

# Orientational ordering of nanorods in diblock copolymers

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## Abstract

Orientational ordering of rod-like nanoparticles in the lamellae phase of diblock copolymers has been considered theoretically using the model of a nanoparticle with two interaction centres. It has been shown that strongly anisotropic nanoparticles order spontaneously in the boundary region between the blocks where the orientational order is induced by the interface and by the interaction with monomer units in different blocks. The nematic order parameter possesses opposite signs in adjacent blocks which means that the nanorods are aligned parallel or perpendicular to the boundary between the blocks on different sides of their interface. Concentration and nematic order parameter profiles have been calculated numerically for different values of the nanoparticle length and compared with the results of recent computer simulations and with the results of the previous molecular theory based on nanoparticles of spherical shape.

## I. INTRODUCTION

Soft matter nanocomposites are considered to be promising materials where the properties of the corresponding soft matter host phases are significantly modified and improved by the presence of metal, dielectric and semiconductor nanoparticles (NPs). In particular, doping of nematic liquid crystals (LCs) with various NPs affects many important properties of nematic materials, resulting, for examples, in an improvement of switching voltages and switching times of LC displays (see [1–5]). Also doping of nematics with ferroelectric NPs is known to enhance dielectric and optical anisotropy of nematic materials and to crease their electro-optic response [6, 7] Metal NPs have been also used to increase the temperature range of LC blue phases [8] while a small admixture of semiconductor quantum dots in smectic LC-polymers may result in the positional ordering of nanosize particles [9, 10].

Anisotropic NPs may be orientationally ordered in LC nanocomposites and may also affect the orientational order in the LC host phase as well as the thermodynamic stability of the LC phase. Recently, it has been experimentally shown that the nematic–isotropic (N-I) phase transition temperature can be affected by the presence of various NPs. For example, a decrease of the N-I transition temperature is observed when the nematic phase is doped with isotropic silver [11], gold [12] or aerosil particles [13, 14], while the N-I transition temperature increases if the nematic LC is doped with strongly anisotropic NPs including nanotubes [15], magnetic nanorods [16] and ferroelectric particles [17, 18]. Recently a molecular-field theory of nematic LCs doped with both isotropic and anisotropic NPs has been developed [19] which enables one to describe the shift of the transition temperature and the effect of the orientational order of the anisotropic NPs on the nematic order of the host phase. The phase separation in nematic nanocomposites, induced by the N-I phase transition, has also been described theoretically [20]. The effect of isotropic NPs has also been considered in [21].

Recently it has been shown experimentally by the group of J. Goodby [22, 23] that gold NPs with mesogenic coatings may be concentrated at the nematic–isotropic liquid interfaces. Such nanocomposites form reversible networks composed of nematic droplets accompanied by disclination lines and loops. These works by Goodby et.al. open a new direction in the study of LC nanocomposites because so far only systems with a homogeneous distribution of NPs have been investigated.

One notes that in principle anisotropic NPs may be orientationally ordered at an interface

between two different media even if the latter are isotropic in the bulk. Such an ordering has indeed been observed in the lamellae and the hexagonal phases of diblock copolymers. For example, it has been found that poly(ethylene glycol) (PEG) functionalized gold nanorods are aligned parallel to the lamellae planes [24]. At the same time, the polystyrene functionalized nano-rods are orientationally ordered in the hexagonal phase of the same block copolymer with their long axes perpendicular to the cylinders [25, 26]. In contrast, the alkyl phosphonic acid capped nano-rods are ordered parallel to the cylinders [27]. In block copolymers, each block is isotropic in the bulk but there exists also a regular structure of interfaces between the blocks which determines the macroscopic anisotropy of the system. In particular, the lamellae phase contains the one-dimensional periodic sequence of parallel boundaries between the different blocks with the periodicity of the order of 100 nm. The lamellae phase is macroscopically uniaxial but its anisotropy is determined by the regular structure of parallel flat interfaces. In general, the interactions between a NP and the monomers of the two adjacent blocks are likely to be different, and thus one expects that anisotropic NPs will be orientationally ordered only in some interfacial region where they interact with both blocks. On the other hand, there may be also some orientational order of the NPs in the bulk if the length of the NP is comparable to the size of the block.

