THE JOURNAL OF CHEMICAL PHYSICS **129**, 224310 (2008)

Measurement of the electron attachment rates for SF_6 and C_7F_{14} at $T_e = 0.2$ eV in a magnetized Q machine plasma

Robert L. Merlino[a] and Su-Hyun Kim
Department of Physics and Astronomy, The University of Iowa, Iowa City, Iowa 52242, USA

(Received 14 May 2008; accepted 6 November 2008; published online 12 December 2008)

Electron attachment rates for SF_6 and C_7F_{14} were measured in a magnetized Q machine plasma at an electron temperature of 0.2 ± 0.02 eV and with neutral gas pressures of $P \sim 10^{-4}$ Torr. The rate constants for attachment to SF_6 and C_7F_{14} were $(7.6 \pm 2.0) \times 10^{-8}$ and $(2.2 \pm 0.9) \times 10^{-7}$ cm^3 s^{-1}, respectively. © *2008 American Institute of Physics*. [DOI: 10.1063/1.3039078]

I. INTRODUCTION

Experimental studies on electron attachment to sulfur hexafluoride (SF_6) and perfluoromethylcyclohexane (C_7F_{14}) have been performed by a number of groups using a variety of techniques. The continuing interest in perfluorocarbons is due to their practical value as gaseous insulators and the need to understand the role of electron attachment in increasing their dielectric strength.[1] Early studies on electron attachment to SF_6 and C_7F_{14} include the electron beam studies of Asundi and Craggs,[2] who obtained the cross sections for both electron capture and ionization, and measurements of the attachment rate constants at $T_e = 300$ K using a microwave cavity technique by Mahan and Young,[3] and pulse-sampling techniques by Chen *et al.*[4] An important issue, both from the point of view of the basic chemical physics of electron/molecule interactions, as well as technical applications, is how the attachment rates depend on electron temperature or mean electron energy. This is of particular importance in understanding the role of electron attachment in the lower ionosphere where the electron temperature is in the range of 1000–2000 K.

A. SF_6

Smith *et al.*,[5] using the flowing afterglow/Langmuir probe (FALP) method, reported that there was an indication of a peak in the attachment rate k_a within the 400–500 K range. Subsequent measurements of Petrović and Crompton,[6] using the Cavalleri electron density sampling technique, which is considered to be one of the most accurate methods for the determination of attachment rate constants, did not support the temperature dependence seen by Smith *et al.*[5] and showed that the attachment rates at 300 and 500 K were the same within the error bounds. Klar *et al.*,[7] using the laser photoelectron method, measured electron attachment to SF_6 in the energy range of 0–200 meV with sub-meV resolution and found energy-dependent rate constants that decreased with electron energy in this range. Datskos *et al.*,[8] using a time-resolved electron swarm technique, also reported electron attachment rate constants for SF_6 that decreased with mean electron energy in the range of 0.2–1.0 eV. Braun *et al.*[9] obtained electron attachment rates for electron energies up to 200 meV using the laser photoelectron attachment method for various nozzle temperatures of the helium carrier gas. The attachment cross section for SF_6^- decreased by five orders of magnitude over the energy range of 1–500 meV, with little effect of changing the nozzle temperature in the range of 300–600 K. Recent FALP measurements by Viggiano *et al.*,[10] of attachment rate coefficients for SF_6, were in excellent agreement with the results of Petrović and Crompton.[6] Electron attachment rates for SF_6 in the range of 200–600 K obtained from calculated cross sections showed good agreement with the experimental measurements in Ref. 6 and poorer agreement with those in Ref. 5. An extended study on the electron temperature dependence of the attachment rate was performed by Spanel *et al.*[11] using the FALP technique with argon rather than helium as the buffer gas allowing electron temperatures up to about 4000 K to be achieved. The FALP attachment rate at 300 K, reported by Spanel *et al.*,[11] was smaller than the original FALP value of Smith *et al.*[5] but only slightly (13%) above the value of Petrović and Crompton.[6]

