Observation of quartet-state fine structures and lifetimes in lithiumlike Ne VIII

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Wavelength and lifetime measurements for the fine-structure components of the $1s2s2p\,^4P^o$–$1s2p^2\,^4P$ multiplet in lithiumlike Ne VIII have been made using foil excitation of a fast-ion beam. The results are compared with recent theoretical calculations and with previous measurements for other ions of the same isoelectronic sequence. An apparent discrepancy between theory and experiment for the $1s2p^2\,^4P_{3/2}$ lifetime is removed.

I. INTRODUCTION

Core-excited three-electron systems are the simplest multiple-open-shell atomic structures and are thus a natural testing ground for the complexities of multielectron correlation effects and relativistic contributions in a simple atomic system.

Quartet states in the lithium isoelectronic sequence represent the simplest atomic systems for which the spin multiplicity differs from that of the singly excited states. They are metastable both to Coulomb autoionization and to transitions to the singly excited states. This allows $E1$ transitions among doubly excited states to compete favorably with the other deexcitation modes and to significantly affect x-ray fluorescence yields. In particular, for ionized systems, direct observation of ultraviolet transitions connecting doubly excited states enables high-precision measurements of transition energies and fine structures to be made that exceed by two or three orders of magnitude the experimental resolution capabilities of spectroscopies associated with deexcitation via x-ray and Auger-electron processes. From such detailed studies it is possible to identify differential metastability among fine-structure states that is important for the interpretation both of satellite-line structure near two-electron x-ray transitions and of time-delayed autoionization spectra.

The $1s2s2p\,^4P^o$ and $1s2p^2\,^4P$ lowest-lying quartet states in three-electron ions are strongly populated by the fast-ion-foil excitation process.[1] Recent spectroscopic measurements of the fine-structure wavelengths of the $1s2s2p\,^4P^o$–$1s2p^2\,^4P$ transition[2–5] and the fine-structure lifetimes of the $1s2p^2\,^4P$ state[2,5–7] have stimulated theoretical interest[8–11] in these systems. The precision wavelength measurements provide multiplet transition energies as well as upper and lower state fine-structure intervals that are sensitive to strong effects of the Breit interaction in these core-excited ions. The lifetime measurements for the $1s2p^2\,^4P$ fine-structure levels reveal J-dependent metastability against autoionization that characterizes such doubly excited states.

We report here the first measurements of spectroscopically resolved energies and lifetimes for this $^4P^o$-^4P transition in lithiumlike Ne VIII. The results are compared with recent measurements for other ions and with theoretical calculations in this lithium isoelectronic sequence. A discrepancy between theory and an earlier measurement for the $^4P_{3/2}$ lifetime is removed. Recent calculations[9] indicate that these lifetimes are very sensitive to relativistic intermediate coupling and configuration interaction, which motivates precision measurements.

II. EXPERIMENT

The excited Ne^{+7} ions were produced by directing Ne^{+2} ions of 7-MeV energy from the Argonne National Laboratory (ANL) Dynamitron Accelerator through carbon foils of 5-$\mu g/cm^2$ surface density. The resulting photon emission at approximately 90° was spectroscopically analyzed using a 1-m normal-incidence monochromator equipped with a channel electron multiplier operated in the single photon counting mode. Through the use of optical refocusing, spectroscopic linewidths of 0.4 Å were achieved. The wavelength and lifetime measurement procedures have been described elsewhere.[12]

Spectra were taken in each grating order (1st–4th) and at several different ion-beam energies to help to identify and

