Classifications of Some Transitions in Doubly Excited Li I and Li II

J. P. Buchet,* M. C. Buchet-Poulizac,* and H. G. Berry*†
Laboratoire de Spectrométrie Ionique et Moléculaire, Université de Lyon I, 43 Bd du 11 novembre 1918, 69 Villeurbanne, France

G. W. F. Drake
Department of Physics, University of Windsor, Windsor, Ontario, Canada
(Received 19 September 1972)

Using the beam-foil technique, we have observed several new transitions in lithium between 100 and 2000 Å. We suggest classifications for some of these transitions in the doubly excited term schemes of Li I and Li II. The lifetimes and wavelengths of the Li II transitions are found to be in reasonable agreement with variational calculations.

INTRODUCTION

Recent beam-foil work in helium[1] and lithium[2] at near-ultraviolet and visible wavelengths has resulted in many new classifications of transitions between doubly excited terms in He I and Li I. These terms, which are up to 60 eV above their respective first-ionization limits, are stable against autoionization under Coulomb selection rules, and consequently decay principally by photon emission. As the calculations in the He I sequence for these doubly excited terms have been carried out for higher-Z members,[3-5] it is of interest to search for the same transitions in Li II. In the Li I spectrum we have searched principally for the radiative decay from the lowest doubly excited doublet term which is stable against autoionization.

THEORETICAL CALCULATIONS

The positions and radiative lifetimes of the nonautoionizing $2p^2\,{}^3P$, $2p3p\,{}^{1,3}P$, and $2p3d\,{}^{1,3}D$ states of Li^+ have been calculated previously by the $1/Z$-expansion technique,[3-5] but no data are available for the autoionizing $(2p3p \pm 2s3d)\,{}^3D$ states. The lower-lying (+) state is unusually stable against autoionization and can be expected to contribute to the optical spectrum. The positions and widths of the $(\pm)\,{}^3D$ states were calculated using the $1/Z$-expansion technique for autoionizing states described in Ref. 6, with a 50-term correlated basis set for the $(\pm)\,{}^3D$ states and a screened Coulomb function for the $1skd\,{}^3D$ continuum. The results are given in Table I, along with the oscillator strengths and radiative decay rates for electric dipole transitions to the $1s2p\,{}^3P$, $1s3p\,{}^3P$, and $1s4p\,{}^3P$ states. The singly excited ^3P wave functions are also represented by $1/Z$ expansions with a 50-term correlated basis set.[3-5] All other radiative transitions from the $(\pm)\,{}^3D$ states involve a two-electron jump and should be very weak. The results clearly indicate that while the $(-)\,{}^3D$ state decays primarily by autoionization, the $(+)\,{}^3D$ state decays primarily by radiation to the $1s2p\,{}^3P$ and $1s3p\,{}^3P$ states with a mean life of 0.0221 nsec (including the small contribution from autoionization).

EXPERIMENT

A thermionic source in the head of a 2-MV van de Graaff accelerator produced a Li^+ beam with currents of up to 10 μA after magnetic analysis. After excitation by a thin carbon foil, the light emitted from the beam was viewed at approximately 90° by either a 1-m normal-incidence concave-grating monochromator or a 2-m grazing-incidence monochromator. Our wavelength detection range was thus continuous between 20 and 2000 Å. More complete experimental details have been de-

TABLE I. Theoretical data for the $(2p3p \pm 2s3d)\,{}^3D$ states of Li^+.[a]

	$(2p3p+2s3d)^3D$	$(2p3p-2s3d)^3D$
E (a.u.)	−1.405 562	−1.362 929
γ_{auto} (sec^{-1})	1.4×10^9	8.4×10^{11}
$1s2p\,{}^3P-(2p3p\pm2s3d)\,{}^3D$ transition		
wavelength (Å)	125.8	124.3
$f(i\to j)$ length	0.060 14	0.014 35
$f(i\to j)$ velocity	0.060 21	0.014 43
$A(j\to i)$ (sec^{-1})	1.52×10^{10}	3.72×10^9
$1s3p\,{}^3P-(2p3p\pm2s3d)\,{}^3D$ transition		
wavelength (Å)	137.0	135.3
$f(i\to j)$ length	0.131 26	0.041 34
$f(i\to j)$ velocity	0.131 08	0.041 37
$A(j\to i)$ (sec^{-1})	2.79×10^{10}	9.04×10^9
$1s4p\,{}^3P-(2p3p\pm2s3d)\,{}^3D$ transition		
wavelength (Å)	141.4	139.5
$f(i\to j)$ length	0.003 51	0.0004
$f(i\to j)$ velocity	0.003 62	0.0002
$A(j\to i)$ (sec^{-1})	7.2×10^8	6×10^7

