THE ASTROPHYSICAL JOURNAL, 504:921–924, 1998 September 10

SELECTED LIFETIME AND OSCILLATOR STRENGTH MEASUREMENTS IN Si II

RICHARD M. SCHECTMAN, HENRY S. POVOLNY, AND LORENZO J. CURTIS
Department of Physics and Astronomy, University of Toledo, Toledo, OH 43606
Received 1998 January 26; accepted 1998 April 8

ABSTRACT

We have remeasured the lifetimes of the $3s^2 4s$ and $3s^2 5s\,^2S_{1/2}$ levels in Si II using beam foil spectroscopic techniques. Measured values for the lifetimes and oscillator strengths derived from them are presented and compared with previous measurements and theoretical calculations. Agreement with recent theoretical calculations is now quite good: for $3s^2 4s$ it is excellent and for $3s^2 5s$ it is satisfactory, although the theoretical uncertainties in that calculation are still somewhat larger than desired.

Subject headings: atomic data — ISM: atoms

1. INTRODUCTION

Measurements of element abundances in interstellar space provide a probe of the nature and composition of the interstellar medium (Savage & Sembach 1996). The abundance of silicon in the gas phase can be derived from astronomical observations carried out with the *Hubble Space Telescope* (*HST*) and other satellite-based spectroscopic facilities. The data obtained with the Goddard High Resolution Spectrograph (GHRS) exhibit very high signal-to-noise ratios and allow routine measurement of equivalent widths with previously unattainable accuracy; they also allow measurement of very weak lines. In order to exploit this accuracy, accurate values for atomic oscillator strengths of resonance transitions are needed to interpret the *HST* data.

Since silicates are among the most common minerals in the universe, the abundance of Si is of particular interest. For observations along a line of sight containing large amounts of Si, where most absorption lines tend to be saturated, measurement of the weak line at 1808 Å is the preferred choice for determining the amount of silicon present in the intervening space. The oscillator strength for this line recently has been measured by Bergeson & Lawler (1993) using time-resolved laser-induced fluorescence, and can provide a precise Si abundance. The unusually long lifetime of this level (420 ns) led to its earlier underestimation in modulated electron beam phase-shift measurements (Curtis & Smith 1974; Savage & Lawrence 1966), presumably due to the escape of Coulomb-scattered ions from the viewing volume during the microsecond modulation times necessary for its access (Curtis & Erman 1977). On the other hand, for observations carried out along lines of sight where silicon is less abundant, the situation is quite different: while the line at 1808 Å may be too weak for reliable measurement, stronger transitions are often not saturated and can be used for analysis.

Using beam foil spectroscopic techniques, we have remeasured the lifetimes of the $3s^2 4s$ and $3s^2 5s\,^2S_{1/2}$ levels in Si II. In this paper, we report results of greatly improved precision for these cases and, where possible, derive oscillator strengths from the lifetimes for use in abundance determinations.

2. THE $3s^2 4s\,^2S_{1/2}$ LEVEL

2.1. *Lifetime*

A beam of 230 keV Si$^+$ ions was accelerated by the University of Toledo Heavy Ion Accelerator (THIA) and traversed 2.4 μg cm^{-2} carbon foils. Radiation subsequently emitted was analyzed by a 1 m vacuum ultraviolet monochromator, and time-resolved decay curves were obtained for the $3s^2 3p\,^2P^o_{3/2}$–$3s^2 4s\,^2S_{1/2}$ transition at 1533.4 Å by moving the foil relative to the monochromator. The result of superposing five such determinations is shown in Figure 1. The smooth curve is the result of a two-exponential least-squares fit to the data. The decay length of the second exponential, due to cascade repopulation of the $3s^2 4s\,^2S_{1/2}$ level, is an order of magnitude longer than that of the first, primary, exponential, and its relative intensity is an order of magnitude smaller. Thus, a lifetime extracted from exponential fitting is expected to be quite accurate. After using the known prefoil beam energy and the energy loss in the foil to convert the distance scale to a timescale, a mean life of $\tau = 0.91 \pm 0.04$ ns was obtained. The uncertainty quoted here includes the uncertainty in the postfoil beam velocity as well as the effect of the inability to treat the long-time tail of the decay curve precisely and uncertainties associated with the monitoring system. The $3s^2 3p\,^2P^o_{3/2}$–$3s^2 4s\,^2S_{1/2}$ transition at 1533 Å the decay curve of which was measured is not the desired resonance line (the $3s^2 3p\,^2P^o_{1/2}$–$3s^2 4s\,^2S_{1/2}$ transition at 1526.7 Å is). However, since these two lines both arise from the decay of the same state ($3s^2 4s\,^2S_{1/2}$), their decay curves must have identical shapes, and the stronger transition at 1533.4 Å was studied.

