ELECTRON CAPTURE AND LOSS IN COLLISIONS OF FAST CARBON AND OXYGEN ATOMS WITH GAS MOLECULES

Ia. M. FOGEL', V. A. ANKUDINOV and D. V. PILIPENKO

Physico-Technical Institute, Academy of Sciences, Ukrainian S.S.R.

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The electron capture and loss cross sections have been measured for carbon and oxygen atoms with energies between 10 and 65 kev in collisions with He, Ne, Ar, Kr, Xe and H_2, N_2 and O_2 molecules. The electron capture cross section for fast atoms increases with increasing electron affinity. The electron loss cross section for fast atoms is a non-monotonic function of the first ionization potential of the atom. Massey's adiabatic criterion is found to apply for electron capture by fast atoms. The value of the constant a in these processes is 3 A.

INTRODUCTION

In an earlier work[1] we have measured the electron capture and loss cross sections for collisions between fast hydrogen atoms and gas molecules. It is of interest to extend this investigation to other atoms in order to determine the influence of the electron affinities of the fast atoms on the electron capture cross section σ_{0-1} and the effect of the ionization potential on the electron loss cross section σ_{01}. It is reasonable to expect that the main effect will be due to the configuration of the electron shell of the fast atom. However, the possibility is not excluded that there will be a correlation between the cross sections σ_{0-1} and σ_{01} and the binding energy of the electron in the negative ion which is formed and the binding energy of the electron which is detached from the fast atom.

In the present work these problems were studied by measuring the cross sections σ_{0-1} and σ_{01} for fast carbon and oxygen atoms. These atoms were chosen on the basis of the following considerations: (1) the electron affinity of H, C and O atoms is an increasing function which takes on the following values 0.75, 1.13 and 1.48 ev;[2] (2) the ionization potentials are the same in H and O, but the electron shell configurations are different ($1s^1$ and $1s^2\ 2s^2\ 2p^4$ respectively); (3) the ionization potential of the C atom is smaller than that of the H and O atoms.

RESULTS OF THE MEASUREMENTS AND DISCUSSION

The experimental setup for investigating electron capture and loss in fast atoms and the method of measuring σ_{0-1} and σ_{01} has been described in detail in reference 1.

A beam of fast C and O atoms was obtained by neutralizing C^+ and O^+ ions which passed through a mercury-vapor target.[3] The optimum target thickness was chosen (of the order of 10^{15} atoms/cm^2) and it was verified experimentally that the energy loss of the C^+ and O^+ ions in the target was very small.

The electron capture and loss cross sections were measured for C and O atoms with energies between 10 and 65 kev in collisions with He, Ne, Ar, Kr, Xe and the molecules H_2, N_2 and O_2. The values of σ_{0-1} and σ_{01} for each energy were obtained by averaging two measurements. The cross sections were computed for particles of a gas, i.e. for molecular gases consisting of one kind of gas molecule. The random error in these measurements of σ_{0-1} and σ_{01} was ±15%. The error in the measurement of the energy of the C and O atoms was ±3%.

Figures 1 to 8 show the cross sections σ_{0-1} and σ_{01} as functions of the energy and velocity of the C and O atoms for atomic and molecular gases. An examination of these curves indicates the following.

1. For the majority of atom-molecule pairs, σ_{0-1} and σ_{01} increase with increasing energy of the C and O atoms. For the pairs O-Xe, O-Kr, and C-Xe, however, σ_{0-1} passes through a maximum as the energy is increased. For O-Ar and C-Kr the curve $\sigma_{0-1} = f(E)$ reaches a plateau at the extremity of the energy region.

2. σ_{0-1} and σ_{01} are fairly sensitive functions of the type of gas particle. For the $C^0 \rightarrow C^-$ and

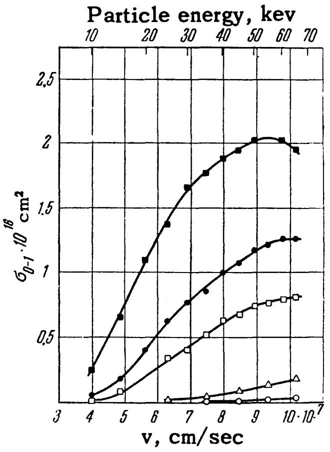

FIG. 1. Electron capture cross sections for carbon atoms in inert gases: ■) Xe, ●) Kr, □) Ar, △) Ne, ○) He.

