Non-local diffusion equations with Lévy-type operators and divergence free drift

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Abstract

In this paper we are interested in some properties related to the solutions of non-local diffusion equations with divergence free drift. Existence, maximum principle and a positivity principle are proved. In order to study Hölder regularity, we apply a method that relies in the Hölder-Hardy spaces duality and in the molecular characterisation of local Hardy spaces. In these equations, the diffusion is given by Lévy-type operators with an associated Lévy measure satisfying some upper and lower bounds.

Keywords: Lévy-type operators, Lévy-Khinchin formula, Hölder regularity, molecular Hardy spaces.

1 Introduction

We study in this article a class of non-local diffusion equations with divergence free drift of the following form:

\[
\begin{align*}
\partial_t \theta(x,t) - \nabla \cdot (v \theta)(x,t) + \mathcal{L}_\alpha \theta(x,t) &= 0, \\
\theta(x,0) &= \theta_0(x),
\end{align*}
\]

(1)

with \( \text{div}(v) = 0 \) and \( t \in [0,T] \).

This type of transport-diffusion equations is a generalization of a well-known equation from fluid dynamics. Indeed, in space dimension \( n = 2 \) if \( \mathcal{L} = (-\Delta)^\alpha \) is the fractional Laplacian, with \( 0 < \alpha \leq 1/2 \), and if \( v = (-R_2 \theta, R_1 \theta) \) where \( R_{1,2} \) are the Riesz Transforms defined in the Fourier level by \( \hat{R}_j \theta(\xi) = -i\xi_j |\xi|^{-1} \hat{\theta}(\xi) \) for \( j = 1,2 \), we obtain the quasi-geostrophic equation \((QG_\alpha)\) which has been recently studied by many authors with different approaches and with a variety of results, see [1], [6], [12], [4], [5], [14] and the references there in for more details.

Inspired by the work of Kiselev and Nazarov [12], it is possible to study the Hölder regularity of the solutions of the \((QG_\alpha)\) equation by a duality-based method. The aim of this article is to generalize this method to a wider family of operators and we will consider here Lévy-type operators under some hypothesis that will be stated in the lines below.

This class of operators corresponds to a natural generalization of recent works where some results are obtained for different operators using quite specific techniques: for example see the article [13] where the operator’s kernel satisfies some similar bounds to those imposed in our hypothesis.

In this paper we will mainly consider problems of existence of the solutions, a maximum principle, a positivity principle and of course we will study Hölder regularity of the solutions of equation (1).

Let us start by describing our setting in a general way. This framework will be made precise later on.

• In the formula (1) we noted \( \theta : \mathbb{R}^n \times [0,T] \to \mathbb{R} \) a real-valued function, where \( n \geq 2 \) is the euclidean dimension.

• The drift (or velocity) term \( v \) is such that \( v : \mathbb{R}^n \times [0,T] \to \mathbb{R}^n \) and we will always assume that \( \text{div}(v) = 0 \) and that \( v \) belongs to \( L^\infty([0,T];\text{bmo}(\mathbb{R}^n)) \). Recall that local \( \text{bmo}(\mathbb{R}^n) \) space is defined as locally integrable functions \( f \) such that

\[
\sup_{|B| \leq 1} \frac{1}{|B|} \int_B |f(x) - f_B| dx < M \quad \text{and} \quad \sup_{|B| > 1} \frac{1}{|B|} \int_B |f(x)| dx < M \quad \text{for a constant} \ M;
\]

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we noted $B(R)$ a ball of radius $R > 0$ and $f_B = \frac{1}{|B|} \int_{B(R)} f(x)dx$. The norm $\| \cdot \|_{bmo}$ is then fixed as the smallest constant $M$ satisfying these two conditions.

- The operator $\mathcal{L}$ is a Lévy operator which has the following general form called the Lévy-Khinchin representation formula:

$$
\mathcal{L}(f)(x) = b \cdot \nabla f(x) + \sum_{j,k=1}^{n} a_{j,k} \frac{\partial^2 f(x)}{\partial x_j \partial x_k} + \int_{\mathbb{R}^n \setminus \{0\}} \left[ f(x) - f(x - y) + y \cdot \nabla f(x) \mathbb{1}_{\{|y| \leq 1\}}(y) \right] \Pi(dy),
$$

where $b \in \mathbb{R}^n$ is a vector, $a_{j,k}$ are constants (note that the matrix $(a_{j,k})_{1 \leq j,k \leq n}$ should be positive semi-definite) and $\Pi$ is a nonnegative Borel measure on $\mathbb{R}^n$ satisfying $\Pi(\{0\}) = 0$ and

$$
\int_{\mathbb{R}^n} \min(1, |y|^2) \Pi(dy) < +\infty.
$$

In the Fourier level we have $\widehat{\mathcal{L}f}(\xi) = a(\xi) \widehat{f}(\xi)$ where the symbol $a(\cdot)$ is given by the Lévy-Khinchin formula

$$
a(\xi) = ib \cdot \xi + q(\xi) + \int_{\mathbb{R}^n \setminus \{0\}} \left( 1 - e^{-iy \cdot \xi} - iy \cdot \xi \mathbb{1}_{\{|y| < 1\}}(y) \right) \Pi(dy),
$$

where $q(\xi) = \sum_{j,k=1}^{n} a_{j,k} \xi_j \xi_k$.

Our main references concerning Lévy operators and the Lévy-Khinchin representation formula are the books [9], [10] and [16]. See also the lecture notes [11] for interesting applications to the PDEs.

We need to make some assumptions over the Lévy operator considered before. First we will set $b = 0$ and $a_{j,k} = 0$. We assume then that the measure $\Pi$ is absolutely continuous with respect to the Lebesgue measure, so this measure can be written as $\Pi(dy) = \pi(y)dy$, this hypothesis is important as it simplifies considerably the computations. We will also require some symmetry in the following sense: $\pi(y) = \pi(-y)$. Finally, the most crucial issue concerns estimates over the function $\pi$ and we will assume the inequalities:

$$
c_1 |y|^{-n - 2\alpha} \leq \pi(y) \leq c_2 |y|^{-n - 2\beta} \quad \text{over } |y| \leq 1,
$$

$$
0 \leq \pi(y) \leq c_3 |y|^{-n - 2\delta} \quad \text{over } |y| > 1,
$$

where $c_1, c_2, c_3 > 0$ are positive constants. We need to define the values of the parameters $\alpha, \beta, \delta$ and we will study the following cases:

- **(a)** $0 < \alpha \leq \beta < 1/2$ and $0 < \delta < 1/2,$
- **(b)** $0 < \alpha = \beta = \delta < 1/2,$
- **(c)** $\alpha = \beta = 1/2$ and $0 < \delta < 1/2,$
- **(d)** $\alpha = \beta = \delta = 1/2.$

The choice of these bounds is mainly technical and it will be explained in Remark [11] below.

Note that these two conditions [11] and [12] imply the next pointwise property which will be useful in the sequel

$$
0 \leq \pi(y) \leq c_4 (|y|^{-n - 2\beta} + |y|^{-n - 2\delta}) \quad \text{for all } y \in \mathbb{R}^n \text{ and } c_4 > 0.
$$

We observe now that these assumptions for the function $\pi$ imply that the operator $\mathcal{L}$ and its symbol $a(\cdot)$ can be rewritten in the following way:

$$
\mathcal{L}(f)(x) = \text{v.p.} \int_{\mathbb{R}^n} \left[ f(x) - f(x - y) \right] \pi(y)dy
$$

and

$$
a(\xi) = \int_{\mathbb{R}^n \setminus \{0\}} \left( 1 - \cos(\xi \cdot y) \right) \pi(y)dy.
$$

As we can see, the properties of the operator $\mathcal{L}$ can be easily read, in the real variable or in the Fourier level, by the properties of the function $\pi$.

In order to have a better understanding of these properties it is helpful to consider an important example which is given by the fractional Laplacian $(-\Delta)^{\alpha}$ defined by the expression

$$
(-\Delta)^{\alpha} f(x) = \text{v.p.} \int_{\mathbb{R}^n} \frac{f(x) - f(x - y)}{|y|^{n+2\alpha}} dy, \quad \text{with } 0 < \alpha \leq 1/2.
$$
Note that we have here $\pi(y) = |y|^{-n-2\alpha}$ and $\pi$ satisfies (4) and (5) with $\alpha = \beta = \delta$, so this example corresponds to the cases (b) and (d) stated above. Equivalently, we have a Fourier characterisation by the formula $(-\Delta)^\alpha f(x) = |x|^{2\alpha} \hat{f}(x)$ so the function $a(x)$ is equal to $|x|^{2\alpha}$.

With this example we observe that the lower bound in (4) guarantees a diffusion or regularization effect like $(-\Delta)^\alpha$ and this is an important assumption for the function $\pi$. Indeed, in some general sense, only the part of the integral (7) near the origin is critical as $\pi$ satisfies (5). We note also that the upper bounds given in (4) and (5) imply the property (2) since in any case we have $\beta, \delta \leq 1/2$.

Remark 1.1 As the previous example shows, when $\alpha = \beta = \delta$ we obtain the fractional Laplacian $(-\Delta)^\alpha$ and thus the equation (7) studied here can be considered as a linearization of the quasi-geostrophic equation where we have an interesting competition between this operator and the drift term. In the framework of this equation it is classical to distinguish three regimes: super-critical if $0 < \alpha < 1/2$, critical if $\alpha = 1/2$ and sub-critical if $1/2 < \alpha < 1$, from which only the two first are of interest since in the sub-critical case the regularization effect is in some sense “stronger” than the drift, see [9] for more details.

This explains the upper bound given for the parameters $\alpha, \beta, \delta$. The main reason to divide our study following the cases (a)-(d) is technical as some of the results stated below are valid in some special cases.

Let us consider more examples: it is shown in Theorem 3.7.7 of [9], that each continuous negative definite function $a(\cdot)$ can be written in the form (3), so under hypothesis (4) and (5) we can obtain a large class of operators that are in the scope of this work. In the paper [13] another approach is given: the assumptions for the function $\pi$ are quite similar but they are stated in a different way, furthermore the authors of this article only consider the case $\alpha = \beta = \delta$ in their hypothesis, so our framework is slightly more general. However they dependence of the function $\pi$ in the $x$ variable and in the time variable $t$. A further work could follow this path, assuming for example in formula (7) that $\pi = \pi(x, y, t)$ instead of $\pi = \pi(y)$. Note that some amount of work is already done in this direction, see chapter 4 and Definition 4.5.10 of [9] for more information.

Presentation of the results

We assume from now on that the operator $\mathcal{L}$ is of the form (17). We will work with a function $\pi$ satisfying the hypothesis (4) and (5) with the parameters $\alpha, \beta, \delta$ satisfying (a)-(d) unless otherwise specified.

In this article we present some results concerning non-local diffusion equation (11). Maybe the three first of them are well known for different mathematical communities, so perhaps the only novelty here is the use of the $bmo$ space. Nevertheless we will give the proofs for the sake of completeness.

Theorem 1 (Existence and uniqueness for $L^p$ initial data) If $\theta_0 \in L^p(\mathbb{R}^n)$ with $1 \leq p \leq +\infty$ is an initial data, then equation (11) has a unique weak solution $\theta \in L^\infty([0, T]; L^p(\mathbb{R}^n))$.

Theorem 2 (Maximum Principle) Let $\theta_0 \in L^p(\mathbb{R}^n)$ with $1 \leq p \leq +\infty$ be an initial data, then the weak solution of equation (11) satisfies the following maximum principle for all $t \in [0, T]$:

$$\|\theta(\cdot, t)\|_{L^p} \leq \|\theta_0\|_{L^p}.$$

Theorem 3 (Positivity Principle) Let $\beta$ and $\delta$ be the parameters given in cases (a)-(d). Let $\frac{n}{\min(\beta, \delta)} \leq p \leq +\infty$ and $M > 0$ a constant, if the initial data $\theta_0 \in L^p(\mathbb{R}^n)$ is such that $0 \leq \theta_0 \leq M$ then the weak solution of equation (11) satisfies $0 \leq \theta(x, t) \leq M$ for all $t \in [0, T]$.

Our main theorem is the following one which is a generalization of a duality method used in the framework of the quasi-geostrophic equation. With this method we obtain a small regularity gain, but for technical reasons we need to consider here the cases (c) and (d).

Theorem 4 (Hölder regularity) Let $\mathcal{L}$ be a Lévy operator of the form (7) with a Lévy measure $\pi$ satisfying hypothesis (17) and (3), with $\alpha = \beta = 1/2$ and $\delta < 1/2$ or $\alpha = \beta = \delta = 1/2$. Fix a small time $T_0 > 0$. Let $\theta_0$ be a function such that $\theta_0 \in L^\infty(\mathbb{R}^n)$. If $\theta(x, t)$ is a solution for the equation (11), then for all time $T_0 < t < T$, we have that $\theta(x, t)$ belongs to the Hölder space $C^0(\mathbb{R}^n)$ with $0 < \gamma < 2\delta < 1$ in the case (c) or $0 < \gamma < 1$ in the case (d).

The plan of the article is the following: in the section 2 we study existence and uniqueness of solutions with initial data in $L^p$ with $1 \leq p < +\infty$. Section 3 is devoted to a positivity principle that will be useful in our proofs and section 4 studies existence of solution with $\theta_0 \in L^\infty$. In section 5 we study the Hölder regularity of the solutions of equation (11) by a duality method.

1 The term “diffusion” must be taken in the sense of the PDEs considered by analysts.
2 Existence and uniqueness with $L^p$ initial data.

In this section we will study existence and uniqueness for weak solution of equation \([1]\) with initial data $\theta_0 \in L^p(\mathbb{R}^n)$ where $p \geq 1$. We will start by considering viscosity solutions with an approximation of the velocity field $v$, and we will prove existence and uniqueness for this system. To pass to the limit we will need a further step that is a consequence of the maximum principle.

Remark 2.1 Since the velocity $v$ is a data of the problem, it is equivalent to consider $-v$ instead of $v$, thus for simplicity we fix velocity’s sign as in equation \([10]\) below. The same proofs are valid for equation \([7]\).

2.1 Viscosity solutions

Before passing to further computations, we give an approximation for functions that belong to the $bmo$ space that will be very useful in the sequel.

Lemma 2.1 Let $f$ be a function in $bmo(\mathbb{R}^n)$. For $k \in \mathbb{N}$, define $f_k$ by

$$f_k(x) = \begin{cases} -k & \text{if } f(x) \leq -k \\ f(x) & \text{if } -k \leq f(x) \leq k \\ k & \text{if } k \leq f(x). \end{cases}$$

(9)

Then $(f_k)_{k \in \mathbb{N}}$ converges weakly to $f$ in $bmo(\mathbb{R}^n)$.

A proof of this lemma can be found in \([18]\). Having this result in mind, we can begin our study of Theorem \([1]\). For this, we will work with the following approximation of the equation \([1]\):

$$
\begin{aligned}
\partial_t \theta(x, t) + \nabla \cdot (v \varepsilon \theta)(x, t) + \mathcal{L}\theta(x, t) = \varepsilon \Delta \theta(x, t) \\
\theta(x, 0) = \theta_0(x)
\end{aligned}
$$

(10)

where $v \varepsilon$ is defined by $v \varepsilon = v \ast \omega_{\varepsilon}$ with $\omega_{\varepsilon}(x) = \varepsilon^{-n} \omega(x/\varepsilon)$ and $\omega \in C_0^\infty(\mathbb{R}^n)$ is a function such that $\int_{\mathbb{R}^n} \omega(x)dx = 1$. Here $\mathcal{L}$ is a Lévy operator of the form \([7]\) with hypothesis \([1]\) and \([3]\) with $\alpha, \beta, \delta$ satisfying the bounds given in the cases (a)-(d). Following \([3]\), the solutions of this problem are called viscosity solutions.

Note that the problem \([10]\) admits the following equivalent integral representation:

$$
\theta(x, t) = e^{t\varepsilon \Delta} \theta_0(x) - \int_0^t e^{(t-s)\varepsilon \Delta} \nabla \cdot (v \varepsilon \theta)(x, s)ds - \int_0^t e^{(t-s)\varepsilon \Delta} \mathcal{L}\theta(x, s)ds,
$$

(11)

In order to prove Theorem \([1]\), we will first investigate a local result with the following theorem where we will apply the Banach contraction scheme in the space $L^\infty([0, T]; L^p(\mathbb{R}^n))$ with the norm $\|f\|_{L^\infty(L^p)} = \sup_{t \in [0, T]} |f(\cdot, t)|_{L^p}$.

Theorem 5 (Local existence) Let $1 \leq p < +\infty$ and let $\theta_0$ and $v$ be two functions such that $\theta_0 \in L^p(\mathbb{R}^n)$, $\nabla \cdot v = 0$ and $v \in L^\infty([0, T^*]; L^\infty(\mathbb{R}^n))$. If the initial data satisfies $\|\theta_0\|_{L^p} \leq K$ and if $T^*$ is a time small enough, then \([11]\) has a unique solution $\theta \in L^\infty([0, T^*]; L^p(\mathbb{R}^n))$ on the closed ball $B(0, 2K) \subset L^\infty([0, T^*]; L^p(\mathbb{R}^n))$.

Remark 2.2 Observe that we fixed here the velocity $v$ such that $v \in L^\infty([0, T^*]; L^\infty(\mathbb{R}^n))$. This is not very restrictive since by Lemma \([24]\) we can construct a sequence $v_{\varepsilon} \in L^\infty(\mathbb{R}^n)$ that converge weakly to $v$ in $bmo(\mathbb{R}^n)$.

Proof of Theorem \([5]\). We note $L_{\varepsilon}(\theta)$ and $N_{\varepsilon}^v(\theta)$ the quantities

$$
L_{\varepsilon}(\theta)(x, t) = \int_0^t e^{(t-s)\varepsilon \Delta} \mathcal{L}\theta(x, s)ds \quad \text{and} \quad N_{\varepsilon}^v(\theta)(x, t) = \int_0^t e^{(t-s)\varepsilon \Delta} \nabla \cdot (v \varepsilon \theta)(x, s)ds.
$$

We begin with general remarks concerning these two formulas. For the first expression we have:
Proposition 2.1 If \( f \in L^\infty([0,T]; L^p(\mathbb{R}^n)) \), then

\[
\|L\varepsilon(f)\|_{L^\infty(L^p)} \leq C\Phi(T', \varepsilon) \|f\|_{L^\infty(L^p)} \tag{12}
\]

where \( \Phi(T', \varepsilon) = \left( \frac{T^{1-\beta}}{\varepsilon} + \frac{T^{1-\alpha}}{\varepsilon^2} \right) \left( \frac{T^{1/2}}{\varepsilon^{1/2}} + T' + \frac{T^{1-\beta}}{\varepsilon} \right) \) and \( \left( \frac{T^{1/2}}{\varepsilon^{1/2}} \right) \), for the cases (a)-(d) respectively.