B. C_7F_{14}

Mahan and Young[3] determined the attachment rate at 300 K but noted that the rate constant remained unchanged or slightly increased if the electron temperature was increased. This conclusion was supported by measurements of Chen *et al.*[4] using the pulse sampling technique. Davis *et al.*,[12] using an electron swarm method, reported a thermal attachment rate which increased with increasing mean energy of the electron swarm. Using a similar swarm technique, Christodoulides and Christophorou[13] studied electron attachment in both *l*- and *c*-C_7F_{14} up to electron energies of about 3 eV. For both molecules, the attachment cross sections showed resonance maxima at 0.07 and 0.25 eV, and they were much larger for the cyclic isomer. Alge *et al.*[14] studied electron attachment using the FALP method in the electron temperature range of 200–600 K under truly thermalized conditions in which both the carrier gas and attaching gas were at the same temperature. They found that the attachment rate increased with increasing T_e and approached the theoretical maximum value[15,16] of $k_a^{\max} = 5 \times 10^{-7} (300/T_e)^{1/2}$ cm^3/s at the higher temperatures.

---

[a] Electronic mail: robert-merlino@uiowa.edu.

Downloaded 12 Dec 2008 to 128.255.32.146. Redistribution subject to AIP license or copyright; see http://jcp.aip.org/jcp/copyright.jsp

Chutjian and Alajajian[17] performed attachment measurements using the threshold photoionization method over the energy range of 0–160 meV. Attachment rates $k_a(\bar{\varepsilon})$ as a function of mean electron energy $\bar{\varepsilon}$ were derived from the measured cross sections and compared with the results of Davis *et al.*,[12] Christodoulides and Christophorou,[13] and Alge *et al.*[14] Chutjian and Alajajian[17] found a broad peak in $k_a(\bar{\varepsilon})$ at around 100 meV, which was in general agreement with the results of Davis *et al.*[12] but in disagreement with those of Christodoulides and Christophorou[13] and Alge *et al.*[14] Walter *et al.*[18] obtained attachment cross sections for C_7F_{14} in the 1–100 meV range through studies of high Rydberg K(nd)-C_7F_{14} collisions. The cross section at 1 meV was $\sim 2 \times 10^{-14}$ cm^2 and decreased monotonically thereafter. These results were in agreement with those in Ref. 17 but differed substantially with those in Ref. 13, which showed a peak in the cross section at 70 meV. Shimamori *et al.*[19] measured attachment rate constants for C_7F_{14} from thermal energies to about 1 eV using a microwave cavity/pulse radiolysis method. The rate constant peaked at mean electron energy of 0.2 eV. The energy dependence of k_a was similar to that found by Christodoulides and Christophorou[13] but with a peak value that was about 30% lower. Spanel *et al.*[11] reported new FALP measurements of electron attachment constants over an extended electron temperature range from 300 to about 4000 K.[4] In contrast to the earlier FALP measurements of Alge *et al.*,[14] which were conducted under truly thermalized conditions ($T_e = T_{\mathrm{gas}}$), the present experiment was carried out with $T_{\mathrm{gas}} = 300$ K. The rate constants were substantially lower than those of Alge *et al.*[14] in the temperature range common to both sets of measurements. The results of Spanel *et al.*[11] are interesting because they showed that in systems in which activation barriers exist to the attachment process, the required activation energy can be supplied either by going to higher electron temperatures or by increasing the vibrational temperature of the molecule.

Here we report a direct comparison of measurements of the electron attachment rates of SF_6 and C_7F_{14} in a plasma at an electron temperature of $T_e \simeq 0.2$ eV. The experimental apparatus (Q machine[20]) used is somewhat similar to the FALP apparatus[15,16] in that it uses a localized plasma source at one end of a long cylindrical vacuum chamber and a Langmuir probe (LP) to measure the reduction in electron density along the axis of the device when an electron-attaching species is present. The Q machine differs from the FALP device in that the plasma is magnetized, no carrier or buffer gases are used, and the pressures of the attaching gases are $\lesssim 10^{-4}$ Torr. At the low pressures and high magnetic strengths used, the effects of radial diffusion of the electrons in the Q machine are relatively unimportant. This is in contrast to the FALP technique in which the effects of diffusion are often significant and a detailed analysis is required to obtain electron attachment rates from the electron density gradient.

