consist of moving the foil from a position slightly downstream of the monochromator entrance slit to a position upstream of the slit. The reverse lifetime measurement consists of moving the foil from upstream of the slit to a position just downstream of the slit (i.e., opposite of the forward lifetime measurement). This is done to account for any distortion in the timescale due to foil thickening and to check for the effects of foil aging (Federman et al. 1992). The third measurement consists of repeating the forward lifetime measurement at a different energy. Lifetimes measured at two different energies allow us to check for the effects of foil aging, for the effects due to different energy losses in the foil, and for the effects of different amounts of beam divergence (Federman et al. 1992).

The foils used for these experiments are made from thin carbon films deposited on microscope slides. The foils have an area density that varies from slide to slide but is in the range 2.1–2.5 μg cm^{-2}. When trying to decide the parameters of a data scan, how long the foil lasts is a large concern. The foil lifetime is determined from the atomic number, the atomic mass, and the acceleration energy of the incident ion as well as the foil material and the foil thickness.

3. RESULTS

The lifetime of the primary upper level of interest, $4p\,^{1}P^{\rm o}_{1}$, was obtained from the full suite of measurements. Forward and reverse decay curves were acquired at 170 keV. An additional forward decay curve was obtained at 240 keV. In each case, multiexponentials involving two lifetimes yielded the best fits, as revealed by reduced chi squares. The three determinations were consistent within their mutual uncertainties (statistical plus systematic), and a weighted average gave 1.37 ± 0.04 ns and 9.83 ± 0.94 ns, respectively, for the primary and secondary decays. An example of a fitted decay curve appears in Figure 1; the curve was acquired in the forward direction at 170 keV.

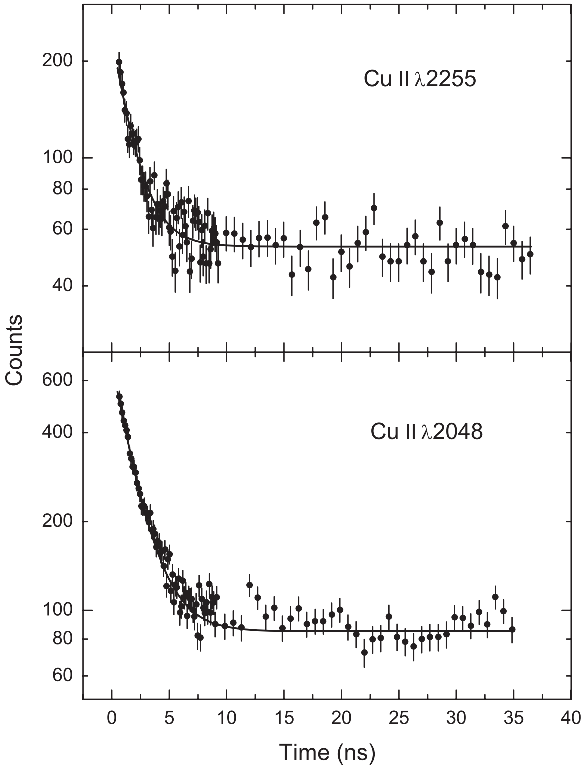

Figure 2. Decay curves with exponential fits that included a background of Cu II lines at 2255 Å (top panel) and 2048 Å (bottom panel), both at 170 keV in the forward direction.

In light of the secondary decay, we also sought possible contributions to the population in $4p\,^{1}P^{\rm o}_{1}$ from cascades involving higher energy levels. Three transitions that could contribute to the upper level of primary interest were identified, occurring at approximately 2048 Å ($4d\,^{1}S_{0}$), 2225 Å ($4d\,^{3}F_{2}$), and 2255 Å ($4d\,^{3}D_{1}$). The line at 2225 Å was severely blended with another line and lifetime measurements were not possible. These data were obtained in the forward direction at 170 keV. A single-exponential (plus background) fit to the decay curves yielded lifetimes of 1.88 ± 0.06 ns and 1.65 ± 0.13 ns, respectively, for the levels $4d\,^{1}S_{0}$ and $4d\,^{3}D_{1}$, where the uncertainties are statistical only. The fitted decay curves are displayed in Figure 2. The results were incorporated into an analysis to determine the importance of these transitions in repopulating the $4p\,^{1}P^{\rm o}_{1}$ level. The method of Arbitrarily Normalized Decay Curves (ANDC) of Curtis et al. (1970) was used. The ANDC analysis showed that $\lambda2048$ played a role in repopulating the $4p\,^{1}P^{\rm o}_{1}$ level, but not significantly enough to affect our results.