Recently orientational order and spatial distribution of anisotropic NPs in the lamellae and hexagonal phases of diblock copolymers have been studied theoretically by two of the authors [28] in the case of strong segregation. Explicit analytical results have been obtained for the distribution of anisotropic NPs in the lamellae phase and the nematic order parameter profiles have been calculated numerically. It has been shown that anisotropic NPs are orientationally ordered in the boundary region between the blocks. Moreover, their nematic order parameter possess opposite signs in different blocks i.e., on the different sides of the interface. These qualitative results have been confirmed by a very recent computer simulation study of diblock copolymer nanocomposites where the anisotropic NPs have been modelled by a rigid array of spheres interacting with the monomers of the two different blocks. At the same time, there exists a substantial quantitative discrepancy between the simulation results and the results of the theory. Firstly, in computer simulations the NPs are ordered both in the interfacial region and inside the domains. Secondly, the absolute value of the nematic order parameter, extracted from the simulation data, appears to be higher than the corresponding values obtained from the molecular theory.

These discrepancies can be explained by taking into consideration large geometrical anisotropy of the NPs used in simulations. In fact, these NPs are composed of 5 spheres which is of the same order as the periodicity of the simulated lamellae structure [29]. In contrast, in the theoretical model the NPs are assumed to possess the spherical shape. Such NPs, however, interact with the monomers of the polymer chains via both isotropic and anisotropic central model potentials. In this case the anisotropic interaction may be determined by the polarizability anisotropy of the NP or by its quadrupole moment, i.e by the parameters which are not directly related to the shape.

In this paper, we consider a different model of a NP which is composed of two equal spheres separated by the distance  $L$ . Both spheres interact with the monomers via a model isotropic potential, but the effective interaction between such a NP and a monomer appears to be anisotropic due to the geometrical anisotropy of the “dumbbell”. This anisotropy can be varied by changing the length  $L$ . The paper is arranged as follows. In Section II we summarise the results of the existing molecular theory [28] based on the simple model potential and present typical numerical profiles of the NP concentration and the nematic order parameter. In Section III we investigate the orientational ordering of the anisotropic NPs in the lamellae phase using the new model of the NP and compare the results with those of the previous theory. Finally, in Section IV we present our conclusions.

## II. MOLECULAR FIELD THEORY OF THE ORIENTATIONAL ORDERING OF NANOPARTICLES IN THE LAMELLAE PHASE

The molecular theory of diblock copolymers doped with NPs is based on the following simple interaction potential between the rod-like NP and the isotropic monomer units which is composed of the isotropic and anisotropic parts:

$$U_i = \sum_{l=l_A} [J_A(r_{il}) + I_A(r_{il})(\mathbf{a}_i \cdot \mathbf{u}_{il})^2] + \sum_{l=l_B} [J_B(r_{il}) + I_B(r_{il})(\mathbf{a}_i \cdot \mathbf{u}_{il})^2], \quad (1)$$

where  $\mathbf{r}_i$  is the position vector of the NP  $i$  and  $\mathbf{a}_i$  is the unit vector in the direction of the long axis of the rod-like NP. Here  $J_A(r_{il}), I_A(r_{il})$  and  $J_B(r_{il}), I_B(r_{il})$  are the isotropic and anisotropic coupling constants between the NP and the monomers A and B, respectively,  $\mathbf{r}_{lA}$  and  $\mathbf{r}_{lB}$  are the position vectors of the monomers A and B, respectively,  $\mathbf{r}_{il} = \mathbf{r}_i - \mathbf{r}_l$  and  $\mathbf{u}_{il}$  is the unit vector in the direction of  $\mathbf{r}_{il}$ .

The anisotropic interaction between isotropic monomers and anisotropic NPs in Eq. (1) describes the coupling between the long axis of a NP  $\mathbf{a}_i$  and the unit vector  $\mathbf{u}_{il}$  pointing from the particle to the monomer.

