Lifetime and binding energy of the metastable $(1s2s2p)\,^4P^\circ_{5/2}$ state in S^{13+}†

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The lifetime and binding energy of the lowest-lying metastable quartet state, $(1s2s2p)\,^4P^\circ_{5/2}$, in S^{13+} have been measured by studying the forbidden (spin-spin-induced) autoionizing decay in flight of the state after foil excitation. The state is found to be bound by -4988 ± 26 eV and has a lifetime of 1.1 ± 0.1 nsec. A summary of our previous measurements of these same quantities for other members of the lithiumlike sequence is also given, along with an estimate of the branching ratio for the autoionization process.

I. INTRODUCTION

The $(1s2s2p)\,^4P^\circ_{5/2}$ state of lithiumlike ions has a lifetime determined primarily by the combined rates for two forbidden decay modes: one an autoionizing transition and the other a radiative transition. Specifically, these processes are

(i) forbidden autoionizing transitions arising from the tensor part of the spin-spin interaction,

$$(1s2s2p)\,^4P^\circ_{5/2} \to (1s^2)\,^1S_0 + K\,^2F^\circ_{5/2};$$

(ii) forbidden radiative transitions (arising from an intermultiplet $M2$ process),

$$(1s2s2p)\,^4P^\circ_{5/2} \to (1s^2 2s)\,^2S_{1/2}.$$

The relative branching for these radiative and autoionizing transitions will vary along the lithiumlike sequence, since the rate for each process scales differently with Z. In this paper we report a measurement of the lifetime and binding energy of the $(1s2s2p)\,^4P^\circ_{5/2}$ state in S^{13+} in which the autoionizing-decay channel was studied. A summary of our previous results for other members of the lithiumlike isoelectronic sequence is also given.

II. EXPERIMENT

The apparatus used in this experiment has been described in detail previously.[1] A fast beam of highly stripped and excited sulfur ions was produced by passing a 39-MeV sulfur beam from the Oak Ridge tandem accelerator through a thin carbon foil target. Electrons emitted in flight by the decay of autoionizing states associated with the beam ions were collected and energy analyzed. The temporal decay in flight of a particular state could be studied by translating (parallel to the beam axis) the foil target with respect to the entrance-slit system of the spectrometer. The electron counts at a given foil position were normalized to a fixed amount of beam charge collected in a Faraday cup. Using the methods and procedures described in Ref. 1, it was determined that the $(1s2s2p)\,^4P^\circ_{5/2}$ state in S^{13+} was bound by -4988 ± 26 eV and that it had a lifetime of 1.1 ± 0.1 nsec. One of several decay curves obtained for this state is shown in Fig. 1.

The resolution of the electron spectrometer was insufficient to spectrally separate the $J=\frac{1}{2}$, $\frac{3}{2}$, and $\frac{5}{2}$ fine-structure components of the $(1s2s2p)$ $^4P^\circ$ state, but the fact that all these components decay at different rates allowed us to isolate the $J=\frac{5}{2}$ component using the time-of-flight method. This component can only autoionize via the spin-spin interaction, whereas the $J=\frac{1}{2}$ and $\frac{3}{2}$ components autoionize via spin-orbit, spin-other-orbit, and spin-spin interactions, as well as mix with neighboring doublets of the same parity and J. Thus the data were accumulated at sufficient distances downstream from the foil target that the shorter-lived components had effectively decayed away. The linearity of the $J=\frac{5}{2}$-component decay curve as obtained in this and previous experiments[1] further indicates that this is the case.

III. DISCUSSION

For completeness we also quote our previous measurements of the binding energies and lifetimes of other members of the lithiumlike sequence. These results, along with the present results, are shown in Table I. Theoretical estimates of these quantities where available are also shown in Table I. The binding energies of the $(1s2s2p)\,^4P^\circ_{5/2}$ states are obtained by subtracting the observed autoionizing electron-emission energies, expressed in the ionic rest frame, from the sum of the well-established one- and two-electron ionization potentials.[2] The uncertainties in the absolute binding energies of the states

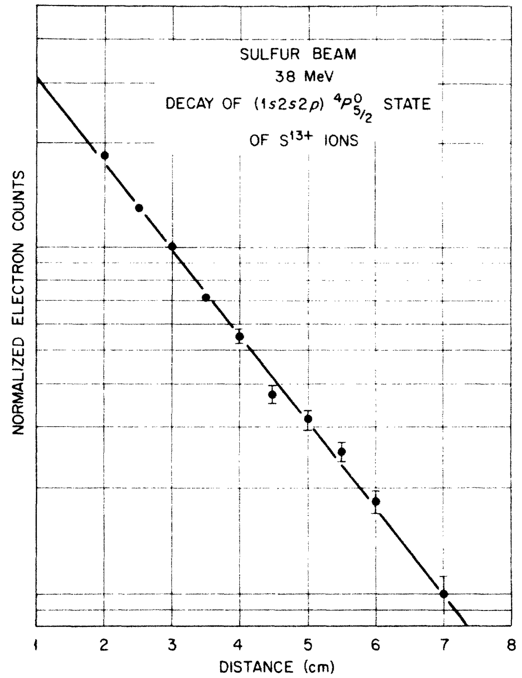

FIG. 1. Decay in flight, after foil excitation, of the $(1s2s2p)\ ^4P^o_{5/2}$ state in S^{13+}. The curve was obtained using a 39-MeV sulfur-ion beam.