**Proof.** We write

\[
\|L\varepsilon(f)\|_{L^\infty(L^p)} = \sup_{0 < t < T'} \left\| \int_0^t e^{(t-s)\Delta} L f(s) \, ds \right\|_{L^p} = \sup_{0 < t < T'} \left\| \int_0^t L f \ast h\varepsilon(t-s) \, ds \right\|_{L^p}
\]

where \( h\varepsilon \) is the heat kernel on \( \mathbb{R}^n \). By the properties of the Lévy operator \( L \) we can write \( L f \ast h\varepsilon(t-s) = f \ast L h\varepsilon(t-s) \) and then we obtain the estimate

\[
\|L\varepsilon(f)\|_{L^\infty(L^p)} \leq \sup_{0 < t < T'} \left\| \int_0^t f(s) \|L h\varepsilon(t-s)\|_{L^1} \, ds \right\|_{L^1} \leq \|f\|_{L^\infty(L^p)} \sup_{0 < t < T'} \left\| \int_0^t L h\varepsilon(t-s) \|_{L^1} \, ds \right\| \tag{13}
\]

We need now to study the quantity \( \|L h\varepsilon(t-s)\|_{L^1} \), for this we will use Besov spaces and a short lemma. We recall that for \( 0 < s < 1 \) and \( 1 \leq p < +\infty \), homogeneous Besov spaces \( B^s_p, \dot{p}(\mathbb{R}^n) \) may be defined as

\[
\|f\|_{B^s_p} = \left( \int_{\mathbb{R}^n} \int_{\mathbb{R}^n} \frac{|f(x) - f(x-y)|^p}{|y|^{n+p}} \, dy \, dx \right)^{1/p}.
\]

Now, here is the lemma:

**Lemma 2.2** Let \( \mathcal{L} \) be a Lévy operator satisfying the hypothesis stated above.

(a) If \( 0 < \alpha \leq \beta < 1/2 \) and \( 0 < \delta < 1/2 \) then, for all \( f \in B^s_{2,1}(\mathbb{R}^n) \cap \dot{B}^s_{2,1}(\mathbb{R}^n) \) we have \( \|L f\|_{L^1} \leq \|f\|_{B^s_{2,1}} + \|f\|_{\dot{B}^s_{2,1}} \).

In particular we have for the heat kernel \( \|L h\varepsilon(t-s)\|_{L^1} \leq C([\varepsilon(t-s)]^{-\beta} + [\varepsilon(t-s)]^{-\alpha}) \).

(b) If \( \alpha = \beta = \delta < 1/2 \), we have \( \mathcal{L} = (-\Delta)^{\alpha} \) and thus \( \|L h\varepsilon(t-s)\|_{L^1} \leq C[\varepsilon(t-s)]^{-\alpha} \).

(c) If \( \alpha = \beta = 1/2 \) and \( 0 < \delta < 1/2 \) we have \( \|L f\|_{L^1} \leq C(\|(-\Delta)^{1/2} f\|_{L^1} + \|f\|_{L^1} + \|f\|_{\dot{B}^s_{2,1}}) \) where the quantities above are assumed to be bounded. In particular we have \( \|L h\varepsilon(t-s)\|_{L^1} \leq C([\varepsilon(t-s)]^{-1/2} + 1 + [\varepsilon(t-s)]^{-2}) \).

(d) If \( \alpha = \beta = \delta = 1/2 \), we have \( \mathcal{L} = (-\Delta)^{1/2} \) and thus \( \|L h\varepsilon(t-s)\|_{L^1} \leq C[\varepsilon(t-s)]^{-1/2} \).

**Proof of the lemma.** By homogeneity the cases (b) and (d) are straightforward. If \( 0 < \alpha \leq \beta < 1/2 \) and \( 0 < \delta < 1/2 \), using (14) and (15) we obtain

\[
\|L f\|_{L^1} \leq \int_{\mathbb{R}^n} \int_{\mathbb{R}^n} \frac{|f(x) - f(x-y)|}{|y|^{n+\beta}} \, dy \, dx + \int_{\mathbb{R}^n} \int_{|y| \leq 1} \frac{|f(x) - f(x-y)|}{|y|^{n+\delta}} \, dy \, dx.
\]

If \( \alpha = \beta = 1/2 \) and \( \delta < 1/2 \), we simply write

\[
\|L f\|_{L^1} \leq \int_{\mathbb{R}^n} \left| \int_{|y| \leq 1} \frac{f(x-y) - f(x-y)}{|y|^{n+1}} \, dy \right| \, dx + \int_{\mathbb{R}^n} \left| \int_{|y| > 1} \frac{f(x-y) - f(x-y)}{|y|^{n+1}} \, dy \right| \, dx
\]

Now, since \( (-\Delta)^{1/2} f(x) = v.p. \int_{\mathbb{R}^n} \frac{f(x-y) - f(x-y)}{|y|^{n+1}} \, dy \), it is easy to obtain that

\[
\|L f\|_{L^1} \leq \|(-\Delta)^{1/2} f\|_{L^1} + C\|f\|_{L^1}.
\]

Finally, by homogeneity and since the heat kernel \( h\varepsilon \) is a smooth function, we obtain the wished estimates for this function.

With these estimates at our disposal for the quantity \( \|L h\varepsilon(t-s)\|_{L^1} \), we obtain for (13) -after an integration in time and following the different cases- the inequality \( \|L\varepsilon(f)\|_{L^\infty(L^p)} \leq C\Phi(T', \varepsilon) \|f\|_{L^\infty(L^p)} \) and the Proposition 2.1 is proven.

For the term \( N^\varepsilon \) we have:
Proposition 2.2 If \( f \in L^\infty([0, T^*]; L^p(\mathbb{R}^n)) \) and \( v \in L^\infty([0, T^*]; L^\infty(\mathbb{R}^n)) \), then

\[
\|N^v_\varepsilon(f)\|_{L^\infty(L^p)} \leq C \sqrt{\frac{T^*}{\varepsilon}} \|v\|_{L^\infty(L^\infty)} \|f\|_{L^\infty(L^p)}
\]  

(14)

Proof. We write:

\[
\|N^v_\varepsilon(f)\|_{L^\infty(L^p)} = \sup_{0 < t < T^*} \left\| \int_0^t e^{(t-s)\Delta} \nabla \cdot (v \cdot f)(s) \, ds \right\|_{L^p} = \sup_{0 < t < T^*} \left\| \int_0^t \nabla \cdot (v \cdot f)(t-s) \, ds \right\|_{L^p}
\]

\[
\leq \sup_{0 < t < T^*} \int_0^t \|v\|_{L^p} \|\nabla h_{\varepsilon(t-s)}\|_{L^1} \, ds \leq \sup_{0 < t < T^*} \int_0^t \|v\|_{L^\infty} \|f(\cdot, s)\|_{L^p} C(\varepsilon(t-s))^{-1/2} \, ds
\]

\[
\leq \|v\|_{L^\infty(L^\infty)} \|f\|_{L^\infty(L^p)} \sup_{0 < t < T^*} \int_0^t C(\varepsilon(t-s))^{-1/2} \, ds \leq C \sqrt{\frac{T^*}{\varepsilon}} \|v\|_{L^\infty(L^\infty)} \|f\|_{L^\infty(L^p)}.
\]

To the preliminary remarks we note, that since \( e^{t\Delta} \) is a contraction operator, the estimate \( \|e^{t\Delta}f\|_{L^p} \leq \|f\|_{L^p} \) is valid for all function \( f \in L^p(\mathbb{R}^n) \) with \( 1 \leq p \leq +\infty \), for all \( t > 0 \) and all \( \varepsilon > 0 \). Thus, we have:

\[
\|e^{t\Delta}f\|_{L^\infty(L^p)} \leq \|f\|_{L^p}.
\]  

(15)

Now we can use the Banach contraction scheme: we construct a sequence of functions in the following way

\[
\theta_{n+1}(x, t) = e^{t\Delta} \theta_0(x) - L_\varepsilon(\theta_n)(x, t) - N^v_\varepsilon(\theta_n)(x, t)
\]

and we take the \( L^\infty L^p \)-norm of this expression to obtain

\[
\|\theta_{n+1}\|_{L^\infty(L^p)} \leq \|e^{t\Delta} \theta_0\|_{L^\infty(L^p)} + \|L_\varepsilon(\theta_n)\|_{L^\infty(L^p)} + \|N^v_\varepsilon(\theta_n)\|_{L^\infty(L^p)}
\]

Using estimates (12), (13) and (15) we have

\[
\|\theta_{n+1}\|_{L^\infty(L^p)} \leq \|\theta_0\|_{L^p} + C \left( \Phi(T^*, \varepsilon) + \frac{T^{1/2}}{\varepsilon^{1/2}} \|v\|_{L^\infty(L^\infty)} \right) \|\theta_n\|_{L^\infty(L^p)}
\]

Thus, if \( \|\theta_0\|_{L^p} \leq K \) and if we define the time \( T^* \) to be such that \( C \left( \Phi(T^*, \varepsilon) + \frac{T^{1/2}}{\varepsilon^{1/2}} \|v\|_{L^\infty(L^\infty)} \right) \leq 1/2 \), we have by iteration that \( \|\theta_{n+1}\|_{L^\infty(L^p)} \leq 2K \): the sequence \( \{\theta_n\}_{n \geq 0} \) constructed from initial data \( \theta_0 \) belongs to the closed ball \( B(0, 2K) \). In order to finish this proof, let us show that \( \theta_n \rightharpoonup \theta \) in \( L^\infty([0, T^*]; L^p(\mathbb{R}^n)) \). For this we write

\[
\|\theta_{n+1} - \theta_n\|_{L^\infty(L^p)} \leq \|L_\varepsilon(\theta_n - \theta_{n-1})\|_{L^\infty(L^p)} + \|N^v_\varepsilon(\theta_n - \theta_{n-1})\|_{L^\infty(L^p)}
\]

and using the previous results we have

\[
\|\theta_{n+1} - \theta_n\|_{L^\infty(L^p)} \leq C \left( \Phi(T^*, \varepsilon) + \frac{T^{1/2}}{\varepsilon^{1/2}} \|v\|_{L^\infty(L^\infty)} \right) \|\theta_n - \theta_{n-1}\|_{L^\infty(L^p)}
\]

so, by iteration we obtain

\[
\|\theta_{n+1} - \theta_n\|_{L^\infty(L^p)} \leq \left[ C \left( \Phi(T^*, \varepsilon) + \frac{T^{1/2}}{\varepsilon^{1/2}} \|v\|_{L^\infty(L^\infty)} \right) \right]^n \|\theta_1 - \theta_0\|_{L^\infty(L^p)}
\]

hence, with the definition of \( T^* \) it comes \( \|\theta_{n+1} - \theta_n\|_{L^\infty(L^p)} \leq \left( \frac{1}{2} \right)^n \|\theta_1 - \theta_0\|_{L^\infty(L^p)} \). Finally, if \( n \rightharpoonup +\infty \), the sequence \( \{\theta_n\}_{n \geq 0} \) converges towards \( \theta \) in \( L^\infty([0, T^*]; L^p(\mathbb{R}^n)) \). Since it is a Banach space we deduce uniqueness for the solution \( \theta \) of problem (11). The proof of Theorem 3 is finished. \( \blacksquare \)

Corollary 2.1 The solution constructed above depends continuously on the initial value \( \theta_0 \).

Proof. Let \( \varphi_0, \theta_0 \in L^p(\mathbb{R}^n) \) be two initial values and let \( \varphi \) and \( \theta \) be the associated solutions. We write

\[
\theta(x, t) - \varphi(x, t) = e^{t\Delta}(\theta_0(x) - \varphi_0(x)) - L_\varepsilon(\theta - \varphi)(x, t) - N^v_\varepsilon(\theta - \varphi)(x, t)
\]

Taking \( L^\infty L^p \)-norm in formula above and applying the same previous calculations one obtains

\[
\|\theta - \varphi\|_{L^\infty(L^p)} \leq \|\theta_0 - \varphi_0\|_{L^p} + C_0 \|\theta - \varphi\|_{L^\infty(L^p)}
\]

This shows continuous dependence of the solution since \( C_0 = C \left( \Phi(T^*, \varepsilon) + \frac{T^{1/2}}{\varepsilon^{1/2}} \|v\|_{L^\infty(L^\infty)} \right) \leq 1/2 \). \( \blacksquare \)
Remark 2.3 (From Local to Global) Once we obtain a local result, global existence easily follows by a simple iteration since problems studied here (equations (1) or (10)) are linear as the velocity v does not depend on θ.

We study now the regularity of the solutions constructed by this method.

Theorem 6 Solutions of the approximated problem (10) are smooth.

Proof. By iteration we will prove that θ ∈ \( L^\infty(0, t_1; W^{s,p}(\mathbb{R}^n)) \) for all k ≥ 0 where we define the Sobolev space \( \dot{W}^{s,p}(\mathbb{R}^n) \) for s ∈ \( \mathbb{R} \) and 1 < p < +∞ by \( \| f \|_{\dot{W}^{s,p}} = \| (-\Delta)^{s/2} f \|_{L^p} \). Note that this is true for k = 0. So let us assume that it is also true for k > 0 and we will show that it is still true for k + 1.

Set t such that 0 < T_0 < T_1 < t < T_2 < T^* and let us consider the next problem

\[
\theta(x, t) = e^{(t-T_0)\Delta} \theta(x, T_0) - \int_{T_0}^{t} e^{(t-s)\Delta} \nabla \cdot (v_\varepsilon \theta)(x, s) ds - \int_{T_0}^{t} e^{(t-s)\Delta} \mathcal{L} \theta(x, s) ds
\]

We have then the following estimate

\[
\| \theta \|_{L^\infty(0, t_1; W^{s,p})} \leq \| e^{(t-T_0)\Delta} \theta(\cdot, T_0) \|_{L^\infty(0, t_1; W^{s,p})} + \int_{T_0}^{t} \| e^{(t-s)\Delta} \nabla \cdot (v_\varepsilon \theta)(\cdot, s) \|_{W^{s,p}} ds + \int_{T_0}^{t} \| e^{(t-s)\Delta} \mathcal{L} \theta(\cdot, s) \|_{W^{s,p}} ds
\]

Now, we will treat separately each of the previous terms.

(i) For the first one we have

\[
\| e^{(t-T_0)\Delta} \theta(\cdot, T_0) \|_{W^{s,p}} = \| \theta(\cdot, T_0) \ast (-\Delta)^{s/4} h_{\varepsilon(t-T_0)} \|_{L^p} \leq \| \theta(\cdot, T_0) \|_{L^p} \| (-\Delta)^{s/4} h_{\varepsilon(t-T_0)} \|_{L^1}
\]

where \( h_t \) is the heat kernel, so we can write

\[
\| e^{(t-T_0)\Delta} \theta(\cdot, T_0) \|_{W^{s,p}} \leq C \| \theta(\cdot, T_0) \|_{L^p} \sup \{ [\varepsilon(t - T_0)]^{-\frac{4}{1+4s}} ; 1 \}
\]

(ii) For the second term, one has

\[
\int_{T_0}^{t} \| e^{(t-s)\Delta} \nabla \cdot (v_\varepsilon \theta)(\cdot, s) \|_{W^{s,p}} ds \leq \int_{T_0}^{t} \| \nabla \cdot (v_\varepsilon \theta) \ast h_{\varepsilon(t-s)} \|_{W^{s,p}} ds \leq \int_{T_0}^{t} \| (-\Delta)^{s/4} \nabla \cdot (v_\varepsilon \theta) \ast h_{\varepsilon(t-s)} \|_{L^p} ds \leq C \int_{T_0}^{t} \| v_\varepsilon \theta(\cdot, s) \|_{W^{s,p}} [\varepsilon(t - s)]^{-\frac{4}{s+4}} ds.
\]

Note now that we have here the estimations below for N ≥ k/2

\[
\| v_\varepsilon \theta(\cdot, s) \|_{W^{s,p}} \leq \| v_\varepsilon(\cdot, s) \|_{L^\infty} \| \theta(\cdot, s) \|_{W^{s,p}} \leq C \varepsilon^{-N} \| v(\cdot, s) \|_{L^\infty} \| \theta(\cdot, s) \|_{W^{s,p}}
\]

hence, we can write

\[
\int_{T_0}^{t} \| e^{(t-s)\Delta} \nabla \cdot (v_\varepsilon \theta)(\cdot, s) \|_{W^{s,p}} ds \leq C \| v(\cdot, s) \|_{L^\infty} \| \theta(\cdot, s) \|_{W^{s,p}} \int_{T_0}^{t} \varepsilon^{-N} \sup \{ [\varepsilon(t - s)]^{-\frac{4}{s+4}} ; 1 \} ds
\]

(iii) Finally, for the last term we have

\[
\int_{T_0}^{t} \| e^{(t-s)\Delta} \mathcal{L} \theta(\cdot, s) \|_{W^{s,p}} ds \leq \int_{T_0}^{t} \| (-\Delta)^{\frac{s}{4}} \theta(\cdot, s) \ast \mathcal{L} (-\Delta)^{\frac{s}{4}} h_{\varepsilon(t-s)} \|_{L^p} ds \leq \int_{T_0}^{t} \| \theta(\cdot, s) \|_{W^{s,p}} \| \mathcal{L} (-\Delta)^{\frac{s}{4}} h_{\varepsilon(t-s)} \|_{L^1} ds
\]

now, applying Lemma 2.2 to the function \( (-\Delta)^{\frac{s}{4}} h_{\varepsilon(t-s)} \) we obtain by homogeneity that

\[
\| \mathcal{L} (-\Delta)^{\frac{s}{4}} h_{\varepsilon(t-s)} \|_{L^1} \leq \phi(\varepsilon(t - s))
\]

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where $\phi(\varepsilon(t-s)) = [\varepsilon(t-s)]^{-\frac{4}{p-1}} + [\varepsilon(t-s)]^{-\frac{4}{p+1}}$; $[\varepsilon(t-s)]^{-\frac{4}{p-1}} + [\varepsilon(t-s)]^{-\frac{4}{p+1}}$ for the cases (a)-(d) respectively. So we obtain:

$$\left\| \int_{T_0}^t e^{\varepsilon(t-s)\Delta}L\theta(s, s) ds \right\|_{L^\infty(W^{\frac{4}{p+1}}(p))} \leq C\|\theta\|_{L^\infty(W^{\frac{4}{p+1}}(p))} \int_{T_0}^t \sup \{\phi(\varepsilon(t-s)); 1\} ds.$$

Now, with formulas (i)-(iii) at our disposal, we have that the norm $\|\theta\|_{L^\infty(W^{\frac{4}{p+1}}(p))}$ is controlled for all $\varepsilon > 0$: we have proven spatial regularity.

