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ELECTRON CAPTURE AND DETACHMENT IN COLLISIONS OF FAST HELIUM, BORON, AND FLUORINE ATOMS WITH GAS MOLECULES

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Results are reported for measurements of the cross sections σ_{0-1} and σ_{01} for electron capture and detachment in collisions of fast He, B, and F atoms (10 — 60 kev) with inert gas atoms. It has been established that the behavior of the $\sigma_{0-1}(v)$ curves and the position of the maxima on these curves can be explained by the Massey adiabatic hypothesis. The admixture of metastable He atoms in the primary beam has an effect on the $\sigma_{0-1}(v)$ curve for He atoms. The Massey adiabatic hypothesis does not apply to the electron detachment process in fast atoms.

INTRODUCTION

In earlier work[1,2] we have measured the cross sections for electron capture and detachment in collisions between fast H, C, and O atoms and gas molecules. A number of conclusions follow from an analysis of the experimental results obtained in that work. In order to evaluate the generality of these conclusions we have also measured the cross sections for electron capture and detachment for He, B, and F atoms. In addition, the measurements for H atoms in argon and krypton have been extended to energies of 3 to 8 kev in order to determine the positions of the maxima on the $\sigma_{0-1}(v)$ curve.

The present measurements were carried out with the apparatus which was used earlier for studying electron capture and detachment for H, C, and O atoms.[1] The atomic beam is obtained by neutralizing accelerated positive ions in a mercury-vapor target; when this method is used the atomic beam may contain an admixture of particles in excited metastable states. The presence of this admixture affects both the shape of the cross section vs velocity curve and the value of the cross section at a given velocity. Because of the presence of excited atoms in the beam, the thickness of the target in which the ions are neutralized affects the value of the measured cross section.[3]

We have investigated the cross sections σ_{0-1} and σ_{01} as functions of the thickness of the mercury-vapor target for He, B, C, O, and F atoms. With the exception of He, in all cases σ_{0-1} and σ_{01} are independent of target thickness. Thus, only the He atomic beam contains particles in excited states.

RESULTS OF THE MEASUREMENTS AND DISCUSSION

1. Electron Capture by H, He, B and F Atoms

The electron capture cross section has been measured for H atoms in the energy range 3 — 8 kev in argon and krypton, for He atoms in the energy range 10 — 50 kev in neon, argon, krypton, and xenon, and for B and F atoms in the energy range 10 — 60 kev in helium, neon, argon, krypton, and xenon. The value of σ_{0-1} for each energy was obtained by averaging the results of two measurements. In the region of the maxima of the $\sigma_{0-1}(v)$ curves for He the values of σ_{0-1} were obtained by averaging the data of five or six measurements. The random error of the measurements varied from ±7%, for cross sections of the order of 10^{-16} cm² to ±30% for cross sections of the order of 10^{-18} cm². The error in the measurement of the energy of the atoms was ±3%.

Curves showing σ_{0-1} as a function of the energy and velocity of the H, He, B and F atoms are given in Figs. 1 — 4. Examination of these figures shows that just as in the case of electron capture in H, C and O atoms, which we have investigated earlier, σ_{0-1} for He, B and F is strongly affected by the nature of the gas atom. This dependence is found not only in the numerical value of the cross section for a given velocity, but also in the shape of the $\sigma_{0-1}(v)$ curve. In the light gases (helium and neon) σ_{0-1} increases monotonically with increasing velocity;* in the heavier gases it goes through a maximum or reaches a plateau at the end of the investigated velocity range. Sometimes (boron in krypton and

*The reason the $\sigma_{0-1}(v)$ curves for He atoms are not monotomic is discussed below.

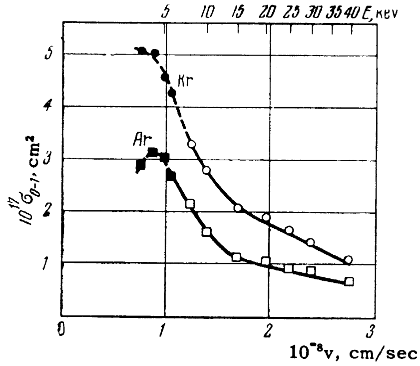

FIG. 1. Cross sections for electron capture by H atoms in argon and krypton. The dark points refer to the present work and the light points refer to the data of reference 1.