The principal cascade contribution to the population of the $3s^2 4s\,^2S$ level comes from the transitions from $3s^2 4p\,^2P^o$ shown schematically in Figure 2*a*. Curtis, Berry, & Bromander (1971) and Curtis (1976) developed a procedure (denoted ANDC) to account for the effects of cascade repopulation in a lifetime determination such as this. To implement this technique one measures both the decay curve of the level whose lifetime is to be determined, $I_1(t)$, and that of the source of the principal cascade repopulation, $I_2(t)$. It then follows that

$$d[\ln I_1(t)]/dt = -1/\tau_1 + \xi[I_2(t)/I_1(t)]\ ,$$

where τ_1 is the desired lifetime and ξ is a constant. In this experiment, $I_1(t)$ is the decay curve shown in Figure 1, while $I_2(t)$ was determined by measuring the decay curve of the cascading level for the alternate branch $3s3p^2\,^2D$–$3s^2 4p\,^2P^o$ at 3856 Å. These measurements were used to produce the ANDC plot $\{d[\ln I_1(t)]/dt$ vs. $[I_2(t)/I_1(t)]\}$ which is displayed in Figure 2*b*. A mean life of $\tau = 0.89 \pm 0.05$ ns was obtained from the intercept, in good agreement with the result from the exponential fit.

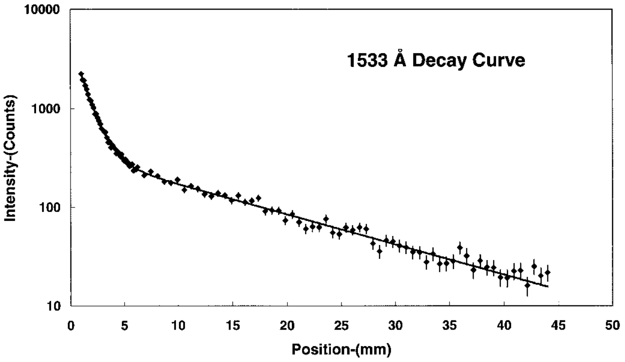

FIG. 1.—Time-resolved decay curve showing the decay of the $3s^24s\,^2S_{1/2}$ level; the solid curve shows the results of fitting the decay to the sum of two exponentials.

2.2. *A-Values and f-Values*

Transition probabilities per unit time (*A*-values) may be obtained from the measured lifetime of the $3s^24s\,^2S_{1/2}$ level if the branching ratio between the transitions to the two lower levels, $3s^23p\,^2P^o_{1/2,3/2}$, is known. The earlier measurement of Hofmann (1969) implied a branching ratio of $A(1533.4)/A(1526.7) = 2.03 \pm 0.04$.[1] In addition, we have remeasured this ratio as $A(1533.4)/A(1526.7) = 2.08 \pm 0.06$. These values agree well with each other and with the prediction of the Cowan relativistic code (Cowan 1981) and of Weiss (1969), both calculations predicting a branching ratio of 1.98. Combining the weighted mean of the two experimental branching ratios with our lifetime measurement gives rise to the *A*-values, $A(1526.7) = 0.364 \pm 0.017$ ns^{-1} and $A(1533.4) = 0.747 \pm 0.033$ ns^{-1}, and to the oscillator strengths, $f(1526.7) = 0.127 \pm 0.006$ and $f(1533.4) = 0.132 \pm 0.006$.

2.3. *Comparison with Previous Determinations and with Theory*

A comparison of these measurements with previous determinations is shown in Table 1. It can be seen that our new results agree well with the early measurement of Savage & Lawrence (1966) and are in reasonable agreement with the astronomical determination of Spitzer & Fitzpatrick (1993); however, there are significant differences from the other results shown. The value of the lifetime obtained by Curtis & Smith (1974) using phase-shift methods was substantially longer but was reported as cascade-free. Our ANDC results indicated significant cascading from $3s^24p\,^2P^o$ with a replenishment ratio (Curtis, Berry, & Bromander 1970) of 6% and an effective composite *e*-folding time approximately 10 times the primary mean life. Thus it is likely that cascading may account for this discrepancy. A comparison with theoretical predictions is shown in Table 2. The agreement with the early calculation of Weiss (1969) and with most of the recent theoretical work is excellent.