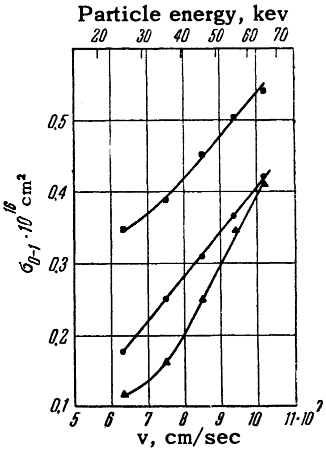

FIG. 2. Electron capture cross sections for carbon atoms in molecular gases: ●) H_2, ▲) N_2, ■) O_2.

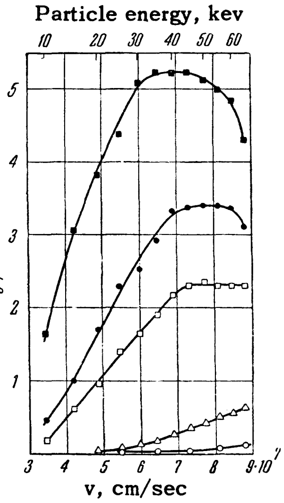

FIG. 3. Electron capture cross section for oxygen atoms in inert gases: ■) Xe, ●) Kr, □) Ar, △) Ne, ○) He.

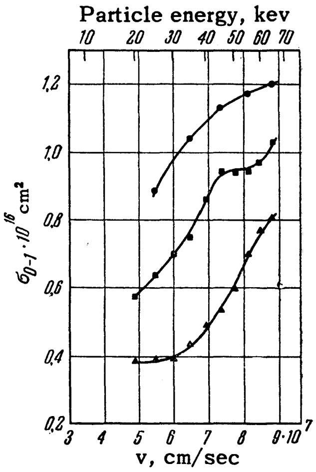

FIG. 4. Electron capture cross section for oxygen atoms in molecular gases: ●) H_2, △) N_2, ■) O_2.

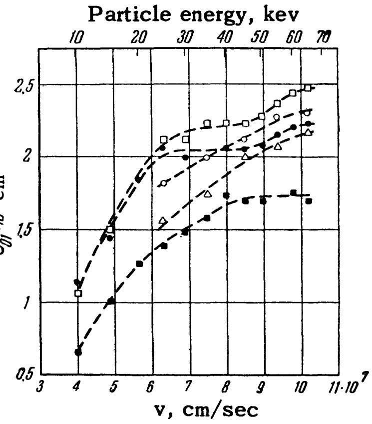

FIG. 5. Electron loss cross section for carbon atoms in inert gases: ■) Xe, ●) Kr, □) Ar, △) Ne, ○) He.

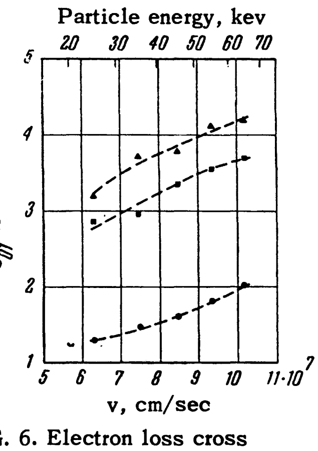

FIG. 6. Electron loss cross sections for carbon atoms in molecular gases: ●) H_2, ▲) N_2, ■) O_2.

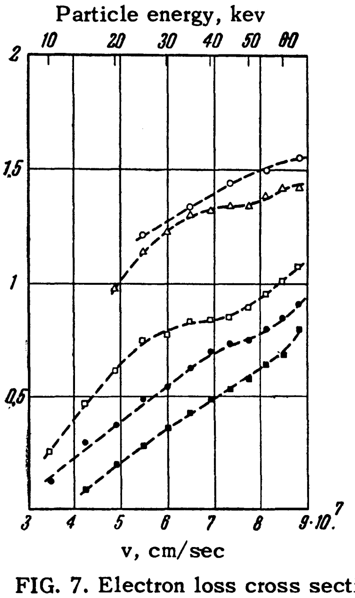

FIG. 7. Electron loss cross section for oxygen atoms in inert gases: ■) Xe, ●) Kr, □) Ar, △) Ne, ○) He.

