where the spectral function has been written in an approximate form with an assumption that the quantities Γ are constant, then by integrating in the complex ω plane we find the appearance of a decaying time exponential of the form

$$e^{-(\Gamma+\Gamma'+\bar{\Gamma}+\bar{\Gamma}')t} .$$

The quantities Γ themselves depend upon the density of the system being considered. This result may physically be compared to a cutting down of the length of a collision cylinder. A very similar effect is postulated by Cohen[10] using a resummation process when considering the divergences that arise from higher-order collision processes. It may be that this feature will build itself naturally when such higher-order processes are considered in the framework of the present technique. In effect, one is considering a many-body effect upon the scattering process. A very different many-body effect was introduced by Chapman and Cowling by considering the pair-correlation function at collision distances. This feature too may be incorporated.

The reasons for the appearance of the various terms may be attributed to the fact that we are dealing with a fairly exact equation of motion (14). Moreover, an examination of Eq. (93) shows that a distribution function is obtained from a Green's function by an integration process, implying thereby that a Green's function carries more information than a distribution function; it is this feature which is carried over into the final results providing the Γ-dependent quantities.

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PHYSICAL REVIEW A VOLUME 5, NUMBER 6 JUNE 1972

Reaction Rate Constant for $Ne^+ + 2Ne \rightarrow Ne_2^+ + Ne$ †

A. P. Vitols and H. J. Oskam
Department of Electrical Engineering, University of Minnesota, Minneapolis, Minnesota 55455

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The time dependence of the Ne^+ ion density was measured during the decay period of plasmas produced in neon for reduced gas pressures varying from 0.33 to 7.6 Torr and a gas temperature of 300 °K. The reaction rate constant for the termolecular ion-neutral association reaction $Ne^+ + 2Ne \rightarrow Ne_2^+ + Ne$ was found to be $k = (4.4 \pm 0.4) \times 10^{-32}$ cm^6 sec^{-1}. The value of the mobility of Ne^+ in neon was confirmed to be $\mu(Ne^+) = (4.0 \pm 0.1)$ cm^2 sec^{-1}. At gas pressures smaller than about 1.7 Torr the phenomenon of diffusion cooling was observed.

I. INTRODUCTION

In 1966, Sauter *et al.*[1] reported a reaction rate constant $k = 4.2 \times 10^{-32}$ cm^6 sec^{-1} for the termolecular ion neutral association reaction

$$Ne^+ + 2Ne \rightarrow Ne_2^+ + Ne. \tag{1}$$

They obtained this value from studies of the time dependence of the number density of Ne^+ during the decay period of plasmas produced in neon at gas pressures varying from about 2 to 8 Torr. The value obtained by Sauter *et al.* was about 25% smaller than the value of $k = (5.8 \pm 0.8) \times 10^{-32}$ cm^6 sec^{-1} reported by Beaty and Patterson[2] in 1963 from ion-mobility studies using ion transit-time techniques.

Several subsequent studies have been reported resulting in values of the rate constant for process (1) varying from about 6 to 9×10^{-32} cm^6 sec^{-1}.[3–6] However, recent results obtained by Märk and Oskam[7] during studies of the decay period of plasmas produced in neon-nitrogen mixtures showed that a value of a rate constant for process (1) larger than 5.2×10^{-32} cm^6 sec^{-1} would lead to physically unrealistic conclusions. Therefore, it was believed to be worthwhile to extend the studies of Sauter *et al.*[1] to a larger number of gas pressures.

The phenomenon of diffusion cooling and its influence on the decay properties of plasmas produced in neon at low gas pressures was first observed by Biondi[8] during studies of the time dependence of the electron density using microwave-cavity techniques. Recently, Ingold[9] reported an improvement of the theory of diffusion cooling as published by Biondi and obtained good agreement with the data published by Oskam and Mittelstad[10] relating to the time dependence of the electron density during the decay period of low-pressure neon plasmas. Measurements reported by Bhattacharya[6] of the time dependence of the number density of Ne^+ in these plasmas resulted in reasonable agreement in a rather limited pressure region with the theory of Ingold. However, at pressures below 1 Torr, Bhattacharya found that the time dependence of the number density of Ne^+ was nonexponential, and that the rate of Ne^+ ion loss was considerably smaller than expected. The present studies also cover the pressure region in which the influence of diffusion cooling on the rate of charged-particle loss from the plasma has to be taken into account, and no such anomalies were found.

