Long time behavior of solutions to Nernst-Planck and Debye-Hückel drift-diffusion systems

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Abstract

We study the convergence rates of solutions to drift-diffusion systems (arising from plasma, semiconductors and electrolytes theories) to their self-similar or steady states. This analysis involves entropy-type Lyapunov functionals and logarithmic Sobolev inequalities.

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1 Introduction

We consider the long time asymptotics of solutions to drift-diffusion systems

$$u_t = \nabla\cdot(\nabla u + u\nabla\phi)\,, \tag{1.1}$$

$$v_t = \nabla\cdot(\nabla v - v\nabla\phi)\,, \tag{1.2}$$

$$\Delta\phi = v - u\,, \tag{1.3}$$

where u, v denote densities of negatively, respectively positively, charged particles. The Poisson equation (1.3) defines the electric potential ϕ coupling the equations (1.1)-(1.2) for the temporal evolution of charge distributions. The system (1.1)-(1.3) was formulated by W. Nernst and M. Planck at the end of the nineteenth century as a basic model for electrodiffusion of ions in electrolytes filling the whole space $\mathbb{R}^3$. Note that the case of multicharged particles is also covered by (1.1)-(1.3) since u and v denote the charge densities.

Supplemented with the no-flux boundary conditions

$$\frac{\partial u}{\partial\nu} + u\frac{\partial\phi}{\partial\nu} = 0\,, \tag{1.4}$$

$$\frac{\partial v}{\partial\nu} - v\frac{\partial\phi}{\partial\nu} = 0 \tag{1.5}$$

on the boundary of a bounded domain $\Omega\subset\mathbb{R}^d$, $d\le 3$, and either

$$\phi = 0 \quad \text{on } \partial\Omega\,, \tag{1.6}$$

or

$$\phi = E_d * (v-u)\,, \tag{1.7}$$

where E_d is the fundamental solution of the Laplacian in $\mathbb{R}^d$, the system (1.1)-(1.3) was also studied by P. Debye and E. Hückel in the 1920's. (1.6) signifies a conducting boundary of the container, while in the case of a bounded domain the "free" boundary condition (1.7) corresponds to a container immersed in a medium with the same dielectric constant as the solute.

These equations, together with their generalizations including *e.g.* an exterior potential, known as drift-diffusion Poisson systems, also appear in plasma physics and (supplemented with some mixed linear boundary conditions instead of (1.4)-(1.5)) in semiconductor device modelling.

To determine completely the evolution, the initial conditions

$$u(x,0) = u_0(x)\,, \quad v(x,0) = v_0(x) \tag{1.8}$$

are added. Obviously, positivity of $u_0 \geq 0$, $v_0 \geq 0$ is conserved: $u(x,t) \geq 0$, $v(x,t) \geq 0$, as well as the total charges

$$M_u = \int u_0(x)\,dx = \int u(x,t)\,dx\,, \quad M_v = \int v_0(x)\,dx = \int v(x,t)\,dx\,. \tag{1.9}$$

Here M_u, M_v are not necessarily the same, *i.e.* the electroneutrality condition

$$M_u = M_v \tag{1.10}$$

is not, in general, required. Condition (1.10) must be satisfied in the case of the homogeneous Neumann boundary conditions $\frac{\partial\phi}{\partial\nu} = 0$ (*i.e.* an isolated wall of the container) leading together with (1.4)-(1.5) to

$$\frac{\partial u}{\partial \nu} = \frac{\partial v}{\partial \nu} = \frac{\partial \phi}{\partial \nu} = 0\,.$$

Our results (Theorem 1.2 below) are valid in that case, with even a simpler proof.

The asymptotic properties of solutions to (1.1)-(1.3), (1.7) have been studied recently in [1]. The authors proved that (for $d \geq 3$, $M_u = M_v = 1$ and u_0 and v_0 regular enough) u, v tend to their self-similar asymptotic states at an algebraic rate. We improve these results by relaxing assumptions on the initial data and showing a stronger (still algebraic) decay rate, which we expect to be optimal (see Theorem 1.1 below).