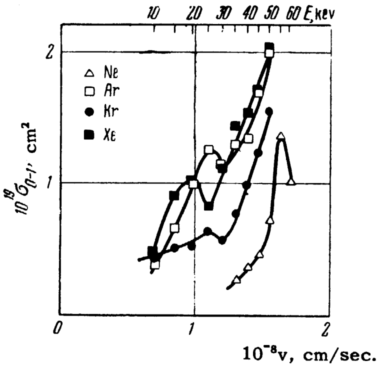

FIG. 2. The process $He^0 \rightarrow He^-$.

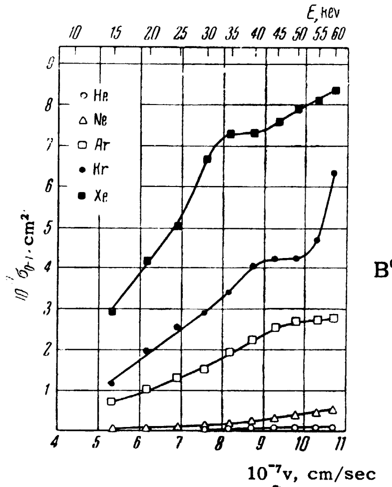

FIG. 3. The process $B^0 \rightarrow B^-$.

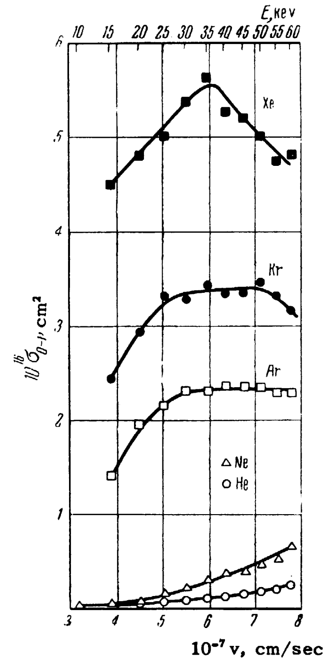

FIG. 4. The process $F^0 \rightarrow F^-$.

xenon) σ_{0-1} increases with increasing velocity after the plateau is traversed. The cross section for He in argon, krypton and xenon (σ_{0-1}) exhibits a further increase in velocity after passing through a maximum.

An analysis of the measurements for H, C, and O indicates that the Massey adiabatic hypothesis can explain the features of the $\sigma_{0-1}(v)$ curves.[4] As will be seen in the analysis given below, the experimental data of the present work support the conclusion that the Massey adiabatic hypothesis can be applied in electron capture by fast atoms.

The resonance defect for electron capture by fast atoms $A + B \rightarrow A^- + B^+$ (process I) can be written in the following form, if we assume that all participating particles are in the ground state:

$$\Delta E = S_A - V_B^{\mathrm{I}}, \qquad (1)$$

where S_A is the electron affinity of particle A and V_B^{I} is the first ionization potential of particle B. Because excited particles can also undergo a process in which an electron is captured by a fast atom, the following channels are available for the process:

$$A^* + B \rightarrow A^- + B^+, \qquad \Delta E = (S_A + E_A) - V_B^{\mathrm{I}}; \qquad \text{(II)}$$

$$A + B \rightarrow A^- + B^{+*}, \qquad \Delta E = S_A - (V_B^{\mathrm{I}} + E_{B^+}); \qquad \text{(III)}$$

$$A^* + B \rightarrow A^- + B^{+*}, \quad \Delta E = (S_A + E_A) - (V_B^{\mathrm{I}} + E_{B^+}) \qquad \text{(IV)}$$

(E_A and E_{B^+} are the excitation energies of particles A and B^+).

In analyzing the shapes of the $\sigma_{0-1}(v)$ curves for He, B, and F atoms we assume that the maxima or plateaus on these curves are to be associated with process I for B and F and with process II for He (metastable helium atoms in the $2s^3S$ state). Processes II and IV are excluded for B and F because the fact that σ_{0-1} is independent of the thickness of the mercury-vapor target indicates that there are no excited atoms in the primary beam. It may be assumed that the

