

# Anisotropic electrostatic screening of charged colloids in nematic solvents

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The physical behavior of anisotropic charged colloids is determined by their material dielectric anisotropy, affecting colloidal self-assembly, biological function, and even out-of-equilibrium behavior. However, little is known about anisotropic electrostatic screening, which underlies all electrostatic effective interactions in such soft or biological materials. In this work, we demonstrate anisotropic electrostatic screening for charged colloidal particles in a nematic electrolyte. We show that material anisotropy behaves markedly different from particle anisotropy. The electrostatic potential and pair interactions decay with an anisotropic Debye screening length, contrasting the constant screening length for isotropic electrolytes. Charged dumpling-shaped near-spherical colloidal particles in a nematic medium are used as an experimental model system to explore the effects of anisotropic screening, demonstrating competing anisotropic elastic and electrostatic effective pair interactions for colloidal surface charges tunable from neutral to high, yielding particle-separated metastable states. Generally, our work contributes to the understanding of electrostatic screening in nematic anisotropic media.

## INTRODUCTION

Colloidal particles in nematic solvents exhibit a rich variety of self-assembly behaviors, ranging from isotropic to nematic, smectic, and cholesteric phases. The physical behavior of anisotropic charged colloids is determined by their material dielectric anisotropy, affecting colloidal self-assembly, biological function, and even out-of-equilibrium behavior. However, little is known about anisotropic electrostatic screening, which underlies all electrostatic effective interactions in such soft or biological materials. In this work, we demonstrate anisotropic electrostatic screening for charged colloidal particles in a nematic electrolyte. We show that material anisotropy behaves markedly different from particle anisotropy. The electrostatic potential and pair interactions decay with an anisotropic Debye screening length, contrasting the constant screening length for isotropic electrolytes. Charged dumpling-shaped near-spherical colloidal particles in a nematic medium are used as an experimental model system to explore the effects of anisotropic screening, demonstrating competing anisotropic elastic and electrostatic effective pair interactions for colloidal surface charges tunable from neutral to high, yielding particle-separated metastable states. Generally, our work contributes to the understanding of electrostatic screening in nematic anisotropic media.

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$$\phi(\mathbf{r}) = \mathcal{A}(\mathbf{r}, \lambda_D^I) \left( \frac{\lambda_D^I}{r} \right)^{\nu}, \quad (\nu = 1, 2) \quad (1)$$

where  $\mathcal{A}(\mathbf{r}, \lambda_D^I)$  is the electrostatic potential,  $\lambda_D^I$  is the Debye screening length, and  $\nu$  is the screening exponent. The electrostatic potential and pair interactions decay with an anisotropic Debye screening length, contrasting the constant screening length for isotropic electrolytes. Charged dumpling-shaped near-spherical colloidal particles in a nematic medium are used as an experimental model system to explore the effects of anisotropic screening, demonstrating competing anisotropic elastic and electrostatic effective pair interactions for colloidal surface charges tunable from neutral to high, yielding particle-separated metastable states. Generally, our work contributes to the understanding of electrostatic screening in nematic anisotropic media.





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in the case of a function  $f$  of a variable  $x$ , we have

$$\frac{D(f)}{D(x)} = \frac{f'(x)}{1} = f'(x) \quad (10)$$

where  $\Delta x \neq 0$  ( $\Delta x \rightarrow 0$ ),  $f(x) = f(x)$

...  $n_0$ , ...  
 ... (2) ...  
 ...  
 ... + ...  
 ...  
 ... (10) ...

