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Effects of electrostatic interactions and geometrical confinements on depletion interactions in charged colloidal system*

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In a charged colloidal system, the influence on depletion interaction between two like-charged macro-ions is studied through Monte Carlo simulation in this paper. The numerical results show that this depletion force is affected by both the electrostatic interactions between charged spheres and charged plates and by the geometrical factor of the two charged plates, and they further indicate that the influence of geometrical confinement on the depletion interaction is larger than that of electrostatic potential.

Keywords: depletion interaction, geometrical confinement
PACC: 8270D, 7115Q

1. Introduction

An argument about whether the attraction between two like-charged colloidal spheres ("macroions") is possibly present has never stopped since the 1990s.[1] The notable theory developed by Derjaguin–Landau–Verwey–Overbeek (DLVO) predicts that an isolated pair of like-charged colloidal particles in an electrolyte should experience a purely repulsive electrostatic interaction.[2−4] However, recent experiments have provided evidence that the effective inter-particle potential in a charged system under geometrical confinement can have an attractive component in more concentrated suspensions.[5−15] Obviously, this attraction is very important for both experimental and theoretical studies. Allahyarov *et al* [12,13] proposed that the depletion interaction played a very important role for the attraction between like-charged colloidal spheres, and found that the sign of the effective force was dependent on the distance of the charged sphere to the plates and on the inter-particle spacing. In this case, the magnitude of the depletion force is almost the same as, or even larger than, a total electrostatic interaction, which has been verified by numerical simulations.[16] Depletion forces in uncharged systems are well studied, however they are different from those in charged systems. It is interesting to show their difference. In fact, it is known that in an uncharged or a neutral colloidal system, the depletion interaction between two large colloidal spheres is strengthened if the system is confined between two parallel plates.[17] We believe that in a charged system, the depletion force is also affected by the geometrical confinement. On the other hand, as the depletion forces acting on macro-ions are related to the distribution of the micro-ions which is further affected by the electrostatic interactions, therefore, it is possible that the depletion interactions are also affected by the electrostatic interactions among the macro-ions, micron-ions and the charged plates. In this paper, we study the effects of electrostatic interaction and the geometrical confinement on the depletion force by Monte Carlo simulation. However, it is not so easy to deal with the long-ranged electrostatic interactions among charged spheres in simulation. The conditional periodic-boundary condition method developed

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by Wood and Parker[18] was first used to calculate the electrostatic energy of such a system. A truncation must be made while calculating, which can induce a serious cut-off error. On the other hand, the Ewald summation proposed by Die Ewald[19] is a very effective way for a periodic system, and its accuracy has been improved, however, this method costs much CPU time. Recently another interesting way, called hyper-sphere method, has been successfully employed to study charged colloidal systems on the hyper-sphere surface of a four-dimensional sphere with no truncation and less CPU time required.[20−24] So, in our simulation, we make use of the hyper-sphere method to deal with the electrostatic interaction.

The remainder of the present paper is organized as follows. The model is presented in Section 2. The details of simulation is presented in Section 3. The numerical results and the brief discussion are given in Section 4. Finally, the conclusions drawn from the present study are given in Section 5.

2. Model

In the present paper, we consider two macroions each with bare charge $-Ze(Z>0)$ where e denotes the elementary charge, and radius $r_{\rm m}$, which are immersed in the sea of the microscopic counterions. The charge and the radius of a counterion are qe and $r_{\rm c}$ respectively. The system under study is further confined between two parallel plates that carry surface charge density $\sigma_{\rm p}$. We assume that the plates and the macroions are likely charged. Both the macroions and the charged plates provide neutralizing counterions which are dissolved in the solution with relative permittivity $\varepsilon_{\rm r}$ (we choose $\varepsilon_{\rm r}$=78.5 for aqueous solution at temperature T=293 K). Electro-neutrality of the simulation model requires

$$2Z - N_{\rm c}q + 2\sigma_{\rm p}S_{\rm p} = 0, \tag{1}$$

where $N_{\rm c}$ represents the number of the counterions, and $S_{\rm p}$ is the surface area of the plate. In the frame work of the primitive model, we assume that the pair interaction potentials $V_{\rm mm}(r)$ between macroions, $V_{\rm mc}(r)$ between the macroions and counterions, and $V_{\rm cc}(r)$ between counterions are, respectively,[13]

