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Experimental investigation of the formation of N atoms in N^+–Ne, Kr, and Xe collisions

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Abstract

Total cross sections for single electron capture by N^+ ions impinging on Ne, Kr, and Xe were measured in the energy range of 1.0–5.0 keV. The electron capture cross sections for all the targets studied are found to be in excellent agreement with previous data in the low-energy range. These results give a general shape of the whole curve of single electron capture cross sections for the N^+–Ne system over a wide range of energy. For the cases of N^+–Kr and N^+–Xe systems, semiempirical calculation using the two-state approximation are in very good agreement with present cross-section data. (Int J Mass Spectrom 208 (2001) 81–88) © 2001 Elsevier Science B.V.

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1. Introduction

Currently there is much interest in electron capture processes in astrophysics [1–4] and plasma research [5], in particular fusion reactor design, where currently the emphasis is on atomic collisions in the divertor region [6]. With high probability, electrons are transferred quasiresonantly into excited states of the ion. Earlier studies involving electron capture by N^+ ions in collisions with atomic targets were concerned with total cross-section measurements in the low and intermediate energy range. Pivovar et al. [7] carried out measurements of single electron capture of N^+ in Ne, Ar, and Xe atoms in the energy range 250–1400 keV. Vujović et al. [8] measured the single electron capture cross section in the energy range 2–30 keV for ground-state N^+ ions and 5–20 keV for metastable state N^+ ions in collisions with inert gases. Lo and Fite [9] wrote a review article on single electron capture cross sections of N^+ ions passing through gases. Fedorenko [10] reported measurements of single electron capture cross sections of N^+ ions on Ar and Xe, for energies between 5 and 30 keV. Matić et al. [11] investigated experimentally and calculated theoretically the total charge-transfer cross sections for ground-state and metastable N^+ ions colliding with inert gas atoms. Identification of the various direct and exchange processes was achieved using energy loss techniques by Thielmann et al. [12] in the 500–2000 eV energy range.

In the present work, an experiment is carried out

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for the measurements of the charge transfer cross sections of N^+ incident on rare gases such as Ne, Kr, and Xe. Data were measured for 1.0–5.0 keV and over the angular range of $|\theta| \leq 4.0°$.

2. Experiment

The experimental apparatus and technique needed to generate the fast ion beam were recently reported [13]. Briefly, the N^+ ions formed in an arc discharge source containing N_2 gas (99.99% purity) at ion source pressures of 0.04–0.07 mTorr were accelerated to 1.0–5.0 keV and selected by a Wien velocity filter. In experiments of this nature the electron energy must however, be kept low enough to prevent formation of N_2^{2+} in the ion source. The N^+ ions were then allowed to pass through a series of collimators before entering the gas target cell, which was a cylinder of 2.5 cm in length and diameter, with a 1 mm entrance aperture, and a 2-mm-wide, 6-mm-long exit aperture. The target cell 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 and two channel-electron multipliers (CEMs) attached to its exit ends. The neutral beam (N^0) passed straight through the analyzer and impinged on a CEM so that the neutral counting rate ($I_f(\theta)$ particles per unit solid angle per second detected at a laboratory angle θ with respect to the incident beam direction) could be measured. Separation of charged particles occurred inside the analyzer, which was set to detect the N^+ ions with the lateral CEM. The CEMs were calibrated in situ with low-intensity N^0 and N^+ beams, which were measured as a current in a Faraday cup by a sensitive electrometer. The uncertainty in the detector calibration was estimated to be less than 3%. A retractable Faraday cup was located 33 cm away from the target cell, allowing the measurement of the incoming N^+ ion-beam current (I_0 is the number of N^+ ions incident per second on the target).

Under the thin target conditions used in this experiment, the differential cross sections for the N^0 formation were evaluated from the measured quantities by

$$\frac{d\sigma(\theta)}{d\Omega} = \frac{I_f(\theta)}{I_0\, nl}$$

where n is the number of target atoms per unit volume (typically 1.2×10^{13} atoms/cm^3) and l is the length of the scattering chamber ($l = 2.5$ cm). Laboratory angular distributions were measured over the range $\pm 4°$ in steps of 0.15°.

