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Transfer of regularity for Markov semigroups

Vlad Bally
Lucia Caramellino

Abstract
We study the regularity of a Markov semigroup \((P_t)_{t>0}\), that is, when \(P_t(x, dy) = p_t(x, y)dy\) for a suitable smooth function \(p_t(x, y)\). This is done by transferring the regularity from an approximating Markov semigroup sequence \((P^n_t)_{t>0}, n \in \mathbb{N}\), whose associated densities \(p^n_t(x, y)\) are smooth and can blow up as \(n \to \infty\). We use an interpolation type result and we show that if there exists a good equilibrium between the blow up and the speed of convergence, then \(P_t(x, dy) = p_t(x, y)dy\) and \(p_t\) has some regularity properties.

Keywords: Markov semigroups; regularity of probability laws; interpolation spaces.

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1 Introduction

In this paper we study Markov semigroups, that is, strongly continuous and positive semigroups $P_t$, $t \geq 0$, such that $P_t 1 = 1$. We set the domain equal to the Schwartz space $S(\mathbb{R}^d)$ of the $C^\infty(\mathbb{R}^d)$ functions all of whose derivatives are rapidly decreasing.

The link with Markov processes gives the representation

$$P_t f(x) = \int_{\mathbb{R}^d} f(y) P_t(x, dy), \quad t \geq 0, \ f \in S(\mathbb{R}^d).$$

We study here the regularity of a Markov semigroup, which is the property $P_t(x, dy) = p_t(x, y)dy$, $t > 0$, for a suitable smooth function $p_t(x, y)$, by transferring the regularity from an approximating Markov semigroup sequence $P^n_t$, $n \in \mathbb{N}$.

To be more precise, let $P_t$ be a Markov semigroup on $S(\mathbb{R}^d)$ with infinitesimal operator $L$ and let $P^n_t$, $n \in \mathbb{N}$, be a sequence of Markov semigroups on $S(\mathbb{R}^d)$ with infinitesimal operators $L_n$, $n \in \mathbb{N}$. Classical results (Trotter Kato theorem, see e.g. [13]) assert that, if $L_n \to L$ then $P^n_t \to P_t$. The problem that we address in this paper is the following. We suppose that $P^n_t$ converges to some $P_t$ in a sufficiently strong sense, of course we obtain $P_t(x, dy) = p_t(x, y)dy$.

But in our framework $p^n_t$ does not converge: here, $p^n_t$ can even “blow up” as $n \to \infty$. However, if we may find a good equilibrium between the blow up and the speed of convergence, then we are able to conclude that $P_t(x, dy) = p_t(x, y)dy$ and $p_t$ has some regularity properties. This is an interpolation type result.

Roughly speaking our main result is as follows. We assume that the speed of convergence is controlled in the following sense: there exists some $a \in \mathbb{N}$ such that for every $q \in \mathbb{N}$

$$\| (L - L_n) f \|_{q, \infty} \leq \varepsilon_n \| f \|_{q + a, \infty} \quad (1.1)$$

Here $\| f \|_{q, \infty}$ is the norm in the standard Sobolev space $W^{q, \infty}$. In fact we will work with weighted Sobolev spaces, and this is an important point. And also, we will assume a similar hypothesis for the adjoint $(L - L_n)^*$ (see Assumption 2.1 for a precise statement).

Moreover we assume a “propagation of regularity” property: there exist $b \in \mathbb{N}$ and $\Lambda_n \geq 1$ such that for every $q \in \mathbb{N}$

$$\| P^n_t f \|_{q, \infty} \leq \Lambda_n \| f \|_{q + b, \infty} \quad (1.2)$$

Here also we will work with weighted Sobolev norms. And a similar hypothesis is supposed to hold for the adjoint $P^{*n}_t$ (see Assumption 2.2 for a precise statement).

Finally we assume the following regularity property: for every $t \in (0, 1]$, $P^n_t(x, dy) = p^n_t(x, y)dy$ with $p^n_t \in C^\infty(\mathbb{R}^d \times \mathbb{R}^d)$ and for every $\kappa \geq 0$, $t \in (0, 1]$,

$$\left| \partial^\alpha_x \partial^\beta_y p^n_t (x, y) \right| \leq \frac{C}{(\lambda_n t)^{\theta_0(|\alpha| + |\beta| + \theta_1)}} \times \frac{(1 + |x|^2)^{\pi(\kappa)}}{(1 + |x - y|^2)^\kappa}. \quad (1.3)$$

Here, $\alpha, \beta$ are multi-indexes and $\partial^\alpha_x, \partial^\beta_y$ are the corresponding differential operators. Moreover, $\pi(\kappa), \theta_0$ and $\theta_1$ are suitable parameters and $\lambda_n \to 0$ as $n \to \infty$ (we refer to Assumption 2.9).

By (1.1)–(1.3), the rate of convergence is controlled by $\varepsilon_n \to 0$ and the blow up of $p^n_t$ is controlled by $\lambda_n^{-\theta_0} \to \infty$. So the regularity property may be lost as $n \to \infty$. However, if there
is a good equilibrium between \( \varepsilon_n \to 0 \) and \( \lambda_n^{-\theta_0} \to \infty \) and \( \Lambda_n \to \infty \) then the regularity is saved: we ask that for some \( \delta > 0 \)
\[
\lim_n \frac{\varepsilon_n \Lambda_n}{\Lambda_n^{(a+b+\delta)}} < \infty, \tag{1.4}
\]
the parameters \( a, b \) and \( \theta_0 \) being given in (1.1), (1.2) and (1.3) respectively. Then \( P_t(x,dy) = p_t(x,y)dy \) with \( p_t \in C^\infty(\mathbb{R}^d \times \mathbb{R}^d) \) and the following upper bound holds: for every \( \varepsilon > 0 \) and \( \kappa \in \mathbb{N} \) one may find some constants \( C, \pi(\kappa) > 0 \) such that for every \( (x,y) \in \mathbb{R}^d \times \mathbb{R}^d \)
\[
\left| \partial_x^a \partial_y^b p_t(x,y) \right| \leq \frac{C}{\varepsilon^{\theta_0(1+\frac{a+b}{2})(|\alpha|+|\beta|+2d+\varepsilon)}} \times \frac{(1+|x|^2)^{\pi(\kappa)}}{(1+|x-y|^2)^\kappa}. \tag{1.5}
\]
This is the “transfer of regularity” that we mention in the title and which is stated in Theorem 2.7. The proof is based on a criterion of regularity for probability measures given in [3], which is close to interpolation spaces techniques.

A second result concerns a perturbation of the semigroup \( P_t \) by adding a compound Poisson process: we prove that if \( P_t \) verifies (1.2) and (1.3) then the perturbed semigroup still verifies (1.3) – see Theorem 2.11. A similar perturbation problem is discussed in [19] (but the arguments there are quite different).

The regularity criterion presented in this paper is tailored in order to handle the following example (which will be treated in a forthcoming paper). We consider the integro-differential operator
\[
L f(x) = \langle b(x), \nabla f(x) \rangle + \int_E \left( f(x + c(z,x)) - f(x) - \langle c(z,x), \nabla f(x) \rangle \right) d\mu(z) \tag{1.6}
\]
where \( \mu \) is an infinite measure on the normed space \( (E, |\cdot|_E) \) such that \( \int_E 1 \wedge |c(z,x)|^2 d\mu(z) < \infty \). Moreover, we consider a sequence \( \varepsilon_n \downarrow \emptyset \), we denote
\[
A_n^{i,j}(x) = \int_{\{|z|_E \leq \varepsilon_n\}} c^i(z,x)c^j(z,x) d\mu(z)
\]
and we define
\[
L_n f(x) = \langle b(x), \nabla f(x) \rangle + \int_{\{|z|_E \geq \varepsilon_n\}} (f(x + c(z,x)) - f(x) - \langle c(z,x), \nabla f(x) \rangle) d\mu(z) + \frac{1}{2} \operatorname{tr}(A_n(x) \nabla^2 f(x)). \tag{1.7}
\]
By Taylor’s formula,
\[
\|L f - L_n f\|_\infty \leq \|f\|_{3,\infty} \varepsilon_n \quad \text{with} \quad \varepsilon_n = \sup_x \int_{\{|z|_E \leq \varepsilon_n\}} |c(z,x)|^3 d\mu(z)
\]
Under the uniform ellipticity assumption \( A_n(x) \geq \lambda_n \) for every \( x \in \mathbb{R}^d \), the semigroup \( P^n_t \) associated to \( L_n \) has the regularity property (1.3) with \( \theta_0 \) depending on the measure \( \mu \). The speed of convergence in (1.1), with \( a = 3 \), is controlled by \( \varepsilon_n \downarrow 0 \). So, if (1.4) holds, then we obtain the regularity of \( P_t \) and the short time estimates (1.5).