$$V_{\rm mm}(r) = \begin{cases} \infty & \text{for } r < d_{\rm m}, \\ \dfrac{Z^2e^2}{\epsilon r} & \text{for } r > d_{\rm m}, \end{cases} \tag{2}$$

$$V_{\rm mc}(r) = \begin{cases} \infty & \text{for } r < (d_{\rm m}+d_{\rm c})/2, \\ \dfrac{-Zqe^2}{\epsilon r} & \text{for } r > (d_{\rm m}+d_{\rm c})/2, \end{cases} \tag{3}$$

$$V_{\rm cc}(r) = \begin{cases} \infty & \text{for } r \le d_{\rm c}, \\ \dfrac{Z^2e^2}{\epsilon r} & \text{for } r > d_{\rm c}, \end{cases} \tag{4}$$

where r denotes the corresponding interparticle spacing, $d_{\rm m}$ and $d_{\rm c}$ are the diameters of macroion and counterion, respectively. The interaction between the particles and the plate is[15]

$$V(z)_{{\rm p}i}(r) = \begin{cases} \infty \text{ for } x \le d_i/2, \\ 0 \quad \text{for } x > d_i/2, \end{cases} \tag{5}$$

where x is the distance between particles and plate, and i=m, c.

In the charged colloidal system, besides the electrostatic interactions between the charged particles, the depletion interaction should be included. So the total effective force exerted on the j-th (j=1, 2) macroion comprises three different parts:[13]

$$\boldsymbol{f}_j = \boldsymbol{f}_j^{(1)} + \boldsymbol{f}_j^{(2)} + \boldsymbol{f}_j^{(3)}. \tag{6}$$

Here,

$$\boldsymbol{f}_j^{(1)} = -\nabla\Big(\sum_{i=1;j\neq i}^{2} V_{\rm mm}(|\boldsymbol{R}_i - \boldsymbol{R}_j) + V_{\rm pm}(x)\Big), \tag{7}$$

$$\boldsymbol{f}_j^{(2)} = -\Big\langle \sum_{i=1}^{N_{\rm c}} \nabla \frac{Zqe^2}{\epsilon|\boldsymbol{R}_j - \boldsymbol{r}_i|} \Big\rangle_{\rm c}, \tag{8}$$

$$\boldsymbol{f}_j^{(3)} = k_{\rm B}T \int_s {\rm d}\boldsymbol{n}\rho_{\rm c}, \tag{9}$$

where $\boldsymbol{R}_i$ and $\boldsymbol{r}_i$ denote the positions of a macroion and a counterion respectively, $\langle\ldots\rangle_{\rm c}$ represents the canonical counterion average, $k_{\rm B}$ is the Boltzmann's constant and T the absolute temperature, $\boldsymbol{n}$ is the surface vector pointing towards the macroion centre, $\rho_{\rm c}$ the contact density of counterions on the surface of the macroion, and s is the surface area of the macroion. The first part $\boldsymbol{f}_j^{(1)}$ is the direct Coulomb repulsion between the macroions and the confined plates, the second part $\boldsymbol{f}_j^{(2)}$ is the counterions-induced electrostatic force and the third part $\boldsymbol{f}_j^{(3)}$ is the depletion force. As is known, $\boldsymbol{f}_j^{(1)}$ and $\boldsymbol{f}_j^{(2)}$ can be analytically obtained through the hyper-sphere method (see Appendix A), and $\boldsymbol{f}_j^{(3)}$ can be determined by using the acceptance ratio method (ARM)[17,25−28] or by using the density

integration method (DIM) described by Eq.(9) in Refs.[25].[1)] In this paper, the DIM is used.