The total cross section σ_{10} for the production of the N^0 particles was obtained by the numerical integration of $d\sigma/d\Omega$ over all angles measured; this is

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

For $\theta > \theta_m$ the differential cross sections vanish.

Extreme 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 substraction of both angular distributions 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 scan. Measurements not agreeing to within 5% were discarded. Angular distributions were measured on both sides of the forward direction to ensure they were symmetric.

The estimated rms error is 15%, whereas the total cross sections were reproducible to within 15% from day to day. Changes were not observed in the absolute differential and total cross sections values with respect to the ion source conditions. Also, no variation in the distributions was detected over a target pressure range of 0.2–0.6 mTorr.

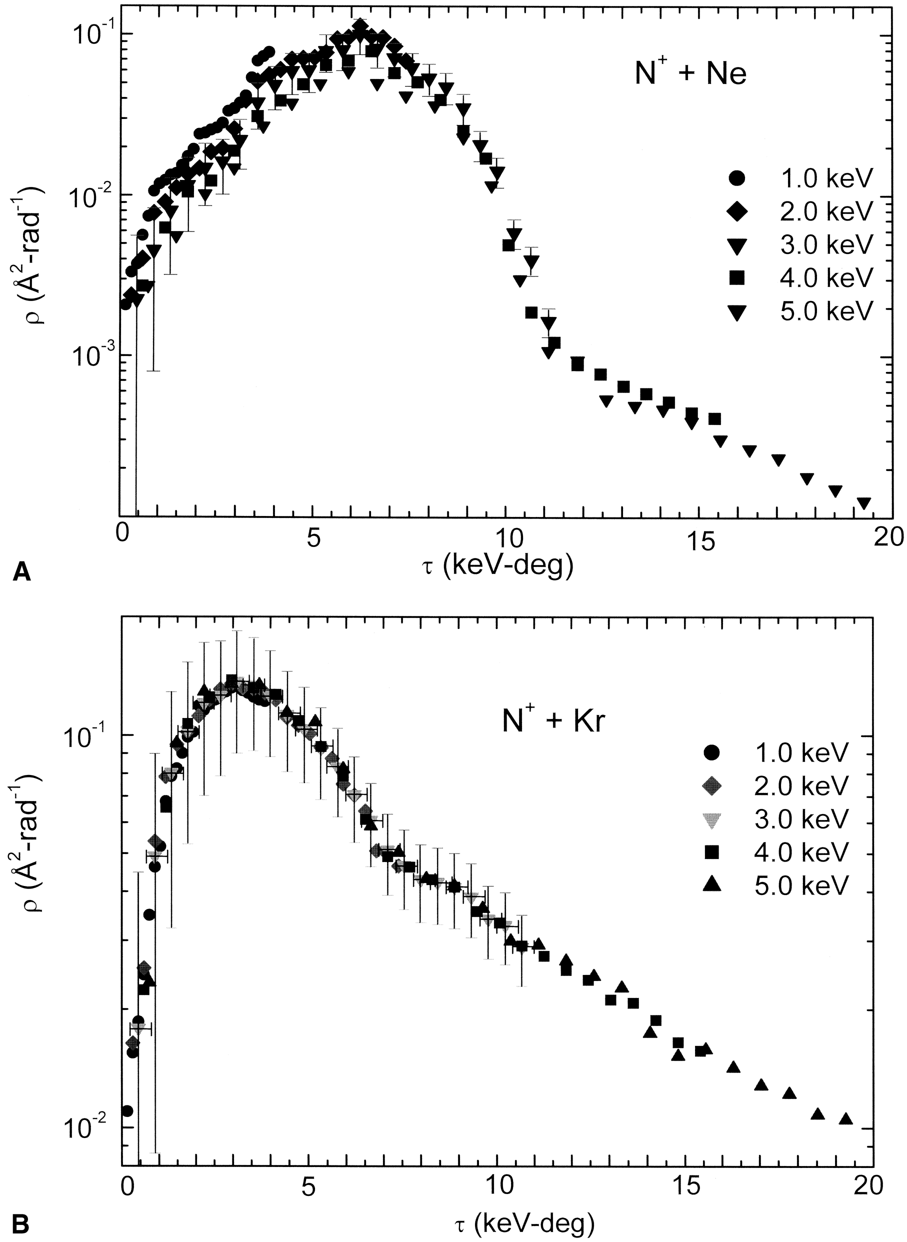

Fig. 1. Reduced differential cross sections for single electron capture of N^+ ions in (a) Ne, (b) Kr, and (c) Xe.

