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State-selective electron capture by slow N^{4+} ions in collisions with helium

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Abstract. Translational energy spectroscopy in an apparatus previously developed in this laboratory has been used to study one-electron capture by 4–28 keV N^{4+} ions in collisions with helium. The main excited N^{3+} product channels have been clearly identified and the relative cross sections determined. The two main channels are found to involve core rearrangement. While the N^{3+} $2p^2\,{}^1S$ product channel is dominant, it is shown that other channels involving large energy defects contribute significantly at the higher energies thereby resulting in an essentially energy invariant total one-electron capture cross section: MCLZ calculations, which have also been carried out, satisfactorily predict the main $2p^2\,{}^1S$ product channel but fail to account for the other channels arising from curve crossings at small internuclear separations.

1. Introduction

In previous work in this laboratory (cf Wilkie *et al* 1986, Wilson *et al* 1988) we have used the technique of translational energy spectroscopy (TES) to study one-electron capture in collisions between multiply charged ions and simple atoms including atomic hydrogen. In slow collisions of this type at impact velocities $v<1$ au, where a quasi-molecular description is appropriate, electron capture may take place selectively through pseudocrossings of the potential energy curves describing the initial and final molecular systems. These crossings occur at internuclear separations $R_c \simeq (q-1)/\Delta E$ (neglecting polarization) where ΔE is the energy defect for the particular collision channel for a projectile ion of charge q. TES studies allow the main excited product states to be identified and the relative formation cross sections to be determined. Apart from leading to a better understanding of such collisions, such measurements can provide data directly relevant to the diagnostics of fusion plasmas (cf Drawin and Katsonis 1981) and to an understanding of astrophysical plasmas (cf Péquignot 1978).

In the present work we have carried out TES studies of one-electron capture

$$N^{4+} + He \rightarrow N^{3+}(n, l) + He^{+}(n', l') \tag{1}$$

by lithium-like nitrogen ions in collisions with helium. The main excited product channels leading to N^{3+} and He^{+} in specified states have been identified and the separate cross sections determined within the energy range 4–28 keV. Total cross sections for

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one-electron capture in N^{4+}–He collisions have been measured by Hoekstra *et al* (1987) in the range 3.5–27.9 keV and by Iwai *et al* (1982) in the range 6.0–9.9 keV. However in the only previous TES studies of (1) carried out by Kimura *et al* (1982) which were limited to the single energy of 4 keV the energy resolution was insufficient to clearly identify all the collision product channels.

2. Experimental approach

The translational energy spectrometer and the measurement and calibration procedure have been described in detail previously (Wilkie *et al* 1986, Wilson *et al* 1988) so that only a summary of the main features need be given here.

A momentum analysed beam of N^{4+} ions derived from an electron cyclotron resonance ion source and accelerator system was focused and decelerated to 480 eV before being passed through a pair of hemispherical analysers to reduce the energy spread to about 2 eV FWHM. After focusing, the beam was accelerated to the required final energy within the range 4–28 keV and arranged to pass through two diametrically opposed apertures in the target gas cell. The fast forward scattered N^{3+} ions (within a mean half angle of 0.5°) arising from one-electron capture were energy analysed by passage through a hemispherical electrostatic analyser and then recorded as individual particle counts by a computer controlled position-sensitive detector.

The measured difference ΔT between the kinetic energy T_1 of the primary N^{4+} ion and the kinetic energy T_2 of the product N^{3+} ion can be expressed as

$$\Delta T = T_2 - T_1 = \Delta E - \Delta K \tag{2}$$

where ΔK is a small target recoil correction. Provided that $\Delta E/T_1 \ll 1$ and the scattering is confined to small angles (McCullough *et al* 1984), $\Delta T \simeq \Delta E$. Thus an analysis of the N^{3+} yields in the observed energy change spectra provides, within the available energy resolution, relative cross sections for particular excited product channels. Careful checks were made to ensure that the N^{3+} product yields corresponding to each collision channel were linearly dependent on the target gas thickness thereby indicating single collision conditions.

The energy scale on our measured energy change spectra was calibrated by reference to our previous data for Ar^{4+}–He collisions (McCullough *et al* 1987) while energy defects ΔE for possible product channels were determined by reference to the energy level compilations of Bashkin and Stoner (1978) and Kelly (1982).

3. Results and discussion

Energy change spectra for one-electron capture by N^{4+} ions in He at 4, 16 and 28 keV are shown in figure 1. At 28 keV five clearly discernible peaks A, B, C, D and E are evident but at 4 keV only peaks A and B are significant. The collision channels corresponding to these peaks are identified in table 1.

