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Charging of dust grains in a plasma with negative ions

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The effect of negative ions on the charging of dust particles in a plasma is investigated experimentally. A plasma containing a very low percentage of electrons is formed in a single-ended Q machine when SF_6 is admitted into the vacuum system. The relatively cold Q machine electrons ($T_e \approx 0.2$ eV) readily attach to SF_6 molecules to form SF_6^- negative ions. Calculations of the dust charge indicate that for electrons, negative ions, and positive ions of comparable temperatures, the charge (or surface potential) of the dust can be positive if the positive ion mass is smaller than the negative ion mass and if ϵ, the ratio of the electron to positive ion density, is sufficiently small. The Q machine plasma is operated with K^+ positive ions (mass 39 amu) and SF_6^- negative ions (mass 146 amu), and also utilizes a rotating cylinder to dispense dust into the plasma column. Analysis of the current-voltage characteristics of a Langmuir probe in the dusty plasma shows evidence for the reduction in the (magnitude) of the negative dust charge and the transition to positively charged dust as the relative concentration of the residual electrons is reduced. Some remarks are offered concerning experiments that could become possible in a dusty plasma with positive grains.
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I. INTRODUCTION

The charge on a dust grain in a plasma in which photoelectron emission can be ignored is determined by the requirement that the number of electrons absorbed by the grain per second equals the corresponding absorption rate of positive ions.[1–3] Since typically the electrons move considerably more rapidly, they collide more frequently with the dust grains than the positive ions, and for a balance to occur, the grain will acquire a negative potential relative to the plasma, so that the electrons will be repelled and the positive ions attracted. This has been observed in laboratory experiments.[4,5] Photoelectron emission from dust grains exposed to UV radiation is often the dominant charging mechanism for dust in space and astrophysical environments,[1,2] and this has also been investigated in the laboratory.[6]

It has also become apparent that in plasmas used for technological applications and in plasmas in the Earth's upper atmosphere, the presence of negative ions can be an important factor in fixing the charge on dust particles. Hydrogenated amorphous silicon photovoltaics are typically grown in rf discharges operating with silane (SiH_4). An unintended by-product of these discharges is silicon particles which grow in the plasma. Although most of the particles are trapped in the plasma by electrostatic forces, a significant fraction of particles in the 2–8 nm range escape and become incorporated into the depositing films. To escape, these particles must become neutral. Gallagher[7] explains this with a model that takes into account the fact that in an electron attaching gas like silane, the electron density can be much less than the positive ion density, causing a large fraction of the particles to be neutral, since electrons attached to heavy negative ions are far less effective in charging the dust. Klumov *et al.*[8] have recently shown theoretically that adding even a small amount of molecular oxygen (which forms O- ions) to an rf gas-discharge dusty plasma can have very strong effects on both the plasma transport properties and the microparticle force balance.

Recent *in situ* measurements of charged particles and plasma parameters in the nighttime polar mesosphere revealed the presence of positively charged nanoparticles in the altitude range between 80 and 90 km.[9] These positively charged particles were observed in a region dominated by positive and negative ions and very few electrons. The positive dust charge was explained as the result of the dominant charging effect of the lighter positive ions compared to the heavier negative ions and the small number of electrons present.

The two examples just presented point to the need for basic laboratory investigations of the effect of negative ions on charging of dust grains. The charging of dust grains in a plasma with negative ions has been discussed theoretically by Mamun and Shukla,[10] D'Angelo,[11] and Annaratone and Allen.[12] In this paper we describe an experimental investigation of the effects of negative ions on the charging of dust grains in a plasma. The results show that as the relative concentration of negative ions in the plasma is increased, the magnitude of the negative charge decreases, and eventually a transition to positively charged dust is observed. This is facilitated by the experimental design in which the positive ion mass is less than the negative ion mass and the residual electron density is negligible. This is only possible, in large part due to the choice of the Q machine plasma source operated with singly charged potassium ions (K^+) and the addition of SF_6 gas. Our motivation here is to provide evidence that, under the right conditions, positively charged dust can be produced in a negative ion plasma. In this investigation, the actual magnitude of the charge is not determined, but only