In the case of a bounded domain, the convergence (with no specific speed) in the L^1-norm of u and v solving (1.1)-(1.5) to their corresponding steady states has been proved in [5] (as well as the L^∞-convergence for more regular u_0, v_0). Here we prove the exponential convergence towards the steady states with a decay rate depending on $\Omega \subset \mathbb{R}^d$, $d \geq 2$, and the initial value of the entropy functional only (see Theorem 1.2 below).

Notation. The L^p-norm in $\mathbb{R}^d$ or $\Omega \subset\subset \mathbb{R}^d$ is denoted by $|\cdot|_p$, and inessential constants (which may vary from line to line) are denoted generically by C.

Define the asymptotic states in $\mathbb{R}^d$ by

$$u_{as}(x,t) = \frac{M_u}{(2\pi(2t+1))^{d/2}} \exp\left(-\frac{|x|^2}{2(2t+1)}\right), \tag{1.11}$$

$$v_{as}(x,t) = \frac{M_v}{(2\pi(2t+1))^{d/2}} \exp\left(-\frac{|x|^2}{2(2t+1)}\right), \tag{1.12}$$

where the charges of the solution $\langle u,v\rangle$ of (1.1)-(1.2) are given by (1.9), and the entropy functional by

$$L(t) = \int u(x,t)\log\left(\frac{u(x,t)}{u_{as}(x,t)}\right) dx + \int v(x,t)\log\left(\frac{v(x,t)}{v_{as}(x,t)}\right) dx + \frac{1}{2}|\nabla\phi(t)|_2^2 . \tag{1.13}$$

Theorem 1.1 *There exists a constant $C = C(d, M_u, M_v, L_0)$ such that for each solution $\langle u,v\rangle$ of (1.1)-(1.3), (1.7)-(1.8) in $\mathbb{R}^d$, $d \geq 3$, if $L(0) = L_0$, then for all $t \geq 0$,*

$$L(t) \leq C\, H(t) \tag{1.14}$$

and

$$|u(t) - u_{as}(t)|_1^2 + |v(t) - v_{as}(t)|_1^2 + |\nabla\phi(t)|_2^2 \leq C\, H(t), \tag{1.15}$$

where

$$H(t) = \begin{cases} (2t+1)^{-1/2}, & d=3, \\ (2t+1)^{-1}\Big(\log(2t+1)+1\Big), & d=4, \\ (2t+1)^{-1}, & d>4. \end{cases}$$

Moreover if $M_u = M_v$, then $H(t) = (2t+1)^{-1}$ for any $d \geq 3$.

In the case of a bounded domain, define the entropy functional

$$\begin{aligned} W(t) &= \int u(x,t)\log u(x,t)\,dx - \int U(x)\log U(x)\,dx \\ &+ \int v(x,t)\log v(x,t)\,dx - \int V(x)\log V(x)\,dx \\ &+ \frac{1}{2}\int (u-v)\phi\,dx - \frac{1}{2}\int (U-V)\Phi\,dx, \end{aligned} \tag{1.16}$$

for the solution $\langle u,v,\phi\rangle$ of (1.1)-(1.5), (1.6) or (1.7), (1.8) and the unique steady state $\langle U,V,\Phi\rangle$ of the Debye-Hückel system with

$$M_u = \int U(x)\,dx\,, \quad M_v = \int V(x)\,dx\,. \tag{1.17}$$

Note that for the condition (1.6) the fifth and the sixth terms in $W(t)$ take the form $\frac{1}{2}|\nabla\phi|_2^2 - \frac{1}{2}|\nabla\Phi|_2^2$.