In the molecular field approximation, the one-particle distribution function of NPs is given by the following standard expression:

$$f(\mathbf{a}_i, \mathbf{r}_i) = Z^{-1} \exp[-U_{MF}(\mathbf{a}_i, \mathbf{r}_i)/k_B T], \quad (2)$$

where  $Z$  is the normalization factor and the mean-field potential  $U_{MF}(\mathbf{a}_i, \mathbf{r}_i)$  is expressed as:

$$U_{MF}(\mathbf{a}_i, \mathbf{r}_i) = \int [J_A(r_{il}) + I_A(r_{il})(\mathbf{a}_i \cdot \mathbf{u}_{il})^2] \rho_A(\mathbf{r}_l) d^3 \mathbf{r}_l + \int [J_B(r_{il}) + I_B(r_{il})(\mathbf{a}_i \cdot \mathbf{u}_{il})^2] \rho_B(\mathbf{r}_l) d^3 \mathbf{r}_l. \quad (3)$$

The local scalar nematic order parameter  $S(\mathbf{r})$  of the NPs which is defined with respect to the axis  $\mathbf{k}$  of the lamellae phase (which is normal to the boundaries between the blocks) is then expressed as

$$S(\mathbf{r}) = \langle P_2(\mathbf{a}_i \cdot \mathbf{k}) \rangle = \frac{\int P_2(\mathbf{a}_i \cdot \mathbf{k}) f(\mathbf{a}_i, \mathbf{r}) d^2 \mathbf{a}_i}{\int f(\mathbf{a}_i, \mathbf{r}) d^2 \mathbf{a}_i}, \quad (4)$$

while the density distribution of NPs, averaged over all their orientations, is given by

$$\rho_N(\mathbf{r}) = \rho_{N0} \int f(\mathbf{a}_i, \mathbf{r}) d^2 \mathbf{a}_i, \quad (5)$$

where  $\rho_{N0}$  is the average NP number density and  $P_2(x)$  is the second Legendre polynomial.

As shown in Ref. [28], in the limiting case of strong segregation it is possible to obtain an explicit analytical expression for the mean-field potential assuming for simplicity that  $J_\alpha(r) = J_\alpha r^{-6}$  and  $I_\alpha(r) = I_\alpha r^{-6}$  with the steric cut-off  $r_0$ , where  $\alpha = A, B$ . The potential is given by different expressions for different values of the distance  $z$  from the NP to the boundary between the blocks.

i) Far from the interface, for  $z > R_0$ , where  $R_0$  is the radius of NP-monomer interaction and the  $z$ -axis is normal to the interface, the mean-field potential is expressed as

$$\begin{aligned} U_{MF}^{(0)}(\mathbf{a}, z) &= - \int_{r_0}^{R_0} z^{-4} dr \int_0^1 d \cos \theta \int_0^{2\pi} d\phi [\Delta + \Delta I(\mathbf{a} \cdot \mathbf{u})^2] = \\ &= -2\pi \int_{r_0}^{R_0} z^{-4} dr \int_0^1 d \cos \theta \left[ \Delta J + \frac{1}{2} \Delta I \sin^2 \theta + \Delta I P_2(\cos \theta)(\mathbf{k} \cdot \mathbf{a})^2 \right] = \\ &= \frac{2\pi}{3} \left( \Delta J + \frac{\Delta I}{3} \right) (R_0^{-3} - r_0^{-3}), \quad (6) \end{aligned}$$

where  $r_0$  is the NP radius. One notes that in this range the NP interacts only with the monomers of the same kind, and as a result the mean-field potential appears to be constant and the orientational order parameter vanishes.

ii) In the boundary layer  $r_0 < z < R_0$ , the potential takes the form

$$\begin{aligned}
U_{MF}^{(1)}(\mathbf{a}, z) &= - \left[ \int_{r_0}^z dr \int_0^1 d \cos \theta + \int_z^{R_0} dr \int_0^{z/r} d \cos \theta \right] \\
&= 2\pi r^{-4} \left[ \Delta J + \frac{1}{2} \Delta I \sin^2 \theta + \Delta I P_2(\cos \theta) (\mathbf{k} \cdot \mathbf{a})^2 \right] = \\
&= \frac{2\pi}{3} \left( \Delta J + \frac{\Delta I}{3} \right) (z^{-3} - r_0^{-3}) + \\
&+ \frac{\pi z}{2} \left[ \Delta J + \frac{\Delta I}{3} - \frac{\Delta I}{3} P_2(\mathbf{k} \cdot \mathbf{a}) \right] (R_0^{-4} - z^{-4}) + \frac{\pi z^3}{9} \Delta I P_2(\mathbf{k} \cdot \mathbf{a}) (R_0^{-6} - z^{-6}), \quad (7)
\end{aligned}$$