The ambipolar diffusion coefficient of Ne^+ in neon is well known.[1-3,8,11] Therefore, studies during the decay period of plasmas produced in neon should result in a value of the ambipolar diffusion coefficient of Ne^+ close to this value. Otherwise, they may be suspected of being influenced by experimental errors and/or gas impurities.

II. EXPERIMENTAL METHOD

The experimental system used to study the time dependence of the ions during the afterglow period consists of a differentially pumped mass spectrometer which samples ions diffusing to the walls of a discharge tube.[12] The mass spectrometer used is of the electric-quadrupole type.[13]

The discharge region is a glass cylinder with metal endplates. One endplate is a molybdenum electrode, while the other is made of Kovar metal and contains a small hole (60 μ diam and 40 μ length) through which the ions effuse into the mass-spectrometer region.

The gas-handling system is analogous to that developed by Alpert.[14] The ultimate pressure was about 10^{-9} Torr following a system bakeout at 325 °C for a period of 24 h. The research-grade neon gas (purchased from Air Reduction Company) admitted to the discharge region was purified by means of the cataphoretic-segregation method.[15] The final cleaning of the discharge region was achieved by covering the discharge tube wall with a molybdenum layer obtained from sputtering the discharge electrode. This cleaning process was continued until the impurity-ion signal was less than 0.5% of that of the dominant ion throughout the afterglow. This condition was necessary to achieve reproducibility of the data. The gas pressure was measured by a capacitance manometer which controlled a servo-operated valve to maintain a constant preset pressure in the discharge tube.

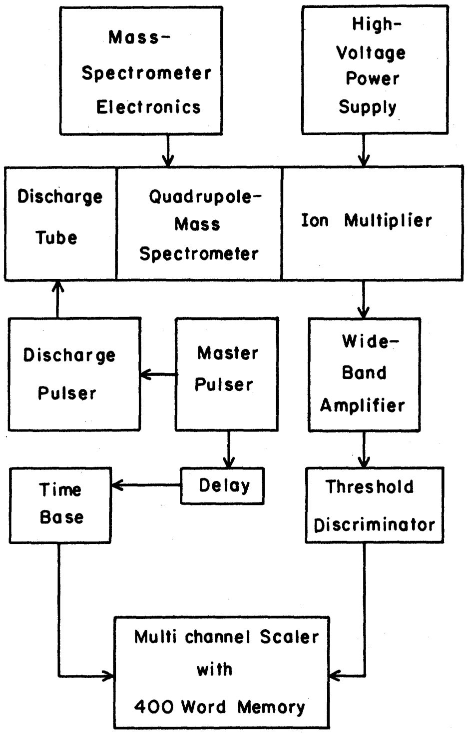

FIG. 1. Block diagram of the experimental system.

A block diagram of the measuring system is shown in Fig. 1. The discharge was produced by a high-voltage dc pulse applied between the discharge-tube electrodes or by a pulsed 85-MHz rf generator, which was coupled to the discharge region by an external ring electrode. The ions passing through the quadrupole mass spectrometer are detected by a Bendix magnetic electron multiplier, model M310B. The resulting anode pulses are amplified by a wide-band amplifier and those above a minimum pulse height are selected by a discriminator in order to reduce the background count rate. The pulses from the discriminator are then fed into a multichannel scaler. The afterglow is divided into 100, 200, or 400 time intervals which have a minimum duration of 25 μsec (12.5 μsec of which is dead time). As the multichannel scaler advances from channel to channel, the number of pulses in the corresponding time intervals in the afterglow are recorded in the memory

