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N^+ charge transfer in N_2 at low-keV collisions

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Abstract

The absolute differential and total cross-sections for single electron capture at energies between 0.5 and 5.0 keV are reported. The reduced differential cross-sections shows an overall increase of at least one order of magnitude and a monotonic decreasing behavior at all the collision energies studied in this work. The total cross-sections for single electron capture are compared with previous experimental measurements. The total cross-section results presented in this paper and obtained by integration of the measured differential cross-sections agree with previous measurements using a beam of pure ground state ions. (Int J Mass Spectrom 218 (2002) 161–165)

Keywords: N^+; Charge transfer; Angular distributions; Absolute cross-sections

1. Introduction

Understanding the details of the interaction of N^+ ions and N_2 might be important in a wide range of energy. That interaction plays a central role in the charge and energy balances of different types of plasmas, e.g., aeronomy [1] and astrophysical plasmas [2,3]. For collisions of singly charged N^+ ions with N_2 targets, several experimental studies [4–12] have been performed at low-keV energies. Phelps [9] made a data compilation and pointed out that there still exist large discrepancies among cross-section data for the charge transfer process, and that there might be ascribed partly to the use of different experimental apparatus and measurement techniques. The survey also suggest that much additional work is necessary in order to obtain accurate data below 1 keV energies where cross-section measurements are difficult to perform with standard beam techniques. Therefore, it is important to carry out additional measurements for the N^+–N_2 collisions at lower energies using a different experimental technique. Differential cross-section (DCS) is an alternative way of studying such reaction. In this work, we have reinvestigated the following reaction:

$$N^+ + N_2 \rightarrow N^0 + \cdots$$

and present absolute measurements of the differential and total cross-sections. The energy range covered by the present experimental study is 0.5–5.0 keV.

2. Experiment

Details of the experimental arrangement have been given previously [13,14], so only a brief description

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of the experimental setup will be given here. N^+ ions were formed in an arc discharge source containing N_2 gas (99.99% purity) at ion source pressures of 0.04–0.07 mTorr. Ions were extracted and accelerated in the energy range of 0.5–5.0 keV. The N^+ beam is passed through an Einzel-type lens and directed to a Wien velocity filter in order to obtain an analyzed beam at the desired velocity. Next, the N^+ ions are passed between cylindrical electrostatic deflection plates that were used both to steer the beam and to bend it by 10° to prevent photons in the ion source from reaching the detection system. Following that, the collimated N^+ beam entered the scattering chamber, which housed a gas target cell where capture phenomena to form N^0 took place. The gas target cell was a 2.54 cm long cylinder and of 2.54 cm diameter in which the target gas pressure (typically 0.4 mTorr) was measured with a calibrated MKS capacitance manometer (model 270C). The entrance aperture was 1 mm in diameter and the exit aperture was 2 mm wide and 6 mm long. This geometry permitted the measurements of the N^0 particles, the directions of which make an angle of up to ±7° with respect to the incoming beam direction. Path lengths and apertures gave an overall angular resolutions of the system of 0.1°. All apertures and slits have knife edges. The cell target was located at the center of a rotatable, computer-controlled vacuum chamber that moved the whole detector assembly, which was located 47 cm away from the target cell. A precision stepping motor ensured a high repeatability in the positioning of the chamber over a large series of measurements. The detector assembly consisted of a Harrower-type parallel plate analyzer with a 0.36 mm entrance aperture and two channel-electron multiplier (CEM) attached to its exit end. The beam entered the uniform electric field of the analyzer at an angle of 45°. The neutral beam (N^0) passed straight through the analyzer through a 1 cm orifice on its rear plate and impinged on a CEM so that the neutral counting rate could be measured. Separation of charged particles occurred inside the analyzer, which was set to detect the N^+ ions with the lateral CEM. The multiplier counting efficiencies for N^0 were assumed to be the same as H^+ at the same energy [15]. A retractable Faraday cup was located 33 cm away from the target cell, allowing the measurement of the incoming N^+ ion-beam current. A Keithley Instruments Electrometer model 610C was used to measure the beam current entering the Faraday cup. Vacuum base pressures in the system were 2.0×10^{-7} Torr without gas in the cell and 1.0×10^{-6} Torr with gas.

Thin target conditions were used in this experiment, the differential cross-sections for the formation of N^0 was evaluated from the measured quantities by the following expression:

$$\frac{d\sigma}{d\Omega} = \frac{I(\theta)}{nLI_0} \quad (1)$$

where I_0 is the number of N^+ ions incident per second on the target, n the number of target atoms per unit volume, L the length of the scattering chamber, and $I(\theta)$ is the number of N^0 particles per unit solid angle per second detected at a laboratory angle θ with respect to the incident beam direction. The total cross-section for the production of the N^0 particles was obtained by the integration of $d\sigma/d\Omega$ over all measured angles; i.e.

$$\sigma = 2\pi \int_0^{\theta_{max}} \frac{d\sigma}{d\Omega} \sin(\theta)\, d\theta \quad (2)$$

For $\theta > \theta_{max}$ the differential cross-sections drop below the experimental detection limit.

