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# Cross sections for fast neutral-atom and positive-ion production in collisions of $Br^-$ ions with rare-gas atoms

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Atomic single- and double-electron-detachment cross sections from $Br^-$ ions in He, Ne, Ar, Kr, and Xe, from 10 to 100 keV, are reported. The data fit well with other halogen-negative-ion cross sections on the same targets. There are indications that the double-detachment cross section is the same, up to about $5\times10^5$ cm/s, for all halogen ions on He. Above this energy, and for other beams, the cross section increases both with the beam-atom mass and with the target-atom mass. The single-detachment cross section can be fitted by the Gauyacq theory, except at the highest energies of our experiments.

## I. INTRODUCTION

In earlier papers,[1–4] measurements of the single-detachment cross section $\sigma_{-0}$ and the double-detachment cross section $\sigma_{-+}$ were reported for $F^-$, $Cl^-$, and $I^-$ ions colliding with single atoms of all the rare gases. The same cross-section data for the remaining halogen negative ion, $Br^-$, are reported here.

Because of the absence of data in some energy regions, and the difficulties in normalizing data from different measurements, it is not clear whether there is structure in the energy dependence of the single-detachment cross section $\sigma_{-0}$. All measurements show a rise with increasing energy in the low-energy region,[5] to a roughly constant value at about 100 eV relative energy. Above this energy, there seems to be a gradual increase, which is most evident for the lighter halogen ions colliding with the heavier rare gases.

The low-energy $\sigma_{-0}$ data, up to a few hundred eV, are well understood in terms of the direct detachment of the extra electron, and the complex potential model is able to quantitatively fit the energy dependence of the cross section.[6] The rapid increase with increasing energy is, in this model, explained as the penetration of the distance of closest approach through the crossing radius at which the negative ion-target atom molecular state becomes unbound. The higher energy behavior, which cannot be fitted by the complex potential model, may be partly due to dynamic effects, as the electron tunnels through the small barrier at atomic separations outside the crossing radius, and partly due to the onset of more endothermic collisions to excited final states of the negative ion or the recoil atom.

Double electron detachment in a single collision was first identified by Dukel'skii and Fedorenko[7] in 1955. They measured cross sections for double detachment from $Br^-$, $Cl^-$, $I^-$, and $Na^-$ ions in argon and nitrogen gases. They found that double detachment from $Br^-$ was unusually large compared to the other negative-ion beams. Their cross-section values are a significant proportion of the total detachment cross section above a few keV.

Single-detachment cross sections have been reported by Bydin and Dukel'skii,[8] using the electron collection method, on all the stable rare gases up to 2 keV. Their results are in good agreement with other cross-section measurements, also by the electron collection method, by Smith, Edwards, Doverspike, and Champion[5] in the low-energy region from threshold to 200 eV, center of mass. At higher energies, Lichtenberg, Bethge, and Schmidt-Böcking[9] have reported total-detachment cross sections and double-detachment cross sections obtained by beam attenuation and positive-ion collection measurements for several negative-ion beams, including $Br^-$, in thin rare-gas targets, from 20–200 keV.

## II. EXPERIMENT

The experimental arrangement was unchanged from the previous measurements, except for the introduction of bromine vapor into the rf ion source. Some difficulties were found in controlling the vapor pressure. The final procedure was to contaminate the argon-buffer gas supply by briefly exposing it to liquid bromine in a side tube. The ion source would then produce a steady $Br^-$ beam for several hours from surface-absorbed bromine.

## III. RESULTS AND DISCUSSION

The $\sigma_{-+}$ data are shown in Fig. 1 and Table I. The only previously reported $Br^-$ double-detachment measurements are the ones from the original observation of the process by Dukel'skii and Fedorenko[7] up to 17.5 keV, in an argon target (crosses), and the higher-energy data, also on argon, of Lichtenberg *et al.*[9] (open circles). Dukel'skii and Fedorenko found the $Br^-$ double-detachment cross section to be by far the largest for the argon target among the several negative-ion beams which they investigated. Our measurements and those of Lichtenberg *et al.* suggest that the $Br^-$-Ar cross section is somewhat larger than in the other rare gases at our lower energies, but does not rise as rapidly as the Dukel'skii and Fedorenko data. The present cross-section data fit well with the systematic variation of the other halogen-negative-ion–rare-gas-atom double-detachment cross sections. If these are compared as a function of relative velocity, then there is some indication of a common double-detachment cross section for all the halogen-negative ions in the He target up to about $5\times10^5$ cm/sec. This is in contrast to the heavier targets, where the cross section increases significantly from $F^-$ to $I^-$ throughout our velocity range.

