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Electron-impact detachment from B^-

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Cross sections for electron-impact single and double detachment from B^- have been measured from 0 to 200 eV. The single-detachment cross section peaks at 4–5 eV with a cross-section maximum of about 10^{-14} cm^2. A $(2p^3)$ ^4S state has recently been predicted to give rise to a resonance state in the H^{2-} dianion [T. Sommerfeld *et al.*, Phys. Rev. A **55** 1903 (1997)]. We observe no resonances in the detachment cross section of B^- and hence no sign of an equivalent shortlived $B^{2-}(2p^3)$ state. The ratio of the double- to single-detachment cross section reaches a constant value of 3% at energies above 50 eV. A simple model relates this number to a shake-off probability of about 90%. The ratio between double and single ionization of neutral atomic targets at high energy is also discussed, and the model relates this ratio to the shake-off probability in the sudden approximation. [S1050-2947(98)09709-1]

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I. INTRODUCTION

Electron-impact detachment from negative ions is a discipline which has received relatively little attention, and only a few of the many elements which form stable negative ions have been studied in this connection. The negative hydrogen ion H^- and the isotope D^- have been studied in the threshold region [1–3] as well as at high energy [4–7]. A few other ions like C^-, O^-, and F^- have also been studied [2,8,9]. Although a theoretical understanding of the detachment dynamics with the Coulomb repulsion and the electronic correlation in the initial state is emerging [10–12], there are still unsolved issues to be addressed.

In the present paper we report on electron-impact single and double detachment from B^- in the energy regime from 0 to 200 eV:

$$B^- + e^- \rightarrow \begin{cases} B^0 + 2e^- & (\sigma^0) \\ B^+ + 3e^- & (\sigma^+). \end{cases} \tag{1}$$

We have chosen the boron ion for several reasons. It has an electron affinity of 0.28 eV [13], which is considerably lower than the corresponding value for other atomic negative ions studied so far. The B^- ion has a large polarizability and a large extension of the electronic cloud. This makes the release process particularly interesting to study in the threshold region where, for ions with much higher electron affinity, we have seen [1,2,14] that the cross section has an effective threshold typically 2–3 times the electron affinity.

It has been suggested [15] that the addition of an extra electron to the ground state $B^-(1s^22s^22p^2)$ might form a resonance state of the dianion $B^{2-}(1s^22s^22p^3)$ with $^4S^o$ symmetry. The analogous state of $H^{2-}(2p^3\ ^4S^o)$ is calculated to form a resonance state[15], but experimentally it cannot be formed when scattering on the ground state of $H^-(^1S)$. This limitation is not present for B^-, which has the ground-state term ^{3}P and where a resonance, if existing, could show up in the detachment cross section. Recently, resonances structures have been observed in electron scattering from the molecular ions C_2^- [16] and B_2^- [17].

Finally, we address the problem of double-electron removal from atomic negative ions. More than 15 years ago, Haugen *et al.* [18] discovered that electrons and protons were not associated with the same cross section for double ionization of He, and since then there has been intense research activity to describe the many-body dynamics of double-electron removal from atomic species [19]. With noble gases as targets, the double-ionization process has been studied to a large extent with various projectiles acting as ionizing particles (e.g., electrons, positrons, protons, and antiprotons) [19], and the role played by electronic correlation has been one of the main issues. A series of electron-impact measurements of double-detachment of H^- have been performed, and after some initial inconsistency it may appear [20] that the double detachment cross section by electron impact is now well-known for this ion. By combining available experimental and theoretical data for H^-, it has been established that the double-detachment cross section is about 0.4 % of the single-detachment cross section at high energy. This number is (by coincidence, perhaps) close to that obtained for the other two-electron target He. In this paper we present double-detachment data for B^-. As a consequence of the low binding energy of this ion, the shake-off probability is presumably large, and this should be reflected in the data. Before we discuss these issues in detail, the experimental procedure will be described.