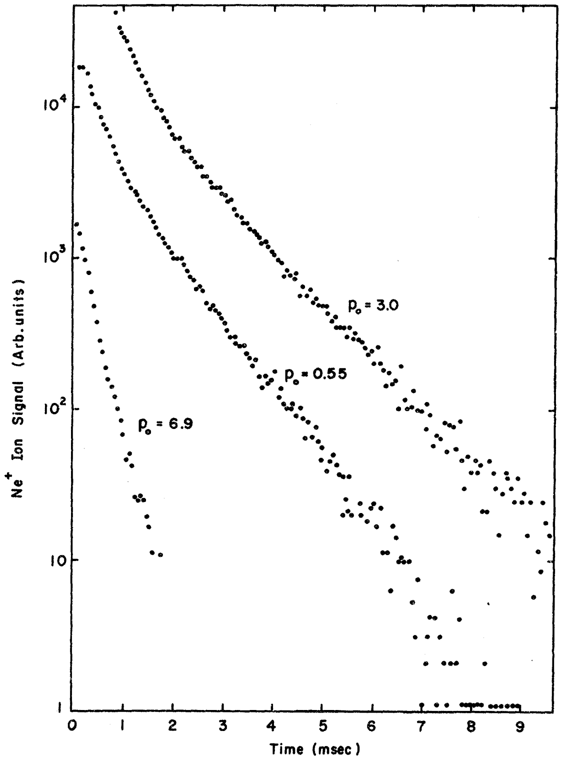

FIG. 2. The time dependence of the number density of Ne^+ ions during the decay period of plasmas produced in neon for three different gas pressures.

section. By accumulating the afterglow counts for a sufficient number of afterglow repetitions, a statistically significant number of counts can be recorded in each channel of the memory.

III. RESULTS AND DISCUSSION

The time dependence of the number density of Ne^+ during the plasma decay period is shown in Fig. 2 for three different gas pressures. When Ne^+ disappears from the plasma by a combination of ambipolar diffusion towards the plasma container walls and conversion into N_2^+ by process (1) the time constant τ of the fundamental-mode density distribution can be shown to be given by[1]

$$\frac{p_0}{\tau} = \frac{D_a p_0}{\Lambda^2} + C p_0^3 . \qquad (2)$$

Here, p_0 is the reduced gas pressure; D_a is the ambipolar diffusion coefficient of Ne^+ in neon; Λ is the characteristic diffusion length of the plasma container; $C = k \times 1.25 \times 10^{33}$ sec^{-1} Torr^{-2}, where k is the reaction rate constant of process (1).

The values measured for p_0/τ are plotted in Fig. 3 vs ρ_0^3 for pressures varying from 1.7 to 7.6 Torr. The slope of the solid line drawn through the data results in $k = (4.4 \pm 0.4) \times 10^{-32}$ cm^6 sec^{-1}. This value is in excellent agreement with the value reported by Sauter *et al.*[1] The value obtained in 1968 by Beaty and Patterson[3] from ion transit-time studies is about 60% larger. It is interesting to note that about the same magnitude of disagreement exists for the rate coefficient related to the conversion of He^+ into He_2^+.[16,17] It is as yet not understood why the two different measuring techniques yield different rate coefficients for this type of collision process. It is believed, however, that

