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LETTER

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Nonlinear electrophoresis of dielectric and metal spheres in a nematic liquid crystal

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OTS coated Silica sphere in E7

(a)

nature09427-s2.mov

DDMAC coated borosilicate sphere

(b)

nature09427-s3.mov

✓ **Nematic liquid crystal E7**

- isotropic phase at T_{NI}=58 ℃
- dielectric anisotropy of E7, $\Delta\varepsilon=\varepsilon_{\parallel}-\varepsilon_{\perp}=13.8$
- A liquid-crystal layer of thickness h=50~80㎛ between two glass plates is aligned uniformly along the x axis , using layers of buffed polyimide
- E=(E,0,0) is parallel x axis

✓ Dielectric spheres (made of **silica**, **borosilicate**, **soda lime glass**, diameter 2a=5~50㎛)
Metal spheres (gold, 2a=5.5~9㎛)

✓ Octadecyltrichlorosilane (OTS)
N,N-didecyl-N-methyl-(3-trimethoxysilylpropyl) ammonium chloride (DDMAC)

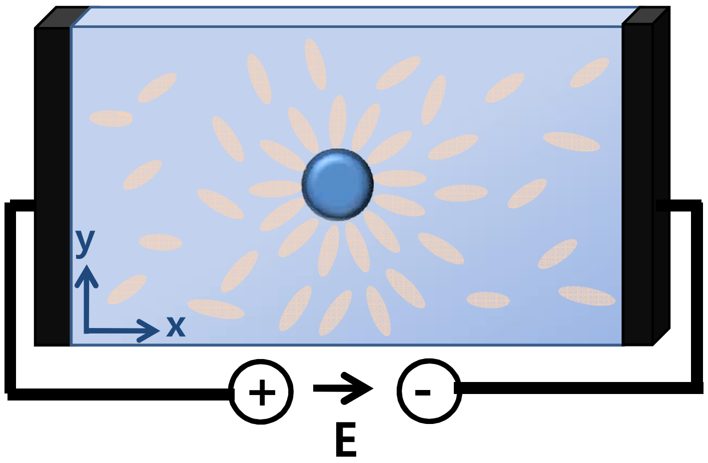
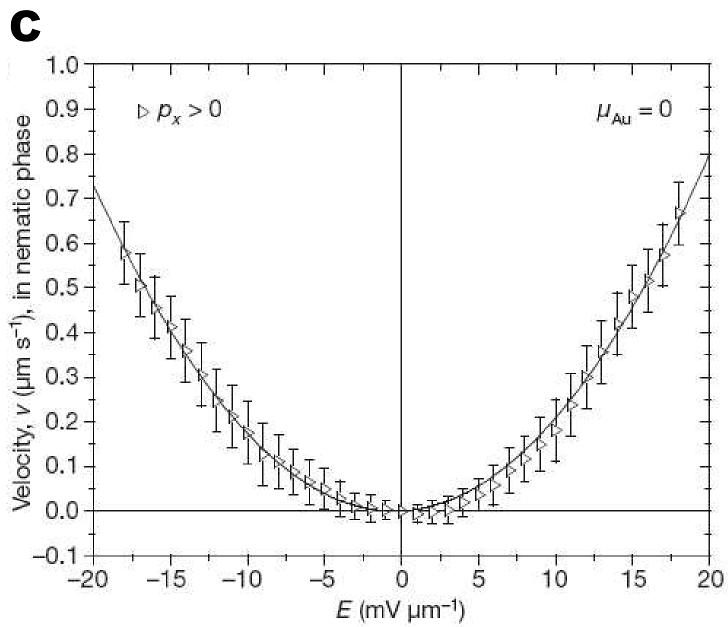
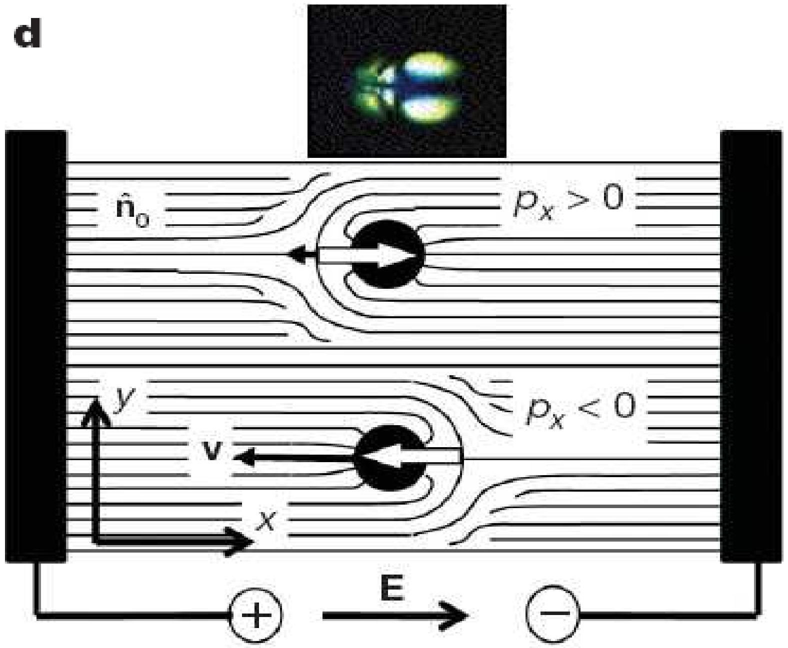