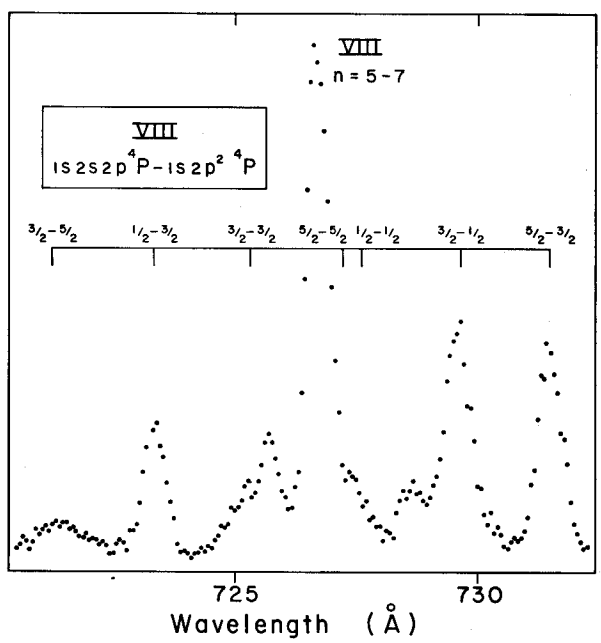

FIG. 1. Spectrum of foil-excited 7-MeV neon showing the resolved fine structure of the multiplet connecting the two lowest quartet terms and the quasihydrogenlike $n=5-7$ manifold in lithiumlike Ne VIII.

TABLE I. $1s2s2p\,^4P^o$–$1s2p^2\,^4P$ fine-structure wavelengths.

Transition	Wavelength (Å) Measured This work	Calculated Chung[a]	Hata and Grant[b]	Chen *et al.*[c]	Cheng *et al.*[d]
	(±0.05)				
$\frac{3}{2}$-$\frac{5}{2}$	721.12	720.79	720.1	726.2	714.1
$\frac{1}{2}$-$\frac{3}{2}$	723.27	723.09	722.3	728.5	716.3
$\frac{3}{2}$-$\frac{3}{2}$	725.60	725.14	724.5	730.5	718.2
$\frac{5}{2}$-$\frac{5}{2}$	(726.90)	726.87	726.2	732.4	720.1
$\frac{1}{2}$-$\frac{1}{2}$	(727.19)	727.29	726.5	732.8	720.4
$\frac{3}{2}$-$\frac{1}{2}$	729.55	729.39	728.6	734.9	722.4
$\frac{5}{2}$-$\frac{3}{2}$	731.45	731.28	730.6	736.8	724.2
c.g.	726.51	726.36	725.5	731.9	719.5

[a]Chung (private communication); see also Ref. 11.
[b]Reference 10.
[c]Reference 9.
[d]Reference 8.

resolve the quartet spectrum. This procedure was necessary because of the many weak and unidentified lines in this region of the spectrum. The wavelength dispersion scale was determined from the many well-known ionized neon transitions in the spectra. The precision of the profile-fitting program was also checked through these known transition wavelengths.

III. RESULTS

A spectral scan through the $1s2s2p\,^4P^o$–$1s2p^2\,^4P$ multiplet of Ne VIII is shown in Fig. 1. Seven fine-structure components can be discerned, as well as the $n=5-7$ hydrogenic transition of lithiumlike Ne VIII. The latter consists primarily of the $5g$-$7h$ transition at 726.72 Å with some blending with the $5f$-$7g$ transition at 726.63 Å. These wavelengths have been semiempirically fitted with high accuracy by Edlén[13] and provide a convenient wavelength calibration for our measurements. By fitting our spectra to five of the quartet lines (i.e., all but the weak $\frac{5}{2}-\frac{5}{2}$ and $\frac{1}{2}$-$\frac{1}{2}$ lines), we completely determine the four fine-stucture intervals of the upper and lower ^4P states. In Table I we present our measured fine-structure wavelength values and compare these with theoretical values for Ne VIII. The associated fine-structure energy intervals are shown in Table II.

Detailed lifetime measurements were performed on the $\frac{1}{2}$-$\frac{3}{2}$, and $\frac{5}{2}$-$\frac{3}{2}$ fine-structure transitions. Excellent consistency was observed in the lifetime results for the $\frac{1}{2}$-$\frac{3}{2}$ and $\frac{5}{2}$-$\frac{3}{2}$ transitions representing the $^4P_{3/2}$ upper state. In Table III we present our measured lifetime values for $1s2p^2$ $^4P_{3/2}$ and $^4P_{1/2}$ and compare these with theoretical values as well as with a previous measurement of the $J=\frac{3}{2}$ level. We also include our measured upper limit for the very short $J=\frac{5}{2}$ lifetime. This approximate result is due to the very short decay length and weak intensity of the $\frac{5}{2}$-$\frac{5}{2}$ transition.