II. EXPERIMENT

The present experiment was carried out at the ASTRID storage ring [21]. The ring is 40 m in circumference, and it has a square geometry with two 45° bending magnets in each of the four corners (see Fig. 1). We used a sputter-ion source for the production of B^-. The B^- beam of approximately 200 nA was preaccelerated to 150 keV, injected into the ring, and then accelerated to 2.5 MeV. At this energy, the lifetime

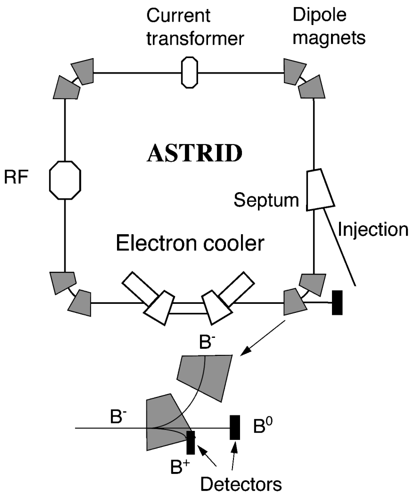

FIG. 1. Schematic drawing of the ASTRID storage ring showing the positions of the particle detectors.

of the beam was 0.5 s, which is determined by collisions with the residual gas (2×10^{-11} torr). In the ring the ions were merged with an essentially monoenergetic electron beam which was provided by the electron cooler [22,2].

The detachment cross section as a function of relative energy was measured by varying the electron energy. The relative energy E is related to the ion-beam energy E_i and the kinetic energy of the electrons E_e through the relation

$$E=\tfrac{1}{2}m(v_i-v_e)^2=\left[\left(\frac{m}{M_i}\right)^{1/2}\sqrt{E_i}-\sqrt{E_e}\right]^2, \tag{2}$$

where m is the electron mass, M_i is the ion mass, and v_i and v_e are the laboratory velocities of the ions and the electrons, respectively. With the given ion mass and energy, electrons at 125 eV have zero kinetic energy in the ion-rest frame (i.e., they move with the same average speed as the ions). At this energy we had an electron current of a few milliamps and a density of $6\times10^6/\mathrm{cm}^3$.

Neutral boron atoms produced by the single-detachment process [Eq. (1)] were detected by a 60×40-mm^2 surface barrier detector located behind the dipole magnet following the electron cooler (see Fig. 1). Another surface barrier detector was placed in the dipole magnetic field to detect B^+ ions. This detector had a diameter of 20 mm, and it was verified that it was large enough to detect all B^+ ions by making a horizontal scan across the B^+, beam and by comparing countrates of the large and small detector when located at the position of the neutral beam (we assume that the B^+, and B^0 beams had similar diameters).

Due to the electron-velocity spread, we consider the *rate coefficient*

$$\langle v\sigma\rangle=\int v\sigma(v)f(\mathbf{v})d\mathbf{v}. \tag{3}$$

It is the velocity weighted cross section averaged over the velocity distribution $f(\mathbf{v})$ of the electrons. The distribution function $f(\mathbf{v})$ in the rest frame of the ions is given by the flattened Maxwellian function [22]

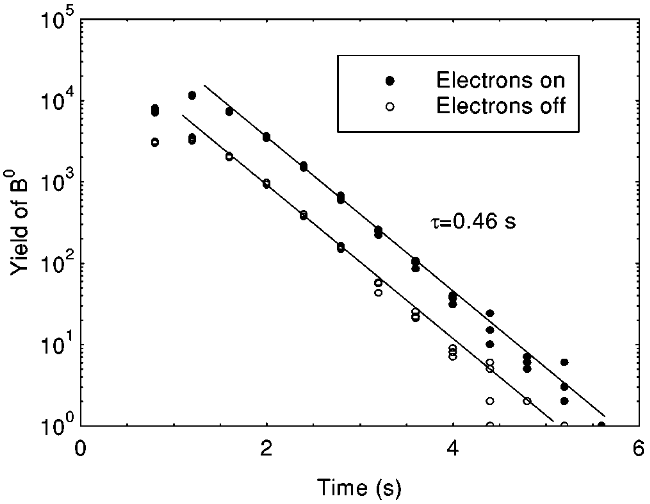

FIG. 2. Count of neutral particles as a function of time with the electron beam on and off in the chopped mode. When the electron beam is turned off, the signal is due to collisional detachment in the background gas.

$$f(\mathbf{v})=\frac{m_e}{2\pi kT_\perp}e^{-m_e v_\perp^2/2kT_\perp}\sqrt{\frac{m_e}{2\pi kT_\parallel}}e^{-m_e(v_\parallel-\Delta)^2/2kT_\parallel}, \tag{4}$$

where $v_\perp$ and $v_\parallel$ are the relative electron velocity components perpendicular and parallel to the ion beam direction, and $\Delta=|v_i-v_e|$ is the detuning velocity between electrons and ions. The electron beam was adiabatically expanded in a decreasing magnetic field [23], and the expected temperatures are $kT_\perp\sim20$ meV and $kT_\parallel\sim0.5-1$ meV. Above the detachment energy (280 meV) we have $E>kT_\perp$ and the cross section is to a good approximation given by $\langle v\sigma\rangle/\Delta$ [24].