Several sources of systematic errors are present and have been discussed in a previous paper [14]. The absolute error of the reported cross sections is believed to be less than ±15%. This estimate represents both random and systematic errors.

3. Results and discussions

In Fig. 1(a)–(c), we show the angular and energy dependence (the reduced differential cross sections (RDCS) $\rho = (d\sigma/d\Omega)\theta \sin(\theta)$) of the single electron

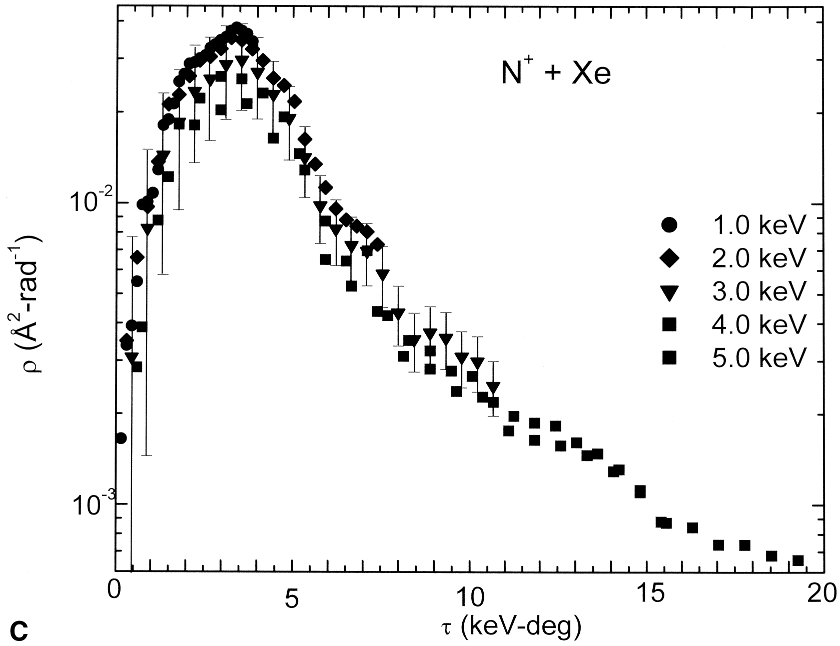

Fig. 1. (Continued)

capture differential cross section in the laboratory system for the N^+–Ne, N^+–Kr, and N^+–Xe systems, respectively, at several energies, where the abscissa is the reduced angle $\tau = E_{lab}\theta$. For clarity in Fig. 1(a)–(c), error bars were put only on the data of 3 keV. In this normalized form, all electron capture data for a charged particle would fall on a general curve that is described only by a given velocity-independent interaction potential and each τ value thus belonging to a certain value of the collisional impact parameter b. Data taken at different energies and plotted in (τ,ρ) coordinates should then fall on a single curve. For the N^+–Ne system (Fig. 1(a)), the curves representing the RDCS for the different energies studied in this work have an overall increase of two orders of magnitude. This is followed by a structure and a decrease beyond 6.33 keV deg. At all the energies studied $\rho(\tau)$ has a rather similar behavior within the experimental uncertainty; although for the two lowest energies study in this work (1.0 and 1.5 keV), the structure cannot be observed, due to the largest value of τ observed are 4 and 6 keV deg, respectively. The general behavior for these curves displays a tendency to fall into a single pattern. For N^+–Kr system (Fig. 1(b)), the curves representing the RDCS for the different energies have an overall increase of one order of magnitude. At all the energies studied $\rho(\tau)$ has a rather similar behavior within the experimental uncertainty; the general behavior for these curves show a tendency to fall into a single pattern. The results have a structure at 3.25 keV deg and decrease beyond that value of τ. For the N^+–Xe system (Fig. 1(c)), several remarkable features can be observed which are worth pointing out: (a) $\rho(\tau)$ shows a similar behavior at all energies within the experimental uncertainty; (b) it increases up to 3.70 keV deg by one order of magnitude. This is followed by a maximum and decrease beyond 3.70 keV deg. The features that occur at the same value of τ for different energies indicate that they originate at a common region of the interaction potential, since constant τ implies nearly constant impact parameter and distance of closest approach [15]. In this particular case, the impact parameter b was evaluated using an exponentially shielded coulomb potential [15,16]. In the present case, the experimental results for the N^+–Ne system present a maximum at 6.33 keV deg