...  $\Phi(\dots)$ , ...  
 ...  $\Phi(\dots)$ , ...  
 ...  $\Phi(\dots)$

$$\Phi(\dots) = \Phi_E(\dots) + \Phi_{II}(\dots) + \Phi(\dots)$$

The first term in the right-hand side of (1) is the
 contribution of the direct path, and the second term
 is the contribution of the indirect path.

$$\Phi_E(\omega, \mathbf{r}) = \alpha^2 \gamma \int_{\mathcal{V}_B} \lambda_B(\mathbf{r}') \frac{e^{-i\omega(\mathbf{r}-\mathbf{r}') \cdot \mathbf{c}^{-1}}}{|\mathbf{r}-\mathbf{r}'|} d\mathbf{r}' \quad (1)$$

The second term in the right-hand side of (1) is the
 contribution of the indirect path. It is given by
 the following equation:

$$\Phi_E(\omega, \mathbf{r}) = \alpha^2 \gamma \int_{\mathcal{V}_B} \lambda_B(\mathbf{r}') \frac{e^{-i\omega(\mathbf{r}-\mathbf{r}') \cdot \mathbf{c}^{-1}}}{|\mathbf{r}-\mathbf{r}'|} d\mathbf{r}' \quad (2)$$

where  $\mathbf{c}$  is the speed of light, and  $\mathbf{r}'$  is the position
 vector of the source.

在  $\mathbb{R}^n$  中, 设  $\Omega$  为有界区域,  $\partial\Omega$  为  $\Omega$  的边界,  $\nu$  为  $\partial\Omega$  的外法向量. 考虑如下边值问题:

$$\begin{cases}
 \Delta u = f & \text{in } \Omega, \\
 u = g & \text{on } \partial\Omega.
 \end{cases}$$

其中  $f \in C(\Omega)$ ,  $g \in C(\partial\Omega)$ . 记  $u$  为上述边值问题的解. 设  $\Omega$  的直径为  $d$ , 且  $d \leq 1$ . 则有以下估计:

$$\|u\|_{C(\bar{\Omega})} \leq C \|f\|_{C(\Omega)} + C \|g\|_{C(\partial\Omega)},$$

其中  $C$  为仅依赖于  $n$  的常数. 特别地, 若  $f \equiv 0$ , 则有

$$\|u\|_{C(\bar{\Omega})} \leq C \|g\|_{C(\partial\Omega)}.$$

以上估计在偏微分方程理论及数值分析中均有重要应用.



... (51), ... (42, 52-54), ... (55), ... (56).

**MATERIALS AND METHODS**  
**Synthesis and characterization of charged colloidal dumpings**

... (57) ...

$\nabla^2 \phi(\mathbf{r}) = -\frac{1}{\epsilon_0} \rho(\mathbf{r})$ ,  $\nabla \phi(\mathbf{r}) = -\mathbf{E}(\mathbf{r})$ ,  $\mathbf{E}(\mathbf{r}) = -\nabla \phi(\mathbf{r})$ ,  $\nabla \cdot \mathbf{E}(\mathbf{r}) = \frac{\rho(\mathbf{r})}{\epsilon_0}$ ,  $\nabla \cdot (-\nabla \phi(\mathbf{r})) = \frac{\rho(\mathbf{r})}{\epsilon_0}$ ,  $-\nabla^2 \phi(\mathbf{r}) = \frac{\rho(\mathbf{r})}{\epsilon_0}$ ,  $\nabla^2 \phi(\mathbf{r}) = -\frac{\rho(\mathbf{r})}{\epsilon_0}$ .

$$\nabla^2 \phi(\mathbf{r}) = -\frac{\rho(\mathbf{r})}{\epsilon_0} \quad (1)$$

$\epsilon_0$

$$\epsilon_0 = \frac{1}{\kappa^2}$$

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... (2) ...  
... 2 ...  
... (5)

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 / 014604/1. **Author contributions:** J.M.C. conceived the project and designed the experiments. J.M.C. and J.S. performed the experiments. J.M.C. and J.S. analyzed the data. J.M.C. wrote the paper. J.S. contributed to the writing of the paper.  
**Competing interests:** The authors declare that they have no competing interests.  
**Data and materials availability:** All data generated during this study are available in the public domain. The accession number for the *Dictyostelium* strains used in this study is <https://www.dictpedia.org/>.  
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