Theorem 1.2 *If $d \geq 2$, then there exist two constants $\lambda = \lambda(\Omega) > 0$ and $C = C(M_u, M_v, W_0)$ such that for each solution $\langle u,v,\phi\rangle$ of (1.1)-(1.6), (1.8) in a bounded uniformly convex domain Ω, if $W(0) = W_0$, then for all $t \geq 0$,*

$$W(t) \leq W(0)\,e^{-\lambda t}\,, \tag{1.18}$$

and

$$|u(t)-U|_1^2 + |v(t)-V|_1^2 + |\nabla(\phi-\Phi)|_2^2 \leq C\,e^{-\lambda t}\,. \tag{1.19}$$

2 Proof of Theorem 1.1

We begin with a rescaling of the system (1.1)-(1.3) which will lead to a system with a quadratic confinement potential, and therefore (eliminating the dispersion) to the expected exponential convergence to the steady states. This idea was applied in [8] and [7], as well as in [1], to a variety of problems ranging from kinetic equations to porous media equations.

Let $\bar{x} \in \mathbb{R}^d$, $\tau > 0$, be the new variables defined by

$$\bar{x} = \frac{x}{R(t)}\,, \quad \tau = \log R(t)\,, \quad R(t) = (2t+1)^{1/2}, \tag{2.1}$$

and consider the rescaled functions $\bar{u}$, $\bar{v}$, $\bar{\phi}$ such that

$$\begin{aligned} u(x,t) &= \frac{1}{R^d(t)}\bar{u}(\bar{x},\tau)\,,\\ v(x,t) &= \frac{1}{R^d(t)}\bar{v}(\bar{x},\tau)\,,\\ \phi(x,t) &= \bar{\phi}(\bar{x},\tau)\,. \end{aligned} \tag{2.2}$$

This whole section will deal with the rescaled system, so omitting the bars over x, u, v, ϕ will not lead to confusions with the original system, which now takes, after rescaling, the form

$$u_\tau = \nabla \cdot (\nabla u + ux + u\nabla\phi)\,, \tag{2.3}$$

$$v_\tau = \nabla \cdot (\nabla v + vx - v\nabla\phi)\,, \tag{2.4}$$

$$\Delta\phi = e^{-\tau(d-2)}(v-u)\,. \tag{2.5}$$

The scaling (2.2) preserves the L^1-norms, so the rescaled initial data u_0, v_0 still satisfy

$$M_u = \int u_0(x)\,dx = \int u(x,\tau)\,dx\,, \quad M_v = \int v_0(x)\,dx = \int v(x,\tau)\,dx\,. \tag{2.6}$$

Denote by $\langle u_\infty, v_\infty\rangle$ the steady state of (2.3)-(2.4), that is

$$u_\infty(x) = \frac{M_u}{(2\pi)^{d/2}}\exp\left(-\frac{|x|^2}{2}\right)\,, \tag{2.7}$$

$$v_\infty(x) = \frac{M_v}{(2\pi)^{d/2}}\exp\left(-\frac{|x|^2}{2}\right)\,. \tag{2.8}$$

Of course, going back to the original variables x, t, $\langle u_\infty, v_\infty\rangle$ corresponds to the asymptotic state $\langle u_{as}, v_{as}\rangle$ defined by (1.11)-(1.12). Writing $\phi = \beta\psi$ with $\beta = \beta(\tau) = e^{-\tau(d-2)} \to 0$ as $\tau \to +\infty$, we introduce the relative entropy

$$W(\tau) = \int u\log\left(\frac{u}{u_\infty}\right)dx + \int v\log\left(\frac{v}{v_\infty}\right)dx + \frac{\beta}{2}|\nabla\psi|_2^2 \tag{2.9}$$

corresponding to the original entropy functional L in (1.13). The evolution of W is given by

$$\frac{dW}{d\tau} = -\int u\left|\nabla\left(\log\frac{u}{U}\right)\right|^2 dx - \int v\left|\nabla\left(\log\frac{v}{V}\right)\right|^2 dx - \left(\frac{d}{2}-1\right)\beta|\nabla\psi|_2^2\,, \tag{2.10}$$

