# **Studies of Electron Capture by Multiply Charged Ions from Molecules using Translational Energy Spectroscopy**

D.M. Kearns, R.W. McCullough\* and H.B. Gilbody

Atomic and Molecular Physics Research Division, School of Mathematics and Physics, Queen's University Belfast, Belfast BT7 1NN, N. Ireland, U.K. rw.mccullough@qub.ac.uk \*Author to whom correspondence should be addressed.

Received: 14 December 2001 / Accepted: 30 January 2002 / Published: 28 March 2002

**Abstract:** Both single (TES) and double (DTES) translational energy spectroscopy has been used to study one-electron capture processes by  $N^{2+}$ ,  $C^{2+}$ ,  $He^{2+}$ ,  $N^{5+}$ , and  $O^{6+}$  ions in H<sub>2</sub> and CO at energies < 1keV/amu. The main excited product channels have been identified. In the case of He<sup>2+</sup> in H<sub>2</sub> and CO, one electron capture with dissociation becomes increasingly important as the collision energy is decreased. In the case of N<sup>5+</sup> in H<sub>2</sub>, autoionising double capture with dissociation is an important process at the lowest energies considered. All the measurements are in good agreement with theoretical predictions where available. **Keywords:** One electron capture, dissociative capture, multiply charged ions.

### Introduction

Electron capture is the dominant inelastic process during the interaction of multiply charged ions and neutral atoms and molecules at energies less than 25 keV/amu. There is currently strong interest in these interactions due their importance in many astrophysical and terrestrial environments. For example, electron capture by solar wind ions interacting with cometary gases [1], by auroral ions interacting with planetary atmospheres [2], and stellar wind ions with the interstellar medium [3], results in the formation of excited states of either or both collision partners with the resultant visible, UV and X-ray emissions. The thermal and ionisation balance of astrophysical plasmas are influenced by one-electron capture processes [4] involving a wide variety of partially ionised ions. Modeling of ion transport and radiative cooling processes in the divertor region of current large Tokamak fusion plasma devices requires detailed information on the relevant electron capture processes [5].

There have been a large number of experimental measurements of total one-electron capture cross sections by multiply charged ions in atomic and molecular targets (see for example [6], [7]). Experi-

mental studies of state selective electron capture have been carried out primarily via photon emission spectroscopy (PES) or translational energy spectroscopy (TES), see for example [8-10]. Theoretical calculations of electron capture cross sections have been carried out using both semi-classical and quantal approaches. See for example [11], [12].

In many of the collision systems investigated, a comparison of theoretical and experimental data was complicated by the presence of unknown fractions of low-lying metastables in the primary ion beams used in the experiments. These metastable ions can have a significantly different capture probability than ground state ions [13]. Therefore, to obtain information on collision processes of ground state ions in atomic and molecular targets, it is necessary to either determine the metastable fraction of the ion beam or produce an ion beam free from metastable contamination. We have developed an experimental system that makes it possible to produce pure primary ion beams in either ground or metastable states using double translational energy spectroscopy (DTES) [14]. This technique has been used to identify the significant capture channels and determine their relative importance, of a wide variety of multiply charged ions in both ground and metastable states in atomic and molecular targets (see [15], [16]). A particular feature of the DTES technique is its ability, in the case of molecular targets, to determine the relative importance of capture involving both dissociative and non-dissociative processes where the projectile is left in either a ground or metastable state. Information can also be obtained on the distribution of the final vibrational state population of the target product ion [17].

### **Experimental method**



A schematic diagram of the DTES system is shown in figure 1.

Figure 1: Schematic Diagram of DTES apparatus.

In order to illustrate the technique, the production of a ground state beam of  $N^{2+}(2s^22p) {}^{2}P^{0}$  ions is described. A beam of ions is produced by an all-permanent magnet 9-10.5GHz ECR ion source [18]. A characteristic of such sources is the existence of a positive plasma potential that must be accounted