3. Simulation details

As is known, the charged system is very complex. In this paper, we study only the influence of electrostatic interactions among the counterions and the two charged plates on depletion interaction. To show the effect of the electrostatic potential on depletion interaction, a comparison between depletion interactions in a charged system and an uncharged system is needed. In the simulations, the two charged or uncharged plates are located in the x direction at $x_1 = -L_x/2$ and $x_2 = L_x/2$, where $L_x = 20r_c$, and the two charged or uncharged large-spheres or macroions are placed in the middle plane between the two plates (A corresponding schematic diagram is shown in Fig.1). For simplicity, we take the radius ratio r_m/r_c=5 and the charge ratio Z/q=100 between macroion and counterion, then the number of the counterions, N_c, is determined while the volume fraction η is given. Usually, η is defined as $\eta = N_c V_c/(V - 2V_m)$, where V is the total volume, V_c represents the volume of a counterion, V_m the volume of a macroion, and the zero point of the depletion potential is set at the position where the two macroions contact each other. Though the hyper-sphere method is very efficient, the amount of calculation is still very large for charged systems, So, in this paper, the systems only with η=0.10 and 0.15 are studied. On the other hand, it is known that in Ref.[24], only 2.5×10^3 Monte Carlo steps (MCSs) were performed for the thermalization of an ionic system and other 1.0×10^4 MCSs were used to collect data. To reduce the statistic errors, in this paper, for the charged system, 2.0×10^4 MCSs are used for equilibrium of the system and other 6.0×10^4 MCSs were used to collect data; for the uncharged system, 2.0×10^5 MCSs are used for equilibrium of the system and other 2.0×10^5 MCSs were for collecting data.[25]

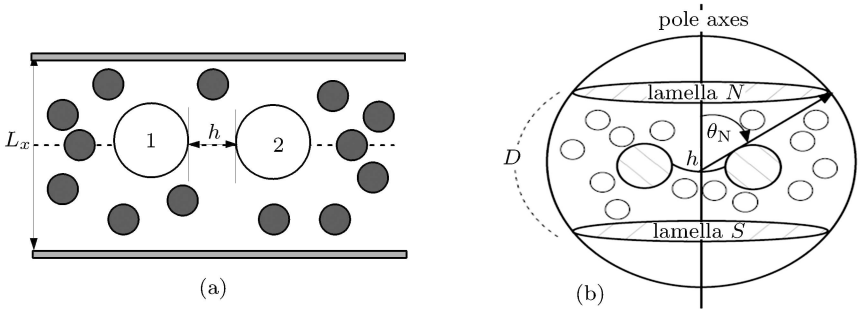


Fig.1. Schematic drawing of a pair of large spheres or macroions confined between two hard or two likely charged plates, where the separation between the two plates is $D = L_x$ and h is the surface spacing between the two large-spheres (a) and schematic drawing of the hyper-sphere in (a).

4. Results and discussion

4.1. Effect of electrostatic potential on depletion force

The depletion interactions in a charged system and an uncharged system of η=0.1 and 0.15 are determined by using the DIM and the results are shown in Figs.2(a) and 2(b) respectively. In Fig.2, the depletion forces are plotted in units of $\pi r_m \rho\, k_B T$, where h is measured in units of $2r_c$, and the depletion forces of the charged and the neutral colloidal systems are described by the lines with open squares and solid circles respectively, and their largest errors are less than sizes of the symbols. From Fig.2(a), we find that the depletion forces are almost unaffected by the electrostatic potential when $0 < h < r_c$. However, as distance h increases, the amplitude of oscillation of the depletion

[1)] For DIM, in the Monte Carlo simulation, the density profile can be obtained through an extrapolation procedure: the space around the large-sphere is divided into shells of thickness d, and the density of small-sphere fluid in each shell as a function of θ is obtained through the simulation by simply collecting the number of times that a small sphere is centred in the shell at the angle position θ, then the average densities of small fluids in a shell around the large spheres of thickness d, $2d$, ..., etc. can be obtained, and the depletion force can thus be obtained by extrapolating I_i to d=0 using the spline method, where $I_i = \int_0^\pi \mathrm{d}\theta \rho_i \sin\theta \cos\theta$.[25]

force in the charged system increases: the peak value of the repulsive part is larger than that in a hard-sphere system, but the bottom value of the attractive part (the second attractive part) is smaller than that in the hard-sphere system. In other words, the depletion force in the charged system is strengthened by the electrostatic interactions when $r_c < h < 4r_c$. Obviously, the same conclusion can also be obtained from Fig.2(b). As the minimum values of the depletion forces are almost unchanged, to describe the influence on the depletion force in detail, it is useful to make a comparison between the maximum values of the depletion forces in the charged and the uncharged colloidal systems. The maximum values of the depletion forces in a charged colloidal system of η=0.1, 0.15 can be obtained from Table 1, and the maximum values of the depletion forces of the neutral colloidal systems are 0.25 and 0.51 respectively. It is easy to see that the maxima of the depletion forces of charged colloidal systems increase by 0.07 and 0.16 for the cases of η=0.1, 0.15 respectively as compared with those of neutral systems. Obviously, the depletion interactions are affected by the electrostatic interactions, and this influence is enlarged with the increase of volume fraction.