A summary of results on lifetimes appears in Table 1, where our values are compared to previous experimental and theoretical determinations. Our lifetime for the $4p\,^{1}P^{\rm o}_{1}$ level is in excellent agreement with the value of 1.34 ± 0.22 ns reported by Pinnington et al. (1997) using fast beam/laser interaction. Our value is shorter by slightly more than two standard deviations compared to the value of 1.8 ± 0.2 ns reported by Curtis et al. (1976) using beam-foil techniques and slightly more than one standard deviation from the measured value of 1.7 ± 0.3 ns quoted by Kono & Hattori (1982) based on delayed-coincidence techniques. Of the suite of available measurements, ours is the most precise, improving upon previous results by a factor of 5.

A variety of theoretical methods were applied to studies of lifetimes in Cu II. Theodosiou (1986) used the Coulomb approximation. Loginov (1993) obtained lifetimes from intermediate

Table 1

Measured and Calculated Lifetimes and Branching Fractions of Cu II

	Lifetimes (ns)			B_{ul}
Upper Level	$4p\ ^1P_1^o$	$4d\ ^1S_0$	$4d\ ^3D_1$	
Wavelength (Å)	1358	2048	2255	1358
Reference				
Experimental				
This work	1.37 ± 0.04	1.88 ± 0.06	1.65 ± 0.13	...
Curtis et al. (1976)	1.8 ± 0.2	...	...	...
Kono & Hattori (1982)	1.7 ± 0.3	...	...	0.255
Pinnington et al. (1997)	1.34 ± 0.22	...	...	...
Theoretical				
Theodosiou (1986)	1.056	1.498	1.319	0.48
Loginov (1993)	0.940	...	...	0.468
Pinnington et al. (1997)	0.87	...	...	0.576
Donnelly et al. (1999)	1.39[a]	1.72[a]	1.54[a]	0.440[a]
	1.61[b]	1.79[b]	1.61[b]	...
Biémont et al. (2000)	0.84	...	1.46	0.616
Dong & Fritzsche (2005)	1.15[a]	...	...	0.46[a]
	1.13[b]	...	...	...

Notes.

[a] Length formalism.

[b] Velocity formalism.

Table 2

Oscillator Strengths for the $3d^{10}\ ^1S_0$–$3d^9 4p\ ^1P_1^o$ Transition of Cu II

Reference	*f*-Values
This work	0.273 ± 0.028
Froese Fischer & Glass (1980)	0.368
Kono & Hattori (1982)	0.124
Theodosiou (1986)	0.403
Loginov (1993)	0.412
Pinnington et al. (1997)	0.548
Donnelly et al. (1999)	0.262
Biémont et al. (2000)	0.602
Dong & Fritzsche (2005)	0.331

coupling (IC) calculations. Pinnington et al. (1997) reported lifetimes based on a relativistic Hartree–Fock (HFR) calculation. Donnelly et al. (1999) determined values using configuration interaction plus relativistic effects. Biémont et al. (2000) performed calculations using HFR plus core polarization. Finally, Dong & Fritzsche (2005) reported values with multi-configurational Dirac–Fock computations. Both the length and velocity formalism were used by Donnelly et al. (1999) and Dong & Fritzsche (2005); both results are listed, the length form first, in this table. Most theoretical results yield somewhat shorter lifetimes than found experimentally for the decay of primary interest to interstellar studies. The lifetimes of Donnelly et al. (1999) and Dong & Fritzsche (2005) are most consistent with the two most recent experimental determinations, including the present one.