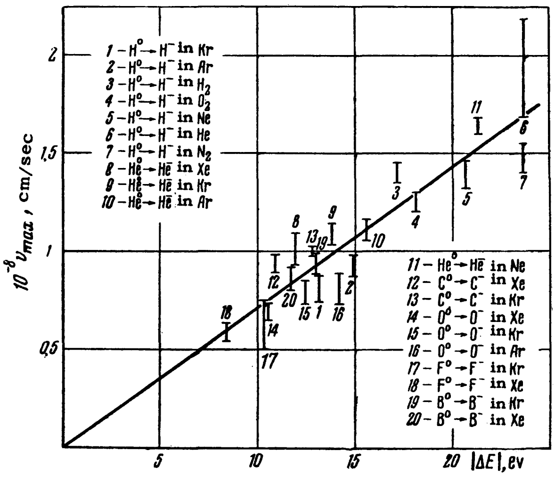

FIG. 5

maxima and plateaus on the $\sigma_{0-1}(v)$ curves for F and B correspond to III, corresponding to the excitation of the lowest level of the slow B^+ ion.

Under this assumption, the constant a which appears in the adiabatic criterion has approximately the same value for all atom-atom pairs for which the maxima on the $\sigma_{0-1}(v)$ curves are observed at 1.2 A. The maxima on the $\sigma_{0-1}(v)$ curves for H, C, and O may also be assigned to III, in which case a has a value which is only slightly different from the value 1.2 A for B and F atoms. However, the $\sigma_{0-1}(v)$ curves obtained indicate that the maxima on these curves cannot be assigned to III. If these maxima are assigned to III, there should be maxima corresponding to I in the low energy range and maxima corresponding to III in the high energy range, due to excitation of higher levels of the slow ion (up to the ionization level). For example, in the case of the pairs B-Ar, B-Kr, and O-Ar there should be maxima due to I near 11.8, 12, and 17 kev. However, no such maxima are observed for these pairs. In the case of H-Ar there are two maxima in the range 4.5 — 10 kev due to processes which are associated with excitation of the slow ion. Consequently, it is reasonable to expect that the $\sigma_{0-1}(v)$ curve will have a broad maximum in this energy range. Actually for H-Ar σ_{0-1} falls off rather rapidly with increasing energy in the range 4 — 10 kev.

The findings given above, which can be supplemented, force us to reject the assumption that the maxima on the $\sigma_{0-1}(v)$ curves for H, B, C, O, and F atoms are due to III. The only remaining explanation is that these maxima are to be associated with electron capture processes in which all participating particles are in the ground state. The value of a is approximately the same (3 A) for all atom-atom pairs for which a maximum is observed on the $\sigma_{0-1}(v)$ curve. The degree to which this quantity remains constant is apparent from Fig. 5, in which the dependence of v_{max} on $|\Delta\epsilon|$ is shown. If a is a constant all points should lie on a straight line. As is apparent from Fig. 5, the experimental points are well grouped about a straight line whose slope corresponds to a = 3 A. The maxima on the $\sigma_{0-1}(v)$ curves for the $He \rightarrow He^-$ process in neon, argon, krypton, and xenon fall on this line if it is assumed that these maxima are to be associated with the capture of the electron by metastable helium atoms in the $2s^3S$ state. This assumption is supported by the experiments in which the cross sections σ_{0-1} and σ_{01} are found to be functions of the thickness of the mercury-vapor target, indicating the existence of metastable helium atoms in the primary beam.

The further increase in σ_{0-1} beyond the maximum on the $\sigma_{0-1}(v)$ curves for $He \rightarrow He^-$ or beyond the plateau for the $B \rightarrow B^-$ process is due to maxima at high velocities, which are to be associated with I and III in the first case and with III in the second case.

It is of considerable interest to examine the factors which affect the maximum value of the cross section for inelastic processes. In processes such as $A \rightarrow A^-$ one of the factors which determines the value of $(\sigma_{0-1})_{max}$ may be the binding energy of the captured electron in the negative ion which is formed, i.e., the electron affinity. Curves showing $(\sigma_{0-1})_{max}$ as a function of electron affinity for krypton and xenon are given in Fig. 6. In plotting these curves we have taken the electron affinity values for H, C, O, F atoms from the survey paper by Branscomb[5] and the electron affinity of He and B from the work of Holpien and Midtal,[6] and Ginsberg and Miller,[7] respectively.