Time regularity follows since we have

$$\frac{\partial^k}{\partial t^k} \theta(x,t) + \nabla \cdot \left( \frac{\partial^k}{\partial t^k}(v_\varepsilon \theta) \right) (x,t) + \mathcal{L} \left( \frac{\partial^k}{\partial t^k} \theta \right) (x,t) = \varepsilon \Delta \left( \frac{\partial^k}{\partial t^k} \theta \right) (x,t).$$

\[\blacksquare\]

**Remark 2.4** The solutions $\theta(\cdot, \cdot)$ constructed above depend on $\varepsilon$.

### 2.2 Maximum principle and Besov regularity

The maximum principle we are studying here will be a consequence of few inequalities, some of them are well known. We will start with the solutions $\theta(\cdot, \cdot)$ obtained in the previous section:

**Proposition 2.3 (Viscosity version of Theorem 2)** Let $\theta_0 \in L^p(\mathbb{R}^n)$ with $1 \leq p \leq +\infty$ be an initial data, then the associated solution of the viscosity problem \[\text{(10)}\] satisfies the following maximum principle for all $t \in [0, T]$:

$$\|\theta(\cdot, t)\|_{L^p} \leq \|\theta_0\|_{L^p}.$$

**Proof.** We write for $1 \leq p < +\infty$:

$$\frac{d}{dt}\|\theta(t, \cdot)\|_{L^p}^p = p \int_{\mathbb{R}^n} |\theta|^{p-2}\theta (\varepsilon \Delta \theta - \nabla \cdot (v_\varepsilon \theta) - \mathcal{L} \theta) dx = p\varepsilon \int_{\mathbb{R}^n} |\theta|^{p-2}\theta \Delta \theta dx - p \int_{\mathbb{R}^n} |\theta|^{p-1} sgn(\theta) \mathcal{L} \theta dx$$

where we used the fact that $\text{div}(v) = 0$. Thus, we have

$$\frac{d}{dt}\|\theta(t, \cdot)\|_{L^p}^p = p\varepsilon \int_{\mathbb{R}^n} |\theta|^{p-2}\theta \Delta \theta dx + p \int_{\mathbb{R}^n} |\theta|^{p-1} sgn(\theta) \mathcal{L} \theta dx = 0,$$

and integrating in time we obtain

$$\|\theta(t, \cdot)\|_{L^p}^p = p\varepsilon \int_0^t \int_{\mathbb{R}^n} |\theta|^{p-2}\theta \Delta \theta dx ds + p \int_0^t \int_{\mathbb{R}^n} |\theta|^{p-1} sgn(\theta) \mathcal{L} \theta dx ds = \|\theta_0\|_{L^p}^p. \quad (16)$$

To finish, we have the following lemma

**Lemma 2.3** The quantities $-p\varepsilon \int_0^t \int_{\mathbb{R}^n} |\theta|^{p-2}\theta \Delta \theta dx ds$ and $p \int_0^t \int_{\mathbb{R}^n} |\theta|^{p-1} sgn(\theta) \mathcal{L} \theta dx ds$ are both positive.

**Proof.** For the first expression, since $e^{s\Delta}$ is a contraction semi-group we have $\|e^{s\Delta}f\|_{L^p} \leq \|f\|_{L^p}$ for all $s > 0$ and all $f \in L^p(\mathbb{R}^n)$. Thus $F(s) = \|e^{s\Delta}f\|_{L^p}$ is decreasing in $s$; taking the derivative in $s$ and evaluating in $s = 0$ we obtain the desired result. The positivity of the second expression follows immediately from the Strook-Varopoulos estimate for general Lévy-type operators given by the following formula (see remark 1.23 of \[\text{[11]}\] for a proof, more details can be found in \[\text{[19]}\] and \[\text{[20]}\]):

$$C\langle \mathcal{L} |\theta|^{p/2}, |\theta|^{p/2} \rangle \leq \langle \mathcal{L} \theta, |\theta|^{p-1} sgn(\theta) \rangle$$

To conclude it is enough to note that $\langle \mathcal{L} |\theta|^{p/2}, |\theta|^{p/2} \rangle = \|\mathcal{L}^{\frac{1}{2}} |\theta|^{p/2} \|_{L^2}^2 \geq 0$, where the operator $\mathcal{L}^{\frac{1}{2}}$ is defined by the formula $(\mathcal{L}^{\frac{1}{2}} f)(\xi) = a^{\frac{1}{2}}(\xi) f(\xi)$.

\[\blacksquare\]

Getting back to (16), we have that all these quantities are bounded and positive and we write for all $1 \leq p < +\infty$:

$$\|\theta(\cdot, t)\|_{L^p} \leq \|\theta_0\|_{L^p}.$$

Since $\|\theta(\cdot, t)\|_{L^p} \xrightarrow{p \to +\infty} \|\theta(\cdot, t)\|_{L^\infty}$, the maximum principle is proven for viscosity solutions.

\[\blacksquare\]

In order to deal with Theorem 2 we will need some aditional results. Indeed, a more detailed study of expression (16) above will lead us to a result concerning weak solution’s regularity.
Lemma 2.4 If the function $\pi$ satisfies the conditions (3) and (5), then we have for the cases (a)-(d) the following pointwise estimates on the symbol $a(\cdot)$ for all $\xi \in \mathbb{R}^n$:

1) $a(\xi) \leq |\xi|^{2\alpha} + |\xi|^{2\delta}$

2) $|\xi|^{2\alpha} \leq a(\xi) + C$.

Proof. We use the Lévy-Khinchin formula to obtain $|\xi|^{2\alpha} = \int_{\mathbb{R}^n \setminus \{0\}} (1 - \cos(y : \xi)) |y|^{-n-2\alpha} dy$. It is enough to apply the hypothesis (3), (5) and to use the inequality (1) to conclude. ☐

Theorem 7 (Besov Regularity) Let $\mathcal{L}$ be a Lévy-type operator of the form (7) with hypothesis (3) and (5) for the measure $\pi$ with $\alpha, \beta, \delta$ satisfying the bounds given in the cases (a)-(d). Let $2 \leq p < +\infty$ and let $f : \mathbb{R}^n \rightarrow \mathbb{R}$ be a function such that $f \in \dot{L}^p(\mathbb{R}^n)$ and

$$\int_{\mathbb{R}^n} |f(x)|^{p-2}f(x)\mathcal{L}f(x)dx < +\infty, \quad \text{then} \quad f \in \dot{B}^{2\alpha/p,p}_p(\mathbb{R}^n).$$

Proof. We will prove the following estimates valid for a positive function $f$:

$$\|f\|_{\dot{B}^{2\alpha/p}_p}^p \leq C\|f^{p/2}\|_{\dot{B}^{2\alpha}_2}^2 \leq \|f^{p/2}\|_{L^2}^2 + \int_{\mathbb{R}^n} |f(x)|^{p-2}f(x)\mathcal{L}f(x)dx$$

(18)

The first inequality can be found in [2], so we only need to focus on the right-hand side of the previous estimate. For this, we will start assuming that the function $f$ is positive.

Using Plancherel’s formula, the characterisation of $\dot{L}^p$ via the symbol $a^+(\xi)$ and Lemma 2.4 we write

$$\|f^{p/2}\|_{B^{2\alpha}_2}^2 = \|f^{p/2}\|_{H^n}^2 = \int_{\mathbb{R}^n} |\xi|^{2\alpha} |\hat{f}^{p/2}(\xi)|^2 d\xi \leq \int_{\mathbb{R}^n} (a^+(\xi) + C)^2 |\hat{f}^{p/2}(\xi)|^2 d\xi \leq c \left( \|f^{p/2}\|_{L^2}^2 + \|\mathcal{L}^{+^{p/2}}\|_{L^2}^2 \right).$$

Now, using the Strook-Varopoulos inequality (17) we have

$$\|f^{p/2}\|_{L^2}^2 + \|\mathcal{L}^{+^{p/2}}\|_{L^2}^2 \leq \|f^{p/2}\|_{L^2}^2 + c \int_{\mathbb{R}^n} f^{-2}f\mathcal{L}f dx$$

So inequality (18) is proven for positive functions. For the general case we write $f(x) = f_+(x) - f_-(x)$ where $f_\pm(x)$ are positive functions with disjoint support and we have:

$$\int_{\mathbb{R}^n} |f(x)|^{p-2}f(x)\mathcal{L}f(x)dx = \int_{\mathbb{R}^n} f_+(x)^{p-2}f_+(x)\mathcal{L}f_+(x)dx + \int_{\mathbb{R}^n} f_-(x)^{p-2}f_-(x)\mathcal{L}f_-(x)dx$$

(19)

We only need to treat the two last integrals, and in fact we just need to study one of them since the other can be treated in a similar way. So, for the third integral we have

$$\int_{\mathbb{R}^n} f_+(x)^{p-2}f_+(x)\mathcal{L}f_-(x)dx = \int_{\mathbb{R}^n} f_+(x)^{p-2}f_+(x)\int_{\mathbb{R}^n} [f_-(x) - f_-(y)]\pi(x - y)dydx$$

$$= \int_{\mathbb{R}^n} f_+(x)^{p-2} \int_{\mathbb{R}^n} [f_+(x) - f_+(y)]\pi(x - y)dydx$$

However, since $f_+$ and $f_-$ have disjoint supports we obtain the following estimate:

$$\int_{\mathbb{R}^n} f_+(x)^{p-2}f_+(x)\mathcal{L}f_-(x)dx = -\int_{\mathbb{R}^n} f_+(x)^{p-2} \int_{\mathbb{R}^n} [f_+(x)f_-(y)]\pi(x - y)dydx \leq 0$$

Recalling that $\pi$ is a positive function we obtain that this quantity is negative as all the terms inside the integral are positive. With this observation we see that the last terms of (19) are positive and we have

$$\int_{\mathbb{R}^n} f_+(x)^{p-2}f_+(x)\mathcal{L}f_+(x)dx + \int_{\mathbb{R}^n} f_-(x)^{p-2}f_-(x)\mathcal{L}f_-(x)dx \leq \int_{\mathbb{R}^n} |f(x)|^{p-2}f(x)\mathcal{L}f(x)dx < +\infty.$$

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Then, using the first part of the proof we have $f_{\pm} \in \dot{B}^{2n/p,p}_{p}(\mathbb{R}^n)$ and since $f = f_+ - f_-$ we conclude that $f$ belongs to the Besov space $\dot{B}^{2n/p,p}_{p}(\mathbb{R}^n)$.

**Proof of Theorem**\textsuperscript{[2]} We have obtained with the previous results a family of regular functions $(\theta^{(c)})_{c} > 0 \in L^{\infty}([0,T]; \mathbb{R}^n)$ which are solutions of (10) and satisfy the uniform bound $\|\theta^{(c)}(\cdot,t)\|_{L^p} \leq \|\theta_0\|_{L^p}$.

Since $L^{\infty}([0,T]; \mathbb{L}^p(\mathbb{R}^n)) = (L^{1}([0,T]; \mathbb{L}^{p}(\mathbb{R}^n)))'$, with $\frac{1}{p} + \frac{1}{q} = 1$, we can extract from those solutions $\theta^{(c)}$ a subsequence $(\theta_k)_{k \in \mathbb{N}}$ which is *-weakly convergent to some function $\theta$ in the space $L^{\infty}([0,T]; \mathbb{L}^p(\mathbb{R}^n))$, which implies convergence in $\mathbb{P}'(\mathbb{R}^+ \times \mathbb{R}^n)$. However, this weak convergence is not sufficient to assure the convergence of $(v_\varepsilon \theta_k)$ to $v \theta$ for. For this we use the remarks that follow.

First, using remark 2.2 we can consider a sequence $(v_\varepsilon)_{k \in \mathbb{N}}$ with $v_\varepsilon$ as in formula (9) such that $v_\varepsilon \longrightarrow v$ weakly in $\mathbb{bmo}(\mathbb{R}^n)$. Secondly, combining Proposition 2.3 and Theorem 7 we obtain that solutions $\theta_k$ belong to the space $L^{\infty}([0,T]; \mathbb{L}^p(\mathbb{R}^n)) \cap L^1([0,T]; \dot{B}^{2n/p,p}_{p}(\mathbb{R}^n))$ for all $k \in \mathbb{N}$.

To finish, fix a function $\varphi \in C_0^\infty([0,T] \times \mathbb{R}^n)$. Then we have the fact that $\varphi \theta_k \in L^1([0,T]; \dot{B}^{2n/p,p}_{p}(\mathbb{R}^n))$ and $\partial_t \varphi \theta_k \in L^1([0,T]; \dot{B}^{-N,p}_{p}(\mathbb{R}^n))$. This implies the local inclusion, in space as well as in time, $\varphi \theta_k \in \mathbb{W}^{2n/p,p}_{t,x} \subset \mathbb{W}^{2n/p-2}_{t,x}$ so we can apply classical results such as the Rellich’s theorem to obtain convergence of $v_\varepsilon \theta_k$ to $v \theta$.

Thus, we obtain existence and uniqueness of weak solutions for the problem (11) with an initial data in $\theta_0 \in \mathbb{L}^p(\mathbb{R}^n)$, $2 \leq p < +\infty$ that satisfy the maximum principle. Moreover, we have that these solutions $\theta(x,t)$ belong to the space $L^{\infty}([0,T]; \mathbb{L}^p(\mathbb{R}^n)) \cap L^p([0,T]; \dot{B}^{2n/p,p}_{p}(\mathbb{R}^n))$.

**Remark 2.5** These lines explain how to obtain weak solutions from viscosity ones and it will be used freely in the sequel.

### 3 Positivity principle

We prove in this section Theorem\textsuperscript{[3]} Recall that by hypothesis we have $0 \leq \psi_0 \leq M$ an initial datum for the equation (1) with $\psi_0 \in \mathbb{L}^p(\mathbb{R}^n)$ and $\frac{n}{2 \min(n,p)} \leq p \leq + \infty$.

To begin with, we fix two constants, $\rho, R$ such that $R > 2\rho > 0$. Then we set $A_0,R(x)$ a function equals to $M/2$ over $|x| \leq 2R$ and equals to $\psi_0(x)$ over $|x| > 2R$ and we write $B_0,R(x) = \psi_0(x) - A_0,R(x)$, so by construction we have

$$\psi_0(x) = A_0,R(x) + B_0,R(x)$$

with $\|A_0,R\|_{L^\infty} \leq M$ and $\|B_0,R\|_{L^\infty} \leq M/2$. Remark that $A_0,R, B_0,R \in \mathbb{L}^p(\mathbb{R}^n)$.

Now fix $v \in L^{\infty}([0,T]; \mathbb{bmo}(\mathbb{R}^n))$ such that $\text{div}(v) = 0$ and consider the equations

\[
\begin{aligned}
&\partial_t A_R(x,t) + \nabla \cdot (v A_R)(x,t) + \mathcal{L} A_R(x,t) = 0, \\
&A_R(x,0) = A_{0,R}(x)
\end{aligned}
\quad \quad \quad \quad \quad
\begin{aligned}
&\partial_t B_R(x,t) + \nabla \cdot (v B_R)(x,t) + \mathcal{L} B_R(x,t) = 0 \\
&B_R(x,0) = B_{0,R}(x).
\end{aligned}
\tag{20}
\]

Using the maximum principle and by construction we have the following estimates for $t \in [0,T]$:

\[
\begin{aligned}
\|A_R(\cdot,t)\|_{L^p} &\leq \|A_{0,R}\|_{L^p} \leq \|\psi_0\|_{L^p} + CMR^{n/p} \quad (1 \leq p < +\infty) &\tag{21} \\
\|A_R(\cdot,t)\|_{L^\infty} &\leq \|A_{0,R}\|_{L^\infty} \leq M. \\
\|B_R(\cdot,t)\|_{L^\infty} &\leq \|B_{0,R}\|_{L^\infty} \leq M/2.
\end{aligned}
\]

where $A_R(x,t)$ and $B_R(x,t)$ are the weak solutions of the systems (20).

**Lemma 3.1** The function $\psi(x,t) = A_R(x,t) + B_R(x,t)$ is the unique solution for the problem

\[
\begin{aligned}
&\partial_t \psi(x,t) + \nabla \cdot (v \psi)(x,t) + \mathcal{L} \psi(x,t) = 0 \\
&\psi(x,0) = A_{0,R}(x) + B_{0,R}(x).
\end{aligned}
\tag{22}
\]
Proof. Using hypothesis for $A_R(x,t)$ and $B_R(x,t)$ and the linearity of equation (22) we have that the function $\psi_R(x, t) = A_R(x, t) + B_R(x, t)$ is a solution for this equation. Uniqueness is assured by the maximum principle and by the continuous dependence from initial data given in corollary 2.1, thus we can write $\psi(x, t) = \psi_R(x, t)$. 

