CONF-890708--1

DE89 015908

PHOTODETACHMENT COLLISIONS

David J. Pegg

Department of Physics, University of Tennessee, Knoxville, Tennessee 37996-1200, USA
and
Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831-6377, USA

A crossed-beams apparatus has been used to measure the cross sections (angular differential and integral) for photodetaching electrons from metastable He^- and stable B^- ions at $\lambda = 696.2$ nm. Kinematic effects were exploited, in a novel way, to enhance the precision of the measurements. The partial (angular integral) cross sections for He^- photodetachment are $\sigma(2^3\text{S}) = 22.9 \pm 1.0$ Mb and $\sigma(2^3\text{P}) = 10.0 \pm 0.6$ Mb. The corresponding cross section for B^- is $\sigma(2^2\text{P}) = 16.5 \pm 2.1$ Mb. The calculated cross section for the photodetachment of D^- was used to establish an absolute scale for the relative measurements. Radiative attachment cross sections are derived from the photodetachment results using the principle of detailed balance.

I. INTRODUCTION

Interest in photon-ion interactions has grown rapidly over the past few decades, due primarily to the advent of lasers and synchrotron light sources. At the Brighton ICPEAC, for example, Dolder¹ reported on elegant experiments designed to measure cross sections for photoionization of positive atomic ions. In this progress report, I shall attempt to complement that contribution by describing measurements of cross sections for the photodetachment of negative atomic ions made recently at the Oak Ridge National Laboratory.

The pioneering work on photodetachment began at NBS in the 1950's and early 1960's with the development, by Branscomb and Fite,² of a crossed photon-negative ion beams apparatus. In these early experiments, an arc lamp was used as the light source. The absolute cross sections that were measured have been reviewed by Branscomb³ and Smith.⁴ A second generation of crossed-beams experiments began at JILA in the late 1960's and 1970's, when the conventional light source was replaced by a laser. This modification not only greatly enhanced available photon fluxes but also made it possible, for the first time, to measure photoelectron angular distributions with relative ease. Most of the experiments of this period were designed primarily, however, to measure electron affinities and determine relative changes in cross

sections, particularly in the vicinities of thresholds and resonances. This work has been reviewed by Lineberger.⁵ Somewhat surprisingly perhaps, only a few absolute photodetachment cross section measurements have been reported to date. Photodetachment cross sections are not only of intrinsic interest but they frequently form the most accessible path to the determination of cross sections for the far less probable process of radiative attachment.

The present paper describes the use of energy- and angle-resolved photoelectron detachment spectroscopy to determine partial cross sections (angular differential and integral) for the photodetachment of the metastable He^- ion at a wavelength of $\lambda = 696.2$ nm. Brehm et al.⁶ reported the first energy-resolved studies of the photodetachment of He^- . In this experiment, a crossed-beams technique, which employed a fixed-frequency laser, was used to determine the electron affinity of $\text{He}(2^3\text{S})$. As a by-product of these measurements, the investigators were also able to estimate, within a factor of two, the cross sections for photodetaching He^- at $\lambda = 514.5$ nm. The large quoted uncertainties reflect the fact that no information on the photoelectron angular distributions was obtained in the experiment. Total cross sections for the photodetachment of He^- (via two competing unresolved exit channels) have been reported by Compton et al.⁷ and Hodges et al.⁸ The cross section for photo-

MASTER

The submitted manuscript has been authored by a contractor of the U.S. Government under contract No. DE-AC05-84OR21400. Accordingly, the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

detachment of B^- at $\lambda = 696.2$ nm has also been measured in the present work for the first time.

II. THEORETICAL CONSIDERATIONS

The He^- ion is unstable as a result of being formed in the spin-aligned $(1s2s2p)^4P$ state (see Fig. 1) when an electron is captured by an excited He $(1s2s^3S)$ atom. The quartet state, unable to decay via allowed radiative or autodetachment processes, autodetaches via forbidden processes induced by the relatively weak spin-dependent interactions. The varying strengths of these interactions result in a differential metastability among the fine structure levels. Lifetimes of the $J = 1/2, 3/2$, and $5/2$ levels have been measured⁹ to be 10, 16, and 500 μ sec, respectively. Metastable He^- ions are therefore sufficiently long lived that they undergo very little exponential depletion by autodetachment prior to photodetachment in the present crossed-beams apparatus. Small corrections ($\sim 2\%$) to the measured yields are, however, made to account for the unstable nature of this ion.