All the observed product channels involve ground state $He^{+}(1s)$ formation. The main N^{3+} product channel (corresponding to peak A) leading to the ^1S state involves 2p capture simultaneous with 2s→2p excitation. A similar two-electron process accounts for peak B which appears to be dominated by the N^{3+} ^1D product channel. Although the energy defects for the channels corresponding to peaks C, D and E are very large,

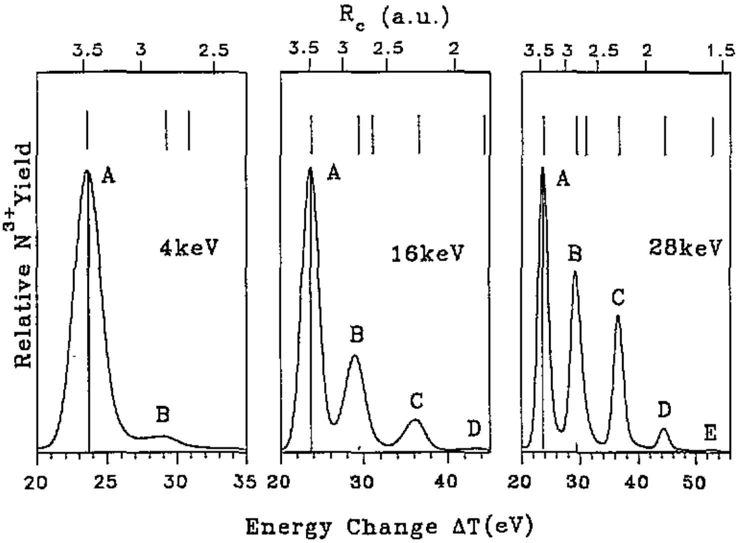

Figure 1. Energy change spectra for one-electron capture by 4 keV, 16 keV and 28 keV N^{4+} ions in helium. Energy defects corresponding to possible N^{3+} excited product states (table 1) are indicated. Vertical lines indicate results of MCLZ calculations for collision channels (see text).

contributions can be seen (figure 1) to become progressively more important with increasing energy. Channels C and D involve 2p capture leading to the ^1P and ^3P states of N^{3+} respectively whereas channel E involves 2s capture leading to a ^1S state. Our measurements provided no evidence of any significant contributions to one-electron capture arising as a result of two-electron capture into states which undergo autoionization.

There have been no detailed theoretical studies of one-electron capture in N^{4+}–He collisions. We have therefore carried out multichannel Landau–Zener (MCLZ) calculations using a method which we have described in detail previously (Wilson *et al* 1988) to calculate cross sections for individual product channels. The method utilizes a probability accumulation procedure (cf Janev and Winter 1985) and an expression given by Taulbjerg (1986) which allows for the l dependence of the coupling element H_{12} at the pseudo-crossing of the adiabatic curves. The results of our MCLZ calculations for individual product channels are included in figure 1 as vertical lines the heights of which are proportional to the magnitude of individual cross sections. To facilitate comparison with experiment the largest cross section has been normalized to the maximum peak

Table 1. Collision product channels for one-electron capture by $N^{4+}(1s^22s)^2S$ ions in collisions with helium.

Peak designation	Product channels	ΔE (eV)	R_c (au)
A	$N^{3+}(1s^22p)2p\ ^1S + He^+(1s)$	23.7	3.4
B	$N^{3+}(1s^22p)2p\ ^1D + He^+(1s)$	29.5	2.8
	$N^{3+}(1s^22p)2p\ ^3P + He^+(1s)$	31.1	2.6
C	$N^{3+}(1s^22s)2p\ ^1P + He^+(1s)$	36.7	2.2
D	$N^{3+}(1s^22s)2p\ ^3P + He^+(1s)$	44.5	1.8
E	$N^{3+}(1s^22s)2s\ ^1S + He^+(1s)$	52.9	1.5

height in each of the spectra in figure 1. It can be seen that the calculations correctly predict the main $N^{3+}(1s^2 2p)2p\ ^1S$ product channel corresponding to peak A. However the relative cross section for $N^{3+}(1s^2 2p)2p\ ^1D$ production corresponding to B is much smaller than that observed. In addition, the MCLZ calculations fail to predict significant cross sections for the channels corresponding to peaks C, D and E which involve very small crossing distances R_c.

