scattering angles at all energies are due to the fact that we have neglected the long-range forces. The inclusion of above-mentioned effects is expected to improve the results substantially.

Figure 2 represents my curve and the measured values.[7] The agreement between the present results and the experimental values is very satisfactory. The effect of the double scattering can be judged by comparing the Born (single scattering) and the present curves. This effect is appreciable for large scattering angle. It has been seen that with the increase of energy, the agreement between the present results and observed values are also improving.

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Doubly Excited Autoionization Resonances in the Absorption Spectrum of Li^+ Formed in a Laser-Produced Plasma*

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In a technique using a continuum generated by focusing a laser beam on a target of high atomic number, the spatially resolved absorption spectrum of Li^+ formed in a second laser-produced plasma was studied from 200 to 50 Å. The doubly excited resonances, $1s^2\,{}_1S$-$2snp\,{}^1P$, as well as the principal series and its adjoining photoionization continuum were observed. The Fano parameters, q and Γ, of the $2s2p\,{}^1P$ were derived from the absorption profile. Comparison is made with theory.

Controlled experiments on the absorption spectra of atomic ions are of importance because they can provide information which cannot be obtained from emission spectra, particularly on inner-shell and double electron excitation and also on photoionization continua. Little work however has been done in this field, although some recent experiments have shown promising results.[1-3] In this Letter we report some work on what promises to be a relatively simple procedure for obtaining the absorption spectra of a wide range of ionic species.

In our experiments, the absorption spectra of laser-produced plasmas were systematically studied. The main effort was concentrated on lithium because in its singly ionized state it constitutes the second member of the heliumlike isoelectronic sequence and consequently its double electron transitions, if observed and studied, would be of considerable theoretical interest. A single Q-switched ruby laser (pulse length, 40–50 nsec; pulse energy, 1 J) was used to produce both the ionized species and the background continuum. To generate the continuum, part of the laser beam was sharply focused on a tungsten target (Fig. 1). Following the work of Ehler and Weissler[4] we found, in a separate series of experiments,[5] that plasmas generated on tungsten, uranium and other targets of high atomic number gave continua of various degrees of uniformity

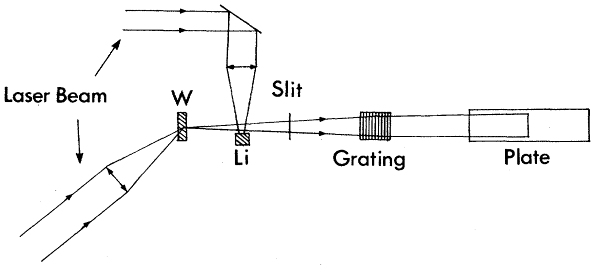

FIG. 1. Schematic diagram of experimental arrangement.

which could be used for absorption studies in the soft-x-ray region. To produce the absorbing plasma the remainder of the beam was diverted by prisms onto the lithium target, the surface of which was prepared freshly *in vacuo*. Sharply focused beams gave a strong emission spectrum of Li III and a much weaker spectrum of Li II; to maximize the column density (nl) of ground state Li^+, the beam was defocused and optimum conditions for absorption found empirically. The plasma plume was directed parallel to the spectrograph slit and as the continuum was emitted from an essentially point source, spatial resolution, with a magnification factor of about 20, was attained on the photographic plate (Fig. 1). The spectrograph was a 2-m grazing incidence instrument which used a Bausch and Lomb grating (1200 grooves/mm) at an incident angle of 86°.

Figure 2 shows the absorption spectrum of the principal series, $1s^2\,{}^1S - 1snp\,{}^1P$ of Li II taken through a plasma produced by a relatively sharply focused laser beam. It is seen that the absorption is very strong, indicating a high density of Li^+ ground-state ions, and that it falls off rapidly with the distance, x, from the target surface. The photoionization continuum is clearly in evidence. The line broadening is also very pronounced, especially near the target; the absorption profile is not simple and in particular shows a strong, relatively narrow core. These phenomena are a reflection of conditions in the plasma. Indeed the technique of ionic absorption combined with spatial resolution may prove a useful tool in plasma diagnostics.

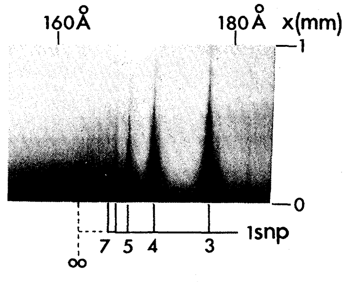

FIG. 2. One-electron of Li^+. The scale in the vertical (x) direction measures the distance from the target surface.

