The electrostatic spray is generated by applying a high voltage to a metal capillary needle that is fed the working octoil fluid. For a typical experiment, the needle is maintained at a voltage between −2.5 and −9 kV. The octoil is doped with tetrabutyl ammonium picrate to increase the conductivity. The octoil is driven to the needle by a pressure difference between the vacuum tank and the reservoir pressure which is typically kept at 25–100 Torr.

The largest component of the experimental apparatus is the high charge-to-mass ratio quadrupole mass spectrometer consisting of four stainless steel rods that are 1.43 m long and arranged in a square array. Oscillating voltages with a dc bias are applied to the isolated poles in diagonal pairs. The quadrupole mass spectrometer is a dynamic filter that can separate charged droplets of an electrostatic spray according to their charge-to-mass ratios. The range of accessible charge-to-mass ratio is controlled by the resolution R which is defined by $R=(Q/M)/\Delta Q/M$ where Q/M is the central value and $\Delta Q/M$ is its accessible width. The resolution in turn is controlled by the dc bias voltage. Typically $R=10$ or larger is desirable although such a high resolution was not always attained in the experiments.

The filtered droplets by the mass spectrometer transfer their charge to the charge detector which is a 1.88 cm circular stainless steel plate located at the exit of the quadrupole. Only droplets within a narrow band of charge-to-mass ratio defined by R are able to transverse the length of the quadrupole. The filtered droplets transfer their charge to the plate when they contact thereby generating current and voltage which are then fed into a high speed precision electrometer, an Amptek A250. By determining the charge of these filtered droplets, all other parameters of a droplet can be calculated as the charge-to-mass ratio is already known. The Amptek A250 is a fast integrating electrometer whose output voltage increases proportionally to the number of electrons detected. The output of the A250 charge detector is amplified and collected by a Canberra multichannel analyzer (MCA). The data accumulated on the MCA are transferred to a personal computer for data analysis using various softwares. It should be noted that the quadrupole mass filter does not by itself influence the electrometer, since no current is detected with the quadrupole mass filter operating when no droplets are present. Charges accumulated on the stainless steel bars of the mass filter are discharged to the ground through the power supply cables which are grounded.

IV. RESULTS OF THE EXPERIMENTS

All the experiments were run in the same general manner. First, the capillary needle position relative to the quadrupole axis is fixed and the entire components placed in the vacuum tank. Once a hard vacuum was achieved, the voltage and operating frequency would be set for the desired charge-to-mass ratio and resolution. The fluid reservoir pressure which controls octoil flow rate, and the needle voltage would then be adjusted to maximize the number of the droplets passing through the quadrupole mass spectrometer and reaching the detector.

Distributions of more than 10,000 droplets are generally desired for a good statistical representation of the electrostatic spray. To get this many droplet counts can take more than a few hours. For this reason, the experimental apparatus has been modified so that the data are automatically taken and stored. In case of emergencies such as power failure or leak to the vacuum tank, a feedback system is installed so that the system shuts off automatically thereby avoiding a damage to the charge detector by a gas breakdown.

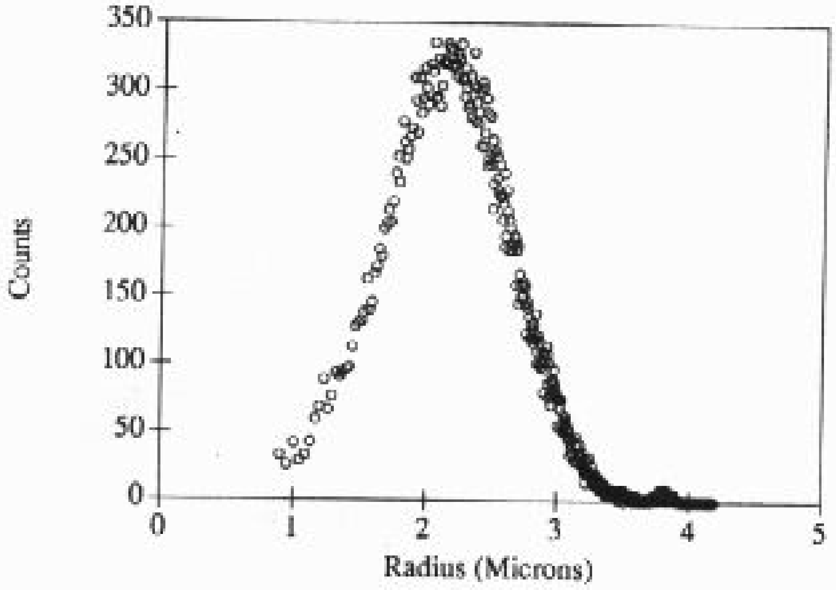

FIG. 2. An example of the droplet size distribution for the charge-to-mass ratio of 0.285 C/kg with the quadrupole mass filter resolution of 9. An octoil was used. The peak of the distribution is near 2.2 μm with the spread of about 1 μm.

Shown in Fig. 2 is a typical distribution of charged droplets showing the number of the counts versus radius of the droplets for the charge-to-mass ratio equal to 0.285 C/kg with the resolution equal to 9. It is clear that the center radius of the droplets is slightly larger than 2 μm with the spread of about 1 μm. It is straightforward to calculate the classical Rayleigh limit for the size of the droplet confirming the observed level of charging is a fraction of that limit.

For larger charge-to-mass ratio droplets, counts can be double peaked as shown in Fig. 3 for $Q/M=0.757$ C/kg. Both the Rayleigh theory and the minimum energy theory cannot explain the split of the distribution. The maximum

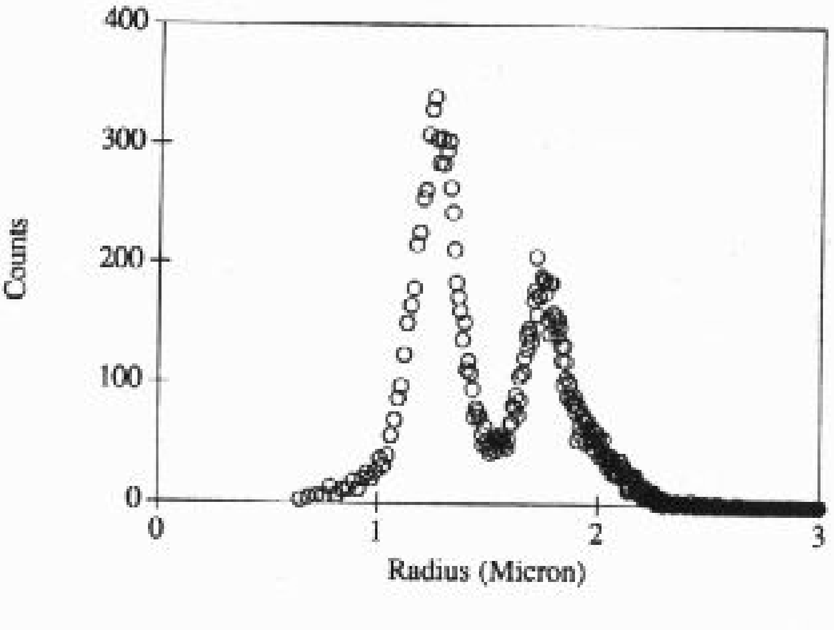

FIG. 3. The same as in Fig. 2 with the charge-to-mass ratio equal to 0.757 C/kg and the resolution of 4. Note the two sharp peaks near 1.2 and 1.7 μm.