Measurement of the charge of a single dust particle

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Abstract. In this work the method of a single particle charge and mass measurement in electrodynamic Paul trap is proposed. In the experiments polydisperse Al₂O₃ particles were used. The measured masses were in the range from \(1 \times 10^{-8}\) to \(9 \times 10^{-8}\) g. The measured charges were in the range from \(2 \times 10^5\) to \(1.3 \times 10^6\) e.

1. Introduction
To measure the charge of a single particle in gas medium three methods are known: the direct measurement of the charge [1], the induction method [2] and the method based on the particle deflection in an electric field [3]. In the case of a direct measurement of the charge, it is a problem to select individual particles and to measure small values of the charge. The essence of the induction charge measurement is a registration of the charge, induced in a ring electrode, when a charged particle flies through it. The substantial restriction for an use of this method is a concentration of particles in a volume, which should not exceed \(10^{-3}\) cm\(^{-3}\). The method based on the particle deflection in an electric field is a development of the Millikan work [4]. It based on the observation of a trajectory of a particle moving in mutually perpendicular electric and gravitational fields. With the knowledge of components of the particle velocity in the vertical (gravity) and horizontal (electric field strength) directions and taking into account the viscosity of the medium, it is possible to measure the particle charge and size.

The measuring of a charge of particles is required in the study of Coulomb clusters [5–8]. In [9, 10] by mathematical simulation methods, we have shown that with the electrodynamic traps it is possible to confine charged dust particles in an air flow. Highly charged dust particles can form ordered structures of strongly interacting particles in the electrodynamic traps. The conditions at which a confinement of dust particles is possible were formulated. In particular, requirements to a value of the particle charge were determined. For dust particle charging the corona discharge is often used in practice.

The aim of this study is to measure the charge and the mass of a single particle in a linear electrodynamic trap.

2. Experimental setup
In this work, we measured the charge of a particle by analyzing its position in the gravitational and electric fields. The mass of the particle was determined by analyzing its motion in a gravitational field.
The experimental setup includes the corona discharger and the linear electrodynamic trap. Particles illumination is provided by a laser with wavelength of 532 nm and a maximum power of 150 mW, that allows to record the particles with diameters larger than 1 micron. Visualization of particles is provided by a CCD camera HiSpec 1 with a maximum resolution of 1280x1024 pixels. The camera allows us to record video frames with a maximum resolution at up to 506 frames/sec. During the experiments at first stage we confined an ensemble of dust particles and then removed all the particles except one, which was investigated in the next stage. The sketch of the electrodynamic trap is shown in figure 1.

Figure 1. Sketch of the electrodynamic trap; 1, 2, 3, 4 is trap electrodes, where 5 is the laser; 6 is a charged particle; 7 is a metal ball; 8 is the CCD camera.

The AC voltage of the same amplitude is applied to the vertically oriented electrodes of the trap. In this case \( U_{12} = U_{34} = Usin(\omega t) \). The sign of the electric potential applied to the ball is the same as the sign of the charge of the particle. The charged particle levitates at some distance from the ball. The laser provides illumination of the particle. The distance between the ball and the particle is measured by processing the frames received from a CCD camera.

3. The particle mass measurement
We measured the mass of the particle by its free fall velocity. The electric potential \( U = 8000 \) V was applied to the ball. Then the ball was grounded, and the trajectory of the particle was recorded by the CCD camera. In the experiment a polydisperse powder \( \text{Al}_2\text{O}_3 \) was used. In the
experiment, a position of the particle relative to the center of the ball at equal time intervals 
\( t = 30 \) msec was determined. The particle velocity \( v \) on each segment of the trajectory defined
as \( v_i = (R_i - R_{i+1})/t \), where \( R_i \) is coordinate of segment beginning, \( R_{i+1} \) is coordinate of
the segment end. Figure 2 shows results of the measurement of the free fall particle velocity as an
example of the experiments performed.

\[
\begin{align*}
\text{Figure 2.} & \quad \text{Results of the free fall velocity measurements. The dash lines indicate the 95}\% \\
& \quad \text{confidence interval.}
\end{align*}
\]

If a particle falls in a viscous medium under its own weight, a steady velocity is reached when
the weight is balanced by the force of friction. Assuming the particle has a spherical shape, the
resulting velocity is equal to

\[
v = \frac{2r^2 g \rho}{9 \eta},
\]

where \( \rho \) is a particle density, \( r \) is a particle radius, \( \eta \) is dynamic viscosity of the medium. Hence,
the particle diameter can be expressed by

\[
d = 2r = \sqrt{\frac{9 \eta \mu}{2 g \rho}}.
\]

Taking a steady particle velocity equal to the average free fall velocity \( v_a = 14.9 \) cm/sec we
obtain the particle diameter \( d = 35.4 \) micron and the particle mass \( m = 9.25 \times 10^{-8} \) g.

4. The particle charge measurement
If the particle is confined in the electrodynamic trap at some distance from the charged ball it
means that the force of gravity is equal to the force of the electric field.

\[
mg = qE,
\]

where \( q \) is the particle charge. It should be noted the following. The vertical component of
the force acting on the particle by the electrodynamic trap is negligibly small. Considering the
electric field \( E \) acting on the particle we should take into account not only the electric field
produced by the ball but the electric field from charges induced at the trap electrodes.

To determine the particle charge twelve measurements were carried out. Different values of
potential were applied to the ball and the distance from the particle to the center of the ball
was determined. The initial value of the potential was equal to 15000 V. The final value of the
potential was equal to 150 V. After the final measurement the potential value was increased to the initial value. The position of the particle coincided with the first measurement. Thus, during the experiment the particle charge has not changed. Figure 3 shows the calculated values of the particle charge. The electric field intensity was calculated numerically using special program. The mean particle charge value is equal to $12 \times 10^5$ e.

![Figure 3](image_url)

**Figure 3.** Results of the particle charge measurement. The dash lines indicate the 95% confidence interval.

The table 1 shows the results of measurements of masses and charges for three different particles. The relative error in the charge measurement is equal to 20%. The relative error in the mass measurement is equal to 10%.

| $q, 10^5$ e | $m, 10^{-8}$ g |
|------------|----------------|
| 2.5        | 1.15           |
| 3.5        | 2.42           |
| 12.3       | 9.25           |

### Table 1. Results of particles charges and masses measurements.

5. **Conclusion**

The method for measuring the mass and the charge of a single dust particle confined in the electrodynamic Paul trap has been proposed. The particle mass was measured by its free fall velocity. The particle charge was measured from the condition of a balance between the gravitational and electric field forces acting on the dust particle. In the experiments polydisperse Al$_2$O$_3$ particles were used. The measured masses were in the range from $1 \times 10^{-8}$ to $9 \times 10^{-8}$ g. The measured charges were in the range from $2 \times 10^5$ to $1.3 \times 10^6$ e.

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