EXPERIMENT 45
Driving Force and Terminal Velocity

To answer the question "Is there a smallest unit of electric charge?" we must be able to work with and measure extremely small charges. We detect electric charges through the electric forces exerted on charged bodies. To detect very small charges, therefore, we must be able to handle very small forces. The weight and other forces acting on bodies of ordinary size are so large that electric forces are insignificant unless the charge is great; therefore, very small objects are essential. Useful objects for this purpose are the small plastic spheres made for calibrating electron microscopes. Figure 45.1 shows a few of them. The spheres are rarely neutral; most of them carry a small electric charge. We shall attempt to measure the charge by measuring the electric forces acting on them.

The apparatus is shown in Fig. 45.2. The only critical adjustment involves positioning the light source so that the image of the bulb filament is formed right at the center of the plates. To adjust the light source, you can hold a piece of paper vertically over the center of the plates, tilt the light source so that it shines on the paper, and slide the light-source tube back and forth until a clear image is formed on the paper. The filament of the light source should be vertical.

Plug the wires from the plates into the connectors. CAUTION: The voltage is dangerously high; do not turn on the power supply until you have finished making the connections.

The switch controls the charge on the plates. In the center position there is no charge; with the switch up, one plate is positive, the other negative; and with the switch down, the polarities are reversed.

With the light turned on, squeeze the bulb to bring in a cloud of spheres, leaving the switch centered. What do the spheres do? (Note that everything appears inverted when you look through the microscope.) Are they all moving in the same direction? Are they accelerating as they move across the field?

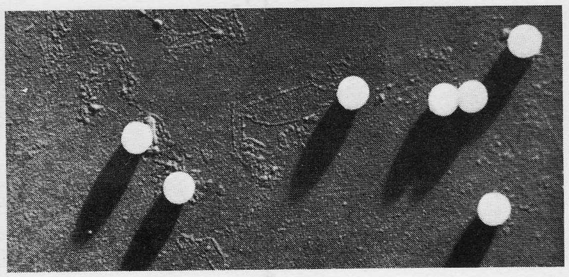

FIGURE 45.1 An electron-microscope photograph of a few latex spheres of diameter 1.8 microns. Those used in the experiment are a little smaller.

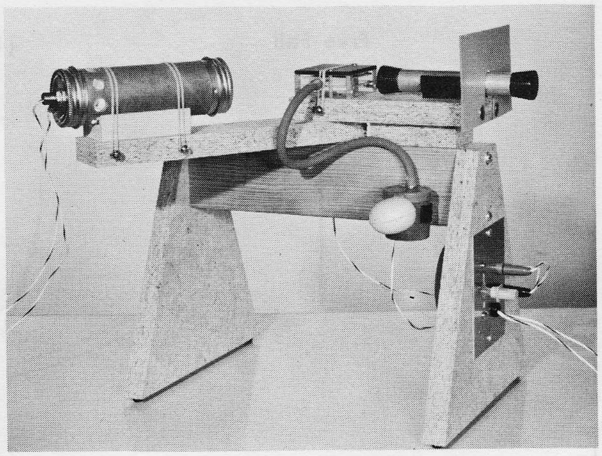

FIGURE 45.2 The jar contains a suspension of the spheres in water. When you squeeze the bulb, a fine spray of water with many spheres is blown into the region between the plates. The water rapidly evaporates, leaving a cloud of spheres visible through the microscope as bright points.

ments or clumps of spheres; look for those which move slowly in free fall.

Plot the data for any one sphere on a graph like that in Fig. 45.4. How does the velocity V^+, observed when the driving force is $F_g + F_e$, compare with the velocity when gravity alone is the driving force? How does the velocity V^-, observed when the driving force is $F_g - F_e$ for the same sphere, compare with the velocity when gravity alone is the driving force? What is the shape of the graph of velocity as a function of driving force for one sphere? What is the shape of the graph of velocity versus force for your other spheres? What can you conclude about the relation between velocity and driving force?