with U, V denoting the local Maxwellians

$$U(x,\tau) = M_u\,\frac{\exp\left(-\frac{1}{2}|x|^2 - \phi(x,\tau)\right)}{\int\exp\left(-\frac{1}{2}|y|^2 - \phi(y,\tau)\right)dy}\,, \tag{2.11}$$

$$V(x,\tau)=M_v\,\frac{\exp\left(-\frac{1}{2}|x|^2+\phi(x,\tau)\right)}{\int\exp\left(-\frac{1}{2}|y|^2+\phi(y,\tau)\right)\,dy}\,, \tag{2.12}$$

so that $\nabla U/U=-(x+\nabla\phi)$, $\nabla V/V=-(x-\nabla\phi)$. Using the notation

$$J=\frac{1}{2}\int u\left|\frac{\nabla u}{u}+x\right|^2 dx+\frac{1}{2}\int v\left|\frac{\nabla v}{v}+x\right|^2 dx\,, \tag{2.13}$$

(2.10) can be rewritten as

$$\begin{aligned}\frac{dW}{d\tau}\;&=-2J-2\int(\nabla u-\nabla v)\cdot\nabla\phi\,dx-2\int(u-v)\,x\cdot\nabla\phi\,dx\\&\qquad-\int(u+v)|\nabla\phi|^2\,dx-\left(\frac{d}{2}-1\right)\beta|\nabla\psi|_2^2\\&=-2J-\beta^2\int(u+v)|\nabla\psi|^2\,dx-2\beta|u-v|_2^2+\left(\frac{d}{2}-1\right)\beta|\nabla\psi|_2^2\,.\end{aligned} \tag{2.14}$$

The quantity J in (2.13) can be estimated from below using the Gross logarithmic Sobolev inequality

$$\int f\log\left(\frac{f}{|f|_1}\right)\,dx+d\left(1+\frac{1}{2}\log(2\pi a)\right)|f|_1\le\frac{a}{2}\int\frac{|\nabla f|^2}{f}\,dx \tag{2.15}$$

valid for each $a>0$, see *e.g.* [11] or a thorough discussion of different versions of logarithmic Sobolev inequalities in [2]. (2.15) becomes an equality if and only if $f(x)=C\exp\left(-|x|^2/(2a)\right)$ (up to a translation).

Taking $a=1$ in (2.15), the relation (2.14) leads to

$$-\left(\frac{dW}{d\tau}+2W\right)\ge 2\beta|u-v|_2^2-\beta\frac{d}{2}|\nabla\psi|_2^2\ge -C\beta(M_u+M_v)^2 \tag{2.16}$$

with a constant $C=C(d)=\frac{2}{d}\left(\frac{d-2}{4}\right)^{(d-2)/2}\Sigma^{d/2}$, because by the Hardy-Littlewood-Sobolev inequality and an interpolation

$$|\nabla\psi|_2^2\le\Sigma|u-v|_{2d/(d+2)}^2\le\Sigma|u-v|_1^{4/d}|u-v|_2^{2-4/d}\le\frac{4}{d}|u-v|_2^2+C|u-v|_1^2\,.$$

Clearly, (2.16) implies

$$\frac{d}{d\tau}\left(e^{2\tau}W(\tau)\right)\le C(M_u+M_v)^2e^{\tau(4-d)}$$

and, after one integration, we obtain

$$W(\tau) \le \Big(W(0)e^{-\tau} + C(M_u+M_v)^2\Big)e^{-\tau} \tag{2.17}$$

in the case $d=3$,

$$W(\tau) \le \Big(W(0) + C(M_u+M_v)^2\tau\Big)e^{-2\tau} \tag{2.18}$$

if $d=4$, and finally for all $d>4$

$$W(\tau) \le \Big(W(0) + C(M_u+M_v)^2\Big)e^{-2\tau}\,. \tag{2.19}$$

Since from the Csiszár-Kullback inequality (*cf.* (1.9) in [2], App. D in [7], [6] or [10]) $W(\tau)$ controls the L^1-norm of $u-u_\infty$ and $v-v_\infty$, we get the same decay rates as in (2.17)-(2.19) for

$$|u(\tau)-u_\infty|_1^2 + |v(\tau)-v_\infty|_1^2 + \beta|\nabla\psi(\tau)|_2^2 \le 2\Big(\max(M_u,M_v)+1\Big)W(\tau)\,. \tag{2.20}$$

Returning to the original variables x, t, this implies, of course, the estimates (1.14)-(1.15) of Theorem 1.1 in the general case.