FIG. 1. Partial energy level diagram for the He and He^- systems. The He^- ion exists in the metastable $(1s2s2p)^4P$ state. The $(1s^2s)^2S$ ground state is unbound.

When the $He^-(2^4P)$ ion interacts with visible radiation, two competing photodetachment channels to the continuum are open:

$$h\nu + He^-(2^4P) \rightarrow He(2^3S) + e^-(ks,d) \quad (1)$$

$$h\nu + He^-(2^4P) \rightarrow He(2^3P) + e^-(kp). \quad (2)$$

In this paper, photodetachment processes will frequently be labeled by their exit channels. In an independent electron description of process (1), a p-orbital electron is ejected, resulting in an outgoing electron represented by s- and d-waves. In process (2), a s-orbital electron is ejected, leading to a pure outgoing p-wave in the independent electron model. The spectral dependences of the asymmetry parameters for both of these processes have recently been measured by Thompson et al.¹⁰ Correlation effects are found to play a significant role in determining the shape of the electron emission patterns following photodetachment.

The B^- ion is stable, being formed in the $(1s^22s^22p^2)^3P$ state when an electron is captured by a ground state B($2P$) atom. At visible wavelengths, only one photodetachment channel is open when $B^-(2^3P)$ interacts with radiation

$$h\nu + B^-(2^3P) \rightarrow B(2^2P) + e^-(ks,d). \quad (3)$$

Since a p-orbital electron is ejected, the outgoing electron is characterized by s- and d-partial waves in the independent electron model.

In the present work, the partial cross sections, $\sigma(^3S)$ and $\sigma(^3P)$, for the photodetachment processes shown in Eqs. (1) and (2) have each been measured relative to the cross section, $\sigma(^2S)$, for the photodetachment of $D^-(1^1S)$ ions via the process

$$h\nu + D^-(1^1S) \rightarrow D(1^2S) + e^-(kp). \quad (4)$$

In this process, the emission is well described by an independent electron model and the photoelectron is represented by a pure p-wave resulting in a $\cos^2\theta$ distribution.

III. EXPERIMENTAL CONSIDERATIONS

The technique of energy- and angle-resolved photoelectron spectroscopy has been used to investigate the interaction between negative ions and radiation. Cross sections for photodetachment are determined from measurements of the yields and angular distributions of photoelectrons ejected from the ions at the interaction of crossed laser and negative ion beams. Fig. 2 is a schematic of the crossed-beams apparatus. A fast moving ($v \sim 10^8$ cm/sec) and tenuous beam ($\rho \sim 10^3$ ions/cm³) of negative ions is intersected perpendicularly by an energy-resolved and linearly-polarized beam of photons from a pulsed dye laser. As a result of the photon-ion interaction, precisely known amounts of energy and angular momentum are transferred to the ion. Following photodetachment events, electrons ejected from the field-free interaction region in the direction of motion of the ion beam (forward-directed electrons) are collected, energy analyzed, and detected. The angular dis-

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

tribution of the detached photoelectrons can be determined by measuring their yield as a function of the angle between the electric field vector of the linearly polarized laser beam and the collection direction. This is achieved in the present apparatus by keeping the collection fixed in the forward direction and rotating the laser polarization vector, using a $\lambda/2$ phase retarder (double Fresnel rhomb). Fig. 3 shows the result of an angular distribution measurement. A typical photoelectron spectrum, taken in this case with the polarization vector parallel to the collection direction, is shown in Fig. 4.

FIG. 2. A schematic view of the crossed laser-ion beams apparatus used in the energy- and angle-resolved photoelectron spectroscopy measurements.

FIG. 3. Angular distribution of electrons photodetached from a 40 keV beam of He^- ion at $\lambda = 638.4$ nm.