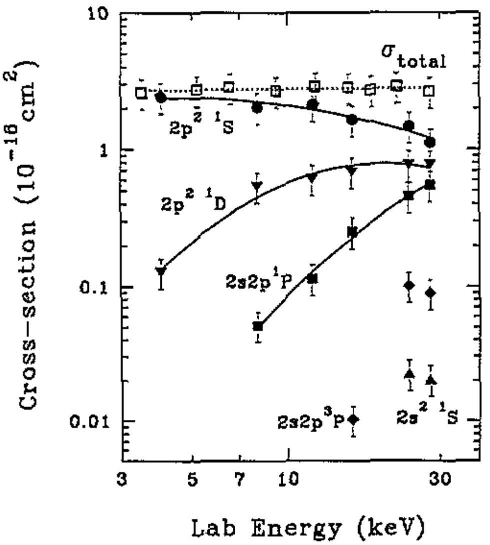

Figure 2. Cross sections for one-electron capture by N^{4+} ions in collisions with helium. □, total electron capture cross sections σ_{43} measured by Hoekstra *et al* (1987). ●, ▼, ■, ◆, ▲ ; cross sections for electron capture into $2p^2\ ^1S$, $2p^2\ ^1D$, $2s2p\ ^1P$, $2s2p\ ^3P$ and $2s^2\ ^1S$ states of N^{3+}, respectively; present data obtained by normalization of the measured relative cross sections to total one-electron capture cross sections measured by Hoekstra *et al* (1987).

In figure 2 are shown total cross sections σ_{43} for one-electron capture by N^{4+} ions in He in the range 3.5–27.9 keV measured by Hoekstra *et al* (1987) taken from the compilation of Wu *et al* (1989). Our calculated MCLZ values of σ_{43} (not shown) range from 5% at 4 keV to 82% at 28 keV of these measured cross sections. We have normalized our measured total N^{3+} yields obtained from our measured energy change spectra to the total cross sections σ_{43} measured by Hoekstra *et al* (1987). A simple deconvolution procedure (see McCullough *et al* 1984) was then used to derive the separate cross section for N^{3+} formation in the $2p^2\ ^1S$, $2p^2\ ^1D$, $2p\ ^1P$ and $2s2p\ ^3P$ states. These values which are shown in figure 2 are also tabulated in table 2. The indicated uncertainties represent the root mean values of the quadrature sum of errors involved in the deconvolution procedure and those associated with the measurements of σ_{43}.

While $2p^2\ ^1S$ formation provides the main contribution to σ_{43}, it is evident from figure 2 that the collision channels involving larger energy defects compensate for the fall in the $2p^2\ ^1S$ cross section at high energies thereby resulting in total cross sections σ_{43} which are essentially energy invariant over the range considered.

Table 2. Cross sections for excited product channels in one-electron capture by N^{4+} ions in collisions with helium obtained by normalization of measured relative cross sections to total one electron capture cross sections measured by Hoekstra *et al* (1987).

	Cross section (10^{-16} cm^2)					
Products	4 keV	8 keV	12 keV	16 keV	24 keV	28 keV
$N^{3+}(1s^22p)2p\ ^1S + He^+(1s)$	2.44±0.3	2.04±0.3	2.12±0.27	1.65±0.2	1.48±0.18	1.12±0.14
$N^{3+}(1s^22p)2p\ ^1D + He^+(1s)$	0.129±0.016	0.540±0.068	0.610±0.076	0.686±0.086	0.770±0.097	0.772±0.097
$N^{3+}(1s^22s)2p\ ^1P + He^+(1s)$		0.051±0.006	0.114±0.014	0.252±0.032	0.456±0.057	0.549±0.069
$N^{3+}(1s^22s)2p\ ^3P + He^+(1s)$				0.010±0.001	0.101±0.013	0.089±0.011
$N^{3+}(1s^22s)2s\ ^1S + He^+(1s)$					0.022±0.003	0.020±0.003

4. Conclusions

Our TES measurements for one-electron capture by N^{4+} ions in collisions with helium in the range 4–28 keV have allowed the excited N^{3+} product channels to be clearly identified for the first time and the relative cross sections determined. The results show that the previously measured total cross sections contain contributions from several well separated collision channels involving large energy defects. The two main channels leading to $N^{3+}(1s^22p)2p$ formation involve core rearrangement wheras in the other channels the core is conserved. While our MCLZ calculations correctly identify the dominant N^{3+} $2p^2\ ^1S$ product channel, the calculations fail to account for the significant contributions made by the other measured collision channels which involve curve crossings corresponding to relatively small internuclear separations R_c.

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