Charge transfer of ground-state C^+, N^+, and O^+ in N_2 and H_2

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The single-electron charge-transfer cross sections for ground-state C^+, N^+, and O^+ ions colliding with N_2 and H_2 are reported. Comparison with results from a mixed-state beam (i.e., an ion beam containing both ground-state and metastable-state ions) of C^+ and O^+ ions indicate that single-electron charge-transfer cross sections are equal for ground-state and metastable-state C^+ and O^+ ions for velocities greater than $\sim 5\times 10^7$ cm sec^{-1}.

I. INTRODUCTION

Previously we have published total charge-transfer cross sections involving collisions of O^+, N^+, and O^+ ions with N_2 and H_2 targets.[1] These data covered the energy range 5.5 – 100 keV. In that work the ion beam was produced using an rf ion source, which produced an unknown fraction of these ions in metastable states. In a series of papers, Moran and Wilcox[2–4] and Moran and Mathur[5] have pointed out explicitly that for the energy range 0.6 – 3.0 keV metastable components of C^+ and O^+ ion beams have a major influence on the measured charge-transfer cross section. In the case of $C^+(^4P)$ and $O^+(^2D)$, the one-electron charge-exchange process involving N_2 and H_2 are in near resonance with the product channels involving the $N_2{}^+(A\,^2\Pi_u,v')$ and $H_2{}^+(x\,^2\Sigma_g^+,v')$ states. Because of this near resonance, the one-electron charge-exchange process may have a large cross section at low and medium energies since it is likely to occur at a large internuclear separation of the collision partners.[6] The charge-transfer cross section from a mixed-state ion beam (ground-state and metastable-state) would be larger than the cross section measured from a pure ground-state ion beam. In the case of metastable $N^+(^1D)$, there is a near resonance for charge transfer to both $N_2{}^+$ and $H_2{}^+$, but this channel is not likely since it cannot occur by a single one-electron charge-transfer process.

Besides the measurements by Moran and coworkers,[2–5] Nutt, McCullogh, and Gilbody[7] have also measured the one-electron capture by C^+, N^+, and O^+ ions in H and H_2. These data cover the energy range 0.1 – 13 keV and pertain to ground-state ions. The Nutt *et al.*[7] cross-section data agree with those which Moran and Wilcox obtained with their mixed-state ion beam. Since Moran and Wilcox indicate that their mixed beam contained a metastable population while Nutt *et al.* state that their results were for ground-state ions, this agreement represents an inconsistency. If, as Moran and Wilcox indicate, the metastable charge-transfer cross section is much larger than the ground-state cross section, then the results should differ. Phaneuf, Meyer, and McKnight[8] have also measured single-electron capture for these same ions in H and H_2 although they do not state if these data pertain to ground-state ions. These data were obtained in an energy range 20 – 600 keV with only one data point below 20 keV (8.6 keV) and so are not directly comparable with the results of Nutt *et al.* and Moran and Wilcox.

In order to help resolve the differences between the data of Moran and Wilcox and Nutt *et al.* and to compare our previous measurements with those for charge transfer from ground-state ions, we have remeasured the single-electron-capture cross section for ground-state ions of $C^+(^2P)$, $N^+(^3P)$, and $O^+(^4S)$ interacting with N_2 and H_2. These new measurements cover the energy range from 3 to 100 keV.

II. EXPERIMENTAL METHOD

The measuring technique and apparatus, except for the ion source, have been described previously[1] and will not be discussed here in detail. In the present measurements, the reactant ion beam is produced in an electron-impact ion source rather than the rf ion source used in the original measurements. The reactant ion electronic-state population distribution is determined by the electron kinetic energy in the source. Only ground-state ions will be produced in the source if the electron kinetic energy is below the threshold for production of excited states. In the present case, the electron accelerating potential consisted of a dc bias potential with the ac filament excitation potential superimposed on it. The latter was approximately 1.5 V, while the former was (in the worst case) 1.9 V less than the energy required to produce the metastable atomic ion. No consideration was given to space-charge or plasma effects which might result in greater electron energy. However, the source pressure was varied from about 5 to about 50 mTorr with no measurable difference in the cross section obtained. A reactant ion beam with a mixed-state population distribution can be produced by increasing the electron kinetic energy above the various thresholds for production of excited states. For this case, the dc potential between filament and anode was 105 V, approximately 4 times the value necessary to produce metastable atomic ions. The relative abundance of the metastable ions in the beam which is extracted from the source will depend upon the pressure in the source as well as electron energy. Measurements of the single-electron-capture cross section have been made for both the reaction ions in their ground state and for a mixed beam. This latter measurement was made so that we could compare results with our data obtained using an rf ion source. We have not obtained single-electron-capture cross sections for metastable reactant ions because we have not determined the mixed-beam composition.