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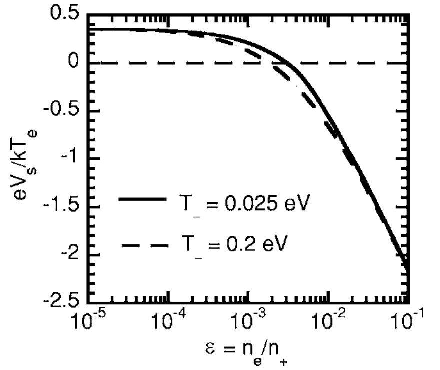

FIG. 1. Normalized dust floating (surface) potential (relative to the plasma potential) versus $\epsilon = n_e/n_+$, the fraction of free electrons in the plasma, computed from Eqs. (2) and (3). $T_e = T_+ = 0.2$ eV, and for $T_- = 0.025$ eV (solid line) and 0.2 eV (dashed line).

the sign of the dust charge. More detailed studies are expected to follow.

In Sec. II, the theory of dust charging in a plasma with negative ions is presented. Section III describes the experimental apparatus and methods used in this investigation. The experimental results are presented and discussed in Sec. IV. In Sec. V we discuss possible experiments that can be performed in a dusty plasma with positive dust. Section VI provides a brief summary of the results and main conclusions.

II. THEORY OF DUST CHARGING IN A PLASMA WITH NEGATIVE IONS

Consider an *isolated* spherical dust grain of radius a introduced into a plasma consisting of electrons of density n_e, singly charged positive ions of density n_+, and singly charged negative ions of density n_-. Define $\epsilon \equiv n_e/n_+$ as the fraction of electrons relative to positive ions. Using the charge neutrality condition $n_+ = n_e + n_-$, we can express the negative ion density in terms of the positive ion density as $n_- = (1-\epsilon)n_+$. The charge on a spherical dust grain is given by $Q = 4\pi\epsilon_o a V_s$, where V_s is the dust grain floating (surface) potential relative to the plasma potential. The temperatures of the positive ions, electrons, and negative ions are T_+, T_e, and T_-, respectively. Since the potential V_s can be positive or negative, depending upon the conditions, it is necessary to use different expressions for the positive ion, negative ion, and electron currents to the dust grain for the case in which $V_s > 0$ and $V_s < 0$. For $V_s > 0$, electrons and negative ions are accelerated toward the dust grain and the positive ions are repelled. For $V_s < 0$, the positive ions are accelerated to the dust grain and the electrons and negative ions are repelled. We assume that the repelled species can be treated using the Boltzmann relation and the attracted species follows the usual orbital motion limiting theory.[10–12] The grain surface potential is determined by the condition that the total current to the grain be zero (electrically floating); i.e.,

$$I_e + I_- + I_+ = 0. \tag{1}$$

For $V_s < 0$, this condition is

$$-\epsilon\left(\frac{kT_e}{2\pi m_e}\right)^{1/2} e^{eV_s/kT_e} - (1-\epsilon)\left(\frac{kT_-}{2\pi m_-}\right)^{1/2} e^{eV_s/kT_-} + \left(\frac{kT_+}{2\pi m_+}\right)^{1/2}\left(1 - \frac{eV_s}{kT_+}\right) = 0, \tag{2}$$

while for $V_s > 0$, the condition is

$$-\epsilon\left(\frac{kT_e}{2\pi m_e}\right)^{1/2}\left(1 + \frac{eV_s}{kT_e}\right) - (1-\epsilon)\left(\frac{kT_-}{2\pi m_-}\right)^{1/2}\left(1 + \frac{eV_s}{kT_-}\right) + \left(\frac{kT_+}{2\pi m_+}\right)^{1/2} e^{-eV_s/kT_+} = 0. \tag{3}$$

The grain surface potential is determined by numerical solution of Eqs. (2) and (3). Figure 1 shows a plot of eV_s/kT_e versus $\epsilon = n_e/n_+$ for parameters relevant to our experimental conditions: K^+/SF_6^-, $T_e = T_+ = 0.2$ eV and for two values of the negative ion temperature $T_- = 0.025$ and 0.2 eV. The transition from negative to positive dust occurs for $\epsilon \approx 2 \times 10^{-3}$. A grain of 10 μm radius would then acquire a maximum positive charge corresponding to $Z = Q/e \approx 500$.