The semigroup \( P_t \) associated to \( L \) corresponds to stochastic equations driven by the Poisson point measure \( N_\mu(dt,dz) \) with intensity measure \( \mu \), so the problem of the regularity of \( P_t \) has
been extensively discussed in the probabilistic literature. A first approach initiated by Bismut [8], Leandre [16] and Bichteler, Gravereaux and Jacod [7] (see also the recent monograph of Bouleau and Denis [9] and the bibliography therein), is done under the hypothesis that $E = \mathbb{R}^m$ and $\mu(dz) = h(z)dz$ with $h \in C^\infty(\mathbb{R}^m)$. Then one constructs a Malliavin type calculus based on the amplitude of the jumps of the Poisson point measure $N_\mu$ and employs this calculus in order to study the regularity of $P_t$. A second approach initiated by Carlen and Pardoux [11] (see also Bally and Clément [5]) follows the ideas in Malliavin calculus based on the exponential density of the jump times in order to study the same problem. Finally a third approach, due to Picard [17, 18] (see also the recent monograph by Ishikawa [14] for many references and developments in this direction), constructs a Malliavin type calculus based on finite differences (instead of standard Malliavin derivatives) and obtains the regularity of $P_t$ for a general class of intensity measures $\mu$ including purely atomic measures (in contrast with $\mu(dz) = h(z)dz$). We stress that all the above approaches work under different non degeneracy hypotheses, each of them corresponding to the specific noise that is used in the calculus. So in some sense we have not a single problem but three different classes of problems. The common feature is that the strategy in order to solve the problem follows the ideas from Malliavin calculus based on $N_\mu$. Our approach is completely different because, as described above, we use the regularization effect of $\text{tr}(A_n(x)\nabla^2)$. This regularization effect may be exploited either by using the standard Malliavin calculus based on the Brownian motion or using some analytical arguments. The approach that we propose in [4] is probabilistic, so employs the standard Malliavin calculus. But anyway, as mentioned above, the regularization effect vanishes as $n \to \infty$ and a supplementary argument based on the equilibrium given in (1.4) is used. We precise that the non degeneracy condition $A_n(x) \geq \lambda_n > 0$ is of the same nature as the one employed by J. Picard so the problem we solve is in the same class.

The idea of replacing “small jumps” (the ones in $\{|z|_E \leq \varepsilon_n\}$ here) by a Brownian part (that is $\text{tr}(A_n(x)\nabla^2)$ in $L_n$) is not new - it has been introduced by Asmussen and Rosinski in [2] and has been extensively employed in papers concerned with simulation problems: since there is a huge amount of small jumps, they are difficult to simulate and then one approximates them by the Brownian part corresponding to $\text{tr}(A_n(x)\nabla^2)$. See for example [1, 6, 12] and many others. However, at our knowledge, this idea has not been yet used in order to study the regularity of $P_t$.

The paper is organized as follows. In Section 2 we give the notation and the main results mentioned above and in Section 4 we give the proof of these results. Section 3 is devoted to some preliminary results about regularity. Namely, in Section 3.1 we recall and develop some results concerning regularity of probability measures, based on interpolation type arguments, coming from [3]. These are the main instruments used in the paper. In Section 3.2 we prove a regularity result which is a key point in our approach. In fact, it allows to handle the multiple integrals coming from the application of a Lindeberg method for the decomposition of $P_t - P^n_t$. The results stated in Section 2 are then proved in the subsections in which Section 4 is split. Finally, in Appendix A.1, A.2 and A.3 we prove some technical results used in the paper.

2 Notation and main results

2.1 Notation

For a multi-index $\alpha = (\alpha_1, ..., \alpha_m) \in \{1, ..., d\}^m$ we denote $|\alpha| = m$ (the length of the multi-index) and $\partial^\alpha$ is the derivative corresponding to $\alpha$, that is $\partial^{\alpha_1} \cdots \partial^{\alpha_m}$, with $\partial^{\alpha_1} = \partial_{z_{\alpha_1}}$. For
\( f \in C^\infty(\mathbb{R}^d \times \mathbb{R}^d), \ (x, y) \in \mathbb{R}^d \times \mathbb{R}^d \) and two multi-indexes \( \alpha \) and \( \beta \), we denote by \( \partial^\alpha_x \) the derivative with respect to \( x \) and by \( \partial^\beta_y \) the derivative with respect to \( y \).

Moreover, for \( f \in C^\infty(\mathbb{R}^d) \) and \( q \in \mathbb{N} \) we denote

\[
|f|_q(x) = \sum_{0 \leq |\alpha| \leq q} |\partial^\alpha f(x)|.
\] (2.1)

If \( f \) is not a scalar function, that is, \( f = (f^i)_{i=1,\ldots,d} \) or \( f = (f^{i,j})_{i,j=1,\ldots,d} \), we denote \( |f|_q = \sum_{i=1}^d |f^i|_q \) respectively \( |f|_q = \sum_{i,j=1}^d |f^{i,j}|_q \).

We will work with the weights

\[
\psi_\kappa(x) = (1 + |x|^2)^\kappa, \quad \kappa \in \mathbb{Z}.
\] (2.2)

The following properties hold:

- for every \( \kappa \geq \kappa' \geq 0 \),
  \[
  \psi_\kappa(x) \leq \psi_{\kappa'}(x);
  \] (2.3)

- for every \( \kappa \geq 0 \), there exists \( C_\kappa > 0 \) such that
  \[
  \psi_\kappa(x) \leq C_\kappa \psi_\kappa(y) \psi_\kappa(x - y);
  \] (2.4)

- for every \( \kappa \geq 0 \), there exists \( C_\kappa > 0 \) such that for every \( \phi \in C_0^\infty(\mathbb{R}^d) \),
  \[
  \psi_\kappa \phi(x) \leq C_\kappa \psi_\kappa(0)(1 + \|\nabla \phi\|_{\infty}^2)^\kappa \psi_\kappa(x);
  \] (2.5)

- for every \( q \in \mathbb{N} \) there exists \( C_q \geq C_\kappa > 0 \) such that for every \( \kappa \in \mathbb{R} \) and \( f \in C^\infty(\mathbb{R}^d) \),
  \[
  C_q \psi_\kappa |f|_q(x) \leq |\psi_\kappa f|_q(x) \leq C_q \psi_\kappa |f|_q(x).
  \] (2.6)

Note that (2.3)–(2.5) are immediate, whereas (2.6) is proved in Appendix A.1 (see Lemma A.1).

For \( q \in \mathbb{N}, \ \kappa \in \mathbb{R} \) and \( p \in (1, \infty] \) (we stress that we include the case \( p = +\infty \)), we set \( \| \cdot \|_{p,q} \) the usual norm in \( L^p(\mathbb{R}^d) \) and

\[
\|f\|_{q,p} = \|\psi_\kappa f\|_p.
\] (2.7)

We denote \( W^{q,\kappa,p} \) to be the closure of \( C^\infty(\mathbb{R}^d) \) with respect to the above norm. If \( \kappa = 0 \) we just denote \( \|f\|_{q,p} = \|f\|_{q,0,p} \) and \( W^{q,p} = W^{q,0,p} \) (which is the usual Sobolev space). So, we are working with weighted Sobolev spaces. The following properties hold:

- for every \( q \in \mathbb{N} \) there exists \( C_q \geq C_q > 0 \) such that for every \( \kappa \in \mathbb{R}, \ p > 1 \) and \( f \in W^{q,\kappa,p}(\mathbb{R}^d) \),
  \[
  C_q \|\psi_\kappa f\|_p \leq \|f\|_{q,\kappa,p} \leq C_q \|\psi_\kappa f\|_p;
  \] (2.8)

- for every \( q \in \mathbb{N} \) and \( p > 1 \) there exists \( C_{q,p} > 0 \) such that for every \( \kappa \in \mathbb{R} \) and \( f \in W^{q,\kappa,p}(\mathbb{R}^d) \),
  \[
  \|f\|_{q,\kappa,p} \leq C_{q,p} \|f\|_{q,\kappa+d,\infty} \tag{2.9}
  \]
  \[
  \text{and if } p > d, \quad \|f\|_{q,\kappa,\infty} \leq C_{q,p} \|f\|_{q+1,\kappa,p} \tag{2.10}
  \]

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• for \( \kappa, \kappa' \in \mathbb{R}, \ q, q' \in \mathbb{N}, \ p \in (1, \infty) \) and \( U : C^\infty(\mathbb{R}^d) \to C^\infty(\mathbb{R}^d) \), the following two assertions are equivalent: there exists a constant \( C_* \geq 1 \) such that for every \( f \),

\[
\|Uf\|_{q,\kappa,\infty} \leq C_* \|f\|_{q',\kappa',p} \tag{2.11}
\]

and there exists a constant \( C^* \geq 1 \) such that for every \( f \),

\[
\left\| \psi_n U\left( \frac{1}{\psi_{n'}} f \right) \right\|_{q,\infty} \leq C^* \|f\|_{q',p}. \tag{2.12}
\]

Notice that (2.8) is a consequence of (2.6). The inequality (2.9) is an immediate consequence of (2.6) and of the fact that \( \psi_d \in L^p(\mathbb{R}^d) \) for every \( p \geq 1 \). And the inequality (2.10) is a consequence of Morrey’s inequality (Corollary IX.13 in [10]), whose use gives \( \|f\|_{0,\infty} \leq \|f\|_{1_{,0,p}} \), and of (2.6). In order to prove the equivalence between (2.11) and (2.12), one takes \( g = \psi_{n'} f \) (respectively \( g = \frac{1}{\psi_{n'}} f \)) and uses (2.6) as well.