Photodetachment of He^- at 40 keV
 $\lambda = 698.5$ nm

FIG. 4. Energy spectrum of electrons photodetached from a 40 keV beam of He^- ions at $\lambda = 689.5$ nm.

The beam that is the source of negative ions in these measurements is produced by double charge transfer (sequential electron capture) when a momentum-selected positive ion beam from an accelerator is passed through a Li vapor charge-exchange cell. After a delay of a few microseconds, the beam exiting the cell is charge state analyzed. The negative ion component ($\sim 1\%$) is then deflected by 10° into a beam line containing an electron spectrometer consisting of a spherical-sector energy analyzer and a channel-electron multiplier detector. The analyzer is operated in the fixed pass energy, preacceleration mode. About 2 cm in front of the entrance to the electron spectrometer, the ion beam is crossed with the laser beam. Sets of apertures are used to ensure that the overlap of the two beams remains unaltered during the measurements. The flashlamp-pumped pulsed dye laser used in this investigation has a maximum repetition rate of 10 Hz and a pulse duration of 2.2 μsec . The operating laser bandwidth was 0.2 nm. The output power of the laser was carefully chosen to avoid saturation on each of the photodetachment processes studied. A 10-cm focal length injection lens focussed the laser beam onto the ion beam in the interaction region. The whole apparatus is surrounded by three mutually orthogonal sets of Helmholtz coils designed to reduce the effect of stray magnetic fields on the electron trajectories.

The data is stored in a CAMAC-based multi-channel analyzer data acquisition system. A synchronous detection scheme is used to extract the photoelectron signal from a rather large

REPRODUCED FROM BEST
AVAILABLE COPY

electron background. The time structure of the detection scheme is illustrated in Fig. 5. Four multichannel scalars (MCS) are used to record the data. MCS1 is triggered by the laser pulse via a fast photodiode detector. It is gated on for 4 μ sec, after a 1 μ sec delay, to record the electron signal associated with the laser being on. The delay is set to allow for the finite transit time of electrons through the spectrometer and to avoid noise associated with the "firing" of the laser. MCS2, which is operated with the same gate width as MCS1, is triggered on 2 μ sec after MCS1 is turned off. The purpose of MCS2 is to record, with the laser off, the background associated with electrons generated by ion impact with apertures and, to a lesser extent, electrons produced by detachment following collisions between the ions and the residual gas. In the case of metastable ions, a small contribution arises from autodetachment. Subtraction of the contents of MCS1 and MCS2 allows one to effectively discriminate against the background contributions. MCS3 and MCS4 are used to monitor the ion and laser beam intensities for normalization purposes. The ion beam current is collected and integrated in a Faraday cup situated directly downstream of the electron spectrometer. The ion beam intensities were chosen so that approximately the same background of electrons was always incident on the detector. This made it less likely that pulse pile-up effects and count rate-dependent gain changes would affect the relative measurements. The intensity of the photon beam is recorded by monitoring the light scattered from the front face of the injection lens with a photodiode detector. Further details of the apparatus can be found in the paper by Pegg et al.¹¹

As a consequence of the fast moving and unidirectional nature of the source, the kinetic

FIG. 5. The time structure of the synchronous detection scheme.

energies, yields, energy distributions, and angular distributions of the photoelectrons ejected from the moving ions will be modified by kinematics. The combination of high-energy beams and forward-directed collection used in the present experiment permits one to effectively exploit kinematic effects such as spectral peak shifting and doubling. Previous cross section measurements using crossed beams have employed ion beam energies an order of magnitude lower than those used in the present work and collection has been perpendicular to the ion beam direction. The kinematically-shifted energy of a forward-directed ($\theta_L = 0$) electron in the laboratory frame, E_L , is related to its energy in the ion frame, E_C , via the relationship $E_L = ME_C$, where M represents a kinematic "magnification" factor, $M = (1 \pm \sqrt{\epsilon/E_C})^2$. Here, ϵ is the energy of an electron moving with the same velocity as the ions of the beam. The positive sign in the factor M corresponds to emission of electrons in the forward direction ($\theta_C = 0$) in the ion frame and the negative sign corresponds to backward-directed ($\theta_C = \pi$) emission in the ion frame. If the ion beam velocity exceeds the electron velocity in the ion frame, both the forward and backward electrons will be swept forward in the laboratory frame. Kinematic peak doubling arises since E_L becomes double valued in this case. The separation of the twin peaks is $\Delta E_L = 4\sqrt{\epsilon E_C}$. Details of these and other kinematic modifications have been discussed previously by Pegg et al.¹²

