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THE PRODUCTION AND DESTRUCTION OF
NEGATIVE IONS

Progress Report

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A. Introduction

During the grant period, 1994-97, we continued to investigate the structure of few-electron atomic negative and the manner in which they interact with electromagnetic radiation. The experimental procedures and the results of this work have been described in detail in the published papers cited in Section G.

Two complementary laser-ion beam apparatus were used in the measurements. A crossed beam apparatus, situated at Oak Ridge National Laboratory(ORNL), was used to perform a spectroscopic study of the electrons ejected, in the forward direction, from moving negative ions in the photodetachment process. In this work, we isolated specific detachment channels by energy analyzing the electrons. The apparatus was used to investigate photodetachment of an electron from a negative ion in an excited state. The C^- ion is unusual in that it can be produced in a bound excited state as well as the ground state. We also used this apparatus, with a gaseous target replacing the laser beam, to study resonances in collisional detachment cross sections. In particular, we investigated the simplest of all shape resonances, the $3P^o$ state in Li^- . This state was produced in $Li-He$ collisions. A collinear beam apparatus, situated at Chalmers University of Technology(CUT) in Gothenburg, Sweden, has been used in spectroscopic studies of the He^- and Li^- ion in the ultraviolet. Here, the emphasis is on the production and detection of highly correlated, doubly excited states. Specific channels were isolated, in this case, by state selectively detecting the residual atoms produced in the photodetachment process. The apparatus has excellent sensitivity and energy resolution, attributes needed to produce highly excited states and to detect the corresponding close lying resonances.

B. Collisional detachment of Li^- and B^- ions

This work is described in detail in publication G(1a). Here we look for structure in the collisional detachment cross section for negative ions projectiles incident on atomic targets. The structure arises from the excitation and subsequent decay of intermediate resonance states of negative ions. We have investigated the $Li+He(Ar)$ and $B+He(Ar)$ collisions systems using an incident beam energy of 100 keV.

Our initial interest in the field of negative ion-atom collisions stemmed from calculations[1] of the position and width of the

($2s2p$) $^3P^o$ shape resonance of Li^- , which lies just above the ground state of the Li atom. This is the simplest shape resonance since the parent atom is in its ground state. Analogous resonances in the structurally simpler H^- and He^- ions are more complex, in the sense that the parent atoms are excited. To our surprise, this resonance had not previously been studied experimentally, in spite of its fundamental nature. Undoubtedly, this is related to the inherent difficulties associated with detecting the very low energy electrons that are ejected when the ion autodetaches. To overcome this problem, we decided to exploit the large kinematic energy shifts associated with a fast beam source to "amplify" the energy of the detached electrons to a more measurable value. In our apparatus, the electrons detached from a fast beam of Li^- ions were collected in the forward direction i.e. in the same direction as the ion beam. A typical spectrum is shown in Fig.1. Analysis of the detached electron spectrum allowed us to determine the parameters of the $^3P^o$ shape resonance. The energy and width were found to be 50(6) and 64(25) meV, respectively.

A similar experiment was performed using B^- projectiles. Here we found a previously unobserved resonance which we tentatively identified with the ($2p^2$) 1D shape resonance. The measured energy and width are 104(8) and 68(25) meV, respectively. We also observed other, as yet unidentified, resonances (see Fig.2). It is suspected that these resonances might arise from the decay of transiently excited states of B^- that lie close in energy to excited states of the B atom.

C. Photodetachment of the C^- ion

This work is described in detail in publication G(1d) and a pending publication. Negative ions typically possess a single bound state. Fig.3 shows a partial energy level diagram for the C^-/C systems. The C^- ion is the simplest negative ion to possess more than one bound state. This unusual ion can be formed in the excited 2D state as well as the 4S ground state. The success of this experiment depended on our ability to produce a beam of C^- ions with an appreciable fraction in the excited state. By charge changing a 80 keV beam of C^+ ions in a Li vapor cell, we were able to produce a beam of C^- ions with an excited state fraction of about 50%.

We have reported the first measurement of a partial cross section, $\sigma(i)$, for photodetaching an electron from an excited negative ion.