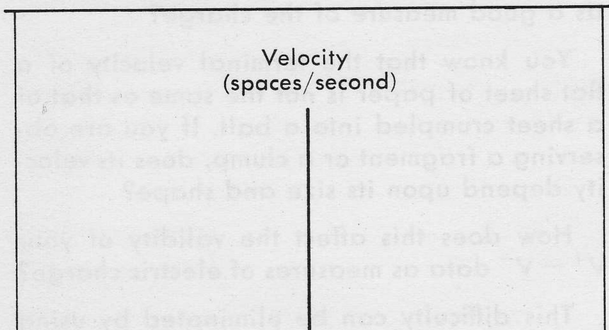

FIGURE 45.4

Select a sphere and measure its speed in two parts of the field of view. What forces are acting on it?

How does charging the plates affect the motion of the spheres? What happens when you reverse the direction of the electric field? Measure again the velocity of a sphere in two parts of the field of view to see whether it is accelerating when an electric force is being applied. An explanation for the observed motion is that the air resistance on these tiny spheres increases rapidly and they very soon move at a constant terminal velocity with the force of air resistance equal and opposite to the driving force (which may be gravity alone or gravity plus an electric force). In this experiment we wish to find the relation between the terminal velocity and the force driving the sphere.

You will need three measurements on each of about a dozen spheres. A set for one sphere consists of: a velocity in free-fall under gravity alone with no charge on plates; a velocity V^+ where the electrical force is in the same direction as the gravitational force and the magnitudes of the forces add ($F_g + F_e$); and a velocity V^- where the electrical force is opposite to the gravitational force ($F_g - F_e$). The diagram of Fig. 45.3 shows the forces involved.

For each sphere you will therefore have three velocities: one for which the driving force is gravity alone; one, V^+, with an electric force added; and one, V^-, with the same electric force subtracted.

Measure the velocities by timing the motion over, say, ten spaces. Try to avoid frag-

