the drift time to the wall in the absence of $\tilde{I}_z$ to the quarter period of the $\tilde{I}_z$ current was 7 in the PRE II experiments.

The fact that Δ differs for the two plasmas can probably be ascribed to the difference in their β values. In general, the equilibrium shift in screw pinches is an increasing function of β. A comparison of the measured and calculated values of Δ (the calculation being made on the assumption that Δ is determined by the rms value of $\tilde{I}_z$) indicates that a theoretical model based on a vacuum B_θ distribution and a sharp-boundary plasma does not apply in the present experiments. Indeed, preliminary magnetic probe measurements of the oscillating field component B_θ show that after the first 1.3 μsec of the experiment, during which the distribution of B_θ outside the dense plasma column has a $1/r$ dependence, the axial current switches to the region of the discharge tube wall where it forms a layer characterized by a skin depth of 7.5 mm. It is conjectured that the switching of the current to the wall, and also the background light which is apparent in the streak photographs, is due to the ionization of the neutral filling gas which is not collected during the initial implosion of the θ pinch.

The streak photographs do not reveal the presence of any gross magnetohydrodynamic instabilities. It is interesting to note that if the parameters of this experiment are inserted into the Kruskal-Shafranov theory, then the growth rate of the most dangerous $m=1$ mode in the equivalent dc screw pinch (axial current equal to rms $\tilde{I}_z$) is 1.6×10^6 sec^{-1}.

It is a pleasure to acknowledge the competent technical assistance of A. Simik. This work was financed by the "Fonds National Suisse de la Recherche Scientifique."

[1]T. Uchida *et al.*, in Proceedings of the Fourth International Atomic Energy Agency Conference on Plasma Physics and Controlled Nuclear Fusion Research, Madison, Wisconsin, 1971 (to be published), paper No. CN-28/J-1.

[2]H. J. Belitz *et al.*, in Proceedings of the Fourth International Atomic Energy Agency Conference on Plasma Physics and Controlled Nuclear Fusion Research, Madison, Wisconsin, 1971 (to be published), paper No. CN-28/J-2.

[3]E. Fünfer *et al.*, in Proceedings of the Fourth International Atomic Energy Agency Conference on Plasma Physics and Controlled Nuclear Fusion Research, Madison, Wisconsin, 1971 (to be published), paper No. CN-28/J-3.

[4]W. R. Ellis *et al.*, in Proceedings of the Fourth International Atomic Energy Agency Conference on Plasma Physics and Controlled Nuclear Fusion Research, Madison, Wisconsin, 1971 (to be published), paper No. CN-28/J-4.

[5]C. Bobeldijk *et al.*, in *Proceedings of the Third International Atomic Energy Agency Conference on Plasma Physics and Controlled Nuclear Fusion Research, Novosibirsk, U. S. S. R., 1968* (International Atomic Energy Agency, Vienna, Austria, 1969), Vol. I, p. 287.

[6]R. Wilhelm and H. Zwicker, Z. Phys. 240, 295 (1970).

[7]E. S. Weibel, Phys. Fluids 3, 946 (1960).

[8]R. F. Gribble *et al.*, in *Proceedings of the Third European Conference on Controlled Fusion and Plasma Physics, Utrecht, 1969* (Wolters-Noordhoff Publishing, Groningen, The Netherlands, 1969), p. 79.

[9]E. S. Weibel, Rev. Sci. Instrum. 35, 173 (1964).

[10]R. Keller, Helv. Phys. Acta 38, 328 (1965).

[11]A. Lietti, Rev. Sci. Instrum. 40, 473 (1969).

[12]J. Junker, Phys. Fluids 11, 646 (1968).

[13]H. A. B. Bodin *et al.*, in Proceedings of the Fourth International Atomic Energy Agency Conference on Plasma Physics and Controlled Nuclear Fusion Research, Madison, Wisconsin, 1971 (to be published), paper No. CN-28/B-5.