We also measured the lifetimes of two potential cascades into the upper state of interest, λλ2048, 2255. The lifetime for the upper level of the 2048 Å line was 1.88 ± 0.06 ns and that of the 2255 Å line was 1.65 ± 0.13 ns. Our values as well as previously reported values are summarized in Table 1; all results agree quite well.

To obtain an oscillator strength, or *f*-value, for the line at 1358 Å, we used

$$f = \frac{g_u}{g_l}\left(\frac{\lambda}{2582.7}\right)^2 A_{ul}, \qquad (1)$$

where f is the oscillator strength, g_u and g_l are statistical weights for the upper and lower levels, λ is the wavelength in Å, and A_{ul} is the transition probability in $10^9\ \mathrm{s}^{-1}$. The transition probability is related to the lifetime, τ, in ns by $A_{ul} = B_{ul}\tau^{-1}$, where B_{ul} is the branching fraction for each decay channel. Besides transitions to $3d^{10}\ ^1S_0$, the $^1P_1^o$ level decays to $3d^9 4s\ ^3D_2$, $^3D_1$, and $^1D_2$. We obtained an *f*-value of 0.273 ± 0.028 based on a branching fraction of 0.45, the average of the theoretical results of Donnelly et al. (1999) and Dong & Fritzsche (2005). As shown in Table 1, their lifetimes are most consistent with our precise determination, and their branching fraction is similar to the results of Theodosiou (1986) and Loginov (1993). The branching fractions of Pinnington et al. (1997) and Biémont et al. (2000) are substantially larger, while that of Kono & Hattori (1982) based on IC calculations is smaller. For completeness, previous theoretical branching fractions for λ1358 are included in Table 1. The clustering of values around 0.45 and the spread among all theoretical results suggest an uncertainty of about 10% for the branching fraction. This uncertainty was added in quadrature with that for our lifetime measurement to obtain the uncertainty in our *f*-value. Froese Fischer & Glass (1980), who performed multi-configurational HFR calculations, reported an *f*-value of 0.368. Theodosiou (1986) calculated a value of 0.403. Donnelly et al. (1999) gave 0.262, and Biémont et al. (2000) obtained 0.602. Morton's (2003) compilation recommends an *f*-value of 0.263 for this transition, based mainly on the results of Donnelly et al. (1999). Table 2 shows a summary of the *f*-values. The other entries are based on the lifetimes and branching fractions given in Table 1. Our oscillator strength agrees very well with that of Donnelly et al. (1999), which is essentially the same as Morton's (2003) recommended value. The value from the results of Kono & Hattori (1982) is much smaller because the lifetime is longer and the branching fraction is smaller. The other results tend to be larger, mainly the result of a shorter lifetime.

4. SUMMARY AND CONCLUSIONS

We measured the lifetime of the $4p\ ^1P_1^o$ level of Cu II. The value is in excellent agreement with the most recent experimental results and is in good agreement with other previous experimental results as well as with available theoretical lifetimes. Furthermore, our lifetimes for the levels $4d\ ^1S_0$ and $4d\ ^3D_1$ agree very well with theoretical determinations. Our oscillator strength for λ1358 based on a branching fraction of 0.45 is in very good agreement with that reported by Donnelly et al. (1999) and recommended by Morton (2003); differences with other determinations arise from longer experimental or shorter theoretical lifetimes, combined with the use of a different branching fraction. The significant improvement in precision of our measurements and the consistency with other recent efforts suggest that the recommended *f*-value in Morton (2003) is appropriate for studies of the interstellar copper abundance.

The determination of interstellar abundances is usually based on Morton's compilations for oscillator strength. Since our measured value for the oscillator strength is within 5% of the value recommended by Morton (2003), studies of the interstellar Cu abundance are now more secure. In particular, the Cu abundances described by Cartledge et al. (2006), which were based on the earlier recommendation of Morton (1991), need to be raised by a factor of ∼ 1.40. While the trends as a function of average gas density and path length noted by Cartledge et al. (2006) are not affected by this revision, it now appears there is less Cu incorporated into grains than once thought.

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