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# Electrorotation of novel electroactive polymer composites in uniform DC and AC electric fields

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**Abstract**
Novel electroactive polymer composites have been developed that could spin in uniform DC and AC electric fields. The angular displacement as well as rotation of polymer disks around an axis that is perpendicular to the direction of the applied electric field was studied. It was found that the dynamics of the polymer rotor is very complex. Depending on the strength of the static DC field, three regimes have been observed: no rotation occurs below a critical threshold field intensity, oscillatory motion takes place just above this value and continuous rotation can be observed above the critical threshold field intensity. It was also found that low frequency AC fields could also induce angular deformation.

S Online supplementary data available from stacks.iop.org/SMS/21/065022/mmedia

(Some figures may appear in colour only in the online journal)

## 1. Introduction

Electroactive polymers (EAP) exhibit changes in size and shape when stimulated by electric fields [1–4]. The application of these materials as actuators is based on their ability to induce large actuation strains in the form of stretching, contracting, or bending. EAP can be deformed repetitively by applying external voltage, and they can quickly recover their original shape upon reversing the polarity of the applied voltage. The shape change is smooth and gentle, similar to that observed in muscle. Due to this behavior, EAPs are often referred to as artificial muscles in the field of robotics. Despite the great variety of strains induced by shape change, no rotary motion performed by electroactive polymers has been discovered as of yet.

Electrorotation is the circular movement of an electrically polarized, micron sized, particle or material. AC electric field induced rotation has been reported for linear chains of cells [6]. It has became a very powerful diagnostic technique for measurement of certain dielectric properties of cells. In 1987 Turcu published a mathematical approach to the problem of homogeneous dielectric spheres in a uniform linearly polarized AC electric field [9]. He has shown that under certain conditions a spherical particle can exhibit stable rotational equilibrium. However this prediction has not been confirmed experimentally as yet.

The wide range of applications (e.g. in microscopic motors) motivates researchers to find materials showing electrorotation with microfabrication possibilities. Here we present the development of novel electroactive polymer composites that perform rotation in uniform DC and AC electric fields.

The idea of developing novel polymers showing rotation in uniform electric field is based on an old discovery. In 1896 Quincke observed that some solid particles (glass, aragonite, sulfur, topaz, tourmaline, ...) could spontaneously rotate in certain media (ether, carbon disulfide, benzyl, and different oils) if a large uniform electric field is applied [5]. The Quincke rotation is a spontaneous rotation of small non-conducting objects dispersed in liquid dielectrics and

 

subjected to homogeneous DC electric field exceeding some threshold value. The phenomenon occurs only if certain conditions concerning to the conductivity and permittivity of the particles and of the liquid are satisfied. Due to these special criteria for the material characteristics, it is not easy to observe the phenomenon. Only a limited number of experimental studies are available [10–12].

The basic theoretical approach of the Quincke rotation, for rigid spherical particles, was provided by several authors [5–9]. These approaches are based on the assumption that free charges which are present in the liquid and in the particle accumulate at the surface of the particle, inducing dipole moment, $P$. Depending on the relative magnitude of the charge relaxation times in the liquid and in the particle, the induced dipole is either in the direction of or opposite to the field. If the charge relaxation time of the liquid is shorter than that of the solid, the direction of the induced dipole is antiparallel to the direction of the electric field. This configuration is unstable and the particle begins to rotate in order to flip its dipole moment. The particle rotation reaches a stationary state where the electric torque is balanced by the viscous one. The rotational axis is perpendicular to the electrostatic field.

The conditions of spontaneous rotation can be expressed in terms of the permittivity, $\varepsilon$, and conductivity, $\sigma$, data: $\varepsilon_2\sigma_1 < \varepsilon_1\sigma_2$ where the subscripts 1 and 2 refer to the liquid and the dispersed particles, respectively.