Fig1. Nonlinear electrophoresis in a d.c. field.



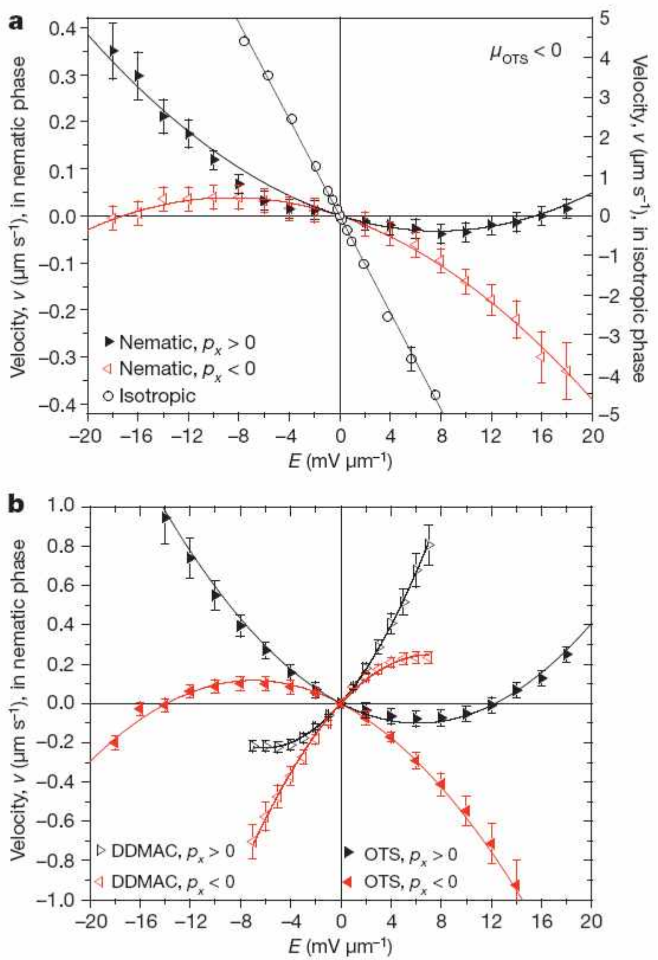


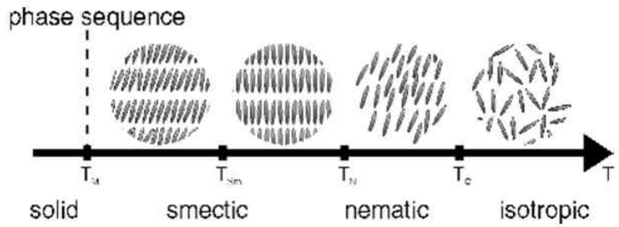
✓ neutral gold spheres (2a=10 ㎛) in the nematic liquid crystal