III. RESULTS AND DISCUSSION

Our measured single-electron-capture cross section results for C^+, N^+, and O^+ ions incident onto H_2 and N_2 targets are shown in Figs. 1–6. These data for ground-state ions are listed in Table I. The present data shown in the figures are for ground-state ions and a mixed beam of ground- and metastable-state ions. Notice that the mixed-beam data are not plotted for $E > 20$ keV since these data are the same as the data previously reported using an rf ion source. We estimate the experimental uncertainty in the data to be $\pm 10\%$. (See Ref. 1 for details of this estimate.) Also shown are our previous results which were obtained using an rf ion source. The data of Moran and Wilcox[2–4] and Nutt *et al.*[7] are also shown along with the data of Phaneuf *et al.*[8] where applicable.

Figures 1 and 2 show the results for single-electron-capture for C^+ ions incident on N_2 and H_2. At incident energies greater than 20 keV (5.7×10^7 cm/sec) the single-electron cross section data for ground state $C^+(^2P)$ ions reacting with N_2

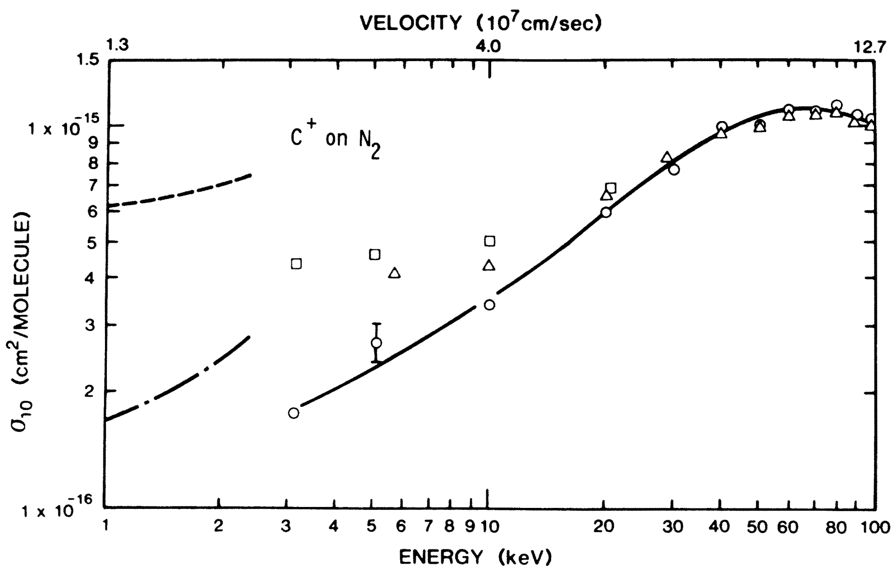

FIG. 1. Single-electron-capture cross section for ground-state C^+ incident onto N_2. ○, present ground-state results; □, present mixed-state results; △ , Lockwood *et al.* (Ref. 1) rf ion-source results; —·—, — — —, Moran and Wilcox, (Ref. 4) ground-state and mixed-state results.