Care was taken when the absolute differential cross-section was measured. The reported value of the angular distribution was obtained by measuring it with and without gas in the target cell with the same steady beam. Then point-to-point subtraction of both angular distribution was carried out to eliminate the counting rate due to neutralization of the N^+ beam on the slits and those arising from background distributions. The N^+ beam intensity was measured before and after each angular scan. Measurements not agreeing to within 5% were discarded. Angular distributions were measured on both sides of the forward direction to assure they were symmetric. The estimated RMS error is 15%, while the cross-sections were reproducible to within 15% from day-to-day.

Several runs were made at different gas pressures and $d\sigma/d\Omega$ was determined for each run. These were compared in order to estimate the reproducibility of the experimental results as well as to determine the limits of the 'single-collision regime' since the differential and total cross-sections reported are absolute.

In the present work changes were not observed in the absolute values with respect to the different ion source conditions. Also, no variation in the distributions were detected over a target pressure range of 0.2–0.6 mTorr.

3. Results and discussion

Measurements of DCS were performed at laboratory angles of $-3.5^\circ \leq \theta \leq 3.5^\circ$ and collision energies of $0.5 \leq E_{lab} \leq 5.0$ keV. Angular distributions of one electron charge transfer in the laboratory systems for N^+ in N_2 are presented in Fig. 1. The curves representing the DCS for the different energies have an overall increase of at least one order of magnitude and they all have a rather similar behavior.

The measured differential cross-section for single electron capture of N^+ impacting on N_2 were integrated over the observed angular range. The trend of these data together with previous experimental data over a wide range of energy as a function of the incident energy is shown in Fig. 2. The cross-sections measured in this work are found to vary between 10^0 and 10^1 Å^2. Error bars are given as an indication of the maximum reproducibility of the data in the present energy range. It is important to mention that existing experimental information [16] indicates that only one metastable state is present in the N^+ ion beam produced in single electron–molecule collisions for electrons having energies up to 100 eV. At 100 eV ionizing electron energy only the lowest metastable $N^+(^1D)$ ion state is present in beams produced via ionization fragmentation of N_2 and that metastable state has a relative abundance of 0.15 in the ion beam [16]. This state distribution was found to be constant for electron energies in excess of 35 eV [16]. Also, it is to

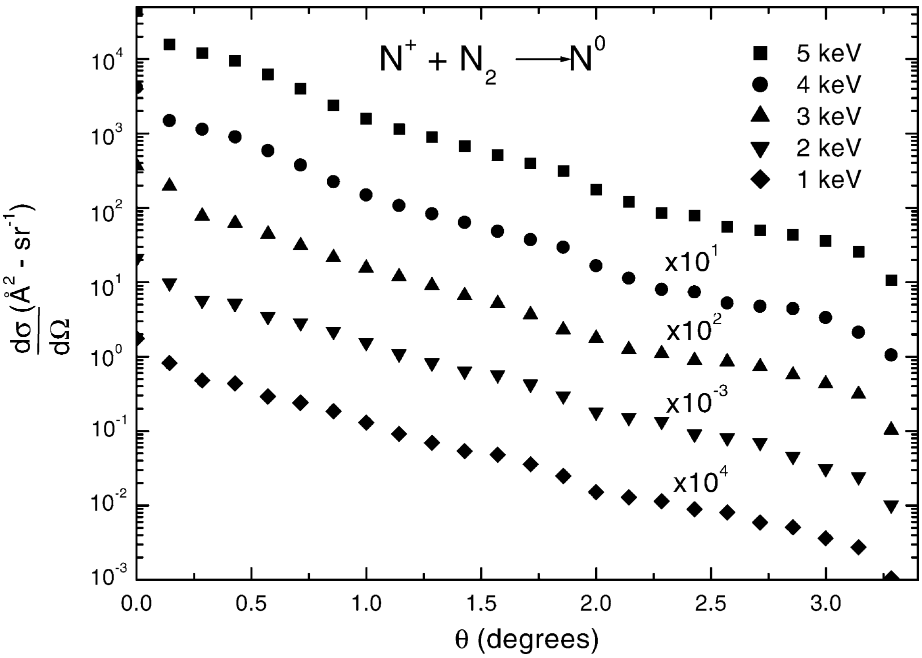

Fig. 1. Differential cross-sections for single electron capture of N^+ ions in N_2.