Table 1. Maximum and minimum values of the depletion forces in the systems of different volume fractions and different separations between two plates..

	$L_x = 16r_c$			$L_x = 20r_c$			$L_x = 22r_c$		
	f_{max}	f_{min}	Δf_e	f_{max}	f_{min}	Δf_e	f_{max}	f_{min}	Δf_e
η=0.1	0.42	–2.72	3.14	0.32	–2.45	2.77	0.19	–2.11	2.30
η=0.15	0.82	–4.27	5.09	0.67	–4.06	4.73	0.50	–3.68	4.18

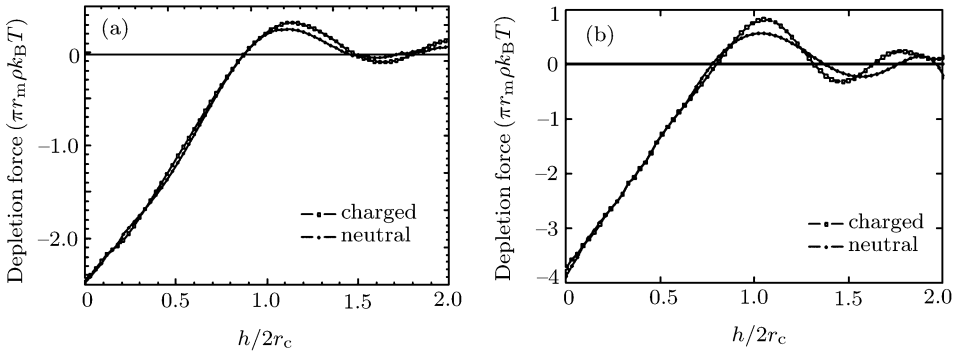


Fig.2. Depletion forces between two large-spheres in the charged and the neutral colloidal systems with η=0.1 (a) and 0.15 (b).

4.2. Effect of geometrical confinement on depletion force

To expose the effect of geometrical confinement on depletion interaction, we study the depletion interactions in the charged systems with the same volume fraction but different separations between the two charged plates L_x.[17] In the systems under study, the size ratio and charge ratio of the macroion to counterion are still 5 and 100, and the two macroions are placed in the middle plane between the two plates(see Fig.1(a)). For the cases where η=0.1 and 0.15, the depletion forces of the systems with $L_x = 22r_c$, $20r_c$, and $16r_c$ are determined by using the DIM, and the results are shown in Fig.3. In the same way as that mentioned above, the depletion forces are normalized by $\pi r_m \rho k_B T$. In both Figs.3(a) and 3(b), the depletion forces of the systems with $L_x = 22r_c$, $20r_c$, and $16r_c$ are described by the solid lines with open squares, solid circles and solid triangles respectively, with errors less than the sizes of symbols. From Figs.3(a) and 3(b), it is evident that depletion forces are affected by the geometrical confinement of the two parallel plates: when the spacing between two macroions changes from 0 to $4r_c$, especially from 0 to r_c, the depletion forces are strengthened due to the geometrical confinement.