Ion-Molecular Reactions in Plasma Containment Devices*

B. H. Ripin,† M. Okabayashi, J. Schmidt, V. Voitsenja,‡ and S. Yoshikawa
Plasma Physics Laboratory, Princeton University, Princeton, New Jersey 08540
(Received 18 October 1971)

We investigate ion-molecule charge exchange followed by dissociative electron recombination with molecular ions due to the presence of common impurities in a plasma-containment device . For a He^+ plasma with N_2 impurity, the ionic constituency of plasmas is changed from He^+ to nitrogen ions with a time constant τ^* given by $\tau^* P(N_2) \simeq 24$ msec μTorr. However, those ion-molecular recombination processes are not responsible for the enhanced plasma loss in the Princeton spherator at the best vacuum condition.

Recently, plasma decay times of 200–500 msec have been obtained in toroidal multipoles.[1,2] This is 100–300 times the so-called Bohm time. However, He^+ plasma in the spherator device still decays somewhat faster than expected from classical collisional processes, which indicates that there may exist other plasma-loss mechanisms. One of the possible mechanisms is the annihilation of the charged particles due to atomic or molecular processes occurring between plasma ions and impurity molecules.

In this Letter we present results concerning the effects of increasing the partial molecular-impurity background pressure upon the plasma decay time in the levitated spherator. We report also the effect on a He^+ plasma of known molecular gases, N_2 or O_2, injected during the He^+ afterglow. Furthermore, we discuss the possible cause of the plasma-density decay time using rate coefficients which are available from ion-beam experiments and those obtained in our experiments.

The Princeton levitated spherator has a plasma confinement volume $\sim 2 \times 10^5$ cm^3 and an average magnetic field of about 1000 G as described earlier.[1] The afterglow plasma in the levitated spherator was produced by applying an electron-cyclotron-resonance heating pulse (30–100 msec) with 500 W at 2.5 GHz or 70 W at 3.5 GHz. The electron density was measured with a 4-mm interferometer, and the electron temperature was measured by a swept Langmuir probe.

It was found during initial spherator experiments that the electron-density decay time of a helium plasma was a very strong function of the background pressure. The mass analysis of base pressure gases showed H_2O to be the main impurity in the vacuum chamber. With the gradual improvement of vacuum conditions, the plasma lifetime was found to increase significantly. The dependence of the plasma decay time on the impurity pressure is summarized in Fig. 1.

The magnitude of this effect is too large to be explained by diffusion due to elastic electron or ion-neutral collisions, electron attachment, ionization, etc. Atomic or molecular processes are required to explain this experimental result. The mechanism of these processes is the charge exchange between He^+ ions and impurity molecules which is followed by dissociative electron recombination with molecular ions. These processes are similar to those proposed for the explanation of the observed lifetime of He^+ ions in upper atmosphere (although their lifetime is still longer than expected from the laboratory-determined cross sections).

In order to investigate the possibility of ion-molecule charge exchange in the helium plasma, nitrogen or oxygen was injected into the helium afterglow plasma under the best background pressure. To illustrate the possible interactions, the relevant nitrogen and oxygen reactions in He^+ plasma are listed in Table I. It should be noted that the rate coefficients for the charge exchange of helium ions with impurity molecules are of the order of 10^{-9} cm^3/sec and are large compared to the typical ion-atom rate coefficient.

For the case of nitrogen, the charge-exchange process replaces helium ions either with molecular nitrogen ions (which then dissociatively recombine with electrons very rapidly, i.e., with the rate coefficient $\langle \sigma v \rangle \sim 2\times10^{-7}$ cm^3/sec), or by atomic nitrogen ions (which may undergo a fur-

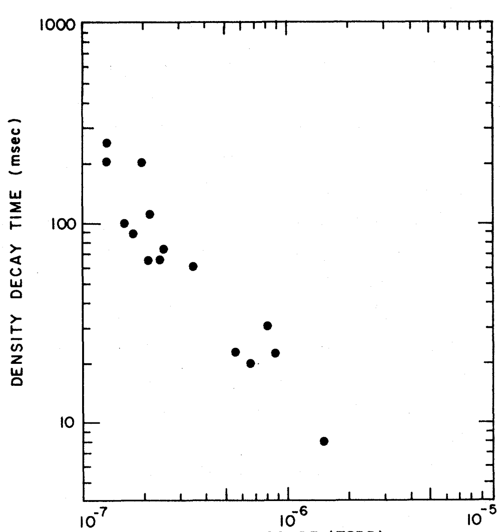

FIG. 1. The dependence of the electron-density decay time on the background pressure.