✓ μ_{Au}=0

✓ Scheme of experiment with **E** parallel to $\mathbf{n}_0$; the hyperbolic hedgehog is either on the left-hand side of the sphere (p_x>0) or the right (p_x<0). Inset, polarizing microscope image of a glass sphere with 2a=50 ㎛ and p_x>0.

Fig1. Nonlinear electrophoresis in a d.c. field.



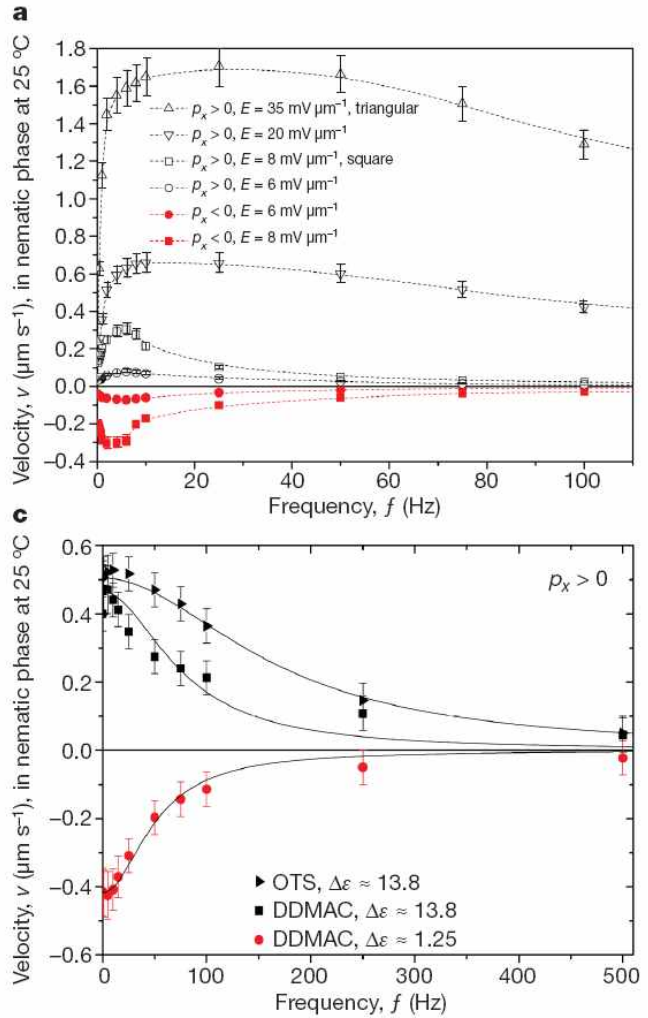


- ✓ OTS-coated silica spheres (2a=5.08 μm)
- ✓ ○ E7 isotropic phase (t=65 ℃)
- ✓ ◁ E7 nematic phase (t=25 ℃), $\rho_x<0$
- ✓ ▶ E7 nematic phase (t=25 ℃), $\rho_x>0$

- ✓ E7 nematic phase (t=25 ℃)
- ✓ negatively charged OTS-coated borosilicate spheres (2a=9.6 μm)
- ✓ positively charged DDMAC-coated borosilicate spheres (2a=17.3 μm)

Smoluchowski's formula : $v = \mu E + \beta E^2$

Fig2. A.C. electrophoresis in the nematic liquid crystal.