IV. DISCUSSION AND SUMMARY

In Fig. 2 we show a plot of the $1s2s2p\,^4P^o$–$1s2p^2\,^4P$ center of gravity (c.g.) transition wavelength for lithiumlike

TABLE II. Fine-structure intervals for $1s2s2p\,^4P^o$ and $1s2p^2\,^4P$.

Interval		Interval (cm^{-1}) Measured This work	Calculated Chung[a]	Hata and Grant[b]	Chen *et al.*[c]	Cheng *et al.*[d]
		(± 15)				
$1s2p^2\,^4P$	$\frac{5}{2}$-$\frac{3}{2}$	856	832	821	816	789
	$\frac{3}{2}$-$\frac{1}{2}$	746	805	812	810	804
$1s2s2p\,^4P$	$\frac{5}{2}$-$\frac{3}{2}$	1102	1160	1179	1169	1154
	$\frac{3}{2}$-$\frac{1}{2}$	444	394	398	389	371

[a]K. T. Chung (private communication); see also Ref. 11.
[b]Reference 10.
[c]Reference 9.
[d]Reference 8.

TABLE III. Lifetime results for upper levels $1s2p^2\,{}^4P$.

Level J	Lifetime (10^{-12} s) Measured: This work	Measured: Schumann *et al.*[a]	Calculated: Chen *et al.*[b]	Calculated: Tunnell and Bhalla[c]
$\frac{1}{2}$	540 ± 50	· · ·	530	529
$\frac{3}{2}$	408 ± 40	190 ± 90	449	110
$\frac{5}{2}$	< 50	· · ·	28	21

[a]Reference 7.
[b]Reference 9.
[c]Reference 14.

ions. Our result for Ne VIII displays good consistency with the trend of our earlier measurements for $Z=6$–8 as well as with recent values reported for $Z=9$ and $Z=12$. (We point out that in Ref. 2, a numerical error appears in the c.g. energies for $Z=7$ and 8 quoted in Table I. These values are derived from the fine-structure wavelength values in that table and should read 1110.7 and 945.9 Å instead of 1111.1 and 946.8 Å.) The sensitivity of this quartet transition energy to both relativistic and electron correlation effects is evident from a comparison of our value for $Z=10$ with early[8] and with more recent[9,10] relativistic Hartree-Fock calculations. The most accurate calculations for this transition energy at low Z appear to be the very recent relativistic perturbation results of Chung (Ref. 11 and private communication). For Ne VIII this latter calculation differs from our measured c.g. wavelength by 0.15 Å (2 parts in 10^4) or by three standard deviations of our estimated precision (±0.05 Å, or 7 parts in 10^5). These results show that we are sensitive at the 10% level to the QED corrections[10] of about 0.50 Å for these transitions.

Comparison of our measured fine structures with theoretical values (see Table I) shows reasonable consistency, beyond the mean-wavelength discrepancies that range from 0.1 to 7.4 Å. We summarize these results in more detail in Table II, where comparison is made between our derived fine-structure intervals and available theoretical values. Our results suggest a ratio of $\frac{5}{2}$-$\frac{3}{2}$ to $\frac{3}{2}$-$\frac{1}{2}$ intervals that is larger for $1s2p^2$ and smaller for $1s2s2p$ than the theoretical results.