II. EXPERIMENTAL

A schematic of the experimental setup, which has been discussed in detail previously,[21] is shown in Fig. 1. The plasma device is a Q machine[20] in which potassium atoms from an atomic beam oven are formed by contact ionization (the capture of a valence electron from an atom by a metal surface[22]) on the surface of a 6 cm diameter electrically grounded tantalum hot plate (HP). The HP is heated to $\sim 2200-2400$ K by bombardment of electrons emitted by a spiral filament located behind the plate. The HP also emits thermionic electrons and together with the K^+ ions form a nearly fully ionized plasma that is ~ 1 m in length and 6 cm in diameter. The plasma is confined radially by a uniform magnetic field with a maximum strength of 0.5 T, which is provided by a set of water-cooled solenoid coils powered by a direct current supply. The plasma is terminated on an electrically floating cold end plate. The stainless steel vacuum vessel, approximately 2 m in length and 33 cm in diameter, is cooled to -10 °C to maintain the neutral K pressure $< 10^{-6}$ Torr. The electron density and temperature were measured with a planar (disk) LP that could be moved radially and axially. The plasma ion density (n_+), determined from the ion saturation current to the LP, was $\sim 10^9$ cm^{-3}. Due to the strong magnetic field and relatively infrequent collisions, electron diffusion out of the plasma column is strongly inhibited.[23]

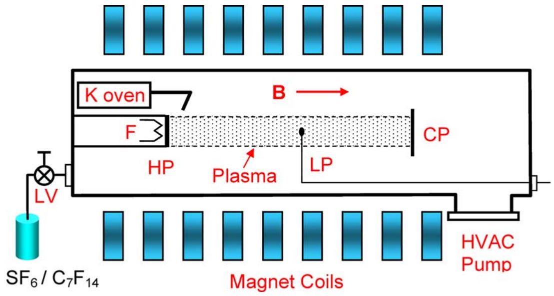

FIG. 1. (Color online) Schematic of the experimental device. The plasma is produced by surface ionization of potassium atoms on a hot tantalum plate. The plasma is confined radially by a magnetic field up to 0.5 T and is terminated on a floating cold plate. The electron density and temperature are measured with a planar LP, which is movable in the radial direction and along the plasma column. Electron attachment rates are inferred from measurements of the spatial gradient of the electron density when the electron attaching gases are introduced.

A typical example of a LP current (I) versus voltage (V) characteristic used for the determination of the electron temperature is shown in Fig. 2(a). The positive current in this plot is the electron current collected by the probe. The electron temperature was obtained from the probe characteristic by the following method. The space or plasma potential is first determined as the voltage at which d^2I/dV^2 equals zero. A linear fit is made to the positive ion current, which is then subtracted from the total current to obtain the electron current. A semilog plot of the electron current in the retarding potential region (below the plasma potential) is shown in Fig. 2(b). A plot of log I versus V will be linear in the retarding potential region for a Maxwellian plasma, and the electron temperature is determined from the slope of this line. The solid line in Fig. 2(b) is the exponential fit from which we obtained $k_BT_e \approx 0.20 \pm 0.02$ eV.

