

X-ray emission from foil-excited sulphur beams*

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Emission of $K\alpha$ x rays from foil-excited sulphur beams at 40, 50, and 55 MeV has been observed. Lifetimes of the $(1s2p)^3P_2$ state in helium-like and the $(1s2s2p)^4P_{5/2}$ state in lithium-like sulphur, which decay partially by magnetic-quadrupole transitions, have been determined. The energies of several transitions to the ground state in two- and three-electron sulphur ions have been determined by using a Doppler-tuned spectrometer and observing the beam both downstream and close to the exciting foil. It is pointed out that the identification of lines in the prompt spectrum of such highly ionized systems in terms of configuration-averaged satellites is inappropriate.

I. INTRODUCTION

Observation of the transition energies and state lifetimes of highly stripped heavy ions can provide tests of relativistic and quantum-electrodynamic effects on the energies and transition rates in atomic systems.^{1,2} Forbidden decays in few-electron systems whose rates are too small to be observable for low Z may be observed more readily at higher Z and a number of measurements of lifetimes and transition energies have been reported for one- and two-electron heavy ions.³⁻⁷

In a previous paper⁸ we have reported measurements of the energies and lifetimes for several long-lived states in helium-like and lithium-like chlorine. It was observed that the measured lifetimes of the 2^3P_2 state in helium-like chlorine was in agreement with the theoretical value and that the measured lifetime of the $(1s2s2p)^4P_{5/2}$ state of lithium-like chlorine agreed with measurements⁷ of the lifetime obtained from observation of Auger electrons. The measured energies of K x rays from chlorine were sufficiently well determined to show clearly the need for relativistic correction to nonrelativistic calculations of the energies of these transitions.

This paper presents the results of measurement of K x-ray energies and state lifetimes for the same metastable states in helium-like and lithium-like sulphur and, in addition, presents the spectrum of prompt K x-ray radiation observed from the excitation region under moderately high resolution. These lines are partially identified and the general problems of line identification for such highly stripped systems is discussed.

II. SPECTRA

Energy resolved spectra were obtained from the beam using a Doppler-tuned x-ray spectrometer

(DTS), similar to that described by Schmieder and Marrus,⁸ which has been employed in a previous study of foil-excited chlorine beams.⁶ The DTS is capable of high resolution while at the same time providing much higher efficiency than that typical of a crystal spectrometer of equivalent resolution. In a DTS an absorber with a large characteristic absorption discontinuity at an energy E_{abs} is placed in front of the detector. A collimating system allows the detector-absorber system to view the beam at an angle θ to the beam with a small acceptance angle $\Delta\theta$. If the absorber is essentially opaque to radiation of energy $E_\nu > E_{\text{abs}}$, then one can obtain an integral scan of intensity versus photon energy by scanning θ . As θ is increased photons with energy E_ν in the rest frame of the emitter will suffer a smaller Doppler shift and only those with energy below a cutoff value E_ν will be detected. If ν is the velocity of the beam, the expression relating the cutoff energy to angle is

$$E_\nu = E_{\text{abs}} \frac{1 - (v/c) \cos\theta}{[1 - (v/c)^2]^{1/2}}.$$

In order to observe the energies of the short-lived transitions in the sulphur beam a DTS spectrum was obtained by scanning in such a manner that the x-ray emission at and a few millimeters beyond the foil was detected. For these measurements the acceptance angle of the detector was determined by collimating the beam to a width of 2 mm and placing a 1-mm slit in front of the detector, which yielded an average acceptance angle, over the region scanned, of 2.5° . This acceptance angle gives the DTS a spectral resolution of about 6 eV. The absorber used was a 0.075-mm-thick film of polystyrene containing about 50% by weight of sulphur and which had calculated transmissions of 0.16 for energies below and 4×10^{-6} for energies above the sulphur K absorption edge at 2472.0 eV.⁹

The DTS was scanned in steps of 0.178° and the

angular calibration was obtained by 180° scans through the beam so that the spectrum was obtained on both sides of the beam. The summed results of nine such DTS scans, obtained over a three-hour period, are shown in Fig. 1(a). Five abrupt decreases in intensity may be seen in this integral spectrum as the viewing angle of the detector is changed. In order to show the observed x-ray energies more clearly the differential spectrum of Fig. 1(a) was obtained from the average over three channels (0.178°/channel) of the slope of a cubic equation which was least-squares fitted to the seven channels centered on the point of interest. This differential spectrum displays five definite peaks with a strong shoulder on one of the peaks. The measured energies are given in the first column of Table I along with values calculated for some transitions in two- and three-electron sulphur ions. The width at half-height of the best resolved peak in Fig. 1(b) is 6 eV. A scan taken with a 0.5-mm slit on the detector and 1-mm beam collimation failed to show any improvements in resolution and contributions to the resolution from uncertainty in the vector velocity of the beam are expected to be small. Part of the observed linewidth (especially for the 2P and 4P lines) may be due to the presence of unresolved line structure.