Specifically, we have photodetached, at a photon energy of 2.077 eV, the excited C-(²D) ion via the competing ³P_{ks,d} and ¹D_{ks,d} channels and measured the branching ratio. We also photodetached the C-(⁴S) ion via the ³P_{ks,d} channel at the same energy. All measurements were made relative to those obtained by photodetaching, under the same experimental conditions, D⁻ ions in a reference beam. The results were then normalized to the theoretical value of the H-(D⁻) cross section. We have also measured the asymmetry parameters, $\beta(i)$, characterizing the angular distribution of photoelectrons detached via these channels. Transitions via the three channels are labeled 1,2 and 3 in Fig.3. The results are: $\beta(1)=-0.91(9)$, $\beta(2)=0.41(3)$, $\beta(3)=-0.88(9)$ and $\sigma(1)=5(2)$, $\sigma(2)=13(2)$, $\sigma(3)=12(2)$ Mb. The cross sections results agree with the theoretical values from the R-matrix calculation of Ramsbottom, Bell and Berrington[2].

The lines arising from transitions 1 and 3 were unresolved in our photoelectron spectra. We initially attempted to separate their relative contributions by studying the angular distribution of the blended lines, assuming an incoherent sum of the two distributions. This novel approach would have been successful if nature hadn't chosen the two asymmetry parameters to be the same sign and roughly the same magnitude. Eventually, we were able to determine the individual photoelectron yields and asymmetry parameters associated with the unresolved lines by use to a least-squares fitting technique based on the convolution of two "model" peaks of fixed width and separation. The "model" peak was obtained, at the same laboratory-frame energy, by photodetaching a beam of D⁻ ions. The procedure is illustrated in Fig.4.

D. Photodetachment of the Li⁻ and He⁻ ions

This work is described in detail in publications G(1b,c,e). Our interest in He⁻ and Li⁻ lies in the fact that they are structurally the simplest negative ions beyond the prototypical H⁻ ion. The resonance spectrum of this fundamental ion has been thoroughly investigated, both experimentally[3] and theoretically[4]. One can expect interesting similarities and differences between the spectra of resonances in the photodetachment cross sections of the H⁻, He⁻ and Li⁻ ions. Most of the differences for ions with finite cores, such as He⁻ and Li⁻, arise from the lifting of the degeneracy of the thresholds characteristic of the H⁻ spectrum. We have studied the cross section

for photodetachment of the Li^- ion in the vicinities of the $\text{Li}(2p, 3p, 4p \text{ and } 5p)$ thresholds. Feshbach resonances, associated with the decay of doubly excited states, are expected to modulate the cross section over narrow energy regions just below these thresholds. No resonances were found above or below the $\text{Li}(2p)$ threshold. Instead, we used this threshold to make a new measurement of the electron affinity of Li that is an order of magnitude more accurate than any previous measurement. In order to achieve this, we developed a new method of detection involving the selective resonant photoionization of the excited residual Li atoms. A broad resonance structure was observed below the $\text{Li}(3p)$ threshold. In this case, the total cross section was sufficiently modulated by the resonances that it was enough to detect the residual Li atoms without knowledge of their internal energy. This was not the case, however, below the $\text{Li}(4p, 5p)$ thresholds. Here, we used the state selective, channel specific technique described above to study resonances in the partial cross section for photodetachment of Li^- via the $3s\text{kp}$ channel. Fig.5 shows the spectra of "window" resonances. As expected, the resonance spectrum becomes more complex as the degree of excitation in increased. Our results, with minor exceptions, are in good agreement with the R-matrix calculation of Pan, Starace and Greene[5](see solid line in Fig.5). We also have some preliminary results on the double excitation of He^- . Fig.6 shows resonances associated with the decay of the $(1s3s4s) \ ^4S$ doubly excited state via the two open channels: the $\text{He}(1s2s^3S) + e(ks,d)$ and $\text{He}(1s2p^3P) + e(kp)$. The resonance parameters, obtained from a fit of a Fano profile to the data, appear to be in agreement with the calculation of Xi and Froese Fischer[6].

E. References

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F. Figures

Fig.1 Zero-degree electron energy spectrum for 100 keV Li^- ions incident on a He gas target showing the central cusp peak and the kinematically doubled resonance structure.

Fig.2 Zero-degree electron energy spectra for 100 keV B^- ions incident on He(A) and Ar(B) gas targets showing the cusp (a) and the kinematically doubled resonance peaks(b). Weaker and higher lying resonances are displayed in the inset of (A).

Fig.3 Partial energy level diagram for the C-/C systems.