IV. RELATIVE CROSS SECTIONS

The angular integral cross section, $\sigma(x)$, for photodetachment of an ion via an exit channel labeled x can be expressed in terms of the yield of photoelectrons, $Y(x)$, ejected in the direction of the linear polarization vector of the light beam in the following manner:

$$\sigma(x) = \frac{4\pi Y(x)}{[1+\beta(x)]g(x)\phi(x)k(x)p(x)V\Delta\Omega GT} \quad (5)$$

In this expression, β is the asymmetry parameter characterizing the shape of the emission pattern, g is the frame-transformed solid-angle ratio, k represents the photoelectron collection and detection efficiency, p is the ion beam density, ϕ is the photon flux, V is the interaction volume, $\Delta\Omega$ is the solid angle defined by the collection geometry, G measures the spatial overlap of the two crossed beams, and T is the integration time for each yield measurement. In the present work, relative cross sections are obtained by comparing, under identical geometrical conditions, the yields of electron produced in the photodetachment of the ions of interest, $Y(x)$, and a beam of reference ions, $Y(r)$, whose cross section is known. Thus the relative cross sections for the two photodetachment processes can be written as

$$\frac{\sigma(x)}{\sigma(r)} = \frac{Y(x) \rho(r) \phi(r) g(r) [1 + \beta(r)]}{Y(r) \rho(x) \phi(x) g(x) [1 + \beta(x)]}. \quad (6)$$

Here the measured yield ratio is multiplied by several measured factors in order to account for the different frame-transformed solid angles, photon fluxes, ion densities, and asymmetry parameters associated with photodetaching electrons from the two beams. All geometric factors, being equal, cancel out. In this work it is arranged by appropriate choice of beam energies, that the photoelectron peaks in each spectra are kinematically shifted so that they coincide in energy in the laboratory frame. The efficiency factors, $k(x)$ and $k(r)$, associated with the collection and detection of photoelectron at the same energy from the ions of interest and the reference ions will then be equal and hence cancel out. For example, Fig. 6 shows three photoelectron spectra in which the electron peaks all occur at ~ 11 eV in the laboratory frame. The top and bottom peaks are associated with the photodetachment of He^- via the $\text{He}(^3\text{S})$ and $\text{He}(^3\text{P})$ exit channels, respectively. The peak of the middle spectrum arises from the photodetachment of D^- ions in the reference beam via the $\text{D}(^2\text{S})$ exit channel. To ensure that the electrons from these three different photodetachment channels are analyzed at the same energy in the laboratory frame, the ion beam energies for the top, middle, and bottom spectra were chosen to be 29.19, 19.17, and 50.47 keV, respectively.

The ion beam densities, ρ , and the solid-angle transformation factors, g , both depend on the velocity of the ion beam. This quantity can be determined very precisely ($\sim 0.1\%$), *in situ*, by simply analyzing the photoelectron spectra. In Fig. 4, the backward-directed peak 1 ($\theta_c = \pi$) and the forward-directed peak 2 ($\theta_c = 0$) form a kinematically-doubled pair, both being associated with the photodetachment process that leaves the He atom in the 2^3P state. Their separation, in the laboratory frame, is $\Delta E_L(12) = 4\sqrt{eE_c(1)}$. The quantity E_c , the energy of the electron in the ion frame, can be determined from a measurement of the photon wavelength and the use of the precise theoretical value of the electron affinity of $\text{He}(2^3\text{S})$ calculated by Bunge et al.¹³ Thus by measuring $\Delta E_L(12)$, one can determine the reduced ion beam energy, ϵ , and hence the ion beam energy itself. Another way of determining the ion beam energy is by measuring the separations of peaks 2 and 3. Peak 3 is due to the forward-directed electrons associated with the competing process via the $\text{He}(2^3\text{S})$ exit channel. In the ion frame, peaks 2 and 3 are separated by the $2^3\text{S} - 2^3\text{P}$ transition energy, E_e , known precisely from optical spectroscopy. The separation of peaks 2 and 3 in the laboratory frame is given by

$$\Delta E_L(23) = E_e + 2\sqrt{e} [\sqrt{E_c(2)} + E_e - \sqrt{E_c(2)}]. \quad (7)$$