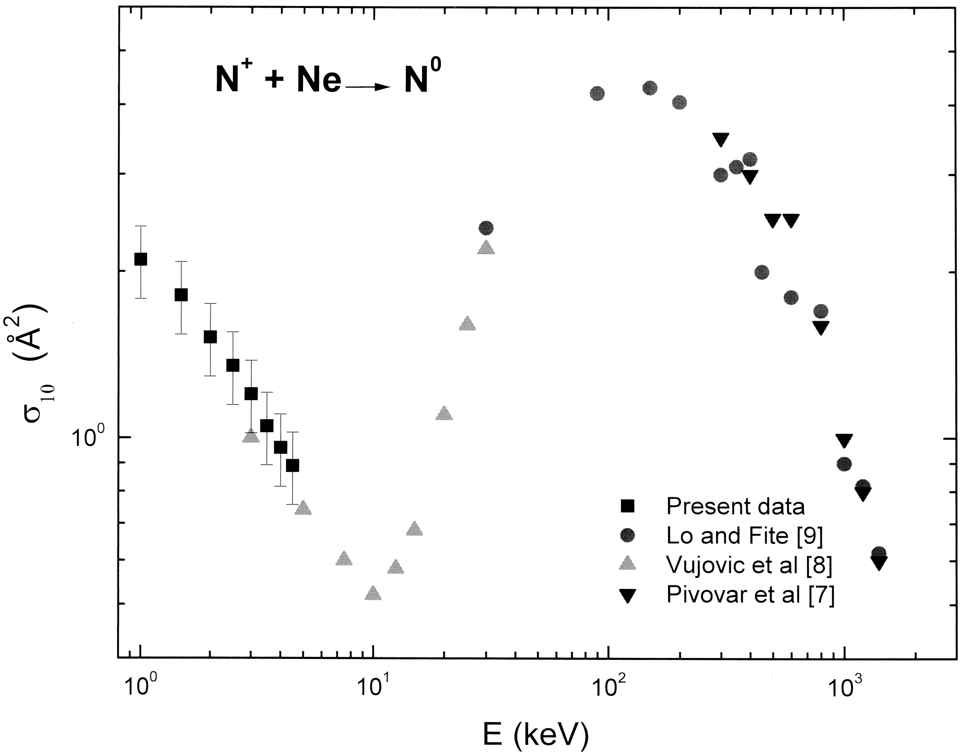

Fig. 2. Total cross sections for single electron capture of N^+ ions in Ne.

(corresponding to the impact parameter $b = 3.44a_0$); for the N^+–Kr shows a maximum at 3.25 keV deg ($b = 3.15a_0$) and for the case of N^+–Xe system display a maximum at 3.70 keV deg ($b = 2.93a_0$). The impact parameter estimated through the exponentially shielded coulomb potential is probably not accurate, but it is sufficient for the present purpose. These results suggest that when the N^+ projectile penetrates below a critical projectile–target separation (here corresponding to $b = 3.44a_0$ for Ne target; $b = 3.15a_0$ for Kr case and $b = 2.93a_0$ for Xe) the electron capture channel "opens." It is not possible at this time to identify the specific channels.