iii) Finally, in a thin layer very close to the block boundary,  $z < r_0$ , the potential can be written in the form:

$$\begin{aligned}
U_{MF}^{(2)}(\mathbf{a}, z) &= - \int_{r_0}^{R_0} r^{-4} dr \int_0^{z/r} d \cos \theta \int_0^{2\pi} d\phi [\Delta J + \Delta I (\mathbf{a} \cdot \mathbf{u})^2] = \\
&= \frac{\pi z}{2} \left[ \Delta J + \frac{\Delta I}{3} - \frac{\Delta I}{3} P_2(\mathbf{k} \cdot \mathbf{a}) \right] (R_0^{-4} - r_0^{-4}) + \frac{\pi z^3}{9} \Delta I P_2(\mathbf{k} \cdot \mathbf{a}) (R_0^{-6} - r_0^{-6}). \quad (8)
\end{aligned}$$

One notes that in the boundary region the mean-field potential depends on the NP position  $z$  and on the orientation of the NP long axis with respect to the boundary normal  $\mathbf{k}$ . The orientational order parameter profile can now be obtained by a numerical integration in Eq. (4). Characteristic spatial distributions of the NP density and the nematic order parameter are presented in Fig. 1 and Fig. 2. One can readily see that the nematic order parameter  $S(z)$  possesses opposite signs on different sides of the boundary, that is the anisotropic NPs have a tendency to align parallel to the interface in one block and perpendicular to the interface in another. At the same time the absolute value of the orientational order parameter is rather small and the orientational ordering exists only in a relatively narrow boundary region where the concentration of NPs is small.

### III. ORDERING OF ANISOMETRIC NANOPARTICLES OF DIFFERENT LENGTH

Let us consider the model of the anisotropic NP composed of two equal spheres of radius  $r_0$  separated by the distance  $L$  (see Fig...) Each sphere interacts with the monomers A

and B via the simple model interaction potential  $V(r) = J_\alpha r^{-6}$  with the steric cut-off  $r_0$  and  $\alpha = A, B$ . The position of such a NP can be specified by the radius vector  $\mathbf{r}$  and the orientation of the NP is specified by the unit vector  $\mathbf{a}$  in the direction of the NP axis. Now the total interaction potential between the NP  $i$  and the monomer  $j$  of the sort  $\alpha$  can be expressed as:

$$V_{ij}(\mathbf{r}_i, \mathbf{a}_i) = J_\alpha r_{1j}^{-6} + J_\alpha r_{2j}^{-6}, \quad (9)$$

where  $\mathbf{r}_{1j} = \mathbf{r}_{ij} + (L + r_0)\mathbf{a}_i$ ,  $\mathbf{r}_{2j} = \mathbf{r}_{ij} - (L + r_0)\mathbf{a}_i$  and where  $\mathbf{r}_{ij}$  is the vector between the centre of the NP and the monomer  $j$ .

The total NP-monomer interaction potential is anisotropic because it explicitly depends on the orientation of the NP primary axis  $\mathbf{a}$ . Its anisotropy is illustrated in Fig. 3. Indeed, let us fix the centre of the NP at a distance  $z < L$  from the boundary between the blocks. If the NP centre is located in the block A with the strongest interaction between the NP and the monomers, the minimum of the interaction potential corresponds to the configuration when both spheres are located in the block A. One can readily see from Fig. 3 that this is possible only if the NP is approximately parallel to the boundary between the blocks. In contrast, if the NP centre is located in the block B, the two spheres cannot be located in the block A simultaneously, and the minimum of the interaction energy is achieved when the NP is approximately perpendicular to the boundary and one sphere is in the block A. This explains qualitatively why the NPs align parallel to the interface in one block and perpendicular to the interface in the adjacent block.