for in defining the final energy of the beam. In our case, the source plasma tube is held at a small negative potential approximately equal and opposite to the positive plasma potential. The plasma potential is measured using a retarding potential analyzer (RPA) at the rear of energy analyzer 1. The ion beam is then extracted from the ECR source via a 'floating beam-line accelerator' in which the beam-line is held at a potential of -4kV. N<sup>3+</sup> ions are selected using a 90° double focusing analysing magnet. A switching magnet is used to deflect the beam into the DTES apparatus. After entering the DTES beamline, the N<sup>3+</sup> ions are decelerated by a cylindrical lens system L1 into the first hemispherical energy analyser EA1. The beam passes through EA1 and then is accelerated by lens system L2 into the first target T1, containing helium. The N<sup>3+</sup> ions undergo one-electron capture collisions in this first gas target and the resulting beam, now containing N<sup>2+</sup> and N<sup>3+</sup> ions in both ground and metastable states, is accelerated by lens system L3 into a second energy analyser, EA2. Applying a suitable retarding voltage on L3, L4, and EA2 ensures only the N<sup>2+</sup> ions pass through. By scanning this voltage, a translational energy spectrum is obtained of the N<sup>2+</sup> ions as shown in figure 2.



Figure 2: Energy change spectrum for one-electron capture by  $N^{3+}$  in He at 3 keV [19].

It is possible to select product  $N^{2+}$  (<sup>2</sup>P) ions from the main observed channel:

$$N^{3+} (1s^{2}2s2p) {}^{3}P + He \rightarrow N^{2+} (2s2p^{2}) {}^{2}P + He^{+} (2s)$$
(1)

corresponding to peak C. The excited  $N^{2+}$  (<sup>2</sup>P) ions decay rapidly (1.4ns) to the ground state within the minimum flight time to the second target (10µs), and so produce a beam of ground state  $N^{2+}$  ions. This is the first stage of double translational energy spectroscopy.

The ion beam, now consisting of only ground state  $N^{2+}$  ions, is accelerated by lens system L4 into the second target region (T2). T2 consists of an aluminium cell coupled to a microwave-driven atomic hydrogen source that can be used to provide beams of highly dissociated hydrogen [20] or other target species as required. A schematic diagram of this T2 region is shown in figure 3. It should be noted that at this stage the beam energy is uniquely defined and independent of any plasma potential changes. The N<sup>2+</sup> ions undergo charge transfer collisions in the hydrogen target and the product N<sup>+</sup> ions, forward scattered within an angular range of ±3°, pass through a set of horizontal and vertical deflection plates into L5, where they are decelerated into the final energy analyser EA3. Again, by ap-



plying a suitable retarding voltage on L5 and EA3, only the passage of the product  $N^+$  ions is allowed. The  $N^+$  ions pass through EA3 and are detected by a position sensitive detector (PSD).

Figure 3: Schematic diagram of the microwave driven atomic hydrogen source.

Again, by scanning the retarding voltage on L5 and EA3, a translational energy spectrum of the product  $N^+$  ions can be obtained whilst maintaining a constant energy resolution of 0.5q eV (q=primary ion charge). The translational energy change is equal to the energy defect of the particular capture channel with a small correction for non-zero degree scattering and target recoil.

## **Results and discussion**

In the present study we have used both single (TES) and double (DTES) translational energy spectroscopy to study state selective electron capture processes in collisions of  $C^{2+}$ ,  $N^{2+}$ ,  $He^{2+}$ ,  $N^{5+}$ , and  $O^{6+}$  in H<sub>2</sub>, and He<sup>2+</sup> ions in CO at energies < 1keV/amu. In the case of  $C^{2+}$  and  $N^{2+}$  where metastable contamination is evident in beams derived directly from ion sources [21], the experimental system was operated in the DTES mode. The TES mode was used for measurements with the other ions where metastables either do not exist or are too high-lying to contribute to the one electron capture spectra.

 $N^{2+} + H_2$ 

Figure 4 shows the translational energy spectra [22] obtained for (a) a mixed beam containing both ground state and metastable  $N^{2+}$  ions and (b) a pure ground state beam of  $N^{2+}$  ions in H2 at 428eV/amu. Table 1 lists the energy defects for each peak shown in figure 4. It can be seen in figure 5 that the unknown metastable content of the ion beam greatly influences the total measured  $N^{+}$  signal.

DTES is therefore an effective way of ensuring that the primary ion beams are free from metastable contamination. Full details are given in [19]. Previous measurements with beams containing both ground state and metastable  $N^{2+}$  ions must be treated with caution.



**Figure 4:** Energy change spectra for electron capture by (a) a mixed beam of ground state and metastable  $N^{2+}$  ions and (b) a pure ground state beam of  $N^{2+}$  ions in H<sub>2</sub> at 428 eV/amu.