2.2 Main results

We consider a Markov semigroup \( P_t \) on \( S(\mathbb{R}^d) \) with infinitesimal operator \( L \) and a sequence \( P^*_n, n \in \mathbb{N} \) of Markov semigroups on \( S(\mathbb{R}^d) \) with infinitesimal operator \( L_n \). We suppose that \( S(\mathbb{R}^d) \) is included in the domain of \( L \) and of \( L_n \) and we suppose that for \( f \in S(\mathbb{R}^d) \) we have \( Lf \in S(\mathbb{R}^d) \) and \( L_n f \in S(\mathbb{R}^d) \). We denote \( \Delta_n = L - L_n \). Moreover, we denote by \( P^*_n \) the formal adjoint of \( P^*_n \) and by \( \Delta^*_n \) the formal adjoint of \( \Delta_n \) that is

\[
\langle P^*_n f, g \rangle = \langle f, P^n g \rangle \quad \text{and} \quad \langle \Delta^*_n f, g \rangle = \langle f, \Delta_n g \rangle, \tag{2.13}
\]

\( \langle \cdot, \cdot \rangle \) being the scalar product in \( L^2(\mathbb{R}^d, dx) \).

We present now our hypotheses. The first one concerns the speed of convergence of \( L_n \to L \).

**Assumption 2.1** Let \( a \in \mathbb{N} \), and let \( (\varepsilon_n)_{n \in \mathbb{N}} \) be a decreasing sequence such that \( \lim_n \varepsilon_n = 0 \). We assume that for every \( q \in \mathbb{N}, \kappa \geq 0 \) and \( p > 1 \) there exists \( C > 0 \) such that for every \( n \) and \( f \),

\[
\|\Delta_n f\|_{q,-\kappa,\infty} \leq C \varepsilon_n \|f\|_{q+a,-\kappa,\infty}, \tag{A1}
\]

\[
\|\Delta^*_n f\|_{q,k,p} \leq C \varepsilon_n \|f\|_{q+a,k,p}. \tag{A1^*}
\]

Our second hypothesis concerns the “propagation of regularity” for the semigroups \( P^*_n \).

**Assumption 2.2** Let \( \Lambda_n \geq 1, n \in \mathbb{N} \) be an increasing sequence such that \( \Lambda_n < 1 \) for some \( \gamma \geq 1 \). For every \( q \in \mathbb{N} \) and \( \kappa \geq 0, p > 1 \), there exist \( C > 0 \) and \( b \in \mathbb{N} \), such that for every \( n \in \mathbb{N} \) and \( f \),

\[
\sup_{s \leq t} \|P^*_n f\|_{q,-\kappa,\infty} \leq C \Lambda_n \|f\|_{q+b,-\kappa,\infty}, \tag{A2}
\]

\[
\sup_{s \leq t} \|P^*_n f\|_{q,k,p} \leq C \Lambda_n \|f\|_{q+b,k,p}. \tag{A2^*}
\]

The hypothesis \((A^*_2)\) is rather difficult to verify so, in Appendix A.2, we give some sufficient conditions in order to check it (see Proposition A.7).

Our third hypothesis concerns the “regularization effect” of the semi-group \( P^n_t \).
Assumption 2.3 We assume that
\[ P_t^n f(x) = \int_{\mathbb{R}^d} p_t^n(x,y) f(y) dy \]  
with \( p_t^n \in C^\infty(\mathbb{R}^d \times \mathbb{R}^d) \). Moreover, we assume there exist \( \theta_0 > 0 \) and a sequence \( \lambda_n, n \in \mathbb{N} \) with
\[ \lambda_n \downarrow 0, \quad \lambda_n \leq \gamma \lambda_{n+1}, \]  
for some \( \gamma \geq 1 \), such that the following property holds: for every \( \kappa \geq 0 \), \( q \in \mathbb{N} \) there exist \( \pi(q, \kappa) \), increasing in \( q \) and in \( \kappa \), a constant \( \theta_1 \geq 0 \), and a constant \( C > 0 \) such that for every \( n \in \mathbb{N}, t \in (0,1] \), for every multi-indexes \( \alpha \) and \( \beta \) with \( |\alpha| + |\beta| \leq q \) and \( (x,y) \in \mathbb{R}^d \times \mathbb{R}^d \)
\[ (A_3) \quad \left| \frac{\partial^\alpha \partial^\beta_y p_t^n(x,y)}{p_t^n(x,y)} \right| \leq C \frac{1}{(\lambda_n t)^\theta_0(q+\theta_1)} \times \frac{\psi_{\pi(q,\kappa)}(x)}{\psi_{\kappa}(x-y)} \]  
(2.20)

Note that in (2.20) we are quantifying the possible blow up of \( |\partial^\alpha \partial^\beta_y p_t^n(x,y)| \) as \( n \to \infty \).

We also assume the following statement will hold for the semigroup \( P_t \).

Assumption 2.4 For every \( \kappa \geq 0, q \in \mathbb{N} \) there exists \( C \geq 1 \) such that
\[ \| P_t f \|_{q,-\kappa,\infty} \leq C \| f \|_{q,-\kappa,\infty}. \]  
(2.21)

For \( \delta \geq 0 \) we denote
\[ \Phi_n(\delta) = \varepsilon_n \Lambda_n \times \lambda_n^{-\theta_0(a+b+\delta)}, \]  
(2.22)

where \( a \) and \( b \) are the constants in Assumption 2.1 and 2.2 respectively. Notice that
\[ \Phi_n(\delta) \leq \gamma^{1+\theta_0(a+b+\delta)} \Phi_{n+1}(\delta). \]  
(2.23)

And, for \( \kappa \geq 0, \eta \geq 0 \) we set
\[ \Psi_{\eta,\kappa}(x,y) := \frac{\psi_{\kappa}(y)}{\psi_{\eta}(x)}, \quad (x,y) \in \mathbb{R}^d \times \mathbb{R}^d. \]  
(2.24)

Our first result concerns the regularity of the semigroup \( P_t \):

Theorem 2.5 Suppose that Assumption 2.1, 2.2, 2.3 and 2.4 hold. Moreover we suppose there exists \( \delta > 0 \) such that
\[ \limsup_n \Phi_n(\delta) < \infty, \]  
(2.25)

\( \Phi_n(\delta) \) being given in (2.22). Then the following statements hold.

A. Let \( P_t f(x) = \int_{\mathbb{R}^d} p_t(x,y) dy \) with \( p_t \in C^\infty(\mathbb{R}^d \times \mathbb{R}^d) \).

B. Let \( n \in \mathbb{N} \) and \( \delta_* > 0 \) be such that
\[ \overline{\Phi}_n(\delta_*) := \sup_{n' \geq n} \Phi_{n'}(\delta_*) < \infty. \]  
(2.26)

We fix \( q \in \mathbb{N}, p > 1, \varepsilon_* > 0, \kappa \geq 0 \) and we put \( m = 1 + \frac{q+2d/p_*}{\delta_*} \) with \( p_* \) the conjugate of \( p \). There exist \( C \geq 1 \) and \( \eta_0 \geq 1 \) (depending on \( q,p,\varepsilon_*,\delta_*,\kappa \) and \( \gamma \)) such that for every \( \eta > \eta_0 \) and \( t > 0 \)
\[ \| \Psi_{\eta,\kappa} p_t \|_{q,p} \leq C \times Q_n(q,m) \times t^{-\theta_0(a+b)m+q+2d/p_*}(1+\varepsilon_*) \]  
with
\[ Q_n(q,m) = \left( \frac{1}{\lambda_n^{\theta_0(a+b)m+q+2d/p_*} + \overline{\Phi}_n(\delta_*)} \right)^{1+\varepsilon_*}, \]  
(2.27)

(2.28)
C. Let $p > 2d$. Set $\bar{m} = 1 + \frac{t^{1+2d/p}}{\delta_*}$. There exist $C \geq 1, \eta \geq 0$ (depending on $q, p, \varepsilon, \delta_*, \kappa$) such that for every $t > 0$, $n \in \mathbb{N}$ and for every multi-indexes $\alpha, \beta$ such that $|\alpha| + |\beta| \leq q$,

$$
\left| \partial_x^\alpha \partial_y^\beta p_t(x, y) \right| \leq C \times Q_n(q + 1, \bar{m}) \times t^{-\theta_0((a+b)m+q+1+2d/p_n)(1+\varepsilon_*)} \times \frac{\psi_{\eta+\kappa}(x)}{\psi_{\kappa}(x-y)} \quad (2.29)
$$

for every $t \in (0, 1]$ and $x, y \in \mathbb{R}^d$.

**Remark 2.6** We stress that in hypothesis (2.26) the order of derivation $q$ does not appear. However the conclusions (2.27) and (2.29) hold for every $q$. The motivation of this is given by the following heuristics. The hypothesis (2.20) says that the semi-group $P_t^n$ has a regularization effect controlled by $1/(\lambda_n t)^{\theta_0}$. If we want to decouple this effect $m_0$ times we write $P_t^n = P_{t/m_0}^m \ldots P_{t/m_0}^m$ and then each of the $m_0$ operators $P_{t/m_0}$ acts with a regularization effect of order $(\lambda_n \times t/m_0)^{\theta_0}$. But this heuristics does not work directly: in order use it, we have to use a development in Taylor series coupled with the interpolation type criterion given in the following section.

The proof of Theorem 2.5 is developed in Section 4.1. We give now a variant of the estimate (2.29), whose proof can be found in Section 4.2.

