

## OSCILLATOR STRENGTHS OF SELECTED RESONANCE TRANSITIONS IN NEUTRAL SULFUR

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### ABSTRACT

Mean lives and branching ratios for the  $4s\ ^3S_1^o$  and  $4s\ ^3P_{1,2}^o$  levels of neutral sulfur were determined at the Toledo Heavy Ion Accelerator using beam-foil spectroscopic techniques. The mean lives obtained for the  $4s\ ^3S_1^o$ ,  $4s\ ^3P_1^o$ , and  $4s\ ^3P_2^o$  levels,  $1.875 \pm 0.094$  ns,  $2.034 \pm 0.102$  ns, and  $2.146 \pm 0.129$  ns, respectively, represent the most accurate results available to date. Oscillator strengths for the transitions  $3p^4\ ^3P_{2,1,0} - 4s\ ^3S_1^o$  and  $3p^4\ ^3P_{2,1,0} - 4s\ ^3P_{1,2}^o$  were derived from these mean lives together with the measured branching ratios. For comparison with published results which present only multiplet  $f$ -values, such  $f$ -values were computed from the measured individual line oscillator strengths. The value obtained for the  $3p^4\ ^3P - 4s\ ^3S^o$  multiplet at 1814 Å is  $0.088 \pm 0.005$ , in good agreement with the mean of previous experimental measurements and theoretical calculations. With the mean life for the  $4s\ ^3P_0^o$  level set equal to the mean of our determination for the other two  $4s\ ^3P^o$  levels (a valid assumption for  $LS$  coupling conditions, and consistent with the observed equality of the mean lives within the accuracy of our measurement), an oscillator strength for the 1299 Å multiplet of  $0.121 \pm 0.004$  was found. Both results are in good agreement with recent large-scale theoretical calculations that incorporate the effects of configuration interaction.

*Subject heading:* atomic data

### 1. INTRODUCTION

Accurate oscillator strengths are important for determining the composition and nature of the interstellar medium. Analysis of absorption lines yields information about the amount of material present in the gas phase in the interstellar region and about the distribution of interstellar matter and the physical conditions under which it occurs. An important example of such investigations is furnished by observational studies of elemental depletion (defined as the logarithmic ratio of the gas-phase abundance to the solar abundance) in the interstellar medium. The fraction of each element which is "locked up" in grains can be estimated by comparing the observed gas-phase abundance in all ionization stages to the cosmic (or solar) abundance (Spitzer 1978). Such measurements not only provide a means of determining the composition of grain material in diffuse interstellar clouds, but also can yield information on the time variation of the composition (Joseph 1988). Information concerning the physical environment of interstellar matter can be obtained from absorption lines. For example, York (1983) analyzed absorption profiles of Ar I lines observed toward  $\lambda$  Sco with the *Copernicus* satellite and obtained an estimate of the gas temperature from the Doppler widths needed to fit the profiles; recently, Federman et al. (1992) determined more precise oscillator strengths and used them in a curve-of-growth analysis to improve the estimate of the Doppler width. Gas density and temperature can be obtained when the relative populations of levels in an atom can be determined (e.g., Jenkins & Shaya 1979; Lambert et al. 1994). All of these observations require accurate atomic oscillator strengths for their interpretation. In addition, oscillator strengths of neutral sulfur are important in probing the physical conditions within the Io torus (Durrance, Feldman, & Weaver 1983) and in cometary comae (Roettger et al. 1989). In this paper, we present accurate experimental measurements of oscillator strengths for several transitions in neutral sulfur which are important for these purposes.

The dominant ionization stage of an element in the gas

phase is determined by the fact that only photons with energies lower than the ionization potential of hydrogen are present in the interstellar medium. Since the ionization potential of S I is 10.36 eV, most of the sulfur is present as S II. Nevertheless, the study of S I lines and their transition probabilities is important in investigating the interstellar medium. For example, it is difficult to determine the abundance of sulfur accurately from observations of S II because its absorption lines are very strong and typically saturated. In such cases, it is usually preferable to assume ionization balance, where the photoionization of S I is in equilibrium with the recombination of S II, to establish the ratio of S II to S I. Together with an accurate measurement of the S I abundance, this establishes the abundance of S II. Federman et al. (1993) applied this method to estimate the sulfur depletion in the main neutral component toward  $\zeta$  Oph, relying on the electron density derived from carbon ionization balance to compute the S II to S I ratio.