Fig.4 Yields of photoelectrons detached from a 80 keV beam of C⁻ ions(upper and middle) and a 10 keV reference beam of D⁻ ions(lower). The C⁻ spectra are taken with the laser linear polarization vector parallel(upper) and perpendicular(middle) to the electron collection direction(direction of the ion beam). In each case the blended C⁻ peak was fitted to a convolution of two "model" peaks, obtained from the D⁻ peak(lower).

Fig.5 The partial cross section for photodetachment of Li^- via the $\text{Li}(3s) + e^-(kp)$ channel. The spectrum of "window" resonances arise from the decay of doubly excited states below the $\text{Li}(4p)$ [upper] and $\text{Li}(5p)$ [lower] thresholds. The solid line represents the calculation of Ref. 5.

Fig.6 Resonances arising from the decay of the doubly excited $(1s3s4s)^4S$ state in He^- via the $\text{He}(1s2s^3S) + e^-(ks,d)$ [upper] and $\text{He}(1s2p^3P) + e^-(kp)$ [lower] channels.

G. Publications:1996-97

G(1). Referred journals

G(1a). Report No: DOE/ER/13456-77

"Resonance states in Li⁻ and B⁻", D.H.Lee, W.D.Brandon, D.Hanstorp and D.J.Pegg, Phys. Rev. A53, R633(1996).

Reprint *

G(1b). Report No: DOE/ER/13456-78

"Electron affinity of Li: a state selective measurement", G.Haeffler, D.Hanstorp, I.Kiyan, A.Klinkmueller, U.Ljungblad and D.J.Pegg, Phys. Rev., A53, 4127(1996).

Reprint *

G(1c). Report No: DOE/ER/13456-79

"Observation of doubly excited states of Li⁻ using resonance ionization spectroscopy", U.Ljungblad, D.Hanstorp, U.Berzinsh and D.Pegg, Phys. Rev. Lett., 77, 3751(1996).

Reprint *

G(1d). Report No: DOE/ER/13456-80

"Cross section for photodetachment of the excited C-(²D) ion using fast ion-laser beam electron spectroscopy", D.H.Lee, W.D.Brandon, D.Hanstorp and D.J.Pegg, Phys. Rev.A (to be published,1997).

Reprint *

G(1e). Report No: DOE/ER/13456-81

"Observation of doubly excited states in negative ions using resonance ionization spectroscopy", D.Hanstorp, U.Ljungblad, U.Berzinsh and D.J.Pegg, in *Resonance Ionization Spectroscopy*, eds. N.Winograd and J.Parks (AIP,1997).

Reprint *

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G. Publications:1996-97 (continued)

G(2). Conference/workshop abstracts

G(2a). Report No: DOE/ER/13456-82

" Observation of doubly excited states of Li⁻ using resonance ionization spectroscopy", U.Ljungblad, D.Hanstorp, U.Berzinsh and D.Pegg, Book of Abstracts, Fifteenth ICAP, Amsterdam, NL, 1996, p ThE7.

G(2b). Report No: DOE/ER/13456-83

" Photodetachment of the C⁻ ion", D.H.Lee, W.D.Brandon, D.Hanstorp and D.J.Pegg, Book of Abstracts, Fifteenth ICAP, Amsterdam, NL, 1996, p ThE3.

G(2c). Report No: DOE/ER/13456-84

" Observation of doubly excited states in negative ions using resonance ionization spectroscopy", D.Hanstorp, U.Ljungblad, U.Berzinsh and D.Pegg, Book of Abstracts, Resonance Ionization Spectroscopy Conference, State College, PA, 1996, p 55.

G(2d). Report No: DOE/ER/13456-85

" The electron affinities of As, Te and Li", A.Klinkmueller, G.Haeffler, U.Berzinsh, D.Hanstorp, I.Kiyan, U.Ljungblad, D.Pegg and J.Rangell, Book of Abstracts, Resonance Ionization Spectroscopy Conference, State College, PA, 1996, p 55.

G(2e). Report No: DOE/ER/13456-86

" Negative ion physics", D.J.Pegg, Book of Abstracts, DOE(BES) Workshop on Atomic Physics, Fullerton, CA, 1996.

G(2f). Report No: DOE/ER/13456-87

" Photodetachment studies of the C⁻ ion in the 4S and 2D states" W.D.Brandon, D.H.Lee, D.Hanstorp and D.J.Pegg, Book of Abstracts, SESAPS, Decatur, GA, 1996.

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