The rate coefficient is, in terms of measurable quantities given by

$$\langle v\sigma\rangle=\frac{N_{\mathrm{signal}}v_i}{N_{\mathrm{ion}}n_eL\epsilon}, \tag{5}$$

where N_{signal} is the number of atoms (B^o) or positive ions (B^+) detected per second (with a possible background subtracted), N_{ion} the ion flux passing through the electron cooler, n_e the electron density, L (=0.95m) the length of the electron cooler, and $\epsilon(=1)$ is the detector efficiency.

Two different modes of operation were used in the experiment. In the first mode, N_{signal} in Eq. (5) was determined by turning the electron beam on and off (chopping) at a frequency of 20 Hz. Figure 2 shows the yield of neutrals as a function of time after the full beam energy (2.5 MeV) has been reached. It is seen that the overall reproducibility is very high (the figure contains data from three different ion-beam injections), and in the beginning there is some saturation due to a high count rate. The decay is exponential, and the lifetime of the beam is found to be 0.46 s, which is rather short due to the small binding energy of B^-. To avoid saturation effects of the neutral detector we calculated the absolute cross section after 2 s of storage at an energy of 2.5 MeV, at which time we only had 0.4 nA of ion beam current. We obtained an absolute cross section of (8.3 ± 2.5)

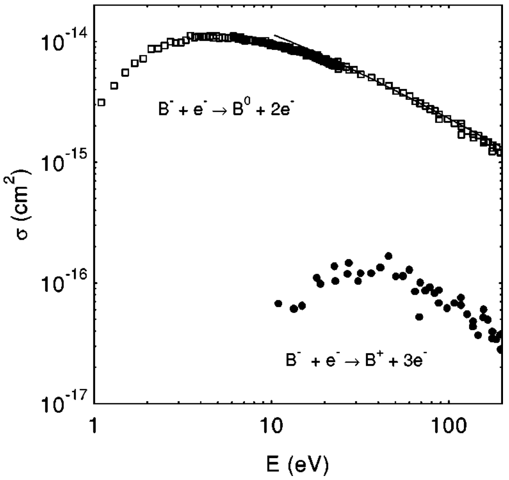

FIG. 3. Electron-impact single- and double-detachment cross-sections as functions of electron energy. The solid line through the single detachment data shows the ln(E)/E energy dependence.

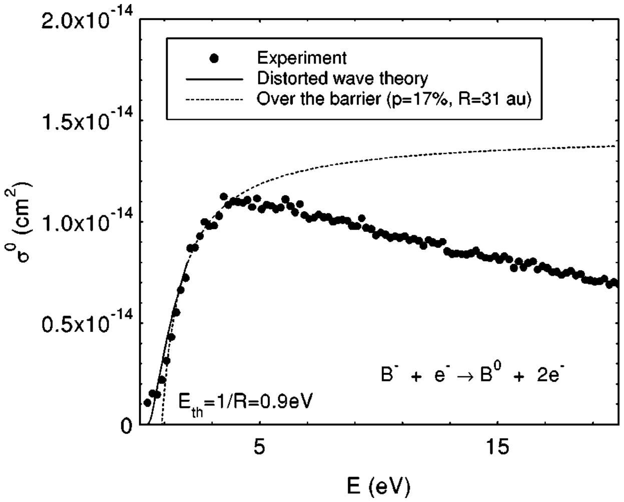

FIG. 4. Single-detachment cross section in the near-threshold region. Shown are the data (binned with a bin width of 0.2 eV) together with the classical fit to the data near threshold (dashed line) and the distorted-wave calculation of Pindzola (solid line).

$\times 10^{-15}$ cm^2 at a relative energy of 15 eV. The somewhat large error bar stems from the uncertainty of the current measurement with the ion-current transformer. Relative rate coefficients as a function of electron energy were obtained by normalizing to the neutral count rate resulting from collisions in the residual gas and are with much smaller error bars. In another mode of operation, the electron-beam energy could be modulated between the cooling energy ($E=0$) and a measuring energy E. The chopping and the modulation techniques yielded consistent results.

The measured cross section receives contributions both from the central part of the electron cooler, where the ions and electrons have parallel velocity vectors, and from the smaller toroid regions, where the two beams merge and separate. In these regions, relative energies different from the one in the straight section are encountered. The measured cross sections were corrected for this ''toroid part'' by subtraction of a calculated contribution from the toroid regions.