[a] $f(i\to j)$ is the absorption oscillator strength and $A(j\to i)$ is the Einstein A coefficient for spontaneous emission.

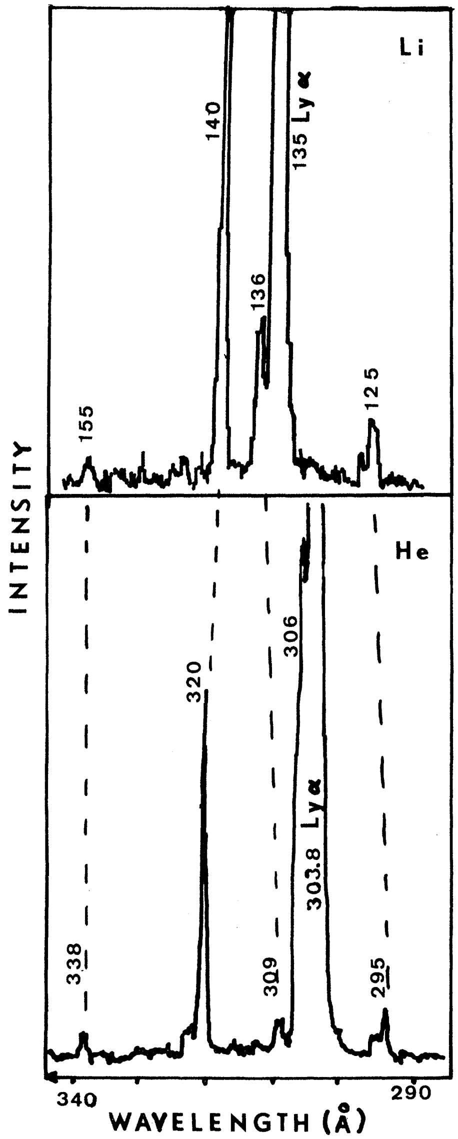

FIG. 1. Beam-foil spectra of helium (300-keV beam energy) near 300 Å, and of lithium (1.4-MeV beam energy) near 135 Å. The transitions indicated are the same in both spectra.

scribed previously.[7,8] Decay times of the transitions observed were measured by moving the foil in steps of 0.1 mm along the beam, collecting photons at each step for a fixed beam charge monitored by a Faraday cup. Lifetimes were very short and typically 0.01 nsec which corresponds to 0.1 mm or less of beam length at the energies used (500 keV–1.5 MeV).

RESULTS

Spectra

The one-electron spectrum of Li III appeared very strongly excited and many members of the Lyman and Balmer series were observed in this wavelength region.[9]

The singly excited Li II spectrum is also well known[10] and we observed all known transitions of this spectrum in this wavelength region. In addition, a number of new transitions were observed between known terms and also from new terms of high principal quantum number.

We are able to suggest classification for the remaining lines as originating from doubly excited terms of either Li I or Li II.

In Fig. 1 we compare our beam-foil spectra of He and Li around the respective Lyman-α wavelengths. The scales have been adjusted to indicate the close correspondence of the transitions observed. From the previous measurements on helium[1,11] and the calculations,[3] the classification appears straightforward, although there is certainly some blending present. In Table II we give the wavelengths and suggested classifications for these lines, and compare with theory and previous measurements.[11] We should note that the blended line at 306 Å in He I has been resolved for the first time from the Lyman α and also that the transition $1s3p\ ^3P$-$2p^2\ ^3P$ had not previously been observed. Its intensity is low, as expected from its low transition probability.[6] No transitions are observed from terms which are expected to have appreciable autoionization rates to adjacent continua.