One notes that the interaction potential (9) has exactly the same mathematical form as the isotropic part of the potential used in the previous section. Thus the mean field potential for a single sphere in the “dumbbell” NP is also given by the same expressions as the mean-field potential in Section II. Taking into account that the NP is composed of two spheres, the total mean-field potential is expressed as:

$$U_{MF}(z, \theta) = U_{MF1}(z_1) + U_{MF2}(z_2), \quad (10)$$

where  $z_1 = z + (L/2 + r_0) \cos \theta$  is the distance from the sphere “1” to the flat interface and  $z_2 = z - (L/2 + r_0) \cos \theta$  is the corresponding distance from the sphere “2”.

The mean-field potential  $U_{MF_i}(z_i)$ ,  $i = 1, 2$  is given by the Eqs. (6–8) with  $\Delta I = 0$ . Assuming that  $R_0 \gg r_0$ , the potential can be written in the form:

For  $z_i > r_0$

$$U_{MF_i}(z_i) = \frac{\pi}{6}\Delta J z_i^{-3} - \frac{2\pi}{3}\Delta J r_0^{-3}, \quad (11)$$

and for  $0 < z_i < r_0$

$$U_{MF_i}(z_i) = -\frac{\pi z_i}{2}\Delta J r_0^{-4}. \quad (12)$$

One notes that the inequalities  $|z_i| < r_0$  and  $|z_i| > r_0$ , which determines the particular expression for the mean-field potential, split the  $(z, \cos\theta)$  into several regions where the integration should be undertaken separately using the variable limits. Such a cumbersome procedure can be dramatically simplified by using the following interpolated mean-field potential which is qualitatively valid for all values of  $z$  and  $\theta$ :

$$U_{MF}^*(z, \theta) = -\frac{\pi}{6}\Delta J \tanh(z_1^6/r_0^6)z_1^{-3} - \frac{2\pi}{3}\Delta J \tanh(z_1/r_0)r_0^{-3} \\ - \frac{\pi}{6}\Delta J \tanh(z_2^6/r_0^6)z_2^{-3} - \frac{2\pi}{3}\Delta J \tanh(z_2/r_0)r_0^{-3}, \quad (13)$$

where  $\tanh(z/r_0)$  and  $\tanh(z^6/r_0^6)$  are the interpolation functions. For  $z > r_0$  both functions are approximately equal to one, while for  $z < r_0$  the function  $\tanh(z/r_0) \approx z/r_0$  and the term proportional to the second function  $\tanh(z_2^6/r_0^6) \approx z_2^6/r_0^6 \ll 1$  can be neglected.

Now the orientational order parameter  $S(z)$  and the local NP concentration can be calculated numerically substituting the mean-field potential (13) into Eqs. (4) and (5). The corresponding concentration and order parameter profiles are presented in Figs. 4, 6, 7 for two different lengths of the NPs. One can readily see that the nematic order parameter possesses opposite signs in different blocks similar to the results obtained in Section II. At the same time, the absolute value of the order parameter is significantly higher and may reach the values of 0.6 – 0.7 for reasonable values of the interaction constant. Moreover, the width of the interfacial region, where a significant orientational order of the NPs is found, appears to be much wider and increases with the increasing NP length. Also the concentration of NP in this interfacial region is higher than in Section II. This can be explained by taking into account that the length of the NP is larger than the radius of the sphere  $r_0$ , and as a result the elongated NPs may order orientationally when their centre is separated at least by the distance  $z \sim L + 2r_0$  from the boundary. This can be seen comparing Fig. 4 and Fig. 6.