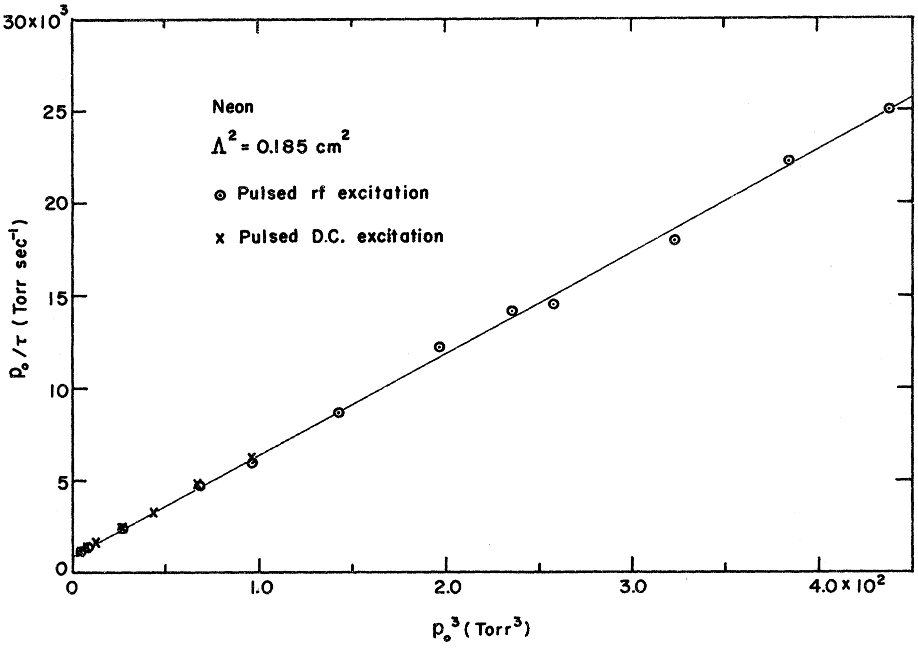

FIG. 3. Measured values of p_0/τ for Ne^+ as a function of p_0^3 at a gas temperature of 300 °K and gas pressures varying from 1.7 to 7.6 Torr (p_0 is the reduced gas pressure).

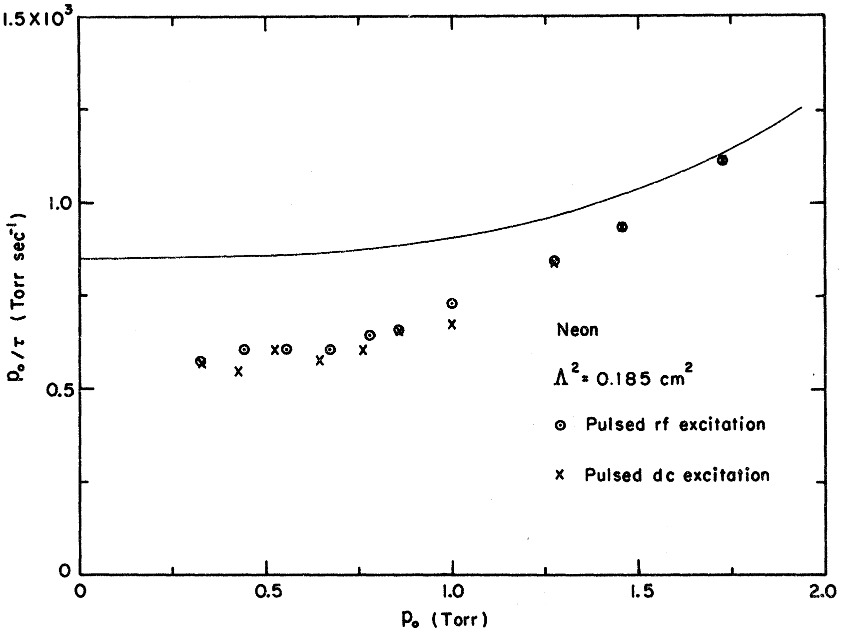

FIG. 4. Measured values of p_0/τ for Ne^+ as a function of p_0 at a gas temperature of 300 °K and gas pressures varying from 0.33 to 1.7 Torr.

the study of decaying plasmas is a more direct method of measuring the relevant rate coefficient since it only involves the direct determination of a time constant of the ion density time dependence, while the ion transit-time techniques require curve fitting by numerical methods.

Studies of decaying neon plasmas reported by Smith and Cromey[4] and by Battacharya[6] yielded rate constants for process (1) which are about 80% larger than the present value, although analogous measuring methods were used. It was observed that extensive purification of the neon gas and cleaning of the discharge region by sputtering of the molybdenum electrode after the bakeout procedure was required in order to obtain reproducible data which led to the present value of the rate constant for process (1). Without these precautions a larger value of the rate constant was obtained.

The intercept of the straight solid line at $p_0 = 0$ on an enlarged version of Fig. 3 yielded $D_a p_0 = 157 \pm 5$ cm² sec⁻¹, which corresponds to $\mu_0(Ne^+) = 4.0 \pm 0.1$ cm² V⁻¹ sec⁻¹ for the mobility of Ne^+ in neon. This value is in excellent agreement with previously reported values.[1–3,8,11] The value reported by Smith and Cromey[4] is about 15% larger than this generally accepted value for $\mu_0(Ne^+)$. Their larger value of $\mu_0(Ne^+)$ may have the same origin as their larger value of the rate constant for process (1).