TABLE 1

COMPARISON OF MEASURED 1531.2 Å MULTIPLET OSCILLATOR STRENGTH WITH PREVIOUS DETERMINATIONS

Measurements	*f*-Value
Laboratory:	
This Measurement	0.130 ± 0.006
Curtis & Smith 1974	0.078 ± 0.016
Hofmann 1969	0.087
Savage & Lawrence 1966	0.130 ± 0.029
Astronomical:	
Spitzer & Fitzpatrick 1993	0.110
Van Buren 1986	0.21 ± 0.07
Shull et al. 1981[a]	0.230

[a] Basis for old "recommended" value of Morton 1991.

3. THE $3s^25s\,^2S_{1/2}$ LEVEL

3.1. *Lifetime*

Here, 170 keV Si$^+$ ions traversed 2.4 μg cm^{-2} carbon foils, and decay curves were obtained for the $3s^23p\,^2P^o_{3/2}$–$3s^25s\,^2S_{1/2}$ transition at 1023.7 Å. The result of superposing 10 such measurements is shown in Figure 3. The dashed curve is the result of a two-exponential least-squares fit to the data. The primary decay length inferred from the fit is 2.11 ± 0.09 mm. For a postfoil beam velocity of 1.06 ± 0.02 mm ns^{-1}, we obtain a mean life of

---

[1] While the absolute values of the transition probabilities per unit time measured by Hofmann seem to be in error (see Table 1), the *relative A*-values he obtained are likely to be significantly more accurate.

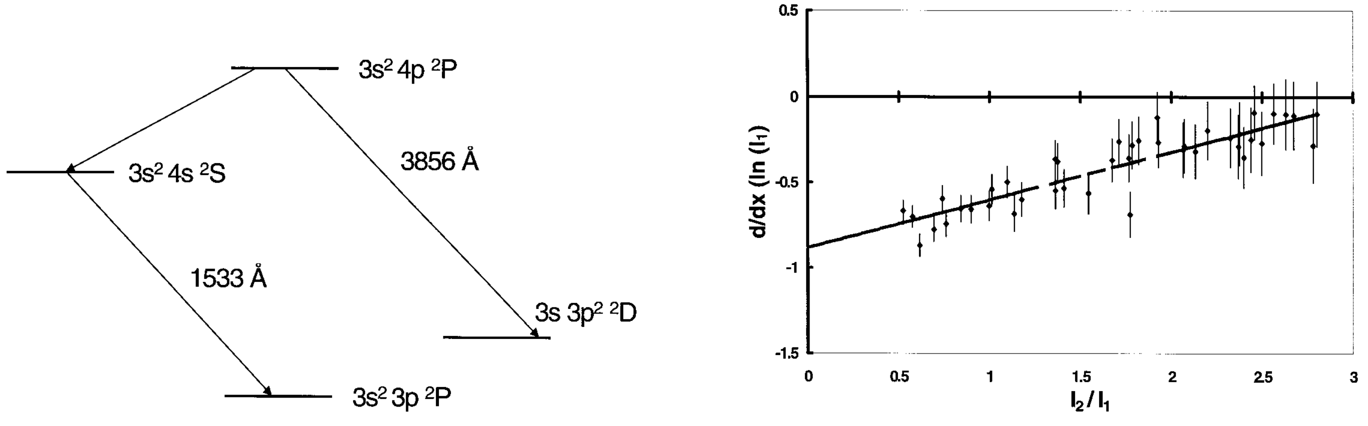

FIG. 2*a* FIG. 2*b*

FIG. 2.—(*a*) Schematic level scheme showing the principal cascade repopulating the $3s^24s\,^2S$ level in Si II. (*b*) ANDC plot for the level scheme illustrated. The analysis incorporates measurements of the decay of the $3s^24s\,^2S$ level decaying with the emission of 1533 Å photons with measurements of the decay of the $3s^24p\,^2P$ level through detection of 3856 Å photons. The lifetime of the $3s^24s\,^2S$ level is obtained from the *y*-intercept of the above graph.

TABLE 2

COMPARISON OF MEASURED 1531.2 Å MULTIPLET OSCILLATOR STRENGTH WITH THEORETICAL CALCULATIONS

Measurements	*f*-Value
This Measurement	0.130 ± 0.006
Mendoza et al. 1995	0.131
Marciniak & Migdalek 1993	0.133
Hibbert et al. 1992	0.130
Hjorth-Jensen & Aashamar 1990	0.141
Luo, Pradhan, & Shull 1988	0.118
Aashamar, Luke, & Talman 1984	0.13
Dufton et al. 1983	0.119
Artru et al. 1981	0.126
Nussbaumer 1977	0.118
Weiss 1969	0.130

$\tau = 1.99 \pm 0.12$ ns. Again, the uncertainty also includes effects of the unknown long-time behavior of the decay curve and uncertainties associated with the monitoring system.