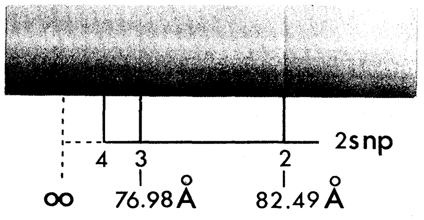

FIG. 3. Two-electron absorption of Li^+.

The wavelengths of the first three lines of the principal series are given from emission observations by Kelly[6]; the present work gives for $n = 5$, 6, and 7 the wavelengths 168.74, 167.27, and 166.39 Å (± 0.07 Å), respectively.

The main objective of the present work was to observe the doubly excited states of Li^+ (i.e., the analogs of the states involved in the Madden-Codling[7] series of He), to determine their energies, and to study their profiles. The first three members of the $1s^2\,{}^1S - 2snp\,{}^1P$ series were indeed observed and the $n = 2$ member can be clearly seen on Fig. 3 which shows the absorption spectrum in the 70–90 Å region. A profile of the feature is shown in Fig. 4. The focusing of the laser beam

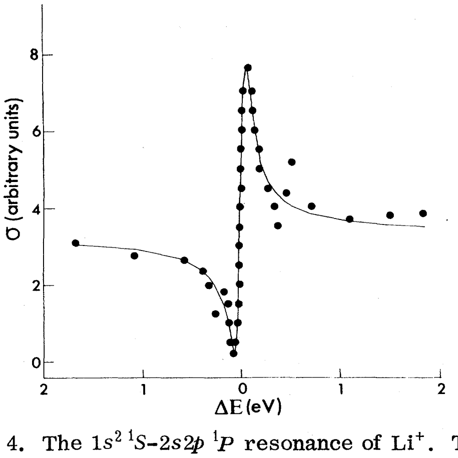

FIG. 4. The $1s^2\,{}^1S$-$2s2p\,{}^1P$ resonance of Li^+. The points represent a typical set of experimental data. The line shows the computer output for the calculated profile. For the particular set of data used the values of q and Γ were -1.31 and 0.074 eV, respectively (least-squares values). The triangular instrumental function had a full width at half-maximum of 0.08 eV.

TABLE I. Values of λ, E_0, n^*, Γ, and q for the $1s^2\,^1S$-$2snp\,^1P$ resonances of Li^+.

		$2s2p\,^1P$
This work	λ (Å)	82.49 ±0.03
	E_0 (eV)	150.29 ±0.05
	n^*	1.779±0.003
	Γ (eV)	0.075±0.025
	q	$-1.5^{+0.3}_{-0.5}$
Theory		
Balashov *et al*[8]	E_0 (eV)	150.59
	Γ (eV)	0.0605
Bruch *et al*[9]	E_0 (eV)	150.54
Chan and Stewart[10]	E_0 (eV)	150.32
Drake and Dalgarno[11]	E_0 (eV)	150.25
	Γ (eV)	0.0592
Sharma and Wilson[12]	E_0 (eV)	151.52

	$2s3p\,^1P$	$2s4p\,^1P$
This work		
λ (Å)	76.98±0.05	75.64±0.05
E_0 (eV)	161.06±0.10	163.91±0.10
n^*	2.91±0.02	3.90±0.06

in obtaining these results was considerably less than that used in observing the principal series (Fig. 2). In this way extraneous broadening effects were reduced to a minimum so that good wavelengths and reliable line profiles could be determined. Measurements were made on a photoelectric comparator and the wavelengths (Table I) were taken at the point of maximum slope in the center of the profiles.

To study the profiles quantitatively, microdensitometer traces were taken of a number of plates of varying exposures and at various points (x positions) along the line. The microdensitometer readings were converted into plate density, D, and this in turn was taken to be proportional to $\log_{10} I$, where I is the intensity of the radiation transmitted through the absorbing plasma. This procedure was justified because the total variation in density across the profile was relatively small compared to the background and because the plates used for the final measurements were of intermediate blackening so that it could be assumed that the observed densities lay on, or near, the linear part of the characteristic curve for the emulsion. Hence if the slope of the latter is γ, we may write $\Delta D = \gamma \Delta(\log_{10} I)$. From Beer's Law, $2.3\Delta(\log_{10} I) = -\Delta(\sigma n l)$ and hence for a given absorption path there is a direct proportionality between ΔD and $\Delta\sigma$. [The number density of the absorbing species is not constant along the path and the column density should be expressed as $\int n(l)dl$; this does not, however, affect the argument.] Thus, from the densitometer traces σ could be plotted as a function of wavelength. Despite the fact that such plots, constructed as they are from incremental values, ΔD, of the density, are indeterminate in absolute magnitude and scale, they may nevertheless be used to extract values for q and Γ, the parameters which characterize, respectively, the shape and width of the resonance.