III. EXPERIMENTAL SETUP AND METHODS

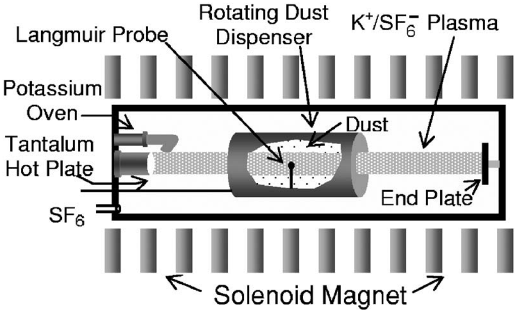

FIG. 2. Schematic of the negative ion dusty plasma device. The plasma is produced by surface ionization of K atoms on a hot (~2300 K) tantalum plate. Dust grains are introduced using the rotating dust dispenser. Negative ions are produced by admitting SF_6 gas into the system.

The experiment utilized the setup shown schematically in Fig. 2. The device is a single-ended *Q* machine[13] that produces a fully ionized K^+/e plasma of approximately 6 cm diameter and 1 m length by surface ionization of K atoms on a hot (~2300 K) tantalum plate. The plasma is radially confined by a longitudinal magnetic field of 0.3 T. The electrons and ions have roughly the same temperature of 0.2 eV at a density of $\sim 10^{10}$ cm^{-3}. The main diagnostic is a planar (2 mm diameter disk) Langmuir probe with its surface normal parallel to the magnetic field.

Dust grains can be dispersed into a portion of the plasma column using a rotating cylinder described in detail by Xu *et al.*[14] The rotating cylinder (Fig. 2) surrounds a 30 cm portion of the plasma column and is lined with aluminum wool into which dust particles are embedded. As the cylinder rotates around the plasma, dust grains fall through the plasma where they are charged by collection of electrons and ions, as described in our earlier work.[4] The dust particles were

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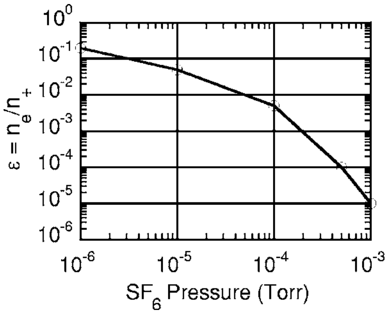

FIG. 3. The dependence of the parameter $n_e/n_+=\epsilon$, on SF_6 pressure. Data reprinted with the permission of N. Sato (Ref. 16).

hollow glass microspheres with a relatively broad size distribution, with the majority if particles having a diameter of approximately 35 μm.

A plasma containing negative ions was produced by leaking into the vacuum chamber the highly electronegative gas SF_6 at partial pressures in the range of $10^{-6}-10^{-3}$ Torr.[15,16] The relatively low-energy electrons in the plasma attach to the SF_6 molecules to form SF_6^- negative ions. Negative ion formation readily occurs since the attachment cross section for SF_6^- formation peaks roughly in the energy range of the Q machine electrons.[17] In addition, the absence of high-energy electrons ($\sim$ few to tens of eVs), which are present in other types of plasma sources, greatly minimizes the formation of multiple negative ion species such as SF_5^- and F^- as well as positive ion species due to electron impact ionization of SF_6. Negative ion production is evidenced by the reduction in the negative Langmuir probe saturation current when SF_6 gas is admitted into the plasma, since the thermal speed of the SF_6^- negative ions is much less than the electron thermal speed. Only relatively small amounts of SF_6 need to be added to produce significant reductions in the negative probe saturation current. At an SF_6 partial pressure of only 6×10^{-6} Torr, the current is reduced by a factor of 2.