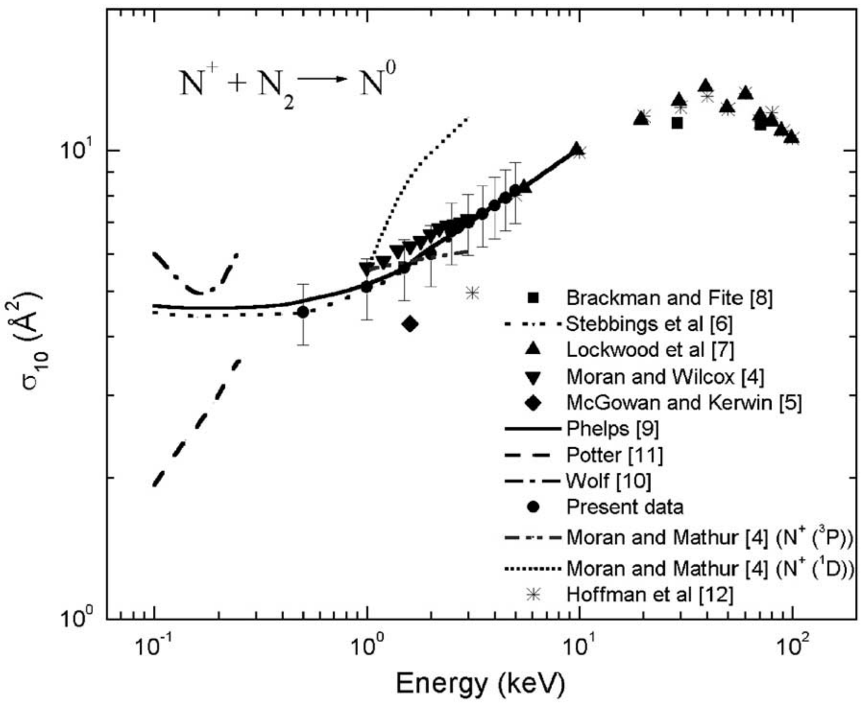

Fig. 2. Total cross-sections for single electron capture of N^+ ions in N_2.

be noted that electronically excited $N^+(^1D)$ ion can be de-excited by inelastic processes occurring in the ion source operated at high pressures [16]. However, our ion source operating at 10^{-5} Torr pressures and 50 eV ionizing electron energy indicate that the state distribution of our N^+ ion beam is approximately 85% formed in the $N^+(^3P)$ ground state and 15% in the $N^+(^1D)$ metastable state. These effects can be seen in Fig. 2, from the Moran and Mathur [4] results, the charge transfer process which has a large cross-section is for reactions involving an excited state and a small cross-section for reactions of ground state ions, while for the data of Stebbings et al. [6], Lockwood et al. [7], Moran and Wilcox [4], and McGowan and Kerwin [5] which are measured for ions with a mixed state ($N^+(^3P)$ and $N^+(^1D)$) distribution (MSD) are close or lower to the results with ions in the ground state (GSD). The rather large differences observed in Fig. 2 between charge transfer cross-sections using ions in the ground state and ions with a mixed state distribution illustrate the importance of the incident ion electronic state population distribution on the N^+ charge transfer reaction. We can see from Fig. 2 that our data merge smoothly with the results of Lockwood et al. [7] at high energy. The present data (MSD) are in excellent agreement with the data (MSD) of Stebbings et al. [6] at all the collision energies studied in this work. The Phelps recommended cross-section data [16] is slightly higher than the present data, but within the experimental uncertainty at energies below 1.0 keV, while at energies above 1.0 keV the agreement is excellent. The data (MSD) of Moran and Wilcox [4] are slightly more higher than the present data, but within the experimental uncertainty at energies below 2.5 keV, while at 3.0 keV the agreement is excellent. The data (MSD) of McGowan and Kerwin [5] are approximately lower than the present data by a factor of 1.3. Hoffman et al. [12] have also measured the one-electron capture by ground state of N^+ in N_2 in the energy range from 3 to 100 keV. Their results at 3 keV is lower than the present results by approximately a factor of 1.4, while their data at 5 keV is in excellent agreement with the present data. Also, the present results merge smoothly with the results of Hoffman et al. [12] at energies above 5 keV. The charge transfer cross-section involving ground-state ions of $N^+(^3P)$ in collisions with N_2 measured by Moran and Mathur [4] are in good agreement with the present data within the experimental uncertainty, while their charge transfer cross-section for the excited metastable ions $N^+(^1D)$ are considerably larger than the present data and previous results using GSD [4] and MSD [4–6].

As can be seen from Fig. 2, these data show no difference between the cross-section obtained with GSD and MSD, which suggest that the percentage of metastable states contained in the ion beam of the MSD should be small enough to be neglected. The data of Stebbings et al. (MSD) [6], Phelps [9], Moran and Wilcox (MSD) [4], Lockwood et al. (MSD) [7], Hoffman et al. (GSD) [12] (at energies above 5 keV) and present data give a general shape of the whole curve of the single electron capture cross-sections for the N^+–N_2 system over a wide range of energies (0.1–100 keV).

4. Conclusions

We have presented values of absolute differential and total cross-sections for single electron capture of N^+ in N_2 at impact energies between 0.5 and 5.0 keV. The results of the present work can be summarized as follows:

(a) The differential cross-sections shows an overall increase of at least one order of magnitude and a monotonic decreasing behavior at all the collision energies studied in this work.

(b) The total cross-section for single electron capture is compared with previous experimental measurements. The total cross-section results presented in this paper and obtained by integration of the measured differential cross-sections agree with previous measurements using a beam of pure ground state ions. These results are consistent with the general shape of the whole curve of the single electron capture cross-sections.

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