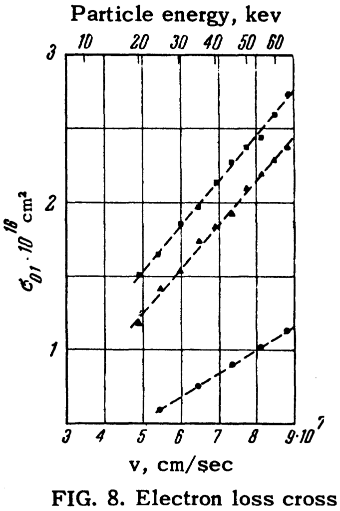

FIG. 8. Electron loss cross sections for oxygen atoms in molecular gases: ●) H_2, ▲) N_2, ■) O_2.

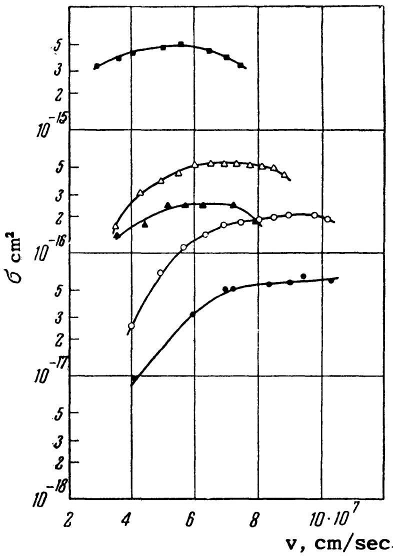

FIG. 9. Electron capture cross sections: ■) σ_{01}, ▲) σ_{0-1}, ●) σ_{1-1} for carbon; △) σ_{0-1}, o) σ_{1-1} for oxygen (in Xe).

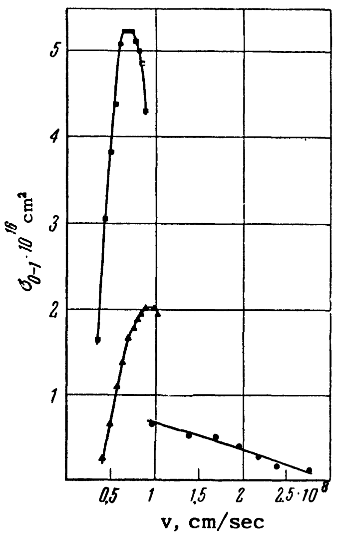

FIG. 10. Cross sections for the capture of one electron in atoms: ■) O, ▲) C, ●) H (in Xe).

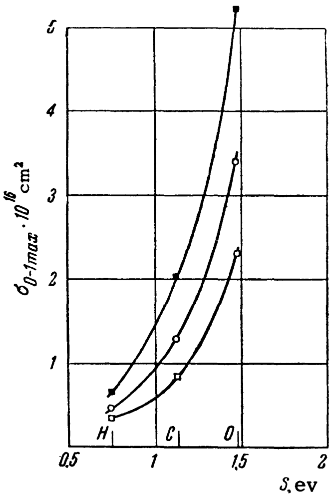

FIG. 11. The dependence of $\sigma_{0-1\,max}$ on electron affinity: □) Ar, o) Kr, ■) Xe.

$O^0 \rightarrow O^-$ reactions in inert gases the values of σ_{0-1} are the same at the same atomic velocities and fall off monotonically as the atomic number of the inert gas is reduced. For $O^0 \rightarrow O^+$ reactions, on the other hand, σ_{01} increases as the atomic number of the inert gas is reduced. In the $C^0 \rightarrow C^+$ reactions these cross sections are non-monotonic functions of the atomic number of the gas. In molecular gases, a monotonic dependence of cross section on atomic number of the gas is observed only for σ_{01} in the $O^0 \rightarrow O^+$ reactions, in which case this quantity increases with the atomic number.

3. The cross sections σ_{0-1} and σ_{01} are also functions of the type of fast atom. σ_{0-1} is larger for O atoms than for C atoms. On the other hand σ_{01} is smaller for O atoms than for C atoms.

4. For O atoms in the light inert gases He and Ne and the molecular gases N_2 and O_2, σ_{01} is greater than σ_{0-1}; in the heavier inert gases Ar, Kr, and Xe, it is smaller. In the case of C atoms $\sigma_{01} > {}_{0-1}$ for all gases except Xe, in which case $\sigma_{01} \approx \sigma_{0-1}$.

