Oscillator strengths for in-shell ($\Delta n = 0$) dipole transitions in Li- and Be-like sulfur*

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(Received 23 September 1976)

The foil-excitation method has been employed to determine lifetimes, transition probabilities, and f values for $\Delta n = 0$ dipole transitions between the $n = 2$ states of the highly stripped ions, S^{12+} and S^{13+}. The fine-two structure interval between the $J = 1/2$ and $3/2$ levels of the $1s^2 2p$ $^2P^o$ term in S^{13+} was also determined, and the result confirms recent astrophysical observations.

I. INTRODUCTION

For more than a decade now the beam-foil time-of-flight technique has been used to study the lifetimes of excited electronic states in atoms and ions of varying degrees of ionization. The method is perhaps most useful, however, when applied to highly ionized systems, for which no alternative time-resolved method is currently available. Characteristic radiation emitted by highly stripped ions primarily falls in the far-ultraviolet or x-ray regions of the electromagnetic spectrum where line strengths are typically intrinsically stronger than in the visible region. In addition, detectors used in this spectral region (for example, continuous-strip electron multipliers) exhibit much lower "noise" rates than those used for softer-wavelength work, thus providing higher detection sensitivity.

In order to maximize the high post-foil charge states required, the incident beam energies are large, typically 1–5 MeV/amu. At such beam energies the correction for energy loss suffered during the passage of the ion through the foil material is usually negligibly small (at lower energies this correction can become a major source of systematic uncertainty in the lifetime measurement). Thus, a combination of the aforementioned source and detection properties makes this wavelength region rather attractive to work in.

In the present paper, we describe an experiment performed in the extreme ultraviolet (EUV) region in which we have investigated the radiative decay of excited ($n=2$) levels of both Li-like and Be-like sulfur. Dipole oscillator strengths (f values) for the important dipole resonance transitions in these ions can be derived from the present results. Figure 1 shows a partial energy level diagram of S^{12+} indicating the $\Delta n = 0$ transitions studied in the present experiment.

Accurate f values for highly ionized systems find practical applications in the study of both laboratory and astrophysical plasmas. For example, such line-strength parameters are currently needed in both diagnostic work and investigations of the unwanted cooling of magnetically confined thermonuclear plasmas by radiative energy losses from heavy highly stripped impurity ions.[1] On the astrophysical side, both rocket-borne and satellite instruments have indicated the presence of Be-like ions of high Z in the quiet-sun coronal spectrum[2] and recent solar flare spectra[3] from Skylab show that the $2s$-$2p$ resonance doublet in Li-like ions of high Z is prominent. Such lines have indeed been used as a diagnostic tool to determine plasma temperatures at the time of the flares.

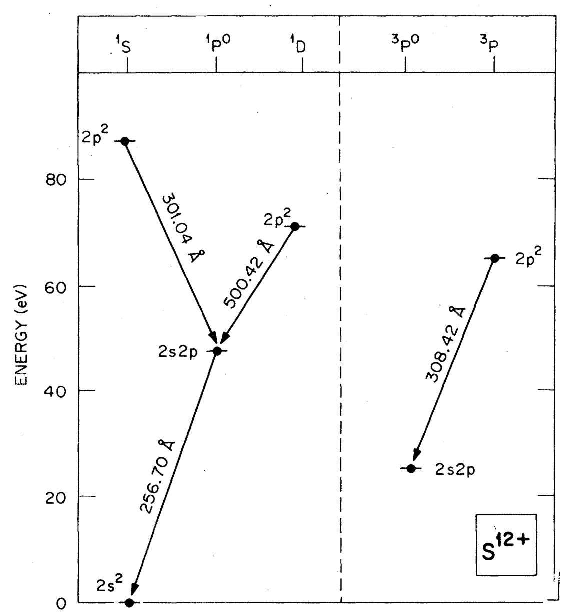

FIG. 1. Partial energy-level diagram of S^{12+} showing the $\Delta n = 0$ transitions studied in the present work.