TABLE I. Selected ion-molecule charge exchange and molecular-ion recombination rate coefficients ($T \approx 300$°K).

Reaction			$\langle \sigma v \rangle$ ($\times 10^{-9}$ cc/sec)		Reference
$He^+ + N_2 \rightarrow$	$He + N_2^+ + 9.0$ eV	(1a)	1.7	$(1.2)^a$	[3,4]
	$He + N^+ + N + 0.3$ eV	(1b)			
	$(N_2^+ + e \rightarrow N_2)$	(2)	~ 200		[5]
$N^+ + O_2 \rightarrow$	$NO^+ + O + 6.7$ eV	(3a)	0.5	$(0.4)^a$	[3,6]
	$O_2^+ + N + 2.47$ eV	(3b)	0.5		[3,6]
	$(NO^+ + e \rightarrow N + O)$	(4)	~ 100		[5]
	$(O_2^+ + e \rightarrow O + O)$	(5)	~ 100		[5]
$He^+ + O_2 \rightarrow$	$He + O_2^+ + ?$ eV	(6a)	~ 0.3		[7]
	$He + O^+ + O + 5.9$ eV	(6b)	1.5		[3,4]

[a]Values obtained from this experiment.

ther charge exchange with another molecule, such as molecular oxygen producing NO^+ or O_2^+, and then dissociatively recombine in the same time scale as N_2^+).[8] These reactions are exothermic and thus do not easily occur in the reverse direction. In addition, these reactions have little temperature dependence up to ~10 eV as compared with atomic recombination which has a strong inverse temperature dependence. These processes can play an important role in plasma confinement devices where the plasma-density decay time is comparable to these charge-exchange times.

The effect of the injection of nitrogen molecules into the He^+ plasma is shown in Fig. 2. The plasma density decayed with the time constant $\tau \simeq 200$ msec for the helium neutral pressure of about 6×10^{-6} Torr and the background pressure $\sim 1 \times 10^{-7}$ Torr as it is shown in Fig. 2(a). For the same case the electron temperature decayed from ~10 eV with a 10-msec time constant, presumably because of (He^+, He) charge-exchange cooling.

When the nitrogen was injected by a fast-acting

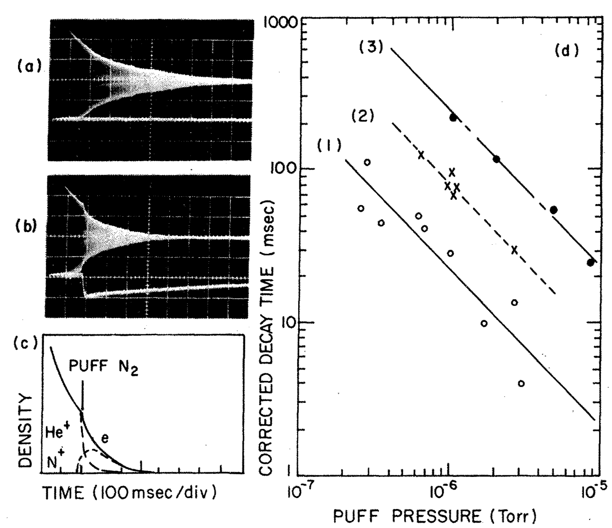

FIG. 2. The effect of injecting a small partial pressure of N_2 gas into the He^+ afterglow plasma. (a),(b) Oscillograms showing the decay of electron density (upper traces) without and with N_2 injection, respectively. The electron density is 1×10^{10} cm^{-3}/div and the fast-ionization gauge scale (lower traces) is 1×10^{-6} Torr/div. (c) Scheme of the variation of the composition of plasma with time. (d) Corrected decay times [using Eq. (2)] versus peak partial pressure of injected gases. Line 1 was obtained from the decay of 5876-Å helium line intensity after the injection of N_2. Line 3 is the decay time of the electron density due to N^+ ion recombination. Line 2 presents the electron-density decay time when the O_2 gas was injected into the N^+ afterglow plasma.

valve, the plasma density decayed rapidly [Fig. 2(b)]. (The absolute value of injected gas pressure was measured with a fast ionization gauge.) The electron temperature was about 0.2 eV just before and after the injection of the gas. The plasma loss across the magnetic field as well as the plasma density were observed to decay just after the gas injection. These results indicate that the charged particles were annihilated in the plasma volume and that atomic or molecular processes are responsible for the increased plasma-density decay.