The measured RDCS for single electron capture of N^+ impacting on Ne, Kr, and Xe gases were integrated over the observed angular range. Figs. 2–4 show a comparison of our values of the total cross sections for the three collision systems with the data of various other groups. The error bars are given as an indication of the maximum reproducibility of the data in the present energy range (15%).

The energy dependence of the total single electron capture cross section for an N^+ ion colliding with Ne is shown in Fig. 2 and exhibits a monotonic decreasing behavior as a function of the incident energy at energies below 10 keV. The present data confirm this behavior, which was first observed by Vujović et al. [8]. Our data agree well with the measurements of Vujović et al. [8] in the overlapping region and merge smoothly into de cross sections measured by Vujović et al. [8] and Lo and Fite [9] at energies greater than 5.0 keV. The behavior at energies below 10 keV has been explained by Vujović et al. [8] as due to a pseudocrossing between the potential curves of the $(NeN)^+$ system, which has been confirmed by the behavior observed in the RDCS of this work. The shapes of the cross sections of the four sets of data (Lo and Fite [9], Vujović et al. [8], Pivovar et al. [7], and

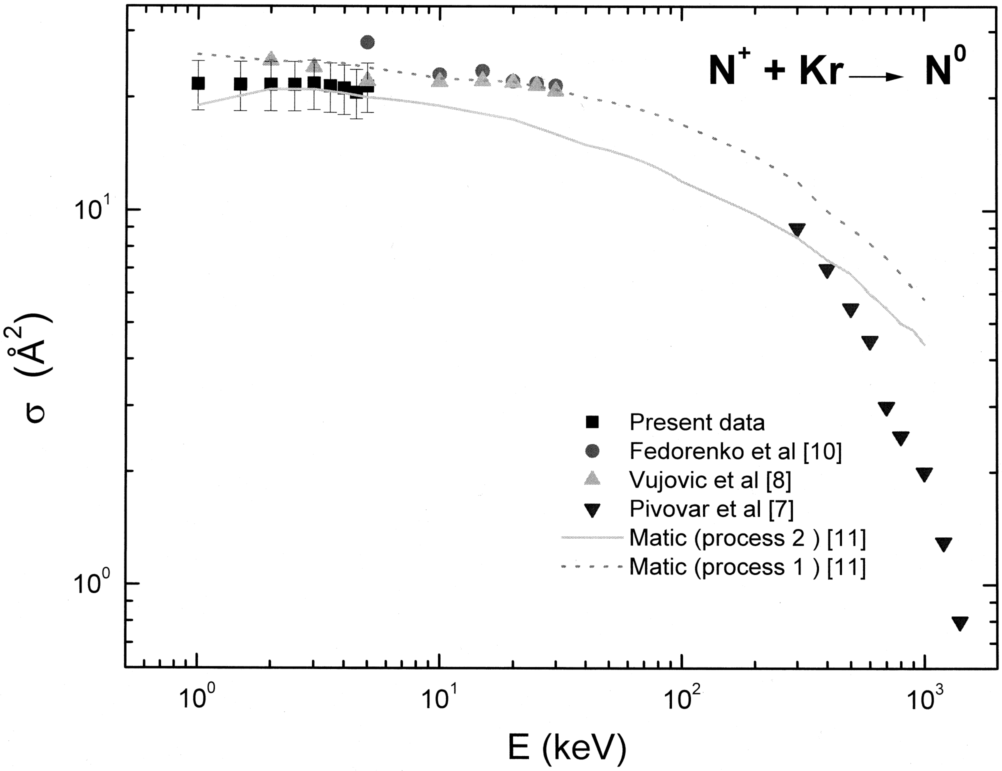

Fig. 3. Total cross sections for single electron capture of N^+ ions in Kr.

present data) indicate that the data from all the four measurements are mutually consistent. These results give a general shape of the whole curve of single electron capture cross sections for the N^+–Ne system over a wide range of energies (1.0–1400 keV).