Neutral sulfur has numerous spectral lines in the ultraviolet portion of the spectrum. Because the first excited level in the ground term has an energy of  $396\text{ cm}^{-1}$ , essentially all of the observed absorption lines arise from the ground state  $3p^4\ ^3P_2$ . Many such lines have been detected in the interstellar spectrum toward  $\zeta$  Oph (Morton 1975; Federman et al. 1993). Federman et al. (1993) produced a curve of growth from lines of varying strengths and obtained a Doppler width of  $1.2\text{ km s}^{-1}$ , a value consistent with that obtained using other atomic tracers such as C I (Crutcher 1975; Morton 1975). Such analyses, however, are only as reliable as the atomic data upon which they are based.

For some of the most frequently observed transitions in neutral sulfur, there are large discrepancies in the literature between calculations and significant differences between calculations and laboratory data which have been reported. The theoretical values for the oscillator strength of the 1814 Å multiplet are 30% lower on average than previous experimental values, and the quoted theoretical values vary by a factor of 2. For the 1299 Å multiplet, the available oscillator strengths

differ by as much as a factor of 4 (Fawcett 1986; Gruzdev 1969). The mean lives for the multiplet from two experimental measurements (Müller 1968; Smith 1978) differ by 25%. An estimate of the accuracy of the oscillator strengths for this multiplet of 50% was suggested by Wiese, Smith, & Miles (1969) and Morton (1991). It is clear that additional experimental measurements are needed for more quantitative interpretation of astrophysical data. We therefore present here the results of precise experimental laboratory measurements of the mean lives and branching ratios for the upper levels in the 1814 Å and 1299 Å multiplets and the accurate  $f$ -values which are derived from them.

## 2. EXPERIMENT

The ultraviolet transitions described above were studied using the beam-foil spectroscopy facility at the University of Toledo Heavy Ion Accelerator. Beams of  $S^+$  ions at energies of 130 keV and 170 keV were neutralized and excited by traversal through thin ( $2 \mu\text{g cm}^{-2}$ ) carbon foils. An Acton 1 m normal incidence vacuum ultraviolet monochromator was used for wavelength selection. Spectral lines were detected with a Hamamatsu R1459 solar blind photomultiplier. Time-resolved decay curves were obtained by recording the intensity of the radiation selected as a function of the distance between the exciter foil and the monochromator entrance slits. The various uncertainties associated with this type of measurement and the means to assess them are described in detail in Federman et al. (1992); similar tests were performed here. The mean lives extracted from the decay curves were combined with measured branching ratios to calculate oscillator strengths.

### 2.1. 1814 Å Multiplet

The 1807 Å line of this multiplet is the line of primary interest for determination of abundances of neutral sulfur in the interstellar medium because it involves a transition from the ground state,  $3p^4\ ^3P_2$ . There are five lines that must be measured in order to determine the branching ratios out of the upper level  $4s\ ^3S_1^o$ . Attempts were made to measure the two intercombination lines  $3p^4\ ^1D_2-4s\ ^3S_1^o$  (2168.9 Å) and  $3p^4\ ^1S_0-4s\ ^3S_1^o$  (3015.7 Å); no evidence of these lines was seen. Our measurement established a conservative upper limit for the intensities of these lines at 1% of the intensity of the 1807.34 Å line. This result is not particularly surprising since reported  $A$ -values for these transitions are very small compared to the  $A$ -values of the 1814 Å multiplet (Wiese et al. 1969), and the actual intensities of the 2168.9 Å and 3015.7 Å lines may well be much less than 1% of the 1807.34 Å line. For the remainder of this analysis, these two lines were ignored.

While the 1807.3 Å line appeared to be Gaussian in shape, it was much wider than the  $S\ I$  lines at 1666.7 Å and 1820.4 Å, apparently due to blending with a line or lines of unknown origin. A fit was made allowing for blends on both the left and right-hand sides of the peak; the resulting fit was quite good, with a  $\chi^2$  per degree of freedom of 1.14. It should be noted that the blends with 1807.34 Å made only a small correction, about 6%, to the final value of its peak intensity. Subsequent Doppler refocusing of the monochromator using the technique of Stoner & Leavitt (1977) confirmed the presence of these two lines and the accuracy of the conclusions drawn from the previous fit.