In a similar manner, the velocities of beams of other ions, such as D^- and B^- , can be precisely determined by measuring the separation between the peaks of their photoelectron spectra and the peaks of the He^- spectrum.

Angle-resolved measurements are made to determine the asymmetry parameter, β . The yield of a photoelectron peak is measured as a

FIG. 6. Three spectral peaks kinematically shifted to the same laboratory-frame energy by an appropriate choice of ion beam energy. The peak yields were used in the measurement of relative cross sections for photodetachment of He^- and D^- ions.

function of the angle, θ , between a fixed collection direction (in the present case, the direction of motion of the ion beam) and the variable direction defined by the electric field vector of the linearly polarized laser beam. For the case of plane polarized radiation in the electric dipole approximation (assuming an independent electron model), the angular correlation between the outgoing photoelectron and the incoming photon should take the form, $f(\theta) = 1 + \beta P_2(\cos\theta)$. Here $P_2(\cos\theta)$ is the second-order Legendre polynomial. Multiphoton absorption or an ion state that is prepared anisotropically prior to photoabsorption would produce higher (even) order polynomials in the fit. It has been demonstrated that both processes make a negligible contribution in the present work. The angular distribution measurement technique has been tested, at several different wavelengths in the visible, by photodetaching beams of D^- and Li^- ions. The predicted $\cos^2\theta$ ($\beta = 2$) distribution was obtained in all cases.

Angular differential cross sections, $I_c(\theta)$, can most easily be determined from the measured angular integral cross sections, σ , and the asymmetry parameters, β , using the expression

$$I_c(\theta) = \frac{\sigma}{4\pi} [1 + \beta P_2(\cos\theta)] \quad (8)$$

V. RESULTS

A. Partial Cross Sections for He^- Photodetachment

The partial (angular integral) cross sections, $\sigma(^3S)$ and $\sigma(^3P)$, for photodetaching electrons from $He^-(2^4P)$ via the $He(2^3S)$ and the $He(2^3P)$ exit channels, respectively, have been measured relative to the cross section, $\sigma(^2S)$, for photodetaching D^- via the $D(1^2S)$ exit channel. The ratio of the $\sigma(^3S)$ to $\sigma(^3P)$ cross sections has also been measured. At a wavelength of $\lambda = 696.2$ nm, the following results were obtained: $\sigma(^3S)/\sigma(^2S) = 0.60 \pm 0.02$, $\sigma(^3S)/\sigma(^3P) = 2.28 \pm 0.10$, and $\sigma(^3P)/\sigma(^2S) = 0.27 \pm 0.02$. The uncertainties quoted on these values are at the level of two standard deviations of the weighted mean obtained from about ten data sets, each consisting of a number of individual spectra. The major source of statistical error in the ratios obtained from the individual data sets stems from measurements of the photoelectron yield (~4%) and asymmetry parameter (~3%) ratios. Uncertainties in the measurement of other factors in Eqn. (6) are negligibly small. Systematic errors are also estimated to be within the quoted limits. The asymmetry parameters characterizing the photoelectron angular distributions have also been measured at $\lambda = 696.2$ nm. The results are shown in Table I along with the angular integral cross section results. An

