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Field Ionization of Highly-excited Helium and Hydrogen Atoms Produced by Electron Impact

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Synopsis. The ionization of long-lived highly-excited helium atoms produced by electron impact was observed using an electrostatic field up to 8.3 kV/cm; the decrease of the He^+ intensity produced by collisions of He** with H_2O was measured as a function of the field strength using a mass filter. By use of the theory of Bailey *et al.*, the principal quantum numbers of the highly excited He were estimated to range from 16 to 40. A similar but slower decrease of H^+ due to H** atoms produced by electron impact on H_2O was also observed.

In previous papers[1,2] by the authors long-lived excited states of helium, He* (2^1S and 2^3S) and He** (in the highly-excited states) were produced by electron impact, and the ions formed by collisions with H_2O were detected by a mass filter. The observed ions, H^+, HeH^+, OH^+, and H_2O^+, which exhibited similar dependences on the target pressure and the electron accelerating voltage (with appearance potentials of about 20 eV), were assigned to be those produced by impact of He* on H_2O. On the other hand, another observed species, He^+, varied differently with the target pressure and the accelerating voltage (with an appearance potential of about 25 eV). It was then concluded that the He^+ ions were produced by collisions of He** with H_2O. In parallel with this observation, H^+ ions were observed when H_2O vapor was used in place of He, and their origin was interpreted to be due to highly-excited hydrogen atoms, H**, produced by electron impact dissociation of H_2O.

Various experiments[3-8] and theories[9,10] have shown that highly-excited atoms are ionized by a moderate electric field. For example, field ionization of highly-excited hydrogen atoms were observed by Riviere and Sweetman.[4] They derived an empirical relation for the smallest principal quantum number n of the states which can be ionized by a field of given strength, E_n. In their work, highly-excited hydrogen atoms with n=9—23 and with kinetic energies of 50 keV were produced by charge transfer collisions of protons with gas molecules. According to the calculations of Bailey *et al.*[10] on the ionization probability for hydrogen with n=1—25, E_n is a very slowly-varying function of the time spent by the atom in the field.[5]

The purpose of the present study is two-fold: (1) to confirm by means of field ionization that highly-excited states are in fact produced by electron impact and are involved in the above-mentioned processes, and (2) to estimate, even roughly, the range of their principal quantum numbers using the relationship between the field strength and the fraction of excited states ionized by the field.[8]

Experimental

The apparatus used in the present study was described in the previous paper.[1] A parallel-plate condenser (9 mm × 25 mm with a 3 mm spacing) was placed between the excitation region and collision chamber, as shown in Fig. 1. One of the plates was grounded, and the potential of the other plate was varied from 0 to −2.5 kV. The field strength was calculated from the potential applied to the electrodes divided by the spacing and was estimated to have an uncertainty of about 10%.

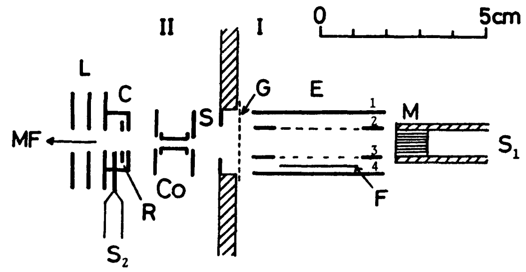

Fig. 1. Apparatus composed of section I for producing long-lived excited atoms by electron impact and section II, in which a parallel-plate condenser Co, a collision chamber C, and a mass filter MF are installed.

The helium gas was introduced into the excitation region through a multichannel orifice M and was subjected to electron impact. The He pressure at source S_1 was about 0.4 Torr. The accelerating voltage of the exciting electrons was about 100 V, and the trap current measured at electrode 1 was about 400 μA. The excited neutral species were separated from accompanying ions by electrostatic potentials and were allowed to collide with the H_2O target in the collision chamber C. The pressure of the target H_2O measured at source S_2 was about 0.3 Torr. The sample pressures were measured using oil manometers. The background pressure outside the collision chamber was about 2×10^{-6} Torr. Ions produced in the collision chamber were measured by a quadrupole mass filter.