The relative concentration of "free" electrons, $\epsilon=n_e/n_+$, can be estimated by analysis of the Langmuir probe characteristics in the negative ion plasma, using $\epsilon=(I_-/I_+)\times(m_e/m_+)^{1/2}(T_+/T_e)^{1/2}-(m_e/m_-)^{1/2}(T_-/T_e)^{1/2}$, where I_-/I_+ is the ratio of the negative saturation current to positive saturation current.[16] The probe measurement is useful in providing an estimate of ϵ, but this method is increasingly less accurate as ϵ gets smaller (as the SF_6 partial pressure is increased). A more accurate determination of ϵ in a Q machine has been made by Sato[16] using the well-known dispersion properties of electron and ion plasma waves, which are very sensitive to the electron fraction. By comparing the measured dispersion relations of electron and ion waves launched into the negative ion plasma with the theoretical dispersion relations, values of ϵ as a function of the SF_6 pressure were determined in a single-ended Q machine operated with potassium under conditions that were essentially the same as those in our experiments. Sato's results, shown in Fig. 3, indicate that values of $\epsilon<10^{-4}$ are possible for $P(SF_6)\gtrsim5\times10^{-4}$ Torr.

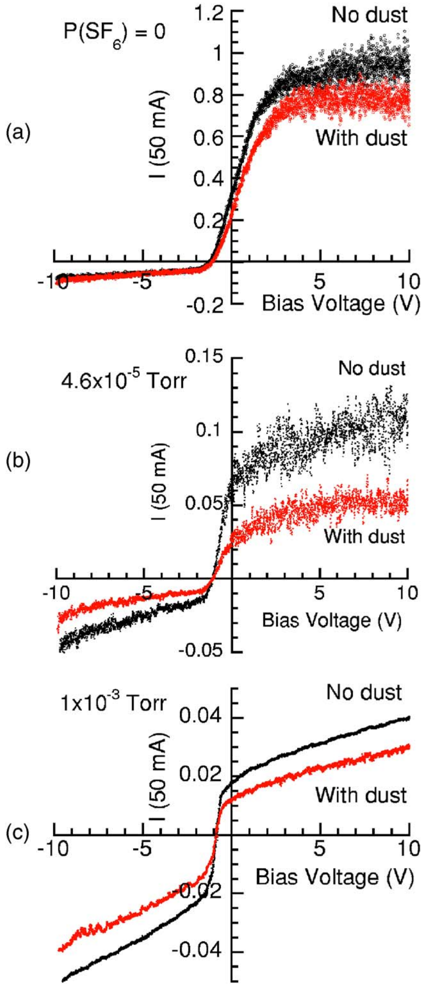

FIG. 4. (Color online) Langmuir probe current-voltage characteristics obtained in the absence of and in the presence of dust grains, for (a) $P(SF_6)=0$, (b) $P(SF_6)=4.6\times10^{-5}$ Torr, and (c) $P(SF_6)=1.0\times10^{-3}$ Torr.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

The procedure consisted of producing a negative ion plasma at a particular value of the SF_6 pressure (or ϵ, according to Fig. 3) and then introducing dust into this plasma from the rotating dispenser. The effect of dust charging was inferred by measuring the reductions in the negative saturation current (I_-) and positive saturation current (I_+) of a Langmuir probe when the dust was introduced. Additional, indirect evidence was obtained by measuring the difference between the floating potential (V_f) of the Langmuir probe and the plasma potential (V_p).

Representative sets (with no dust present and with dust present) of Langmuir probe current-voltage I-V characteristics obtained at three values of $P(SF_6)$ are shown in Fig. 4. In these probe I-V characteristics positive currents correspond to the collection of electrons and negative ions. Figure 4(a) shows the case in which there were no negative ions in the plasma; i.e., $P(SF_6)=0$. This case, which corresponds to that in our earlier study,[4] shows a reduction in the negative (electron) saturation current when the dust is present due to the fact that electrons, which are attached to the dust grains of extremely low mobility, are not collected by the probe. In

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Fig. 4(b), the $P(\mathrm{SF}_6)$ was increased to 4.6×10^{-5} Torr ($\epsilon\approx10^{-2}$). Note that the negative saturation current, before the dust is present, has been reduced by about a factor of 10 compared to the $P(\mathrm{SF}_6)=0$ case of Fig. 4(a). With the dust present, both the negative and positive saturation currents are reduced, although the reduction in the negative saturation current is larger than the reduction in the positive saturation current. In Fig. 4(c) with $P(\mathrm{SF}_6)=1\times10^{-3}$ Torr ($\epsilon\approx10^{-5}$), the reduction in the positive saturation when the dust is present is *larger* than the reduction in the negative saturation current. The ratio of the positive probe saturation currents with and without dust is about 10%–20% smaller than the corresponding ratio of the negative probe saturation currents. The reductions in positive and negative saturation currents in Figs. 4(b) and 4(c) occur now since, with the removal of a substantial fraction of the electrons, the positive and negative ions have comparable mobilities.