In the electroneutrality case (1.10): $M_u = M_v$, since $u_\infty = v_\infty$, so for $d=3$, $|u-v|_1^2 = |u-u_\infty+v_\infty-v|_1^2 \le Ce^{-\tau}$. Next, a modification of (2.16) reads

$$\frac{d}{d\tau}\Big(e^{2\tau}W(\tau)\Big) \le Ce^{2\tau}\beta|u-v|_1^2 \le C\,,$$

and this leads to $W(\tau) \le C(1+\tau)e^{-2\tau}$. Inserting this into (2.20) and (2.16) once again implies

$$\frac{d}{d\tau}\Big(e^{2\tau}W(\tau)\Big) \le C(1+\tau)e^{-\tau}\,,$$

so that $W(\tau) \le Ce^{-2\tau}$. If $d=4$, the same reasoning once again applies providing also the same improved decay rate. □

Remark 2.1 *Note that the constant C in (1.15) depends on d, M_u, M_v and $L(0)$ only, and is independent of* e.g. *$|u_0|_r$, $|v_0|_r$ with some $r > d/2$ — as it was in fact in [1]. Conditions like $|u_0|_r + |v_0|_r < \infty$ are sufficient for (local in* *time) existence of solutions to the considered systems (cf. Theorem 2 in [5]), but they can be relaxed — as it was done for a related parabolic-elliptic system describing the gravitational interaction of particles in [4]. Thus, compared to [1], Theorem 1.1 gives not only an improvement of the exponents but also gets rid of the unnecessary dependence on quantities other than $L(0)$, M_u, M_v. We do not know if the exponents in Theorem 1.1 are optimal, but such a conjecture is supported by the calculations in the proof of the following*

Proposition 2.2 *There exists a constant $\lambda > 0$ depending only on d with $\lambda \geq \lambda(d) = (d-2)\left(\sqrt{(d-1)^2+3}-(d-1)\right)$, such that*

$$W(\tau) \quad \leq \quad W(0)\, e^{-\lambda\tau} \tag{2.21}$$

and hence

$$L(t) \quad \leq \quad L(0)\,(2t+1)^{-\lambda/2}$$

for each solution $\langle u,v\rangle$ to the Nernst-Planck system.

Remark 2.3 *The interest of this proposition is that the constants controlling the convergence of $W(t)$, $L(t)$, and hence $|u-u_{as}|_1$, $|v-v_{as}|_1$ in (1.15), depend on the initial values of $W(0)$, $L(0)$ only (and not on $|u|_1 = M_u$, $|v|_1 = M_v$, which are quantities not comparable with, say, $\int u \log u\, dx$, $\int v \log v\, dx$ in the whole $\mathbb{R}^d$ space case). However, the exponent λ — which is evaluated explicitly — is not as good as the one in Theorem 1.1.*

Proof of Proposition 2.2. Using (2.9), (2.13), (2.14), we may write for any positive λ

$$\begin{aligned} -\left(\frac{dW}{d\tau}+\lambda W\right) &= \lambda\left(J - \int u \log\left(\frac{u}{u_\infty}\right) - \int v \log\left(\frac{v}{v_\infty}\right)\right) \\ &\quad + (2-\lambda)J + B + 2E - \mu F\,, \end{aligned} \tag{2.22}$$

where

$$\begin{aligned} B &= \beta^2 \int (u+v)|\nabla\psi|^2\, dx\,, \\ E &= \beta|u-v|_2^2\,, \\ F &= \left(\frac{d}{2}-1\right)\beta|\nabla\psi|_2^2\,, \\ \mu &= 1+\frac{\lambda}{d-2}\,. \end{aligned}$$