The spectrum obtained 1.5 cm beyond the exciting foil using the DTS with 1° soller slits and a polystyrene-sulphur absorber of 0.025-mm thickness with calculated transmissions of 0.54 and 0.016 on each side of the sulphur K edge is shown in Fig. 1(d). This spectrum is considerably less complicated than the spectrum obtained viewing the foil region. There are only two rapid changes in x-ray intensity as the detector angle is changed. The half-width of each "line" observed beyond the foil is about 3 eV which corresponds to the expected half-width owing to the 1° acceptance angle of

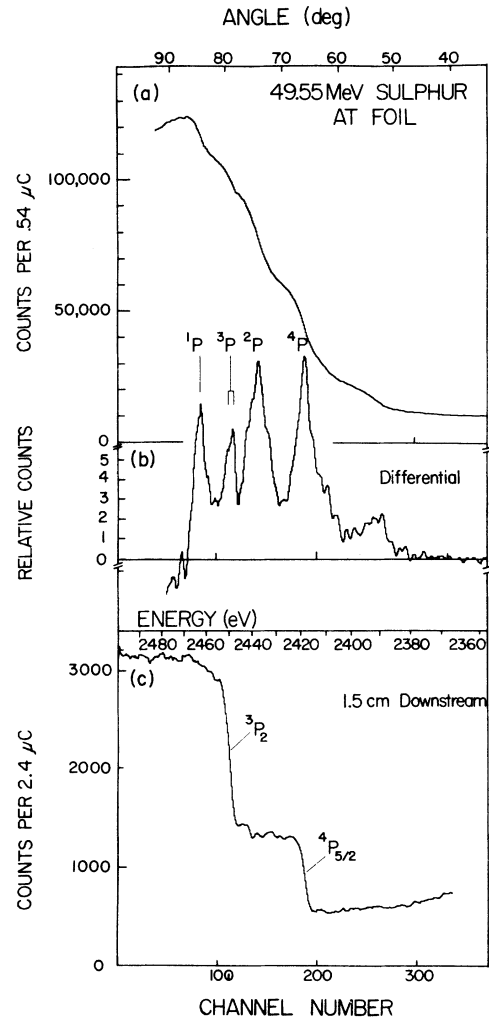


FIG. 1. Spectra of sulphur x rays taken with the Doppler-tuned spectrometer (a) viewing the foil directly, and (c) viewing the beam 115 cm downstream. Spectrum (b) results from differentiating spectrum (a). Angle and energy scales refer to θ and E_ν , as discussed in Sec. II.

TABLE I. Sulphur transition energies (in eV).

| Initial state | Final state | Theory | Observed At foil | Observed Downstream | Configuration average ^a |
|-------------------|-------------------|---------------------|------------------|------------------------|------------------------------------|
| $(1s2p)^1P^o$ | $(1s^2)^1S^e$ | 2461.1 ^b | 2461.8 ± 3 | | Helium-like |
| $(1s2p)^3P_1^o$ | $(1s^2)^1S^e$ | 2447.7 ^b | 2448.0 ± 3 | | 2448 |
| $(1s2p)^3P_2^o$ | $(1s^2)^1S^e$ | 2449.2 ^b | | 2448 ± 2 | |
| $(1s2p^2)^2P^e$ | $(1s^22p)^2P^o$ | 2438.2 ^c | 2435.3 ± 3 | | |
| $(1s2p^2)^4P^e$ | $(1s^22p)^2P^o$ | 2419.6 ^c | 2416.5 ± 3 | 2416.5 ± 2, | Lithium-like |
| $(1s2s2p)^4P^o$ | $(1s^22s)^2S^e$ | 2416.8 ^d | | 2426 ± 26 ^e | 2427 |
| $(1s2p^3)^3S^o$ | $(1s^22p^2)^3P^e$ | 2413.3 ^c | (2409) | | Beryllium-like |
| $(1s2s2p^2)^5P^e$ | $(1s^22s2p)^3P^o$ | 2390.2 ^c | 2388.0 ± 3 | | 2408 |

^aReference 16.

