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TRANSITION PROBABILITIES FOR THE 3s^23p(^2P)–3s3p(^4P) INTERSYSTEM LINES OF Si II

ANTHONY G. CALAMAI, 1 PETER L. SMITH, 2 AND S. D. BERGESON 3

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ABSTRACT

Intensity ratios of lines of the spin-changing “intersystem” multiplet of Si II (4P → 4P) at 234 nm have been used to determine electron densities and temperatures in a variety of astrophysical environments. However, the accuracy of these diagnostic calculations have been limited by uncertainties associated with the available atomic data. We report the first laboratory measurement, using an ion-trapping technique, of the radiative lifetimes of the three metastable levels of the 3s3p^2^4P term of Si II. Our results are 104 ± 16, 406 ± 33, and 811 ± 77 µs for lifetimes of the J = 1/2, 5/2, and 3/2 levels, respectively. A-values were derived from our lifetimes by use of measured branching fractions. Our A-values, which differ from calculated values by 30% or more, should give better agreement between modeled and observed Si II line ratios.

Subject heading: atomic data

1. INTRODUCTION

In diffuse plasmas, the rates for radiative decay—i.e., transition probabilities or A-values—of low-lying metastable atomic levels can be of the same order of magnitude as the rates for excitation and deexcitation by electron collisions. In such cases, intensity ratios involving emission lines from metastable levels are sensitive to electron densities and temperatures. Because of this sensitivity, such ratios are often the basis of diagnostic techniques (Jordan 1979; Doschek 1985; Dere & Mason 1981) used to determine these parameters in diffuse astrophysical plasmas. The accuracies of such diagnostic methods depend critically upon knowledge of the A-values of the transitions involved.

We report the first measured radiative lifetimes of the J = 5/2, 3/2, and 1/2 levels of the 3s3p^2^4P metastable term of Si II (see Martin & Zalubas 1983) and A-values determined from these lifetimes. This project (Calamai et al. 1992b) demonstrated for the first time that, under the right conditions, multiple-component decay curves obtained from observations of excited ions in a low-energy ion trap environment can be unambiguously analyzed to provide accurate radiative lifetimes for multiple metastable atomic levels.

The five spin-changing “intersystem” lines of Si II multiplet 0.01 at ~234 nm, emitted as the fine-structure levels of the 3s3p^2^4P metastable term decay to the 3s^2^3p^2^3P ground term, are prominent features in the UV spectra of a variety of astrophysical objects: e.g., the solar chromosphere (Doschek et al. 1976), planetary nebulae (Küppen & Aller 1987), and the slow nova RR Tel (Penston et al. 1983). However, two recent attempts (Dufton et al. 1991; Judge, Carpenter, & Harper 1991) to use the Si II line ratios as diagnostics were limited by uncertainties associated with the available atomic data, possibly the A-values. The results of our measurements should reduce these uncertainties.

2. LIFETIME AND BRANCHING FRACTION MEASUREMENTS

The apparatus and procedures used for the lifetime measurements were similar to those of Calamai, Han, & Parkinson (1992a). Si^+ ions were produced and 3s3p^2^4P levels were excited inside an ion trap by electron bombardment (at 350 V for 2 ms) of research grade SiH_4 at four pressures between 1 and 13 x 10^-8 torr. Cracking pattern data (O’Hanlon 1989) indicates that approximately 11% of the fragments were Si^+ ions. We estimated that our photon-counting efficiency was about 0.05% and, therefore, our observed signals indicate that more than 10^3 metastable ions were created and stored during each cycle of the trap. Most of our data were collected with spherical potential wells that ranged from 10 to 20 eV in depth.

Following ion creation, there was a 82 µs delay period during which the ion cloud stabilized and highly excited ions radiatively decayed to the lowest terms of each spin, i.e., to the ground and metastable terms. An f/2 CaF_2 lens focused light emitted by the decaying metastable ions onto a narrow-band interference filter (14% peak transmittance and 12 nm FWHM) in front of an EMR 541Q photomultiplier tube (PMT) operated in photon counting mode. Detected photon counts were accumulated with a 40 Hz, two-phase, data accumulation technique that incorporated real-time background subtraction during alternate phases (Calamai et al. 1992a). This method produced 29 photon-decay curves, about seven at each pressure, with very good signal-to-noise ratios (see Fig. 1). The trap was cycled about 10^6 times, i.e., for about 12 hr, for each curve.