In order to measure the influence on the depletion interaction, the maximum and the minimum values of the depletion forces in the systems with different volume fractions and different separations between the two plates are listed in Table 1. Furthermore, quantity $\Delta f_{\rm e}$, defined as the difference between maximum and minimum of depletion force, is introduced. From Table 1, it is easy to see that for η=0.1, the values of $\Delta f_{\rm e}$ corresponding to different separations between the two plates are $\Delta f_{\rm e}^{16}$=3.14, $\Delta f_{\rm e}^{20}$=2.77, and $\Delta f_{\rm e}^{22}$=2.30, and the relative values are $(\Delta f_{\rm e}^{16}-\Delta f_{\rm e}^{20})/\Delta f_{\rm e}^{20}$ = 13.4%, $(\Delta f_{\rm e}^{20}-\Delta f_{\rm e}^{22})/\Delta f_{\rm e}^{22}$ = 20.4%, and $(\Delta f_{\rm e}^{16}-\Delta f_{\rm e}^{22})/\Delta f_{\rm e}^{22}$ = 36.5%, respectively; for η = 0.15, $\Delta f_{\rm e}^{16}$ = 5.09, $\Delta f_{\rm e}^{20}$ = 4.73, and $\Delta f_{\rm e}^{22}$ = 4.18, then $(\Delta f_{\rm e}^{16}-\Delta f_{\rm e}^{20})/\Delta f_{\rm e}^{20}$ = 7.6%, $(\Delta f_{\rm e}^{20}-\Delta f_{\rm e}^{22})/\Delta f_{\rm e}^{22}$ = 13.2%, and $(\Delta f_{\rm e}^{16}-\Delta f_{\rm e}^{22})/\Delta f_{\rm e}^{22}$ = 21.8%. From the above data, it is clear that both $\Delta f_{\rm e}$ and its relative value increase with the decrease of the separation between the two plates; though $\Delta f_{\rm e}$ increases with the increase of volume fraction, its relative value decreases. Furthermore, a comparison between the absolute values of $\Delta f_{\rm e}$ shows that the value of $\Delta f_{\rm e}$, caused by the geometrical factor of the two plates, is larger than that due to the electrostatic interaction, i.e. the influence of geometrical confinement on the depletion interaction is larger than that of electrostatic potential.

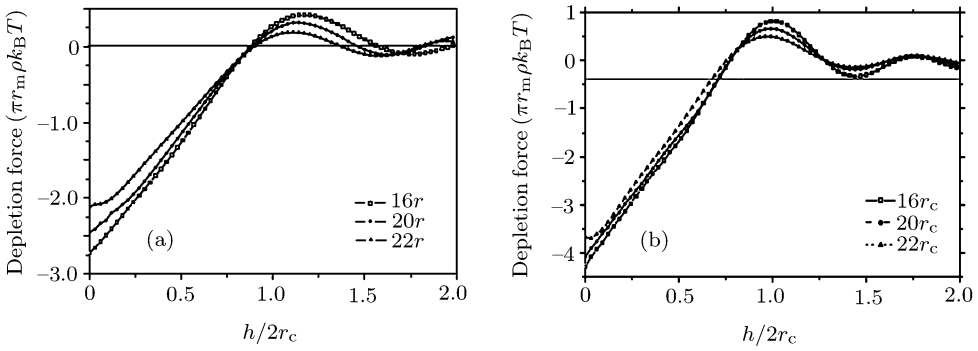


Fig.3. Depletion forces between the two macroions confined between two charged plates with separations being $22r_{\rm c}$, $20r_{\rm c}$ and $16r_{\rm c}$, and the volume fractions of the systems η=0.1 (a) and 0.15 (b).

5. Conclusions

With the aid of hyper-sphere method, we have numerically studied the effects of electrostatic interaction and geometrical confinement on depletion interaction through Monte Carlo simulation. The results show that when distance $h > r_{\rm c}$, the depletion force between the macroions is strengthened by the electrostatic interactions among charged spheres and charged plates. Meanwhile, this depletion force is further strengthened by the geometrical confinement of the two charged plates, especially when the spacing between two macroions is small. In other words, no matter whether the spacing between two macroions is large or small, the depletion force between them is strengthened by the geometrical confinement or by the electrostatic interactions. Furthermore, the influence of geometrical confinement on depletion interaction is larger than that of electrostatic potential.