Table 1. Main reaction channels for electron capture by  $N^{2+}$  ions in  $H_2^{-1}\Sigma_g^{+}$ 

Peak	Reaction channels	Energy defects / eV
	$N^{2+}$ (1s <sup>2</sup> 2s <sup>2</sup> 2p) <sup>2</sup> P <sup>o</sup> + H <sub>2</sub> X <sup>1</sup> Σ <sub>g</sub> <sup>+</sup> →	
	$N^{+} \left(1 s^{2} 2 s^{2} 2 p^{2}\right) {}^{3}P + H_{2}^{+} {}^{2} \Sigma_{g}^{+}$	14.18 (v=0) – 11.53 (Dissociation limit DL)
A, G1	$N^{+} (1s^{2}2s^{2}2p^{2}) \ ^{1}D + H_{2}^{+}$ "	12.28 (v=0) - 9.63 (DL)
B, G2	$N^{+} (1s^{2}2s^{2}2p^{2}) \ ^{1}S + H_{2}^{+}$ "	10.12 (v=0) - 7.47 (DL)
D, G3	$N^{+} \ (1s^{2}2s2p^{3}) \ ^{3}D^{o} + {H_{2}}^{+} \ \ "$	2.74 (v=0) - 0.09 (DL)
E, G4	$N^{+} (1s^{2}2s2p^{3}) {}^{3}P^{o} + H_{2}^{+}$ "	0.63 (v=0)2.02 (DL)
	$N^{+}  (1s^2 2s 2p^3)  ^1D^o + {H_2}^+  "$	-3.70 (v=0)6.35 (DL)
	$N^{2+} (1s^22s2p^2) \ ^4P + H_2 X \ ^1\Sigma_g \ ^+ 1s\sigma \rightarrow$	
В	$N^{+} \ (1s^{2}2s2p^{3}) \ ^{3}D^{o} + H_{2}^{+} \ ^{2}\Sigma_{g}^{+}$	9.83 (v=0) - 7.18 (DL)
С	$N^{+} (1s^{2}2s2p^{3}) \ ^{3}P^{o} + H_{2}^{+} \ \ "$	7.72 (v=0) - 5.07 (DL)
D	$N^{+} (1s^{2}2s^{2}2p3s) \ ^{3}P^{o} + H_{2}^{+}$ "	2.80 (v=0) - 0.15 (DL)
D, E	$N^{+} \; (1s^{2}2s2p^{3}) \; {}^{3}S^{o} + H_{2}{}^{+} \; \; "$	2.03 (v=0)0.62 (DL)
Е	$N^{+} (1s^{2}2s^{2}2p3p) {}^{3}D + H_{2}^{+}$ "	0.62 (v=0)2.03 (DL)

 $C^{2+} + H_2$ 

Figure 5 shows the measured energy change spectrum obtained for  $C^{2+}$  ions in H<sub>2</sub> at 500 eV/amu. The main reaction channels are listed in table 2.



**Figure 5:** Energy change spectra for electron capture by (a) a mixed beam of ground state and metastable  $C^{2+}$  ions, (b) a pure ground state beam of  $C^{2+}$  ions, and (c) a pure metastable  $C^{2+}$  beam [22].

Peak	Product channels	Energy defects / eV
$C^{2+}(1s^22s^2) + H_2 {}^{1}\Sigma_g^{+} \rightarrow$		
G1	$C^{+} (1s^{2}2s^{2}2p) + H_{2}^{+}{}^{2}\Sigma_{g}^{+}$	8.96 (v=0) – 6.31 (Dissociation limit DL)
G2	$C^{+}(1s^{2}2s2p^{2}) + H_{2}^{+}$ "	-0.33 (v=0)2.98 (DL)
G3	$C^{+}(1s^{2}2s2p^{2}) + H_{2}^{+}$ "	-3.01 (v=0)5.66 (DL
G3	$C^{+}(1s^{2}2s2p^{2}) + H_{2}^{+}$ "	-4.76 (v=0)7.41 (DL)
G3	$C^{+}(1s^{2}2s^{2}3s) + H_{2}^{+}$ "	-5.49 (v=0)8.14 (DL)
$C^{2+}(1s^22s2p) + H_2^{-1}\Sigma_g^{+} \rightarrow$		
	$C^{+}(1s^{2}2s^{2}2p) + H_{2}^{+}$ "	15.45 (v=0) - 12.80 (DL)
	$C^{+}(1s^{2}2s2p^{2}) + H_{2}^{+}$ "	10.12 (v=0) - 7.47 (DL)
M1	$C^{+}(1s^{2}2s2p^{2}) + H_{2}^{+}$ "	6.16 (v=0) - 3.51 (DL)
	$C^{+}(1s^{2}2s2p^{2}) + H_{2}^{+}$ "	3.49 (v=0) – 0.84 (DL)
	$C^+ (1s^22s2p^2) + H_2^+$ "	1.73 (v=0)0.92(DL)