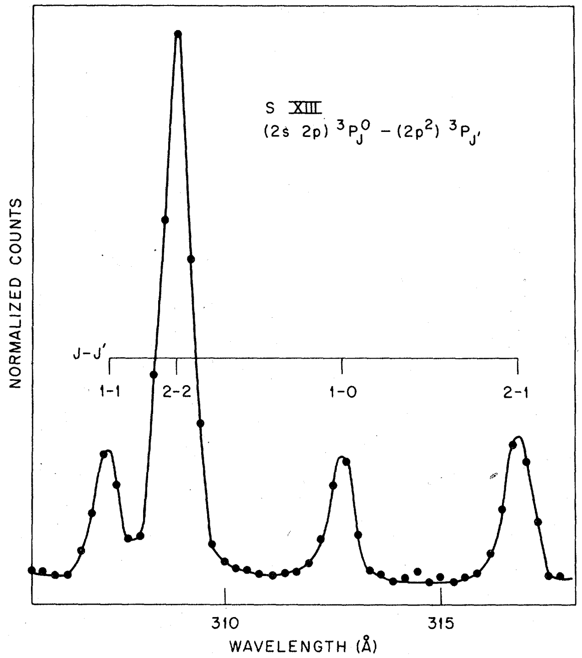

FIG. 2. Portion of the EUV foil-excited spectrum of highly ionized sulfur showing different components of the $2s2p\ ^3P^o_J - 2p^2\ ^3P_{J'}$ multiplet in S^{12+}.

II. EXPERIMENTAL METHOD

The foil-excitation technique has been used in this investigation. Details of the experimental arrangement has been described previously by Pegg *et al.*[4] In the present work an ~46-MeV sulfur-ion beam from the Oak Ridge National Laboratory tandem accelerator was analyzed, collimated, and passed through a thin (~5-μg/cm^2) carbon foil placed perpendicular to the beam axis. EUV radiation emitted in flight by the decaying ions of the foil-excited beam was collected and dispersed by a 2.2-m grazing incidence spectrometer (McPherson Model 247). In this experiment, we used an 87.5° angle of incidence and a 300 grooves/mm gold-coated grating. Figure 2 shows a portion of the foil-excited sulfur spectrum containing several lines of the $2s2p\,^3P^o_J$-$2p^2\,^3P_J$ multiplet in S^{12+}. Time-of-flight lifetime measurements were made in the usual manner by studying the change in intensity of a wavelength-selected transition from a particular excited state as a function of the distance between the foil (the point of initial excitation) and the viewing region of the spectrometer. The resulting photon signal was normalized at each foil position to the amount of beam charge collected in a shielded Faraday cup.

III. RESULTS

Figure 3 shows a decay curve for the $2p^2\ ^1D_2$ level in S^{12+} which is well fitted to a single exponential function over two decay lengths. Figure 4 shows the result of a similar study on the decay in flight of the $2s2p\ ^1P^o_1$ level. In this case, however, the curve is best represented by the sum of several exponentials due to strong cascading effects. The specific cascades can be identified in this case with $\Delta n = 0$ transitions from the $2p^2\ ^1D_2$ and $2p^2\ ^1S_0$ levels (see Fig. 1) whose lifetimes were studied independently. The decay constant of the long-lived component shown in Fig. 4, for example, agrees well with that of the $2p^2\ ^1D_2$ level whose decay is shown in Fig. 3. The shorter-lived "growing in" component shown in Fig. 4 is primarily associated with the cascade decay of the $2p^2\ ^1S_0$ level. Cascading from out-of-shell ($\Delta n \neq 0$) states are expected to produce very short-lived components which decay close to the foil. Such components do not appreciably affect the decay of the $2s2p\ ^1P^o_1$ level whose lifetime is represented by τ_2 in Fig. 4 but do somewhat affect the $2p^2\ ^1S_0$ decay component.

The Doppler-shifted wavelengths of the foil-excited $2s$-$2p$ resonance doublet lines in the Li-like ion, S^{13+}, were measured using certain stan-