III. RESULTS AND DISCUSSION

In Fig. 3, we show the single- and double-detachment cross sections as a function of electron energy in the rest frame of B$^-$. The single-detachment cross section has a maximum value of about 10^{-14} cm^2 at 4–5 eV. At higher energy ($E>30$ eV) the experimental cross section falls off as (1/E) ln(E) in agreement with the Bethe-Born approximation [25]. The double detachment cross section is considerably lower than the single-detachment cross section. It peaks at around 40 eV with a maximum of about 10^{-16} cm^2.

A. Single detachment

Figure 4 focuses on the single-detachment cross section in the near-threshold region. There is a clear cutoff in the data with a threshold energy E_{th} at 0.9 eV, as obtained from a fit to the data with a function of the type

$$\sigma = p\pi R^2\left(1-\frac{E_{\mathrm{th}}}{E}\right). \tag{6}$$

For a discussion of the classical model leading to this expression see Refs. [1,2]. Briefly, p is the probability for a detachment event given that the distance of closest approach in the collision is smaller than some ''reaction radius'' R, and E_{th} is the threshold energy given by $1/R$ [1,2]. The physics is not completely represented by the model since it ignores tunneling effects, which are important near threshold and for large-impact paramenter collisions in general, and it contains the arbitrary scaling factor p. It is easy to show [2] that over the barrier transitions can occur for $E>E_{\mathrm{th}}$, and that this threshold energy is (in a.u.)

$$E_{\mathrm{th}} = \sqrt{E_B/a}, \tag{7}$$

where E_B is the electron affinity, and a is a measure of the extension of the ion [26]. The analysis shows that $R=31$ a.u. which corresponds to a classical threshold of 0.9 eV and an extension a of 9.4 a.u. The extension is 2–3 times larger than for H$^-$/D$^-$ and O$^-$ [2] due to the weak binding. To fit the absolute magnitude of the cross section (the shape is solely determined by R), we find $p=17\%$, very similar to the values obtained for D$^-$ and O$^-$ [1,2]. In the case of D$^-$ and O$^-$ the cross section of Eq. (6) traces the data well up to energies of about 12 and 16 eV, respectively, but in the case of B$^-$ clear deviations already appear at an energy of 4 eV, which shows that high-energy effects start at lower energy because of the small binding energy (see Fig. 4). We note that the electron-impact cross section has an effective threshold energy (E_{th}) which is notably larger than the binding energy - by about a factor of 3. This is also found to be the case for D$^-$ and O$^-$ [1,2], and due to the fact that energy has to be provided not only for release, but also for kinetic energy of the escaping electrons.

Figure 4 also presents a comparison of the data with a distorted-wave calculation by Pindzola [12,27]. He used a polarization potential of the form

$$V_{\mathrm{pol}} = \frac{\alpha}{2}\,\frac{r^2}{(r^2+r_c^2)^3}, \tag{8}$$

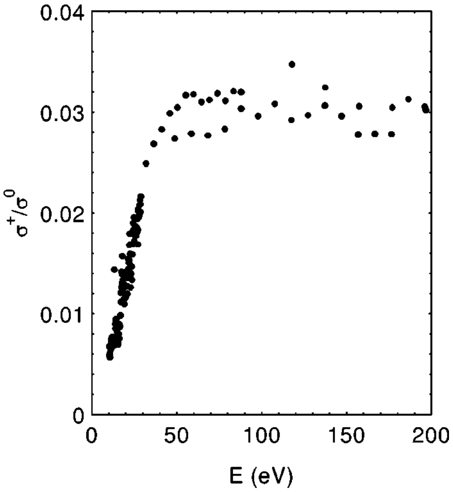

FIG. 5. Ratio σ^+/σ^0. The data have been smoothed to eliminate the scattering of the double-detachment data (σ^+).

with a polarizability $\alpha = 23.2$ a.u. and a cutoff at $r_c = 2.0$ a.u [27]. With these values the theory reproduces the data well in the threshold region. However the cross section changes dramatically with the cutoff radius which is rather arbitrarily chosen [27]. Due to the small binding energy (and hence the large extension of the negative ion), and the fact that many particles interact by long-range Coulomb forces, the system is difficult to treat by standard theory.

The ground state configuration of B^- is $1s^2 2s^2 2p^2 (^3P)$. Thus, the B^{2-} $1s^2 2s^2 2p^3 (^4S)$ state could in principle be formed upon electron bombardment. It is, however, readily seen from our single-detachment data that there are no resonances which can be ascribed to such dianion states. Thus, the $(2p^3)$ ^4s state which has been predicted to yield a H^{2-} resonance [15] apparently does not give rise to a short-lived dianion for boron as suggested recently [15] (at least not visible in the detachment channel). We note that there is still doubt whether the $(2p^3)$ ^4s state of H^{2-} exists because other calculations lead to the conclusion that there are no resonances of any kind associated with H^{2-} [28].