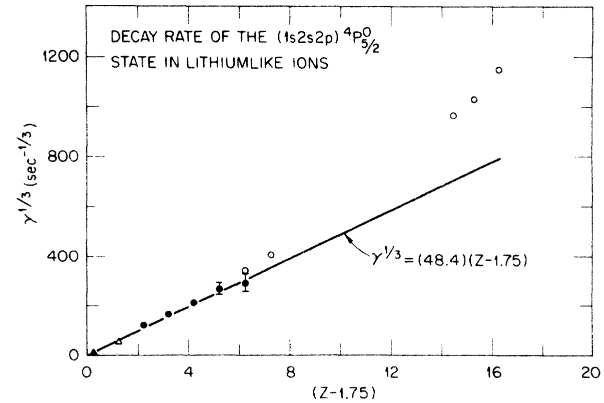

FIG. 2. Total decay rate (inverse lifetime) of the $(1s2s2p)\ ^4P^o_{5/2}$ level in some three-electron ions taken to the one-third power and plotted against an effective nuclear charge of $Z-1.75$. ▲ (Ref. 9); △ (Ref. 8); ● (Ref. 10); ○ (present work).

are quoted in parentheses after each result. The theoretically predicted energies of these states in O^{5+} and F^{6+} are due to Holøien and Geltman[3] and Junker and Bardsley.[4] The estimates quoted for S^{13+}, Cl^{14+}, and Ar^{15+} have been derived by extrapolating the nonrelativistic results of Holøien and Geltman[3] ($Z=2-10$) to the cases $Z=16$, 17, and 18. Relativistic corrections to these extrapolated values were made using the technique outlined by Snyder.[5] The theoretical estimates of the lifetime of the $(1s2s2p)\ ^4P^o_{5/2}$ state in O^{5+} are due to Manson[6] and Balashov *et al.*[7]

Figure 2 shows a plot of the inverse lifetime of the $(1s2s2p)\ ^4P^o_{5/2}$ state to the one-third power against a screened Z for several members of the lithiumlike sequence. Our results are shown in this figure, as well as those of other experimenters obtained using different methods.[8-10] Whereas the lower members of the sequence follow an approximate screened Z^3 scaling law, it is obvious that higher members of the sequence depart appreciably from such scaling. It appears that the $M2$ decay channel does not make a significant contribution to the total rate for low-Z ions, but does so for the higher-Z ions of the sequence. This is consistent with the fact that the $M2$ rate is expected to scale approximately as Z^8 for this transi-

TABLE I. Lifetime and binding energies of the $(1s2s2p)\ ^4P^o_{5/2}$ state in some three-electron ions.

Ion	Total binding energy (eV) Expt.	Total binding energy (eV) Theory	Lifetime (nsec) Expt.	Lifetime (nsec) Theory	Autoionization branching ratio
O^{5+}	−1193.7 (3.0)	−1193.7[a] −1193.1[d]	25±3	31[b], 75[c]	1.00
F^{6+}	−1526.5 (3.0)	−1525.7[a] −1525.7[d]	15±1	···	0.99
S^{13+}	−4988 (26)	−5008[e]	1.1±0.1	···	0.86
Cl^{14+}	−5655 (24)	−5652[e]	0.91±0.04	···	0.80
Ar^{15+}	−6369 (33)	−6352[e]	0.66±0.04	···	0.76

[a] Reference 3.
[b] Reference 6.
[c] Reference 7.
[d] Reference 4.
[e] Extrapolated, relativistically corrected value from Ref. 3.

tion, whereas presumably the spin-spin autoionizing rate scales less strongly with Z, perhaps closer to Z^3.

The lifetime of the $(1s2s2p)\,^4P^{\circ}_{5/2}$ state in Cl^{14+} has also been recently measured by Cocke *et al.*,[11] who studied the decay in flight of the $M2$ radiation. The lifetime result of their experiment is in very good agreement with the result we obtained by studying the autoionizing-decay channel. Cocke *et al.*[11] also suggest that the rate for the $M2$ transition, $(1s2s2p)\,^4P^{\circ}_{5/2} \rightarrow (1s^2 2s)\,^2S_{1/2}$, in three-electron ions should be approximately equal (except for slight radial integral and energy-level differences) to the rate for the similar $M2$ transition, $(1s2p)\,^3P_2 \rightarrow (1s^2)\,^1S_0$, in two-electron ions. If one assumes that this is true, branching ratios for the autoionization and radiative channels can be obtained by using suitably scaled calculated two-electron $M2$ transition rates of Drake[12] in combination with our experimental lifetime measurements. These autoionization branching ratios are shown in Table I and are based upon this assumption.

It has come to our attention that the lifetime of the $(1s2s2p)\,^4P^{\circ}_{5/2}$ state in S^{13+} has also been very recently measured by Cocke[13] using the radiative-decay channel again. The lifetime obtained is in excellent agreement with the result quoted in the present paper.

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