# Electric charge of the microparticles in a complex plasma with an external magnetic field

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## Ⅰ. INTRODUCTION

Experiments on complex plasmas have been actively conducted for about 15 years. They are described in some text books and review papers[1~4]. Negatively charged microparticles levitate in the ion sheath caused by balancing of the downward gravitational force $Mg$ with the upward force $QE$ where $M$ and $Q$ are the mass and electric charge of particles, respectively, $g$ is the gravitational constant and $E$ is the electric force at the location where the particle is levitating. The electric charge $Q$ is an important physical quantity and was experimentally measured[2,5]. It was recently estimated by measuring electric field $E$ at the height of particles[6]. However, these measurements were performed by indirect methods. In this work, we measure the charge $Q$ using a novel and direct method which is described in the present paper.

The cyclotron radius $R$ of a microparticle moving with a velocity $v$ under a perpendicular magnetic field $B$ is given by

$$R = - Mvc/QB, \qquad (1)$$

where c is the velocity of light. The electric charge $Q$ is obtained by measuring $R$ and $v$. The measured values of $Q$ are compared with those estimated from the relation $Q = aV_s$ where $a$ and $V_s$ are the radius and the electric potential of the particles, respectively. For microparticles of $a \simeq 0.1\mu\text{m}$ when $B$ = 400G and $v$ = 10cm/s, $R$ may become 10cm. However, it is possible to measure $R$ since the used device is of a large surface area[7].

## Ⅱ. EXPERIMENTAL PROCEDURE

The experiment was performed in the YCOPEX device[7]. The schematic diagram of the device is shown in Fig. 1. The glass tube G is of 100cm in length and 15cm in inner diam. A 2mm thick stainless steel plate P(14.5cm×80cm) is inserted in the tube. The left-hand segment(30cm) of the plate can be bent upward. At the left edge of this segment, a buzzer Z is set as a source of the microparticles. The right part(50cm) of the plate is horizontal. Over and under this segment, two Helmholtz coils of 80cm in diam. are placed.

A plasma is produced by applying an rf voltage(13.56MHz and 10W) to the stainless steel mesh M(8cm×80cm) that is placed over the tube and the grounded plate. Argon gas is used at a pressure of 0.01Torr. The plasma parameters are measured with a plane probe of 6mm in diam.[7]. The density and temperature $T_e$ of electrons are $2\times10^8/\mathrm{cm}^3$ and 5.1eV, respectively and the plasma potential is 31V. The floating potential is measured with a cylindrical probe of 0.2mm diameter and 3mm in length and it is equal to that of the plate, i. e., 0V.

For microparticles, acrylic particles of two different diameters($2a$ = 0.3 and 0.5μm) and of which density is $1.19\mathrm{g/cm}^3$ are used. They are illuminated by a horizontal green laser light($\lambda$= 532nm). The light reflected by the particles is recorded with a digital camera which is set above the glass tube. When a dc voltage is applied to the buzzer Z, particles emanate from it and levitate in the ion sheath above the plate. Then they move in the right direction by the gravitational force and flow into the region of the magnetic field. Due to the perpendicular magnetic field, microparticles make cyclotron motions of which radii are measured.

## Ⅲ. EXPERIMENTAL RESULTS AND DISCUSSIONS

An example of arcs of cyclotron motion is shown in Fig. 2. The particle moves from the right to the left direction. From the photographs of the arcs, the cyclotron radii are estimated, from which $Q$s are calculated from Eq. (1). The values $Z = -Q/e$ where $e$ is the elementary charge are shown in Fig. 3 for $2a$ = 0.3 and 0.5μm. The experimental errors have two explanations. One is due to the particle velocity which decreases due to the drug force by argon atoms[8]. The other is inhomogeneous magnetic field.

The solid line in Fig. 3 shows $Z = -aV_s/e$ where $V_s$ = -31V. The voltage $V_s$ is the floating potential measured with respect to the plasma potential. Actually $V_s$ must be the surface potential of the particle against the voltage of the position where the particle is levitating. Since the particle is levitating in a transient sheath[5], $V_s$ must be between – 31 and $-31 + \kappa T_e/2e \simeq -28.5$V. As a result of this, the experimental results are considered to be in agreement with the simple model, that is, $Q = aV_s$.

In the following, the validity of the measured value of $V_s$ is discussed.. At the floating potential $V_s$, the ion current $I_i$ plus the electron current $I_e$ to the surface of a particle must be zero. Due to OML theory, the electron current $I_e$ is given by[9]

$$I_e = -2(2\pi)^{1/2}a^2eN_{e0}(\kappa T_e)^{1/2}\exp(eV_s/\kappa T_e) \qquad (2)$$

where $N_{e0}$ and $m$ are the density and mass of electrons, respectively. The ions enter into an ion sheath with the Bohm velocity $(\kappa T_e/m_i)^{1/2}$ where $m_i$ is the mass of argon ion and with a density of $N_{e0}$exp(- 1/2). Then the ion current $I_i$ to a particle of which cross section is $\pi a^2$ becomes

$$I_i = \exp(-1/2)\ \pi a^2 e N_{e0}(\kappa T_e/m_i)^{1/2}. \qquad (3)$$

Since $I_e + I_i = 0$, we obtain the following simple relation from Eqs. (2) and (3).

$$\exp(eV_s/\kappa T_e) = (0.303)(\pi m/2m_i)^{1/2}.$$

The ions are argon ions so that $eV_s/\kappa T_e = -6.6$. Since the measured $T_e$ is equal to 5.1eV, we obtain $V_s = -34$V which is nearly equal to the measured value -31V.