To continue, we will need an auxiliary function $\phi \in C_0^\infty(\mathbb{R}^n)$ such that $\phi(x) = 0$ for $|x| \geq 1$ and $\phi(x) = 1$ if $|x| \leq 1/2$ and we set $\psi(x) = \phi(x/R)$. Now, we will estimate the $L^p$-norm of $\psi(x)(A_R(x, t) - M/2)$ with $p > \frac{n}{2} \min(\beta, \delta)$, where $\beta$ and $\delta$ are the parameters of the hypothesis for the function $\pi$ in the cases (a)-(d). We write:

$$\begin{align*}
\partial_t \|\phi(\cdot)(A_R(\cdot, t) - M/2)\|_{L^p}^p &= p \int_{\mathbb{R}^n} |\phi(x)(A_R(x, t) - M/2)|^{p-2}(\phi(x)(A_R(x, t) - M/2)) \\
&\quad \times \partial_t (\phi(x)(A_R(x, t) - M/2)) dx
\end{align*}$$

(23)

We observe that we have the following identity for the last term above

$$\begin{align*}
\partial_t (\phi(x)(A_R(x, t) - M/2)) &= -\nabla \cdot (\phi(x) v(A_R(x, t) - M/2)) - \mathcal{L}(\phi(x)(A_R(x, t) - M/2)) \\
&\quad + (A_R(x, t) - M/2) v \cdot \nabla \phi(x) + [\mathcal{L}, \phi]A_R(x, t) - M/2 \mathcal{L} \phi(x)
\end{align*}$$

where we noted $[\mathcal{L}, \phi]$ the commutator between $\mathcal{L}$ and $\phi$. Thus, using this identity in (23) and the fact that $\text{div}(v) = 0$ we have

$$\begin{align*}
\partial_t \|\phi(\cdot)(A_R(\cdot, t) - M/2)\|_{L^p}^p &= -p \int_{\mathbb{R}^n} |\phi(x)(A_R(x, t) - M/2)|^{p-2}(\phi(x)(A_R(x, t) - M/2)) \\
&\quad \times \mathcal{L}(\phi(x)(A_R(x, t) - M/2)) dx \\
&\quad + p \int_{\mathbb{R}^n} |\phi(x)(A_R(x, t) - M/2)|^{p-2}(\phi(x)(A_R(x, t) - M/2)) \\
&\quad \times ([\mathcal{L}, \phi]A_R(x, t) - M/2 \mathcal{L} \phi(x)) dx
\end{align*}$$

(24)

Remark that the integral (24) is positive so one has

$$\begin{align*}
\partial_t \|\phi(\cdot)(A_R(\cdot, t) - M/2)\|_{L^p}^p &\leq p \int_{\mathbb{R}^n} |\phi(x)(A_R(x, t) - M/2)|^{p-2}(\phi(x)(A_R(x, t) - M/2)) \\
&\quad \times ([\mathcal{L}, \phi]A_R(x, t) - M/2 \mathcal{L} \phi(x)) dx
\end{align*}$$

Using Hölder’s inequality and integrating in time the previous expression we have

$$\begin{align*}
\|\phi(\cdot)(A_R(\cdot, t) - M/2)\|_{L^p}^p &\leq \|\phi(\cdot)(A_R(\cdot, 0) - M/2)\|_{L^p}^p + \int_0^t \left( \|\mathcal{L}, \phi \|_{L^p} + \|\mathcal{L} \phi\|_{L^p} \right) ds
\end{align*}$$

(25)

The first term of the right side is null since over the support of $\phi$ we have identity $A_R(x, 0) = M/2$. For the second term $\|\mathcal{L}, \phi \|_{L^p}$ we will need the following lemma

Lemma 3.2 For $1 \leq p \leq +\infty$ we have for the cases (a)-(d) the following inequality:

$$\|\mathcal{L}, \phi \|_{L^p} \leq C(R^{-2\delta} + R^{-2\delta})\|A_{0_R}\|_{L^p}.$$

Proof. We have $[\mathcal{L}, \phi]A_R(x, s) = \int_{\mathbb{R}^n} (\phi(x) - \phi(x-y))A_R(x-y, s)\pi(y)dy$ and we divide our study following the different cases (a)-(d).

For the case (a), where $0 < \alpha \leq \beta < 1/2$ and $0 < \delta < 1/2$, or in the case (b) where $0 < \alpha = \beta = \delta < 1/2$, we proceed as follows. We begin with the case $p = +\infty$ and we write:

$$\begin{align*}
\|\mathcal{L}, \phi \|_{L^p} \leq \int_{\mathbb{R}^n} |\phi(x) - \phi(y)| |A_R(y, s)|dy + \int_{\mathbb{R}^n} |\phi(x) - \phi(y)| |A_R(y, s)|dy
\end{align*}$$

(26)
Again, it is enough to study one of these two integrals since the other can be treated in a totally similar way. We write:

\[
\int_{\mathbb{R}^n} \frac{|\varphi(x) - \varphi(y)|}{|x - y|^{n+2\beta}} |A_R(y, s)| dy = \int_{|x-y|>R} \frac{|\varphi(x) - \varphi(y)|}{|x - y|^{n+2\beta}} |A_R(y, s)| dy + \int_{|x-y|\leq R} \frac{|\varphi(x) - \varphi(y)|}{|x - y|^{n+2\beta}} |A_R(y, s)| dy
\]

\[
\leq 2\|\varphi\|_L^\infty \int_{|x-y|>R} \frac{|A_R(y, s)|}{|x - y|^{n+2\beta}} dy + \int_{|x-y|\leq R} \frac{1}{|x - y|^{n+2\beta}} |A_R(y, s)| dy
\]

\[
\leq 2\|\varphi\|_L^\infty \|A_R(\cdot, s)||_{L^\infty} \int_{|x-y|>R} \frac{1}{|x - y|^{n+2\beta}} dy + C R^{-1} \int_{|x-y|\leq R} \frac{|A_R(y, s)|}{|x - y|^{n+2\beta}} dy
\]

\[
\leq 2C \|\varphi\|_L^\infty \|A_R(\cdot, s)||_{L^\infty} R^{-2\beta} + C \|A_R(\cdot, s)||_{L^\infty} R^{-2\beta} \leq C R^{-2\beta} \|A_{0,R}\|_{L^\infty}.
\]

Then, with the \(\delta\)-part in inequality (26) we have

\[
\|L, \varphi\|A_R(\cdot, s)||_{L^\infty} \leq C(R^{-2\beta} + R^{-2\delta}) \|A_{0,R}\|_{L^\infty}.
\]

The case \(p = 1\) is very similar. Using inequality (26) we have

\[
\int_{\mathbb{R}^n} \|L, \varphi\|A_R(x, s)||_{L^1} dx \leq \int_{\mathbb{R}^n} \int_{\mathbb{R}^n} \frac{|\varphi(x) - \varphi(y)|}{|x - y|^{n+2\beta}} |A_R(y, s)| dy dx + \int_{\mathbb{R}^n} \int_{\mathbb{R}^n} \frac{|\varphi(x) - \varphi(y)|}{|x - y|^{n+2\beta}} |A_R(y, s)| dy dx
\]

We only estimate one of the previous integrals.

\[
\int_{\mathbb{R}^n} \int_{\mathbb{R}^n} \frac{|\varphi(x) - \varphi(y)|}{|x - y|^{n+2\beta}} |A_R(y, s)| dy dx \leq C \|\varphi\|_L^\infty \int_{\mathbb{R}^n} \int_{|x-y|>R} \frac{|A_R(y, s)|}{|x - y|^{n+2\beta}} dy dx
\]

\[
+ R^{-1} \int_{\mathbb{R}^n} \int_{|x-y|\leq R} \frac{|A_R(y, s)|}{|x - y|^{n+2\beta}} dy dx \leq C \|\varphi\|_L^\infty \|A_R(\cdot, s)||_{L^1} R^{-2\beta} + C \|A_R(\cdot, s)||_{L^1} R^{-2\beta} \leq C R^{-2\beta} \|A_{0,R}\|_{L^1}.
\]

With the other integral, we obtain

\[
\|L, \varphi\|A_R(\cdot, s)||_{L^1} \leq C(R^{-2\beta} + R^{-2\delta}) \|A_{0,R}\|_{L^1}.
\]

Finally, the case \(1 < p < +\infty\) is obtained by interpolation. See [8] or [18] for more details about interpolation.

For the remaining cases (c) and (d) (i.e. if \(\alpha = \beta = 1/2\) and \(0 < \delta < 1/2\) or \(\alpha = \beta = \delta = 1/2\)), the result will be a consequence of the Calderón’s commutator inequality (see [5]) and the maximum principle.

Now, getting back to the last term of (25) we have by the definition of \(\varphi\) and the properties of the operator \(L\) the estimate:

\[
\|M/2L\varphi\|_{L^p} \leq CM R_n^{n/p}(R^{-2\beta} + R^{-2\delta}).
\]

We thus have

\[
\|\varphi(\cdot)(A_R(\cdot, t) - M/2)\|_{L^p} \leq C(R^{-2\beta} + R^{-2\delta}) \int_0^t \left( \|A_{0,R}\|_{L^p} + MR_n^{n/p} \right) ds.
\]

Observe that we have at our disposal estimate (21), so we can write

\[
\|\varphi(\cdot)(A_R(\cdot, t) - M/2)\|_{L^p} \leq C(t)(R^{-2\beta} + R^{-2\delta}) \left( \|\psi_0\|_{L^p} + MR_n^{n/p} \right).
\]

Using again the definition of \(\varphi\) one has \(\int_{B(0,R)} |A_R(\cdot, t) - M/2| dx \leq C(R^{-2\beta} + R^{-2\delta}) \left( \|\psi_0\|_{L^p} + MR_n^{n/p} \right).\) Thus, if \(R \to +\infty\) and since \(p > \frac{n}{2\min(\beta, \delta)}\), we have \(A(x, t) = M/2\) over \(B(0, \rho)\).

Hence, by construction we have \(\psi(x, t) = A_R(x, t) + B_R(x, t)\) where \(\psi\) is a solution of (22) with initial data \(\psi_0 = A_{0,R} + B_{0,R}\), but, since over \(B(0, \rho)\) we have \(A(x, t) = M/2\) and \(\|B(\cdot, t)\|_{L^\infty} \leq M/2\), one finally has the desired estimate \(0 \leq \psi(x, t) \leq M\).

4 Existence of solutions with a \(L^\infty\) initial data

The proof given before for the positivity principle allows us to obtain the existence of solutions for the fractional diffusion transport equation (1) when the initial data \(\theta_0\) belongs to the space \(L^\infty(\mathbb{R}^n)\). The utility of this fact will
appear clearly in the next section as it will be used in Theorem 4.

Let us fix $\theta_0^R = \theta_0 \mathbf{1}_{(0,R)}$ with $R > 0$ so we have $\theta_0^R \in L^p(\mathbb{R}^n)$ for all $1 \leq p \leq +\infty$. Following section 2 there is a unique solution $\theta^R$ for the problem

\[
\begin{cases}
\partial_t \theta^R + \nabla \cdot (\nu \theta^R) + L \theta^R = 0 \\
\theta^R(x,0) = \theta_0^R(x) \\
div(v) = 0 \quad \text{and } v \in L^\infty([0,T]; bmo(\mathbb{R}^n)).
\end{cases}
\]

such that $\theta^R \in L^\infty([0,T]; L^p(\mathbb{R}^n))$. By the maximum principle we have $\|\theta^R(\cdot,t)\|_{L^p} \leq \|\theta_0^R\|_{L^p} \leq v_n \|\theta_0\|_{L^\infty} R^{n/p}$. Taking the limit $p \rightarrow +\infty$ and making $R \rightarrow +\infty$ we finally get

$$\|\theta(\cdot,t)\|_{L^\infty} \leq C \|\theta_0\|_{L^\infty}. $$

This shows that for an initial data $\theta_0 \in L^\infty(\mathbb{R}^n)$ there exists an associated solution $\theta \in L^\infty([0,T]; L^\infty(\mathbb{R}^n))$.

## Hölder Regularity

In this section we are going to prove Theorem 4. It is very important to note that we will work only with the cases (c) and (d): from now on the operator $L$ is assumed to be of the form (7) with an associated Lévy measure $\pi$ satisfying the hypothesis (4) and (5) with $\alpha = \beta = 1/2$ and $0 < \delta < 1/2$ or $\alpha = \beta = \delta = 1/2$.

We will now study Hölder regularity by duality using Hardy spaces. These spaces have several equivalent characterizations (see [3], [7] and [18] for a detailed treatment). In this paper we are interested mainly in the molecular approach that defines local Hardy spaces.

**Definition 5.1 (Local Hardy spaces $h^\sigma$)** Let $0 < \sigma < 1$. The local Hardy space $h^\sigma(\mathbb{R}^n)$ is the set of distributions $f$ that admits the following molecular decomposition:

$$f = \sum_{j \in \mathbb{N}} \lambda_j \psi_j$$

(27)

where $(\lambda_j)_{j \in \mathbb{N}}$ is a sequence of complex numbers such that $\sum_{j \in \mathbb{N}} |\lambda_j|^\sigma < +\infty$ and $(\psi_j)_{j \in \mathbb{N}}$ is a family of $r$-molecules in the sense of definition 5.2 below. The $h^\sigma$-norm is then fixed by the formula

$$\|f\|_{h^\sigma} = \inf \left\{ \left( \sum_{j \in \mathbb{N}} |\lambda_j|^\sigma \right)^{1/\sigma} : f = \sum_{j \in \mathbb{N}} \lambda_j \psi_j \right\}$$

where the infimum runs over all possible decompositions (27).

Local Hardy spaces have many remarkable properties and we will only stress here, before passing to duality results concerning $h^\sigma$ spaces, the fact that Schwartz class $\mathcal{S}(\mathbb{R}^n)$ is dense in $h^\sigma(\mathbb{R}^n)$.

Now, let us take a closer look at the dual space of the local Hardy spaces. In [7] D. Goldberg proved the following important theorem:

**Theorem 8 (Hardy-Hölder duality)** Let $0 < \sigma < 1$ and fix $\gamma = n(\frac{1}{\sigma} - 1)$. Then the dual of local Hardy space $h^\sigma(\mathbb{R}^n)$ is the Hölder space $C^\gamma(\mathbb{R}^n)$ fixed by the norm

$$\|f\|_{C^\gamma} = \|f\|_{L^\infty} + \sup_{x \neq y} \frac{|f(x) - f(y)|}{|x - y|^{\gamma}}.$$  

This result allows us to study the Hölder regularity of functions in terms of Hardy spaces and it will be applied to the solutions of the equation (1).

**Remark 5.1** Since $\frac{n}{n+1} < \sigma < 1$, we have $\sum_{j \in \mathbb{N}} |\lambda_j| \leq \left( \sum_{j \in \mathbb{N}} |\lambda_j|^\sigma \right)^{1/\sigma}$ thus for testing Hölder continuity of a function $f$ it is enough to study the quantities $|\langle f, \psi_j \rangle|$ where $\psi_j$ is an $r$-molecule.

---

\[\text{[2]}\text{It is not actually a norm since } 0 < \sigma < 1. \text{ More details can be found in [7] and [18].}\]
Since we are going to work with local Hardy spaces, we will introduce a size threshold in order to distinguish small molecules from big ones in the following way:

**Definition 5.2** (*r*-molecules) Set \( \sigma < \sigma < 1 \), define \( \gamma = \frac{1}{\sigma} - 1 \) and fix a real number \( \omega \) such that \( 0 < \gamma < \omega < 1 \).

An integrable function \( \psi \) is an *r*-molecule if we have

- Small molecules \((0 < r < 1)\):
  \[
  \int_{\mathbb{R}^n} |\psi(x)||x-x_0|^{\omega}dx \leq r^{\omega-\gamma}, \text{ for } x_0 \in \mathbb{R}^n 
  \]
  (concentration condition) \( (28) \)

  \[
  \|\psi\|_{L^\infty} \leq \frac{1}{r^{\gamma+\gamma}}
  \]
  (height condition) \( (29) \)

  \[
  \int_{\mathbb{R}^n} \psi(x)dx = 0 
  \]
  (moment condition) \( (30) \)

- Big molecules \((1 \leq r < +\infty)\):

In this case we only require conditions \( (28) \) and \( (29) \) for the *r*-molecule \( \psi \) while the moment condition \( (30) \) is dropped.

**Remark 5.2**

1) Note that the point \( x_0 \in \mathbb{R}^n \) can be considered as the “center” of the molecule.

2) Conditions \( (28) \) and \( (29) \) imply the estimate \( \|\psi\|_{L^1} \leq C r^{-\gamma} \) thus every *r*-molecule belongs to \( L^p(\mathbb{R}^n) \) with \( 1 < p < +\infty \).

3) In this definition, we find convenient to show explicitly the dependence on the Hölder parameter \( \gamma \) instead of \( \sigma \).

The main interest of using molecules relies in the possibility of transferring the regularity problem to the evolution of such molecules:

**Proposition 5.1** (Transfer property) Let \( \psi(x,s) \) be a solution of the backward problem

\[
\begin{cases}
\partial_s \psi(x,s) = -\nabla \cdot [v(x,t-s)\psi(x,s)] - L\psi(x,s) \\
\psi(x,0) = \psi_0(x) \in L^1 \cap L^\infty(\mathbb{R}^n) \\
div(v) = 0 \text{ and } v \in L^\infty([0,T[;bmo(\mathbb{R}^n))
\end{cases}
\]

If \( \theta(x,t) \) is a solution of \( (7) \) with \( \theta_0 \in L^\infty(\mathbb{R}^n) \) then we have the identity

\[
\int_{\mathbb{R}^n} \theta(x,t)\psi(x,0)dx = \int_{\mathbb{R}^n} \theta(x,0)\psi(x,t)dx.
\]

**Proof.** We first consider the expression

\[
\partial_s \int_{\mathbb{R}^n} \theta(x,t-s)\psi(x,s)dx = \int_{\mathbb{R}^n} \partial_s \theta(x,t-s)\psi(x,s) + \partial_s \psi(x,s)\theta(x,t-s)dx.
\]

Using equations \( (11) \) and \( (31) \) we obtain

\[
\partial_s \int_{\mathbb{R}^n} \theta(x,t-s)\psi(x,s)dx = -\int_{\mathbb{R}^n} \nabla \cdot [(v(x,t-s)\theta(x,t-s))\psi(x,s) + \mathcal{L}\theta(x,t-s)\psi(x,s)]
\]

\[
= -\nabla \cdot [(v(x,t-s)\psi(x,s))] \theta(x,t-s) - \mathcal{L}\psi(x,s)\theta(x,t-s)dx.
\]

Now, using the fact that \( v \) is divergence free and the symmetry of the operator \( \mathcal{L} \) we have that the expression above is equal to zero, so the quantity

\[
\int_{\mathbb{R}^n} \theta(x,t-s)\psi(x,s)dx
\]

remains constant in time. We only have to set \( s = 0 \) and \( s = t \) to conclude. \( \blacksquare \)
This proposition says, that in order to control \( \langle \theta(\cdot, t), \psi_0 \rangle \), it is enough (and much simpler) to study the bracket \( \langle \theta_0, \psi(\cdot, t) \rangle \).