The charge-exchange time of He^+ ions with impurities, τ^*, was calculated from the following relation:

$$\tau_{He^+}^{-1} = \tau_c^{-1} + \tau^{*-1}, \qquad (1)$$

where τ_{He^+} is the observed He^+-ion decay time and τ_c is the plasma confinement time in the absence of impurities. The helium 5876-Å light intensity due to helium recombination was monitored to determine τ_{He^+} when impurities were injected. When the electron temperature and plasma density decay slowly compared to the rate of decrease of the 5876-Å light intensity, the decreased decay time of helium light reflects the replacement of He^+ by nitrogen ions. Figure 2(c) shows schematically how the He^+ plasma is rapidly replaced by a nitrogen plasma as a result of charge exchange with N_2. The charge-exchange time τ^* is plotted versus the peak partial pressure of the injected gas [line 1 in Fig. 2(d)]. The average value of our experimental results yields the relation, τ^* in milliseconds,

$$\tau^* P \simeq 24 \pm 7.5 \qquad (2)$$

where P is the partial pressure of N_2 in units of 10^{-6} Torr. Taking 3.6×10^{10} cm^{-3}, which corresponds to 10^{-6} Torr, we can obtain the rate coefficient $\langle \sigma v \rangle \approx 1.2 \times 10^{-9}$ cm^3/sec. This is in reasonably good agreement with the reported values (Table I). It is possible to estimate the branching ratio for the reaction (He^+, N_2) because there is a large difference between the recombination coefficients for N_2^+ and N^+ ions. The rate coefficient for molecular ion recombination is very high; therefore, N_2^+ ions can be assumed to disappear immediately after they are created. Thus the drop of the electron density just after the injection of nitrogen yields the branching ratio of these two processes. From our measurements [see Fig. 2(b)] it was found that $\langle \sigma v \rangle_{(1a)} : \langle \sigma v \rangle_{(1b)} \sim 1:4$, whereas the published data are 1:1.2[7] and 1:10.[9]

The atomic nitrogen ions N^+ disappeared more slowly [line 3 in Fig. 2(d)]. This slow decay can be explained by electron-ion recombination and by exchanging charge with molecules (such as O_2^+) to produce molecular ions (NO^+ or O_2^+) which then dissociatively recombine rapidly. The presence of 3×10^{-7} Torr partial pressure of O_2 would be sufficient to explain this density-decay-time dependence.

In order to examine the published rate coefficient for charge exchange between N^+ and O_2 [Reaction (3) in Table I] oxygen was injected into a N^+ afterglow plasma. Line 2 in Fig. 2(d) shows the dependence of the decay time of N^+ plasma on O_2 partial pressure. The rate coefficient from this dependence ($\sim 4\times10^{-10}$ cm^3/sec) agrees with previously published values within a factor of 2.5.

To test whether these effects diminish at higher plasma temperatures, low-power nonresonant microwave heating was applied to the afterglow to maintain an electron temperature of about 1 eV. Density decay due to impurity effects occurs with approximately the same magnitude as in the case of the unheated afterglow plasma. Also, when nitrogen gas was injected into a plasma produced with continuous microwave heating at 70 W, resulting in an electron temperature of about 5 eV, both electron density and particle loss to the walls decreased with no detectable change in electron temperature. This is what is expected of charge-exchange processes similar to those described here, and the rate coefficient again agrees with that for the unheated afterglow plasma.

The measurement of the plasma-loss rate across the magnetic field, Γ, provides us with information about the effect of the recombination process on the plasma decay time at the best operating condition (1×10^{-7} Torr). It is observed that in the helium afterglow plasma at 1×10^{-7} Torr, the plasma confinement time $\tau_\perp$ estimated from the measured loss rate,

$$\tau_\perp \equiv \int n dv/\Gamma,$$

is in agreement with the decay time calculated from the microwave interferometer signal within a factor of 1.5. This result indicates that the present upper limit to the plasma confinement time is not due to the ion-molecular process.

