Resonance structure in the Li(4s)+e^-(ϵp) partial photodetachment cross section

Gunnar Haeffler, Igor Yu. Kiyan,* and Dag Hanstorp
Department of Physics, Chalmers University of Technology and Göteborg University, SE-412 96 Göteborg, Sweden

David J. Pegg
Department of Physics, University of Tennessee, Knoxville, Tennessee 37996
(Received 28 October 1997)

We report on a measurement of the photodetachment of the Li^- ion via the Li(4s)+e^-(ϵp) channel. The partial photodetachment cross section below the Li(4p) threshold is dominated by resonance structure. The resonance spectrum in this region is compared to the spectrum of the same resonances recently observed in the Li(3s)+e^-(ϵp) cross section. The two spectra were found to be mirror images of each other. The parameters for the two resonances obtained in the $3s\epsilon p$ measurement were confirmed. In addition, using the $4s\epsilon p$ spectrum, we were able to assign parameters to a third resonance. [S1050-2947(98)07603-3]

PACS number(s): 31.50.+w, 32.80.Fb, 32.80.Gc

Doubly excited negative ions exhibit a strong sensitivity to electron correlation. Here the outermost electron effectively moves in the short-range field of an excited atom, and the normally dominant Coulomb field is suppressed. The autodetaching decay of such states is manifested as resonance structure in detachment cross sections. The structure arises from an interference between two processes that lead to the same final continuum state: direct detachment and resonant detachment via the intermediate doubly excited state. Highly excited states are normally embedded in more than one continuum. The theoretical problem of a single resonant state interacting with two continua was considered by Starace [1]. He demonstrated that the ratio of the partial cross sections representing the two competing channels can change sharply as one tunes across the resonance. The prediction of Starace was subsequently verified in a photoionization study of Xe involving photoelectron spectroscopy [2]. In this Brief Report we present the results of a study of the photodetachment of the Li^- ion via the Li(4s)+e^-(ϵp) channel (hereafter referred to as $4s\epsilon p$). In the region below the Li(4p) threshold the partial cross section is dominated by resonance structure. The resonance spectrum in the $4s\epsilon p$ partial cross section is compared with the recent results of Ljungblad *et al.* [3], who studied the same resonances in the partial cross section for the $3s\epsilon p$ channel.

The two-color excitation and detection scheme used in the present experiment is shown schematically in Fig. 1. A laser of frequency ω_1 is used to detach the Li^- ion, and a laser of frequency ω_2 is used to photoionize the residual Li atom left in the 4s state following photodetachment. The resulting Li^+ signal is proportional to the partial cross section for the $4s\epsilon p$ channel. The scheme is similar to that used by Ljungblad *et al.* [3], except that the resonant step used to selectively detect Li(3s) atoms in the former case is replaced by a nonresonant step to detect residual Li(4s) atoms. This step is still selective, however, since the photon energy associated with the laser used to photoionize the Li(4s) atoms is insufficient to photoionize residual Li atoms left in states below the 4s state, and states above the 4s state are not populated in the photodetachment process.

The experimental arrangement is shown schematically in Fig. 2. A 3.1-keV beam of Li^- ions was produced by passing a beam of Li^+ ions through a Cs charge exchange cell. The ion beam is merged with the detaching laser beam ω_1 and the detecting laser beam ω_2 by use of an electrostatic quadrupole deflector. The ion beam and the detaching laser beam copropagate, while the ion beam and the detecting laser counterpropagate in the interaction region. The collinear interaction region is defined by a pair of apertures of diameter 3 mm placed 0.5 m apart. A second quadrupole deflector is used to charge analyze the beam after it has interacted with the two laser beams. Li^- ions remaining in the beam are

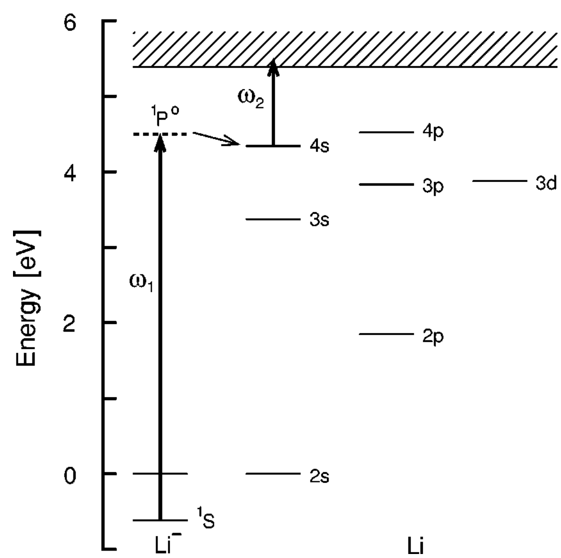

FIG. 1. A schematic illustrating the concept of the experiment. Doubly excited $^1P^o$ states of Li^- lying below the Li(4p) threshold are excited from the ^1S ground state by the absorption of a photon ω_1. Their autodetaching decay via the $4s\epsilon p$ channel is selectively monitored by ionizing the Li atom left in the 4s state by absorption of a photon of frequency ω_2. The resulting Li^+ signal is proportional to the $4s\epsilon p$ partial cross section.