3.2. *Comparison with Previous Determinations and with Theory*

The measured lifetime for the 1023.7 Å line may be compared with our previous determination (Curtis & Smith 1974) and with the calculations of Weiss (1969) and of Hibbert, Ojha, & Stafford (1992). The results are shown in Table 3. Our present result is in excellent agreement with the older calculation of Weiss (1969), who predicted a lifetime of 1.91 ns. It is also clearly much closer to the newer theoretical value of Hibbert et al. (1992), 2.50 ns, than our previous phase-shift value was, although it still differs from this result by 4 experimental standard deviations. Recently (A. Hibbert 1996, private communication) has noted that the disagreement between the length and velocity forms which he reported in his paper suggests that convergence, especially for the 4*p*–5*s* transition, had not been obtained in that calculation. Additional configurations would need to have been included to obtain a 5*s* lifetime with the same precision as he reported for the 4*s* lifetime. Such calculations have not yet been carried out. Hibbert estimates that inclusion of additional configurations would give rise to a lifetime of approximately 2.36 with a precision of some 10%–15%. Thus, the current agreement between experiment and theory is satisfactory when both experimental and theoretical uncertainties are considered. A more precise test awaits the conclusion of a more inclusive calculation.

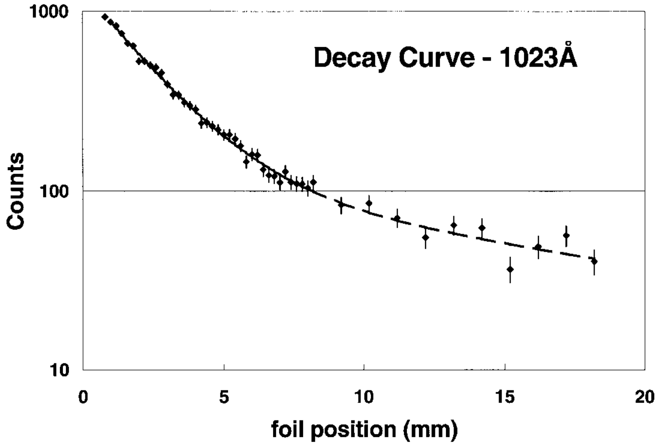

FIG. 3.—Time-resolved decay curve showing the decay of the $3s^2 5s\,^2S_{1/2}$ level. The dashed curve shows the results of fitting the decay to the sum of two exponentials.

TABLE 3

COMPARISON OF MEASURED 1023.7 Å LIFETIME WITH PREVIOUS MEASUREMENT AND THEORETICAL CALCULATIONS

Measurement	Lifetime (ns)
This Measurement	1.99 ± 0.12
Curtis & Smith 1974 (experiment)	0.97 ± 0.2
Weiss 1969 (theory)	1.91
Hibbert et al. 1992 (theory)	2.501

The 5*s* level decays to the two 3*p* levels with the emission of 1020.7 and 1023.7 Å photons and also decays to the two 4*p* levels with the emission of 5957.6 and 5978.9 Å photons. Because of the large difference in wavelength between these two regions, it is difficult to measure precisely the relative efficiency of our detection apparatus. Thus we were unable to measure a branching ratio with sufficient precision to extract accurate *A*-values from the lifetime which we measured. Nevertheless, the measured lifetime is important as a check of theoretical calculations that can then be used to interpret recent astronomical observations.