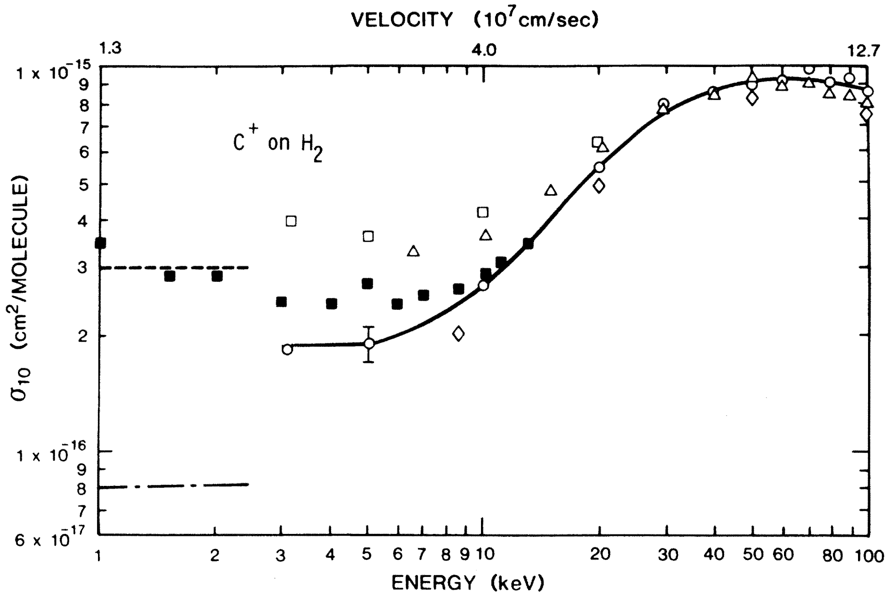

FIG. 2. Single-electron-capture cross section for ground-state C^+ incident onto H_2. ○, present ground-state results; □, present mixed-state results; △ , Lockwood *et al.* (Ref. 1) rf ion-source results; ■, Nutt *et al.* (Ref. 7) ground-state results; ◇, Phaneuf *et al.* (Ref. 8) results; —·—, — — —, Moran and Wilcox (Ref. 4) ground-state and mixed-state results.

and H_2 are the same as that obtained from the rf source and also a mixed-ion beam produced by an electron-impact source operating with a dc bias of 105 V. Below this energy the data for the mixed-ion beams and the rf-source data are in good agreement and are larger than the present ground-state results. The agreement between the rf-source data and the mixed-beam data produced by the electron-impact source must be regarded as fortuitous since we do not know the electronic-state

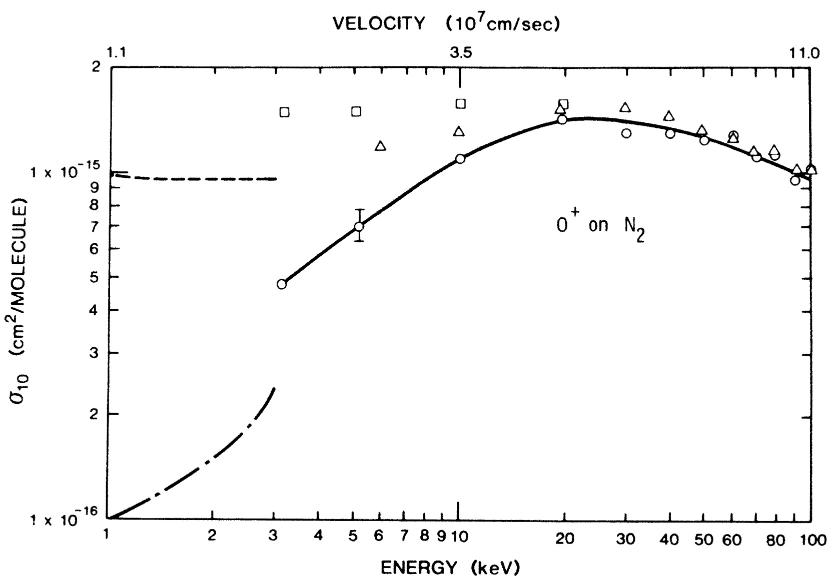

FIG. 3. Single-electron-capture cross section for ground-state O^+ incident onto N_2. ○, present ground-state results; □, present mixed-state results; △ , Lockwood *et al.* (Ref. 1) rf ion-source results; —·—, — — —, Moran and Wilcox (Ref. 2) ground-state and mixed-state results.