Figure 5(a) shows measurements of the quantities $R_-=I_-/I_{-0}$, $R_+=I_+/I_{+0}$, and $\eta=R_-/R_+$, over the full range of SF_6 pressures investigated. Here, $I_{-(+)}$ is the negative (positive) probe saturation current when dust is present, and $I_{-(+)0}$ is the corresponding value of the negative (positive) probe saturation current in the absence of dust. Note that for $P(\mathrm{SF}_6)\sim5\times10^{-5}$ Torr, there is a transition from $\eta<1$ to $\eta>1$. We will show that the reductions in both the positive and negative probe saturation currents that occur at high SF_6 pressures are consistent with the presence of positively charged dust. In all cases the saturation currents were obtained by first identifying the plasma potential (from the location of the maxima in the first derivative of the current) and then extrapolating the linearly fitted currents in the nonexponential portions of the characteristics to the plasma potential.

The Langmuir probe characteristics were also analyzed to see how the difference between the floating potential of the probe (V_f) and the plasma space potential (V_p), changed with SF_6 pressure. A plot of V_f-V_p versus SF_6 pressure is shown in Fig. 5(b). At low values of $P(\mathrm{SF}_6)$, $V_f<V_p$, but with increasing pressures, V_f approaches V_p, eventually overtaking V_p, resulting in relatively small but positive values of V_f-V_p for $P(\mathrm{SF}_6)>\sim5\times10^{-4}$ Torr. In a 0.2 eV plasma, the positive potentials correspond to $e(V_f-V_p)/kT\sim0.2-0.3$. The behavior of the floating potential of the probe (relative to the plasma potential) should correspond to that of the dust particles, which behave a tiny floating "probes" in the plasma.[18] However, although the probe and dust floating potentials may have the same qualitative behavior with $P(\mathrm{SF}_6)$, one might not expect exact correspondence in the magnitudes of the probe and dust floating potentials since the expressions used to compute the probe and dust currents are not the same. The dust particles are spherical collectors with sizes smaller than the Debye length, whereas the probe is planar with a diameter considerably larger than $\lambda_D=(\epsilon_o kT_+/en_+)^{1/2}\sim30\ \mu$m.

We now discuss how the probe measurements are used to obtain information on the dust charge state. The analysis of the variations in the probe saturation currents is considerably simplified by considering the situation in which the ef-