Proof of Theorem 4 Once we have the transfer property proven above, the proof of Theorem 4 is quite direct and it reduces to a \( L^1 \) estimate for molecules. Indeed, assume that for all molecular initial data \( \psi_0 \) we have a \( L^1 \) control for \( \psi(\cdot, t) \) a solution of (31), then Theorem 4 follows easily: applying Proposition 5.1 with the fact that \( \theta_0 \in L^\infty(\mathbb{R}^n) \) we have

\[
|\langle \theta(\cdot, t), \psi_0 \rangle| = \left| \int_{\mathbb{R}^n} \theta(x, t)\psi_0(x)dx \right| = \left| \int_{\mathbb{R}^n} \theta(x, 0)\psi(x, t)dx \right| \leq \|\theta_0\|_{L^\infty} \|\psi(\cdot, t)\|_{L^1} < +\infty. \tag{32}
\]

From this, we obtain that \( \theta(\cdot, t) \) belongs to the Hölder space \( C^\gamma(\mathbb{R}^n) \).

Now we need to study the control of the \( L^1 \) norm of \( \psi(\cdot, t) \) and we divide our proof in two steps following the molecule’s size. For the initial big molecules, i.e. if \( r \geq 1 \), the needed control is straightforward: apply the maximum principle and the remark 5.2 above to obtain

\[
\|\theta_0\|_{L^\infty} \|\psi(\cdot, t)\|_{L^1} \leq \|\theta_0\|_{L^\infty} \|\psi_0\|_{L^1} \leq C \frac{1}{r^\gamma} \|\theta_0\|_{L^\infty},
\]

but, since \( r \geq 1 \), we have that \( |\langle \theta(\cdot, t), \psi_0 \rangle| < +\infty \) for all big molecules.

In order to finish the proof of this theorem, it only remains to treat the \( L^1 \) control for small molecules. This is the most complex part of the proof and it is treated in the following theorem:

Theorem 9 For all small \( r \)-molecules (i.e. \( 0 < r < 1 \)), there exists a time \( T_0 > 0 \) such that we have the following control of the \( L^1 \)-norm.

\[
\|\psi(\cdot, t)\|_{L^1} \leq C T_0^{-\gamma} \quad (T_0 < t < T),
\]

with \( 0 < \gamma < 2\delta \leq 1 \).

This theorem will be proven in sections 5.1, 5.2 and 5.3.

Accepting for a while this result, we have then a good control over the quantity \( \|\psi(\cdot, t)\|_{L^1} \) for all \( 0 < r < 1 \) and getting back to (32) we obtain that \( |\langle \theta(\cdot, t), \psi_0 \rangle| \) is always bounded for \( T_0 < t < T \) and for any molecule \( \psi_0 \); we have proven by a duality argument the Theorem 4.

Let us now briefly explain the main steps of Theorem 9. We need to construct a suitable control in time for the \( L^1 \)-norm of the solutions \( \psi(\cdot, t) \) of the backward problem (31) where the initial data \( \psi_0 \) is a small \( r \)-molecule. This will be achieved by iteration in two different steps. The first step explains the molecules’ deformation after a very small time \( s_0 > 0 \), which is related to the size \( r \) by the bounds \( 0 < s_0 \leq \epsilon r \) with \( \epsilon \) a small constant. In order to obtain a control of the \( L^1 \) norm for larger times we need to perform a second step which takes as a starting point the results of the first step and gives us the deformation for another small time \( s_1 \), which is also related to the original size \( r \). Once this is achieved it is enough to iterate the second step as many times as necessary to get rid of the dependence of the times \( s_0, s_1, \ldots \) from the molecule’s size. This way we obtain the \( L^1 \) control needed for all time \( T_0 < t < T \).

5.1 Small time molecule’s evolution: First step

The following theorem shows how the molecular properties are deformed with the evolution for a small time \( s_0 \).

Theorem 10 Set \( \sigma, \gamma \) and \( \omega \) three real numbers such that \( \frac{\sigma}{\sigma + 1} < \sigma < 1 \), \( \gamma = n(\frac{1}{\sigma} - 1) \) and \( 0 < \gamma < \omega < 2\delta < 1 \) in the case (c) or \( 0 < \gamma < \omega < 1 \) in the case (d). Let \( \psi(x, s_0) \) be a solution of the problem

\[
\begin{aligned}
\partial_{s_0} \psi(x, s_0) &= -\nabla \cdot (v \psi)(x, s_0) - L\psi(x, s_0) \\
\psi(x, 0) &= \psi_0(x) \\
\text{div}(v) &= 0 \quad \text{and} \quad v \in L^\infty([0, T]; bmo(\mathbb{R}^n)) \quad \text{with} \quad \sup_{s_0 \in [0, T]} \|v(\cdot, s_0)\|_{bmo} \leq \mu
\end{aligned} \tag{33}
\]

If \( \psi_0 \) is a small \( r \)-molecule in the sense of definition 5.2 for the local Hardy space \( h^\sigma(\mathbb{R}^n) \), then there exists a positive constant \( K = K(\mu) \) big enough and a positive constant \( \epsilon \) such that for all \( 0 < s_0 \leq \epsilon r \) small we have the following
thus by linearity we have

\[ \int_{\mathbb{R}^n} |\psi(x, s_0)||x - x(s_0)|^\omega dx \leq (r + K s_0)^{\omega - \gamma} \]  

(34)

\[ \|\psi(\cdot, s_0)\|_{L^\infty} \leq \frac{1}{(r + K s_0)^{n+\gamma}} \]  

(35)

\[ \|\psi(\cdot, s_0)\|_{L^1} \leq \frac{\nu_n}{(r + K s_0)^{\gamma}} \]  

(36)

where \( \nu_n \) denotes the volume of the \( n \)-dimensional unit ball.

The new molecule’s center \( x(s_0) \) used in formula [32] is fixed by

\[
\begin{aligned}
x'(s_0) &= \nabla B_r = \frac{1}{|B_r|} \int_{B_r} v(y, s_0) dy \quad \text{where } B_r = B(x(s_0), r). \\
x(0) &= x_0.
\end{aligned}
\]  

(37)

**Remark 5.3**

1) The definition of the point \( x(s_0) \) given by [37] reflects the molecule’s center transport using velocity \( v \).

2) Remark that it is enough to treat the case \( 0 < (r + K s_0) < 1 \) since \( s_0 \) is small: otherwise the \( L^1 \) control will be trivial for time \( s_0 \) and beyond: we only need to apply the maximum principle.

The proof of this theorem follows the next scheme: the small concentration condition [34], which is proven in the Proposition 5.2 implies the height condition [35] (proved in Proposition 5.3). Once we have these two conditions, the \( L^1 \) estimate [36] will follow easily and this is proven in Proposition 5.4.

**Proposition 5.2 (Small time Concentration condition)** Under the hypothesis of Theorem 10, if \( \psi_0 \) is a small \( r \)-molecule, then the solution \( \psi(x, s) \) of [33] satisfies

\[ \int_{\mathbb{R}^n} |\psi(x, s_0)||x - x(s_0)|^\omega dx \leq (r + K s_0)^{\omega - \gamma} \]

for \( x(s_0) \in \mathbb{R}^n \) fixed by formula [37] and with \( 0 < s_0 \leq cr \).

**Proof.** Let us write \( \Omega_0(x) = |x - x(s_0)|^\omega \) and \( \psi(x) = \psi_+(x) - \psi_-(x) \) where the functions \( \psi_\pm(x) \geq 0 \) have disjoint support. We will note \( \psi_\pm(x, s_0) \) solutions of [38] with \( \psi_\pm(x, 0) = \psi_\pm(x) \). At this point, we use the positivity principle, thus by linearity we have

\[ |\psi(x, s_0)| = |\psi_+(x, s_0) - \psi_-(x, s_0)| \leq \psi_+(x, s_0) + \psi_-(x, s_0) \]

and we can write

\[ \int_{\mathbb{R}^n} |\psi(x, s_0)|\Omega_0(x)dx \leq \int_{\mathbb{R}^n} \psi_+(x, s_0)\Omega_0(x)dx + \int_{\mathbb{R}^n} \psi_-(x, s_0)\Omega_0(x)dx \]

so we only have to treat one of the integrals on the right side above. We have:

\[
\begin{aligned}
I &= \left| \partial_{s_0} \int_{\mathbb{R}^n} \Omega_0(x)\psi_+(x, s_0)dx \right| \\
&= \left| \int_{\mathbb{R}^n} \partial_{s_0} \Omega_0(x)\psi_+(x, s_0) + \Omega_0(x) \left[ -\nabla \cdot (v \psi_+(x, s_0)) - \mathcal{L}\psi_+(x, s_0) \right] dx \right| \\
&= \left| \int_{\mathbb{R}^n} -\nabla \Omega_0(x) \cdot x'(s_0)\psi_+(x, s_0) + \Omega_0(x) \left[ -\nabla \cdot (v \psi_+(x, s_0)) - \mathcal{L}\psi_+(x, s_0) \right] dx \right|
\end{aligned}
\]

Using the fact that \( v \) is divergence free, we obtain

\[ I = \left| \int_{\mathbb{R}^n} \nabla \Omega_0(x) \cdot (v \cdot x'(s_0))\psi_+(x, s_0) - \Omega_0(x)\mathcal{L}\psi_+(x, s_0) dx \right|. \]

Since the operator \( \mathcal{L} \) is symmetric and using the definition of \( x'(s_0) \) given in [37] we have

\[ I \leq c \int_{\mathbb{R}^n} \left| x - x(s_0) \right|^{\omega - 1} |v - \nabla B_r| \|\psi_+(x, s_0)\| dx + c \int_{\mathbb{R}^n} \|\mathcal{L}\Omega_0(x)\| |\psi_+(x, s_0)| dx. \]

(38)

We will study separately each of the integrals \( I_1 \) and \( I_2 \) in the Lemmas 5.2 and 5.3 below. But before, we will need the following result
Lemma 5.1 Let $f \in bmo(\mathbb{R}^n)$, then

1) for all $1 < p < +\infty$, $f$ is locally in $L^p$ and
$$\frac{1}{|B|} \int_B |f(x) - f_B|^p dx \leq C\|f\|_{bmo}^p$$

2) for all $k \in \mathbb{N}$, we have $|f_{2^k} - f_B| \leq Ck\|f\|_{bmo}$ where $2^k B = B(x, 2^k R)$ is a ball centered at a point $x$ of radius $2^k R$.

For a proof of these results see [18].

Lemma 5.2 For integral $I_1$ above we have the estimate $I_1 \leq C\mu r^{n-1-\gamma}$.

Proof. We begin by considering the space $\mathbb{R}^n$ as the union of a ball with dyadic coronas centered around $x(s_0)$, more precisely we set $\mathbb{R}^n = B_r \cup \bigcup_{k \geq 1} E_k$ where

$$B_r = \{ x \in \mathbb{R}^n : |x - x(s_0)| \leq r \} \quad \text{and} \quad E_k = \{ x \in \mathbb{R}^n : r2^{k-1} < |x - x(s_0)| \leq r2^k \} \quad \text{for } k \geq 1,$$

(39)

(i) Estimations over the ball $B_r$. Applying Hölder’s inequality to the integral $I_{1,B_r}$ we obtain

$$I_{1,B_r} = \int_{B_r} |x - x(s_0)|^{\omega-1}|v - \nabla_{B_r}||\psi(x, s_0)|dx \leq \|x - x(s_0)|^{\omega-1}\|_{L^p(B_r)} \times \|v - \nabla_{B_r}\|_{L^p(B_r)} \|\psi(x, s_0)|_{L^p(B_r)} \tag{40}$$

where $\frac{1}{p} + \frac{1}{q} + \frac{1}{\omega} = 1$ and $p, q > 1$. We treat each of the previous terms separately:

- First observe that for $1 < p < n/(1 - \omega)$ we have for the term (1) above:
  $$\|x - x(s_0)|^{\omega-1}\|_{L^p(B_r)} \leq C r^n/p + \omega^{-1}.$$

- By hypothesis $v(x, s_0) \in bmo$ and applying the Lemma 5.1 we have $\|v - \nabla_{B_r}\|_{L^p(B_r)} \leq C|B_r|^{1/2}\|v(x, r2^k)\|_{bmo}$. Since $\sup_{s_0 \in [0, \tau]} v(x, s_0) \|_{bmo} \leq \mu$, we write for the term (2):
  $$\|v - \nabla_{B_r}\|_{L^p(B_r)} \leq C\mu r^{n/2}.$$

- Finally for (3) by the maximum principle we have $\|\psi(x, s_0)\|_{L^p(B_r)} \leq \|\psi(x, 0)\|_{L^p}$; hence using the fact that $\psi_0$ is an $r$-molecule and remark 5.2.2 we obtain
  $$\|\psi(x, s_0)\|_{L^p(B_r)} \leq C\left[r^{-\gamma}\right]^{1/p+\gamma} \left[\frac{1}{r^{\gamma-\omega}}\right]^{1-1/q}.$$  

We combine all these inequalities together in order to obtain the following estimation for (40):

$$I_{1,B_r} \leq C\mu r^{n-1-\gamma}.$$  

(ii) Estimations for the dyadic corona $E_k$. Let us note $I_{1,E_k}$ the integral

$$I_{1,E_k} = \int_{E_k} |x - x(s_0)|^{\omega-1}|v - \nabla_{B_r}||\psi(x, s_0)|dx.$$

Since over $E_k$ we have $|x - x(s_0)|^{\omega-1} \leq C2^{k(\omega-1)}r^{\omega-1}$ we write

$$I_{1,E_k} \leq C2^{k(\omega-1)}r^{\omega-1} \left(\int_{E_k} |v - \nabla_{B_{2^k}B_r}||\psi(x, s_0)|dx + \int_{E_k} |\nabla_{B_r} - \nabla_{B_{2^k}B_r}||\psi(x, s_0)|dx\right)$$

where we noted $B_{2^k} = B(x(s_0), r2^k)$, then

$$I_{1,E_k} \leq C2^{k(\omega-1)}r^{\omega-1} \left(\int_{B_{2^k}B_r} |v - \nabla_{B_{2^k}B_r}||\psi(x, s_0)|dx + \int_{B_{2^k}B_r} |\nabla_{B_r} - \nabla_{B_{2^k}B_r}||\psi(x, s_0)|dx\right).$$

\footnote{recall that $0 < \gamma < 2\delta \leq 1$.}
Now, since $v(\cdot, s_0) \in bmo(\mathbb{R}^n)$, using the Lemma 5.1 we have $|\nabla_{B_r} \cdot \nabla_{B_{2r}}| \leq Ck\|v(\cdot, s_0)\|_{bmo} \leq Ck\mu$ and we can write

$$I_{1,E_k} \leq C2^{k(\omega-1)}r^{\omega-1} \left( \int_{B_{2r}} |v - \nabla_{B_{2r}}| \psi(x, s_0) |dx + Ck\mu\|\psi(\cdot; s_0)\|_{L^1} \right) \leq C2^{k(\omega-1)}r^{\omega-1} \left( \|\psi(\cdot; s_0)\|_{L^n} |v - \nabla_{B_{2r}}| \frac{\omega-1}{\omega} + Ck\mu r^{-\gamma} \right)$$

where we used Hölder’s inequality with $1 < a_0 < \frac{n}{n+(\omega-1)}$ and maximum principle for the last term above. Using again the properties of $bmo$ spaces we have

$$I_{1,E_k} \leq C2^{k(\omega-1)}r^{\omega-1} \left( \|\psi(\cdot; 0)\|_{L^1}^{1/a_0} \|\psi(\cdot; 0)\|_{L^{\infty}}^{1-1/a_0} \|B_{2r}\|_{L^\infty} |v(\cdot, s)\|_{bmo} + Ck\mu r^{-\gamma} \right).$$

Let us now apply the estimates given by hypothesis for $\|\psi(\cdot; 0)\|_{L^1}$, $\|\psi(\cdot; 0)\|_{L^{\infty}}$ and $\|v(\cdot, s_0)\|_{bmo}$ to obtain

$$I_{1,E_k} \leq C2^{k(n-n/a_0+\omega-1)}r^{\omega-1-\gamma} \mu + C2^{k(\omega-1)}k\mu r^{\omega-1-\gamma}. \quad (42)$$

Since $1 < a_0 < \frac{n}{n+(\omega-1)}$, we have $n - n/a_0 + (\omega - 1) < 0$, so that, summing over each dyadic corona $E_k$, we have

$$\sum_{k\geq 1} I_{1,E_k} \leq C\mu r^{\omega-1-\gamma}. \quad (42)$$

Finally, gathering together the estimations (41) and (42) we obtain the desired conclusion. \( \square \)

**Lemma 5.3** For integral $I_2$ in inequality (31) we have the estimate $I_2 \leq Cr^{\omega-1-\gamma}$.

**Proof.** As for the Lemma 5.2 we consider $\mathbb{R}^n$ as the union of a ball with dyadic coronas centered on $x(s_0)$ (cf. (39)).