The observed spectrum is the convolution of an instrumental function and the true spectrum. The instrumental function was determined from densitometer scans of sharp atomic lines, both in emission and absorption; scrutiny of the traces indicated that a triangular profile was the most suitable approximation to use. An analytical expression was derived for the convolution of the triangular function with the theoretical resonance profile[13]

$$\sigma = \sigma_0 (q+\epsilon)^2/(1+\epsilon^2), \tag{1}$$

where ϵ is $2\Delta E/\Gamma$, ΔE being the energy measured from the origin of the resonance, E_0. As absolute values of σ were not available σ_0 was taken as unity in calculating the convoluted profile, σ_c, which was then transformed to $\sigma_c^1 = A\sigma_c + B$, where A and B are constant factors which are necessary to bring the calculated and observed profiles onto the same scale. This scaling procedure does not affect the derived values of q and Γ. The values of these parameters were obtained by a least-squares fitting of the observed and computed profile, a process which also involved the determination of the constants A and B (which, of course, are of no physical interest).

The result of the analysis is shown for a typical set of data in Fig. 4. The final numerical results, which are averages of measurements made from several plates, are given in Table I. Table I also includes the results of various theoretical calculations for Li^+.

It is seen that for the $2s2p\,^1P$ resonance, the energy is in excellent agreement with the value of Drake and Dalgarno[11] who, using the Z^{-1} expansion method, made the most comprehensive theoretical calculations for this level. It is also in good agreement with Chan and Stewart's[10] "corrected" value, although it must be noted that the correction applied in this case was of an essentially empirical nature. The discrepancies in the other cases are in the same direction as for the corresponding state in helium. In the case of higher series members, for which fewer calculations have been made, quite good agreement is found with the available calculations.[8,9] The Γ value for the $2s2p\,^1P$ level is, within the rather large experimental error, in good agreement with the values of Drake and Dalgarno[11] and Balashov *et al.*[8] With regard to q, little theoretical information is available for Li^+. Balashov *et al.*[8] estimate that it lies between -2.0 and -4.0, while the semiempirical procedure of Krishtenko[14] gives -2.4.

In the electron spectra generated by the beam-foil excitation of lithium, Bruch *et al.*[9] have interpreted one of their prompt-decay peaks as due to the autoionization of the $2s2p\,^1P$ state. Although problems of blending, energy resolution and linewidth occur in the electron work, the value given for the excitation energy of the peak, 150.3 ± 0.5 eV, is close to the value determined in the present work. There is little doubt therefore that the interpretation of Bruch *et al.*[9] of the peak as due to $2s2p$ decay is correct, although blending with other features as suggested by the authors may also be occurring.

In their recent work, Lucatorto and McIlrath[1] have measured the photoionization cross section at threshold for Na^+. In the present experiment, it is possible to get some information on the strength of the continuum absorption of Li^+ relative to that of the principal series lines. By arguments similar to those already given, it can be shown that the ratio of the differential oscillator strength in the continuum, df/dE, to the oscillator strength, f_L, of a series line is given by

$$(df/dE)f_L^{-1} = \Delta D_c / \textstyle\int_L \Delta D(E)dE,$$

where ΔD_c is the change, due to absorption, in plate density for the continuum and the integral is the change in density for the line evaluated over its width. From plates of medium density obtained with plasmas showing substantial line broadening, the ratio of the oscillator strengths was derived by measuring the continuum at 2 eV above the limit and by using the series line with $n=4$. The value of the ratio obtained was 0.7 eV^{-1} and when this was combined with the f value (0.044) for the $n=4$ line as calculated from the lifetime measurements of Schurmann *et al.*[15] a value of 0.03 eV^{-1} for the differential oscillator strength of the continuum was obtained. This compares favorably with the theoretical value 0.0224 eV^{-1} derived from the work of Bell and Kingston.[16] The good agreement between experiment and theory must be regarded as somewhat fortuitous, especially because the error in the experimental value is estimated to be about a factor of 2.

The current work shows the usefulness of laser-produced continua for absorption studies. Experiments with two lasers exploiting time resolution are currently being initiated in this laboratory.

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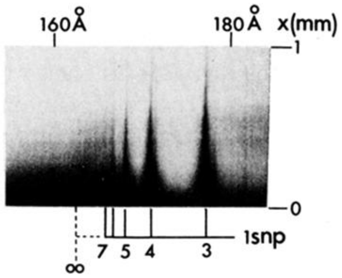

FIG. 2. One-electron of Li$^+$. The scale in the vertical (x) direction measures the distance from the target surface.

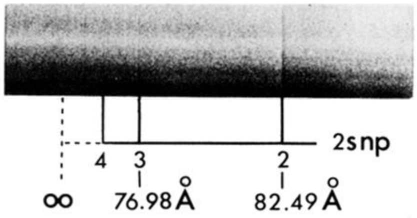

FIG. 3. Two-electron absorption of Li$^+$.