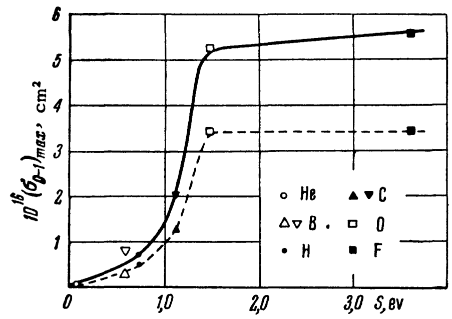

FIG. 6. The cross section $(\sigma_{0-1})_{max}$ as a function of electron affinity for Kr (dashed line) and Xe (solid line).

It is apparent from Fig. 6 that the electron affinity has an important effect on $(\sigma_{0-1})_{max}$ up to the atom O ($S \approx 1.5$ ev). However, there is almost no change in $(\sigma_{0-1})_{max}$ between O and F although the electron affinity increases by approximately a factor of 2.5. This result indicates that the electron affinity is not the only factor which determines the maximum value of σ_{0-1}. Apparently the structure of the electron shell of the negative ion which is formed is also of great importance.

In B and F, just as in H, C, and O, $(\sigma_{0-1})_{max}$ falls off monotonically as the first ionization potential of the target atom increases. This feature is not found in the He case, apparently because of the admixture of metastable atoms in the He beam.

A comparison of the values of σ_{0-1} for He, B, and F, as measured in the present work, with the data for the cross sections σ_{10} for He^+ ions[8] and σ_{1-1} for He^+, B^+, and F^+ ions[9-11] leads to the same conclusion as for H, C, and O atoms and ions: $\sigma_{10} > \sigma_{0-1} > \sigma_{1-1}$ for helium particles and $\sigma_{0-1} > \sigma_{1-1}$ for B and F ions and atoms.

2. Electron Detachment in H, He, B, and F Atoms

The electron detachment cross section σ_{01} for H, He, B, and F atoms was measured in the same energy range and for the same gases as the cross sections σ_{0-1}. Curves showing the dependence of σ_{01} on energy and velocity for H, He, B, and F are shown in Figs. 7 — 10. The electron detachment cross section for He in helium, neon, argon gases have also been measured by Barnett and Stier[3] by a beam-attenuation technique. The He data of the present work are compared with the data obtained by Barnett and Stier in Fig. 11.

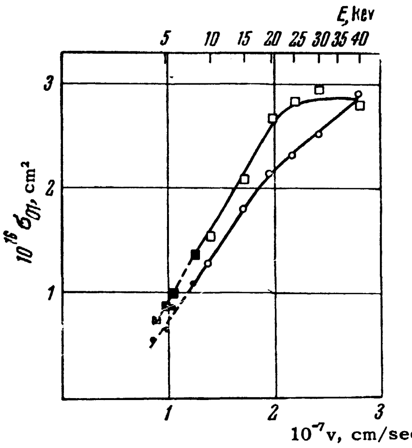

FIG. 7. Cross sections for electron loss by H atoms in argon and krypton. The dark points refer to the present work and the light points to the data of reference 1.

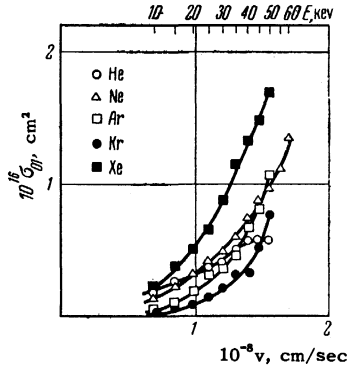

FIG. 8. The process $He^0 \to He^+$.

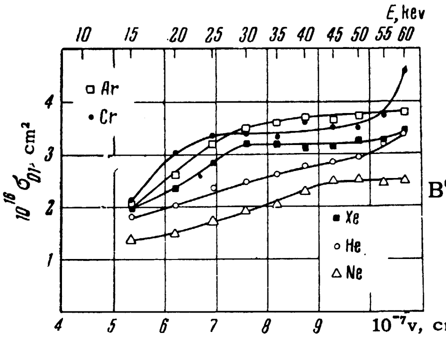

FIG. 9. The process $B^0 \to B^+$.

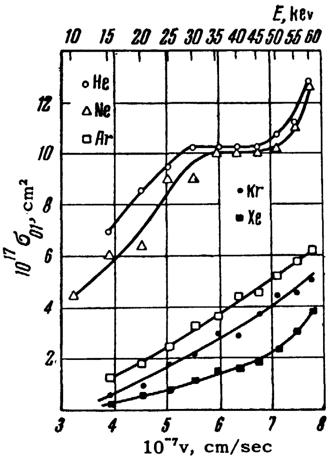

FIG. 10. The process $F^0 \to F^+$.