The electron attaching species, SF_6 or C_7F_{14}, were leaked into the system through a fine needle valve (LV in

Downloaded 12 Dec 2008 to 128.255.32.146. Redistribution subject to AIP license or copyright; see http://jcp.aip.org/jcp/copyright.jsp

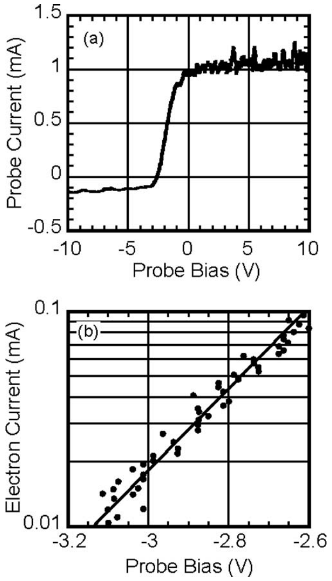

FIG. 2. LP measurements of the electron temperature. (a) Probe current-voltage characteristic $I(V)$. The positive current is the electron current in this plot. (b) Semilogarithmic plot of the electron current in the retarding potential region. The solid line is the exponential fit to the data from which the electron temperature T_e is inferred.

Fig. 1). The C_7F_{14} liquid was degassed using several pressure reduction cycles. The SF_6 and C_7F_{14} reservoirs were maintained at room temperature and we assume that they remain close to room temperature when they are added to the plasma. At the pressures used in this experiment, the mean free paths of the molecules within the system are on the order of the length of the chamber, so there is not enough time for the molecules to heat up or cool down due to conduction with the chilled walls or the HP. We estimated also that heat transfer to the molecules by radiation from the HP would not significantly raise the gas temperature. The pressures of the attaching gases were measured with a Bayard–Alpert ionization gauge. The gas sensitivity factors for SF_6 and C_7F_{14} were determined by calibrating the ionization gauge against an absolute pressure capacitance manometer.[24] The measured gas sensitivity factor for SF_6 (2.3) was in good agreement with the average value provided by the gauge manufacturer. No gas sensitivity factor for C_7F_{14} was available so we used the value of 6.4, which was obtained from the capacitance manometer calibration. We estimate the uncertainty in the absolute pressure measurements to be 15%. Based on our estimates of the maximum possible change in the gas temperature within the vacuum vessel, we place the overall uncertainty in the determination of the gas density to be 25%.

III. RESULTS AND DISCUSSION

A. Electron attachment measurements

Electron attachment rates were determined from LP measurements of the axial gradient of the electron density when the attaching gas was introduced. The attaching gases were continuously leaked into the vacuum system at steady pressures and the variation in the electron density along the axis of the plasma column $n_e(z)$ was measured with the LP. The data were fitted to an exponential $n_e(z)=n_e(0)\exp(-\alpha z)$ to obtain the spatial decay rate α.[25] The electron attachment rate k_a was determined from the spatial decay rates using $k_a=\alpha v_{eT}/N_a$, where $v_{eT}=(k_BT_e/m_e)^{1/2}$ is the electron thermal speed (with $k_BT_e=0.2$ eV) and N_a is the density of the attaching species.

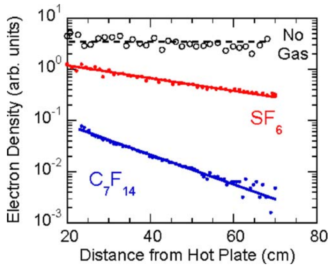

FIG. 3. (Color online) Decay of the electron density n_e along the axis of the plasma when SF_6 or C_7F_{14} is introduced. The uppermost plot (open circles) is the electron density in the absence of any attaching gas. $B=0.3$ T. The HP is located at $z=0$.

1. SF_6

A semilogarithmic plot of the electron density $n_e(z)$ along the axis of the plasma when SF_6 was introduced at a pressure of $P=2.2\times10^{-4}$ Torr is shown in Fig. 3. The upper plot (open circles) in Fig. 3 is $n_e(z)$ when no attaching gases were added to the plasma. The spatial decay rate obtained from the fitting routine was $\alpha(SF_6)=0.029$ cm^{-1}. The resulting electron attachment rate constant for SF_6 at $T_e=0.2$ eV was

$$k_a(SF_6) = (7.6 \pm 2.0) \times 10^{-8}\ \text{cm}^3\ \text{s}^{-1},$$

where the uncertainty is the aggregate of the uncertainties in the gas density, electron temperature, and spatial decay rate.