**Theorem 2.7** Suppose that Assumption 2.1, 2.2, 2.3 and 2.4 hold. Suppose also that (2.25) holds for some $\delta > 0$ and that for every $\kappa > 0$ there exist $\bar{\kappa}, \bar{C} > 0$ such that $P_t \psi_\kappa(x) \leq C \psi_\kappa(x)$, for all $x \in \mathbb{R}^d$ and $t > 0$. Then $P_t(x, y) = p_t(x, y)$ with $p_t \in C^\infty(\mathbb{R}^d \times \mathbb{R}^d)$ and for every $\kappa \in \mathbb{N}$, $\varepsilon > 0$ and for every multi-indexes $\alpha$ and $\beta$ there exists $C = C(\kappa, \varepsilon, \delta, \alpha, \beta)$ such that for every $t > 0$ and $x, y \in \mathbb{R}^d$

$$
\left| \partial_x^\alpha \partial_y^\beta p_t(x, y) \right| \leq C \times t^{-\theta_0((a+b)m+q+1+2d/p_n)(1+\varepsilon_*)} \times \frac{\psi_{\eta+\kappa}(x)}{\psi_{\kappa}(x-y)} \quad (2.30)
$$

with $\theta_0$ from (2.20).

We give now a result which goes in another direction (but the techniques used to prove it are the same): we assume that the semigroup $P_t : C^\infty(\mathbb{R}^d) \rightarrow C^\infty(\mathbb{R}^d)$ verifies hypothesis of type $(A_2)$ (see (2.16) and (2.17)) and $(A_3)$ (see (2.20)), we perturb it by a compound Poisson process, and we prove that the new semigroup still verifies a regularity property of type $(A_3)$. This result will be used in [?] in order to cancel the “big jumps”.

Let us give our hypotheses.

**Assumption 2.8** For every $q \in \mathbb{N}, \kappa \geq 0$ and $p \geq 1$ there exist $C_{q,\kappa,p}(P), C_{q,\kappa,\infty}(P) \geq 1$ such that

$$(H_2) \quad \| P_t f \|_{q,-\kappa,\infty} \leq C_{q,\kappa,\infty}(P) \| f \|_{q,-\kappa,\infty}, \quad (2.31)$$

$$(H_2^*) \quad \| P_t^* f \|_{q,\kappa,p} \leq C_{q,\kappa,p}(P) \| f \|_{q,\kappa,p} \quad (2.32)$$

This means that the hypotheses $(A_2)$ and $(A_3^*)$ (see (2.16) and (2.17)) from Section 3.2 hold for $P_t$ (instead of $P_t^n$) with $\Lambda_n$ replaced by $C_{q,\kappa,\infty}(P)$ or $C_{q,\kappa,p}(P)$ and with $b = 0$. 

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**Assumption 2.9** We assume that \( P_t(x, dy) = p_t(x, y) dy \) with \( p_t \in C^\infty(\mathbb{R}^d \times \mathbb{R}^d) \) and the blow up of \( p_t \to \infty \) as \( t \to 0 \) is controlled in the following way. For every fixed \( q \in \mathbb{N}, \kappa \geq 0 \) there exist some constants \( C \geq 1, 0 < \lambda \leq 1 \) and \( \eta > 0 \) such that for every two multi-indexes \( \alpha, \beta \) with \( |\alpha| + |\beta| \leq q\)

\[
(H_3) \quad \left| \partial_x^\alpha \partial_y^\beta p_t(x, y) \right| \leq \frac{C}{(\lambda t)^{\phi_0(q + \theta_1)}} \times \frac{\psi_\eta(x)}{\psi_\kappa(x - y)}
\]

(2.33)

Here \( \theta_i \geq 0, i = 0, 1 \) are some fixed parameters.

We construct now the perturbed semigroup. We consider a Poisson process \( N(t) \) of parameter \( \rho > 0 \) and we denote by \( T_k, k \in \mathbb{N} \), its jump times. We also consider a sequence \( Z_k, k \in \mathbb{N} \), of independent random variables of law \( \nu \), on a measurable space \((E, \mathcal{E})\), which are independent of \( N(t) \) as well. Moreover we take a function \( \phi : E \times \mathbb{R}^d \to \mathbb{R}^d \) and we denote \( \phi_z(x) = \phi(z, x) \). We will precise in a moment the hypothesis on \( \phi \). We associate the operator

\[ U_z f(x) = f(\phi_z(x)) \]

(2.34)

and we define \( \mathcal{P}_t \) to be the perturbation of \( P_t \) in the following way. Conditionally to \( T_k \) and \( Z_k, k \in \mathbb{N} \) we define

\[
\begin{align*}
P_t^{N, Z} &= P_t & \text{for } t < T_1, \\
P_t^{N, Z} &= U_{Z_k} P_t^{N, Z} & \text{for } T_k \leq t < T_{k+1}, \\
P_t^{N, Z} &= P_{t-T_k} P_t^{N, Z} & \text{for } T_k \leq t < T_{k+1}
\end{align*}
\]

(2.35)

The second equality reads \( P_t^{N, Z} f(x) = P_{T_k} f(\phi_{Z_k}) \). Essentially (2.35) means that on \([T_k-1, T_k]\) we have a process which evolves according to the semigroup \( P_t \) and at time \( T_k \) it jumps according to \( \phi_{Z_k} \). Then we define

\[
\mathcal{P}_t f(x) = \mathbb{E}(P_t^{N, Z} f(x)) = \sum_{m=0}^{\infty} I_m(f)(x)
\]

with

\[
I_0(f)(x) = \mathbb{E}(1_{\{N(t)=0\}} P_t f(x)) = e^{-\rho t} P_t f(x)
\]

and for \( m \geq 1 \),

\[
I_m(f)(x) = \mathbb{E}(1_{\{N(t)=m\}} \frac{m!}{t^m} \int_{0<t_1<...<t_{m-1}<t_{m}=t} P_{t-t_m} \prod_{i=0}^{m-1} U_{Z_{m-i}} P_{t_{m-i}-t_{m-i-1}} f(x) dt_1 ... dt_m)
\]

\[
= \rho^m e^{-\rho t} \mathbb{E} \left( \int_{0<t_1<...<t_{m-1}<t_{m}=t} \left( \prod_{i=0}^{m-1} P_{t_{m-i-1}-t_{m-i}} U_{Z_{m-i}} \right) P_{t_1} f(x) dt_1 ... dt_m \right),
\]

in which \( t_0 = 0 \) and \( t_{m+1} = t \). We come now to the hypothesis on \( \phi \). We assume that for every \( z \in E, \phi_z \in C^\infty(\mathbb{R}^d) \) and \( \nabla \phi_z \in C^\infty(\mathbb{R}^d) \) and that for every \( q \in \mathbb{N} \)

\[
||\phi||_{1,q,\infty} := \sup_{z \in E} ||\phi_z||_{1,q,\infty} = \sum_{1 \leq |\alpha| \leq q} \sup_{z \in E} \sup_{x \in \mathbb{R}^d} |\partial_x^\alpha \phi(z, x)| < \infty,
\]

(2.36)

\[
\hat{\omega} := \sup_{z \in E} |\phi_z(0)| < \infty.
\]

(2.37)

Moreover we define \( \sigma(\phi_z) = \nabla \phi_z(\nabla \phi_z)^* \) and we assume that there exists a constant \( \varepsilon(\phi) > 0 \) such that for every \( z \in E \) and \( x \in \mathbb{R}^d \)

\[
\det \sigma(\phi_z)(x) \geq \varepsilon(\phi).
\]

(2.38)
Remark 2.10 We recall that in Appendix A.3 we have denoted \( V_\phi f(x) = f(\phi(x)) = U_z f(x) \). With this notation, under (2.36), (2.37), (2.38) we have proved in (A.21) and (A.23) that, for every \( z \in E \),

\[
\| U_z f \|_{q, -\kappa, \infty} \leq C 1 \vee \hat{\phi}^{2\kappa} \| \phi \|_{1,q,\infty}^{q+2\kappa} f \|_{q, -\kappa, \infty},
\]

\[
\| U_z^* f \|_{q,\kappa,p} \leq C \frac{1 \vee \hat{\phi}^{2\kappa}}{\varepsilon(\phi)^{q(q+1)+1/p_*}} \times (1 \vee \| \phi \|_{1,q+2,\infty}^{2dq+1+2\kappa}) \times \| f \|_{q,\kappa,p}.
\]

This means that Assumption 3.5 from Section 3.2 hold uniformly in \( z \in E \) and the constant given in (3.20) is upper bounded by

\[
C_{q,\kappa,\infty,p}(U,P) \leq C \frac{1 \vee \hat{\phi}^{\kappa}}{\varepsilon(\phi)^{q(q+1)+1/p_*}} \times (1 \vee \| \phi \|_{1,q+2,\infty}^{2dq+1+2\kappa}) \times (C_{q,\kappa,\infty}(P) \vee C_{q,\kappa,p}(P)).
\]

We are now able to give our result (the proof being postponed for Section 4.3):

**Theorem 2.11** Suppose that \( P_t \) satisfies assumptions 2.8 and 2.9. Suppose moreover that \( \phi \) satisfies (2.36), (2.37), (2.38). Then \( \bar{P}_t(x,dy) = \bar{p}_t(x,y)dy \) and we have the following estimates. Let \( q \in \mathbb{N}, \kappa \geq 0 \) and \( \delta > 0 \) be given. There exist some constants \( C, \chi \) such that for every \( \alpha, \beta \) with \( |\alpha| + |\beta| \leq q \)

\[
\left| \partial_x^\alpha \partial_y^\beta \bar{p}_t(x,y) \right| \leq \frac{C^\rho}{(\lambda t)^{q(1+\delta)}} \times \frac{\psi_\chi(x)}{\psi_\kappa(x-y)}.
\]

We stress that the constant \( C \) depends on \( C_{q,\kappa,\infty,p}(U,P) \) (see (2.42)) and on \( q, \kappa \) and \( \delta \) but not on \( t, \rho \) and \( \lambda \).