**Table 2:** Main reaction channels for one electron capture by  $C^{2+}$  ions in H<sub>2</sub>  $^{1}\Sigma_{g}^{+}$  [22]

It can clearly be seen that one electron capture is dominated by capture from metastable  $C^{2+}$  ions. Figure 6 shows the energy dependence of both ground state and metastable reaction channels. It can be seen in the ground state spectra that the channel corresponding to peak 1 is decreasing in importance with decreasing energy, while peak 2 is increasing. In contrast, the metastable spectra show very little energy dependence. Leputsch et al [17] have carried out a TES study of this system with an ion kinetic energy resolution  $\leq 200$ meV enabling the final vibrational state distribution of the  $H_2^+$  target product ion to be identified.



**Figure 6:** Energy change spectra obtained for  $C^{2+}$  ground and metastable ions in H<sub>2</sub> at (a) 500 eV/amu, (b) 250 eV/amu, and 125 eV/amu [22].

 $He^{2+}H_2$ 

Figure 7 shows the measured energy change spectra obtained for  $He^{2+}$  ions in  $H_2$  at energies of 1 keV/amu and 500 eV/amu.

**Table 3:** Main product channels for one electron capture by He<sup>2+</sup> ions in H<sub>2</sub>  $^{1}\Sigma_{g}^{+}$ 

Product channels	Energy defects / eV
$He^{+}(n=2) + H_2^{+2}\Sigma_g$	-1.794.44
$He^{+}(1s) + H^{+} + H(2s)$	4.30 - 18.36
$He^{+}(1s) + H^{+} + H(2p)$	4.40 - 12.73



**Figure 7:** Translational energy spectra obtained for  $\text{He}^{2+}$  ions in H<sub>2</sub> at 1 keV/amu and 500 eV/amu.

The peak positions were compared with calculated energy defects shown in table 3. The energy spectra contain 2 features. Firstly, a sharp endothermic peak corresponding to He<sup>+</sup>(n=2) formation with H<sub>2</sub><sup>+</sup> in the  ${}^{2}\Sigma_{g}$  state with vibrational excitation. Secondly, a broad distribution corresponding to dissociative capture processes:

$$He^{2+} + H_2 \rightarrow He^+(1s) + H^+ + H(n \ge 2)$$
 (4)

It can be seen that at low energies only dissociative capture processes are important. Hoekstra et al [23] suggested that at energies >5keV/amu, capture into excited states of He<sup>+</sup> is dominant, while at lower energies capture into the ground state of He<sup>+</sup> with dissociation and excitation of the target dominates. These results confirm this suggestion.

# $He^{2+} + CO$

Figure 8 shows the translational energy spectra obtained for the  $He^{2+}$  + CO system at 1keV/amu and 200eV/amu.

**Table 4.** Main endothermic product channels for the  $\text{He}^{2+}$  + CO  $^{1}\Sigma^{+}$  system.

Product channels	Energy defects / eV
$He^{+}(n=2) + CO^{+}[X^{2}\Sigma^{+}]$	- 0.42 (v=0)
$He^{+}(n=2) + CO^{+}[A^{2}\Pi_{i}]$	- 2.94 (v = 0)3.13 (v =1)
$He^{+}(n=2) + CO^{+}[B^{2}\Sigma^{+}]$	-6.07 (v = 0)
$He^{+}(n=2) + CO^{+}[C^{2}\Sigma^{+}]$	- 9.41 (v = 0) 9.60 (v =1)
$He^{+}(n=3) + CO^{+}[X^{2}\Sigma^{+}]$	- 7.98 (v = 0) 8.24 (v = 1)
$He^{+}(n=3) + CO^{+}[A^{2}\Pi_{i}]$	-10.69 (v =2) 10.87 (v = 3)
$He^+(n=3) + CO^+[B^2\Sigma^+]$	- 13.83 (v = 1)



**Figure 8:** Translational energy spectra obtained for  $\text{He}^{2+}$  ions in CO at energies of 200 eV/amu and 1 keV/amu.