Observe that if we define

$$G_1 = \int u\left(\frac{\nabla u}{u} + x\right)\cdot \nabla\phi\, dx\,, \quad G_2 = \int v\left(\frac{\nabla v}{v} + x\right)\cdot \nabla\phi\, dx\,,$$

then

$$G_1 - G_2 = \int \nabla(u-v)\cdot\nabla\phi\, dx + \int (u-v)\,(x\cdot\nabla\phi)\, dx = E - F.$$

Define now

$$f_1 = \sqrt{2-\lambda}\cdot\sqrt{u}\left(\frac{\nabla u}{u} + x\right), \quad g_1 = \sqrt{u}\nabla\phi\,,$$

$$f_2 = \sqrt{2-\lambda}\cdot\sqrt{v}\left(\frac{\nabla v}{v} + x\right), \quad g_2 = \sqrt{v}\nabla\phi\,,$$

$$a_1 = |f_1|_2\,, \quad b_1 = |g_1|_2\,, \quad a_2 = |f_2|_2\,, \quad b_2 = |g_2|_2\,.$$

By the Cauchy-Schwarz inequality we have

$$\begin{aligned}(2-\lambda)^{1/2}|E-F| = &\ (2-\lambda)^{1/2}|G_1 - G_2| \\ = &\ \left|\int (f_1 g_1 - f_2 g_2)\, dx\right| \\ \leq &\ a_1 b_1 + a_2 b_2\,.\end{aligned}$$

But

$$0 \leq (a_1 b_2 - a_2 b_1)^2 = (a_1^2 + a_2^2)(b_1^2 + b_2^2) - (a_1 b_1 + a_2 b_2)^2\,,$$

$$\begin{aligned}a_1 b_1 + a_2 b_2 &\leq \sqrt{2}\sqrt{(a_1^2+a_2^2)/2}\sqrt{b_1^2+b_2^2} \\ &\leq \frac{1}{\sqrt{2}}\left(\frac{1}{2}(a_1^2+a_2^2) + (b_1^2+b_2^2)\right) \\ &= \frac{1}{\sqrt{2}}\Big((2-\lambda)J + B\Big)\,,\end{aligned}$$

and thus

$$(2-\lambda)^{1/2}|E-F| \leq \frac{1}{\sqrt{2}}\Big((2-\lambda)J + B\Big)\,.$$

Using (2.22) we get

$$\begin{aligned}-\left(\frac{dW}{d\tau} + \lambda W\right) \geq &\ \sqrt{2(2-\lambda)}|E-F| + 2E - \mu F \\ &= F\cdot\left(\sqrt{2(2-\lambda)}|X-1| + 2X - \mu\right) \qquad (2.23)\end{aligned}$$

with $X = E/F \geq 0$. For either $d \geq 4$ and $\lambda \leq 2$, or $d = 3$ and $\lambda \leq 1$, we have $\mu \leq 2$. The right hand side of (2.23) (positive for $X \geq \mu/2$) equals (for $X \leq \mu/2 \leq 1$)

$$\sqrt{2(2-\lambda)}(1-X) + 2X - \mu = \left(2 - \sqrt{2(2-\lambda)}\right) X + \sqrt{2(2-\lambda)} - \mu\,,$$

so that

$$\sqrt{2(2-\lambda)} \geq \mu \qquad (2.24)$$

guarantees $\frac{dW}{d\tau} + \lambda W \leq 0$, which implies (2.21). The condition (2.24) is equivalent to $\lambda \leq \lambda(d)$. In particular, $\lambda(d)$ is an increasing function of d, $\lambda(3) = \sqrt{7} - 2 < 1$, $\lambda(4) = 4\sqrt{3} - 6$ and $\lim_{d \to +\infty} \lambda(d) = \frac{3}{2}$. □

Remark 2.4 *In the case of one species of particles, i.e. $v \equiv 0$ as was in [3] and [4], the result of Proposition 2.2 still holds.*

Finally, we remark that there is, in general, no hope to have $\lambda > 2$ in non-trivial cases. This can be inferred from the formula (2.22), where for each $\chi > 1$, $J - \chi\left(\int u \log\left(\frac{u}{u_\infty}\right) dx + \int v \log\left(\frac{v}{v_\infty}\right) dx\right)$ could be negative and dominate the other terms (for instance, in the limit M_u, $M_v \to 0^+$).