This gives the following consequence concerning the semigroup \( P_t \) itself:

**Corollary 2.12** Suppose that (2.31),(2.32),(2.33) hold. Then, does not matter the value of \( \theta_1 \) in (2.33), the inequality (2.33) holds with \( \theta'_1 = 2d + \varepsilon \) for every \( \varepsilon > 0 \).

Proof. Just take \( \phi_z(x) = x \).

3 Regularity results

This section is devoted to some preliminary results allowing us to prove the statements resumed in Section 2.2: in Section 3.1 we give an abstract regularity criterion, in Section 3.2 we prove a regularity result for iterated integrals.

3.1 A regularity criterion based on interpolation

Let us first recall some results obtained in [3] concerning the regularity of a measure \( \mu \) on \( \mathbb{R}^d \) (with the Borel \( \sigma \)-field). For two signed finite measures \( \mu, \nu \) and for \( k \in \mathbb{N} \) we define the distance

\[
d_k(\mu, \nu) = \sup \left\{ \left| \int f d\mu - \int f d\nu \right| : \| f \|_{k,\infty} \leq 1 \right\}.
\]

\[ (3.1) \]
If $\mu$ and $\nu$ are probability measures, $d_0$ is the total variation distance and $d_1$ is the Forté-Mourier distance. In this paper we will work with an arbitrary $k \in \mathbb{N}$. Notice also that $d_k(\mu, \nu) = \|\mu - \nu\|_{W^k,\infty}$ where $W^k,\infty$ is the dual of $W^{k,\infty}$.

We fix now $k, q, h \in \mathbb{N}$, with $h \geq 1$, and $p > 1$. Hereafter, we denote by $p_* = p/(p - 1)$ the conjugate of $p$. Then, for a signed finite measure $\mu$ and for a sequence of absolutely continuous signed finite measures $\mu_n(dx) = f_n(x)dx$ with $f_n \in C^{2h+q}(\mathbb{R}^d)$, we define

$$
\pi_{k, q, h, p}(\mu, (\mu_n)_n) = \sum_{n=0}^{\infty} 2^{n(k+q+d/p_*)} d_k(\mu, \mu_n) + \sum_{n=0}^{\infty} \frac{1}{2^{nqh}} \|f_n\|_{2h+q, 2h, p}. \quad (3.2)
$$

**Remark 3.1** Notice that $\pi_{k, q, h, p}$ is a particular case of $\pi_{k, q, h, e}$ treated in [3]: just choose the Young function $e(x) \equiv e_p(x) = |x|^p$, giving $\beta_{e_p}(t) = t^{1/p_*}$ (see Example 1 in [3]). Moreover, $\pi_{k, q, h, p}$ is strongly related to interpolation spaces. More precisely, let

$$
\pi_{k, q, h, p}(\mu) = \inf\{\pi_{k, q, h, p}(\mu, (\mu_n)_n) : \mu_n(dx) = f_n(x)dx, \ f_n \in C^{2h+q}(\mathbb{R}^d)\}.
$$

Then $\pi_{k, q, h, p}$ is equivalent with the interpolation norm of order $\rho = \frac{k+q+d/p_*}{2h}$ between the spaces $W^{k,\infty}$ (the dual of $W^{k,\infty}$) and $W^{2h+q, 2h, p} = \{f : \|f_n\|_{2h+q, 2h, p} < \infty\}$. This is proved in [3], see Section 2.4 and Appendix B. So the inequality (3.3) below says that the Sobolev space $W^{q,p}$ is included in the above interpolation space. However we prefer to remain in an elementary framework and to derive directly the consequences of (3.3) - see Lemma 3.4 below.

The following result is the key point in our approach (this is Proposition 2.5 in [3]):

**Lemma 3.2** Let $k, q, h \in \mathbb{N}$ with $h \geq 1$, and $p > 1$ be given. There exists a constant $C_*$ (depending on $k, q, h$ and $p$ only) such that the following holds. Let $\mu$ be a finite measure for which one may find a sequence $\mu_n(dx) = f_n(x)dx$, $n \in \mathbb{N}$ such that $\pi_{k, q, h, p}(\mu, (\mu_n)_n) < \infty$. Then $\mu(dx) = f(x)dx$ with $f \in W^{q,p}$ and moreover

$$
\|f\|_{q,p} \leq C_* \times \pi_{k, q, h, p}(\mu, (\mu_n)_n). \quad (3.3)
$$

The proof of Lemma 3.2 is given in [3], being a particular case (take $e = e_p$) of Proposition A.1 in Appendix A.

We give a first simple consequence.

**Lemma 3.3** Let $p_t \in C^\infty(\mathbb{R}^d)$, $t > 0$ be a family of non negative functions and let $\varphi = \varphi(x) \geq 0$ be such that $\int \varphi(x)p_t(x)dx \leq m < \infty$ for every $t < 1$. We assume that for some $\theta_0 > 0$ and $\theta_1 > 0$ the following holds: for every $q \in \mathbb{N}$ and $p > 1$ there exists a constant $C = C(q, p)$ such that

$$
\|\varphi p_t\|_{q,p} \leq C t^{-\theta_0(q+\theta_1)}, \quad t < 1. \quad (3.4)
$$

Let $\delta > 0$. Then, there exists a constant $C_* = C_*(q, p, \delta)$ such that

$$
\|\varphi p_t\|_{q,p} \leq C_* t^{-\theta_0(q+\frac{d}{p_*}+\delta)}, \quad t < 1, \quad (3.5)
$$

where $p_*$ is the conjugate of $p$. So, does not matter the value of $\theta_1$, one may replace it by $\frac{d}{p_*}$.
Proof We take \(n_* \in \mathbb{N}\) and we define \(f_n = 0\) for \(n \leq n_*\) and \(f_n = \varphi p_t\) for \(n > n_*\). Notice that \(d_0(\varphi p_t, 0) \leq m\). Then (3.3) with \(k = 0\) gives (\(C\) denoting a positive constant which may change from a line to another)
\[
\|\varphi p_t\|_{q,p} \leq C \left( \sum_{n=0}^{n_*} 2^{n(q + \frac{d}{p_*})} + \|\varphi p_t\|_{2h+q,2h,p} \sum_{n=n_*+1}^{\infty} \frac{1}{2^{2nh}} \right) 
\leq C \left( m2^{n_*}(q + \frac{d}{p_*}) + \|\varphi p_t\|_{2h+q,2h,p} \frac{1}{2^{2n_*+1}} \right).
\]

We denote \(\rho_h = (q + \frac{d}{p_*})/2h\). We optimize over \(n_*\) and we obtain
\[
\|\varphi p_t\|_{q,p} \leq 2C \times \frac{m^\frac{1}{1+\rho_h}}{\|\varphi p_t\|_{2h+q,2h,p}^{\frac{\rho_h}{1+\rho_h}}} \leq 2Cm^{\frac{1}{1+\rho_h}} \times C\theta_{0}(2h+q+\vartheta(1))^{\frac{\rho_h}{1+\rho_h}}.
\]

Since \(\lim_{h \rightarrow \infty} \rho_h = 0\) and \(\lim_{h \rightarrow \infty} (2h + q + \vartheta)_{\frac{\rho_h}{1+\rho_h}} = q + \frac{d}{p_*}\) the proof is completed, we choose \(h\) large enough and we obtain (3.5). □

We will also use the following consequence of Lemma 3.2.

Lemma 3.4 Let \(k, q, h \in \mathbb{N}\), with \(h \geq 1\), and \(p > 1\) be given and set
\[
\rho_h := \frac{k + q + d/p_*}{2h}.
\]
We consider an increasing sequence \(\vartheta(n) \geq 1, n \in \mathbb{N}\) such that \(\lim_{n} \vartheta(n) = \infty\) and \(\vartheta(n + 1) \leq \Theta \times \vartheta(n)\) for some constant \(\Theta \geq 1\). Suppose that we may find a sequence of functions \(f_n \in C^{2h+q}(\mathbb{R}^d), n \in \mathbb{N}\) such that
\[
\|f_n\|_{2h+q,2h,p} \leq \vartheta(n) \tag{3.7}
\]
and, with \(\mu_n(dx) = f_n(x)dx\),
\[
\limsup_n d_k(\mu, \mu_n) \times \vartheta^{\rho_h + \varepsilon}(n) < \infty \tag{3.8}
\]
for some \(\varepsilon > 0\). Then \(\mu(dx) = f(x)dx\) with \(f \in W^{q,p}\).