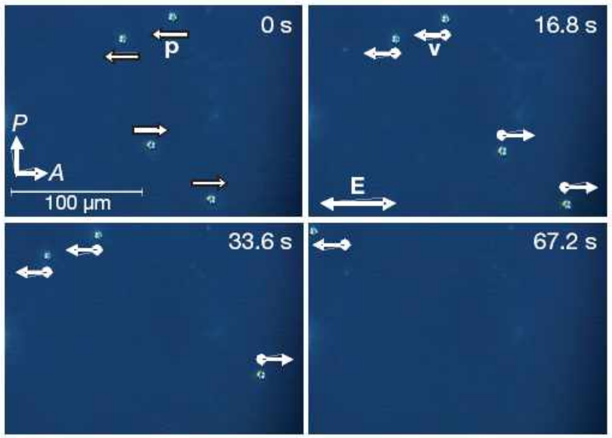


- ✓ OTS-coated silica particles (2a=5.08 μm)
- ✓ ▽ △ : triangular A.C. pulses
- ✓ □ ○ ● ■ : square A.C. pulses

- ✓ ▶ OTS-treated silica particles (2a=5.08 μm) in E7
  sinusoidal field (20 mV/μm)
  Δε=13.8
- ✓ ■ DDMAC treated borosilicate particles (2a=17.3 μm) in E7
  sinusoidal field (10 mV/μm)
  Δε=13.8
- ✓ ● Mixture (MLC7026-000) 18.7wt% of E7
  DDMAC treated borosilicate particles (2a=17.3 μm)
  sinusoidal field (10 mV/μm)
  Δε=1.25

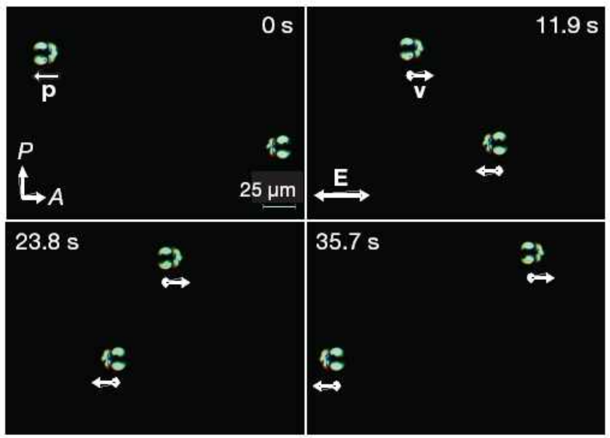
Fig 2. A.C. electrophoresis in the nematic liquid crystal.

b



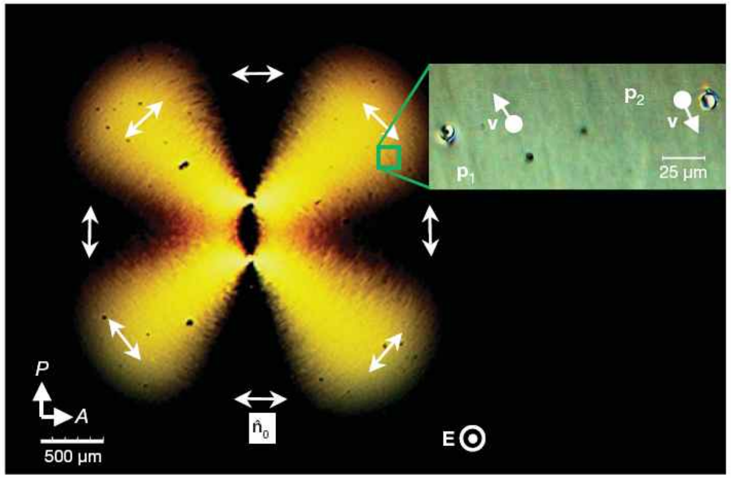
✓ Optical microscope images of particles viewed between a crossed polarizer (P) and analyser (A) at times 0, 16.8, 33.6 and 67.2 s after the triangular-pulse A.C. field (45mV/㎛, 100Hz) is applied.