The measured relative intensities were used to determine the branching ratios of the three lines out of the  $4s\ ^3S_1^o$  level: 1807.34 Å, 1820.36 Å, and 1826.26 Å. Corrections were made to

account for the difference in detector efficiency as a function of wavelength. The branching fractions were found to be  $B(1807) = 0.612 \pm 0.029$ ,  $B(1820) = 0.319 \pm 0.039$ , and  $B(1826) = 0.069 \pm 0.013$ .

An ANDC (Arbitrarily Normalized Decay Curve) analysis (Curtis, Berry, & Bromander 1970) to extract the mean life would have been difficult to carry out here. The cascades into the  $4s\ ^3S_1^o$  level have wavelengths that are difficult or impossible for us to measure. The main problem is posed by the 10456 Å line,  $4s\ ^3S_1^o-4p\ ^3P$ . This line is of much longer wavelength than can be measured with our photodetectors, and is expected to have the shortest mean life, 33 ns (Bridges & Wiese 1967), of all of the cascades. Experimental measurements indicate that the other cascades are likely to have mean lives greater than 50 ns (Foster 1967; Miller et al. 1974; Delalic, Erman, & Källne 1990). On the other hand, the  $4s\ ^3S_1^o$  level is expected to have a mean life near 1.4 ns (Wiese et al. 1969), and thus this is the type of system which is well suited to using a multiexponential fit to extract a mean life.

The mean life of the  $4s\ ^3S_1^o$  level was determined by taking decay curves of the 1807.34 Å and 1820.36 Å lines and fitting them to a two-exponential function, an example of which is shown in Figure 1. Decay curves made by moving the foil upstream and downstream were obtained for the 1807.34 Å line at beam energies of 130 keV and 170 keV. Decay curves of the 1820.36 Å line were obtained only at 130 keV since at 170 keV the intensity of this line was too low for such a measurement. No decay curves of the 1826.26 Å line were made because the line was too weak at both energies. Fits to two exponentials plus a constant and to three exponentials were also made to assess the sensitivity of the measured mean lives to the form used to fit the long-time behavior of the decay curves.

The primary mean lives extracted from the two-exponential fit of the 1807.34 Å line at 170 keV were systematically longer by about 0.12 ns, 6%, than for the other measurements. Several decay curves were measured on the right-hand shoulder of  $\lambda 1807.34$ . The extracted mean lives from these measurements were longer still. We speculate that blending of the line at 1807.34 Å from an unknown line near 1808.6 Å was affecting the measurement at 170 keV. As a result, we decided not to include the 170 keV decay curves at 1807.34 Å in the determination of the mean life. A weighted mean was performed of the primary mean life extracted from the remaining decay curves taken upstream and downstream at 130 keV for the lines at

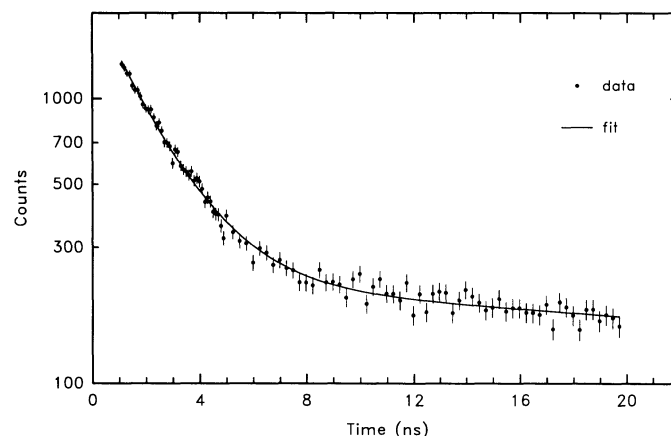


FIG. 1.—A typical time-resolved decay curve for  $\lambda 1807.3$  taken at 130 keV in the upstream direction. The solid line represents a two-exponential fit.

1807.34 Å and 1820.36 Å. The result is  $1.875 \pm 0.094$  ns. The uncertainty includes estimates of error due to systematic effects, as discussed in Federman et al. (1992). We note that if only measurements from the 1820.36 Å line were used, a value of 1.823 ns is obtained; this value is well within one standard deviation of the result quoted here.