At 1keV the spectrum the spectrum exhibits two main features. Firstly, a group of peaks corresponding to energy defects below zero, resulting from capture into He<sup>+</sup>(n=2) and He<sup>+</sup>(n=3) states with the target CO<sup>+</sup> ions in a variety of excited states with low levels of vibrational excitation. These capture channels are listed in table 4 where energy defects shown were calculated from potential energy curves [24], [25] and energy level tabulations [26].

Secondly, a broad distribution of peaks in the energy change region from 0 - 20eV, corresponding to dissociative capture processes of the type:

 $He^{2+} + CO \rightarrow He^{+}(1s) + CO^{+}[dissociative states]$  (2) These dissociative capture channels become more important as the energy decreases and the nondissociative channels become insignificant. The measurements of Folkerts et al [27] have confirmed

the importance of these channels. At 4keV/amu, they found that fragmentation channels account for about 46% of the total products of the ionization of CO. Relative contributions to electron capture from each of the channels have been obtained. By nor-

malising these relative contributions to the total cross sections [28], we obtained the partial cross sections shown in figure 10.

These measurements are relevant to studies of the tail of Hale-Bopp. The characteristic blue emission from the tail of comet Hale-Bopp results from transitions from the  ${}^{2}\Pi_{i}$  to the  $B^{2}\Sigma^{+}$  states of CO<sup>+</sup> [29].



**Figure 10:** Cross sections for one electron capture by  $\text{He}^{2+}$  ions in CO. The present data are normalized to total cross sections  $\sigma_{\text{TOT}}$  [28].

 $N^{5+} + H_2$ 

Figure 11 shows the measured energy change spectra for  $N^{5+}$  ions in H<sub>2</sub> at energies of 857eV/amu and 250eV/amu. The main product channels are listed in table 5 where energy defects shown were calculated from potential energy curves [30] and energy level tabulations [26]. The main features of this system are as follows. At 857eV/amu, capture occurs predominantly into  $N^{4+}(n=3)$  and  $N^{4+}(n=4)$ levels with the H<sub>2</sub><sup>+</sup> product ion in the <sup>2</sup> $\Sigma_g$  state. This agrees with theoretical predictions [31]. There is also some evidence of dissociative capture channels, either by direct capture or autoionising double capture (ADC), with N<sup>4+</sup>(n=2) formation. At 250eV/amu the dissociative electron capture channels are a prominent feature.



**Figure 11:** Translational energy spectra obtained for  $N^{5+}$  ions in H<sub>2</sub> at energies of 857 eV/amu and 250 eV/amu.

**Table 5.** Main product channels for the  $N^{5+}(1s^2)$   ${}^{1}S + H_2$   ${}^{1}\Sigma_{g}$  + system.

Product channels	Energy defects / eV	
$N^{4+}(1s^23s) + H_2^{+2}\Sigma_g$	25.91 (v=0) - 23.86 (v=10)	
$N^{4+}(1s^23p) + H_2^+$ "	23.22 (v=0) - 21.17 (v=10)	
$N^{4+}(1s^{2}3d) + H_{2}^{+}$ "	22.40 (v=0) - 20.35 (v=10)	
$N^{4+}(1s^{2}4s) + H_{2}^{+}$ "	7.29 (v=0) - 5.23 (v=10)	
$N^{4+}(1s^{2}4p) + H_{2}^{+}$ "	4.14(v=0) - 6.19 (v=10)	
$N^{4+}(1s^{2}4d) + H_{2}^{+}$ "	3.80(v=0) - 5.85 (v=10)	
$N^{4+}(1s^{2}4f) + H_{2}^{+}$ "	3.78(v=0) - 5.83 (v=10)	
Dissociative channels		
$N^{4+}(n=2) + H^+ + H(2l)$	36.87 - 61.61	
$N^{4+}(n=2) + H^+ + H^+ + e$	32.87 – 49.86	
Capture into autoionising states (ADC):		
$N^{3+}(^{**}) + H^+ + H^+ \rightarrow$		
$N^{4+}(1s^22s) + H^+ + H^+ + e$	34.152 - 49.664	
$N^{4+}(1s^22p) + H^+ + H^+ + e$	24.152 - 39.664	

 $O^{6+} + H_2$ 

Figure 12 shows the preliminary measurements for  $O^{6+}$  ions in H<sub>2</sub> at 900eV/amu and 225 eV/amu with the energy defects shown listed in table 6. The spectra are consistent with capture occurring predominantly into  $O^{5+}(n=4)$  with possible dissociative capture into n=3 states. In contrast to the N<sup>5+</sup> + H<sub>2</sub> system, there is no strong evidence of dissociative capture.