The angular velocity, $\omega$, as a function of the applied field, $E$, for spherical particles can be given as [6–9]

$$\omega(E) = \pm\frac{1}{\tau_{\mathrm{MW}}}\sqrt{\frac{E^2}{E_{\mathrm{cr}}^2} - 1} \qquad E > E_{\mathrm{cr}} \tag{1}$$

where $\tau_{\mathrm{MW}}$ is the Maxwell–Wagner interfacial polarization relaxation time for spheres defined as

$$\tau_{\mathrm{MW}} = (2\varepsilon_1 + \varepsilon_2)/(2\sigma_1 + \sigma_2). \tag{2}$$

The threshold electric field strength, $E_{\mathrm{cr}}$, at which the solid particles begin to rotate is independent of the size of the dispersed particles and depends on the electric properties of particles and the viscosity of the medium. Equation (1) refers to solid monolith particles with size between 1 and 500 $\mu$m. The $\pm$ sign stands for the two possible directions of rotation around the axis that is perpendicular to the direction of the applied electric field. No theoretical description has been worked out for electrorotation of disks or other shapes.

In previous experiments, the rotating materials were mainly oxides with poor fabrication possibilities. Shaping or microfabricating of the solid particles is a rather difficult task due to their rigidity and fragility. It is therefore an important challenge to find proper materials with controllable shape and size.

Electroactive polymer composites that fulfill these requirements have been developed and disk shaped samples have been prepared as possible candidate rotors for microsized electromotors. In our previous study we have found that orthorhombic FeO(OH) particles dispersed in linseed oil show the Quincke rotation phenomenon [10]. In the present work we have used these particles as fillers in two different host polymers [13]. We are convinced that these composites are good candidates for ultra-precision manufacturing for microrotors in micromotors.

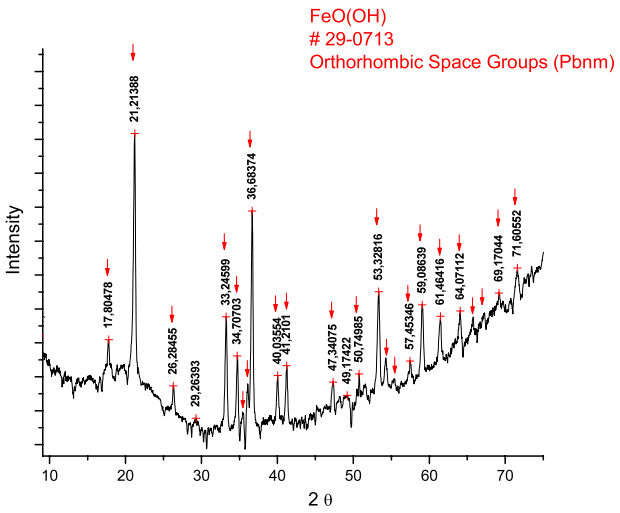


**Figure 1.** X-ray spectra of FeO(OH) powder.

## 2. The experimental part

### *2.1. Sample preparation*

In our previous work, we have found that $\alpha$-FeO(OH) goethite particles immersed in slightly conducting oil subjected to a uniform DC field show the Quincke rotation phenomenon [10]. We have used these particles as filler particles in polymers. The crystal structure of the $\alpha$-FeO(OH) was modified by thermal treatment, keeping the particles in a vacuum oven at 200°C for 5 min. The acircular FeO(OH) particles show polydispersity with an average size of 0.1 $\mu$m (short axis) and 0.6 $\mu$m (long axis). The density of the modified FeO(OH) particles was measured as 4.1 g cm$^{-3}$ in the dry state.

X-ray diffraction (XRD) measurements were carried out by using a Philips (PW1130) x-ray generator, which was set up with a Guinier chamber. The chamber has a diameter of 100 mm and the patterns were recorded on Fuji Imaging Plates (BAS MS2025). The XRD data were collected over the $2\theta$ range of 9°–90°with a step size 0.005°. The phases were identified by comparing the diffraction patterns with standard PDF cards.

The x-ray measurements evidenced that FeO(OH) particles can be characterized by means of orthorhombic space groups as shown in figure 1.

The orthorhombic FeO(OH) particles with conductivity of $\sigma_2 = 5 \times 10^{-1}$ S m$^{-1}$ and relative permittivity of $\varepsilon_2 = 8.37$ were used to prepare polymer composites using different host polymers: polyvinyl alcohol, PVA (Merck PVA 72 000), and gelatine (Reanal, Hungary).