Moreover, for \(\delta, \varepsilon > 0\) and \(n_* \in \mathbb{N}\), let
\[
A(\delta) = |\mu| (\mathbb{R}^d) \times 2^{l(\delta)(1+\delta)(q+k+d/p_*)} \quad \text{with} \quad l(\delta) = \min\{l : 2^{l\times \frac{\delta}{1+\delta}} \geq l\}, \tag{3.9}
\]
\[
B(\varepsilon) = \sum_{l=1}^{\infty} \frac{2^{l(q+k+d/p_*)+\varepsilon}}{2^{2l\delta}}, \tag{3.10}
\]
\[
C_{h,n_*}(\varepsilon) = \sup_{n \geq n_*} d_k(\mu, \mu_n) \times \vartheta^{\rho_h + \varepsilon}(n). \tag{3.11}
\]

Then, for every \(\delta > 0\)
\[
\|f\|_{q,p} \leq C_* (\Theta + A(\delta)\vartheta(n_*)^{\rho_h(1+\delta)} + B(\varepsilon)C_{h,n_*}(\varepsilon)), \tag{3.12}
\]
\(C_*\) being the constant in (3.3) and \(\rho_h\) being given in (3.6).
**Proof of Lemma 3.4.** We will produce a sequence of measures \( \nu_l(dx) = g_l(x)dx, l \in \mathbb{N} \) such that
\[
\pi_{k,q,h,p}(\mu, (\nu_l)_l) \leq \Theta + A(\delta)\theta(n_\ast)^{\theta_h(1+\delta)} + B(\varepsilon)C_{h,n_\ast}(\varepsilon) < \infty.
\]
Then by Lemma 3.2 one gets \( \mu(dx) = f(x)dx \) with \( f \in W^{q,p} \) and (3.12) follows from (3.3). Let us stress that the \( \nu_l \)'s will be given by a suitable subsequence \( \mu_{n(l)}, l \in \mathbb{N} \), from the \( \mu_n \)'s.

**Step 1.** We define
\[
n(l) = \min\{n : \theta(n) \geq \frac{2^{2hl}}{l^2}\}
\]
and we notice that
\[
\frac{1}{\Theta} \theta(n(l)) < \theta(n(l)-1) < \frac{2^{2hl}}{l^2} \leq \theta(n(l)).
\]  
Moreover we define
\[
l_\ast = \min\{l : \frac{2^{2hl}}{l^2} \geq \theta(n_\ast)\}.
\]
Since
\[
\theta(n(l_\ast)) \geq \frac{2^{2hl_\ast}}{l_\ast^2} \geq \theta(n_\ast)
\]
it follows that \( n(l_\ast) \geq n_\ast \).

We take now \( \varepsilon(\delta) = \frac{h\delta}{1+\delta} \) which gives \( \frac{2h}{2\delta(1+\delta)} = 1 + \delta \). And we take \( l(\delta) \geq 1 \) such that \( 2^{l(\delta)}(1+\delta) \geq l \) for \( l \geq l(\delta) \). Since \( h \geq 1 \) it follows that \( \varepsilon(\delta) \geq \frac{\delta}{1+\delta} \) so that, for \( l \geq l(\delta) \) we also have \( 2^{l(\delta)}(1+\delta) \geq l \). Now we check that
\[
2^{2(h-\varepsilon(\delta))(l_\ast)} \leq 2^{2hl_\ast}\theta(n_\ast).
\]  
If \( l_\ast \leq l(\delta) \) then the inequality is evident (recall that \( \theta(n) \geq 1 \) for every \( n \)). And if \( l_\ast > l(\delta) \) then \( 2^{l_\ast(\varepsilon(\delta))} \geq l_\ast \). By the very definition of \( l_\ast \) we have
\[
\frac{2^{2h(l_\ast-1)}}{(l_\ast-1)^2} \leq \theta(n_\ast)
\]
so that
\[
2^{hl_\ast} \leq 2^{2h(l_\ast-1)}2^{2hl_\ast} \leq 2^{2h} \times 2^{2l_\ast(\varepsilon(\delta))}\theta(n_\ast)
\]
and this gives (3.14).

**Step 2.** We define
\[
\nu_l = 0 \text{ if } l < l_\ast \text{ and } \nu_l = \mu_{n(l)} \text{ if } l \geq l_\ast
\]
and we estimate \( \pi_{k,q,h,p}(\mu, (\nu_l)_l) \). First, by (3.7) and (3.13)
\[
\sum_{l=l_\ast}^{\infty} \frac{1}{2^{2hl}} \|f_n(l)\|_{q+2h,2h,p} \leq \sum_{l=l_\ast}^{\infty} \frac{1}{2^{2hl}} \theta(n(l)) \leq \Theta \sum_{l=l_\ast}^{\infty} \frac{1}{l^2} \leq \Theta.
\]
Then we write
\[
\sum_{l=1}^{\infty} 2^{(q+k+d/p_\ast)l}d_k(\mu, \nu_l) = S_1 + S_2
\]
with
\[
S_1 = \sum_{l=1}^{l_\ast-1} 2^{(q+k+d/p_\ast)l}d_k(\mu, 0), \quad S_2 = \sum_{l=l_\ast}^{\infty} 2^{(q+k+d/p_\ast)l}d_k(\mu, \mu_{n(l)}).
\]
Since \( d_k(\mu, 0) \leq d_0(\mu, 0) \leq |\mu| (\mathbb{R}^d) \) we use (3.14) and we obtain

\[
S_1 \leq |\mu| (\mathbb{R}^d) \times 2^{(q+k+d/p_*)} = |\mu| (\mathbb{R}^d) \times (2^{(2(h-\varepsilon(\delta))l_*)} (q+k+d/p_*)/2(h-\varepsilon(\delta)) \\
\leq |\mu| (\mathbb{R}^d) \times (2^{2h_0(\delta)} \theta(n_*)^{\rho_{h}(1+\delta)}) = A(\delta) \theta(n_*)^{\rho_{h}(1+\delta)}.
\]

If \( l \geq l_* \) then \( n(l) \geq n(l_*) \geq n_* \) so that, from (3.11),

\[
d_k(\mu, \mu(l)) \leq C_{h,n_*}(\varepsilon) \frac{\rho_{h} + \varepsilon}{n(l)} \leq C_{h,n_*}(\varepsilon) \frac{l_0^2}{2h_0 l} = C_{h,n_*}(\varepsilon) \frac{l_0^2(\rho_{h} + \varepsilon)}{2h_0 l}.
\]

We conclude that

\[
S_2 \leq C_{h,n_*}(\varepsilon) \sum_{l=l_*/}^{\infty} \frac{l_0^2(\rho_{h} + \varepsilon)}{2h_0 l} \leq C_{h,n_*}(\varepsilon) \times B(\varepsilon).
\]

\[
\square
\]

### 3.2 A regularity lemma

We give here a regularization result in the following abstract framework. We consider a sequence of operators \( U_j : \mathcal{S}(\mathbb{R}^d) \to \mathcal{S}(\mathbb{R}^d), \ j \in \mathbb{N}, \) and we denote by \( U_j^* \) the formal adjoint defined by \( \langle U_j^* f, g \rangle = \langle f, U_j g \rangle \) with the scalar product in \( L^2(\mathbb{R}^d). \)

**Assumption 3.5** Let \( a \in \mathbb{N} \) be fixed. We assume that for every \( q \in \mathbb{N}, \kappa \geq 0 \) and \( p \in [1, \infty) \) there exist constants \( C_{q,\kappa,p}(U) \) and \( C_{q,\kappa,\infty}(U) \) such that for every \( j \) and \( f, \)

\[
(H_1) \quad \| U_j f \|_{q,a,\kappa,\infty} \leq C_{q,\kappa,\infty}(U) \| f \|_{q+a,\kappa,\infty}, \tag{3.15}
\]

\[
(H_2) \quad \| U_j f \|_{q,a,\kappa,p} \leq C_{q,\kappa,p}(U) \| f \|_{q+a,\kappa,p}. \tag{3.16}
\]

We assume that \( C_{q,\kappa,p}(U), p \in [1, \infty], \) is non decreasing with respect to \( q \) and \( \kappa. \)

We also consider a semigroup \( S_t, t \geq 0, \) of the form

\[
S_t(x, dy) = s_t(x,y)dy \quad \text{with} \quad s_t \in \mathcal{S}(\mathbb{R}^d \times \mathbb{R}^d).
\]

We define the formal adjoint operator

\[
S_t^* f(y) = \int_{\mathbb{R}^d} s_t(x,y)f(x)dx, \quad t > 0.
\]

**Assumption 3.6** If \( f \in \mathcal{S}(\mathbb{R}^d) \) then \( S_t f \in \mathcal{S}(\mathbb{R}^d). \) Moreover, there exist \( b \in \mathbb{N} \) such that for every \( q \in \mathbb{N}, \kappa \geq 0 \) and \( p \in [1, \infty) \) there exist constants \( C_{q,\kappa,p}(S) \) such that for every \( t > 0, \)

\[
(H_3) \quad \| S_t f \|_{q,a,\kappa,\infty} \leq C_{q,\kappa,\infty}(S) \| f \|_{q+a,\kappa,\infty}, \tag{3.17}
\]

\[
(H_4) \quad \| S_t^* f \|_{q,a,\kappa,p} \leq C_{q,\kappa,p}(S) \| f \|_{q+a,\kappa,p}. \tag{3.18}
\]

We assume that \( C_{q,\kappa,p}(S), p \in [1, \infty], \) is non decreasing with respect to \( q \) and \( \kappa. \)
We denote
\[ C_{q,k,\infty}(U, S) = C_{q,k,\infty}(U)C_{q,k,\infty}(S), \quad C_{q,k,p}(U, S) = C_{q,k,p}(U)C_{q,k,p}(S), \quad \quad (3.19) \]
\[ C_{q,k,\infty,p}(U, S) = C_{q,k,\infty}(U, S) \lor C_{q,k,p}(U, S). \quad \quad (3.20) \]

Under Assumption 3.5 and 3.6, one immediately obtains
\[ \| (S_t U_j)f \|_{q,-\infty,\infty} \leq C_{q,k,\infty}(U, S) \| f \|_{q+a+b,-\infty,\infty}, \quad (3.21) \]
\[ \| (S_t^* U_j^*)f \|_{q,k,p} \leq C_{q,k,p}(U, S) \| f \|_{q+a+b,k,p}. \quad (3.22) \]

In fact these are the inequalities that we will employ in the following. We stress that the above constants \( C_{q,k,\infty}(U, S) \) and \( C_{q,k,p}(U, S) \) may depend on \( a, b \) and are increasing w.r.t. \( q \) and \( \kappa \).

