Satellite lines from core-excited states in neutral lithium

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The extreme ultraviolet spectrum of foil-excited Li has been recorded at ion energies 100–300 keV with higher spectral resolution than before. Previously assigned decays of core-excited three-electron doublet states (some of which autoionize rapidly) are confirmed with higher wavelength precision.

INTRODUCTION

The extreme ultraviolet (euv) part of the spectrum of lithium contains the ground-state transitions of the ions Li^+ and Li^{2+} and satellite lines to these diagram lines. These satellite lines arise from core-excited states in Li^+ and Li^0, and they have been studied using a number of light sources and excitation conditions (for a recent review and other recent data see Refs. 1–5). Many of the core- or multiply excited states can autoionize, however, and the emission spectra therefore will show the decays of only those states for which the radiative decay accounts for a sizable fraction of the total decay rate. This condition is often fulfilled for high-spin states in systems with more than two electrons as, for instance, the quartet states in three-electron systems, since in these cases the lowest-lying states would require a spin change in order to effect autoionization. In the three-electron systems, a number of odd-parity S states have been predicted to be bound, but their optical decay has not yet been detected, with one notable exception: There is a bound triply excited state, $2p^3\,{}^4S^o_{3/2}$, which predominantly decays radiatively.[6] The radiative decay of this level has recently been observed and has been studied in some detail.[5,6]

This paper concentrates on transitions in core-excited neutral lithium, that is, an atom with three electrons. Whereas the decays of the core-excited quartet states towards other core-excited quartet states are readily studied in emission spectroscopy,[1,4–7] many of the core-excited doublet states will autoionize, and in many of these cases the autoionization rate will exceed the radiative transition rate, even by orders of magnitude. However,the $1s2p^2\,{}^2P$ state is known not to autoionize because of selection rules on L, S, and parity, and other doublet states may be found which at least show a detectable radiative decay branch, even in the presence of autoionization as the preferential decay mode.

The wavelengths of the decays of core-excited states (e.g., $1s^2n'l'$-$1snpn'l'$) are close to those of the resonance lines $1s^2\,{}^1S$–$1snp\,{}^1P^o$ in Li^+ (that is why they are called satellites[8]), and the wavelengths of transitions in the doublet system and of intercombination transitions from core-excited quartet levels to singly excited doublet levels may be very close to each other. The latter ones are readily apparent for ions of higher nuclear charges, but for Li the transition rates will be too low for an observation in time-resolved fast-beam spectroscopy.

The line identifications suggested in the first detailed beam-foil studies of the doublet satellites relied mostly on comparison with calculated line positions. Precision measurements of the absolute-term values of the Li quartet levels[7] and the establishment of the absolute positions of the doublet levels[9] via the observation of a laser-induced intercombination transition,[10] however, led to a revision of some of the earlier assignments,[2] and associated several of the previously observed satellite lines with radiative decays of core-excited and autoionizing doublet states.[3] For example, the optical decay of the lowest ${}^2P^o$ level has been identified for which the branching ratio has been calculated to be higher than 20:1 in favor of autoionization. That study was also aided by comparison with predictions obtained from improved calculations.

The signal level in the earlier beam-foil study, however, was not as good as one may have wanted for a more positive identification, and the present paper reports on new measurements under more favorable conditions which led to a decrease of the wavelength uncertainties by about a factor of 3.

EXPERIMENT

The experiment was done at the Bochum dynamitron tandem laboratory. A 400-kV single-stage electrostatic accelerator delivered Li^+-ion beams of 100, 200, and 300 keV to an experimental chamber containing a displaceable foil wheel and a Faraday cup (for signal normalization). Carbon foils of approximate areal density 20 $\mu g/cm^2$ were used to excite the ion beam. A 2.2-m grazing-incidence spectrometer (McPherson Model No. 247) equipped with a gold-coated, ruled 600-lines/mm grating and a low-dark-rate channeltron detector analyzed the light emitted by the ion beam at right angles. The exit slit displacement, which affects the scanning of a spectrum, was monitored with micrometer precision by a Heidenhain moiré fringe length gauge. Further details of the experimental apparatus and procedures are given elsewhere.[2,4]

TABLE I. Observed lines (see Fig. 1) and proposed identifications.

