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in an Electric Field in a High Vacuum**

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INTERACTION OF A STREAM OF DIELECTRIC SPHERES IN AN ELECTRIC FIELD IN A HIGH VACUUM*

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ABSTRACT

The interaction of a stream of dielectric spheres in an electric field in a high vacuum is investigated both theoretically and experimentally. This investigation is motivated by an elaborate attempt to detect fractional electric charges which might exist in matter, namely, a search for isolated quarks in matter. The theoretical analysis is intended for pinpointing the basic interaction mechanism by which a stream of dielectric spheres becomes destabilized in an electric field. One important result of this analysis is a suggested method by which to eliminate the destabilizing forces. The experiments performed are intended to study the behavior of a stream of monodisperse dielectric liquid drops in an electric field in a high vacuum. It is seen from these experiments that the deflections of any two drops in the stream with charges differing by one electronic charge is not always the same due to the destabilization effects.

1. INTRODUCTION

Several theoretical papers have been published indicating the possibility of the existence of fractional electric charges in matter. Fairbank and his co-workers at Stanford have reported experimental data which are indicative of the presence of fractional charges on superconducting niobium spheres¹. A number of other experiments have been in progress for some time to search for fractional charges in other materials than niobium. Hagstrom, Hirsch and Hendricks use techniques of generating a stream of uniform liquid drops whose trajectories pass vertically through a constant electric field between two parallel vertical plates? If the behavior of each of the drops is independent, the deflection of the drops as they pass through the electric field is a direct measure of the electric charge on the drops (Fig. 1). The deflection in the x-direction (parallel to the electric field) is given by

$$x = \frac{qEv_0^2}{mg^2} \left(1 + \frac{Lg}{v_0^2} - \sqrt{1 + \frac{2Lg}{v_0^2}} \right) \quad (1)$$

where q is the charge on the drop whose mass is m , E is the electric field in the x-direction, v_0 is the initial vertical velocity of the drop (in the z-direction), L is the length of the deflection field in the z-direction, and g is the acceleration due to gravity.

Equation (1) is correct if the drops are very far apart and are freely falling in a vacuum. If the drops are close together, but start downward into the

electric field along the same trajectory, Eq. (1) should be modified to account for the inter-drop forces resulting from polarization charges produced by the electric field.

II. THEORY

Consider a set of three drops, A, B and C, as shown in Fig. 2. The force, F_B in the x-direction on the middle drop due to the polarization charges is given by

$$F_B = 2 \left(\frac{Q^2}{4\pi\epsilon_0 D^2} \right) \left[\frac{2\epsilon}{[\epsilon^2 + 1]^3/2} + \frac{1-\epsilon}{[(1-\epsilon)^2 + 1]^3/2} - \frac{1+\epsilon}{[(1+\epsilon)^2 + 1]^3/2} \right] \quad (2)$$

where $Q = \frac{3\pi\epsilon_0 k}{k+2} Ea^2$ is the dipole charge, $D = \frac{4a}{3}$

is the dipole length, $x_B = \epsilon D$ is the displacement of drop B with respect to a line between drops A and C, $s = 1D$ is the vertical, center-to-center spacing between the drops, and a is the drop radius. This force is similar to the force between dipoles except for the macroscopic separation of the positive and negative induced charges. A true dipole has a length which approaches zero and a charge such that ql is finite and equal to the dipole moment.

A detailed analysis would involve solving the Laplace's equation for a dielectric sphere in a uniform electric field E with a proper set of boundary conditions. After a straightforward algebra, an expression for the surface charge density $\sigma(\theta)$ of the dielectric sphere is then obtained as

$$\sigma(\theta) = \frac{3k}{k+2} \epsilon_0 E \cos\theta \quad (3)$$

where k is the dielectric constant of the sphere, ϵ_0 is the permittivity of free space, and θ is the phase angle of the spherical coordinate system whose origin is at the center of the sphere and which has the azimuthal symmetry about the axis in the direction of the electric field E .