Finally we assume that the (possible) blow up of \( s_t \to \infty \) as \( t \to 0 \) is controlled in the following way.

**Assumption 3.7** Let \( \theta_0, \lambda > 0 \) be fixed. We assume that for every \( \kappa \geq 0 \) and \( q \in \mathbb{N} \) there exist \( \pi(q, \kappa), \theta_1 \geq 0 \) and \( C_{q,k} > 0 \) such that for every multi-indexes \( \alpha \) and \( \beta \) with \( |\alpha| + |\beta| \leq q \), \( (x, y) \in \mathbb{R}^d \times \mathbb{R}^d \) and \( t \in (0, 1] \) one has
\[
(H_3) \quad \| \partial_x^\alpha \partial_y^\beta s_t(x, y) \| \leq \frac{C_{q,k}}{(\lambda t)^{\theta_0(q+\theta_1)}} \times \frac{\psi_{\pi(q, \kappa)}(x)}{\psi_\kappa(x-y)}. \quad (3.23)
\]

We also assume that \( \pi(q, k) \) and \( C_{q,k} \) are both increasing in \( q \) and \( \kappa \).

This property will be used by means of the following lemma:

**Lemma 3.8** Suppose that Assumption 3.7 holds.

**A.** For every \( \kappa \geq 0 \), \( q \in \mathbb{N} \) and \( p > 1 \) there exists \( C > 0 \) such that for every \( t \in (0, 1] \) and \( f \) one has
\[
\| S_t^* f \|_{q,k,p} \leq \frac{C}{(\lambda t)^{\theta_0(q+\theta_1)}} \| f \|_{\nu,1} \quad (3.24)
\]
where \( \nu = \pi(q, \kappa + d) + \kappa + d \).

**B.** For every \( \kappa \geq 0 \), \( q_1, q_2 \in \mathbb{N} \) there exists \( C > 0 \) such that for every \( t \in (0, 1] \), for every multi-index \( \alpha \) with \( |\alpha| \leq q_2 \) and \( f \) one has
\[
\left\| \frac{1}{\psi_\eta} S_t(\psi_\eta \partial_\alpha f) \right\|_{q_1,\infty} \leq \frac{C}{(\lambda t)^{\theta_0(q_1+q_2+\theta_1)}} \| f \|_{\infty} \quad (3.25)
\]
where \( \eta = \pi(q_1 + q_2, \kappa + d + 1) + \kappa \).

**Proof.** In the sequel, \( C \) will denote a positive constant which may vary from a line to another and which may depend only on \( \kappa \) and \( q \) for the proof of **A.** and only on \( \kappa, q_1 \) and \( q_2 \) for the proof of **B.**

**A.** Using (3.23) if \( |\alpha| \leq q \),
\[
|\partial_\alpha S_t^* f(x)| \leq \int |\partial_\alpha s_t(y, x)| \times |f(y)| \, dy \leq \frac{C}{(\lambda t)^{\theta_0(q+\theta_1)}} \int \frac{\psi_{\pi(q, \kappa + d)}(y)}{\psi_{\kappa + d}(x-y)} \times |f(y)| \, dy.
\]
By (2.4) \( \psi_{k+d}(x)/\psi_{k+d}(x-y) \leq C\psi_{k+d}(y) \) so that
\[
\psi_{k+d}(x) |\partial^\alpha S^*_t f(x)| \leq \frac{C}{(\lambda t)^{\theta_0(q+\theta_1)}} \int \frac{\psi_{k+d}(x)\psi_{\pi(k,k+d)}(y)}{\psi_{k+d}(x-y)} \times |f(y)| \, dy \\
\leq \frac{C}{(\lambda t)^{\theta_0(q+\theta_1)}} \int \psi_{\pi(k,k+d)+k+d}(y) \times |f(y)| \, dy \\
= \frac{C}{(\lambda t)^{\theta_0(q+\theta_1)}} \|f\|_{0,\nu,1}
\]
We conclude that
\[
\|S_t^* f\|_{q,k,d,\infty} \leq \frac{C}{(\lambda t)^{\theta_0(q+\theta_1)}} \|f\|_{0,\nu,1}.
\]
By (2.9) \( \|S_t^* f\|_{q,k,p} \leq C \|S_t^* f\|_{q,k,d,\infty} \) so the proof of (3.24) is completed.

**B.** Let \( \gamma \) with \( |\gamma| \leq q_1 \). Using integration by parts
\[
\partial^{\gamma} S_t(\psi_{k}\partial^\alpha f)(x) = \int_{\mathbb{R}^d} \partial_y^\gamma s_t(x,y)\psi_{k}(y)\partial^\alpha f(y) \, dy \\
= (-1)^{|\alpha|} \int_{\mathbb{R}^d} \partial_y^\alpha (\partial_y^\gamma s_t(x,y)\psi_{k}(y)) \times f(y) \, dy.
\]
Using (2.6), (3.23) and (2.4), it follows that
\[
|\partial^{\gamma} S_t(\psi_{k}\partial^\alpha f)(x)| \leq \int_{\mathbb{R}^d} \left| \partial_y^\alpha (\partial_y^\gamma s_t(x,y)\psi_{k}(y)) \right| \times |f(y)| \, dy \\
\leq \int_{\mathbb{R}^d} |s_t(x,y)\psi_{k}(y)|_{q_1+q_2} \times |f(y)| \, dy \\
\leq C \int_{\mathbb{R}^d} |s_t(x,y)\psi_{k}(y)|_{q_1+q_2} \times |f(y)| \, dy \\
\leq \frac{C}{(\lambda t)^{\theta_0(q_1+q_2+\theta_1)}} \|f\|_{\infty} \int_{\mathbb{R}^d} \frac{\psi_{\pi(q_1+q_2,k+d+1)}(x)}{\psi_{k+d+1}(x-y)} \times \psi_{k}(y) \, dy \\
\leq \frac{C}{(\lambda t)^{\theta_0(q_1+q_2+\theta_1)}} \|f\|_{\infty} \int_{\mathbb{R}^d} \frac{\psi_{\pi(q_1+q_2,k+d+1)+k}(x)}{\psi_{d+1}(x-y)} \, dy \\
\leq \frac{C}{(\lambda t)^{\theta_0(q_1+q_2+\theta_1)}} \|f\|_{\infty} \psi_{\pi(q_1+q_2,k+d+1)+k}(x).
\]
This implies (3.25). \( \square \)

We are now able to give the “regularity lemma”. This is the core of our approach.

**Lemma 3.9** Suppose that Assumption 3.5, 3.6 and 3.7 hold. We fix \( t \in (0,1], \ m \geq 1 \) and \( \delta_i > 0, \ i = 1, \ldots, m \) such that \( \sum_{i=1}^{m} \delta_i = t \).

**A.** There exists a function \( \tilde{p}_{\delta_1,\ldots,\delta_m} \in C^\infty(\mathbb{R}^d \times \mathbb{R}^d) \) such that
\[
\prod_{i=1}^{m-1} (S_{\delta_i}U_i)S_{\delta_m} f(x) = \int \tilde{p}_{\delta_1,\ldots,\delta_m}(x,y) f(y) \, dy. \tag{3.26}
\]
B. We fix $q_1, q_2 \in \mathbb{N}, \kappa \geq 0, p > 1$ and we denote $q = q_1 + q_2 + (a + b)(m - 1)$. One may find universal constants $C, \chi, \tilde{p} \geq 1$ (depending on $\kappa, p$ and $q_1 + q_2$) such that for every multi-index $\beta$ with $|\beta| \leq q_2$ and every $x \in \mathbb{R}^d$

$$\left\| \partial_\beta \tilde{p}_{\delta_1, \ldots, \delta_m}(x, \cdot) \right\|_{q_1, \kappa, p} \leq C \left( \frac{2m}{\lambda t} \right)^{\theta_0(q_1 + q_2 + d + 2\delta_1)} \left( C_{q, \lambda, \tilde{p}, \infty}(U, S) \left( \frac{2m}{\lambda t} \right)^{\theta_0(a + b)} \right)^{m - 1} \psi_\chi(x).$$

(3.27)

**Proof.** A. For $g = g(x, y)$, we denote $g^x(y) := g(x, y)$. By the very definition of $U_i^*$ one has

$$S_i U_i f(x) = \int_{\mathbb{R}^d} U_i^* s_i^x(y) f(y) dy.$$

As a consequence, one gets the kernel in (3.26):

$$\tilde{p}_{\delta_1, \ldots, \delta_m}(x, y) = \int_{\mathbb{R}^{d \times (m - 1)}} U_1^* s_{\delta_1}^x(y_1) \left( \prod_{j=2}^{m-1} U_j^* s_{\delta_j}^{y_{j-1}}(y_j) \right) s_{\delta_m}(y_{m-1}, y) dy_1 \cdots dy_{m-1},$$

and the regularity immediately follows.