Several ancillary decay curves, for which experimental parameters such as data accumulation rate, channel bin width, electron bombardment energy, bombardment interval, and trap well depth and asymmetry were varied, were also obtained in order to explore for possible systematic effects. None were found.

Branching fractions (BFs) were needed in order to extract A-values from one of the measured lifetimes. The BF for the 4P_{1/2} level was measured using the apparatus and method of Bergeson & Lawler (1993). A monolithic, B-doped, Si cylinder formed the cathode; the discharge was run in Ar. The lines, which were studied with a signal-to-noise ratio of 10–15, were completely resolved from blends with other lines of Si II, or
with lines of Si I, Ar I or II, and B I or II. The measured BF's showed no dependence upon discharge current or pressure.

3. DATA ANALYSIS

The logarithmic plots of the data indicated that, as expected, they corresponded to several populations exponentially decaying into a background. The data were best fitted to a model consisting of three exponentially decaying populations plus a constant background. Each decay curve was fitted using three different sets of input parameters that varied by more than factors of 2; consistent results, with reduced \( \chi^2 \leq 1.0 \) for nearly all cases, were obtained. The modeled constant background value was consistent with zero, and fits with six parameters gave results that were essentially the same as those from the seven-parameter fits when the data were fitted to an interval with sufficient signal intensity.

Several semiquantitative tests of the three-component model were performed. Fits using two or four initial populations produced large statistical uncertainties and values of reduced \( \chi^2 \geq 3.0 \). Discrete integrals of the data were compared to the integrated form of the model, i.e., \( \sum_{i=1}^{3} N_i / \gamma_i \), where \( \{ N_i \} \) and \( \{ \gamma_i \} \) represent the best-fit values of the relative initial population and decay-rate parameters. Differences were less than 1\%. Graphical measures of the accuracy of the fits were demonstrated by decompositions of the decay curves. In Figure 2a, calculated values of the signal counts associated with the "fast-" and "slow-decay rate" components of the data in Figure 1 have been subtracted from the full data set; in Figure 2b, the fast and medium components have been subtracted. The remaining signals clearly indicate that only one exponentially decaying population remains in either modified data set.

The decay rates measured at each pressure were averaged, plotted versus pressure, and extrapolated to zero. The mean...
No. 1, 1993

TABLE 1

<table>
<thead>
<tr>
<th>Authors</th>
<th>(4^p_{3/2} )</th>
<th>(4^p_{1/2} )</th>
<th>(4^p_{3/2} )</th>
<th>Type</th>
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<tr>
<td>This work</td>
<td>406 ± 33</td>
<td>811 ± 77</td>
<td>104 ± 16</td>
<td>Experiment</td>
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<tr>
<td>Dufton et al. 1991</td>
<td>370</td>
<td>581</td>
<td>89</td>
<td>Theory</td>
</tr>
<tr>
<td>Nussbaumer 1977</td>
<td>417</td>
<td>612</td>
<td>132</td>
<td>Theory</td>
</tr>
</tbody>
</table>

sured rates do not exhibit significance pressure dependence (Calamai et al. 1992b)—a finding expected if the collisional decay rates were not based on (1) good correlation with calculated rates do not exhibit significance pressure dependence (Calamai et al. 1992a). The difference between the mean decay rate for each level and the extrapolated value was less than 2%.

Assignment of the appropriate \(4^p\) level to the measured decay rates was based on (1) good correlation with calculated lifetimes (Nussbaumer 1977; Dufton et al. 1991) for the \(J = 5/2\) and \(1/2\) levels, (2) agreement with the estimated relative photographic intensities from laboratory spectra (Shenstone 1961), and (3) agreement between our estimated relative upper level populations and values predicted by a model that started with a statistical population that was then distributed by allowed radiative decays.

Our measured results for the radiative lifetimes of the \(J = 5/2\), 3/2, and 1/2 metastable levels of Si II are presented in Table 1. Statistical “errors” are the dominant source of uncertainty. We estimated that the sum of the possible systematic uncertainties is not more than \(±3\) of the measured radiative lifetimes, and we have added this systematic uncertainty for each level directly to the statistical uncertainties to arrive at total fractional uncertainties (at the 90% level of confidence) of 8.2, 9.5, and 15.4% for \(J = 5/2\), 3/2, and 1/2 levels, respectively.