*Permanent address: Russian Academy of Sciences, General Physics Institute, Vavilova St. 38, 117942 Moscow, Russia.

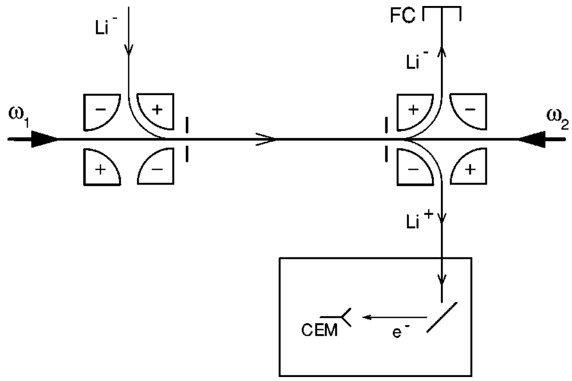

FIG. 2. A schematic of the collinear laser-ion beam apparatus used to investigate the partial cross section for the photodetachment of Li^- ions via the $4s\epsilon p$ channel.

deflected by the second quadrupole deflector into a Faraday cup, where they are monitored for normalization purposes. Li^+ ions produced in the interaction region in the aforementioned two-step photodetachment-photoionization process are deflected into a particle detector placed opposite the Faraday cup. The ions strike a metal plate, and produce secondary electrons that are detected by a channel electron multiplier.

The radiation from the detaching laser ω_1 was produced by frequency doubling, in a BBO-I crystal, the output of an excimer-pumped dye laser operating with Coumarin 102 dye. The typical pulse energy and duration were 400 μJ and 15 ns, respectively. The frequency ω_2 of the detecting laser was produced by the fundamental output of a Nd:YAG (yttrium aluminum garnet) oscillator. The pulse energy in the interaction region was about 20 mJ, which was sufficient to saturate the process that nonresonantly photoionizes the Li$(4s)$ atoms [4]. Laser ω_2 was delayed relative to laser ω_1 by approximately 40 ns to avoid a depletion of the Li^- ions by the detecting laser ω_2 before they could interact with the detaching laser ω_1. To reduce the time jitter between the two lasers, the Q-switch of the Nd:YAG oscillator was triggered by the output of the excimer laser used to pump the detaching dye laser. The Li^+ ions produced in the photoionization of Li$(4s)$ constituted the signal in this experiment. The spectrum is obtained by measuring the Li^+ signal as a function of the frequency of the detaching laser ω_1. The Li^+ signal was counted in the presence of a small background. The principal source of this background was the two-step process involving the production of Li atoms by collisional detachment and their subsequent photoionization by laser ω_2. To reduce this contribution, we maintained a pressure of 5×10^{-9} mbar in the interaction chamber.

The measured partial cross section for the $4s\epsilon p$ channel is shown in Fig. 3, along with that for the $3s\epsilon p$ channel as measured by Ljungblad *et al.* [3]. In both cases an absolute scale has been established by normalizing the data to the calculation of Ref. [5]. This was made by multiplying the experimental values by a number that is the ratio of the areas under the theoretical and experimental spectra between the same energy limits. The photon energy scale $\hbar\omega_1$ of the detaching laser was calibrated by the use of two in-board calibration lines arising from $2s\rightarrow6p$ and $2s\rightarrow7p$ transitions induced in Li atoms in the beam by laser ω_1.

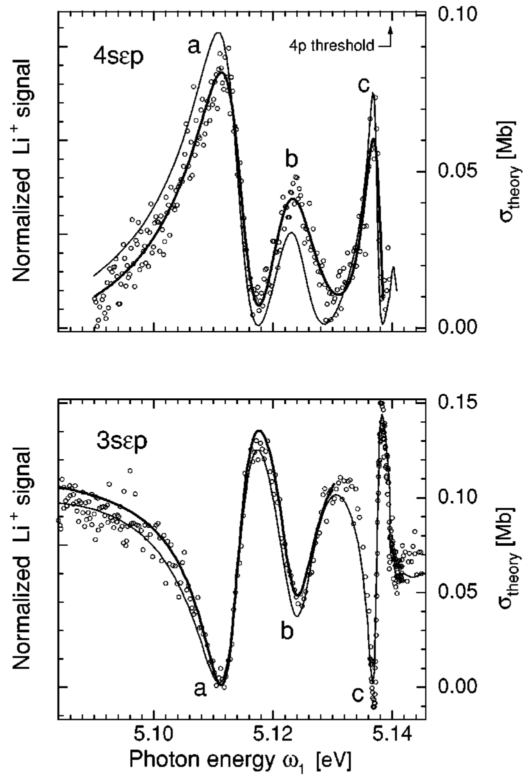

FIG. 3. Resonance structure below the Li$(4p)$ threshold in the $4s\epsilon p$ (upper figure) and the $3s\epsilon p$ (lower figure) partial photodetachment cross sections. The measured data (circles) are normalized to the R-matrix calculation (thin solid line) of Ref. [5]. The thick solid line represents the fit described in the text. The arrow indicates the position of the Li$(4p)$ threshold. The two spectra are seen to be mirror images of each other.