There have been very few measurements of attachment rates for SF_6 at electron temperatures above about twice the room temperature. Spanel *et al.*[11] measured attachment rates for SF_6 up to about 4000 K using the FALP technique. Their measurements at lower temperatures (300–500 K) were in agreement with the previous best measurements of Petrović and Crompton[6] who reported a $k_a=(2.27\pm0.07)\times10^{-7}$ cm^3/s at 300 K as well as recent measurements of Viggiano *et al.*[10] Both Petrović and Crompton[6] and Viggiano *et al.*[10] found only a small decrease in k_a in the temperature range of 300–670 K. Our result for SF_6 at $T_e\approx0.2$ eV agrees with those of Spanel *et al.*[11] who found a $k_a\approx8\times10^{-8}$ cm^3/s at roughly the same temperature. The decrease in k_a at temperatures above thermal is also consistent with the swarm measurements of Datskos *et al.*[8] who found that at a mean electron energy of 0.2 eV, $k_a\approx9\times10^{-8}$ cm^3/s. Our result is also in line with the recommended value with a value of 0.801×10^{-7} cm^3 s^{-1} at $\bar{\varepsilon}=0.2$ eV given by Christophourou and Olthoff.[26]

A plot of the measured attachment rate at $T_e=0.2$ eV, along with rates reported by a number of other workers at various values of either the electron temperature or, in some cases, mean electron energy, is shown in Fig. 4. The present value falls in line with the trend of the attachment rates that decrease with increasing electron temperature.

Downloaded 12 Dec 2008 to 128.255.32.146. Redistribution subject to AIP license or copyright; see http://jcp.aip.org/jcp/copyright.jsp

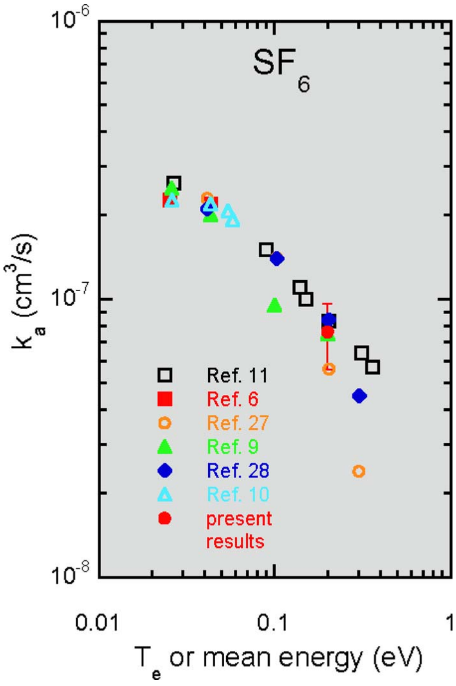

FIG. 4. (Color online) Rate constants for electron attachment to SF_6 as a function of electron temperature or mean electron energy. Present results—solid circle with error bar; solid squares—Ref. 6; solid upward triangles—Ref. 9; open triangles—Ref. 10; open squares—Ref. 11; open circles—Ref. 27; and solid diamonds—Ref. 28.

2. C_7F_{14}

The spatial variation in the electron density along the plasma column when C_7F_{14} was added at a pressure of $P = 1.9 \times 10^{-4}$ Torr is shown in Fig. 3. The decay rate obtained from the exponential fitting function was $\alpha(C_7F_{14}) = 0.070\ \text{cm}^{-1}$. The resulting electron attachment rate constant for C_7F_{14} at $T_e = 0.2$ eV was

$$k_a(C_7F_{14}) = (2.2 \pm 0.9) \times 10^{-7}\ \text{cm}^3\ \text{s}^{-1},$$

where, again, the quoted uncertainty represents the aggregate of the uncertainties in the gas density, electron temperature, and spatial decay rate.