PVA is a water-soluble neutral polymer; gelatine is a polyelectrolyte in the water environment. Both PVA and gelatine powders were dissolved in water and solutions with

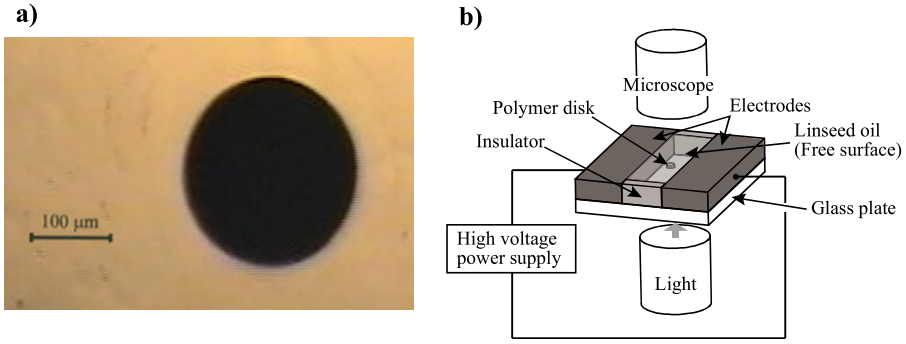


**Figure 2.** Top view of a gelatine based composite (a), and the experimental device used to study the Quincke rotation (b).

**Table 1.** Composition and mechanical properties of FeO(OH) loaded polymers.

| FeO(OH)/polymer mass ratio | Material properties |
|---|---|
| 0.36 | Excellent (resilient) |
| 1.00 | Excellent (resilient) |
| 1.81 | Moderate (hard material) |
| 2.67 | Moderate (hard material) |
| 10.40 | Very poor (friable material) |

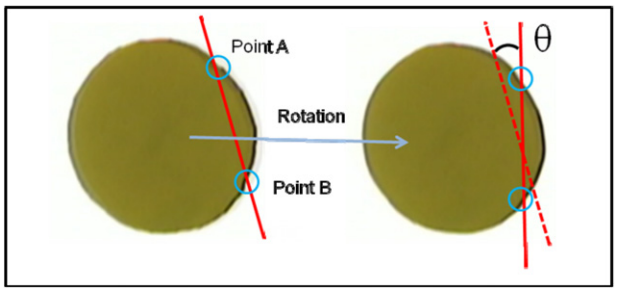


**Figure 3.** Determination of the angular displacement. The angle between the dotted and straight lines characterizes the angular displacement.

variable concentration from 10 to 20 mol% were prepared. The FeO(OH) particles were dispersed in the polymer solution in such a way that the mass ratio of the iron oxide and the dried polymer was varied between 0.36 and 10.4 as shown in table 1.

Next, the mixture was poured into a cylindrical mold and dried carefully at ambient temperature. We have obtained perfectly dried, cylindrical samples as shown in figure 2. Polymer disks, as rotors, were prepared with different diameters and heights. Several composites with a wide range of FeO(OH)/polymer ratio were studied in order to find an ideal composition for Quincke rotation (see table 1 and figure 2(a)).

In order to study the Quincke rotation, several liquids (silicon oil, paraffin oil, and linseed oil) with variable electric properties were tested. We have found that electrorotation was observed only in oils which contained substantial amounts of triglycerides of oleic, palmitic, and linoleic acids, with a conductivity of $\sigma_1 = 9.56 \times 10^{-10}$ S m$^{-1}$ and a relative permittivity of $\varepsilon_1 = 3.32$ respectively. It must be mentioned that the FeO(OH) particles slightly swell in the oil. Rough estimation of oil uptake has indicated a 10% increase in mass. This could significantly modify the material properties.

## 3. The experimental method used to study electrorotation

The experiments were conducted in a specially designed cell where two parallel copper plates, with heights of 1.5 mm, were fixed onto a glass plate with insulation stripes. The gap between the electrodes was 3 mm. The space between the electrodes was filled with oil and the polymer disk was floating in oil, between the electrodes. Despite the slight difference between the density of oil and that of solid particles, no sedimentation was observed. The floating of the polymer disks in oil may be due to dielectrophoretic forces pointing to the middle of the oil filled gap, as a result of field gradients, perpendicular to the direction of the electric field. Figure 2(a) shows the top view of a small disk levitated in the oil.

Figure 2(b) shows an experimental device used to apply electric field to the disks. The electric field was supplied by a high voltage DC power supply (TREC, USA). We have increased the electric field intensity up to $1.6 \times 10^6$ V m$^{-1}$. Both DC and AC electric fields were applied perpendicularly to the axis of the disk.