d



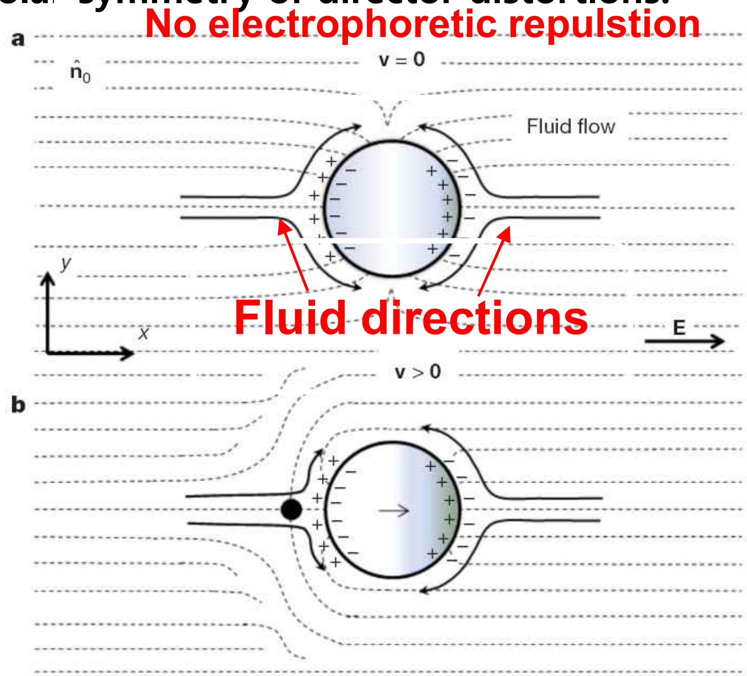
✓ DDMAC-treated particles (2a=17.3 ㎛) in amixture with 13.5wt% of E7 0, 11.9, 23.8 and 35.7 s after a field (30 mV/㎛, 1Hz) is applied.

Fig3. Electrophoretic motion of DDMAC-coated borosilicate spheres (2a=9.6 ㎛)



- ✓ liquid crystal MLC7026-000 , Δε=-3.7
- ✓ E=(0, 0, E_z) , p= (p_x, p_y, 0)
  (using transparent electrodes at the glass plates)

Fig4. Spherical particles with normal anchoring in a nematic liquid crystal with quadrupolar or dipolar symmetry of director distortions.



The Saturn ring (a, quadrupolar) preserves the fore–aft symmetry and results in zero electrophoretic mobility; the hyperbolic hedgehog (b, dipolar) breaks the fore–aft symmetry and is responsible for the nonlinear electrophoresis.

Smoluchowski's formula :

$$v = \mu E + \beta E^2$$

$$\mu = \frac{\varepsilon_m \varsigma}{\eta}$$ (electrophoretic mobility)

(ε_m : dielectric permittivity of the medium

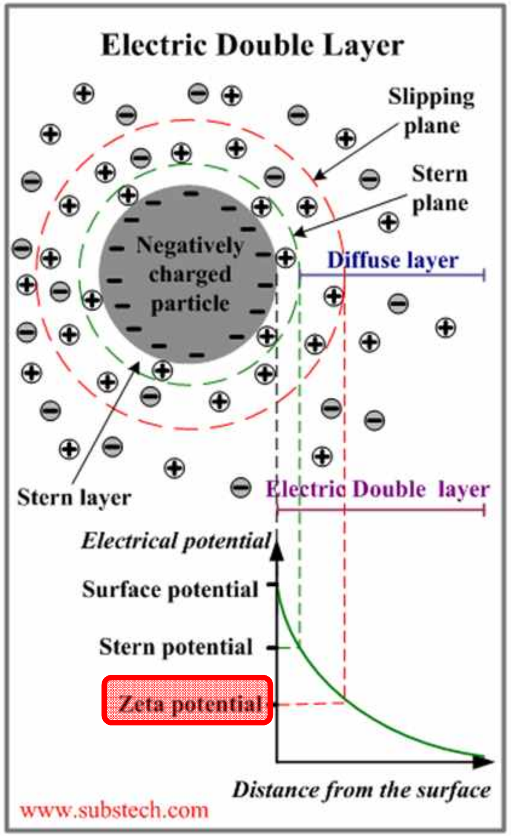
ς : zeta potential

η : medium's viscosity)

$$\beta = \frac{\delta \varepsilon_m a}{\eta}$$ (metallic particle)