It can be seen from Fig. 3 that the shape of the cross section for an N^+ ion colliding with Kr shows an almost flat behavior as a function of the incident energy over most of the energy range. Our data were found to be in excellent agreement with the data of Vujović et al. [8] and merge smoothly into the cross sections measured by Vujović et al. [8] and Fedorenko [10] at energies greater than 5 keV. Also, the present data are in very good agreement with the theoretical calculation of Matić et al. [11], who used the two state approximation considering the processes:

$$N^+(^1D) + Kr(^1S) \rightarrow N(^2D) + Kr^+(^2P)$$

(broken line in Fig. 3) (1)

$$N^+(^3P) + Kr(^1S) \rightarrow N(^4S) + Kr^+(^2P)$$

(solid line in Fig. 3) (2)

which are near-resonant processes due to their energy defect 0.05 and 0.54 eV, respectively. The theoretical calculations agree well with the present measurements, which lie between the experimental errors, however the present data are over all the theoretical calculation of the process (2) in the present energy range.

For N^+–Xe systems, the total cross sections show a monotonic decreasing behavior as a function of the incident energy (see Fig. 4). The present data agree well and merge smoothly into the cross sections measured by Vujović et al. [8]. The present data agree well with the calculation of Matić et al. [11], who used the two state approximation considering the process:

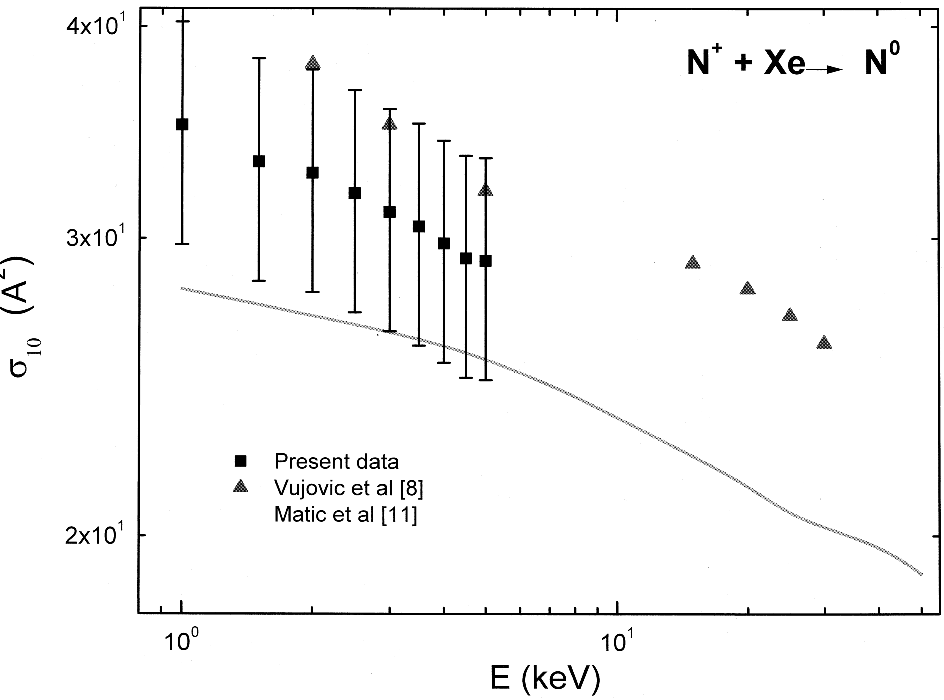

Fig. 4. Total cross sections for single electron capture of N^+ ions in Xe.

$$N^+(^3P) + \mathrm{Xe}(^1S) \rightarrow \mathrm{N}(^4S) + \mathrm{Xe}^2P)$$

(solid line in Fig. 4) (3)

At energies above 3 keV, the calculation is within the experimental error, whereas the present data are slightly over the theoretical values at energies below 3 keV, however the agreement between them is reasonable.

4. Summary

The results of the present work can be summarized as follows. (1) Differential and total cross sections for electron capture in N^+–Ne, Kr, and Xe collisions were measured at laboratory energies between 1.0 and 5.0 keV. (2) The electron capture cross sections for all the targets studied are found to be in excellent agreement with previous data. (3) For the cases of N^+–Kr and N^+–Xe systems the theoretical calculation of Matić et al. [11] are in very good agreement with our experimental data.

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