absolute scale for the He^- partial cross sections has been established by assuming a theoretical value for the $\sigma(^2S)$ cross section. The calculations of Stewart,¹⁴ for example, which are estimated to have an uncertainty of better than 3%, produce a result of $\sigma(^2S) = 38.1$ Mb at $\lambda = 696.2$ nm. Broad and Reinhardt¹⁵ calculate a value within 1% of this result. Combining the theoretical result (assuming a 3% uncertainty) with the measured ratios produces the partial (angular integral) cross sections shown in Table I. Table I indicates that at a wavelength of 696.2 nm, the probability that a given He^- ion photodetaches into the $He(^3S) + e^-(ks,d)$ continuum is 70% (i.e. the branching ratio, $R(^3S) = 0.70 \pm 0.06$). At the present time, there are no other experimental or theoretical results to compare with these measured partial cross sections. The sum of the partial cross sections, σ , can, however, be compared to the total cross section calculations of Hazi and Reed.¹⁶ The scatter plot shown in Fig. 7 indicates that there is excellent agreement between the present result of $\sigma = \sigma(^3S) + \sigma(^3P) = 32.9 \pm 2.4$ Mb and the theoretical result of $\sigma = 33.4$ Mb (length form) and $\sigma = 29.9$ Mb (velocity form). Also shown in Fig. 7 are the experimental results of Compton et al.⁷ and Hodges et al.⁸ These less precise values are also seen to be in agreement with the present result.

The angular integral cross sections, σ , and the asymmetry parameters, β , can be conveniently combined, using Eqn. (7) to determine the angular differential cross sections, $I_c(\theta)$. The results are shown in Fig. 8.

TABLE I. Measured Angular Integral Photodetachment Cross Sections and Asymmetry Parameters at $\lambda = 696.2$ nm.

Exit Channel	σ (Mb)	β
$He(^3S)$	22.9 ± 1.0	1.15 ± 0.02
$He(^3P)$	10.0 ± 0.6	1.52 ± 0.04
$B(^2P)$	16.5 ± 2.1	0.18 ± 0.04
$D(^2S)$	38.1 ± 1.1^a	2.00 ± 0.02

^aReference 14.

Total Cross Section for Photodetachment
of Metastable He^- $\lambda=696.2$ nm

FIG. 7. Scatter diagram showing different experimental and theoretical results for the total (angular integral) cross section for photodetachment of the He^- ion at $\lambda = 696.2$ nm.

Differential Cross Section for the
Photodetachment of He^- $\lambda=696.2$ nm

FIG. 8. Measured angular differential cross sections for the photodetachment of the He^- ion at $\lambda = 696.2$ nm.

B. Cross Section for B^- Photodetachment

The cross section, $\sigma(2P)$, for the photodetachment of B^- via the $\text{B}(2^2P)$ exit channel has been measured relative to the cross section, $\sigma(3P)$, for the photodetachment of He^- via the $\text{He}(2^3P)$ exit channel at a wavelength of $\lambda = 696.2$ nm. The B^- and He^- ion beam energies were chosen to be 51.04 and 30.18 keV, respec-

tively, so that the peaks in the photoelectron spectra coincided in energy in the laboratory frame. This ensured that photoelectrons from the two beams were collected and detected with equal efficiency. The result of the measurement is $\sigma(2P)/\sigma(3P) = 1.65 \pm 0.19$. The asymmetry parameter for this process has been measured and the result is shown in Table I along with angular integral cross section. In this case, an absolute scale for the $\sigma(2P)$ cross section has been established by assuming the value of the $\sigma(3P)$ cross section that had previously been measured relative to the $\sigma(2S)$ cross section of D^- , i.e. $\sigma(3P) = 10.0 \pm 0.6$ Mb. There are no other existing results, experimental or theoretical, to compare with the present measurement.

Again, the angular differential cross section, $I_c(\theta)$, is conveniently determined from the measured angular integral cross section, σ , and the asymmetry parameter, β . The results are shown in Fig. 9.

Differential Cross Section for the
Photodetachment of B^- $\lambda=696.2$ nm

FIG. 9. Measured angular differential cross section for photodetaching the B^- ion at $\lambda = 696.2$ nm.

C. Radiative Attachment Cross Sections

The measured cross sections for photodetaching He^- and B^- ions can be used to indirectly determine, using detailed balance arguments, the cross sections, σ_a , for the far more improbable inverse process of radiative attachment. The processes are the inverse of those shown in Eqns. (1), (2), and (3). The derived radiative attachment cross sections (in barns) at $\lambda = 696.2$ nm are shown in Table II.