The measured rate constant for C_7F_{14} was almost three times as large as the corresponding value for SF_6. Mahan and Young,[3] using a microwave cavity resonance technique, reported a rate constant of $9.8 \times 10^{-8}\ \text{cm}^3/\text{s}$ at 300 K with a maximum error estimate of 25%. They noted a slight increase in the rate constant with increasing temperature. Their value was supported by measurements of Chen *et al.*[4] using a pulse-sampling technique also at 300 K. In an electron swarm experiment Davis *et al.*[12] found a strong dependence of the rate constant on electron energy above thermal rate constant values. They found a value of $k_a(C_7F_{14}) = 7.39 \times 10^{-8}\ \text{cm}^3/\text{s}$ at the mean electron energy of 0.16 eV, which was the highest energy measured. They also noted that C_7F_{14} is a special case in which k_a *increases* with increasing electron energy above the thermal value. Swarm studies were extended to mean electron energies of 3 eV by Christodoulides and Christophorou,[13] who found a rate constant which peaked at a mean electron energy of about 0.2 eV at $k_a \approx 1.4 \times 10^{-7}\ \text{cm}^3/\text{s}$. Shimamori *et al.*[19] carried out a similar set of experiments on the dependence of the attachment rate constants with mean electron energy using a pulse-radiolysis microwave cavity technique. Their rate constants showed very similar dependence on electron energy as those of Christodoulides and Christophorou,[13] although the peak value of the attachment rate was about half of that of Christodoulides and Christophorou.[13] Chutjian and Alajajian[17] reported electron attachment cross section measurements from ultralow electron energies (with meV resolutions) up to 160 meV. They integrated their cross sections with a Maxwellian distribution function to obtain attachment rates as a function of the mean energy $\bar{\varepsilon}$. Their attachment rates increased with $\bar{\varepsilon}$ up to a peak value of $(5 \pm 1) \times 10^{-8}\ \text{cm}^3/\text{s}$ at $\bar{\varepsilon} \approx 100$ meV. They commented that the difference between their results and the swarm results of Christodoulides and Christophorou[13] might be related to non-Maxwellian or nonequilibrium conditions that could be present in the swarm experiments. The results of Chutjian and Alajajian,[17] however, were supported by the Rydberg atom collision studies of Walter *et al.*[18] Finally we compare our results to the 1995 FALP results of Spanel *et al.*[11] who measured attachment rates for a number of selected molecules including SF_6 and C_7F_{14} from 300 to about 4000 K. The rate coefficient for the direct attachment of electrons to C_7F_{14} increased with increasing electron temperature, with a particularly sharp increase from about 0.1 to 0.3 eV. At the electron temperature of ~ 0.2 eV, they obtained a rate coefficient of $k_a \approx (9.5 \pm 1.5) \times 10^{-8}\ \text{cm}^3/\text{s}$, which is in reasonable agreement with the value obtained in the present experiment. We note that the results of Spanel *et al.*[11] for SF_6 were about 10% higher than the accurate results of Crompton and co-workers.[6,29]

For comparison, our value of k_a for C_7F_{14} at 0.2 eV, along with those obtained by other methods as a function of electron temperature or mean electron energy, is shown in Fig. 5. Compared with the data for SF_6, the C_7F_{14} results show considerably greater spread. However, there is a general trend of the attachment rate increasing with T_e from its value at 300 K.

B. Identification of the negative ions and lifetime estimates

When an electron current is drawn along the magnetic field to a LP in the plasma, an ion-cyclotron instability is excited,[30] which produces coherent plasma density oscillations at a frequency slightly above the ion-cyclotron frequency $f_{c\pm} = eB/2\pi m_{\pm}$, where $m_{\pm}$ is the positive/negative ion mass of both the positive and negative ions. The presence of peaks at specific frequencies in the spectrum of oscillations of the electron current was used to identify the formation of both SF_6^- and $C_7F_{14}^-$.[21,31]