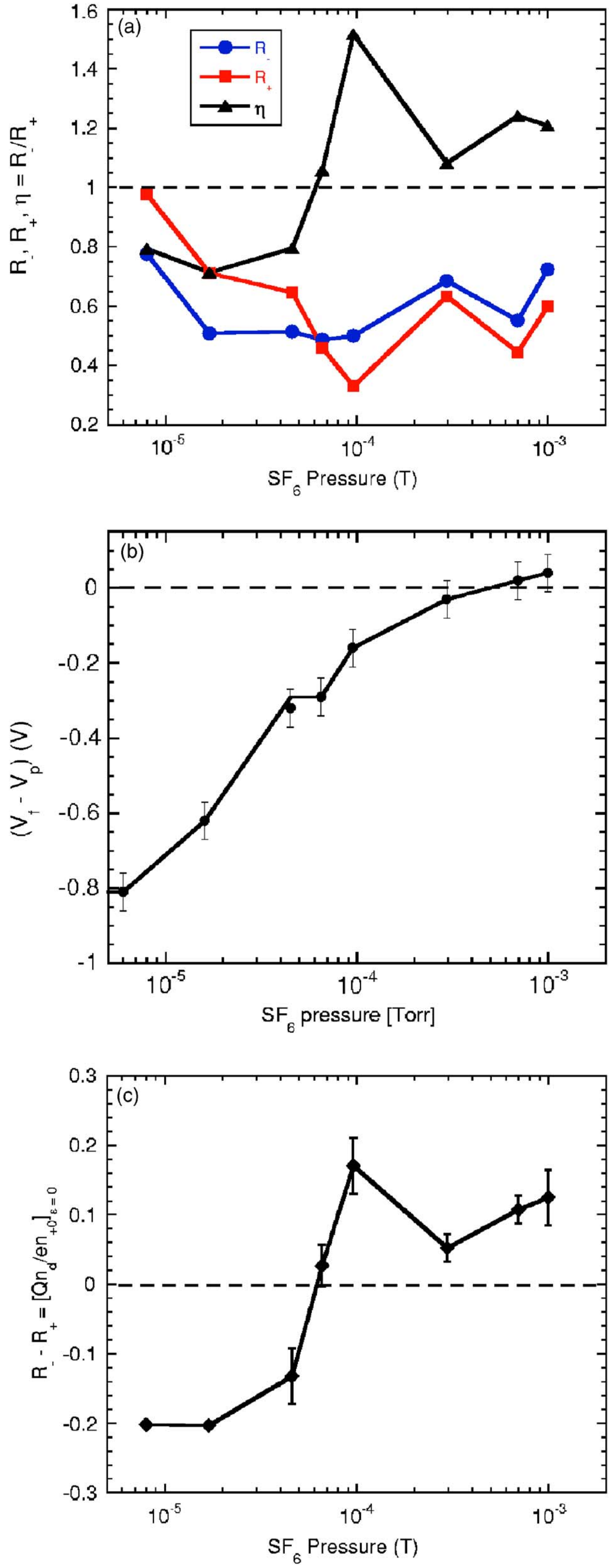

FIG. 5. (Color online) Measurements obtained from an analysis of the probe I-V characteristics with and without dust for various SF_6 pressures. (a) $R_-=I_-/I_{-0}$ (negative saturation current with dust/negative saturation current with no dust), $R_+=I_+/I_{+0}$ (positive saturation current with dust/positive saturation current with no dust), $\eta=R_-/R_+$. (b) Difference between the probe floating potential and plasma space potential, V_f-V_p. (c) The normalized dust charge $[Qn_d/en_{+0}]_{\epsilon=0}$, determined from the difference (R_--R_+) [see Eq. (5)] neglecting the residual electrons.

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fect of residual electrons is ignored. This analysis is first presented before the more detailed analysis which includes the residual electron contribution. The effect of the electron currents are small for values of $\epsilon \sim 10^{-4}$, which holds for $P(\mathrm{SF}_6) > 5\times 10^{-4}$ Torr. Let $n_{+0} \approx n_{-0}$ be the plasma density when no dust is present, and n_+ and n_- the positive ion and negative ion densities, respectively, in the presence of dust. If n_d is the number of dust grains per unit volume and Q the average charge on the grains, the condition for charge neutrality reads $en_+ + Qn_d = en_-$. Define $\eta = en_-/en_+ = (en_-/en_{-0})/(en_+/en_{+0})$ as the ratio of negative charge per unit volume to positive charge per unit volume in the plasma when dust is present. Using the charge neutrality condition, we have that $\eta = (en_+ + Qn_d)/en_+ = 1 + (Qn_d/en_+)$. In terms of η, $(Qn_d/e) = n_+(\eta - 1)$. η can be determined directly from the Langmuir probe characteristics, with dust (negative and positive saturation currents I_- and I_+) and without dust (negative and positive saturation currents I_{-0} and I_{+0}) as

$$\eta = \frac{I_-/I_{-0}}{I_+/I_{+0}} = \frac{R_-}{R_+}, \tag{4}$$

so that

$$\left[\frac{Qn_d}{en_{+0}}\right]_{\epsilon=0} = \left(\frac{I_-}{I_{-0}} - \frac{I_+}{I_{+0}}\right) = (R_- - R_+), \tag{5}$$

where the $\epsilon=0$ subscript indicates that in this analysis the contribution of residual electrons has been neglected. Equation (5) can now be applied to interpret the data in Fig. 5(a) by showing, in Fig. 5(c), the quantity $(R_- - R_+)$ versus $P(\mathrm{SF}_6)$. The change in sign of $(R_- - R_+)$ is then taken as an indication [see Eq. (5)] of the transition from positive to negative dust, as $P(\mathrm{SF}_6)$ increases. Neglecting the residual electrons is an increasingly good approximation as the SF_6 pressure is increased (ϵ decreased), and this approximation does not affect the conclusion that a transition from negative to positive dust occurred, although the value of the pressure at which the transition occurs is underestimated in this approximate analysis.