Only one line could be ascribed to a transition between doubly excited states in Li II. This is the transition $2p^2\ ^3P$-$2p3d\ ^3D$ at 1036 Å. Its wavelength is in good agreement with theory. The only other transition expected to be strong enough to be ob-

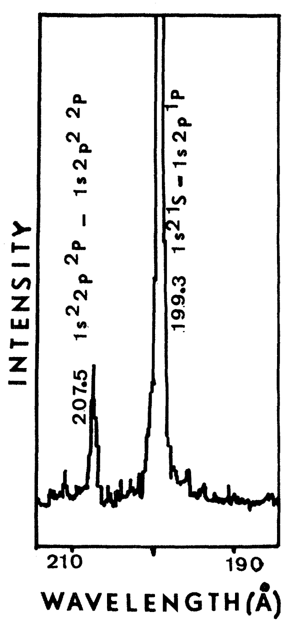

FIG. 2. Beam-foil spectrum of lithium at a beam energy of 600 keV near 200 Å. The transition $1s^22p\ ^2P$-$1s2p^2\ ^2P$ from doubly excited Li I is indicated.

TABLE II. Transitions involving doubly excited states.

Wavelength (Å)			Possible identi-	Mean life (nsec)		
	Calc.				Calc.	
Obs.[a]	sing.	trip.	fication	Obs.	sing.	trip.
		125.8	$1s2p\,^3P^o$-$2p3p\,^3D$			0.0221
125.5			Li II	0.054[b]		
	126.8	124.7	$1s2p\,^3P^o$-$2p3p\,^3P$	± 0.01	0.0179	0.0181
		137.0	$1s3p\,^3P^o$-$2p3p\,^3D$			0.0221
136.5	137.3	135.8	Li II $1s3p\,^3P^o$-$2p3p\,^3P$	0.021[b]	0.179	0.0181
	136.0	135.4	$1s3d\,^3D$-$2p3d\,^3D^o$	± 0.01	0.0213	0.0201
140.5		141.0	Li II $1s2p\,^3P^o$-$2p^2\,^3P$	0.029 ± 0.01		0.0132
155		155.3	Li II $1s3p\,^3P^o$-$2p^2\,^3P$			0.0132
207.5		...	Li I $1s^22p\,^2P^o$-$1s2p^2\,^2P$	0.015[b] ± 0.01		...
1036		1036.6	Li II $2p^2\,^3P$-$2p3d\,^3D^o$	...		...
1141		...	...	...		
338		338.1	He I $1s3p\,^3P^o$-$2p^2\,^3P$	...		

[a]Wavelength accuracy ± 0.5 Å. [b]Corrected for cascade.

served near this wavelength is the $2s2p\,^3P^0$-$2p3p\,^3D$ transition which we calculate to be at 961 Å. It would thus be unfortunately blended with the transitions in second order of $n=2-5$ in Li III at 2×481 Å.

In doubly excited Li I, we observed the transition $1s^22p\,^2P^0$-$1s2p^2\,^2P$ at 207 Å, as shown in the spectrum of Fig. 2. Two other weak lines around 200 Å are the transitions from doubly excited doublets to singly excited terms of the type $1s^23d\,^2D$-$1s2p3d\,^2D$.

Lifetimes

Because of the very rapid decays, our precision in the lifetimes measurements was not very great and the values must be considered more as upper limits to the real mean lives. However, it was sufficient to make sensible comparisons with the theory and thus greatly helped in verifying the tentative classifications of the lines. The measured and theoretical lifetimes are compared in Table I. Reasonable agreement is found with theory. For the blended transitions at 136.5 Å, the theoretical lifetimes of all components are the same to within experimental accuracy and also in agreement with experiment.

CONCLUSION

We have observed transitions from doubly excited terms in the two- and three-electron spectra of Li II and Li I in the vacuum ultraviolet. The energies and their radiative lifetimes are found to agree well with theory. We note that we only observe photon emission from doubly excited terms with small or zero autoionization rates to adjacent continua. The apparent exception of the decay from the $2p3p\,^3D$ term (which is situated in an ^3D even-parity continuum) is explained by its very low autoionization rate.

*Associé au C.N.R.S.
†Present address: Dept. of Physics, University of Chicago, Chicago, Ill.

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