### 2.2. 1299 Å Multiplet

The 1295.66 Å and 1296.17 Å lines in the 1299 Å multiplet,  $3p^4\ ^3P-4s''\ ^3P^o$ , are of interest to interstellar studies since they involve transitions to/from the ground state. There are no cascades into  $^3P^o$  reported in the literature. There are, however, three intercombination lines reported (Wiese et al. 1969),  $\lambda\lambda$  1471.8, 1472.5, and 1819.2, which are expected to be relatively weak but which potentially could be of some concern when determining branching fractions from  $^3P^o$ . Our scan for these lines indicated no evidence of their presence. Two of the lines, 1472.5 Å and 1819.2 Å, were on the shoulders of brighter lines, but the 1471.8 Å line was clear of possible blending and was expected (Kelly & Palumbo 1973) to be by far the strongest of the three intercombination lines. We were able to estimate an upper limit on the intensity of this line of 1% of the intensity of the 1295.66 Å line. A similar upper limit of 1% for the intensity of the 1472.5 Å and 1819.2 Å lines compared to 1295.66 Å is justified from a combination of our measurements with reported Einstein  $A$ -values (Wiese et al. 1969).

The mean life of the  $4s''\ ^3P_1^o$  level was measured by taking decay curves of the 1305.89 Å line. This was done even though the 1296.17 Å line from this level is the one of primary interest. The 1305.89 Å line was chosen because it is completely free of blends and will of course display the same mean life as any other line arising from the same level, including 1296.17 Å. Time-resolved decay curves were made at 130 keV and 170 keV. At both energies, decay curves were made moving the foil upstream and additional decay curves were made moving the foil downstream. A two-exponential fit of the decay curve was found to be most satisfactory. The mean life of  $2.034 \pm 0.102$  ns is the weighted mean of the primary exponential from the four decay curves.

The mean life of the  $4s''\ ^3P_2^o$  level was measured by taking decay curves of the 1295.66 Å line. All lines from this level are blended to some extent, but the 1295.66 Å line is blended by only a small amount, less than 10%, by a line at 1296.17 Å, for which we now know the mean life. Initially, decay curves were

taken at 1295.66 Å, 1295.49 Å, and 1295.16 Å. These measurements should have different levels of blending with  $\lambda$ 1296.17 and, if the mean lives of the two levels differ sufficiently, different mean lives. A two-exponential fit to these decay curves indicated that all measurements gave the same mean life within the expected accuracy of our experiment, roughly 6%, as would be expected for  $LS$  coupling. Thus the two levels had comparable mean lives and blending of them was not a problem. Three additional decay curves at 1295.66 Å were taken, downstream at 130 keV and upstream and downstream at 170 keV. The mean life of  $2.146 \pm 0.129$  ns is the weighted mean from the four different two-exponential fits.

### 3. RESULTS

Our measured mean lives for these levels are the most precise available. Our value for the mean life of the  $4s\ ^3S_1^o$  level of the 1814 Å multiplet,  $1.875 \pm 0.094$  ns, is somewhat longer than the results of two previous experimental measurements. Savage & Lawrence (1966) reported a mean life of  $1.5 \pm 0.3$  ns; our value is slightly greater than one standard deviation longer. The  $A$ -value reported by Müller (1968) implies a mean life of  $1.42 \pm 0.24$  ns for this level, which is approximately two standard deviations shorter than our value. Müller's  $A$ -values also yield a mean life for the  $4s''\ ^3P_0^o$  level of the 1299 Å multiplet of  $2.1 \pm 0.5$  ns. We were unable to measure this level directly, but this mean life is in excellent agreement with the measurements we made for the other two levels of the  $4s''\ ^3P^o$  state,  $2.034 \pm 0.102$  and  $2.146 \pm 0.129$  ns. Smith (1978) reported a mean life of  $2.8 \pm 0.3$  ns for the 1299 Å multiplet, about two standard deviations longer than our value.

From mean lives and branching ratios, oscillator strengths are obtained in a straightforward manner. A compilation of our results and those of others appears in Tables 1 and 2 for  $\lambda$ 1814 and  $\lambda$ 1299, respectively. Müller (1968) reported the only experimental oscillator strengths for individual lines of the 1814 Å and 1299 Å multiplets. Our primary interest is with lines involving the ground state, or resonance lines at  $\lambda\lambda$ 1807.34, 1295.66, and 1296.17. For all three lines, our oscillator strengths are somewhat smaller than Müller's. For  $\lambda\lambda$ 1807.34, 1295.66 Müller's values are approximately one standard deviation larger than our values, while his value for  $\lambda$ 1296.17 is nearly two standard deviations larger than ours. A multiplet oscillator strength can be derived from Müller's individual line oscillator strengths for the 1814 Å multiplet. The