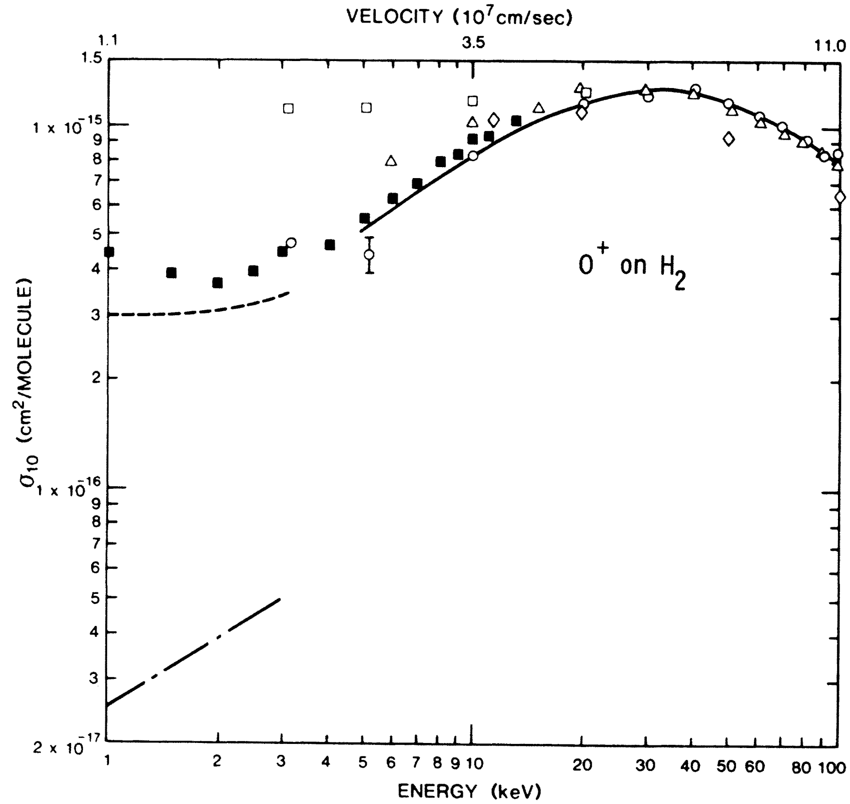

FIG. 4. Single-electron-capture cross section for ground-state O^+ incident onto H_2. ○, present ground-state results; □, present mixed-state results; △ , Lockwood *et al.* (Ref. 1) rf ion-source results; ■, Nutt *et al.* (Ref. 7) ground-state results; ◇, Phaneuf *et al.* (Ref. 8) results; —·—, — — —, Moran and Wilcox (Ref. 2) ground-state and mixed-state results.

population distribution in either beam. Our ground-state data for $C^+(^2P)$ incident onto N_2 is lower than the results of Moran and Wilcox[4] if one extrapolates their data to higher energy. For the case of a ground-state $C^+(^2P)$ beam incident on H_2 there is a very large disagreement with the low-energy data of Moran and Wilcox.[4] Our ground-state results agree very well with the ground-state

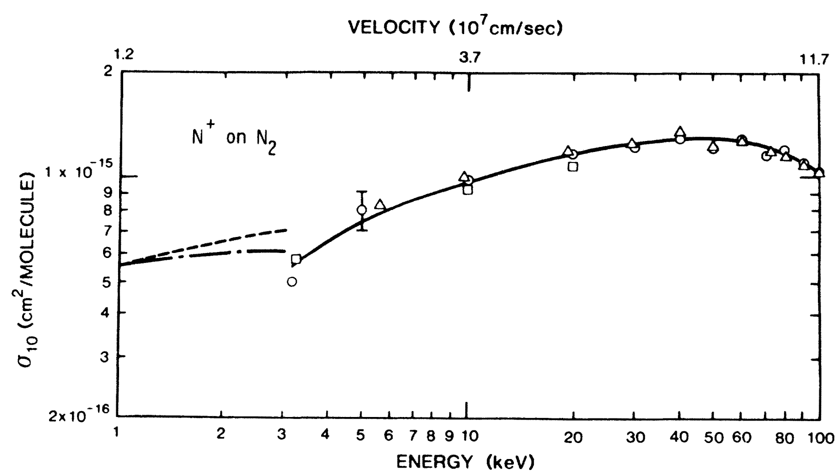

FIG. 5. Single-electron-capture cross section for ground-state N^+ incident onto N_2. ○, present ground-state results; □, mixed-state results; △ , Lockwood *et al.* (Ref. 1) rf ion-source results; —·—, — — —, Moran and Wilcox (Ref. 3) ground-state and mixed-state results.