(i) **Estimations over the ball $B_r$.** We write, using the maximum principle and the hypothesis for $\|\psi(\cdot; 0)\|_{L^\infty}$:

$$I_{2,B_r} = \int_{B_r} |\mathcal{L}(|x - x(s_0)|^\omega)|\psi(x, s_0)|dx \leq \|\psi(x, s_0)\|_{L^{\infty}} \int_{B_r} |\mathcal{L}(|x - x(s_0)|^\omega)|dx \leq \|\psi(\cdot; s_0)\|_{L^n} \int_{|x| \leq r} |\mathcal{L}(|x - x(s_0)|^\omega)|dx.$$

We use now the hypothesis (11) and (13) for the function $\pi$ in the case (c), i.e. $\alpha = \beta = 1/2$ and $0 < \delta < 1/2$, in order to obtain

$$I_{2,B_r} \leq r^{-n-\gamma} \int_{|x| \leq r} \int_{|y| \leq 1} \frac{|x - y|^{\omega}}{|y|^{n+1}} dy \cdot d\mu(x) + r^{-n-\gamma} \int_{|x| \leq r} \int_{|y| > r} \frac{|x - y|^{\omega}}{|y|^{n+1}} dy \cdot d\mu(x). \quad (43)$$

We start studying the first term $I_{2,B_r}^1$ above. Recalling that

$$(-\Delta)^{1/2}(|x|^{\omega}) = v.p. \int_{\mathbb{R}^n} \frac{|x - y|^{\omega}}{|y|^{n+1}} dy = |x|^{-1}, \quad (44)$$

by homogeneity and using the fact that $0 < r < 1$ we obtain:

$$I_{2,B_r}^1 \leq r^{\omega+n-1} \left( \int_{|x| \leq 1} |x|^{\omega-1} dx + \int_{|y| > 1} \frac{|x - y|^{\omega}}{|y|^{n+1}} dy \right) = Cr^{\omega+n-1}. \quad (44)$$

For the second term $I_{2,B_r}^2$ we will proceed as follows. First, by homogeneity we obtain

$$I_{2,B_r}^2 = r^{\omega+n-2\delta} \int_{|x| \leq 1} \int_{\mathbb{R}^n} \frac{|x - y|^{\omega}}{|y|^{n+1}} dy \cdot d\mu(x).$$
Then we decompose this integral $I$ in the following way

$$I = \int_{|x| \leq 1} \int_{|y| \leq 1} \frac{|x|^\omega - |x-y|^\omega}{|y|^{n+2\delta}} dy dx + \int_{|x| \leq 1} \int_{|y| > 1} \frac{|x|^\omega - |x-y|^\omega}{|y|^{n+2\delta}} dy dx$$

$$\leq \int_{|x| \leq 1} \left( \sup_{0 < |y| < 1} \frac{|x|^\omega - |x-y|^\omega}{|y|} \right) \left( \int_{|y| \leq 1} |y|^{1-n-2\delta} dy \right) dx + \int_{|x| \leq 1} \left( \int_{|y| > 1} |y|^{\omega-n-2\delta} dy \right) dx$$

Since $0 < \gamma < \omega < 2\delta < 1$, it is not complicated to see that

$$I \leq C \int_{|x| \leq 1} \left( \sup_{0 < |y| < 1} \frac{|x|^\omega - |x-y|^\omega}{|y|} \right) dx + C \quad (45)$$

and that this latter quantity is bounded. Then, getting back to (43) we write $I_{2,B_r} \leq C(r^{\omega-\gamma-1} + r^{\omega-\gamma-2\beta})$. Recalling that we are working with small molecules, i.e. that $0 < r < 1$, we obtain $r^{\omega-2\beta-\gamma} \leq r^{\omega-1-\gamma}$, so we finally have

$$I_{2,B_r} \leq Cr^{\omega-\gamma-1}.$$  

The case (d), when $\alpha = \beta = \delta = 1/2$, is easier since $(-\Delta)^{1/2}(|x|^\omega) = |x|^{\omega-1}$. Thus, in any case we can write:

$$I_{2,B_r} = \int_{B_r} |L(x - s(0))|\psi_+(x, s_0) dx \leq C|x|^{\omega-1}.$$  

(ii) Estimations for the dyadic corona $E_k$. We start with the case (c) when $\alpha = \beta = 1/2$ and $0 < \delta < 1/2$:

$$I_{2,E_k} = \int_{E_k} |L(|x - s(0)|^\omega)\psi_+(x, s_0)| dx \leq \|\psi_+(\cdot, s_0)\|_{L^1} \sup_{x \in E_k} |L(|x - s(0)|^\omega)|$$

$$\leq r^{-\delta} \left( \sup_{r^{2^{k-1}} < |x| \leq r^{2^k}} v.p. \int_{|y| \leq 1} \frac{|x|^\omega - |x-y|^\omega}{|y|^{n+1}} dy \right) + \sup_{r^{2^{k-1}} < |x| \leq r^{2^k}} \frac{\int_{R^n} \frac{|x|^\omega - |x-y|^\omega}{|y|^{n+2\delta}} dy}{I_{2,E_k}^1}$$

Let us start with $I_{2,E_k^1}$, by homogeneity and using the formula (44) we obtain

$$I_{2,E_k^1} \leq \sup_{r^{2^{k-1}} < |x| \leq r^{2^k}} |x|^{\omega-1} + C(r^{2k})^{\omega-1} \left( \sup_{1 < |x| \leq 2} \frac{\int_{|y| > 1/r^{2^{k-1}}} \frac{|x|^\omega - |x-y|^\omega}{|y|^{n+1}} dy}{r^{2^{k-1}}} \right)$$

We only need to study the last term of this expression. If $0 < r^{2^{k-1}} \leq 1$, the integral above is immediately bounded by a constant. The case when $1 < r^{2^{k-1}}$ is treated as follows:

$$\sup_{1 < |x| \leq 2} \frac{\int_{|y| > 1/r^{2^{k-1}}} \frac{|x|^\omega - |x-y|^\omega}{|y|^{n+1}} dy}{r^{2^{k-1}}} \leq \sup_{1 < |x| \leq 2} \left( \sup_{0 < |y| < 1} \frac{\int_{|y| > 1/r^{2^{k-1}}} \frac{|x|^\omega - |x-y|^\omega}{|y|^{n+1}} dy}{|y|} \right)$$

Thus we obtain $I_{2,E_k^1} \leq C(r^{2k})^{\omega-1}(1 + \ln(2^{k-1}))$.

The term $I_{2,E_k^2}$ is easier: applying essentially the same ideas used in the formulas (43)-(45) above and by homogeneity we have $I_{2,E_k^2} \leq C(r^{2k})^{\omega-2\delta}$.

Finally, we obtain the following inequality for $I_{2,E_k}$:

$$I_{2,E_k} \leq Cr^{-\gamma}\left( (r^{2k})^{\omega-1}(1 + \ln(2^{k-1})) + (r^{2k})^{\omega-2\delta} \right)$$

Since $0 < \gamma < \omega < 2\delta < 1$, summing over $k \geq 1$, we obtain $\sum_{k \geq 1} I_{2,E_k} \leq Cr^{-\gamma}(r^{\omega-1} + r^{\omega-2\delta})$. Repeating the same argument used before (i.e. the fact that $0 < r < 1$), we finally obtain

$$\sum_{k \geq 1} I_{2,E_k} \leq C|x|^{\omega-1-\gamma}.$$  

(47)
The case (d) is straightforward since we have \( \mathcal{L} = (-\Delta)^{1/2} \) and \((-\Delta)^{1/2}(|x|^\omega) = |x|^{\omega - 1} \).

In order to finish the proof of Lemma 5.3, we combine together the estimates \((46)\) and \((47)\).

Now we continue the proof of the Proposition 5.2. Using the Lemmas 5.2 and 5.3 and getting back to estimate \((38)\) we have

\[
\left| \partial_s \int_{\mathbb{R}^n} \Omega_0(x) \psi_+ (x, s \psi) dx \right| \leq C (\mu + 1) r^{\omega - 1 - \gamma}.
\]

This last estimation is compatible with the estimate \((34)\) for \(0 \leq s_0 \leq \epsilon r\) small enough: just fix \(K\) such that

\[
C (\mu + 1) \leq K (\omega - \gamma).
\]

Indeed, since the time \(s_0\) is very small, we can linearize the formula \((r + K s_0)^{\omega - \gamma}\) in the right-hand side of \((34)\) in order to obtain

\[
\phi = (r + K s_0)^{\omega - \gamma} \approx r^{\omega - \gamma} \left( 1 + [K (\omega - \gamma) \frac{s_0}{r}] \right).
\]

Finally, taking the derivative with respect to \(s_0\) in the above expression we have \(\phi' \approx r^{\omega - 1 - \gamma} K (\omega - \gamma)\) and with condition \((48)\) Proposition 5.2 follows.

Now we will give a slightly different proof of the maximum principle of A. Córdoba & D. Córdoba. Indeed, the following proof only relies on the concentration condition proved in the lines above.

**Proposition 5.3 (Small time Height condition)** Under the hypothesis of Theorem 100 if \(\psi(x, s_0)\) satisfies the concentration condition \((33)\), then we have the following height condition

\[
\|\psi(\cdot, s_0)\|_{L^\infty} \leq \frac{1}{(r + K s_0)^{n+\gamma}}.
\]

**Proof.** Assume that molecules we are working with are smooth enough. Following an idea of \([3]\) (section 4 p.522-523) (see also \([3]\) p. 346), we will denote \(\mathcal{B}\) the point of \(\mathbb{R}^n\) such that \(\psi(\mathcal{B}, s_0) = \|\psi(\cdot, s_0)\|_{L^\infty}\). Thus we can write, by the properties of the function \(\pi\) (recall that we assumed \(\alpha = \beta = 1/2\) and \(0 < \delta < 1/2\) or \(\alpha = \beta = \delta = 1/2\):

\[
\frac{d}{ds_0} \|\psi(\cdot, s_0)\|_{L^\infty} \leq - \int_{\mathbb{R}^n} |\psi(\mathcal{B}, s_0) - \psi(\mathcal{B} - y, s_0)| \pi(y) dy \leq - \int_{\{|\mathcal{B} - y| < 1\}} \frac{|\psi(\mathcal{B}, s_0) - \psi(y, s_0)|}{|\mathcal{B} - y|^{n+1}} dy \leq 0.
\]

For simplicity, we will assume that \(\psi(\mathcal{B}, s_0)\) is positive. Let us consider the corona centered in \(\mathcal{B}\) defined by

\[
C(R_1, R_2) = \{ y \in \mathbb{R}^n : R_1 \leq |\mathcal{B} - y| \leq R_2 \}
\]

where \(1 > R_2 = \rho R_1\) with \(\rho > 2\) and where \(R_1\) will be fixed later. Then:

\[
\int_{\{|\mathcal{B} - y| < 1\}} \frac{\psi(\mathcal{B}, s_0) - \psi(y, s_0)}{|\mathcal{B} - y|^{n+1}} dy \geq \int_{C(R_1, R_2)} \frac{\psi(\mathcal{B}, s_0) - \psi(y, s_0)}{|\mathcal{B} - y|^{n+1}} dy.
\]

Define the sets \(B_1\) and \(B_2\) by \(B_1 = \{ y \in C(R_1, R_2) : \psi(\mathcal{B}, s_0) - \psi(y, s_0) \geq \frac{1}{2} \psi(\mathcal{B}, s_0) \}\) and \(B_2 = \{ y \in C(R_1, R_2) : \psi(\mathcal{B}, s_0) - \psi(y, s_0) < \frac{1}{2} \psi(\mathcal{B}, s_0) \}\) such that \(\overline{C(R_1, R_2)} = B_1 \cup B_2\).

We obtain the inequalities

\[
\int_{C(R_1, R_2)} \frac{\psi(\mathcal{B}, s_0) - \psi(y, s_0)}{|\mathcal{B} - y|^{n+1}} dy \geq \int_{B_1} \frac{\psi(\mathcal{B}, s_0) - \psi(y, s_0)}{|\mathcal{B} - y|^{n+1}} dy \geq \frac{\psi(\mathcal{B}, s_0)}{2 R_2^{n+1}} |B_1| = \frac{\psi(\mathcal{B}, s_0)}{2 R_2^{n+1}} (|C(R_1, R_2)| - |B_2|).
\]

Since \(R_2 = \rho R_1\) one has

\[
\int_{C(R_1, R_2)} \frac{\psi(\mathcal{B}, s_0) - \psi(y, s_0)}{|\mathcal{B} - y|^{n+1}} dy \geq \frac{\psi(\mathcal{B}, s_0)}{2 \rho^{n+1} R_1^{n+1}} \left( v_n (\rho^n - 1) R_1^n - |B_2| \right)
\]

where \(v_n\) denotes the volume of the \(n\)-dimensional unit ball.

Now, we will estimate the quantity \(|B_2|\) in terms of \(\psi(\mathcal{B}, s_0)\) and \(R_1\) with the following lemma.

**Lemma 5.4** For the set \(B_2\) we have the following estimations

20
1) if $|\Psi - x(s_0)| > 2R_2$ then $C_1 (r + Ks_0)^{\omega-\gamma} \psi(\Psi, s_0)^{-1} R_1^{\omega} \geq |B_2|$.

2) if $|\Psi - x(s_0)| < R_1/2$ then $C_1 (r + Ks_0)^{\omega-\gamma} \psi(\Psi, s_0)^{-1} R_1^{\omega} \geq |B_2|$.

3) if $R_1/2 \leq |\Psi - x(s_0)| \leq 2R_2$ then $(C_2(r + Ks_0)^{\omega-\gamma} \psi(\Psi, s_0)^{-1})^{1/2} \geq |B_2|$.

Recall that for the molecule’s center $x_0 \in \mathbb{R}^n$ we noted its transport by $x(s_0)$ which is defined by formula (37).

**Proof.** For all these estimates, our starting point is the concentration condition (34):

$$(r + Ks_0)^{\omega-\gamma} \geq \int_{\mathbb{R}^n} |\psi(y, s_0)||y - x(s_0)|^{\omega} dy \geq \int_{B_2} |\psi(y, s_0)||y - x(s_0)|^{\omega} dy \geq \frac{\psi(\Psi, s_0)\int_{B_2} |y - x(s_0)|^{\omega} dy}{2}. $$

We just need to estimate the last integral following the cases given by the lemma. The first two cases are very similar. Indeed, if $|\Psi - x(s_0)| > 2R_2$ then we have

$$\min_{y \in B_2 \subset C(R_1, R_2)} |y - x(s_0)|^{\omega} \geq R_2^{\omega} \geq \frac{R_1^{\omega}}{2}. $$

while for the second case, if $|\Psi - x(s_0)| < R_1/2$, one has

$$\min_{y \in B_2 \subset C(R_1, R_2)} |y - x(s_0)|^{\omega} \geq \frac{R_1^{\omega}}{2}. $$

Applying these results to (52) we obtain $(r + Ks_0)^{\omega-\gamma} \geq \frac{\psi(\Psi, s_0)r^{\omega} R_1^{\omega}}{2 |B_2|}$ and $(r + Ks_0)^{\omega-\gamma} \geq \frac{\psi(\Psi, s_0) R_1^{\omega}}{2 |B_2|}$, and since $\rho > 2$ we have the desired estimate

$$C_1 (r + Ks_0)^{\omega-\gamma} \psi(\Psi, s_0) R_1^{\omega} \geq 2(r + Ks_0)^{\omega-\gamma} \frac{\rho^{\omega} \psi(\Psi, s_0) R_1^{\omega}}{2 |B_2|} \geq |B_2|$$

with $C_1 = 2^{1+\omega}$.

(52)

For the last case, since $R_1/2 \leq |\Psi - x(s_0)| \leq 2R_2$ we can write using the Cauchy-Schwarz inequality

$$\int_{B_2} |y - x(s_0)|^{\omega} dy \geq |B_2|^{\omega/2} \left( \frac{1}{|B_2|} \int_{B_2} |y - x(s_0)|^{\omega} dy \right)^{-1} $$

(53)

Now, observe that in this case we have $B_2 \subset B(x(s_0), 5R_2)$ and then

$$\int_{B_2} |y - x(s_0)|^{\omega} dy \leq \int_{B(x(s_0), 5R_2)} |y - x(s_0)|^{\omega} dy \leq v_n (5\rho R_1)^{n-\omega}.$$

Getting back to (53) we obtain

$$\int_{B_2} |y - x(s_0)|^{\omega} dy \geq \frac{1}{|B_2|^{\omega/2}} v_n^{-1} (5\rho R_1)^{-n+\omega} $$

We use this estimate in (52) to obtain

$$C_2 (r + Ks_0)^{\omega/2-\gamma/2} R_1^{n/2-\omega/2} \frac{\psi(\Psi, s_0)^{1/2}}{\psi(\Psi, s_0)^{1/2}} \geq |B_2|,$$

(54)

where $C_2 = (2 \times 5^{n-\omega} v_n \rho^{n-\omega})^{1/2}$. The lemma is proven.

With estimates (52) and (54) at our disposal we can write

(i) if $|\Psi - x(s_0)| > 2R_2$ or $|\Psi - x(s_0)| < R_1/2$ then

$$\int_{C(R_1, R_2)} \frac{\psi(\Psi, s_0) - \psi(y, s_0)}{|\Psi - y|^{n+1}} dy \geq \frac{\psi(\Psi, s_0)}{2 \rho^{n-1} R_1^{1/2}} \left( v_n (\rho^n - 1) R_1^n - C_1 (r + Ks_0)^{\omega-\gamma} \frac{\psi(\Psi, s_0)^{-1}}{R_1^{\omega}} \right).$$

(ii) if $R_1/2 \leq |\Psi - x(s_0)| \leq 2R_2$

$$\int_{C(R_1, R_2)} \frac{\psi(\Psi, s_0) - \psi(y, s_0)}{|\Psi - y|^{n+1}} dy \geq \frac{\psi(\Psi, s_0)}{2 \rho^{n+1} R_1^{n+1}} \left( v_n (\rho^n - 1) R_1^n - C_2 (r + Ks_0)^{\omega/2-\gamma/2} R_1^{n/2-\omega/2} \frac{\psi(\Psi, s_0)^{-1}}{\psi(\Psi, s_0)^{1/2}} \right).$$
Now, if we set \( R_1 = (r + Ks_0)^{(\frac{\omega-\gamma}{\omega+\gamma})} \) \( \psi(\tau, s_0) \) where \( \rho \) is big enough such that \( \frac{\omega-\gamma}{\omega+\gamma} < 1 \) is a small positive constant. Now, and for all possible cases considered before, we have the following estimate for (53):

\[
\frac{d}{ds_0} \| \psi(\cdot, s_0) \|_{L^\infty} \leq -C(r + Ks_0)^{-\frac{\omega-\gamma}{\omega+\gamma}} \| \psi(\cdot, s_0) \|_{L^\infty}^{1+\frac{\omega-\gamma}{\omega+\gamma}}.
\]

Solving this differential inequality with initial data \( \| \psi(\cdot, 0) \|_{L^\infty} \leq r^{-n-\gamma} \), we obtain \( \| \psi(\cdot, s_0) \|_{L^\infty} \leq (r + Ks_0)^{-(n+\gamma)} \).

The proof of Proposition 5.3 is finished for regular molecules. In order to obtain the global result, remark that, for viscosity solutions (10), we have \( \Delta \theta(\tau, s_0) \leq 0 \) at the points \( \tau \) where \( \theta(\cdot, s_0) \) reaches its maximum value. See [6] for more details.

We treat now the last part of Theorem 10.