TABLE 1  
1814 Å MULTIPLET OSCILLATOR STRENGTHS

SOURCE	OSCILLATOR STRENGTHS			MULTIPL
	1807.34 Å	1820.36 Å	1826.26 Å	
Present work <sup>a</sup> .....	$0.096 \pm 0.007$	$0.085 \pm 0.011$	$0.056 \pm 0.011$	$0.088 \pm 0.005$
Mendoza & Zeippen <sup>b</sup> .....	...	...	...	0.085
Gruzdev & Prokofev <sup>b</sup> .....	...	...	...	$0.06 \pm 0.02$
Ho & Henry <sup>b</sup> .....	...	...	...	$0.073 \pm 0.022$
Ganas <sup>b</sup> .....	...	...	...	0.093
Fawcett <sup>b</sup> .....	0.084	0.082	0.081	0.083
Lawrence <sup>b</sup> .....	0.113	0.110	0.109	0.112
Aymar <sup>b</sup> .....	0.113	0.109	0.108	0.111
Müller <sup>a</sup> .....	$0.12 \pm 0.03$	$0.11 \pm 0.03$	$0.11 \pm 0.03$	$0.12 \pm 0.02$
Savage & Lawrence <sup>a</sup> .....	...	...	...	$0.11 \pm 0.02^c$

<sup>a</sup> Experimental determination.

<sup>b</sup> Theoretical determination.

<sup>c</sup> The value listed was derived using assumptions that  $LS$  approximations are appropriate.

TABLE 2  
1299 Å MULTIPLY OSCILLATOR STRENGTHS

SOURCE	OSCILLATOR STRENGTHS					MULTIPLY
	1295.66 Å	1296.17 Å	1302.34 Å	1302.87 Å	1305.89 Å	
Present work <sup>a</sup> .....	0.087(6)	0.022(2)	0.051(5)	0.039(6)	0.150(13)	0.121(4) <sup>b</sup>
Lawrence <sup>c</sup> .....	0.0826	0.0271	0.0564	0.0282	0.1296	0.116
Fawcett <sup>c</sup> .....	0.149	0.050	0.092	0.051	0.220	0.206
Gruzdev <sup>c</sup> .....	0.037	0.012	0.024	0.013	0.056	0.052
Aymar <sup>c</sup> .....	0.122	0.040	0.078	0.041	0.181	0.169
Ho & Henry <sup>c</sup> .....	...	...	...	...	...	0.086(26)
Mendoza & Zeippen <sup>c</sup> .....	...	...	...	...	...	0.116
Müller <sup>a</sup> .....	0.12(3)	0.037(9)	...	...	...	...
Smith <sup>a</sup> .....	...	...	...	...	...	0.09 <sup>b,d</sup>

<sup>a</sup> Experimental determination.

<sup>b</sup> The value listed was derived using assumptions that *LS* approximations are appropriate.

<sup>c</sup> Theoretical determination.

<sup>d</sup> This value was obtained from the multiplet mean life reported by Smith.

same cannot be done for the 1299 Å multiplet because his line oscillator strengths are incomplete. Müller's 1814 Å multiplet oscillator strength is in good agreement with the experimental measurement by Savage & Lawrence (1966). Both are about one standard deviation larger than our multiplet value.

We did not measure the mean life of the  $4s^2\ ^3P_0$  level of the 1299 Å multiplet because the only known line from this level is heavily blended. The mean lives which we measured for the  $4s^2\ ^3P_1$  and  $4s^2\ ^3P_2$  levels of this multiplet were essentially the same, as would be expected for pure *LS* wave functions. In order to determine a multiplet oscillator strength, we used the mean of these two measurements as the mean life of  $4s^2\ ^3P_0$  with an uncertainty consistent with the measured values for the  $j = 1, 2$  levels. The only other experimental measurement of the 1299 Å multiplet oscillator strength is that of Smith (1978), who quoted an  $f$ -value of 0.031, determined from the mean life which he measured using the phase-shift technique. However, Smith's mean life of 2.8 ns yields an oscillator strength of 0.09; we incorporated the value 0.09 into our Table 2.

There are two "modern" large-scale theoretical calculations which include extensive configuration interaction for the 1814 Å and 1299 Å multiplets. We also compare our results with these calculations in Tables 1 and 2. In general, our results agree well with these two calculations. Our oscillator strengths tend to be a bit larger than those of Ho & Henry (1985), but are within their quoted uncertainty for the 1814 Å multiplet and just a bit outside their error estimates for the 1299 Å multiplet. Our measured oscillator strengths for both multiplets are in excellent agreement with the calculations from Mendoza & Zeippen (1988).