## IV. DISCUSSION

In this paper we have considered the spatial distribution and the orientational ordering of strongly anisotropic NPs in the lamellae phase of diblock copolymers in the strong segregation limit. The NP is modelled by two equal spheres of radius  $r_0$ , separated by the fixed distance  $L$  which is a parameter of the model. Both spheres interact with monomers of the polymer chain via a simple isotropic potential, and the coupling constant in this potential is different for monomers “A” and “B” which are located in different blocks of the lamellae structure. As a result the total potential of interaction between such a NP and a monomer unit is anisotropic and multi centred. The mean-field potential of a NP, which is equal to the interaction potential averaged over the distribution of the monomer units “A” and “B”, also appears to be anisotropic. It depends on the orientation of the NP axis with respect to the boundary normal when the NP is sufficiently close to the boundary between the blocks.

The anisotropy of the mean-field potential is illustrated in Fig. 3. If the NP has the lowest energy when it is located, say, in the block “A”, and if the centre of the NP is sufficiently close to the boundary between the blocks, the anisotropic NP has a strong tendency to align parallel to the interface because only in this configuration both spheres are in the block “A”. In contrast, if the centre of the NP is located in the block “B” close to the boundary, the energy minimum is achieved when the NP axis is approximately perpendicular to the boundary because in this case one of the spheres is located in the block “A”.

Concentration and orientational order parameter profiles of the anisotropic NPs have been calculated numerically in the molecular-field approximation for three different values of the NP length. The results have been compared with the corresponding profiles obtained using the model of spherical NPs with the anisotropic interaction potential, considered in the previous paper [28]. Similarly to the previous study, it has been found that the anisotropic NPs are orientationally ordered in some boundary region between the blocks, and the nematic order parameter possesses opposite signs on different sides of the boundary. At the same time the width of the boundary region is significantly larger than that obtained using the model of spherical NPs with anisotropic interaction potential. Indeed, in the previous model the width of the boundary region is of the order of the NP radius  $r_0$  (see Fig. 1) while in the present model it is of the order of NP length. The absolute value of the nematic order parameter and the concentration of NPs in the boundary region is also

higher than in the previous model.

These quantitative features are related to the large geometric anisotropy of the model NPs and to the existence of two separate interaction centres. The NPs may be ordered also inside the domains if one of their ends is close to the interface and can interact with the monomers in the adjacent block. In general, the order parameter and the concentration profiles, obtained in this paper, are closer to the results of computer simulations [29] than the results of our previous study [28]. One notes that in the computer simulations the NPs are also ordered inside the blocks. This is most probably determined by a very large relative length of the NPs which is comparable to the size of the block.

The results of this theoretical study, supported by very recent computer simulations, indicate that sufficiently anisotropic NPs may spontaneously order in the lamellae phase of diblock copolymers resulting in an optically anisotropic polymer composite. In contrast to the classical nematic LCs, however, the orientational order is not determined by the interaction between NPs but is induced by the interaction with different monomer units of the polymer chain at the interface between the blocks. As a result the orientational order exists only in some boundary region. It should be noted also that the nematic order parameter appears to be sufficiently high to provide a relatively strong coupling with the external electric field. In principle, this opens a possibility to align the polymer nanocomposites by applying the external electric field which will rotate the ordering tensor of the NPs together with the boundaries between blocks. The drawback of this alignment method is related to the low concentration of NPs in the boundary region where the orientational order parameter is relatively high. This problem can be solved by a special tailoring of the NPs which increases their affinity to the interface. In the field of LC nanocomposites, the corresponding NPs have been synthesized by the group of Goodby et.al. [22, 23]. It has been shown that gold nanorods with mesogenic coating may be concentrated at the nematic-isotropic interface and stabilize the nematic droplets. In principle, similar methods can also be applied to synthesize the NPs which will concentrate at the boundaries between different blocks.

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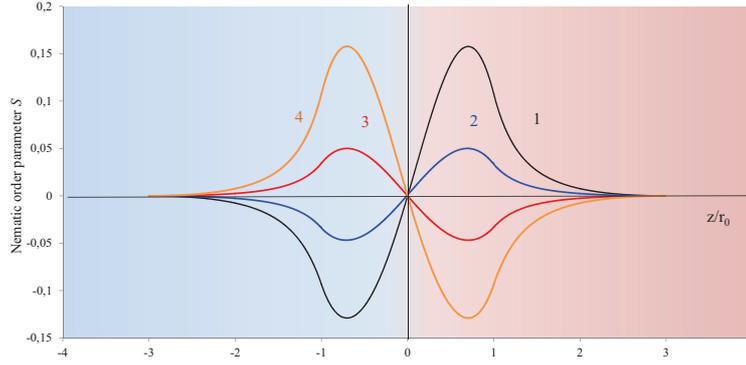