In addition to providing a means of identifying the negative ions present in the plasma, the fact that coherent negative ion-cyclotron oscillations were observed implies that the negative ions were stable against autodetachment for at least several ion-cyclotron periods, $T_{c-} = f_{c-}^{-1} = 2\pi m_- / eB$. For SF_6^-, $T_{c-} = 32\ \mu\text{s}$, while for $C_7F_{14}^-$, $T_{c-} = 77\ \mu\text{s}$. In fact, the ion-cyclotron period is only a lower limit to the negative ion

Downloaded 12 Dec 2008 to 128.255.32.146. Redistribution subject to AIP license or copyright; see http://jcp.aip.org/jcp/copyright.jsp

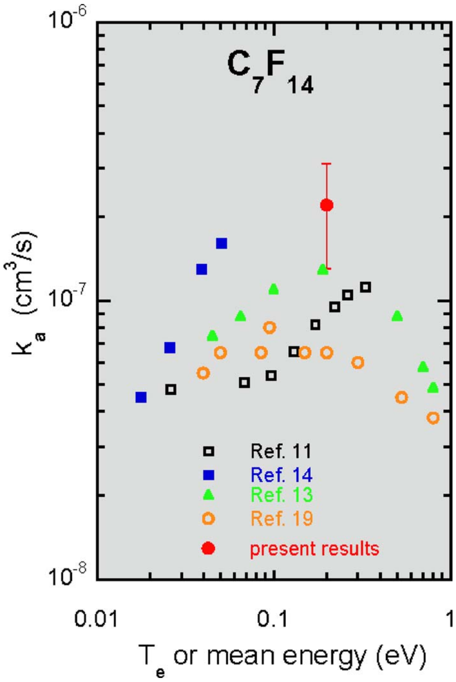

FIG. 5. (Color online) Rate constants for electron attachment to C_7F_{14} as a function of electron temperature or mean electron energy. Present results—solid circle with error bar; open squares—Ref. 11; closed triangles—Ref. 13; closed squares—Ref. 14; and open circles—Ref. 19.

lifetime because typically, the growth time for the ion-cyclotron instability is ~(10–50)T_{c-},[32] which would require lifetimes of approximately a millisecond.

IV. CONCLUSIONS

Attachment rates for both SF_6 and C_7F_{14} at pressures of $P \sim 10^{-4}$ Torr have been measured at an electron temperature of 0.2 ± 0.02 eV in a magnetized Q machine plasma. The attachment rate at 0.2 eV for C_7F_{14} was close to the theoretical s-wave limit and more than twice as large as that of SF_6. The reasonable agreement between the present results and those obtained by other methods demonstrates the potential for using the Q machine for electron attachment measurements, which was one of our goals in performing this experiment.

Miller *et al.*[33] recently pointed out the need for additional studies on electron attachment to SF_6 and detachment from SF_6^- in the μ Torr and mTorr pressure range, as well as at higher temperatures. In future work, we plan to examine the pressure dependence of the attachment rate constants as well as attempt to detect the presence of SF_5^- formed by dissociative attachment. Finally, we point out that thermal and nonequilibrium distributions may yield quite different results, and with cross sections weighed toward low energies and some dissociative attachment and vibrational losses limiting the nonequilibrium distribution functions at high energies, the attachment rates could be quite different.[34]

ACKNOWLEDGMENTS

This work was supported by DOE Grant No. DE-FG02-04ER54795. The authors thank N. D'Angelo and M. Rosenberg for useful suggestions and discussions and M. Miller for technical assistance. The authors are also grateful to the referees for their helpful comments.