Results and Discussion

In Fig. 2, the mass spectra observed with zero electric field (A) and with 0.75 kV applied to the condenser (B) are shown. The variations of the intensities of He^+ and H_2O^+ ions with electric field strength are shown in Fig. 3. The He^+ intensity was found to decrease monotonically with increasing field strength. This behavior can be interpreted as follows: A fraction of the highly-excited states He** are ionized by the field and do not enter the collision chamber. On the other hand, the H_2O^+ intensity did not depend on the electric field; this is because the He* metastable

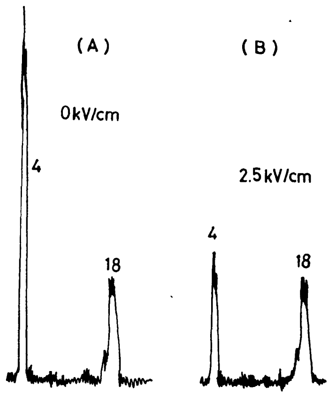

Fig. 2. Mass spectra of the ions produced by collisions of long-lived excited species of He with H_2O.

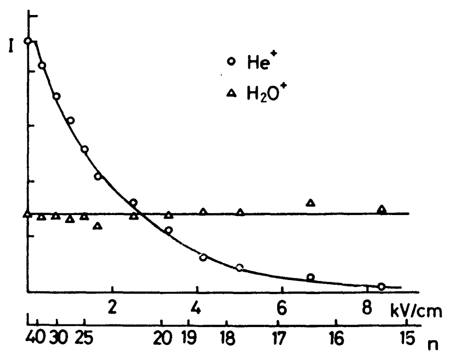

Fig. 3. Ion intensities (in arbitrary units) plotted as a function of electric field strength. The He^+ and H_2O^+ ions are produced by collisions of He** and He* respectively, with H_2O. The principal quantum numbers n which can be ionized by a given field strength are estimated and indicated on the abscissa.

states are not quenched in the range of field strengths applied here.[11] The latter observation also shows that the voltage applied to the condenser plates did not significantly disturb the field in the vicinity of the collision chamber so as to affect the efficiency of the detector.

The principal quantum numbers n which can be ionized by a given field strength E_n were estimated using the theoretical relationship between the lifetime and the electric field strength given by Bailey *et al.*[10] The estimates are indicated along the abscissa of Fig. 3. The correspondence between n and E_n is not unique, however, since the various different states with the same n have different threshold field strengths for ionization. The present estimate shown in Fig. 3 corresponds to the component of the lowest energy given by Bailey *et al.*[12] This choice is given support by the results of Il'in *et al.*;[5] the $n-E_n$ relation they observed in the range $17 \geq n \geq 14$ coincides with that for the lowest components calculated by Bailey *et al.*[10] Figure 3 provides an approximate range of the n values of He** present in the region between the condenser plates, $40 \gtrsim n \gtrsim 16$. Excited states with smaller n probably have lifetimes shorter than the time of flight (about 50 μs) from the excitation region to the electric field, while those with larger n are probably ionized in the excitation region or in its vicinity by a weak electric field.

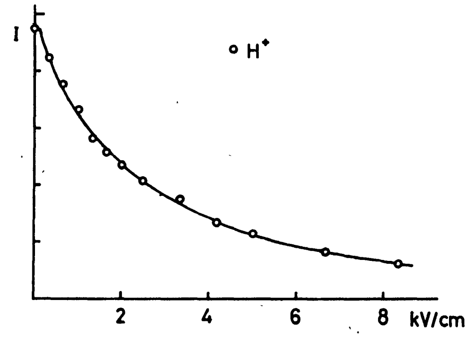

Fig. 4. Ion intensities (in arbitrary units) plotted as a function of electric field strength. The H^+ ion is produced by collision of H** with H_2O.

The corresponding field ionization of the H** species produced from H_2O by electron impact was also observed. The H^+ intensity is plotted as a function of the field strength in Fig. 4. In contrast to the He** case, about 20% of the H^+ intensity observed at zero field was detected even at 8.3 kV/cm. One of the possible explanations for this observation is the following: The highly-excited hydrogen atoms gain kinetic energies as a result of the dissociation of H_2O that are higher than that of the He** atoms (thermal), and hence, the time of flight of H** from the excitation region to the collision chamber is shorter than that of the He**. Therefore, larger fractions of the highly-excited states of hydrogen with shorter lifetimes, *i.e.*, smaller n values, than those of helium can reach the electric field and pass through it without being ionized.

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