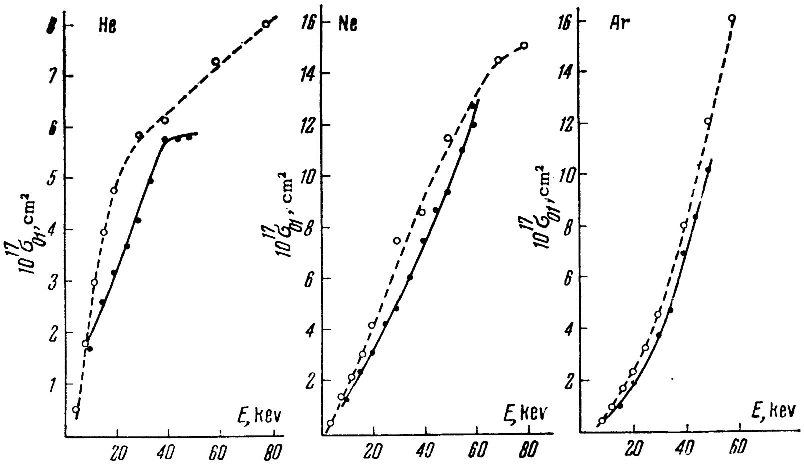

FIG. 11. The process $He^0 \to He^+$; ●) data of the present work, o) data of reference 3.

An analysis of the values of σ_{01} obtained in the present work and in our earlier work[1,2] reveals that the effect of the gas target-atom on the magnitude of σ_{01} is a function of the atomic number of the fast atom. For H, He, B, and C the dependence of σ_{01} on the atomic number of the gas atom is non-monotonic, whereas for the heavier atoms, O and F, σ_{01} increases monotonically as the atomic number of the target-atom decreases. Thus, σ_{0-1} and σ_{01} change in opposite directions for fast O and F atoms as the atomic number of the gas atom changes. It should also be noted that the gas atom has a stronger effect on σ_{0-1} than on σ_{01}. For example, for O atoms with a velocity of 6×10^7 cm/sec, σ_{0-1} increases by a factor of 120 between helium and xenon whereas σ_{01} is reduced by a factor of 4.

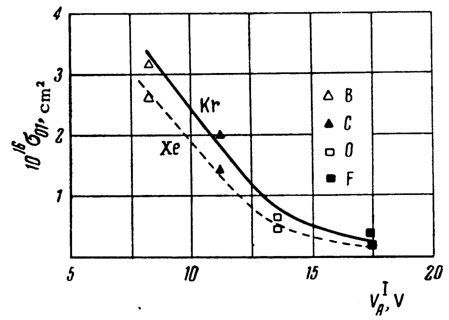

FIG. 12

On the basis of the present work and our earlier work[1,2] certain conclusions may be drawn as to the effect of the fast atom on σ_{01}. For B, C, O, and F, in which the detached electron comes from the same subshell (2p), there is a reduction in the cross section as the first ionization potential of the fast atom increases. This effect is seen in Fig. 12, which shows the dependence of σ_{01} (for the same velocity, 6.5×10^7 cm/sec) on the first ionization potential for B, C, O, and F atoms in the gases krypton and xenon. Presumably the same feature obtains in other atoms in which the detached electron comes from the same subshell. In particular, in the atoms H and He, in which the detached electron comes from the 1s subshell, for all gases except xenon we find $(\sigma_{01})_H > (\sigma_{01})_{He}$. This exception should not occasion surprise since the admixture of metastable atoms, with ionization potentials considerably lower than that of He atoms in the ground state, means that the measured value of σ_{01} is higher than the true value for He atoms in the ground state.

The value of σ_{01} is not determined exclusively by the binding energy of the detached electron. This result follows from the fact that σ_{01} for the O atom is larger than for the H atom, although both atoms have approximately the same ionization potential. Thus it would seem that in this case the electron comes from different electron shells. The number of electrons in the shell from which the electron is detached may also be of importance.

In conclusion we may note that the general behavior of the $\sigma_{01}(v)$ curves and the behavior of these curves for the same fast atom in different target atoms leads to the conclusion that the Massey adiabatic hypothesis does not apply to electron detachment in fast atoms.

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