^bReferences 10 and 11.

^cScaled (see text).

^dFixed for scaling; Refs. 12, 13, and 15.

^eReferences 15 and 19.

the soller slits. The measured energies of the two transitions are given in the second column of Table I.

III. LINE IDENTIFICATION AND DISCUSSION

Identification of lines in the prompt spectrum relies on the availability of theoretical transition energies for few-electron systems. Reliable calculations for sulphur are available for helium-like systems^{10, 11} and the quartet states in lithium-like systems.^{12, 13} More extensive calculations have been made by Junker and Bardsley¹⁴ for analogous systems in fluorine and oxygen. Since matrix elements of the interelectron electrostatic interaction scale as Z for hydrogen-like wave functions, we expect the relative spacings of lines in fluorine and oxygen to be quite similar to those in sulphur. We have roughly calculated selected transition energies E_i in sulphur by scaling up the relative fluorine spacings from Ref. 14. We have held fixed the transition energy from the $(1s2s2p)^4P^o$, taken from Refs. 12, 13, and 15 and the 2^3P-2^1P spacings from Refs. 10 and 11. Scaled energies were then calculated from

$$\frac{[E_i - E(^4P^o)]_S}{[E_i - E(^4P^o)]_F} = \frac{[E(2^3P_1) - E(2^1P_1)]_S}{[E(2^3P_1) - E(2^1P_1)]_F}.$$

Such a process is admittedly approximate but useful to our line identifications in face of the lack of better theoretical energies. Resulting transition energies are shown in Table I.

We identify the four most prominent lines in Fig. 1(b) as due to decay from 2^3P and 2^1P helium-like states and from $(1s2p^2)^2P_{3/2, 1/2}$ and $(1s2p^2)^4P_{3/2, 1/2}$ lithium-like states. The wide peak at 2388 eV and a weak shoulder near 2409 eV may be attributed to decay from 3S and 5P beryllium-like states. The number of states calculated in Ref. 14 is not sufficiently complete to allow us to feel that this assignment is unique.

These identifications are consistent with our interpretation of the delayed spectrum of Fig. 1(d), where we identify the two well-resolved steps as $M2$ transitions originating from the helium-like $(1s2p)^3P_2$ and lithium-like $(1s2s2p)^4P_{5/2}$ states. These identifications are based on the agreement between observed and calculated transition energies.

We point out two features of these identifications:

First, the identification of lines from Hartree-Fock configuration-average calculations is at best treacherous. We display in Table I Hartree-Fock (HF) energies calculated by House¹⁶ for the helium-like through beryllium-like system for sulphur. On the basis of the HF satellite spacings, there is a strong temptation to identify the four strongest

lines in our spectrum as helium-like (two component), lithium-like, and beryllium-like satellites. We believe this identification to be incorrect, and point out simply that the separation of states of different multiplicity is not small compared to the spacing between satellites. In fact, it is not clear that the discussion of x-ray spectra in such few-electron systems, in terms of configuration-averaged satellites, is meaningful.

Second, the prompt x-ray spectrum may be strongly influenced by the fluorescence yields of the individual states. In Table I we have listed those transitions which we believe originate from states of high fluorescence yield. In the case of the lithium-like states, the $(1s2p^2)^2S$, 2D and $(1s2s2p)^2P_{3/2, 1/2}$ states all have allowed Auger emission, while the $(1s2p^2)^2P_{3/2, 1/2}$ states are forbidden to emit electrons and should be making the major contribution to the prompt x-ray peak labeled 2P . Similarly, the $(1s2p^2)^4P_{3/2, 1/2}$ states, which mix strongly in sulphur with the $(1s2p^2)^2P_{3/2, 1/2}$ states, should be the major contributors to the 4P peak near the foil. If the lithium-like systems are populated according to their statistical weights, this interpretation suggests that the 2P and 4P intensities should be roughly equal, a result consistent with the spectrum of Fig. 1(b). The $(1s2s2p)^4P_{3/2, 1/2}$ states will again mix with their 2P counterparts and primarily Auger decay, whereas the $(1s2s2p)^4P_{5/2}$ and the $(1s2p^2)^4P_{5/2}$ states which partially feed it via an allowed $E1$, should contribute little to the prompt spectrum, being primarily responsible for the 4P contribution seen downstream. We note that the roughly equal intensities of the 2^3P and 2^1P_1 line from helium-like systems is consistent with the assumption that the population of these states is proportional to their statistical weights. Only the 2^3P_1 component of the triplet has a prompt decay to the 1^1S_0 .