Thirty-four measurements of the \(4^p_{3/2}\) branching fraction were made. The total uncertainty (systematic and statistical) was about 10% at the 90% level of confidence.

4. DISCUSSION

The possibility of detecting a spurious, time-dependent background luminescence signal is a major concern when making radiative lifetime measurements with our technique. Such a time-dependent background might occur if (1) another metastable state of a stored atomic or molecular ions could decay with the emission of radiation transmitted by the interference filter, (2) a population of stored ions with higher lying, long-lived levels could cascade down and repopulate the metastable levels, and/or (3) radiation could be produced by collisions between the stored ions and the neutral parent vapor.

Our signals were definitely from some Si ions or SiH₄ fragment; no photons were detected unless SiH₄ was present. We could not identify any excited state of a molecular ion that might have been produced from electron bombardment of SiH₄ and that would decay with emission within our detection bandpass. The parent SiH₄ molecules, which might have been excited by collisions, also do not exhibit emission features (Jacox 1988 and references therein) within our bandpass.

We searched for spurious effects by using combinations of interference filters and PMTs that allowed us to detect photons in the range 130–275 nm while blocking Si II radiation at 234 nm. No signals were seen. We believe, therefore, that the only identified possible cascade route, decays of the \(3s3p3d\) \(4^p\) term of Si II producing photons at about 140 nm, did not affect our measurements.

5. RESULTS AND CONCLUSIONS

Although, explicit quantitative comparisons are precluded by the lack of uncertainty information for the calculated data, our measured lifetimes for the \(J = 5/2\) and \(1/2\) levels appear to be in moderately good agreement with the calculated values. However, a significant difference, about 30%, exists between our measured \(4^p_{3/2}\) lifetime and both calculated results.

The A-value of the \(4^p_{3/2}→4^p_{1/2}\) transition is simply the inverse of the radiative lifetime of the \(4^p_{3/2}\) level. Calculations of Dufton et al. (1991) and Nussbaumer (1977) show that the \(4^p_{3/2}\) branching ratio is about 99:1, with the line at 234:42 nm (in air) being stronger. The A-value for the weak branch is very uncertain. Our measured branching fractions were used to extract A-values from the \(4^p_{1/2}\) lifetime.

Our results, and the values of Dufton et al. (1991) and Nussbaumer (1977) are presented in Table 2. There are some differences that are significantly larger than the uncertainties in our results. Using our A-values to calculate intensity ratios involving lines from the \(3s3p\) \(4^p\) metastable levels of Si II will bring the computed intensity ratios into better agreement with those observed by astronomers.

We thank W. H. Parkinson for reading early versions of this paper and providing valuable comments. G. A. Victor was available for several useful discussions, for which we thank him, as do C. E. Johnson for the use of several interference filters and for discussions concerning the multicomponent fitting procedure. We also thank J. E. Lawler for facilitating and guiding the branching fraction measurements. This work was supported in part by NASA Grants NAGW-1596 and NAGW-1687 to Harvard University and NAGW-2908 to the University of Wisconsin-Madison.

TABLE 2

<table>
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<tr>
<th>Transition</th>
<th>(\lambda_{air}) (nm)</th>
<th>Branching Fraction</th>
<th>(A_{\text{this work}}) (Measurement)</th>
<th>(A_{Nussbaumer 1977}) (Calculation)</th>
<th>(A_{Dufton et al. 1991}) (Calculation)</th>
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<td>(2^p_{3/2}→4^p_{3/2})</td>
<td>233.461</td>
<td>1.000</td>
<td>2460 ± 8%</td>
<td>2400</td>
<td>2700</td>
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<td>(2^p_{3/2}→4^p_{1/2})</td>
<td>234.420</td>
<td>0.992</td>
<td>1220 ± 100</td>
<td>1600</td>
<td>1700</td>
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<tr>
<td>(2^p_{1/2}→4^p_{3/2})</td>
<td>232.851</td>
<td>0.008</td>
<td>10 ± 50</td>
<td>13</td>
<td>20</td>
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<tr>
<td>(2^p_{1/2}→4^p_{1/2})</td>
<td>235.017</td>
<td>0.459</td>
<td>4410 ± 21</td>
<td>3000</td>
<td>4900</td>
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<tr>
<td>(2^p_{1/2}→4^p_{3/2})</td>
<td>233.440</td>
<td>0.541</td>
<td>5200 ± 19</td>
<td>4600</td>
<td>6300</td>
</tr>
</tbody>
</table>

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