FIG. 1: The nematic order parameter of anisotropic nanoparticles of spherical shape in the lamellar phase of A diblock copolymer. The isotropic interaction constant  $\Delta J = 3k_B T$  and the anisotropic constant  $\Delta I = 3k_B T, k_B T, -k_B T, -3k_B T$  for the lines from 1 to 4, respectively.

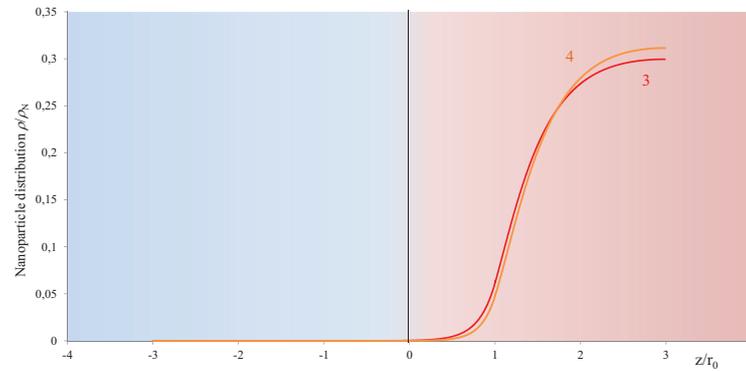


FIG. 2: Local density of the nanoparticles of spherical shape in the lamellar phase of a diblock copolymer. The isotropic interaction constant  $\Delta J = 3k_B T$  and the anisotropic constant  $\Delta I = -k_B T, -3k_B T$  for the lines 3 and 4, respectively.

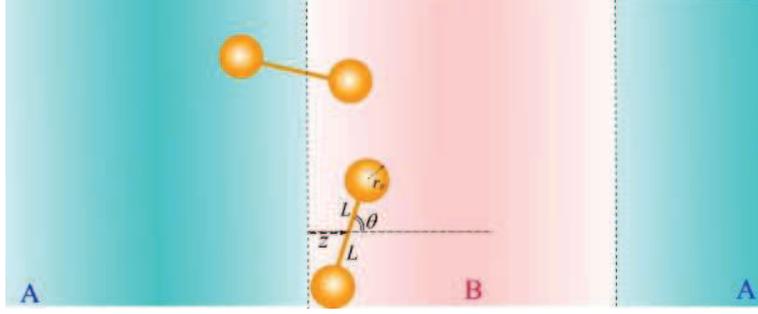


FIG. 3: Orientational ordering of anisotropic nanoparticles with two interaction centres in the boundary region between the blocks. If the NP energy is lower when it is located in the block A and if the NP centre is close to the boundary, the NP is aligned parallel to the boundary with both spheres in the block A. If the NP is located in the block B, it is approximately perpendicular to the boundary which enables one of the spheres to reside in the Block A.

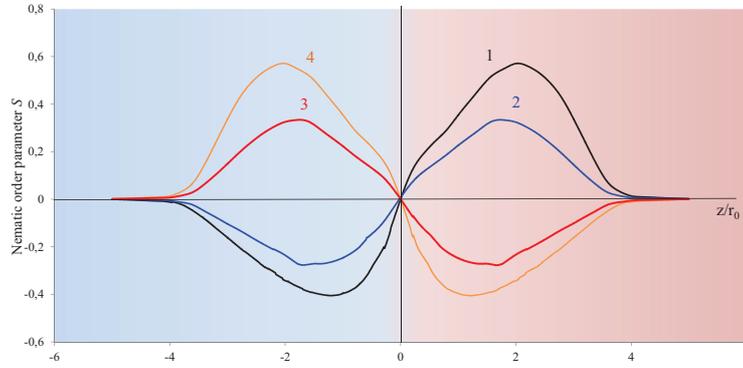


FIG. 4: The nematic order parameter distribution of shorter nanoparticles with two interaction centres and  $L = r_0$  in the lamellar phase of a diblock copolymer. The interaction constant  $\Delta J = -k_B T, -k_B T/2, k_B T/2, k_B T$  for the lines from 1 to 4, respectively.