3 Proof of Theorem 1.2

First, we recall that steady states $\langle U, V, \Phi\rangle$ of (1.1)-(1.3) satisfy the relations

$$\nabla \cdot (e^{-\Phi} \nabla (e^{\Phi} U)) = 0\,, \quad \nabla \cdot (e^{\Phi} \nabla (e^{-\Phi} V)) = 0\,,$$

hence

$$U = M_u \frac{e^{-\Phi}}{\int e^{-\Phi}\, dx}, \quad V = M_v \frac{e^{\Phi}}{\int e^{\Phi}\, dx}\,. \qquad (3.1)$$

Together with (1.3) this leads to the Poisson-Boltzmann equation

$$\Delta \Phi = M_v \frac{e^{\Phi}}{\int e^{\Phi}\, dx} - M_u \frac{e^{-\Phi}}{\int e^{-\Phi}\, dx}\,. \qquad (3.2)$$

This equation, supplemented with the Dirichlet boundary condition (1.6) or the free condition (1.7), for every $M_u, M_v \geq 0$, has a unique (weak) solution

Φ, see [9] or Proposition 2 in [5] (and this solution is classical whenever $\partial\Omega$ is of class $C^{1+\epsilon}$ for some $\epsilon > 0$).

The evolution of the Lyapunov functional defined by (1.16) in the case of the Dirichlet boundary condition (1.6) or in the case (1.7) is given by

$$\frac{dW}{dt} = -\int u|\nabla(\log u + \phi)|^2\,dx - \int v|\nabla(\log v - \phi)|^2\,dx\,, \tag{3.3}$$

cf. (35) in [5], where the above relation is obtained for weak solutions to the Debye-Hückel system.

Concerning the global in time existence of solutions to the Debye-Hückel system with nonlinear boundary conditions (1.4)-(1.5), we note that this was proved for $d = 2$ only in Theorem 3 of [5]. Thus, in higher dimensions $d \geq 3$, we assume that $\langle u(t), v(t)\rangle$ exists for all $t \geq 0$. If equations (1.1)-(1.3) are supplemented with linear type boundary conditions (as it is the case in semiconductor modelling), the assumption $u_0,\ v_0 \in L^r(\Omega)$ with an exponent $r > d/2$ (*cf.* Theorem 2 (ii) in [5] and [1] for the case of the whole space $\mathbb{R}^d$) guarantees the existence of $\langle u(t), v(t)\rangle$ for all $t \geq 0$.

First, we represent the entropy production terms in (3.3) as

$$\int u\left|\nabla\left(\log(ue^{\phi})\right)\right|^2 dx = \int ue^{\phi}\left|\nabla\left(\log(ue^{\phi})\right)\right|^2 \frac{e^{-\phi}}{\int e^{-\phi}\,dx}\,dx \cdot \int e^{-\phi}\,dx, \tag{3.4}$$

with an obvious modification for the second term. Then we recall Remark 3.7 of [2], where counterparts of the logarithmic Sobolev inequality (2.15) (or Poincaré-type inequalities) are discussed in the case of a bounded uniformly convex domain. We apply this remark to the domain Ω and the probability measure

$$\rho_0(x) = \frac{e^{-\phi}}{\int e^{-\phi}\,dx}$$

in the first entropy production term in (3.3) written as in (3.4). This implies the existence of a constant $C(\Omega) > 0$ such that