**Proposition 5.4 (First \( L^1 \) estimate)** If \( \psi(x, s_0) \) is a solution of the problem (55), then we have the following \( L^1 \)-norm estimate:

\[
\| \psi(\cdot, s_0) \|_{L^1} \leq \frac{v_n}{(r + Ks_0)^\gamma}.
\]

**Proof.** We write

\[
\int_{\mathbb{R}^n} |\psi(x, s_0)| dx = \int_{\{x-x(s_0) < D\}} |\psi(x, s_0)| dx + \int_{\{x-x(s_0) \geq D\}} |\psi(x, s_0)| dx 
\leq v_n D^n \| \psi(\cdot, s_0) \|_{L^\infty} + D^{-\gamma} \int_{\mathbb{R}^n} |\psi(x, s_0)| |x - x(s_0)|^\gamma dx
\]

Now using (33) and (34) one has:

\[
\int_{\mathbb{R}^n} |\psi(x, s_0)| dx \leq v_n \frac{D^n}{(r + Ks_0)^{n+\gamma}} + D^{-\omega}(r + Ks_0)^{\omega-\gamma}
\]

where \( v_n \) denotes the volume of the unit ball. To continue, it is enough to choose correctly the real parameter \( D \) to obtain

\[
\| \psi(\cdot, s_0) \|_{L^1} \leq \frac{v_n}{(r + Ks_0)}
\]

\[\blacksquare\]

### 5.2 Molecule’s evolution: Second step

In the previous section we have obtained deformed molecules after a very small time \( s_0 \). The next theorem shows us how to obtain similar profiles in the inputs and the outputs in order to perform an iteration in time.

Recall that we consider here a Lévy-type operator \( L \) of the form (7) with an associate Lévy measure \( \pi \) that satisfies hypothesis (1) and (5) with the following values of the parameters \( \alpha, \beta, \delta \):

- (c) \( \alpha = \beta = 1/2 \) and \( 0 < \delta < 1/2 \),
- (d) \( \alpha = \beta = \delta = 1/2 \).

**Theorem 11** Set \( \gamma \) and \( \omega \) two real numbers such that \( 0 < \gamma < \omega < 2\delta < 1 \) in the case (c) or \( 0 < \gamma < \omega < 1 \) in the case (d). Let \( 0 < s_1 \leq T \) and let \( \psi(x, s_1) \) be a solution of the problem

\[
\begin{align*}
\partial_t \psi(x, s_1) &= -\nabla \cdot (v(\psi)(x, s_1)) - L \psi(x, s_1) \\
\psi(x, 0) &= \psi(x, s_0) \quad \text{with } s_0 > 0 \\
div(v) &= 0 \quad \text{and } v \in L^\infty([0, T]; bmo(\mathbb{R}^n)) \quad \text{with } \sup_{s_1 \in [s_0, T]} \| v(\cdot, s_1) \|_{bmo} \leq \mu
\end{align*}
\]

(55)
If \( \psi(x, s_0) \) satisfies the three following conditions
\[
\int_{\mathbb{R}^n} |\psi(x, s_0)||x - x(s_0)|^{\omega} \, dx \leq (r + Ks_0)^{\omega-1}; \quad \|\psi(\cdot, s_0)\|_{L^\infty} \leq \frac{1}{(r + Ks_0)^{n+\gamma}}; \quad \|\psi(\cdot, s_0)\|_{L^1} \leq \frac{v_0}{(r + Ks_0)^{n}}
\]
where \( K = K(\mu) \) is given by (53) and \( s_0 \) is such that \((r + Ks_0) < 1\). Then for all \( 0 < s_1 \leq \epsilon r \) small, we have the following estimates
\[
\int_{\mathbb{R}^n} |\psi(x, s_1)||x - x(s_1)|^{\omega} \, dx \leq (r + K(s_0 + s_1))^{\omega-1} \quad (56)
\]
\[
\|\psi(\cdot, s_1)\|_{L^\infty} \leq \frac{1}{(r + K(s_0 + s_1))^{n+\gamma}} \quad (57)
\]
\[
\|\psi(\cdot, s_1)\|_{L^1} \leq \frac{v_0}{(r + K(s_0 + s_1))^{n}} \quad (58)
\]

Remark 5.4
1) Since \( s_1 \) is small and \((r + Ks_0) < 1\), we can without loss of generality assume that \((r + K(s_0 + s_1)) < 1\): otherwise, by the maximum principle there is nothing to prove.
2) The new molecule’s center \( x(s_1) \) used in formula (56) is fixed by
\[
\left\{ \begin{array}{l}
x'(s_1) = \nabla v_{B_{r_1}} = \frac{1}{|B_{r_1}|} \int_{B_{r_1}} v(y, s_1) \, dy \\
x(0) = x(s_0).
\end{array} \right. \quad (59)
\]

And here we noted \( B_{f_1} = B(x(s_1), f_1) \) with \( f_1 \) a real valued function given by
\[
f_1 = (r + Ks_0). \quad (60)
\]

Note that by remark 1) above we have \( 0 < f_1 < 1 \).

We will follow the same scheme as before: we prove the concentration condition (56), with this estimate at hand we will control the \( L^\infty \) decay in Proposition 5.6 and then we will obtain the suitable \( L^1 \) control in Proposition 5.7.

Proposition 5.5 (Concentration condition) Under the hypothesis of Theorem 11 if \( \psi(\cdot, s_0) \) is an initial data then the solution \( \psi(x, s_1) \) of (53) satisfies
\[
\int_{\mathbb{R}^n} |\psi(x, s_1)||x - x(s_1)|^{\omega} \, dx \leq (r + K(s_0 + s_1))^{\omega-1}
\]
for \( x(s_1) \in \mathbb{R}^n \) given by formula (59), with \( 0 \leq s_1 \leq \epsilon r \).

Proof. The calculations are very similar of those of Proposition 5.2 the only difference stems from the initial data and the definition of the center \( x(s_1) \). So, let us write \( \Omega_1(x) = |x - x(s_1)|^{\omega} \) and \( \psi(x) = \psi_+(x) - \psi_-(x) \) where the functions \( \psi_\pm(x) \geq 0 \) have disjoint support. Thus, by linearity and using the positivity principle we have
\[
|\psi(x, s_1)| = |\psi_+(x, s_1) - \psi_-(x, s_1)| \leq \psi_+(x, s_1) + \psi_-(x, s_1)
\]
and we can write
\[
\int_{\mathbb{R}^n} |\psi(x, s_1)| \Omega_1(x) \, dx \leq \int_{\mathbb{R}^n} \psi_+(x, s_1) \Omega_1(x) \, dx + \int_{\mathbb{R}^n} \psi_-(x, s_1) \Omega_1(x) \, dx
\]
so we only have to treat one of the integrals on the right-hand side above. We have:
\[
I = \left| \partial_{s_1} \int_{\mathbb{R}^n} \Omega_1(x) \psi_+(x, s_1) \, dx \right| = \left| \int_{\mathbb{R}^n} -\nabla \Omega_1(x) \cdot x'(s_1) \psi_+(x, s_1) + \Omega_1(x) \left[ -\nabla \cdot (v \psi_+(x, s_1)) - L \psi_+(x, s_1) \right] \, dx \right|
\]
Using the fact that \( v \) is divergence free, we obtain
\[
I = \left| \int_{\mathbb{R}^n} \nabla \Omega_1(x) \cdot (v - x'(s_1)) \psi_+(x, s_1) - \Omega_1(x) L \psi_+(x, s_1) \, dx \right|.
\]
Finally, using the definition of \( x'(s_1) \) given in (59) and replacing \( \Omega_1(x) \) by \( |x - x(s_1)|^{\omega} \) in the first integral we obtain
\[
I \leq c \int_{\mathbb{R}^n} |x - x(s_1)|^{\omega-1} |v - \nabla v_{B_{r_1}}| \psi_+(x, s_1) \, dx + c \int_{\mathbb{R}^n} |L \Omega_1(x)| |\psi_+(x, s_1)| \, dx. \quad (61)
\]
We will study separately each of the integrals \( I_1 \) and \( I_2 \) in the next lemma:
Lemma 5.5 For integral $I_1$ we have the estimate $I_1 \leq C \mu (r + KS_0)^{\omega - \gamma - 1}$.

Proof. We begin by considering the space $\mathbb{R}^n$ as the union of a ball with dyadic coronas centered on $x(s_1)$, more precisely we set $\mathbb{R}^n = B_{f_1} \cup \bigcup_{k \geq 1} E_k$ where

\begin{align*}
B_{f_1} &= \{ x \in \mathbb{R}^n : |x - x(s_1)| \leq f_1 \}, \\
E_k &= \{ x \in \mathbb{R}^n : f_1 2^{k-1} < |x - x(s_1)| \leq f_1 2^k \} \text{ for } k \geq 1.
\end{align*}

(i) Estimations over the ball $B_{f_1}$. Applying Hölder’s inequality on integral $I_1$ we obtain

\begin{align*}
I_{1,B_{f_1}} &= \int_{B_{f_1}} |x - x(s_1)|^{\omega - 1} |v - \varphi_{B_{f_1}}| |\psi_+(x, s_1)| dx \\
&\leq \left\| |x - x(s_1)|^{\omega - 1} \right\|_{L^p(B_{f_1})} \times \left\| v - \varphi_{B_{f_1}} \right\|_{L^q(B_{f_1})} \times \left\| \psi_+(\cdot, s_1) \right\|_{L^r(B_{f_1})}
\end{align*}

where $\frac{1}{p} + \frac{1}{q} + \frac{1}{r} = 1$ and $p, q, r > 1$. We treat each of the previous terms separately:

- Observe that for $1 < p < n/(1 - \omega)$ we have

  \[ \left\| |x - x(s_1)|^{\omega - 1} \right\|_{L^p(B_{f_1})} \leq C f_1^{n/p + \omega - 1}. \]

- We have $v(\cdot, s_1) \in bmo(\mathbb{R}^n)$, thus $\left\| v - \varphi_{B_{f_1}} \right\|_{L^q(B_{f_1})} \leq C |B_{f_1}|^{1/q} \left\| v(\cdot, s_1) \right\|_{bmo}$. Since $\sup_{s_1 \in [s_0, T]} \left\| v(\cdot, s_1) \right\|_{bmo} \leq \mu$ we write

  \[ \left\| v - \varphi_{B_{f_1}} \right\|_{L^q(B_{f_1})} \leq C f_1^{n/q} \mu. \]

- Finally, by the maximum principle for $L^2$ norms we have $\left\| \psi_+(\cdot, s_1) \right\|_{L^2(B_{f_1})} \leq \left\| \psi(\cdot, s_0) \right\|_{L^2}^{1/q} \left\| \psi(\cdot, s_0) \right\|_{L^\infty}^{1-1/q}$.

We combine all these inequalities in order to obtain the following estimation for $I_{1,B_{f_1}}$:

\[ I_{1,B_{f_1}} \leq C \mu f_1^{(1-1/q) + \omega - 1} \left\| \psi(\cdot, s_0) \right\|_{L^1}^{1/q} \left\| \psi(\cdot, s_0) \right\|_{L^\infty}^{1-1/q}. \]

(ii) Estimations for the dyadic corona $E_k$. Let us note $I_{1,E_k}$ the integral

\[ I_{1,E_k} = \int_{E_k} |x - x(s_1)|^{\omega - 1} |v - \varphi_{B_{f_1}}| |\psi_+(x, s_1)| dx. \]

Since over $E_k$ we have $|x - x(s_1)|^{\omega - 1} \leq C 2^{k(\omega - 1)} f_1^{\omega - 1}$ we write

\begin{align*}
I_{1,E_k} &\leq C 2^{k(\omega - 1)} f_1^{\omega - 1} \left( \int_{E_k} |v - \varphi_{B(f_1 2^k)}| |\psi_+(x, s_1)| dx + \int_{E_k} |\varphi_{B_{f_1}} - \varphi_{B(f_1 2^k)}| |\psi_+(x, s_1)| dx \right) \\
&\leq C 2^{k(\omega - 1)} f_1^{\omega - 1} \left( \int_{B(f_1 2^k)} |v - \varphi_{B(f_1 2^k)}| |\psi_+(x, s_1)| dx + \int_{B(f_1 2^k)} |\varphi_{B_{f_1}} - \varphi_{B(f_1 2^k)}| |\psi_+(x, s_1)| dx \right).
\end{align*}

where $B(f_1 2^k) = \{ x \in \mathbb{R}^n : |x - x(s_1)| \leq f_1 2^k \}$.

Now, since $v(\cdot, s_1) \in bmo(\mathbb{R}^n)$, using the Lemma 5.1 we have $|\varphi_{B_{f_1}} - \varphi_{B(f_1 2^k)}| \leq C_k |v(\cdot, s_1)|_{bmo} \leq C_k \mu$. We write

\begin{align*}
I_{1,E_k} &\leq C 2^{k(\omega - 1)} f_1^{\omega - 1} \left( \int_{B(f_1 2^k)} |v - \varphi_{B(f_1 2^k)}| |\psi_+(x, s_1)| dx + C_k \mu |\psi_+(\cdot, s_1)|_{L^2} \right) \\
&\leq C 2^{k(\omega - 1)} f_1^{\omega - 1} \left( \left\| \psi_+(\cdot, s_1) \right\|_{L^{\infty}} \left\| v - \varphi_{B(f_1 2^k)} \right\|_{L^\infty} + C_k \mu |\psi_+(\cdot, s_0)|_{L^1} \right).
\end{align*}
where we used Hölder’s inequality with $1 < a_0 < \frac{n}{n+(\omega-1)}$ and maximum principle for the last term above. Using again the properties of $bmo$ spaces we have

$$I_{1,E_k} \leq C 2^{k(\omega-1)} f_1^{\omega-1} \left( \|\psi_+ (\cdot, s_0)\|_{L^1}^{1/a_0} \|\psi_+ (\cdot, s_0)\|_{L^\infty}^{1-1/a_0} |B(f_1^{2k})|_{1-1/a_0} \|\psi (\cdot, s_1)\|_{bmo} + C k \mu \|\psi (\cdot, s_0)\|_{L^1} \right).$$

Since $\|\psi (\cdot, s_1)\|_{bmo} \leq \mu$ and since $1 < a_0 < \frac{n}{n+(\omega-1)}$, we have $n(1 - 1/a_0) + (\omega - 1) < 0$, so that, summing over each dyadic corona $E_k$, we obtain

$$\sum_{k \geq 1} I_{1,E_k} \leq C \mu \left( f_1^{n(1-1/a_0)+\omega-1} \|\psi (\cdot, s_0)\|_{L^1}^{1/a_0} \|\psi (\cdot, s_0)\|_{L^\infty}^{1-1/a_0} + f_1^{\omega-1} \|\psi (\cdot, s_0)\|_{L^1} \right).$$

We finally obtain the following inequalities:

$$I_1 = I_{1,B_{f_1}} + \sum_{k \geq 1} I_{1,E_k} \leq C \mu \left( f_1^{n(1-1/q)+\omega-1} \|\psi (\cdot, s_0)\|_{L^1}^{1/q} \|\psi (\cdot, s_0)\|_{L^\infty}^{1-1/q} \right) + C \mu \left( f_1^{n(1-1/a_0)+\omega-1} \|\psi (\cdot, s_0)\|_{L^1}^{1/a_0} \|\psi (\cdot, s_0)\|_{L^\infty}^{1-1/a_0} + f_1^{\omega-1} \|\psi (\cdot, s_0)\|_{L^1} \right).$$

Now we will prove that each of the terms (a), (b) and (c) above is bounded by the quantity $(r + K s_0)^{\omega-\gamma-1}$:

- for the first term (a) by the hypothesis on the initial data $\psi (\cdot, s_0)$ and the definition of $f_1$ given in (60) we have:
  $f_1^{n(1-1/q)+\omega-1} \|\psi (\cdot, s_0)\|_{L^1}^{1/q} \|\psi (\cdot, s_0)\|_{L^\infty}^{1-1/q} \leq (r + K s_0)^{n(1-1/q)+\omega-1} = (r + K s_0)^{\omega-\gamma-1}$.
- For the second term (b) we have, by the same arguments:
  $f_1^{n(1-1/a_0)+\omega-1} \|\psi (\cdot, s_0)\|_{L^1}^{1/a_0} \|\psi (\cdot, s_0)\|_{L^\infty}^{1-1/a_0} \leq (r + K s_0)^{n(1-1/a_0)+\omega-1} = (r + K s_0)^{\omega-\gamma-1}$.
- Finally, for the last term (c) we write
  $f_1^{\omega-1} \|\psi (\cdot, s_0)\|_{L^1} \leq f_1^{\omega-1} (r + K s_0)^{-\gamma} = (r + K s_0)^{\omega-\gamma-1}$.

Gathering these estimates on (a), (b) and (c), and getting back to (63) we finally obtain

$$I_1 \leq C \mu (r + K s_0)^{\omega-\gamma-1}.$$

The Lemma 5.5 is proven.

**Lemma 5.6** For integral $I_2$ in the inequality (71) we have the following estimate $I_2 \leq C (r + K s_0)^{\omega-\gamma-1}$.

**Proof.** As for the Lemma 5.5 we consider $\mathbb{R}^n$ as the union of a ball with dyadic coronas centered on $x(s_1)$ (cf. (62)).

1. **Estimations over the ball $B_{f_1}$**. We will follow closely the computations of the Lemma 5.5. We write:

$$I_{2,B_{f_1}} = \int_{B_{f_1}} |\mathcal{L}(|x - x(s_1)|^{\omega})| |\psi_+ (x, s_1)| \, dx \leq \|\psi_+ (\cdot, s_1)\|_{L^\infty} \int_{B_{f_1}} |\mathcal{L}(|x - x(s_1)|^{\omega})| \, dx \leq \|\psi_+ (\cdot, s_0)\|_{L^\infty} \int_{|x| \leq f_1} \left| \psi_{+} (\cdot, s_0) \right| \omega \left| x - y \right| dy \, dx.$$

In the case (c) when $\alpha = \beta = 1/2$ and $\delta < 1/2$ we write:

$$I_{2,B_{f_1}} \leq \|\psi_+ (\cdot, s_0)\|_{L^\infty} \int_{|x| \leq f_1} \left| \psi_{+} (\cdot, s_0) \right| \omega \left| x - y \right| dy \, dx \leq \int_{|x| \leq f_1} \int_{|y| \leq 1} \frac{\left| x - y \right|^\omega}{|y|^{n+1}} dy \, dx + \int_{|x| \leq f_1} \int_{\mathbb{R}^n} \frac{\left| x - y \right|^\omega}{|y|^{n+2\delta}} dy \, dx.$$

Following exactly the same arguments used in Lemma 5.5 with the formulas (63)-(65), i.e. essentially by homogeneity, we have

$$I_{2,B_{f_1}} \leq C \|\psi_+ (\cdot, s_0)\|_{L^\infty} \left( f_1^{n+\omega-1} + f_1^{n+\omega-2\delta} \right).$$
Since \( 0 < 2\delta < 1 \), recalling that by the definition of the function \( f_1 \) we have the estimate \( 0 < f_1 < 1 \), we obtain \( f_1^{\omega - 2\delta - \gamma} \leq f_1^{\omega - 1 - \gamma} \). The case (d) is straightforward since \( \mathcal{L} = (-\Delta)^{1/2} \) and \( (-\Delta)^{1/2}(|x|^\omega) = |x|^{\omega - 1} \).