[1] L. G. Christophorou, R. A. Mathis, D. R. James, and D. L. McCorkle, J. Phys. D **14**, 1889 (1981).
[2] R. K. Asundi and J. D. Craggs, Proc. Phys. Soc. London **83**, 611 (1964).
[3] B. H. Mahan and C. E. Young, J. Chem. Phys. **44**, 2192 (1966).
[4] E. Chen, R. D. George, and W. E. Wentworth, J. Chem. Phys. **49**, 1973 (1968).
[5] D. Smith, N. G. Adams, and E. Alge, J. Phys. B **17**, 461 (1984).
[6] Z. Lj. Petrović and R. W. Crompton, J. Phys. B **18**, 2777 (1985).
[7] D. Klar, M.-W. Ruf, and H. Hotop, Chem. Phys. Lett. **189**, 448 (1992).
[8] P. G. Datskos, L. G. Christophorou, and J. G. Carter, J. Chem. Phys. **99**, 8607 (1993).
[9] M. Braun, C. Barsotti, S. Marienfeld, E. Leber, M.-W. Ruf, and H. Hotop, Eur. Phys. J. D **35**, 177 (2005).
[10] A. A. Viggiano, T. M. Miller, J. F. Friedman, and J. Troe, J. Chem. Phys. **127**, 244305 (2007).
[11] P. Spanel, S. Matejcik, and D. Smith, J. Phys. B **28**, 2941 (1995).
[12] F. J. Davis, R. N. Compton, and D. R. Nelson, J. Chem. Phys. **59**, 2324 (1973).
[13] A. A. Christodoulides and L. G. Christophorou, Chem. Phys. Lett. **61**, 553 (1979).
[14] E. Alge, N. G. Adams, and D. Smith, J. Phys. B **17**, 3827 (1984).
[15] D. Smith and P. Spanel, Adv. At., Mol., Opt. Phys. **32**, 307 (1994).
[16] T. M. Miller, Adv. At., Mol., Opt. Phys. **51**, 299 (2005).
[17] A. Chutjian and S. H. Alajajian, J. Phys. B **20**, 839 (1987).
[18] C. W. Walter, C. B. Johnson, A. Kalamarides, D. F. Gray, K. A. Smith, and F. B. Dunning, J. Chem. Phys. **91**, 4284 (1987).
[19] H. Shimamori, Y. Tatsumi, Y. Ogawa, and T. Sunagawa, Chem. Phys. Lett. **194**, 223 (1992).
[20] R. W. Motley, *Q Machines* (Academic, New York, 1975).
[21] S.-H. Kim and R. L. Merlino, Phys. Rev. E **76**, 035401(R) (2007).
[22] I. Langmuir and K. H. Kingdon, Science **57**, 58 (1923).
[23] E. W. McDaniel, *Collision Phenomena in Ionized Gases* (Wiley, New York, 1964), p. 506.
[24] S.-H. Kim, J. R. Heinrich, M. J. Miller, and R. L. Merlino, J. Vac. Sci. Technol. A **26**, 1355 (2008).
[25] D. P. Sheehan and N. Rynn, Rev. Sci. Instrum. **59**, 1369 (1988).
[26] L. G. Christophorou and J. K. Olthoff, J. Phys. Chem. Ref. Data **29**, 267 (2000).
[27] H. Shimamori, Y. Tatsumi, Y. Ogawa, and T. Sunagawa, J. Chem. Phys. **97**, 6335 (1992).
[28] S. R. Hunter, J. G. Carter, and L. G. Christophorou, J. Chem. Phys. **90**, 4879 (1989).
[29] R. W. Crompton and G. N. Haddad, Aust. J. Phys. **36**, 15 (1983).
[30] N. D'Angelo and R. W. Motley, Phys. Fluids **5**, 633 (1962).
[31] S.-H. Kim, J. R. Heinrich, and R. L. Merlino, Planet. Space Sci. **56**, 1552 (2008).
[32] V. W. Chow and M. Rosenberg, Phys. Plasmas **3**, 1202 (1996).
[33] T. M. Miller, A. A. Viggiano, and J. Troe, J. Phys.: Conf. Ser. **115**, 012019 (2008).
[34] Z. Lj. Petrović, M. Šuvakov, Ž. Nikitović, S. Dujko, O. Šašić, J. Jovanović, G. Malović, and V. Stojanović, Plasma Sources Sci. Technol. **16**, S1 (2007).

Downloaded 12 Dec 2008 to 128.255.32.146. Redistribution subject to AIP license or copyright; see http://jcp.aip.org/jcp/copyright.jsp