The revolution of electroactive polymer was monitored using an optical microscope (OLYMPUS, Japan) equipped by a high speed camera (Photron, Japan). The angular frequency of the rotation was determined by recording the motion of the disk. In order to realize perfect visualization of the rotation and to measure the angular displacement, two visible guiding marks (A and B) were plotted on the surface of disks as shown in figure 3. A straight (marker) line connected the two points (A and B). During rotation, the slope of the marker line kept on changing. The angle, $\theta$, between this marker and a horizontal line was considered as the angular displacement. The angular displacement was determined every 33.35 ms from the records. The dependence of the angular displacement on the electric field intensity was determined in both DC and AC fields. All the observations were carried out at room temperature. From the time dependence of the angular displacement, $\theta$, the angular speed, $d\theta/dt$, and the rotation frequency, $\omega$ (defined as the number of revolutions per unit

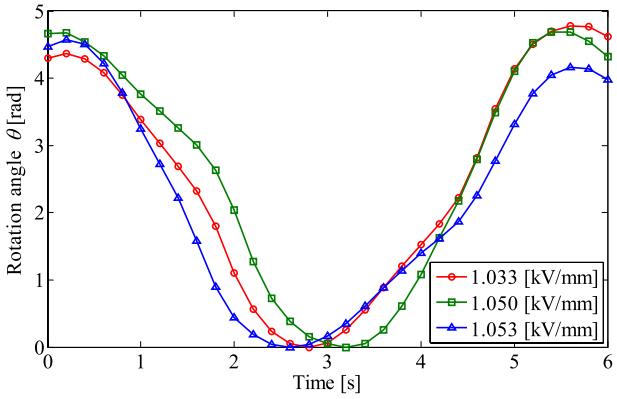


**Figure 4.** Dependence of the angle of revolution on the time slightly above the critical threshold. The applied electric field intensity is given in the box.

time), were determined. The relationship between the angular speed and rotation frequency is

$$\omega = \frac{1}{2\pi}\frac{\mathrm{d}\theta}{\mathrm{d}t} \tag{3}$$

## 4. Results and discussion

### *4.1. Electrorotation in a DC field*

We have found that above a critical value of the electric field, $E_{cr}$, both host polymers (PVA as well as gelatine) loaded with FeO(OH) particles demonstrate the electrorotation phenomena. The electrorotation must be due to the presence of FeO(OH) particles, because neither the unloaded PVA nor the pure gelatine showed electrorotation. The dependence of the angular frequency on the electric field intensity for both kinds of composites has been determined.

It was concluded that the dynamics of the rotary motion is very complex, as a function of the strength of the static DC field. Three regimes can be distinguished.

(1) Below a threshold value, $E_{cr}$, of the electric field no rotary motion occurs. For gelatine based composite $E_{cr} = 0.83 \times 10^6$ V m$^{-1}$ and for PVA containing composite $E_{cr} = 0.68 \times 10^6$ V m$^{-1}$ were obtained.

(2) Close to the threshold value and slightly above ($E_0 \geq E_{cr}$), the disks begin to rotate, but the angular displacement, measured in radians, was found to be much less than $2\pi$. The clockwise angular displacement was always followed by counterclockwise revolution. This is demonstrated in figure 4. In this regime the speed of rotation is not constant, but keeps on changing.

(3) At DC field intensities higher than the threshold value ($E_0 > E_{cr}$), continuous rotation was observed. The disk rotates around its $Z$ axis, with an axis pointing in any direction perpendicular to the DC field. The speed of rotation at constant electric field intensity was found to be constant. With increasing field intensities the angular frequency is increasing, as shown in Figure 5.

Reproducibility studies (see figure 5(b)) have shown that the speed of rotation can be very well controlled by the static electric field. It is also seen in the figure that this dependence significantly differs from the prediction of equation (1). According to equation (1) the curvature of the $\omega = f(E)$ dependence is concave, whereas the experimental data show a convex behavior for rotating polymer disks. Comparing the role of the host polymer, one can see that gelatine provides a stronger electrorotation effect (see figure 5(a)). This decisive difference may be due to the presence of charges on the chains of gelatine.