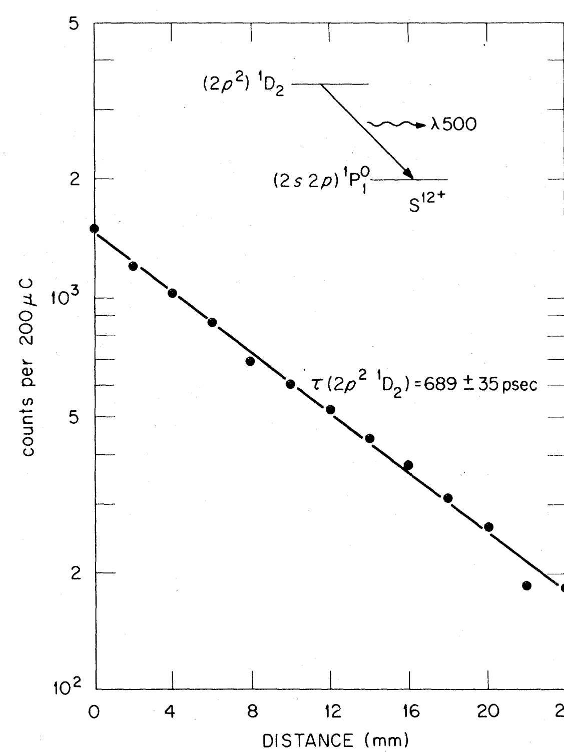

FIG. 3. Typical decay-in-flight curve for the dipole transition shown. The beam energy was 46 MeV.

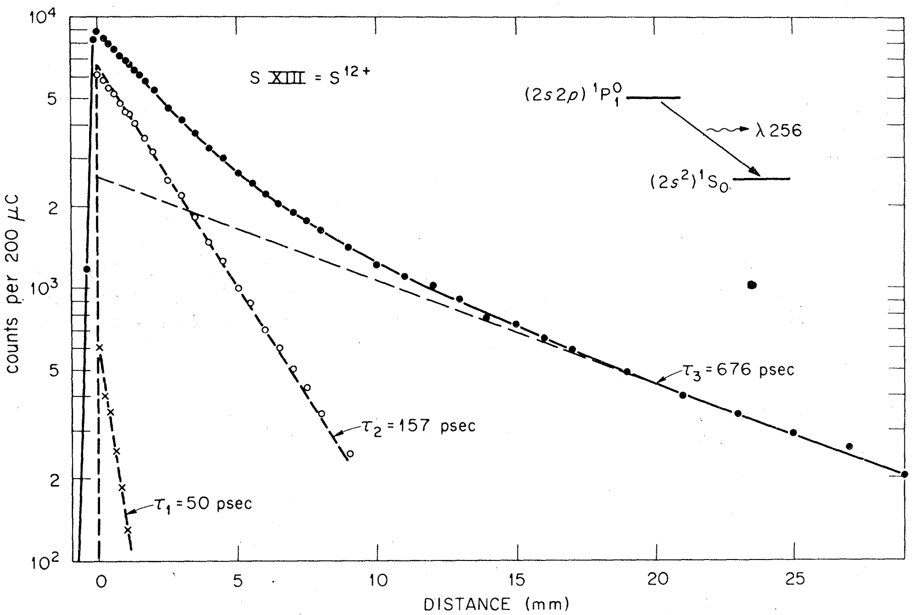

FIG. 4. Intensity decay curve for the resonance transition in Be-like sulfur. The beam energy was 46 MeV. The decay component with lifetime τ_2 is the transition under study. Cascade components from in-shell transitions are characterized by τ_1 and τ_3 in the figure.

dard wavelength Ne^+ lines[5] from a hollow-cathode source situated directly opposite the entrance slit of the spectrometer. These calibration lines appeared both above and below the wavelength region of the resonance doublet. The magnitude of the sum of the first- and second-order Doppler shifts of these lines was then determined in the following manner. The fractional shift of the $2s^2$-$2s2p$ singlet resonance line in S^{12+} was measured by comparing the Doppler-shifted wavelength of this line (which was present in the same beam-foil source) with the rather precisely known rest-frame wavelength of the line.[2] The Doppler-shifted wavelength was determined as usual by calibrating the spectrometer using the He^+ Ly β line from the hollow-cathode source. The fractional Doppler shift thus obtained could then be used to find the shift associated with both components of the $2s$-$2p$ doublet in S^{13+}. Thus we obtain a doublet splitting of 28.03 ± 0.03 Å which is equivalent to a fine-structure interval between $J=\frac{1}{2}$ and $\frac{3}{2}$ levels of the $1s^2 2p\ ^2P_J^o$ term in S^{13+} of 15 056 cm^{-1} or 1.866 eV. The result confirms recent astrophysical measurements taken aboard the Skylab spacecraft at the time of solar flares[3] (15 061 and 15 074 cm^{-1}) but disagrees somewhat with the laboratory plasma result of Fawcett[6] (15 138 cm^{-1}). The radiative lifetimes of the $J=\frac{1}{2}$ and $\frac{3}{2}$ levels were also measured and f values were obtained by combining the aforementioned wavelength measurements with the lifetime results.