The $\sigma_{-0}$ data are shown in Fig. 2 and Table II. At low

 

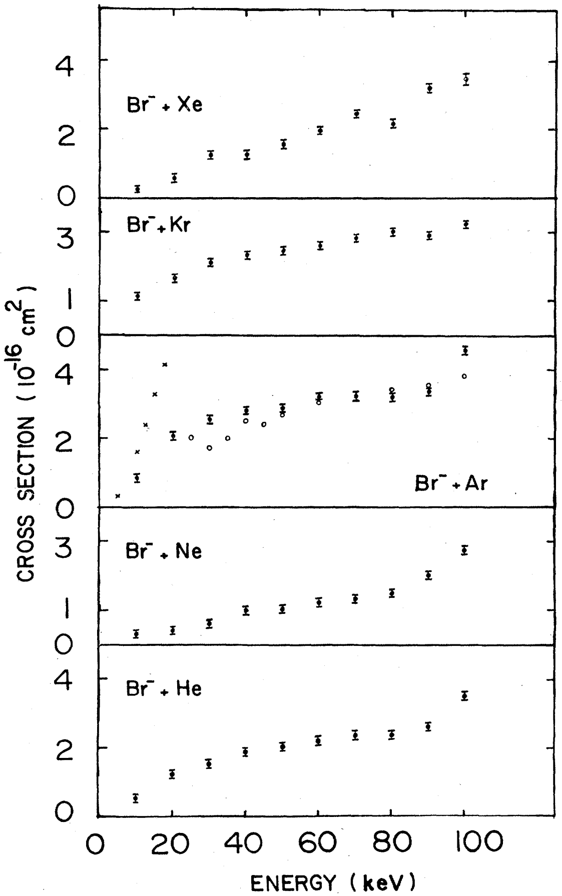


FIG. 1. The cross section $\sigma_{+-}$ for the detachment of two electrons in a single collision of a bromine negative ion with a rare-gas atom. The crosses are the data of Dukel'skii and Fedorenko (Ref. 7). The circles are the data of Lichtenberg *et al.* (Ref. 9).

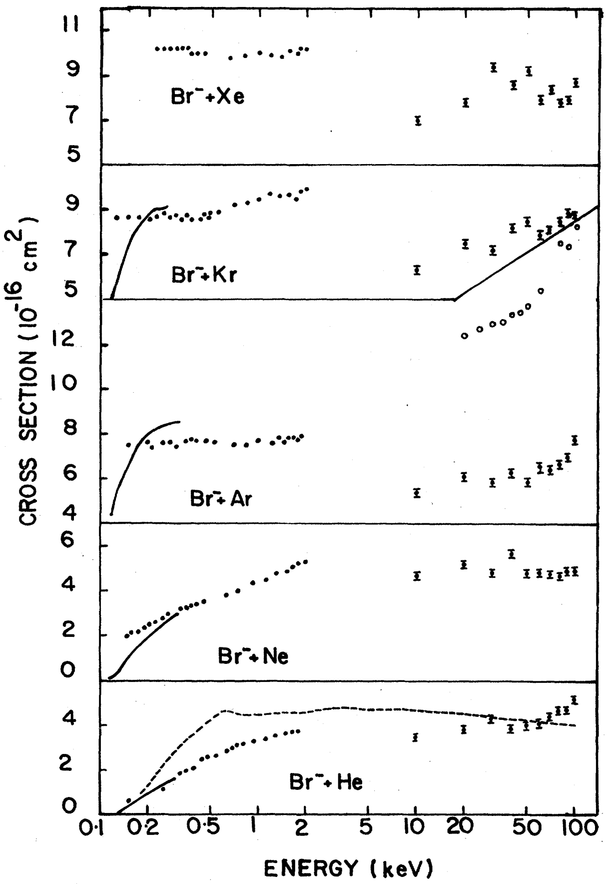


FIG. 2. The cross section $\sigma_{-0}$ for the detachment of an electron from a bromine ion in a single collision with a rare-gas atom. The line is the low-energy electron collection data of Smith *et al.* (Ref. 5). The solid circles are the electron collection data of Bydin and Dukel'skii (Ref. 8). The open circles are the total attenuation cross sections of Lichtenberg *et al.* (Ref. 9).