REPRODUCED FROM BEST
AVAILABLE COPY

TABLE II. Derived Radiative Attachment Cross Sections at $\lambda = 696.2$ nm.

Entrance Channel	$\sigma_a(b)$
He(3S)	166 $\pm$ 7
He(3P)	74.2 $\pm$ 4.5
B(2P)	51.0 $\pm$ 6.5

VI. SUMMARY

A crossed-beams apparatus that employs energy- and angle-resolved photoelectron spectroscopy has been used to measure angular differential and integral cross sections for the photodetachment of He $^-$ and B $^-$ ions at a wavelength of 696.2 nm. An absolute scale has been established by making relative photoelectron yield and angular distribution measurements between beams of the ions of interest and D $^-$ reference ions whose photodetachment cross section is known from theory to better than 3%.

Absolute cross sections are difficult to determine accurately. The relatively high precision (~5% in favorable cases) of the present measurements reflects our ability to exploit, in a novel way, certain kinematic effects associated with a fast moving source of ions and the collection of ejected photoelectrons in the forward direction. The measurements are currently being continued at several discrete wavelengths across the visible spectrum. It is hoped that these new results will stimulate further calculations of photodetachment cross sections and asymmetry parameters.

ACKNOWLEDGMENTS

I wish to acknowledge my fellow collaborators, past and present, at the University of Tennessee (J. S. Thompson and J. Dellwo) and the Oak Ridge National Laboratory (G. D. Alton, R. N. Compton, and T. J. Kvale). Special thanks go to Jeff Thompson. This research was supported by the U.S. Department of Energy, Office of Basic Energy Sciences, Division of Chemical Sciences through the University of Tennessee. Oak Ridge National Laboratory is operated by Martin Marietta Energy Systems, Inc. under Contract No. DE-AC05-84OR21400 with the U.S. Department of Energy.

REFERENCES

1. K. Dolder, in Electronic and Atomic Collisions (invited papers of the XV ICPEAC), ed. by H. B. Gilbody, W. R. Newell, F. H. Read, and A.C.H. Smith (North-Holland, Amsterdam, 1988), p.549.
2. L. M. Branscomb and W. L. Fite, Phys. Rev. **93**, A651 (1954).
3. L. M. Branscomb, in Atomic and Molecular Processes, ed. by D. Bates (Academic, New York, 1962), p. 100.
4. S. J. Smith, in Methods of Experimental Physics, ed. by B. Bederson and W. Fite (Academic, New York, 1968), Vol. 7, p. 179.
5. W. C. Lineberger, in Applied Atomic Collision Physics, ed. by H.S.W. Massey, E. W. McDaniel and B. Bederson (Academic, New York, 1982), Vol. 5, p. 239.
6. B. Brehm, M. A. Gusinow, and J. L. Hall, Phys. Rev. Lett. **19**, 737 (1967).
7. R. N. Compton, G. D. Alton, and D. J. Pegg, J. Phys. B **13**, L651 (1980).
8. R. V. Hodges, M. J. Coggiola, and J. R. Peterson, Phys. Rev. **23**, 59 (1981).
9. L. M. Blau, R. Novick, and D. Weinflash, Phys. Rev. Lett. **24**, 1269 (1970).
10. J. S. Thompson, D. J. Pegg, R. N. Compton, and G. D. Alton, J. Phys. B (to be published).
11. D. J. Pegg, J. S. Thompson, R. N. Compton, and G. D. Alton, Phys. Rev. Lett. **59**, 2267 (1987).
12. D. J. Pegg, J. S. Thompson, R. N. Compton, and G. D. Alton, Nucl. Instrum. Meth. B **40/41**, 221 (1989).
13. A. V. Bunge and C. F. Bunge, Phys. Rev. A **19**, 452 (1979).
14. A. L. Stewart, J. Phys. B **11**, 3851 (1978).
15. J. T. Broad and W. P. Reinhardt, Phys. Rev. A **14**, 2159 (1976).
16. A. U. Hazi and K. Reed, Phys. Rev. A **24**, 2269 (1981).