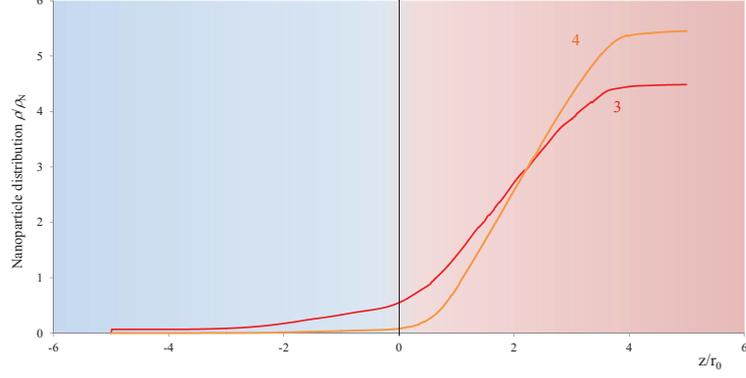


FIG. 5: Local density of shorter nanoparticles with two interaction centres and  $L = r_0$  in the lamellar phase of a diblock copolymer. The interaction constant  $\Delta J = -k_B T$ ,  $-k_B T/2$ ,  $k_B T/2$ ,  $k_B T$  for the lines 3 and 4, respectively.

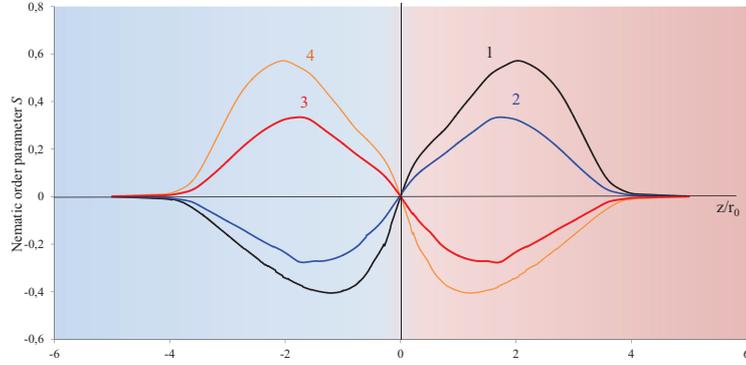


FIG. 6: The nematic order parameter distribution of longer nanoparticles with two interaction centres and  $L = 2r_0$  in the lamellar phase of a diblock copolymer. The interaction constant  $\Delta J = -k_B T$ ,  $-k_B T/2$ ,  $k_B T/2$ ,  $k_B T$  for the lines from 1 to 4, respectively.

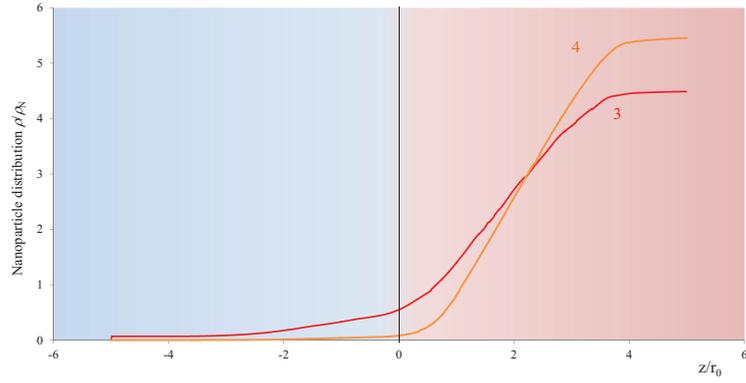


FIG. 7: Local density of longer nanoparticles with two interaction centres and  $L = 2r_0$  in the lamellar phase of a diblock copolymer. The interaction constant  $\Delta J = -k_B T$ ,  $-k_B T/2$ ,  $k_B T/2$ ,  $k_B T$  for the lines 3 and 4, respectively.