At present, therefore, one must rely upon theory to extract from the measured lifetime a transition probability, and thereby an oscillator strength, for the $3s^2 3p\,^2P^o_{1/2}$–$3s^2 5s\,^2S_{1/2}$ resonance transition. The two calculations that give the best agreement with our lifetime determination (Weiss 1969 and use of the Cowan relativistic code) give a branching ratio between the two multiplets of BR(4*p*–5*s*/3*p*–5*s*) = 0.31. Combined with our measured value of $\tau = 1.99 \pm 0.12$, this results in the multiplet *A*-value $A(3p\text{–}5s) = 0.384 \pm 0.023$ ns^{-1}. On the other hand, the more recent calculations of Hibbert et al. (1992) and Mendoza et al. (1995, unpublished), which agree less well with our lifetime measurement, give a very different branching ratio, BR(4*p*–5*s*/3*p*–5*s*) = 0.46. This results in $A(3p\text{–}5s) = 0.344 \pm 0.021$ ns^{-1}. In the absence of additional information, one can use the mean of these two values, $A(3p\text{–}5s) = 0.364 \pm 0.028$ ns^{-1}, a value not as precise as desired but accurate enough for many purposes. [The same procedure gives rise to a multiplet *A*-value for the weaker branch of $A(4p\text{–}5s) = 0.139 \pm 0.028$ ns^{-1}.] Our calculations using the Cowan (1981) code and those of Weiss (1969) suggest that the *LS* prediction of $BR(^2S_{1/2}\text{–}^2P_{1/2}/^2S_{1/2}\text{–}^2P_{3/2}) = 0.5$ is correct for the transitions both to the 3*p* and 4*p* levels. One therefore obtains for the resonance transition $A(3s^2 3p\,^2P^o_{1/2}\text{–}3s^2 5s\,^2S_{1/2}) = 0.121 \pm 0.009$ ns^{-1}, and $f = 0.0189 \pm 0.0014$. This oscillator strength differs significantly from the value $f = 0.0283$ obtained by Shull, Snow, & York (1981) and reported by Morton (1991).

4. DISCUSSION AND CONCLUSIONS

The oscillator strengths measured for the transitions 3*p*–4*s* at 1526.7 and 1533.4 Å are accurate to approximately

5% and are in excellent agreement with recent theoretical calculations. These values may be used with confidence in the analysis of recent astronomical observations. For the 5*s* level, only the lifetime has been accurately measured to an accuracy of about 6%. However, agreement with the most recent theoretical calculations is only at the 10%–15% level. An expanded theoretical calculation is needed to improve the situation (A. Hibbert 1996, private communication), and an experimental determination of branching ratio for the (3*p*–5*s*) and (3*p*–4s) transitions would also be desirable to reach the desired 5%–6% level of accuracy.

This work was supported in part by NASA grant NAGW-3840 and DOE grant DE-FG05-92ER14461. The authors gratefully acknowledge helpful conversations with David G. Ellis and valuable correspondence with Alan Hibbert.

REFERENCES

Aashamar, K., Luke, T. M., & Talman, J. D. 1984, Phys. Scr., 30, 121
Artu, M.-C., Jamar, C., Petrini, D., & Praderie, F. 1981, A&AS, 44, 171
Bergeson, S. D., & Lawler, J. E. 1993, ApJ, 414, L137
Cowan, R. D. 1981 Theory of Atomic Structure and Spectra (Berkeley: Univ. California Press), 1981
Curtis, L. J. 1976, in Topics in Current Physics, ed. S. Bashkin (Heidelberg: Springer), p. 63
Curtis, L. J., Berry H. G., & Bromander, J. 1970, Phys. Scr., 2, 216
———. 1971, Phys. Lett., 34A, 169
Curtis, L. J., & Erman, P. 1977, J. Opt. Soc. Am., 67, 1218
Curtis, L. J., & Smith, W. H. 1974, Phys. Rev., A9, 1537
Dufton, P. L., Hibbert, A., Kingston, A. E., & Tully, J. A. 1983, MNRAS, 202, 145
Hibbert, A., Ojha, P. C., & Stafford, R. P. 1992, J. Phys. B, 25, 4153
Hjorth-Jensen, M., & Aashamar, K. 1990, Phys. Scr., 42, 309
Hofmann, W. 1969, Z. Naturforsch., A24, 990
Luo, D., Pradhan, A. K., & Shull, J. M. 1988, ApJ, 335, 498
Marciniak, R., & Migdalek, J. 1993, J. Phys. B, 26, 1391
Mendoza, C., Eissner, W., Le Dourneuf, M., & Zeippen, C. J. 1995, J. Phys. B, 28, 3485
Morton, D. C. 1991, ApJS, 77, 119
Nussbaumer, H. 1977, A&A, 58, 291
Savage, B. D., & Lawrence, G. M. 1966, ApJ, 146, 940
Savage, B. D., & Sembach, K. R. 1996, ARA&A, 34, 279
Shull, J. M., Snow, T. P., & York, D. G. 1981, ApJ, 246, 549
Spitzer, L., Jr., & Fitzpatrick, E. L. 1993, ApJ, 409, 299
Van Buren, D. 1986, ApJ, 311, 400
Weiss, A. 1969, in Atomic Transition Probabilities, Vol. 2, ed. W. L. Wiese, M. W. Smith, & B. M. Miles (NSRDS-NBS-22; Washington, DC: NBS), 77