Appendix A Hyper-sphere method

As is well known, a hyper-sphere surface of an Euclidian space of dimension four is a closed, homogeneous and isotropic space of dimension three (denoted with S_3, see Fig.1), which is well adapted for the numerical simulation of liquid phase.[20−24] Point M of the hyper-sphere may be determined by the 4D spherical coordinates (u, ν, θ). Let z_i (i=1, 2, 3, 4) be the components of the unit vector $\boldsymbol{Z} = \overrightarrow{OM}/R$, then

$$\begin{aligned} z_1 &= \sin\theta\sin\nu\cos u,\\ z_2 &= \sin\theta\sin\nu\sin u,\\ z_3 &= \sin\theta\cos\nu,\\ z_4 &= \cos\theta,\\ 0 \le u \le 2\pi,\ 0 \le \nu \le \pi,&\quad 0 \le \theta \le \pi, \end{aligned} \tag{A1}$$

R_θ is the geodesic distance between point M and the north pole of the hyper-sphere, and R is the radius of the hyper-sphere. In S_3, the volume element is

$$dV = R^3 \sin^2\theta \sin\nu du d\nu d\theta, \tag{A2}$$

and the volume from a conical section of the hyper-sphere with angular aperture θ is

$$V(\theta) = \pi R^3(2\theta - \sin(2\theta)). \tag{A3}$$

It is limited by interfacial area

$$S(\theta) = 4\pi R^2 \sin^2\theta. \tag{A4}$$

On S_3, the two charged lamellae corresponding to the two charged plates are placed at θ_N, and $\pi - \theta_N$, located symmetrically on opposite sides of the equator and all the ions are confined between the lamellae ($\theta_N \leq \theta \leq \pi - \theta_N$) (see Fig.1(b)). The separation between the two lamellae, D, is constant

$$D = R(\pi - 2\theta_N). \tag{A5}$$

Combined Eqs.(1), (A4) and (A5), the radius of the hyper-sphere R and the angle θ_N are determined.

With the aid of the concept of pseudo-charges, i.e. the association of a bare charge with a uniform neutralizing background, the electric field and the corresponding potential can be obtained by Gauss theorem easily on S_3.[24] When charge q_N is located at the North pole N of S_3, it generates at point M electric field $E_{\rm ion}(\theta_M)$ satisfying Gauss theorem:

$$E_{\rm ion}(\theta_M)S(\theta_M) = Q(\theta_M)/(\varepsilon_0\epsilon_r), \tag{A6}$$

where ε_0 is the permittivity of vacuum, $Q(\theta_M)$ is the net charge included within the volume $V(\theta_M)$ of S_3 limited by the interfacial area $S(\theta_M)$ and can be written as

$$Q(\theta_M) = q_N[1 - V(\theta_M)/V_{\rm T}], \tag{A7}$$

where $V_{\rm T}$=$2\pi^2R^3$ is the total volume of S_3. From Eqs.(A3), (A4), (A6) and (7) one can deduce

$$E_{\rm ion}(\theta_M) = \frac{q_N}{4\pi^2\varepsilon_0\varepsilon_r R^2}\left(\frac{\pi - \theta_M}{\sin^2\theta_M} + \cot\theta_M\right). \tag{A8}$$

From expression (A8), we can write the electrostatic potential at point M by using $E = -\dfrac{1}{R}\dfrac{\partial}{\partial\theta}V(\theta_M)$ as

$$E_{\rm ion}(\theta_M) = \frac{q_N}{4\pi^2\varepsilon_0\varepsilon_r R}[(\pi - \theta_M - \cot\theta_M) - 0.5]. \tag{A9}$$

The constant is set as –0.5 in order to satisfy the following constraint:

$$\int_{S_3} V_{\rm ion}(\theta)d\tau = 0, \tag{A10}$$

where $d\tau = RS(\theta)d\theta = 4\pi R^3 \sin^2\theta d\theta$ is the elementary volume between the conical section of angular aperture θ and $\theta + d\theta$.

Through expression (A9), the Hamiltonian in the field between ions can be expressed as follows:

$$\begin{aligned} H_{\rm II} =& \frac{1}{8\pi^2\varepsilon_0\varepsilon_r R}\sum_{i=1}^{N_i} q_i \sum_{j=1,j\neq 1}^{N_j} q_j[(\pi - \theta_{ij})\cot\theta_{ij} - 0.5] \\ &+ \frac{N_i q_i^2}{8\pi^2\varepsilon_0\varepsilon_r R}[(\pi - 2\alpha)\cot\alpha + 0.5 - \pi/\sin\alpha], \end{aligned} \tag{A11}$$

where N_i and N_j represent the numbers of macroions, microcounter ions respectively, q_i denotes the charge of the i-th ion, θ_{ij} is the angle between the i-th and j-th ions (i, j=m, c), and $\alpha = r_i/R$. The last term of expression (13) results from the self energy of the pseudo-charges. In the same way we can derive the interactions of ions–lamellae and lamella–lamella in the model on S_3.