#### 4. DISCUSSION

Oscillator strengths involving the ground state of S I,  $3p^4\ ^3P_2$ , are needed for determining the abundance of neutral sulfur in diffuse interstellar clouds as well as the amount of Doppler broadening associated with its lines (Federman et al. 1993). The  $j = 1, 0$  levels are not populated to a significant degree by collisions because the prevailing densities and temperatures are too low. The accuracy of the astronomical results depend upon the accuracy with which the oscillator strengths are known. Our results for the three lines at 1295.66 Å, 1296.17 Å, and 1807.34 Å are 0.087, 0.022, and 0.096, respectively. While the multiplet line strengths derived from these measurements are in excellent agreement with the results of recent large-scale

calculations (Mendoza & Zeippen 1988) and in good agreement with those of Ho & Henry (1985), they are significantly smaller than the  $f$ -values tabulated by Morton (1991) for these lines—see Tables 1 and 2. Since the  $f$ -values compiled by Morton (1991) are frequently used in interstellar research, astronomical analyses based solely on previously available  $f$ -values for these lines may need revision.

It is important to note that, while a given theory may be very successful in accurately predicting a wide range of  $f$ -values, there may be individual transitions which are not amenable to the global approach. It seems likely that the neutral sulfur multiplet at 1479 Å is such a transition. For example, Federman et al. (1993) observed  $\zeta$  Oph with the *Hubble Space Telescope* and detected several weak interstellar S I lines, including the multiplets at 1479 Å and 1486 Å and the lines  $\lambda 1444$  and  $\lambda 1262$ . They obtained consistent column densities for the suite of measured lines using an  $f$ -value for  $\lambda 1262$  (not previously measured) which agrees well with the value calculated by Mendoza & Zeippen (1988) for the associated multiplet at 1266 Å. However, consistency could not be obtained using the  $f$ -value for the  $\lambda 1479$  multiplet indicated by the calculations of Ho & Henry (1985) and Mendoza & Zeippen (1988); rather a value much closer to that quoted by Morton (1991) from Wiese et al. (1969) and Wiese & Martin (1980) was required to fit the data. A similar conclusion was reached by Roettger et al. (1989) in their analysis of cometary data, where they discussed the relative intensities of  $\lambda 1814$  to  $\lambda 1479$ .

In addition to these observational problems there are theoretical reasons for suggesting that the  $\lambda 1479$  oscillator strength may require special study. This multiplet is designated  $3p^4\ ^3P-3p^3(^2D^o)4s^2\ ^3D^o$ , but CI calculations show a significant admixture of  $3p^3(^4S^o)3d^3\ ^3D^o$  in the upper state, which creates a strong cancellation in the dipole transition integral. Thus the best available calculations find the  $\lambda 1479$  multiplet oscillator strength to be 0.02 (Mendoza & Zeippen 1988) or 0.01 (Ho & Henry 1985) compared to its Hartree-Fock value of 0.12. Obviously the presence of such a strong cancellation reduces the precision of the result. Furthermore, these calculations have naturally been done entirely in *LS* coupling, in spite of the near-degeneracy between the  $3p^3(^2D^o)4s^2\ ^3D^o$  and the  $3p^3(^4S^o)3d^3\ ^3D^o$  terms. Even though the only interactions between these two are spin-spin, spin-other orbit, and higher-order relativistic effects, the near degeneracy might well allow enough additional mixing to significantly affect the CI results

mentioned above. We were unable to measure  $f$ -values for this multiplet because it did not meet the criteria necessary for us to perform a reliable multiexponential fit to time-resolved decay curves, nor could we measure decay curves for the cascades needed to perform an ANDC analysis. The need for an accurate experimental determination of the  $f$ -value for this multiplet remains.

In conclusion, we have measured mean lives and branching ratios for the  $4s^3S_1^o$  and  $4s''^3P_{1,2}^o$  levels of neutral sulfur. The oscillator strengths derived from these measurements are the most precise experimental determinations to date. Our results are in good agreement with recent large-scale theoretical calcu-

lations by Ho & Henry (1985) and Mendoza & Zeippen (1988). Analyses of interstellar absorption from lines involving the multiplets at 1814 Å and 1299 Å can now be performed with greater confidence.

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