We next discuss how the effects of the electrons can be taken into account. Some approximations are still necessary, since the Langmuir probe does not provide independent measurements of the electron and negative ion contributions to the total negative current. Including the electrons, the condition of charge neutrality now reads $Qn_d = en_e + en_- - en_+ = en_+(\eta - 1)$, where now η is now defined as

$$\eta = \frac{n_e + n_-}{n_+} = \frac{n_e + n_-}{n_{e0} + n_{-0}}\frac{n_{+0}}{n_+} \tag{6}$$

with $n_{e0} = \epsilon n_{+0}$, $n_{-0} = (1-\epsilon)n_{+0}$, $R_- = (I_e + I_-)/(I_{e0} + I_{-0})$, and $R_+ = I_+/I_{+0}$. η can be expressed as

$$\eta = (1/R_+)[(\epsilon\beta_{e,-} + 1 - \epsilon)R_- - (\beta_{e,-} - 1)(n_e/n_{+0})], \tag{7}$$

where $\beta_{e,-} = v_{e,T}/v_{-,T}$ is the ratio of the thermal velocities of the electrons and negative ions. With this η the normalized dust charge density, Qn_d/en_{+0} is determined from

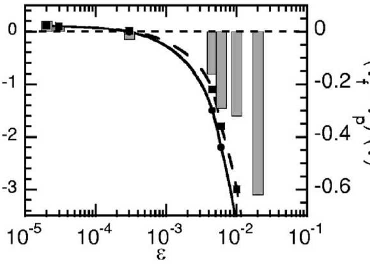

FIG. 6. Qn_d/en_{+0} versus ϵ, obtained from the data in Fig. 5(a) using Eq. (8), (taking into account the effect of the residual electrons) for n_e/n_{+0} values of 1 (solid) and 0.9 (dashed). Also shown as a bar plot is the quantity, $V_f - V_p$, from Fig. 5. The ϵ values corresponding to the SF_6 pressures were obtained from the data in Fig. 3.

$$\frac{Qn_d}{en_{+0}} = [(\epsilon\beta_{e,-} + 1 - \epsilon)R_- - R_+ - (\beta_{e,-} - 1)(n_e/n_{+0})]. \tag{8}$$

Note that for $\epsilon=0$ ($n_e=0$), Eq. (8) reduces to Eq. (5). Equation (7) provides for a more accurate determination of the dust charge (in particular its sign), provided an estimate for n_e/n_{+0} can be made. Now, $n_e/n_{+0} = (n_e/n_{e0})(n_{e0}/n_{+0}) = (n_e/n_{e0})\epsilon$. The quantity $n_e/n_{e0} < 1$, since some of the residual electrons, not attached to SF_6, will attach to the dust. An analysis of the data in Fig. 5, using Eq. (8), and using Fig. 3 to convert from SF_6 pressure to ϵ values, is shown in Fig. 6. A value of $\beta_{e,-} = 733$ was used ($T_- = 0.5T_e$). The two curves represent assumed values of $n_e/n_{e0} = 1$ and 0.9. For low values of ϵ, the curves are identical for both values of n_e/n_{e0}. For low values of ϵ, there is very little change in the curves even for smaller assumed values of n_e/n_{e0}. The change in the probe floating potential relative to the plasma potential ($V_f - V_p$) with ϵ is also shown in Fig. 6 as a bar graph. The reduction in the magnitude of the quantities Qn_d/en_+ and $V_f - V_p$ and the reversal of the sign of these quantities as ϵ is reduced is in general agreement with the theoretical calculations presented in Fig. 1, although the observed value of ϵ at which the transition occurs is lower than the predicted value.

V. EXPERIMENTS IN A DUSTY PLASMA WITH POSITIVE DUST

Having discussed the conditions under which a dusty plasma with positive dust could be found, we now briefly discuss experiments that might now be possible with positive dust.