Thus, in any case, we can write:

\[
I_{2, B_f} \leq C f_1^{n+\omega-1} \| \psi_+ (., s_0) \| L^\infty. \tag{64}
\]

(ii) Estimations for the dyadic corona \( E_k \). Here we have

\[
I_{2, E_k} = \int_{E_k} \left| \mathcal{L}(|x - x(s_1)|^\omega) \right| \| \psi_+ (x, s_1) \| dx \leq \| \psi_+ (., s_0) \|_{L^1} \sup_{f_1^{2k-1} < |x| \leq f_1^{2k}} \left( \text{v.p.} \int_{|y| \leq 1} \frac{|x|^\omega - |x - y|^\omega}{|y|^n} dy \right) + \int_{\mathbb{R}^n} \frac{|x|^\omega - |x - y|^\omega}{|y|^{n+\delta}} dy.
\]

In the case (c) we have:

\[
I_{2, E_k} \leq \| \psi_+ (., s_0) \|_{L^1} \sup_{f_1^{2k-1} < |x| \leq f_1^{2k}} \left( \text{v.p.} \int_{|y| \leq 1} \frac{|x|^\omega - |x - y|^\omega}{|y|^n} dy \right) + \int_{\mathbb{R}^n} \frac{|x|^\omega - |x - y|^\omega}{|y|^{n+2\delta}} dy.
\]

Again, by homogeneity and following the same lines of the Lemma 5.3 above, we have

\[
I_{2, E_k} \leq C \| \psi_+ (., s_0) \|_{L^1} \left( f_1^{2k-1} \omega^{1-\omega} (1 + \ln(2^{k-1})) + f_1^{2k} \omega^{-2\delta} \right)
\]

Since \( 0 < \gamma < \omega < 2\delta < 1 \) we have \( \omega - 1 < 0 \) and \( \omega - 2\delta < 0 \) and thus, summing over \( k \geq 1 \), we obtain

\[
\sum_{k \geq 1} I_{2, E_k} \leq C \left( f_1^0 + f_1^{\omega-2\delta} \right) \| \psi (., s_0) \|_{L^1}.
\]

Repeating the same argument used before (i.e. the fact that \( 0 < f_1 < 1 \)), we finally get

\[
\sum_{k \geq 1} I_{2, E_k} \leq C f_1^{\omega-1} \| \psi (., s_0) \|_{L^1}. \tag{65}
\]

For the case (d), we obtain the same inequality by homogeneity.

To finish the proof of the Lemma 5.6 we combine (64) and (65) and we obtain

\[
I_2 = I_{2, B_f} + \sum_{k \geq 1} I_{2, E_k} \leq C \left( f_1^{n+\omega-1} \| \psi_+ (., s_0) \|_{L^\infty} + f_1^{\omega-1} \| \psi (., s_0) \|_{L^1} \right).
\]

Now, we prove that the quantities (d) and (e) can be bounded by \((r + Ks_0)^{\omega-\gamma-1}\).

- For the term (d) we write \( f_1^{n+\omega-1} \| \psi (., s_0) \|_{L^\infty} \leq f_1^{n+\omega-1} (r + Ks_0)^{-\gamma} = (r + Ks_0)^{\omega-\gamma-1} \).
- To treat the term (e) it is enough to apply the same arguments used to prove the part (c) above.

Finally, we obtain

\[
I_2 = I_{2, B_f} + \sum_{k \geq 1} I_{2, E_k} \leq C (r + Ks_0)^{\omega-\gamma-1}
\]

The Lemma 5.6 is proven.

Now we continue the proof of the Proposition 5.5. Using the Lemmas 5.5 and 5.6 and getting back to the estimate (61) we have

\[
\left| \partial_s \int_{\mathbb{R}^n} \Omega_1(x) \psi_+(x, s_1) dx \right| \leq C (\mu + 1) (r + Ks_0)^{\omega-\gamma-1} \tag{66}
\]

This estimation is compatible with the estimate (58) for \( 0 \leq s_1 \leq \epsilon r \) small enough. Indeed, we can write \( \phi = \epsilon r + K(s_0 + s_1) \omega-\gamma \) and we linearize this expression with respect to \( s_1 \):

\[
\phi \approx (r + s_0)^{\omega-\gamma} \left( 1 + K (\omega - \gamma) \frac{s_1}{s_0} \right)
\]

Taking the derivative of \( \phi \) with respect to \( s_1 \) we have \( \phi' \approx K (\omega - \gamma) (r + Ks_0)^{\omega-\gamma-1} \) and with the condition (48) on \( K (\omega - \gamma) \) we obtain that (66) is bounded by \( \phi' \) and the Proposition 5.5 follows.

Now we write down the maximum principle for a small time \( s_1 \) but with an initial condition \( \psi (., s_0) \), with \( s_0 > 0 \).
Proposition 5.6 (Height condition) Under the hypothesis of Theorem 11, if \( \psi(x,s_1) \) satisfies the concentration condition (56), then we have the following height condition

\[
\|\psi(\cdot,s_1)\|_{L^\infty} \leq \frac{1}{(r + K(s_0 + s_1))^{n+\gamma}}.
\]

Proof. The proof follows essentially the same lines of the Proposition 5.3. Indeed, since we have assumed that the concentration condition (56) is bounded by \( (r + K(s_0 + s_1))^{\omega - \gamma} \), we obtain in the same manner and with the same constants:

\[
\frac{d}{ds_1}\|\psi(\cdot,s_1)\|_{L^\infty} \leq -C(r + K(s_0 + s_1))^{\omega - \gamma}\|\psi(\cdot,s_1)\|_{L^\infty}^{1 + \frac{\omega - \gamma}{n+\gamma}}.
\]

To conclude, it is enough to solve the previous differential inequality with initial data \( \|\psi(\cdot,0)\|_{L^\infty} \leq (r + Ks_0)^{-(n+\gamma)} \) to obtain that \( \|\psi(\cdot,s_1)\|_{L^\infty} \leq (r + K(s_0 + s_1))^{-(n+\gamma)} \).

The crucial part of the proof of Theorem 11 is given by the next proposition which gives us a control on the \( L^1 \)-norm for a time \( s_0 + s_1 \).

Proposition 5.7 (Second \( L^1 \)-norm estimate) Under the hypothesis of Theorem 11, we have

\[
\|\psi(\cdot,s_1)\|_{L^1} \leq \frac{v_n}{(r + K(s_0 + s_1))}
\]

Proof. This is a direct consequence of the concentration condition and of the previous height condition.

5.3 The iteration

In sections 5.1 and 5.2 we studied respectively the evolution of small molecules from time 0 to a small time \( s_0 \) and from this time \( s_0 \) to a larger time \( s_0 + s_1 \) and we obtained a good \( L^1 \) control for such molecules. It is now possible to reapply the previous Theorem 11 in order to obtain a larger time control of the \( L^1 \) norm. The calculus of the \( N \)-th iteration will be essentially the same.

Theorem 12 Set \( \gamma \) and \( \omega \) two real numbers such that \( 0 < \gamma < \omega < 2\delta < 1 \) in the case (c) or \( 0 < \gamma < \omega < 1 \) in the case (d). Let \( 0 < s_N \leq T \) and let \( \psi(x,s_N) \) be a solution of the problem

\[
\begin{aligned}
\partial_{s_N} \psi(x,s_N) &= -\nabla \cdot (v\psi)(x,s_N) - L\psi(x,s_N) \\
\psi(x,0) &= \psi(x,s_{N-1}) \quad \text{with } s_{N-1} > 0 \\
div(v) &= 0 \quad \text{and } v \in L^\infty([0,T];bmo(\mathbb{R}^n)) \quad \text{with } \sup_{s_N \in [s_{N-1},T]} \|v(\cdot,s_N)\|_{bmo} \leq \mu
\end{aligned}
\]

If \( \psi(x,s_{N-1}) \) satisfies the three following conditions

\[
\int_{\mathbb{R}^n} |\psi(x,s_{N-1})| |x - x(s_{N-1})|^\omega \, dx \leq (r + K(s_0 + \cdots + s_{N-1}))^{\omega - \gamma} \\
\|\psi(\cdot,s_{N-1})\|_{L^\infty} \leq \frac{1}{(r + K(s_0 + \cdots + s_{N-1}))^{n+\gamma}} \\
\|\psi(\cdot,s_{N-1})\|_{L^1} \leq \frac{v_n}{(r + K(s_0 + \cdots + s_{N-1}))}
\]

where \( K = K(\mu) \) is given by (43) and \( s_N \) is such that \( (r + K(s_0 + \cdots + s_N)) < 1 \). Then for all \( 0 < s_N \leq c \), small, we have the following estimates

\[
\int_{\mathbb{R}^n} |\psi(x,s_N)| |x - x(s_N)|^\omega \, dx \leq (r + K(s_0 + \cdots + s_N))^{\omega - \gamma} \\
\|\psi(\cdot,s_N)\|_{L^\infty} \leq \frac{1}{(r + K(s_0 + \cdots + s_N))^{n+\gamma}} \\
\|\psi(\cdot,s_N)\|_{L^1} \leq \frac{v_n}{(r + K(s_0 + \cdots + s_N))}
\]

Remark 5.5

1) Again, since \( s_N \) is small and \( (r + K(s_0 + \cdots + s_{N-1})) < 1 \), we can without loss of generality assume that \( (r + K(s_0 + \cdots + s_N)) < 1 \): otherwise, by the maximum principle there is nothing to prove.
2) The new molecule’s center $x(s_N)$ used in formula (69) is fixed by

$$
\begin{cases}
  x'(s_N) = \frac{\partial B_{I_N}}{\partial B_{I_N}} = \int_{B_{I_N}} v(y, s_N) dy \\
  x(0) = x(s_{N-1}).
\end{cases}
$$

(69)

And here we noted $B_{I_N} = B(x(s_N), f_N)$ with $f_N$ a real valued function given by

$$
f_N = (r + K(s_0 + \cdots + s_{N-1})).
$$

(70)

Note that by remark 1) above we have $0 < f_N < 1$.

The proof of Theorem 12 will follow exactly the same steps given in the proof of Theorem 11: we start with the concentration condition studied in Proposition 5.5 and we continue with the Height condition in Proposition 5.6, finally the $L^1$ bound will be an easy consequence of these two estimates.

Proposition 5.8 (Concentration condition) Under the hypothesis of Theorem 12, if $\psi(s, s_{N-1})$ is an initial data then the solution $\psi(x, s_N)$ of (67) satisfies

$$
\int_{\mathbb{R}^n} |\psi(x, s_N)||x - x(s_N)|^\omega dx \leq (r + K(s_0 + \cdots + s_N))^{\omega-\gamma}
$$

for $x(s_N) \in \mathbb{R}^n$ fixed by formula (69), with $0 \leq s_N \leq \epsilon r$.

Proof. Follow the same lines given in the proof of Proposition 5.6. Write $\Omega_N(x) = |x - x(s_N)|^\omega$ and $\psi(x) = \psi_+(x) - \psi_-(x)$, by linearity and using the positivity principle we have $|\psi(x, s_N)| = |\psi_+(x, s_N) - \psi_-(x, s_N)| \leq \psi_+(x, s_N) + \psi_-(x, s_N)$ and we may consider the formula:

$$
I = \int_{\mathbb{R}^n} \Omega_N(x)\psi_+(x, s_N) dx = \int_{\mathbb{R}^n} -\nabla \Omega_N(x) \cdot x' (s_N) \psi_+(x, s_N) + \Omega_N(x) [- \nabla \cdot (v \psi_+(x, s_N)) - L \psi_+(x, s_N)] dx
$$

Using the definition of $x'(s_N)$ given in (69) and replacing $\Omega_N(x)$ by $|x - x(s_N)|^\omega$ in the first integral we obtain

$$
I \leq c \int_{\mathbb{R}^n} |x - x(s_N)|^{\omega - 1} |v - \nabla B_{I_N}| |\psi_+(x, s_N)| dx + c \int_{\mathbb{R}^n} |\Omega_N(x)||\psi_+(x, s_N)| dx.
$$

(71)

We will study each of the integrals $I_1$ and $I_2$ in the next lemmas:

Lemma 5.7 For integral $I_1$ we have $I_1 \leq C\mu(r + K(s_0 + \cdots + s_{N-1}))^{\omega - \gamma - 1}$.

Proof of the lemma. It is enough to repeat the same steps of the previous Lemma 5.5 just consider $\mathbb{R}^n = B_{I_N} \cup \bigcup_{k \geq 1} E_k$ where

$$
B_{I_N} = \{x \in \mathbb{R}^n : |x - x(s_N)| \leq f_N\}, \quad E_k = \{x \in \mathbb{R}^n : f_N r^{k-1} < |x - x(s_N)| \leq f_N r^k\} \quad \text{for } k \geq 1.
$$

(72)

In order to obtain the desired inequality, use exactly the same arguments, the maximum principle and the hypothesis of Theorem 12.

Lemma 5.8 For integral $I_2$ in inequality (71) we have the following estimate

$$
I_2 = \int_{\mathbb{R}^n} |\Omega_N(x)||\psi_+(x, s_N)| dx \leq C(r + K(s_0 + \cdots + s_{N-1}))^{\omega - \gamma - 1}.
$$

Proof of the lemma. As for Lemma 5.7 we consider $\mathbb{R}^n$ as the union of a ball with dyadic coronas centered on $x(s_N)$ (cf. (72)). It is then enough to repeat the corresponding estimates of the $s_1$-case given in Lemma 5.6.

Now we continue the proof of the Proposition 5.8. Using the Lemmas 5.7 and 5.8 and getting back to the estimate (71) we have

$$
|\partial s_N \int_{\mathbb{R}^n} \Omega_N(x)\psi_+(x, s_N) dx| \leq C \mu(r + K(s_0 + \cdots + s_{N-1}))^{\omega - \gamma - 1}
$$

(73)

This estimation is compatible with the estimate (68) for $0 \leq s_N \leq \epsilon r$ small enough. Indeed, we can write $\phi = (r + K(s_0 + \cdots + s_N))^{\omega - \gamma}$ and we linearize this expression with respect to $s_N$:

$$
\phi \approx (r + K(s_0 + \cdots + s_{N-1}))^{\omega - \gamma} \left(1 + K(\omega - \gamma) \frac{s_N}{r + K(s_0 + \cdots + s_{N-1})}\right)
$$

Taking the derivative of $\phi$ with respect to $s_N$ we have $\phi' \approx K(\omega - \gamma)(r + K(s_0 + \cdots + s_{N-1}))^{\omega - \gamma - 1}$ and with the condition (48) on $K(\omega - \gamma)$ we obtain that (73) is bounded by $\phi'$ and the Proposition 5.8 follows.
Proposition 5.9 (Height condition) Under the hypothesis of Theorem 12, if $\psi(x,s_N)$ satisfies concentration condition (68), then we have the next height condition

$$\|\psi(\cdot,s_N)\|_{L^\infty} \leq \frac{1}{(r + K(s_0 + \cdots + s_N))^{n+\gamma}}.$$ 

Proof. The proof follows essentially the same lines of the Proposition 5.3. Indeed, since we have that concentration condition (68) is bounded by $(r + K(s_0 + \cdots + s_N))^{-(n+\gamma)}$, we obtain in the same manner and with the same constants:

$$\frac{d}{ds_N} \|\psi(\cdot,s_N)\|_{L^\infty} \leq -C(r + K(s_0 + \cdots + s_N))^{-\frac{(n+\gamma)}{n+\gamma}} \|\psi(\cdot,s_N)\|_{L^\infty}^{1+\frac{r}{n+\gamma}}.$$ 

Solving this differential inequality we obtain $\|\psi(\cdot,s_N)\|_{L^\infty} \leq (r + K(s_0 + \cdots + s_N))^{-(n+\gamma)}$. ■

Proposition 5.10 ($L^1$-norm estimate) Under the hypothesis of Theorem 12 we have

$$\|\psi(\cdot,s_N)\|_{L^1} \leq \frac{v_0}{(r + K(s_0 + \cdots + s_N))^{\gamma}} \quad (74)$$

Proof. This is a direct consequence of the concentration condition and of the previous height condition. ■

End of the proof of Theorem 9. We have proved with the Theorem 10 that is possible to control the $L^1$ behavior of the molecules $\psi$ from 0 to a small time $s_0$, from time $s_0$ to time $s_1$ with Theorem 11 and by iteration from time $s_{N-1}$ to time $s_N$ with Theorem 12. We recall that we have $s_i \sim cr$ for all $0 \leq i \leq N$, so the bound obtained in (74) depends mainly on the size of the molecule $r$ and the number of iterations $N$.

We observe now that the smallness of $r$ and of the times $s_0, ..., s_N$ can be compensated by the number of iterations $N$ in the following sense: fix a small $0 < \varepsilon < 1$ and iterate as explained before. Since each small time $s_0, ..., s_N$ is of order $cr$, we have $s_0 + \cdots + s_N \sim N \varepsilon$. Thus, we will stop the iterations as soon as $N \varepsilon \geq T_0$.

Of course, the number of iterations $N = N(r)$ will depend on the smallness of the molecule’s size $r$, and more specifically it is enough to set $N(r) \sim \frac{T_0}{\varepsilon}$ in order to obtain this lower bound for $N \varepsilon$.

Proceeding this way we will obtain $\|\psi(\cdot,s_N)\|_{L^1} \leq C(T_0)^{-\gamma} < +\infty$, for all molecules of size $r$. Note in particular that, once this estimate is available, for bigger times it is enough to apply the maximum principle.

Finally, and for all $r > 0$, we obtain after a time $T_0$ a $L^1$ control for small molecules and we finish the proof of the Theorem 9. ■

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