All the present lifetime and f values results for S^{12+} and S^{13+} are summarized in Table I along with

TABLE I. Radiative lifetimes and oscillator strengths for $\Delta n = 0$ transitions in Li-like and Be-like sulfur.

Wavelength (Å)	Transition	Lifetime of upper level (psec)	Oscillator strength Present	Theory
S^{13+}				
417.69	$2s\ ^2S_{1/2}$-$2p\ ^2P^o_{3/2}$	767 ± 39	0.068	0.064,[a] 0.064[b]
445.72	$2s\ ^2S_{1/2}$-$2p\ ^2P^o_{1/2}$	918 ± 92	0.032	0.030,[a] 0.030[b]
S^{12+}				
256.69	$2s\ ^1S_0$-$2s2p\ ^1P^o_1$	157 ± 16	0.189	0.227,[a] 0.235[b] 0.223[c]
301.04	$2s2p\ ^1P^o_1$-$2p^2\ ^1S_0$	79 ± 15	0.057	0.060,[a] 0.056[b]
308.95	$2s2p\ ^3P^o_2$-$2p^2\ ^3P_2$	168 ± 9	0.085	0.068[b]
500.42	$2s2p\ ^1P^o_1$-$2p^2\ ^1D_2$	689 ± 35	0.091	0.112,[a] 0.181[b]

[a]Reference 8. [b]Reference 9. [c]Reference 10.

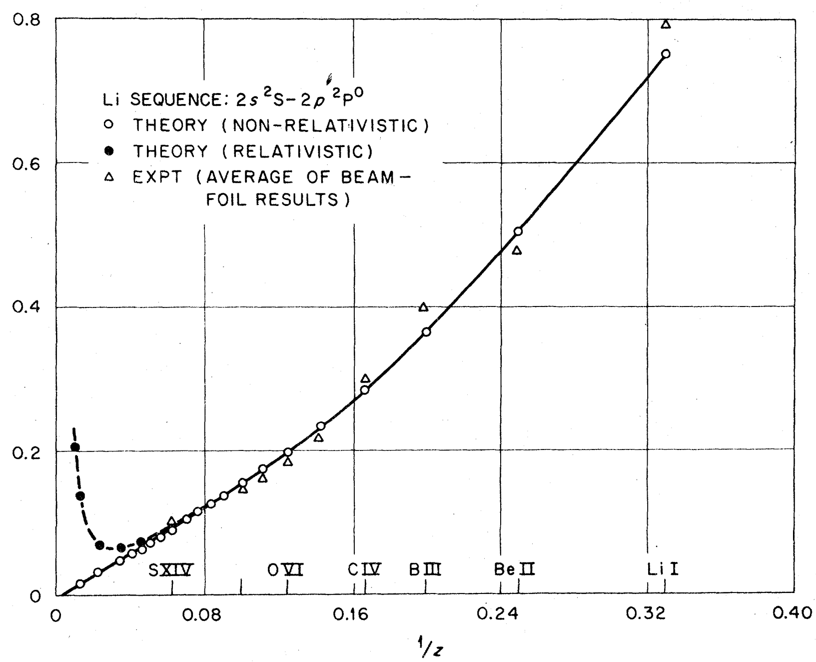

FIG. 5. F-vs-Z^{-1} plot for the $2s\ ^2S - 2p\ ^2P^o$ transition in the Li sequence.

some theoretical f value predictions. There is agreement between the present experimental values and theory to within 25% for most of the S^{12+} transitions and to within 6% for the S^{13+} transitions. We arrived at the uncertainty limits quoted in Table I in the following manner.