The measured $3s\epsilon p$ spectrum agrees very well with the theoretical predictions. In the $4s\epsilon p$ spectrum, however, we observe some differences in the relative strengths of the resonances, particularly in the vicinity of the resonance labeled b. The resonance parameters were obtained by fitting the $4s\epsilon p$ data over the range 5.0901–5.1387 eV using the Shore parametrization method [6]. It is to be expected that when the position and width of an isolated doubly excited state are obtained by the parametrization of the corresponding resonances in two different partial photodetachment cross sections, their respective values should be unchanged. This was found to be the case in our previous study of the $1s3s4s\ ^4S$ state in He^-, which was manifested as a resonance in both the $2\ ^3S\ \epsilon s$, d and $2\ ^3P\ \epsilon p$ partial cross sections [7]. In the present case, however, the resonances are close lying and, to some extent, overlapping. We have therefore applied the parametrization formula to the sum of the three resonances. The results from the fit, together with the values of Ljungblad *et al.* [3], are given in Table I. The quoted uncertainties represent the statistical errors in the fits (one standard deviation). It can be seen that the difference in the positions of the resonances in the $3s\epsilon p$ and $4s\epsilon p$ spectra is of the order of one standard deviation, and substantially smaller than their widths. This indicates that the Shore parametrization method is able to adequately extract the resonance positions for these three partly overlapping resonances. The widths, however, appear to be more affected by the overlap of adjacent reso-

TABLE I. Energies and widths of the resonances in eV.

Resonance	Channel	E_r	Γ
a	$4s\epsilon p$	5.1146(4)	0.0090(7)
	$3s\epsilon p$	5.1132(4)	0.0074(5)
b	$4s\epsilon p$	5.1228(8)	0.0133(18)
	$3s\epsilon p$	5.1234(4)	0.0076(11)
c	$4s\epsilon p$	5.1377(3)	0.0039(4)

nances. This might be expected since the nonresonant contributions in the $3s\epsilon p$ and $4s\epsilon p$ spectra will in general be different. Table I shows that the largest difference in widths occurs for the relatively weak resonance *b* which lies between the two resonances *a* and *c*. On the other hand, the widths of the strongest resonance *a*, which is adjacent to the single, weaker resonance *b*, are comparable in the two spectra.

A comparison of the two measured spectra in Fig. 3 shows that the resonance structure in the $4s\epsilon p$ and $3s\epsilon p$ partial cross sections are almost exact mirror images of each other. This behavior was predicted by Pan, Starace, and Greene [5]. The two continuum channels are mixed as a result of configuration interaction, and probability flux is exchanged between them. A similar mechanism accounts for Wigner cusps observed in certain threshold regions [8]. This behavior was not observed, however, in our previous study of the $1s3s4s\ ^4S$ resonance in He^- [7].

Financial support for this research has been obtained from the Swedish Natural Science Council (NFR). We would like to acknowledge the loan of the Nd:YAG laser by Dr. Ingemar Magnussson at AB Volvo Technological Development. Personal support was received from Wenner-Gren Center Foundation for I. Yu. K. D. P. acknowledges support from the Royal Swedish Academy of Sciences through its Nobel Institute of Physics and the U. S. Department of Energy, Office of Basic Energy Sciences, Division of Chemical Sciences.

[1] A. F. Starace, Phys. Rev. A **16**, 231 (1977).
[2] P. C. Kemeny, J. A. R. Samson, and A. F. Starace, J. Phys. B **10**, L201 (1977).
[3] U. Ljungblad, D. Hanstorp, U. Berzinsh, and D. J. Pegg, Phys. Rev. Lett. **77**, 3751 (1996).
[4] J. Lahiri and S. T. Manson, Phys. Rev. A **48**, 3674 (1993).
[5] C. Pan, A. F. Starace, and C. H. Greene, Phys. Rev. A **53**, 840 (1996).
[6] B. W. Shore, Phys. Rev. **171**, 43 (1968).
[7] D. Hanstorp *et al.*, in *Modern Trends in Atomic Physics*, edited by D. Hanstorp and H. Persson, Advances of Quantum Chemistry, Vol. 30 (Academic, San Diego, 1998).
[8] See, for example, Y. K. Bae and J. R. Peterson, Phys. Rev. A **32**, 1917 (1985); J. Dellwo, Y. Liu, D. J. Pegg, and G. D. Alton, *ibid.* **45**, 1544 (1992).