Transition	Wavelength λ/nm Experiment This work	Other work	Theory
$1s^22p\ ^2P^o$–$(1s2p\ ^3P)3p\ ^2P$	19.768(8)	19.76[a]	19.761[e]
	19.897(8)	19.89[a]	
$1s^2\ ^1S$–$1s2p\ ^1P^o$	19.9282[c]	Calibration	
$1s^23d\ ^2D$–$(1s2p\ ^1P)3d\ ^2D^o$	19.9673(20)	19.96[a]	19.9690[d]
		19.9716[b]	
$1s^23p\ ^2P^o$–$[(1s2p\ ^3P)4p-(1s2p\ ^1P)3p]\ ^2P$			20.029[e]
Blended with		20.0390[b]	20.0392[d]
$1s^23d\ ^2D$–$(1s2p\ ^3P)4d\ ^2D^o$	20.033(4)	20.028[a]	
$1s^23p\ ^2P^o$–$[(1s2p\ ^3P)4p+(1s2p\ ^1P)3p]\ ^2P$	20.101(4)	20.10[a]	
$1s^23d\ ^2D$–$(1s2p\ ^3P)3d\ ^2D^o$	20.284(4)	20.288[a]	20.2860[d]
		20.2862[b]	
$1s^22p\ ^2P^o$–$1s2p^2\ ^2P$	20.7464(20)	20.745[a]	20.7452[e]
		20.7462[b]	
	20.781(10)		
$1s^22p\ ^2P^o$–$1s2p^2\ ^2D$	20.938(8)	20.93[a]	20.9353[f]
		20.9410[b]	
$1s^22s\ ^2S$–$[1s(2s2p)\ ^3P]\ ^2P^o$	21.043(8)	21.05[a]	21.0390[f]
		21.0474[b]	
$1s^23p\ ^2P^o$–$1s2p^2\ ^2P$	21.461(2)	21.456[a]	21.4584[e]
		21.4594[b]	
	21.717(8)	21.665[a]	
	21.838(10)	21.803[a]	

[a]Träbert *et al.* (Ref. 2).
[b]Mannervik *et al.* (Ref. 3) predicted wavelengths from their own and earlier observations in other parts of the electromagnetic spectrum. For references, see Ref. 3.
[c]Edlén (Ref. 12).
[d]Jáuregui and Bunge (Ref. 17).
[e]Bunge (Ref. 18).
[f]Chung (Refs. 19 and 20).

The improvement of the present over the previous experiment[2] lies in the lower-beam energy for which the smaller of the Bochum accelerators could be used, which then delivered a higher-beam current. The signal level improved so much that significantly narrower spectrometer slits (down to 30 μm) could be used which resulted in a smaller linewidth [full width at half-maximum (FWHM) 0.022 nm] at yet better statistics.

DATA AND DISCUSSION

Data were recorded at ion energies 100–300 keV. All the data given in Table I, however, refer to an ion energy of 300 keV, since at this energy the signal level was highest, resulting from the combination of ion-beam production, beam transport, and the actual excitation function of the atomic species of interest.[11]

The wavelength calibration curve of the spectrometer is well known. The first- and second-order Doppler shifts in a good approximation were accounted for by the knowledge of the ion velocity and by reference to a well-known line which appears in the spectrum, the Li^+ first-resonance line $1s^2\ ^1S$–$1s2p\ ^1P^o$ at $\lambda=19.9282$ nm.[12] The line positions in the spectra were obtained from multicomponent line profile fits to the actual spectra. The uncertainties given along with the wavelength results in Table I include estimates of the uncertainties of the calibration curve as well as the (mostly statistical) uncertainty of locating a line with respect to this curve.

A specimen spectrum obtained at high resolution is displayed in Fig. 1. It shows the dominant ($n=1$-$n'=2$) diagram line and a fair number of satellites. Almost all of the previously reported lines[2,3] show up at this beam energy, too. In particular, the lines previously[3] associated

TABLE II. Excitation energies (in eV) of three of the four lowest levels of $^2P^o$ symmetry as determined from this work in conjunction with the data presented earlier (Refs. 3, 8, and 9).

State	E (eV)
$^2P^o$ (1) $1s(2s2p\ ^3P)\ ^2P^o$	58.907(6)
$^2P^o$ (2) $1s(2s2p\ ^1P)\ ^2P^o$	Not observed
$^2P^o$ (3) $(1s2s\ ^3S)3p\ ^2P^o$	62.399(25)
$^2P^o$ (4) $(1s2s\ ^3S)4p\ ^2P^o$	63.353(12)