A limited range of experiments is carried out with a D^+ afterglow plasma. It is found that the injection of N_2 gas reduces the plasma decay time, which is similar to the case of a helium plasma. However, since ion-beam experimental results for these processes are unavailable it is impossible to make any quantitative comparison. These experimental results are not the same as the ones reported by Ohkawa *et al.*,[2] in which they stated that oxygen-containing impurities are responsible for the reduction of the plasma decay time and a small effect was for nitrogen gas. However, we speculate that this difference may be caused by the different species of the remaining background pressure resulting in the subsequent molecular recombination process. In a D^+ afterglow plasma we also observe that under the best operating conditions the estimated confinement time from the loss measurement agrees with the density decay time obtained from the microwave interferometer signal.

To summarize, it is pointed out here that ions and impurity molecules exchange charges and then exhibit dissociative electron recombination even at moderate plasma temperatures and high vacuum conditions. The measurement of the plasma-loss rate shows that under the present best vacuum condition (1×10^{-7} Torr) the effect of recombination processes is not responsible for the difference between the observed confinement time and the decay time expected from classical processes. The rate coefficients obtained in our experiments support the results of other ion-beam experiments[3-7] and can explain the dependence of plasma decay times upon impurity pressure in the levitated spherator.

*Work supported by U. S. Atomic Energy Commission Contract No. AT(30-1)-1238.

†Present address: Department of Physics, University of California, Los Angeles, Calif. 90024.

‡On leave of absence from Kharkov Physical-Technical Institute, Kharkov, U. S. S. R.

[1]R. Freeman, L. Johnson, M. Okabayashi, G. Pacher, J. Schmidt, and S. Yoshikawa, Phys. Rev. Lett. 26, 356 (1971); R. Freeman, M. Okabayashi, G. Pacher, B. Ripin, J. Sinnis, J. Schmidt, and S. Yoshikawa, in Proceedings of the Fourth Conference on Plasma Physics and Nuclear Fusion Research, Madison, Wisconsin, 1971 (unpublished), paper No. CN-28/A-3.

[2]T. Ohkawa, M. Yoshikawa, J. R. Gilleland, and T. Tamano, in Proceedings of the Fourth Conference on Plasma Physics and Nuclear Fusion Research, Madison, Wisconsin, 1971 (unpublished), paper No. CN-28/A-2.

[3]An extensive compilation of ion-molecule reaction data is to be found in E. W. McDaniel, V. Cermak, A. Dalgarno, E. E. Ferguson, and L. Friedman, *Ion-Molecule Reactions* (Wiley, New York, 1970), Chap. 5.

[4]F. C. Fehsenfeld, A. L. Schmeltekopf, P. D. Goldan, H. I. Schiff, and E. E. Ferguson, J. Chem. Phys. 44, 4087 (1966).

[5]E. E. Ferguson, Rev. Geophys. 5, 305 (1967).

[6]P. D. Goldan, A. L. Schmeltekopf, F. C. Fehsenfeld, H. I. Schiff, and E. E. Ferguson, J. Chem. Phys. 44, 4095 (1966).

[7]H. Heimerl, R. Johnson, and M. A. Biondi, J. Chem. Phys. 51, 5041 (1969).

[8]The atomic recombination of N^+ is typically several orders of magnitude slower than molecular recombination and is neglected here.

[9]R. F. Stebbings, A. C. H. Smith, and H. Ehrhardt, J. Chem. Phys. 39, 968 (1963).

Acoustic-Wave Generation in a Low-Pressure Plasma Afterglow

Carl A. Ventrice
Electrical Engineering Department, Tennessee Technological University, Cookeville, Tennessee 38501
(Received 6 July 1971)

The afterglow of a weakly ionized helium plasma is investigated using an electrostatic probe. The existence of acoustic waves generated at the onset, or very early afterglow, is confirmed at neutral gas pressures as low as 0.1 Torr.

Evidence of the spontaneous generation and amplification of acoustic waves in weakly ionized plasmas has been reported by several investigators.[1-4] Berlande, Goldan, and Goldstein,[1] investigating the afterglow of low-temperature pulsed helium and neon plasmas, found that the electron density and light emission were periodically modulated. They associated this modulation with acoustic waves generated by the discharge itself. The frequency of modulation was found to be of the order of the fundamental resonance frequency of a lateral acoustic mode of the discharge tube. Strickler and Stewart,[2] while modulating argon and krypton dc glow discharges at pressures ranging from 13.5 to 38.5 Torr, observed a kinking of the discharge path at a series of discrete modulation frequencies. These frequencies were associated with radial and azimuthal acoustic modes of oscillation of the neutral-gas component.