Systematic uncertainties arising from, for example, the determination of the post-foil beam velocity, the reproducibility of the target position and the beam-charge normalization procedure are estimated to be small at the high-incident beam energies employed. Statistical uncertainties associated with the decay curve fitting process depend to some extent upon the intensity of the spectral line under study and whether or not the analysis is complicated by cascade effects brought about by the nonselective excitation process. A 5% uncertainty limit, based upon the curve fitting analysis, has been quoted on the lifetime results of Table I for those transitions which are intense and are apparently unaffected by cascades. If the line is weaker the uncertainty limit for similar cascade-free transitions has been increased to 10% or more to reflect the poorer counting statistics involved. As is to be expected the only transition which is appreciably affected by cas-

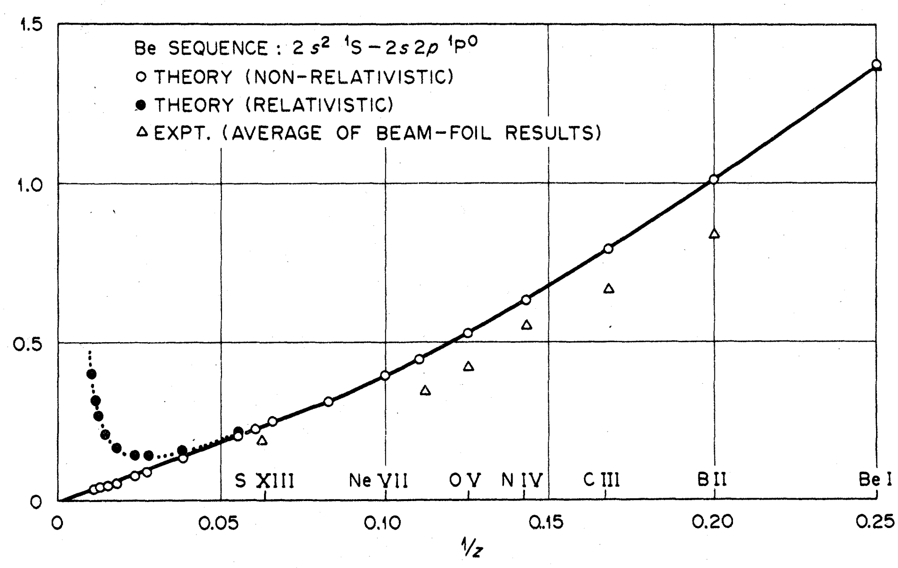

FIG. 6. F-vs-Z^{-1} plot for the $2s^2\ ^1S - 2s2p\ ^1P_1^o$ transition in the Be sequence.

cading is the $2s^2\ ^1S_0$-$2s2p\ ^1P_1^o$ transition in S^{12+} which is fed by two in-shell transitions that were independently studied, i.e., the decay of the $2p^2\ ^1S_0$ and the $2p^2\ ^1D_2$ levels. Fortunately, the lifetimes of both of these cascading levels were sufficiently different from the primary level ($2s2p\ ^1P_1^o$) that they were easy to take into account in the curve-fitting analysis especially since their lifetimes were independently measured. The uncertainty quoted (10%) on the $2s2p\ ^1P_1^o$ lifetime is a range estimate based upon the results of a curve-fitting procedure in which the number of data points used in the fit was varied (by varying the number of points used at the beginning and end of the decay curve).

IV. DISCUSSION

Beam-foil results have been instrumental in the establishment of systematic trends in f values for a particular transition along an isoelectronic sequence. Such trends, which are based upon a nonrelativistic perturbation expansion of f values in terms of the inverse nuclear charge on the ion, have proven to be very useful for low-to-intermediate -Z ions. Electron correlation effects can become very important (particularly for low-Z ions) for $\Delta n=0$ transitions due to the interpenetration of electrons of the same principal quantum number. The persistence of significant correlation effects to intermediate Z ions has been recently noted by Chang[7] in the calculations of photoionization in the Ne and Ar sequences. Recent theoretical efforts[8-10] are attempting to extrapolate the systematic f value curves into the region of high Z where both configurational and orbital relativistic effects can become important. For intermediate Z ions such as sulfur it is expected that the only relativistic effects on the f values will be configurational ones which may affect the transition energy part of this quantity, the affect on the line strength being negligible. Figure 5 shows a f vs. Z^{-1} curve (multiplet f value) for the $2s\ ^2S$-$2p\ ^2P^o$ transition in the Li sequence. Similarly, Fig. 6 shows a plot for the $2s^2\ ^1S$-$2s2p\ ^1P^o$ transition in the Be sequence.

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*Research supported in part by NSF, ONR, and Union Carbide Corp. under Contract with ERDA.

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