The literature contains no data concerning the $C^0 \rightarrow C$ and $O^0 \rightarrow O$ reactions; thus we cannot make a comparison of these results with other experiments.

It is of interest to compare σ_{0-1} and σ_{01} with other electron capture and loss cross sections in carbon and oxygen. The data available in the literature allow a comparison between σ_{0-1} and σ_{1-1} for capture of two electrons by C^- and O^+ ions[4] for all the gases investigated and with the cross section σ_{01} for capture of one electron by C^+ ions[5] in Ar, Kr, Xe, and H_2.

In Fig. 9 are shown the quantities σ_{01}, σ_{0-1}, and σ_{1-1} as functions of the carbon velocity and σ_{0-1} and σ_{1-1} for oxygen (target atom, Xe). It is evident from these curves that the electron capture cross sections for carbon obey the relation $\sigma_{01} > \sigma_{0-1} > \sigma_{1-1}$ which also applies for the capture cross sections in hydrogen (cf. reference 1). σ_{01} is approximately two orders of magnitude greater than σ_{0-1} and σ_{1-1}. σ_{0-1} is two or three times greater than σ_{1-1}. The ratio $\sigma_{0-1}/\sigma_{1-1}$ is smaller for oxygen than for carbon. The characteristics of the electron capture cross section for carbon and oxygen in Xe also apply to other target gases.

Certain conclusions may be drawn from a comparison of σ_{0-1} in H, C and O atoms. In Fig. 10 are shown $\sigma_{0-1}(v)$ curves for H, C and O atoms in Xe;* these curves illustrate the strong dependence of σ_{0-1} on the fast atom. It is apparent from this figure that the highest electron capture cross section is found in O; the cross section in C is somewhat smaller and the smallest values for this cross section are found in H atoms. Similar relations are found for other target atoms. The dependence of σ_{0-1} on the type of fast atoms may be related to the binding energy of the level at which electron capture takes place, i.e., the electron affinity. It is reasonable to assume that σ_{0-1} will increase with increasing electron affinity. The curves shown in Fig. 11, which give the maxi-

*The function $\sigma_{0-1}(v)$ for H atoms was plotted from the data of reference 1.

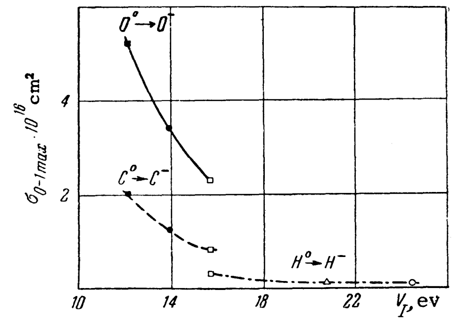

FIG. 12. The dependence of $\sigma_{0-1\max}$ on the ionization potential of the target atom: ■) Xe, ●) Kr, □) Ar, △) Ne, o) He.

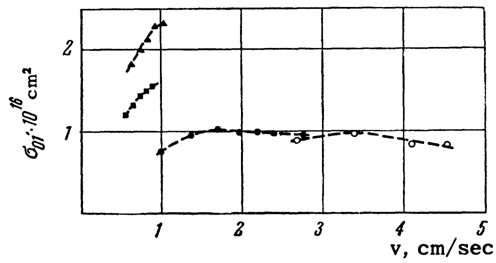

FIG. 13. Electron loss cross sections for fast atoms: ▲) C, ■) O, ●) H, o) He (in He).

mum value of σ_{0-1} as a function of electron affinity, are plotted for Ar, Kr, and Xe and show the rapid growth in σ_{0-1} as the electron affinity of the fast atom increases; these curves tend to support the suggestion made above. The monotonic increase in σ_{0-1} as a function of electron affinity is not disturbed by the fact that the electron is captured at the 1s level in H and at the 2p level in C and O.

The effect of the target atom on σ_{0-1} can be characterized by the binding energy of the electron which is detached, i.e., the first ionization potential of the target atom. Curves showing the dependence of the maximum value of σ_{0-1} on the first ionization potential of the target atoms are plotted for the fast atoms H, C and O in Fig. 12. As is apparent from this figure, σ_{0-1} falls off monotonically with increased binding energy of the detached electron. The points for the $H^0 \rightarrow H^-$, $C^0 \rightarrow C^-$ and $O^0 \rightarrow O^-$ reactions lie on three different curves, reflecting the effect of the electron affinity of the fast atoms.