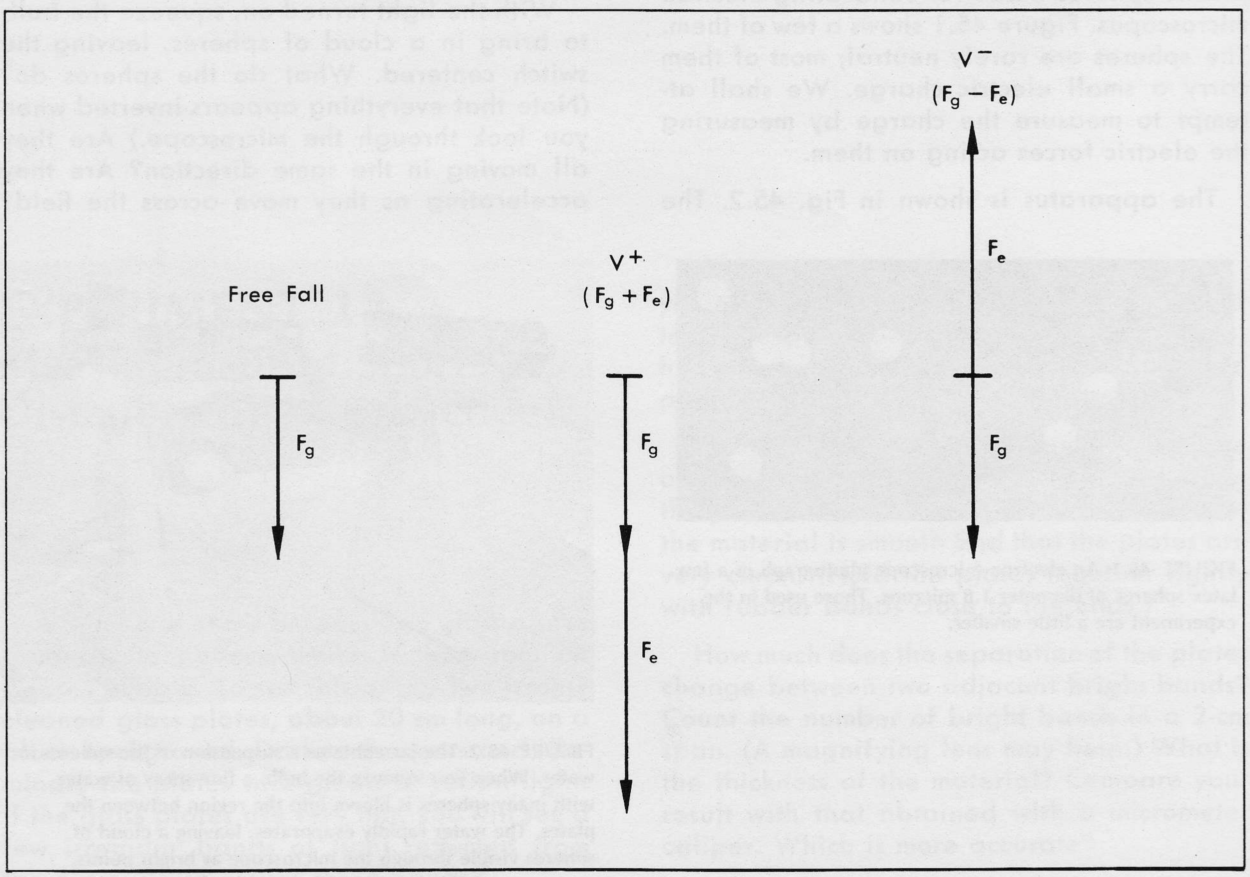

FIGURE 45.3

EXPERIMENT 46

The Millikan Experiment

In the previous experiment we established that the terminal velocity of the small plastic spheres is directly proportional to the driving force acting on them. We shall now use this result to investigate whether the different charges appearing on different spheres are multiples of a unit charge. If we are careful, we can choose spheres of the same mass and thus ensure that the force of gravity is the same on each. Furthermore, since we keep the charge on the plates constant, the electric forces will be proportional to the charges on the spheres, and the differences in observed velocity will be proportional to differences in charge on the spheres.

Set up the apparatus as in the previous experiment. CAUTION: Do not forget that the voltage on the plates is dangerous. Squeeze the bulb to bring in a batch of spheres; then throw the switch to charge the plates and sweep out the fast-moving spheres that have large charges.

With the switch you can get two combinations of forces: either $F_g + F_e$ (electric force in the same direction as gravity) or $F_g - F_e$ (electric force in the direction opposite to gravity). For each of at least 12 to 15 spheres measure the velocity of the V^+ run ($F_g + F_e$) and the V^- run ($F_g - F_e$).

If you were sure that all test objects were the same, you could analyze your results by making a bar graph of the speeds at a definite setting of the switch and looking for evidence that certain speeds are favored. But you have seen that many objects in the field of view fall extremely slowly or very fast, and in Fig. 45.1 (previous experiment) two spheres are shown clumped together. There is little doubt, therefore, that fragments and clumps are common, and we cannot be sure that all the spheres are of the same size.

By canceling out the effect of gravity we can minimize errors resulting from mass differences. We know that the terminal velocity is proportional to the force. For each sphere you have a velocity V^+ proportional to $F_g + F_e$ and a second velocity V^- proportional to $F_g - F_e$. If you subtract V^- from V^+, to what force is the resulting velocity proportional? Could you use these differences of velocity as a good measure of the charge?

You know that the terminal velocity of a flat sheet of paper is not the same as that of a sheet crumpled into a ball. If you are observing a fragment or a clump, does its velocity depend upon its size and shape?

How does this affect the validity of your $V^+ - V^-$ data as measures of electric charge?

This difficulty can be eliminated by using only true spheres, all of the same mass. If you *add* the velocities V^+ and V^-, to what force is the sum proportional? How can you use this result to select a set of identical spheres?

There are various ways in which you could analyze these data to look for evidence of the discreteness of electric charge. One simple way is to plot $V^+ - V^-$, equally spaced along the horizontal axis, in increasing order on a bar graph. What evidence do you see for the existence of a natural unit of charge? What is the smallest number of charges you measured?