$$\int \Psi\left(\frac{f}{\int f\,d\rho_0}\right) d\rho_0 \leq C(\Omega)\int \Psi''\left(\frac{f}{\int f\,d\rho_0}\right)\frac{|\nabla f|^2}{(\int f\,d\rho_0)^2}\,dx,$$

where $\Psi(s) = 1 - s + s\log s$ and $f = ue^{\phi}$. Here we have

$$\int u\left|\nabla\left(\log(ue^{\phi})\right)\right|^2 dx = M_u\int \Psi''\left(\frac{f}{\int f\,d\rho_0}\right)\frac{|\nabla f|^2}{(\int f\,d\rho_0)^2}\,dx$$

since $\int f\,d\rho_0 = \int ue^{\phi}\,d\rho_0 = \frac{M_u}{\int e^{-\phi}\,dx}$. Thus we arrive at

$$\int u\left|\nabla\left(\log(ue^{\phi})\right)\right|^2 dx \geq \frac{M_u}{C(\Omega)}\int\left(\frac{f}{\int f\,d\rho_0}\log\left(\frac{f}{\int f\,d\rho_0}\right)+1-\frac{f}{\int f\,d\rho_0}\right)d\rho_0,$$

or

$$\int u\left|\nabla\left(\log(ue^{\phi})\right)\right|^2 dx \geq \frac{1}{C(\Omega)}\int u\log\left(\frac{ue^{\phi}}{\frac{M_u}{\int e^{-\phi}\,dx}}\right)dx. \tag{3.5}$$

Similarly, we have

$$\int v\left|\nabla\left(\log(ve^{-\phi})\right)\right|^2 dx \geq \frac{1}{C(\Omega)}\int v\log\left(\frac{ve^{-\phi}}{\frac{M_v}{\int e^{\phi}\,dx}}\right)dx. \tag{3.6}$$

Now we compute the expression

$$\delta = \int u\log\left(\frac{ue^{\phi}}{\frac{M_u}{\int e^{-\phi}\,dx}}\right)dx + \int v\log\left(\frac{ve^{-\phi}}{\frac{M_v}{\int e^{\phi}\,dx}}\right)dx.$$

If $\langle U,V,\Phi\rangle$ is the solution of the Poisson-Boltzmann equation (3.2) with the homogeneous Dirichlet boundary conditions, then it can be checked that

$$\delta = W + J[\phi] - J[\Phi], \tag{3.7}$$

where

$$\begin{aligned} W \ &= \int u\log u\,dx + \int v\log v\,dx + \frac{1}{2}\int|\nabla\phi|^2\,dx \\ &\quad - \int U\log U\,dx - \int V\log V\,dx - \frac{1}{2}\int|\nabla\Phi|^2\,dx \end{aligned}$$

is as in (1.16), and

$$J[\phi] = \frac{1}{2}\int|\nabla\phi|^2\,dx + M_u\log\left(\int e^{-\phi}\,dx\right) + M_v\log\left(\int e^{\phi}\,dx\right)$$

is a strictly convex functional reaching its minimum at Φ.

Now it is clear from (3.3), (3.5)-(3.6) and (3.7) that for some $\lambda = \lambda(\Omega) > 0$ $\frac{dW}{dt} + \lambda W \le 0$, *i.e.* $W(t)$ decays exponentially in t

$$W(t) \le W(0)\, e^{-\lambda t}\,. \tag{3.8}$$

By the Csiszár-Kullback inequality (as was in Section 2), $W(t)$ controls the L^1-convergence to the unique steady state, so the conclusion (1.19) of Theorem 1.2 follows from (3.8). This improves (34) in Theorem 6 of [5] in two ways. First, there is an exponential decay rate. Second, (34) is proved under the assumption $W(0) < \infty$, which is much weaker than the assumption on the L^2-boundedness in time of the solution $\langle u, v\rangle$ in Theorem 6 of [5]. Evidently, this result is also valid for one species case (M_u or M_v equal to 0), so Theorem 2 in [3] is also improved. □

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