In order to evaluate the rotational torque of the polymer composite disk, a shaft of nylon fiber string was attached perpendicular to the center of the rotor [14]. The rotor torque was calculated from a relationship between the applied torque and the torsional angle of a nylon string. It was found that the torque generated by the micromotor decreases with increasing rotational speed and also increases with increasing applied

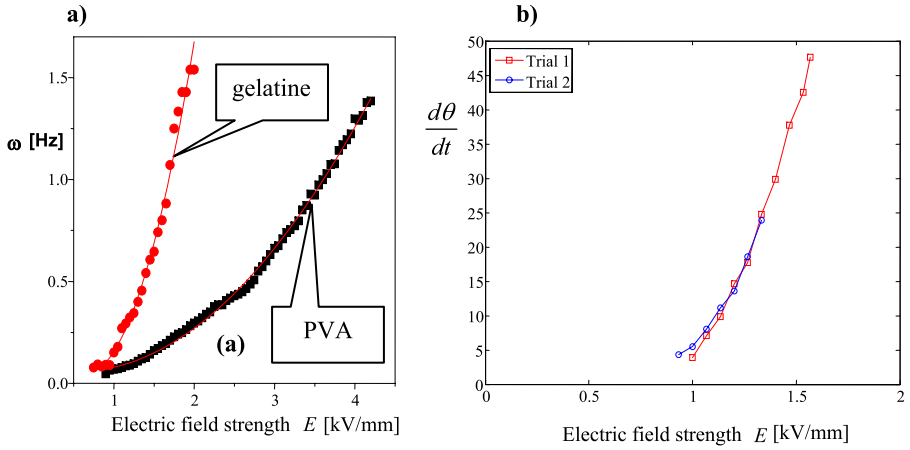


**Figure 5.** Dependence of the rotation frequency (a) and angular frequency (b) as a function of the DC electric field. (a) Disk diameter: 240 $\mu$m, disk height: 80 $\mu$m; FeO(OH)/gelatine mass ratio: 2.67. (b) Disk diameter: 573 $\mu$m, disk height: 208 $\mu$m; FeO(OH)/PVA mass ratio: 8.4.

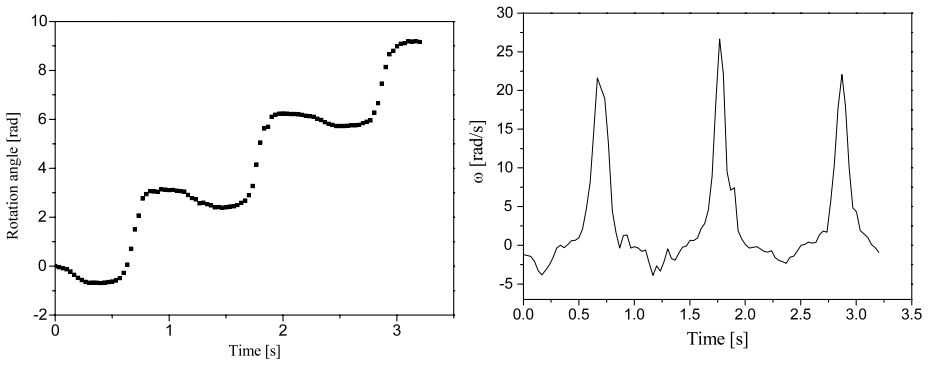


**Figure 6.** Dependence of the rotation angle (a) and speed of rotation (b) on the time at $E = 1.33$ kV mm$^{-1}$ AC field intensity with $f = 0.9$ Hz.

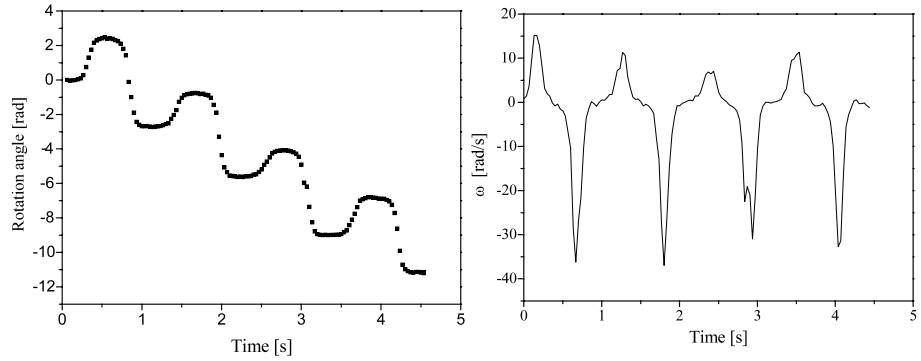


**Figure 7.** Dependence of the rotation angle (a) and speed of rotation (b) on the time at $E = 1.5$ kV mm$^{-1}$ AC field intensity with $f = 0.9$ Hz.