Other atomic dianions have been looked for by storage ring techniques— D^{2-}, and O^{2-} [2] by our group, H^{2-} by Tanabe *et al.* [3]—but no resonances were observed in either case. We have recently found structures in the detachment and dissociation cross sections of C_2^- [16] and B_2^- [17] that may be related to the existence of short-lived dianions, but whether *atomic* dianions exist at all remains an open question.

B. Double detachment

To follow the tradition for neutral targets, in Fig. 5 we show the ratio between the double- and single-detachment cross sections. Already at about 40–50 eV, slightly above the energy at which the single-detachment cross section becomes ‘‘asymptotic,’’ do we see a constant ratio of the cross sections. The ratio, 3%, is basically identical to the asymptotic value obtained for Ne, [29] slightly lower than that obtained with Ar [29], and approximately an order of magnitude larger than that obtained for H^- [20] and He [29].

Clearly, the double-detachment problem is difficult due to the four charged particles in the final state, and a full quantum calculation seems very difficult. Some simple estimates may, however, throw light on the problem of double detachment at high energies where the ratio is independent of energy. It can be argued that one may neglect contributions of the inner shells at the energies considered here [29]. Since the cross sections of single- and double-electron removal are proportional to each other, we assume that the incoming electron creates a hole (detach one of the core electrons), and with a certain probability the loosely bound electron is ejected (shaked off). To remove two electrons from the target an energy transfer of at least the sum of the first and second ionization potential $[I_p(1)+I_p(2)]$ is needed. If we assume that the cross section is inversely proportional to the energy transfer at high energy [25], we can estimate the shake-off probability S from

$$\frac{\sigma^+}{\sigma^0} = \frac{\dfrac{1}{I_p(1)+I_p(2)} S}{\dfrac{1}{I_p(1)}}. \tag{9}$$

For B^- this gives $S \sim 90\%$, which is high in accordance with the low binding of the extra electron. The reason why the cross section ratio is relatively small, despite the magnitude of S, is the large difference between $I_p(1)$ and $I_p(2)$, which for negative ions gives

$$\frac{\dfrac{1}{I_p(1)+I_p(2)}}{\dfrac{1}{I_p(1)}} \sim \frac{I_p(1)}{I_p(2)}. \tag{10}$$

The ratio is about 3% for B^-.

For neutral atoms an estimate of S with the use of Eq. (9), where

$$\frac{\dfrac{1}{I_p(1)+I_p(2)}}{\dfrac{1}{I_p(1)}} \sim \frac{1}{2}, \tag{11}$$

gives $S = 1\%$ for He, 9% for Ne, and 14% for Ar (the ratios of double to single-ionization cross sections were taken from Ref. [29]). It is interesting to compare these numbers with the shake-off probability obtained in the sudden approximation (where one electron is suddenly removed). Such data have been obtained with high-energy photons [30]. The shake-off probabilities from the outermost shell in this limit are 3.5%, 11.9% and 13.5% for He, Ne, and Ar, respectively [30], which are indeed close to the values of S obtained above. The binding in He is particularly large and the shake-off may not be quite ‘‘sudden,’’ which may cause S to be somewhat lower than the shake-off limit in the sudden approximation. In general, the first electron may leave the target with a range of velocities and a corresponding range of shake-off probabilities. The overall agreement indicates that the physical picture of one electron being suddenly removed from the core with a shake-off of the loosely bound electron may to some extent be valid in the description of double-electron removal, and our method [Eq. (9)] may give an estimate of the shake-off probability. With negative ions the binding energy of the ‘‘extra’’ electron is small, and the use of S from the sudden approximation may be particularly appropriate. For H^-, from the cross-section ratio [20] we estimate a shake-off probability of about 10%. Synchrotron-radiation experiments may be able to test this and the estimated large shake-off probability of ~90% for B^-.

IV. CONCLUSIONS

We measured the cross sections for electron-impact single and double detachment of B^-. The data for single detachment in the threshold region show a cutoff at an energy of about 1 eV, which from the classical analysis yields an extension of the ion of about 9 a.u. With a simple model for double detachment we estimate a large shake-off probability of about 90% for B^-. The model gives a way to connect the shake-off probability in the sudden approximation to the ratio of the double- to single-detachment cross sections at high impact energy. Finally, we looked for resonances of the dianion B^{2-}, but found none. It is still an open question whether short-lived atomic dianions exist at all; so far there is no experimental evidence, and the theoretical situation seems to be controversial.

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