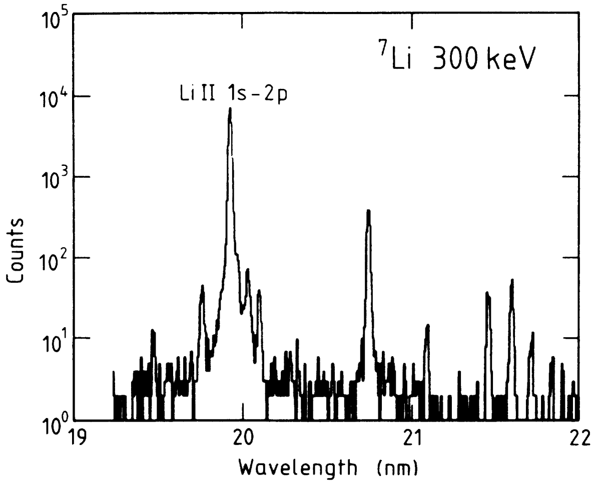

FIG. 1. Spectrum of foil-excited 300-keV Li ions in the wavelength range 19–22 nm. Logarithmic intensity scale. Linewidth (FWHM) 0.022 nm.

with transitions from rapidly autoionizing levels in the doublet term system are confirmed. The new wavelengths of improved precision agree even more significantly with the suggested identifications than the previous ones of lower statistical merit could do. The only exception is the line at $\lambda = 19.9673$ nm which at the newly reached level of wavelength precision appears to deviate from the predicted position by almost 2σ. This, however, may be an artifact which could be caused by the closeness to the strong resonance line from which the line could not be resolved completely, and by the computer analysis remaining imperfect due to the presence of too many unresolved satellite components in this particular line cluster.

It should be noted that the uncertainties of the core-excited doublet line wavelength predictions[3] which resulted from the high-accuracy work in the longer-wavelength ranges of the uv and visible part of the spectrum[7,9] are still more precise than the best directly measured euv wavelengths by about one order of magnitude. The precision of the new data presented here, however, at least equals or even surpasses that of the most precise wavelength data hitherto available from other (stationary) light sources[13–16] and probably exceeds the precision to be expected from most of the recent calculations as put forward in Ref. 3. The excitation energies of three of the four lowest $^2P^o$ states have been redetermined from the new data and the data in Refs. 3, 7, and 9 and are given in Table II.

In conclusion, the new data substantially improve on the old euv beam-foil data and corroborate the previous analysis, lending further support to the identification of radiative transitions from rapidly autoionizing core-excited doublet states by an improved agreement with the predicted wavelength pattern. The data also underline the value and even the necessity of high spectral resolution in beam-foil spectroscopy.

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[1]T. Andersen and S. Mannervik, Comm. At. Mol. Phys. **16**, 185 (1985).
[2]E. Träbert, J. H. Blanke, R. Hucke, and P. H. Heckmann, Phys. Scr. **31**, 130 (1985).
[3]S. Mannervik, H. Cederquist, and E. Träbert, Phys. Scr. **34**, 143 (1986).
[4]S. Mannervik, R. T. Short, D. Sonnek, E. Träbert, G. Möller, V. Lodwig, P. H. Heckmann, J. H. Blanke, and K. Brand, Phys. Rev. A **39**, 3964 (1989).
[5]S. Mannervik, Phys. Scr. (to be published).
[6]M. Agentoft, T. Andersen, and K. T. Chung, J. Phys. B **17**, L433 (1984).
[7]S. Mannervik and H. Cederquist, Phys. Scr. **27**, 175 (1983).
[8]B. Edlén and F. Tyrén, Nature **143**, 904 (1939).
[9]S. Mannervik and H. Cederquist, Phys. Scr. **31**, 79 (1985).
[10]J. R. Willison, R. W. Falcone, J. F. Young, and S. E. Harris, Phys. Rev. Lett. **47**, 1827 (1981).
[11]V. Lodwig and H. v. Buttlar, Nucl. Instrum. Methods B **31**, 342 (1988).
[12]B. Edlén, Nova Acta Reg. Soc. Sci. Uppsala (IV) **9** (6), 153 (1934).
[13]D. L. Ederer, T. Lucatorto, and R. P. Madden, Phys. Rev. Lett. **25**, 1537 (1970).
[14]A. M. Cantu, W. H. Parkinson, G. Tondello, and G. P. Tozzi, J. Opt. Soc. Am. **67**, 1030 (1977).
[15]T. J. McIlrath and T. B. Lucatorto, Phys. Rev. Lett. **38**, 1390 (1977).
[16]J. R. Willison, R. W. Falcone, J. C. Wang, J. F. Young, and S. E. Harris, Phys. Rev. Lett. **44**, 1125 (1980).
[17]R. Jáuregui and C. F. Bunge, Phys. Rev. A **23**, 1618 (1981).
[18]C. F. Bunge, Phys. Rev. A **19**, 936 (1976).
[19]K. T. Chung, Phys. Rev. A **23**, 2957 (1981).
[20]K. T. Chung, Phys. Rev. A **24**, 1350 (1981).