A number of theoretical and numerical investigations of waves in dusty plasmas with positive dust have been reported. D'Angelo and Song[19] studied the effect of positive dust on the Kelvin Helmholtz (KH) instability in a magnetized dusty plasma. The KH instability is driven by perpendicular shear in magnetic field aligned plasma flows. Their results, which may be relevant to the understanding of wave motion in type I comet tails, showed that the presence of positively charged grains reduced the critical shear so that the excitation of the instability becomes easier. On the other hand, Chow and Rosenberg[20] showed that positively charged dust can lead to the stabilization of the electrostatic ion cyclotron instability. Similarly, Merlino[21] found that positive

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dust has a stabilizing effect on the excitation of current-driven ion acoustic waves. D'Angelo[11] investigated the excitation of low frequency ion-acoustic and dust-acoustic waves in collisional positive dust plasmas, under conditions that were essentially identical to those described in this paper. Ghosh and Gupta[22] studied large amplitude dust acoustic solitary waves in a dusty plasma with positive dust. Some of these dusty plasma wave issues could now be addressed experimentally.

Since the charging rates of dust by the positive and negative ions are nearly balanced, it may be possible due to the stochastic nature of the charging process, that under some circumstances a dusty plasma having *both* positive and negative dust may be formed. In such a dusty plasma, the effects of coagulation of dust particles could be studied. The effect of coagulation of dust of opposite sign has been considered theoretically by Horanyi and Goertz[23] in connection with processes in the presolar nebula, and circumstellar and cometary environments. Theoretical studies have also been made of dusty plasma waves in plasmas having both positive and negative dust. D'Angelo[24,25] obtained the dispersion relations for both dust-acoustic and electrostatic dust-cyclotron waves in plasmas with opposite polarity grains. Torney *et al.*[26] analyzed the two-stream instability in a dusty plasma with grains of opposite charge, which may be important in understanding the origin of ultra low frequency fluctuations in the Earth's mesosphere.

The formation of Coulomb crystals in a plasma with positive dust can be investigated. Rosenberg and Mendis[27] considered the conditions for forming a positive dust lattice for grains that are charged positively by ultraviolet induced photoelectron emission. The conditions for Coulomb crystal formation in a plasma with positive and negative ions have not been considered.

A related problem that could be addressed is the effect of the ion drag forces due to positive and negative ions on the dust particles. If an electric field is present in such a dusty plasma, the positive and negative ions will drift in opposite directions. For comparable densities of positive and negative ions, one would expect the drag forces would also be comparable in magnitude but opposite in direction. Since the outward ion drag force is thought to be responsible for the formation of a void under microgravity conditions, the presence of positive and negative ions could thwart the tendency for void formation.

Finally, we mention one additional effect that could be of some importance to dust in electronegative plasmas. As is evident from Fig. 1, the presence of negative ions can have a profound effect on the dust charge state. In a typical electron/positive ion plasma, the potential of a dust grain is determined mainly by the electron temperature, a parameter which the experimentalist has little control over. However, the introduction of relatively small amounts of an electron attaching gas, such as SF_6, could be used as a means of controlling the dust potential and charge. This, for example, might provide as a means of varying the interparticle separation of dust grains in Coulomb crystals.

VI. SUMMARY AND CONCLUSIONS

In a dusty plasma, conditions have been established which cause positive charging of dust grains. Theoretically (see Fig. 1), if the positive ion mass is larger than the negative ion mass and if the negative ion density is comparable to the positive ion density ("electron free"), dust grains will acquire a positive charge. This effect was studied experimentally in a plasma of K^+ positive ions and a substantial concentration of SF_6^- negative ions. In qualitative agreement with the theoretical prediction, we find that as the contribution of the electrons is reduced, the magnitude of the dust charge is reduced and a transition to positively charged dust is observed. Evidence for this was obtained from the behavior of the Langmuir probe saturation currents with and without dust, as well as the direct measurement of the probe floating potential relative to the plasma potential.

We emphasize once again that this experimental investigation was, in part, possible due to the unique plasma conditions present in a *Q* machine. In particular, the relatively low electron temperature facilitates the formation of a high percentage of negative ions and a single negative ion species, SF_6^-. On the other hand, the geometry of the *Q* machine severely restricts access to the dusty plasma for laser imaging diagnostics, and we are forced to rely on information provided by the Langmuir probe.

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