## Ⅳ. CONCLUSION

A simple experiment is proposed to uniquely determine the electric charge $Q$ of a microparticle. The floating potential $V_s$ of the particle is examined using a model including the OML theory and an ion sheath. The measured values of $Q$ and $V_s$ are in agreement with the models.

## ACKNOWLEDGEMENT

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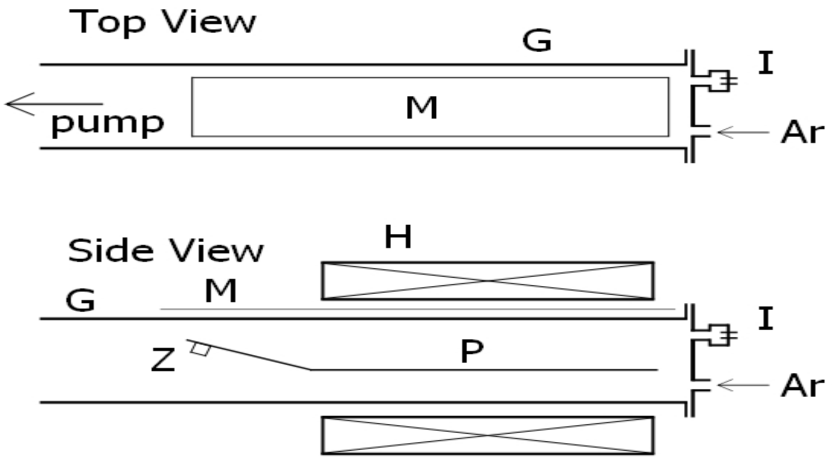

Fig.1. YCOPEX device. G:pyrex glass tube, M:stainless steel mesh, H:Helmholtz coils, P:stainless steel plate, Z:buzzer, I.capacitance manometer.

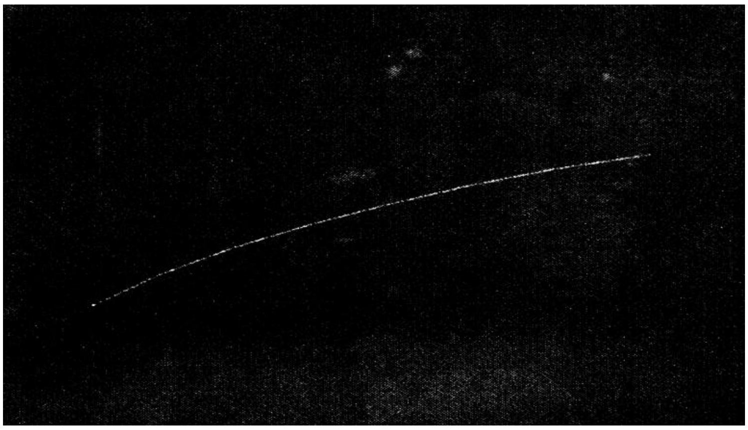

Fig.2. An arch of a microparticle. B=300Gauss. *a* =0.15µm. *v* = 6.7cm/sec. *R* = 7.1cm.

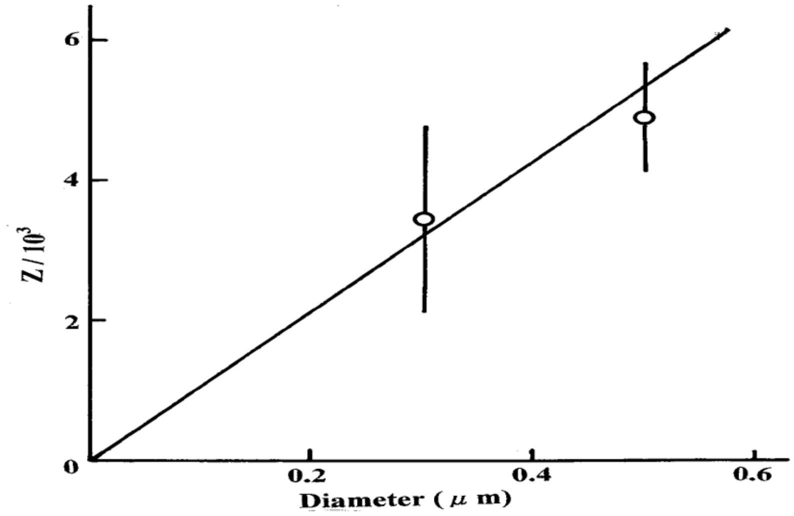

Fig.3. Measured Z for two diameters of microparticles.