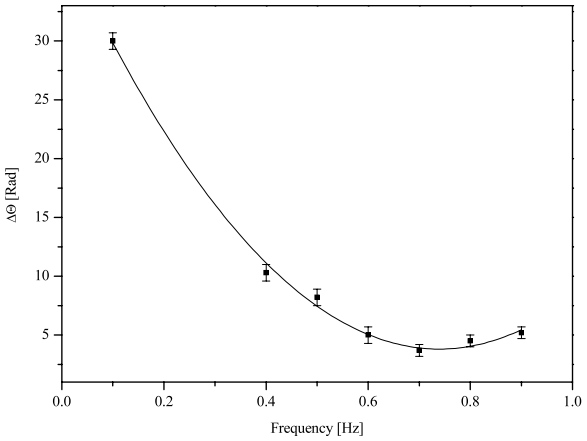


**Figure 8.** Dependence of the maximum angular displacement on the frequency measured at $E = 1.5$ kV mm$^{-1}$ AC field intensity. The solid curve is a guide for the eyes.

electric field intensity. The disk rotor generated the maximum torque of 2.4 $\mu$N m when the electric field intensity of 2.00 kV mm$^{-1}$ was applied. Further details of the torque determination will be published in a forthcoming paper.

### *4.2. Electrorotation in an AC field*

We have found that no electrorotation can be observed in an AC field at moderate and high frequencies. AC field induced angular displacement, with our samples, occurs only if the frequency is rather low, below 1.6 Hz. This critical value might depend on the shape and material characteristics of the polymer composite. A very sensitive relationship of the electrorotation with the frequency, $f$, was established. Instead of a continuous rotation of the disk, it starts rotating, then it stops, and this kind of revolution is repeated again and again as shown in figure 6. It can be seen in this figure that the direction of rotation is the same for every cycle. However the starting direction is selected by randomness. On comparing figures 6(a) and 7(a), these figures clearly show electrorotation in opposite directions. The dependence of the rotation angle on the time is not monotonic. After a slight counterclockwise displacement, the disk begins to turn, and on approaching a maximum angular displacement of $\theta_{\max} \approx 3.2$ rad (which is less than half a revolution), it stops and then starts rotating again. The speed of rotation varies significantly from zero to 20–25 rad s$^{-1}$, as shown in figure 6(b).

The influence of the electric field can be seen in figure 7, where the oscillatory motion of the same polymer disk is shown at $E = 1.5$ kV mm$^{-1}$ field intensity at the same frequency. Due to the higher field intensity, the maximum angular displacement has become a little bit smaller ($\theta_{\max} \approx$ 2.8 rad). What is increased significantly is the maximum speed of rotation. It varies from zero to 35 rad s$^{-1}$ as shown in figure 7(b).

The oscillatory motion of polymer disks under an AC electric field was found to be very sensitive to the frequency. Figure 8 shows the dependence of the utmost angular displacement of the revolution as a function of the frequency.

At very low frequency ($f = 0.9$ Hz) the disk spins more than four full revolutions ($\theta_{max} \approx 30$ rad)! On increasing the frequency the maximum angular displacement decreases significantly, until it disappears completely.

## 5. Summary and conclusion

In this paper we reported experimental evidence on the electrorotation of polymer disks subjected to DC and AC electric fields. The angular motion of insulating polymer composite disks immersed in slightly conducting oil was studied as a function of DC and AC electric field intensities as well as the frequency of the AC field. It was found that above a critical value of the electric field, the disk begins to rotate. In a DC field the disk rotates at a constant rate. This rate is sensitive to the field intensity. With increasing field intensities, the angular velocity of the rotating disk increases. Three regimes have been identified, as the strength of the static DC field is accounted for. We have presented the first experimental observation of AC electric field induced rotational motion. At this point, we are not able to provide a theoretical background for interpreting the complexity of the electrorotation phenomena. Further experiments and analysis are needed in order to provide an understanding of the phenomena.

However, the data and movies (see the supporting materials available at stacks.iop.org/SMS/21/065022/mmedia) show that a rotating disk acts like a microsized motor with tunable angular frequency. A microscopic motor whose operation is based on the principle of electrorotation is just one step away.

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