(δ : dimensionless factor characterizing the medium symmetry)

$$\beta = \frac{\delta \varepsilon_d a}{\eta}$$ (dielectric particle)

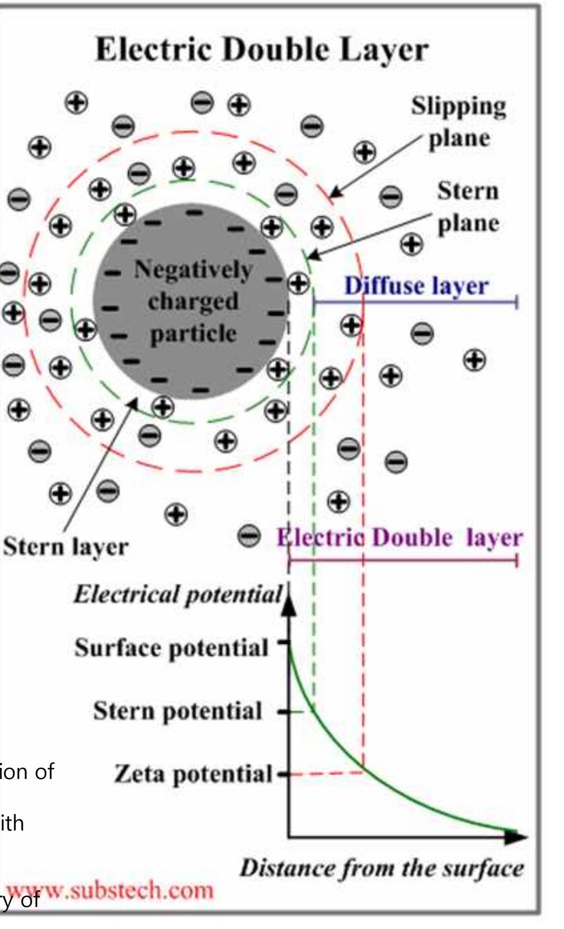


Electric Double Layer

Electric Double Layer is the phenomenon playing a fundamental role in the mechanism of the electrostatic stabilization of colloids.
Colloidal particles gain negative electric charge when negatively charged ions of the dispersion medium are adsorbed on the particles surface.
A negatively charged particle attracts the positive counterions surrounding the particle.

Electric Double Layer is the layer surrounding a particle of the dispersed phase and including the ions adsorbed on the particle surface and a film of the countercharged dispersion medium.
The Electric Double Layer is electrically neutral.

An Electric Double Layer consists of three parts:



Surface charge - charged ions (commonly negative) adsorbed on the particle surface.
Stern layer - counterions (charged opposite to the surface charge) attracted to the particle surface and closely attached to it by the electrostatic force.
Diffuse layer - a film of the dispersion medium (solvent) adjacent to the particle. Diffuse layer contains free ions with a higher concentration of the counterions. The ions of the diffuse layer are affected by the electrostatic force of the charged particle.
The electrical potential within the Electric Double Layer has the maximum value on the particle surface (Stern layer). The potential drops with the increase of distance from the surface and reaches **0** at the boundary of the Electric Double Layer.

When a colloidal particle moves in the dispersion medium, a layer of the surrounding liquid remains attached to the particle. The boundary of this layer is called **slipping plane (shear plane)**.
The value of the electric potential at the slipping plane is called **Zeta potential**, which is very important parameter in the theory of interaction of colloidal particles.