**Figure 12:** Translational energy spectra obtained for  $O^{6+}$  ions in H<sub>2</sub> at 900 eV/amu and 225 eV/amu.

**Table 6.** Main product channels for the  $O^{6+}(1s^2)$   ${}^{1}S + H_2$   ${}^{1}\Sigma_{g}$  + system.

Product channels	Energy defects / eV	
$O^{5+}(1s^23s) + H_2^{+2}\Sigma_g$	43.37 (v=0) - 41.31 (v=10)	
$25 \pm (1, 22) + 11 \pm 11$	40.12 ( 0) 20.07 ( 10)	
$O^{3+}(1s^23p) + H_2^+$	40.13 (v=0) - 38.07 (v=10)	
$O^{5+}(1s^23d) + H_2^+$ "	39.08 (v=0) - 37.02 (v=10)	
$O^{5+}(1s^{2}4s) + H_{2}^{+}$ "	17.00 (v=0) - 14.94 (v=10)	
$O^{5+}(1s^{2}4p) + H_{2}^{+}$ "	15.67(v=0) - 13.62 (v=10)	
$O^{5+}(1s^{2}4d) + H_{2}^{+}$ "	15.24 (v=0) - 13.18 (v=10)	
$O^{5+}(1s^24f) + H_2^+$ "	15.21 (v=0) - 13.16 (v=10)	
Dissociative channels		
$O^{5+}(n=3) + H^+ + H(1s)$	15.47 – 28.26	
Capture into autoionising states (ADC):		
$\mathrm{O}^{4+}(^{**}) + \mathrm{H}^+ + \mathrm{H}^+ \rightarrow$		
$O^{5+}(1s^22p) + H^+ + H^+ + e$	66.03 - 76.03	

### Conclusion

Translational energy spectroscopy has been used to study a variety of ion-molecule collision systems relevant to astrophysical and laboratory plasmas. In the case of  $C^{2+}$ , it was found that oneelectron capture is dominated by capture from metastable  $C^{2+}$  ions. Capture from metastable ions shows very little energy dependence, whereas capture from ground state  $C^{2+}$  ions was found to be energy dependent. In the  $N^{2+} + H_2$  system, it was found that again, the unknown metastable fraction of the primary ion beam greatly influences the total electron capture cross-sections. The  $He^{2+} + H_2$  spectra showed that dissociative capture processes are dominant at low energies. This was also found in the  $He^{2+} + CO$  system where dissociative electron capture processes account for almost 100% of the total capture cross section at the lowest energies considered. The measured  $N^{5+} + H_2$  energy change spectra have also shown the importance of dissociative capture processes at low energies, which in this case have been identified as double electron capture into autoionising states of  $N^{3+}$ . This process becomes increasingly important at the lowest energies considered. In the  $O^{6+} + H_2$  system, it was found that electron capture occurs mainly via the  $O^{6+} + H_2 \rightarrow O^{5+}(n=4) + H_2^+$  channel. Dissociative processes are not as dominant as in the  $He^{2+} + H_2$ ,  $He^{2+} + CO$  and  $N^{5+} + H_2$  systems.

### Acknowledgements

This work was supported by the Engineering and Physical Sciences Research Council of the United Kingdom and also forms part of the LEIF European Community Framework V Thematic Network on Low Energy Ion Facilities. One of us (D.K.) is indebted to the Northern Ireland Department of Employment and Learning for the award of a Research Studentship.