If the moment of the positive and negative surface charge density, σ , is integrated over the right and left halves of the sphere respectively, the centroids of the charges can be found to be at a

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distance of $\frac{2}{3}a$ from the center of the sphere and along the line of the electric field, E . Thus, the equivalent dipole length D is $\frac{4}{3}a$. The dipole charge Q is calculated to be $Q = \frac{3\epsilon_0 k E a^2}{k+2}$.

Getting back to Eq. (2), one observes that the force F_B is always in the direction of the displacement z thus qualifying itself as a destabilizing force. Also, if one is interested in gaining some insight into the force F_B as to its possible effects on the behavior of the middle drop B , a small-displacement-expansion of F_B can be made assuming that $z \ll a$. The net result is an equation of motion for the displacement z , which is

$$d^2z(t)/dt^2 = 2Gz(t) \quad (4)$$

where G is a positive constant characterizing the strength of the force on the drop B due to the drops A and C , and is a function of the dipole charge and length Q and D , the drop mass m , the vertical, center-to-center spacing between the drops z , and the free space permittivity ϵ_0 .

A general solution to Eq. (4) is

$$z(t) = \frac{1}{2} [z(0) - \dot{z}(0)] e^{-t/\beta} + \frac{1}{2} [z(0) + \dot{z}(0)] e^{t/\beta} \quad (5)$$

where $z(0)$ and $\dot{z}(0)$ are, respectively, the initial values of $z(t)$ and its time derivative $dz(t)/dt$, and $\beta = 1/\sqrt{2G}$ is a characteristic time over which the drop B reacts to the force F_B , displacing itself from the original position. For the conditions, under which the present experiments were carried out, $z(0) \gg \dot{z}(0)$, thus simplifying Eq. (5) to:

$$z(t) = z(0) \cosh(t/\beta) \quad (6)$$

where β is on the order of a millisecond. One can also show that for large $z(z \geq 6)$, $\beta = z^2/2$.

III. EXPERIMENT

Experimentally the effects of the induced charges become apparent in the deflections of drops with equal masses whose net charges differ by integer numbers of electrons. By Eq. (1) we see that the differences in the deflections of any two drops with charges differing by one electronic charge should be the same. However, we see experimentally that the deflection differences are not always the same for one electronic charge difference.

This is shown in Fig. 3 where the most closely spaced vertical lines are trajectories of drops whose net charge differs by 1 electron. Because of the drop-drop interactions resulting from the polarization charges, the trajectory spacings are not all integer multiples of a least value of deflection for 1 electron. The drops which produced the lines, shown in Fig. 3, entered the deflection field spaced approximately two diameters apart vertically. If we compare the forces resulting from the electric field acting on the net charge with the forces resulting from the polarized charge interactions, we see that a spacing of 20 diameters between drops would reduce the interactive forces to a reasonable value. Such spacing may be accomplished by removing 9 out of 10 drops in the stream. Several methods are available to effect the removal of the unwanted drops.

If the 9 drops to be removed were highly charged, an electric field could be used to deflect the charged drops into a collector, leaving the remaining, virtually uncharged, drops to continue on through the main deflection field. Because the drops are formed from a high resistivity liquid ($\rho = 10^{14}$ ohm-centimeters), inductive charging during the formation process is difficult. To circumvent this problem a pulsed electron beam will be used to charge the drops which are to be removed. By pulsing the electron beam off at appropriate times, every tenth drop can be left uncharged. Preliminary experiments have provided some encouraging results.

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Drop diameter	$100\ \mu\text{m}$
Liquid density	$934\ \text{kg/m}^3$
Initial velocity	$2.5\ \text{m/sec}$
E-field	$1.67 \times 10^6\ \text{V/m}$
Deflection plates	
Length	$3.1\ \text{m}$
Spacing	$1.8\ \text{cm}$

Figure 1. Deflection of drops with different charges in electric field.

Figure 2. Interaction of three drops, A, B and C, in electric field.

Figure 3. Picture showing drop trajectory destabilization effect due to interaction between drops in electric field.