Our lifetime results for $1s2p^2\,{}^4P_{3/2}$ and ${}^4P_{1/2}$ (see Table III) show good agreement with recent calculations by Chen, Craseman, and Mark.[9] For $J-\frac{1}{2}$ there is also agreement with an earlier intermediate-coupling calculation.[14] However, for $J=\frac{3}{2}$ our result confirms the prediction of Ref. 9

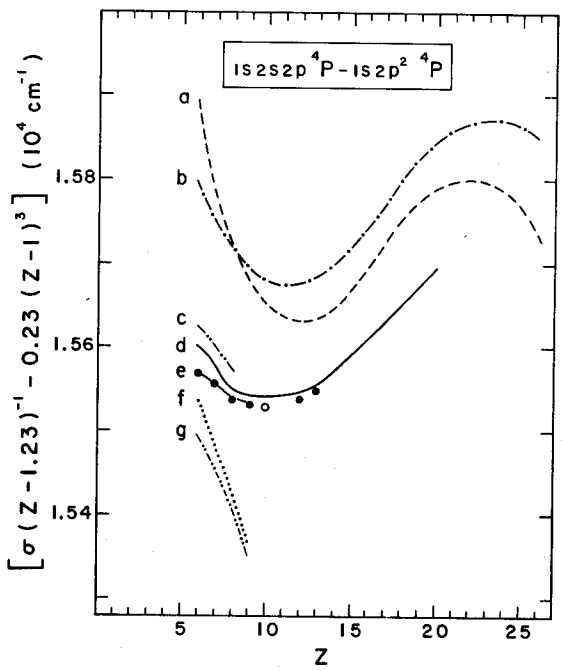

FIG. 2. Scaled isoelectronic plot of the center of gravity wavelength of the $1s2s2p\,{}^4P^o$–$1s2p^2\,{}^4P$ multiplet transition for the Li sequence. The experimental results are from Refs. 2 ($Z=6$–8), 5 ($Z=9$), 3 ($Z=12$), and 4 ($Z=13$) and this work ($Z=10$). The theoretical predictions are from the following references (a) 15, (b) 8, (c) 9, (d) 10, (e) 11, (f) 16, (g) 17.

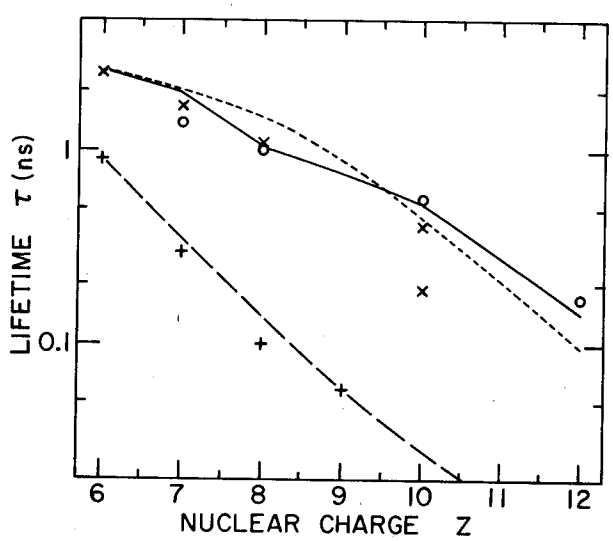

FIG. 3. Semilogarithmic plot of lifetime vs nuclear charge for fine structure levels of the $1s2p^2\,{}^4P$ term for the Li sequence. The experimental points are denoted by the following: o for $J=\frac{1}{2}$, × for $J=\frac{3}{2}$; + for $J=\frac{5}{2}$. They are from Refs. 2 ($Z=6$–8), 5 ($Z=9$), 6 ($Z=10$), and 7 ($Z=23$), and this work ($Z=10$). The theoretical calculations of Ref. 9 are denoted by solid line for $J=\frac{1}{2}$, dotted line for $J=\frac{3}{2}$, and dashed line for $J=\frac{5}{2}$.

that the earlier calculated value and a previous measured value[7] are both too small. This comparison is consistent with the removal of discrepancies between the earlier calculations and our previous $J=\frac{3}{2}$ lifetime measurements[2] for $Z=4-6$ that the Chen *et al.*[9] results accomplish. In Fig. 3 we summarize these experimental and theoretical $1s2p^2\,{}^4P$ lifetimes for the lithium isoelectronic sequence. Our lifetime measurements for Ne VIII represent the highest Z for which the differential metastability in core-excited quartet states has been experimentally verified.

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