## References

- 1. Cravens, T.E. Geophysics Research Lett. 1997, 24, 105-108.
- 2. Liu, W. and Schultz, D. R. Astrophys. J. 1999, 526, 538-543.
- 3. Wargelin, B.J. and Drake, J. Astrophys. J. 2001, 546, L57-L60.
- 4. Kingdon, J.B. and Ferland, G.J. Astrophys. J. 1999, 516, L107-L110.
- 5. Maggi, C.F.; Horton, I.D.; Summers, H.P. *Plasma Physics and Controlled Fusion*, **2000**, *42*, 669-700.
- 6. Phaneuf, R.A.; Havener, C.C.; Dunn, G.H. Rep. Prog. Phys. 1999, 62, 1143-1180.
- 7. Ishii, K.; Tanabe, T.; Lonsadze, R.; Okuno, K. Phys. Scr. 2001, T92, 332-334.
- 8. Lubinski, G.; Juhasz, Z.; Morgenstern, R.; Hoekstra, R. J. Phys. B: At. Mol. Opt. Phys. 2000, 33, 5275-5296.
- 9. Unterreiter, E.; Schweinzer, J.; Winter, H.; J. Phys. B: At. Mol. Opt. Phys. 1991, 24, 1003-1016.
- 10. McCullough, R.W.; Wilkie, F.G.; Gilbody, H.B. J. Phys. B: At. Mol. Opt. Phys. 1984, 17, 1373-1382.
- 11. Errea, L.F.; Macías, A.; Méndez, L.; Riera, A. J. Phys. B: At. Mol. Opt. Phys. 1999, 32, 4065-4077.
- 12. Honvault, P.; Bacchus-Montabonel, M.C.; McCarroll, R. J. Phys. B: At. Mol. Opt. Phys. 1994, 27, 3115-3127.
- 13. Winter, H.P. J. Phys. Chem. 1995, 99, 15448-15453.
- 14. Greenwood, J.B.; Burns, D.; McCullough, R.W.; Geddes, J.; Gilbody, H.B.; J. Phys. B: At. Mol. Opt. Phys. 1996, 29, L599-L603.
- 15. Voulot, D.; Gillen, D.R.; Thompson, W.R.; Gilbody, H.B.; McCullough, R.W.; Errea, L.; Macias, A.; Mendez, L.; Riera, A. J. Phys. B: At. Mol. Opt. Phys. 2000, 33, L187-L192.
- 16. Voulot, D.; Gillen, D.R.; Kearns, D.M.; McCullough, R.W.; Gilbody, H.B. J. Phys. B: At. Mol. Opt. Phys. 2001, 34, 1039-1047.
- 17. Leputsch, P.; Dumitriu, D.; Aumayr, F.; Winter, H.P.; J. Phys. B: At. Mol. Opt. Phys. 1997, 30, 5009-5024.
- 18. Broetz, F.; Trassl, R.; McCullough, R.W.; Arnold, W.; Salzborn, E. Phys Scr. 2001, 792, 278-280.
- 19. Burns, D.; Greenwood, J.B.; McCullough, R.W.; Geddes, J.; Gilbody, H.B. J. Phys. B: At. Mol. Opt. Phys. 1997, 30, L323-L328.
- McCullough, R.W.; Geddes, J.; Donnelly, A.; Liehr, M.; Hughes, M.P.; Gilbody, H.B. Meas. Sci. Technol. 1993, 4, 79-82.
- 21. McCullough, R.W. Int. J. Mass Spectrom. 1999, 192, 141-147.
- 22. D. Voulot, PhD Thesis, Queens University Belfast, United Kingdom 2000.
- 23. Hoekstra, R.; Folkerts, H.O.; Beijers, J.P.M.; Morgenstern, R.; de Heer, F.J. J. Phys. B: At. Mol. Opt. Phys. 1994, 27, 2021-2031.
- 24. M. Carlson-Göthe, Doctoral Dissertation Summary, Faculty of Science, Uppsala University, Sweden **1990**.
- 25. Carlson-Göthe, M.; Wannberg, B.; Falk, F.; Karlsson, L.; Svensson, S.; Baltzer, P. *Phys. Rev. A* **1991**, *44*, R17-R19.
- 26. Bashkin S., and Stoner Jr J.O., *Atomic Energy Levels and Grotrian Diagrams*; Amsterdam: North Holland, **1978**.

- 27. Folkerts, H.O.; Bliek, F.W.; de Jong, M.C.; Hoekstra, R.; Morgenstern, R. J. Phys. B: At. Mol. Opt. Phys. 1997, 30, 5833-5847.
- 28. Ishii, K.; Okuno, K.; Kobayashi, N. Phys. Scr. 1999, T80, 176-178.
- 29. Herzberg, G. Spectra of Diatomic Molecules Van Nostrand Reinhold Company: New York, 1950.
- 30. Sharp T.E. Atomic Data, 1971, 2, 119.
- 31. Gargaud, M. and McCarroll, R. J. Phys. B: At. Mol. Opt. Phys. 1985, 18, 463-477

© 2002 by MDPI (http://www.mdpi.org), Basel, Switzerland.