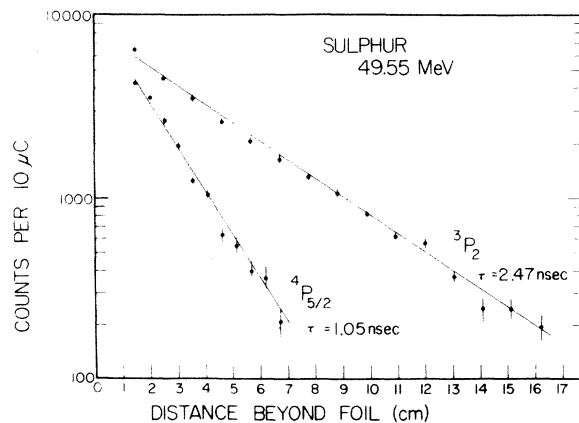


FIG. 2. Decay curves taken with the DTS.

TABLE II. Summary of lifetime measurements.

| State | Beam energy (MeV) | τ (nsec) |
|---------------------|-------------------|-----------------|
| $(1s2p)^3P_2$ | 40 | 2.66 |
| | 49.55 | 2.47 |
| | 55.05 | 2.39 |
| | 55.05 | 2.47 |
| | Average | 2.50 ± 0.10 |
| $(1s2s2p)^4P_{5/2}$ | 40 | 1.31 |
| | 49.55 | 1.05 |
| | 49.55 | 0.94 |
| | 55.05 | 1.13 |
| | Average | 1.11 ± 0.14 |

IV. LIFETIMES

The lifetimes of $(1s2p)^3P_2$ and the $(1s2s2p)^4P_{5/2}$ states were determined at energies of 40, 50 and 55 MeV by measuring, as a function of distance from the exciting foil, the height of each step seen in Fig. 1(c). The decay curve of each step height represents the decay of the intensity of x rays emitted from the corresponding state. Typical decay curves obtained in this manner are shown in Fig. 2, and the results of several lifetime determinations at different beam energies are given in Table II.

The observed lifetimes are in good agreement with calculated values for sulphur as can be seen in Table III. The theoretical lifetime for the 2^3P_2 state, based on an $E1$ rate to the 2^3S_1 state from Drake¹⁷ and on the $M2$ rate to the 1^1S_0 from Drake,¹⁸ is only slightly shorter than the experimental result. The $(1s2s2p)^4P_{5/2}$ state decays via $M2$ radiation to the $(1s^22s)^2S_{1/2}$ ground state and by spin-forbidden autoionization to the helium-like $(1s)^21S_0$. The rate for the $M2$ decay may be taken to be¹⁸ $1.19 \times 10^8 \text{ sec}^{-1}$, as discussed in Ref. 6. From our measured lifetime we then calculate an autoionization rate of $7.9 \times 10^8 \text{ sec}^{-1}$. This value fits well on a smooth curve interpolated between

TABLE III. Lifetimes in sulphur (in nsec).

| State | Observed | Calculated |
|---------------------|-----------------|---------------|
| $(1s2p)^3P_2$ | 2.5 ± 0.2 | 2.29^a |
| $(1s2s2p)^4P_{5/2}$ | 1.1 ± 0.2 | $1.15-1.20^b$ |
| | 1.1 ± 0.1^c | |

^aReferences 17 and 18.

^b A_{M2} from Drake (Ref. 18) and A_{auto} interpolated from Ref. 7.

^cReference 19.

measured rates for $Z = 8, 9, 17, 18$ but persists in disobedience to the scaling law discussed by Pegg *et al.*⁷ Both our measured lifetime and transition energy for this state are in agreement with the results of Haselton *et al.*,¹⁹ who have observed electrons from the autoionization of the state. It is clear that further theoretical effort in the calculation of autoionization rates is in order.

V. SUMMARY

In summary, we have presented moderately high-precision measurements of the transition energies to the ground states from several states in helium-like and lithium-like sulphur. Where comparison with theory is possible, good agreement is found. We have measured the lifetimes of the metastable $(1s2p)^3P_2$ and $(1s2s2p)^4P_{5/2}$ states in the two- and three-electron systems, respectively.

We point out that the prompt x-ray spectrum for systems with so few electrons is strongly influenced by the fluorescent yields from the individual initial states involved. No grouping of lines into well-separated satellites, each characteristic of the presence of a well-defined number of L -shell electrons in the initial state, is apparent in our spectra. We suggest the forcing of such groupings may lead to misinterpretation of spectral lines even in systems of higher electron number.

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