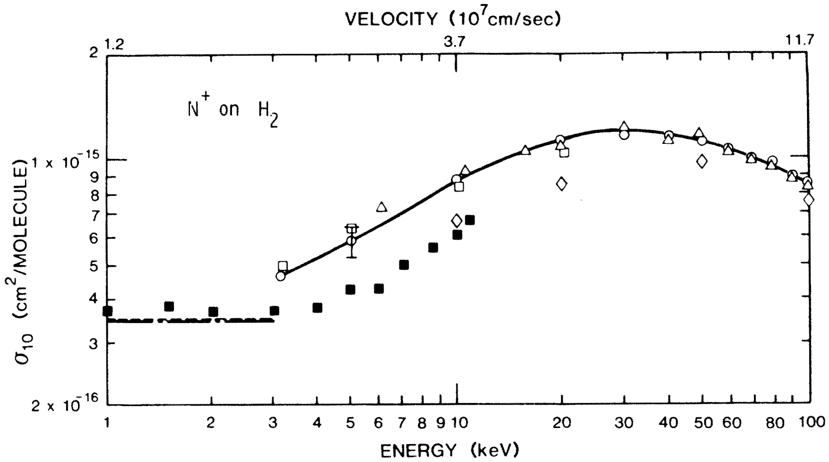

FIG. 6. Single-electron-capture cross section for ground-state N^+ incident onto H_2. ○, present ground-state results; □, mixed-state results; △, Lockwood *et al.* (Ref. 1) rf ion-source results; ■, Nutt *et al.* (Ref. 7) ground-state results; ◇, Phaneuf *et al.* (Ref. 8) results; —-—, — — —, Moran and Wilcox (Ref. 3) ground-state and mixed-state results.

results of Nutt *et al.* in the energy range 3–13 keV. We are also in good agreement with the results of Phaneuf *et al.* over the energy range from 8.5 to 100 keV. Phaneuf *et al.* do not indicate what the electronic-state population distribution of their ion beam is, but most of their measurements are at high enough velocity that the charge-transfer cross section is independent of the metastable population of the ion beam.

As can be seen from Figs. 1 and 2, the total charge-transfer cross section for energies greater than 20 keV (5.7×10^7 cm/sec) does not depend upon the type of ion source which is used to produce the beam, i.e., it does not depend upon the incident-ion electronic-state distribution. Since the excited-state population distribution is unlikely to be the same for the various ion sources, the ground-state and metastable-state charge-transfer cross sections are probably equal for $E > 20$ keV.

Figures 3 and 4 show the results for single-electron capture for O^+ ions incident on N_2 and H_2. We again find that our ground-state results agree with the rf-source data and the mixed-beam data for energies greater than 20 keV (5×10^7 cm/sec). These results indicate that the single-electron-capture cross section is the same for ground-state and metastable-state O^+ at energies above 20 keV. For $O^+(^4S)$ ions incident onto N_2, we find that our data at 3 keV lie between the ground-state data and the mixed-state data of Moran and Wilcox.[2] Our ground-state data for $O^+(^4S)$ incident onto H_2 is in good agreement with the results of Nutt *et al.*,[7] although they state that there is evidence of metastable ions in their beam. Nutt *et al.* also indicate that they found the metastable cross section for $O^+(^2D,^2P)$ equal to the ground-state cross section for energies greater than 5 keV. This result is in disagreement with our data which indicates that the metastable cross section is greater than the ground-state cross section at energies up to about 20 keV. Our present measurements are in good agreement with those of Phaneuf *et al.*[8] in the 10–100-keV energy range. The data of Nutt *et al.* and an extrapolation of our ground-state O^+ data to lower energies are in agreement with the mixed-state ion data of Moran and Wilcox,[2] but show large disagreement with their ground-state data.