This phenomenon has been treated analytically by Ingard[5] and Ingard and Schultz.[6] According to Ingard,[5] spontaneous generation and amplification of acoustic waves can arise in a weakly ionized plasma from the coherent transfer of energy between the electrons and the neutral-gas component. In the ordinary acoustic mode, the neutrals, electrons, and ions all move in phase with respect to one another, provided the acoustic-wave frequency is less than the plasma frequency and the neutral-neutral collision frequency.[7] By comparing the acoustic-wave rate of growth with that of decay, Ingard[5] has obtained the criterion for the onset of spontaneous oscillations:

$$\frac{1}{4\gamma}\frac{d^2}{l_n l_e}\left(\frac{T_e}{T_n}\right)^{3/2}\left(\frac{m_e}{m_n}\right)^{1/2}\frac{N_e}{N_n}>1.$$

In expression (1), a cylindrical chamber of diameter d is assumed; T_e and T_n are the electron and neutral-particle temperatures; m_e and m_n are the electron and neutral-particle masses; N_e and N_n are the electron and neutral-particle densities; γ is the ratio of the specific heat of the neutral gas at constant pressure to that at constant volume; l_e and l_n are quantities of the order of the mean free path of the electrons and neutral particles, respectively.

In this Letter, the results of an experiment are reported which confirm the existence of acoustic waves in a weakly ionized helium plasma afterglow, at a gas pressure as low as 0.1 Torr, with the chamber walls maintained at a temperature of 293°K. It is shown that the generation of these waves is not directly observable, but only their reflections off of the end walls.

The results were accomplished using a cylindrical Pyrex chamber of inside diameter d = 10.4 cm and length L = 340 cm. The plasma was generated by a 10-MHz electric field which was capacitively coupled to the gas by means of two ring electrodes. The electrodes were placed at the center of the chamber and had a separation of 30 cm. This allowed the plasma to be localized to a total length of approximately 70 cm about the center of the chamber. In each case, a balanced steady-state plasma was maintained before the rf power was removed. At the onset of the afterglow, care was taken to assure that no residual voltage remained on the electrodes. A double, floating, planar electrostatic probe was placed on the axis, at the center of the chamber. The probe tips were made of tungsten and each had a diameter of 1 mm. The probe was biased to collect ion satu-

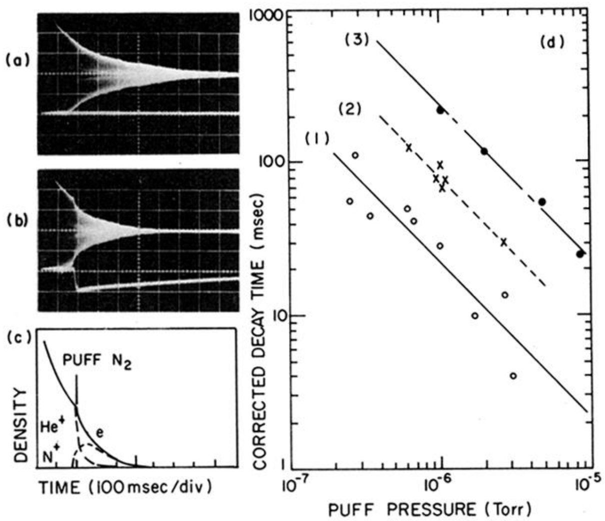

FIG. 2. The effect of injecting a small partial pressure of N_2 gas into the He^+ afterglow plasma. (a), (b) Oscillograms showing the decay of electron density (upper traces) without and with N_2 injection, respectively. The electron density is 1×10^{10} cm^{-3}/div and the fast-ionization gauge scale (lower traces) is 1×10^{-6} Torr/div. (c) Scheme of the variation of the composition of plasma with time. (d) Corrected decay times [using Eq. (2)] versus peak partial pressure of injected gases. Line 1 was obtained from the decay of 5876-Å helium line intensity after the injection of N_2. Line 3 is the decay time of the electron density due to N^+ ion recombination. Line 2 presents the electron-density decay time when the O_2 gas was injected into the N^+ afterglow plasma.