energies, direct detachment is the only process contributing significantly to the total-detachment cross section, so the electron collection data of Smith *et al.*[5] and of Bydin and Dukel'skii[8] can be compared with our $\sigma_{-0}$ measurements. The total-detachment data of Lichtenberg *et al.*[9] above 20 keV, for the argon target, were also obtained by the beam-attenuation technique, and include the other collision processes, such as multiple detachment, which attenuate the negative-ion beam without producing neutral atoms, so that higher values are expected.

A direct-detachment theory, which includes tunneling of the electron into the unbound region, is the zero-range

TABLE I. The cross section for double-electron detachment from $Br^-$ in a single collision with a rare-gas atom ($10^{-16}$ $cm^2$). The total error is estimated at 10%.

| Energy (keV) | Targets He | Ne | Ar | Kr | Xe |
|---|---|---|---|---|---|
| 10 | 0.52 | 0.31 | 0.85 | 1.1 | 0.24 |
| 20 | 1.2 | 0.41 | 2.1 | 1.7 | 0.57 |
| 30 | 1.6 | 0.61 | 2.5 | 2.1 | 1.3 |
| 40 | 1.9 | 1.0 | 2.8 | 2.3 | 1.3 |
| 50 | 2.0 | 1.1 | 2.9 | 2.5 | 1.6 |
| 60 | 2.2 | 1.2 | 3.2 | 2.6 | 2.0 |
| 70 | 2.4 | 1.3 | 3.2 | 2.9 | 2.4 |
| 80 | 2.4 | 1.5 | 3.2 | 3.1 | 2.2 |
| 90 | 2.6 | 2.0 | 3.4 | 2.9 | 3.2 |
| 100 | 3.5 | 2.8 | 4.6 | 3.3 | 3.5 |

TABLE II. The cross section for single-electron detachment from $Br^-$ in a single collision with a rare-gas atom ($10^{-16}$ $cm^2$). The total error is estimated at 10%.

| Energy (keV) | Targets He | Ne | Ar | Kr | Xe |
|---|---|---|---|---|---|
| 10 | 3.5 | 4.7 | 5.4 | 6.4 | 7.1 |
| 20 | 3.9 | 5.3 | 6.2 | 7.6 | 7.8 |
| 30 | 4.3 | 4.9 | 5.9 | 7.2 | 9.5 |
| 40 | 3.9 | 5.7 | 6.3 | 8.2 | 8.7 |
| 50 | 4.0 | 4.8 | 5.9 | 8.5 | 9.3 |
| 60 | 4.2 | 4.9 | 6.6 | 8.0 | 8.0 |
| 70 | 4.4 | 4.8 | 6.5 | 8.0 | 8.4 |
| 80 | 4.7 | 4.7 | 6.7 | 8.5 | 7.8 |
| 90 | 4.8 | 4.9 | 7.1 | 8.9 | 8.0 |
| 100 | 5.2 | 4.9 | 7.8 | 8.5 | 8.7 |

model originally proposed by Demkov.[10] In this theory, the wave function of the weakly bound electron is assumed to be large enough that the electron-molecule interaction can be approximated by a delta function. It is then possible to describe the probability of survival of the negative-ion state in terms of the time dependence of the binding energy of the electron. Gauyacq[11] has given an analytical form for the detachment probability when this time dependence is approximated by a step function. The electron binding energy, as a function of nuclear separation, is available for the $(\mathrm{Br\text{-}He})^-$ system from the calculations of Olson and Liu.[12] We have fitted their binding energy to a Morse function, and used the Guayacq step approximation to obtain a theoretical estimate of the direct-detachment cross section in the zero-range model. This theory is shown in Fig. 2 (dashed line). The agreement is as good as can be expected from the approximations made. The low-energy rise and the magntiude of the prediction are correct. The slight dip near 1 keV is due to the distance of closest approach penetrating into the inner stable region. Gauyacq's step approximation then overestimates the survival probability, because the step is taken from the stable outside region to the stable inside region. The rise of the experimental cross section at the higher energies is probably due to more endothermic processes than direct detachment, which are not contained in the zero-range theory.

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