Figures 5 and 6 show the results for single-electron capture for N^+ ions incident on N_2 and H_2. These data show no difference between the ground-state case and the mixed-ion case. This result is in agreement with the low-energy results of Moran and Wilcox.[3] In both cases there is no allowed channel which is in accidental resonance with the energy levels of $N_2{}^+$ or $H_2{}^+$ so that the charge-transfer cross section for metastable ions is the same as from the ground state. For N^+ incident onto H_2, the results of Nutt *et al.*[7] and Phaneuf *et al.*[8] are consistently lower than our results. At the present time we have no explanation for this rather large discrepancy.

TABLE I. Single-electron-capture sections for ground-state ions of C^+, O^+, and N^+ incident onto N_2 and H_2.

Energy (keV)	V (10^7 cm/sec)	σ_{10} (10^{-16} cm^2)	Energy (keV)	V (10^7 cm/sec)	σ_{10} (10^{-16} cm^2)
	C^+ on N_2			C^+ on H_2	
3.14	2.24	1.74	3.13	2.24	1.87
5.09	2.85	2.69	5.05	2.84	1.91
10.09	4.01	3.40	10.04	4.00	2.69
20.22	5.68	5.94	20.24	5.68	5.39
30.04	6.92	7.72	30.06	6.93	7.85
40.16	8.01	9.88	39.87	7.98	8.53
50.10	8.94	10.2	50.11	8.94	8.86
60.14	9.80	11.0	60.18	9.80	9.05
70.05	10.6	10.8	69.99	10.6	9.94
80.06	11.3	11.5	80.06	11.3	8.99
90.07	12.0	10.7	90.09	12.0	9.34
99.78	12.6	10.3	99.81	12.6	8.70
	O^+ on N_2			O^+ on H_2	
3.14	1.94	4.76	3.13	1.94	4.79
5.18	2.49	7.00	5.15	2.48	4.39
10.20	3.49	10.8	10.04	3.47	8.40
20.15	4.91	14.3	20.02	4.90	11.6
30.11	6.00	13.0	30.04	6.00	12.1
40.05	6.92	13.0	40.22	6.94	12.8
50.09	7.74	12.3	50.01	7.74	11.5
60.11	8.48	12.8	60.01	8.48	11.1
70.07	9.16	11.1	70.17	9.16	10.3
80.06	9.79	11.3	80.14	9.79	9.34
90.00	10.4	9.50	90.04	10.4	8.28
99.94	10.9	10.3	99.91	10.9	8.35
	N^+ on N_2			N^+ on H_2	
3.14	2.07	4.95	3.14	2.07	4.62
5.02	2.62	8.02	5.01	2.62	5.83
10.02	3.70	9.87	10.01	3.70	8.73
20.08	5.24	11.8	20.01	5.23	11.2
30.03	6.41	12.3	30.10	6.42	11.6
40.05	7.40	13.0	40.15	7.41	11.5
49.94	8.27	12.2	49.89	8.26	11.1
60.09	9.07	13.2	60.00	9.06	10.4
70.16	9.80	11.5	70.01	9.79	9.91
80.10	10.5	12.0	80.12	10.5	9.67
90.00	11.1	11.0	90.00	11.1	8.99
100.02	11.7	10.6	100.06	11.7	8.68

IV. CONCLUSIONS

This paper has presented results for single-electron capture for ground-state C^+, N^+, and O^+ ions incident onto N_2 and H_2. Comparison with our previous results for C^+ and O^+ which were obtained using an ion beam containing both ground and metastable states indicates that cross sections for these species are equal at velocities greater than 5×10^7 cm/sec. For velocities less than this value, the near-resonant charge-transfer processes from the metastable state have a much larger cross section than charge transfer from the ground state. Since we have not determined the composition of our mixed beam, we are unable to obtain cross sections for the metastable-state ions. The present data for single-electron capture from ground-state N^+ incident on N_2 and H_2 are in good agreement with our previous results. In this case the near resonance of the metastable state is not important since charge transfer cannot occur by a one-electron process. The results we have presented are in good agreement with those of Nutt, McCullough, and Gilbody[7] except in case of N^+ on H_2 where our results are about 27% higher. For ground-state C^+ and O^+ incident on H_2 our results are in better agreement with the results of the mixed-state ion-beam data of Moran and Wilcox.[2,4]

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