The values measured for p_0/τ for pressures varying from 0.33 to 1.7 Torr are shown in Fig. 4. The solid line corresponds to the values of p_0/τ calculated from the data shown in Fig. 3. For these low gas pressures the measured p_0/τ values are smaller than the values given by Eq. (2) and show the influence of electron-diffusion cooling on the value of $D_a p_0$. At the lowest gas pressure the p_0/τ values were slightly larger than those obtained from the electron density studies reported by Oskam and Mittelstadt.[10] Even at the lowest gas pressure studied ($p_0 = 0.33$ Torr) the time dependence of the Ne^+ number density was an exponentional function of time during the later part of the afterglow period in contrast with the results obtained by Battacharya.[6] Moreover, the value of p_0/τ for Ne^+ was never smaller than the value corresponding to the predicted lower limit $D_a p_0/2\Lambda^2$. The studies reported by Battacharya,[6] however, resulted in p_0/τ values smaller than this predicted limit for gas pressures below 1 Torr. Therefore, the present value for the rate coefficient for process (1) is believed to be more reliable than the value reported by Battacharya, although he obtained the correct value for $D_a p_0$ by extrapolating his high-pressure data to $p_0 = 0$.

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Low-Frequency Grid Excitation in a Magnetized Plasma Column*

Gary Jahns and Gerard Van Hoven
Department of Physics, University of California, Irvine, California 92664

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Low-frequency signals on a grid in a cylindrical plasma column excite both ion acoustic and guided electron plasma waves. Experiments are described which show that the latter provide the dominant asymptotic response. Measurements of phase velocities and excitation levels are consistent with theoretical predictions.

Gould,[1] in calculating the full low-frequency ($\omega \ll \omega_{pi}$) plasma response to a grid antenna, exhibited the expected ion acoustic wave which decayed with distance by Landau damping, leaving an "electron contribution"[2] remaining in the far field. The plasma response enters the calculation through the dielectric function

$$\epsilon(\omega, k) = 1 - \frac{\omega_{pi}^2}{k^2 v_i^2} Z'\left(\frac{\omega}{k v_i}\right) - \frac{\omega_{pe}^2}{k^2 v_e^2} Z'\left(\frac{\omega}{k v_e}\right) , \quad (1)$$

for the infinite collisionless Maxwellian plasma considered by Gould. Here v_i (v_e) is the ion (electron) thermal velocity and Z' is the derivative of the plasma-dispersion function.[3] The associated dispersion relation has an infinite number of solutions for both ions and electrons.[4]

The *fundamental* electron wave is purely cut off ($k_i \lambda_d \lesssim 1$) below ω_{pe}, so that Gould's electron term arises from a sum over all higher-order electron (Landau) waves[5] weakly excited (and weakly damped) in the low-frequency limit.[6] However, a cylindrical column geometry and strong magnetic field significantly modify the dispersion of the fundamental electron mode, which can propagate down to zero frequency as a guided wave.[7,8]

A subsequent Q-machine experiment[9] was performed to test the spatial response predicted by Gould. An asymptotic signal was observed which exhibited approximately stationary phase, but its phase velocity was not reported due to problems of insufficient detector travel and sensitivity. In addition, the far-field amplitude was orders of magnitude larger than that expected.[9]

We have experimentally studied the response, for frequencies below f_{pi}, to signals applied to a single grid in a Q machine. The grid is negatively biased to modulate the ion density,[10] but affects the electrons through the space charge potential. Operating parameters are in the ranges typical of previous Q-machine ion-wave experiments, with $f_{pi} \sim 1$ MHz, $B_0 \sim 5$ kG, and an applied signal voltage of 0.5 V rms (low enough to avoid ballistic effects[11]).

Signals were received on an axially movable grid (also negatively biased) and fed into an interferometer detector. Plotting the phase-locked output vs distance produced traces, such as those shown in Fig. 1, for four detection phases successively differing by 90°. Features to note are the following: (i) The oscillatory signal is a decaying ion acoustic wave, verified by dispersion and Landau damping data. (ii) This response is superimposed on another persistent signal which exhibits only a slight change in phase, indicating a wavelength much longer than the 25-cm distance covered by the trace.

By using a finite wave train, the two responses could be separated by their differing transit times.