$$\begin{aligned} H_{\rm PI} =& \sum_{i=1}^{N_i} \frac{q_i q_p}{4\pi^2 R\varepsilon_0\varepsilon_r}[(\pi - 2\theta_i)\cot\theta_i - 1] \\ &+ \frac{q_p^2}{\pi^2 R\varepsilon_0\varepsilon_r}(\theta_N\cot\theta_N - 1), \end{aligned} \tag{A12}$$

$$H_{\rm pp} = \frac{q_p^2}{4\pi^2\varepsilon_0\varepsilon_r R}[1 + (\pi - 4\theta_N)\cot\theta_N]. \tag{A13}$$

Here, $H_{\rm PI}$ is the Hamiltonian describing the interaction between ions and lamellae, $H_{\rm pp}$ describing the interaction between two lamellae, and q_p is the charge of one lamella $q_p = S_p\sigma_p$. Now we see that the electrostatic potential energy, which is crucial in the Monte Carlo simulation, can be obtained through Expressions (A11), (A12), and (A13).

References

[1] Schmitz K S 1993 *Macroions in Solution and Colloidal Suspension* (New York: VCH)

[2] Stevens M J, Falk M L and Robbins M O 1996 *J. Chem. Phys.* **104** 5209

[3] Derjaguin B V and Landau L 1941 *Acta Physicochimica* (USSR) **14** 633

[4] Verwey E J and Overbeek J T G 1984 *Theory of the Stability of Lyophobic Colloids* (Amsterdam: Elsevier)

[5] Crocker J C and Grier D G 1994 *Phys. Rev. Lett.* **73** 352
[6] Crocker J C and Grier D G 1996 *J. Coll. Interface Sci.* **179** 298
[7] Grier D G 1997 *Curr. Opin Coll. Interface Sci.* **2** 264
[8] Overbeek J T G 1987 *J. Chem. Phys.* **87** 4406
[9] Roij R V and Hansen J P 1997 *Phys. Rev. Lett.* **79** 3082
[10] Crocker J C and Grier D G 1996 *Phys. Rev. Lett.* **77** 1897
[11] Larsen A E and Grier D G 1997 *Nature* **385** 230
[12] Allahyarov E, D′ Amico I and Lowen H 1998 *Phys. Rev. Lett.* **81** 1334
[13] Allahyarov E, D′ Amico I and Lowen H 1999 *Phys. Rev.* E **60** 3199
[14] Li C S and Xiao C M 2007 *Acta Phys. Sin.* **56** 2434 (in Chinese)
[15] He D H, Ma H R,Yang T and Zhang Q L 2005 *Acta Phys. Sin.* **54** 5937 (in Chinese)
[16] Hu P and Xiao C M 2006 *Phys. Lett.* A **353** 422
[17] Xiao C M, Guo J Y and Li C S 2006 *Europhys. Lett.* **73** 443
[18] Wood W W and Parker F R 1957 *J. Chem. Phys.* **27** 720
[19] Die Ewald P P 1921 *Ann. Phys.* **64** 253
[20] Caillol J M and Levesque D 1991 *J. Chem. Phys.* **94** 597
[21] Caillol J M 1992 *J. Chem. Phys.* **96** 1455
[22] Caillol J M and Levesque D 1992 *J. Chem. Phys.* **96** 1477
[23] Caillol J M 1993 *J. Chem. Phys.* **98** 9835
[24] Delville A, Pellenq R J and Caillol J M 1997 *J. Chem. Phys.* **106** 7275
[25] Li W H and Ma H R 2002 *Phys. Rev.* E **66** 61407
[26] Li W H and Ma H R 2005 *Eur. Phys. J.* E **16** 225
[27] Bennet C H 1976 *J. Comout. Phys.* **22** 245
[28] Frenkel D and Smit B 1996 *Understanding Molecular Simulation: From Algorithms to Applications* (New York: Academic)