A comparison of the cross section σ_{01} for different fast atoms is shown in Fig. 13, where the function $\sigma_{01}(v)$ is shown for H, C, O and He atoms in He.* As is apparent from this figure, there is no relation between σ_{01} and the first ionization potential of the fast atom. Although the first ionization potential of the He atom is considerably greater than that of the H atom, σ_{01} is about the same in these atoms; it should be noted that the detached electrons come from the same shell in both atoms (the 1s shell). H and O atoms have the same ionization potential, but σ_{01} in the O atom is higher than in the H atom. It is possible that in this case there is an effect due to the electron shell from which the electron is detached (1s for the H atom and 2p for the O atom). It is only in the C and O atoms that there is an increase in σ_{01} as the ionization potential is reduced. The detached electrons in both atoms come from the 2p shell. The inequality $(\sigma_{01})_H < (\sigma_{01})_O < (\sigma_{01})_C$ is observed for all the gases which were investigated.

It has been established in reference 1 that the maxima on the curve $\sigma_{0-1}(v)$ for $H^0 \rightarrow H^-$ reactions are located in correspondence with the Massey adiabatic criterion $a|\Delta E|/hv_{max} \approx 1$ (a is the distance over which the interaction forces between the colliding particles operate, ΔE is the resonance defect and v_{max} is the ion velocity corresponding to the maximum cross section), where the quantity a changes slightly for different targets, varying about the mean value 3 A. Using the maxima on the curves for $\sigma_{0-1}(v)$ for C atoms and O atoms (cf. Figs. 1 and 3) it is possible to estimate the constant a for the $C^0 \rightarrow C^-$ and $O^0 \rightarrow O^-$ reactions in Ar, Kr and Xe.

If the quantity a is the same for different atom-molecule pairs, it follows from the Massey adiabatic criterion that $v_{max} \sim |\Delta E|$. A graph of the function $v_{max} = f(|\Delta E|)$, plotted for all atom-molecule pairs in which maxima are observed on the $\sigma_{0-1}(v)$ curve is shown in Fig. 14. In plotting these curves we have assumed that all

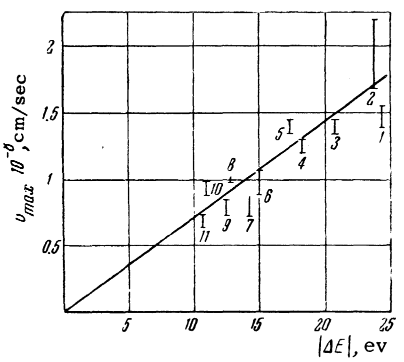

FIG. 14. The quantity v_{max} as a function of resonance defect: for $H^0 \rightarrow H^-$ in: 1) N_2, 2) He, 3) Ne, 4) O_2, 5) H_2, 6) Kr; for $O^0 \rightarrow O^-$ in: 7) Ar, 9) Kr, 11) Xe: for $C^0 \rightarrow C^-$ in: 8) Kr, 10) Xe.

*The curves $\sigma_{01}(v)$ are plotted from the data given in reference 6.

particles which participate in the $A^0 \to A^-$ reactions are in ground states. The resonance defects for $H^0 \to H^-$ reactions in molecular gases were computed under the assumptions that the molecular ion which is formed dissociates into atomic particles. The vertical spreads indicate the error in the determination of v_{max}. In this case, when the curve $\sigma_{0-1}(v)$ reaches a plateau the corresponding vertical section on Fig. 14 has no upper or lower limits.

As is evident from Fig. 14 the points for all $A^0 \to A^-$ reactions for which maxima are observed on the $\sigma_{0-1}(v)$ curves lie about a line which corresponds to $a \approx 3$ A. The quantity a is found to be approximately constant not only for processes such as $A^0 \to A^-$ but also for processes in which one or two electrons are captured by singly charged positive ions; with the sole difference that the mean value of a is 8 A (reference 7) for ordinary charge-exchange processes (capture of one electron) and 1.5 A (reference 8) for double charge-exchange (capture of two electrons). Thus, the available experimental data indicate that the Massey adiabatic criterion applies in all investigations of electron capture by fast particles which have been carried out.

N. V. Topolia participated in these measurements.

In conclusion, we take this opportunity to thank A. K. Val'ter for his continued interest in this work.

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