B. We split the proof in several steps.

**Step 1: decomposition.** Since $\sum_{i=1}^m \delta_i = t$ we may find $j \in \{1, \ldots, m\}$ such that $\delta_j \geq \frac{t}{m}$. We fix this $j$ and we write

$$\prod_{i=1}^{m-1} (S_{\delta_i} U_i) S_{\delta_m} = Q_1 Q_2$$

with

$$Q_1 = \prod_{i=1}^{j-1} (S_{\delta_i} U_i) S_{\frac{1}{2} \delta_j} \quad \text{and} \quad Q_2 = S_{\frac{1}{2} \delta_j} U_j \prod_{i=j+1}^{m-1} (S_{\delta_i} U_i) S_{\delta_m} = S_{\frac{1}{2} \delta_j} \prod_{i=j}^{m-1} (U_i S_{\delta_{i+1}}).$$

Here we use the semi-group property $S_{\frac{1}{2} \delta_j} S_{\frac{1}{2} \delta_j} = S_{\delta_j}$.

We suppose that $j \leq m - 1$. In the case $j = m$ the proof is analogous but simpler. We will use Lemma 3.8 in order to estimate the terms corresponding to each of these two operators. As already seen, both $Q_1$ and $Q_2$ are given by means of smooth kernels, that we call $p_1(x, y)$ and $p_2(x, y)$ respectively.

**Step 2.** We take $\beta$ with $|\beta| \leq q_2$ and we denote $g^{\beta, x}(y) := \partial_\beta g(x, y)$. For $h \in L^1$ we write

$$\int_{\mathbb{R}^d} h(z) \partial_\beta \tilde{p}_{\delta_1, \ldots, \delta_m}(x, z) dz = \int_{\mathbb{R}^d} h(z) \left( \int_{\mathbb{R}^d} \partial_\beta p_1(x, y) p_2(y, z) dy dz \right)$$

$$= \int_{\mathbb{R}^d} \partial_\beta p_1(x, y) \int_{\mathbb{R}^d} h(z) p_2(y, z) dz dy = \int_{\mathbb{R}^d} \partial_\beta p_1(x, y) Q_2 h(y) dy$$

$$= \int_{\mathbb{R}^d} Q_2 \partial_\beta p_1^x(y) h(y) dy.$$

It follows that

$$\partial_\beta \tilde{p}_{\delta_1, \ldots, \delta_m}(x, z) = Q_2^* \partial_\beta p_1^x(z) = \prod_{i=1}^{m-j} (S_{\delta_{m-i}}^* U_{m-i}^*) S_{\frac{1}{2} \delta_j}^* \partial_\beta p_1^x(z).$$

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We will use (3.22) $m - j$ times first and (3.24) then. We denote
\[ q'_1 = q_1 + (m - j)(a + b) \]
and we write
\[
\| \partial_x^\beta p_{q_1,\ldots,q_m}(x,\cdot) \|_{q_1,\ldots,q_m} \leq C_{q_1,\ldots,q_m} S_{\frac{1}{2}a_1} P_1^{\beta,x} \| q'_1,\ldots,q'_m \|
\]
\[
\leq C_{q_1,\ldots,q_m} S_{\frac{1}{2}a_1} (U, S) C \left( \frac{2m}{\lambda t} \right)^{\theta_0(q'_1 + \theta_1)} \| P_1^{\beta,x} \|_{0,\nu,1}
\]
(3.28)
with
\[ \nu = \pi(q'_1, \kappa + d) + \kappa + d. \]

**Step 3.** We denote $g_z(u) = \prod_{l=1}^{d} 1(0,\infty)(u_l - z_l)$, so that $\delta_0(u - z) = \partial_0 g_z(u)$ with $\rho = (1, 2, \ldots, d)$. We take $\mu = \nu + d + 1$ and we formally write
\[ p_1(x, z) = \frac{1}{\psi_\mu(z)} Q_1(\psi_\mu \partial^\rho g_z)(x). \]

This formal equality can be rigorously written by using the regularization by convolution of the Dirac function.

We denote
\[ q'_2 = q_2 + (j - 1)(a + b), \quad \eta = \pi(d + q'_2, \mu + d + 1) + \mu \]
and we write
\[
|p_1^{\beta,x}(z)| = |\partial_x^\beta p_1(x, z)| \leq \frac{\psi_\eta(x)}{\psi_\eta(z)} \left| \partial^\beta Q_1(\psi_\mu \partial^\rho g_z) \right|_{\infty}.
\]
Since $\mu = \nu + d + 1$, $\int \psi_\nu \times \frac{1}{\psi_\mu} < \infty$, so using (2.6), we obtain (recall that $|\beta| \leq q_2$
\[
\| p_1^{\beta,x} \|_{0,\nu,1} \leq C \psi_\eta(x) \sup_{z \in \mathbb{R}^d} \left( \left| \partial^\beta Q_1(\psi_\mu \partial^\rho g_z) \right|_{\infty} \leq C \psi_\eta(x) \sup_{z \in \mathbb{R}^d} \left( \left| \partial^\beta Q_1(\psi_\mu \partial^\rho g_z) \right|_{q_2,\ldots,q_\infty} \right.
\]
\[
\leq C \psi_\eta(x) \sup_{z \in \mathbb{R}^d} \left( Q_1(\psi_\mu \partial^\rho g_z) \right)_{q_2,\ldots,q_\infty}.
\]

Using (3.21) $j - 1$ times and (3.25) (with $\kappa = \mu$) we get
\[
\| Q_1(\psi_\mu \partial^\rho g_z) \|_{q_2,\ldots,q_\infty} \leq C_{q_2,\ldots,q_\infty}(U, S) S_{\frac{1}{2}a_1} \left( \left| \partial^\beta Q_1(\psi_\mu \partial^\rho g_z) \right|_{q_2,\ldots,q_\infty} \right.
\]
\[
\leq C_{q_2,\ldots,q_\infty}(U, S) \| g_z \|_{\infty} \left( \frac{2m}{\lambda t} \right)^{\theta_0(q'_2 + d + \theta_1)}.
\]

Since $\| g_z \|_{\infty} = 1$ we obtain
\[
\| p_1^{\beta,x} \|_{0,\nu,1} \leq \psi_\eta(x) C_{q_2,\ldots,q_\infty}(U, S) C \left( \frac{2m}{\lambda t} \right)^{\theta_0(q'_2 + d + \theta_1)}.
\]
By inserting in (3.28) we obtain (3.27), so the proof is completed. \[\square\]

4 Proofs of the main results

In the present section, we use the results in Section 3 in order to prove Theorem 2.5 (Section 4.1) and Theorem 2.11 (Section 4.3).
4.1 Proof of Theorem 2.5

Step 0: constants and parameters set-up. In this step we will choose some parameters which will be used in the following steps. To begin we stress that we work with measures on \( \mathbb{R}^d \times \mathbb{R}^d \) so the dimension of the space is 2d (and not d). We recall that in our statement the quantities \( q, d, p, \delta, \varepsilon, \kappa \) and \( n \) are given and fixed. In the following we will denote by \( C \) a constant depending on all these parameters and which may change from a line to another. We define

\[
m_0 = 1 + \left[ \frac{q + 2d/p_\delta}{\delta} \right] > 0
\]

and given \( h \in \mathbb{N} \) we denote

\[
\rho_h = \frac{(a + b)m_0 + q + 2d/p_\delta}{2h}.
\]

Notice that this is equal to the constant \( \rho_h \) defined in (3.6) corresponding to \( k = (a + b)m_0 \) and \( q \) and to 2d (instead of d).

Step 1: a Lindeberg-type method to decompose \( P_t - P_t^n \). We fix (once for all) \( t \in (0, 1] \) and we write

\[
P_t f - P_t^n f = \int_0^t \partial_s (P_t^n P_s) f ds = \int_0^t P_t^n (L - L_n) P_s f ds = \int_0^t P_t^n \Delta_n P_s f ds
\]

We iterate this formula \( m_0 \) times (with \( m_0 \) chosen in (4.1)) and we obtain

\[
P_t f(x) - P_t^n f(x) = \sum_{m=1}^{m_0-1} I^n_m f(x) + R^n_{m_0} f(x)
\]

with (we put \( t_0 = t \))

\[
I^n_m f(x) = \int_0^t dt_1 \int_0^{t_1} dt_2 \ldots \int_0^{t_{m-1}} dt_m \prod_{i=0}^{m-1} (P^n_{t_i-t_{i+1}} \Delta_n) P^n_{t_m} f(x), \quad 1 \leq m \leq m_0 - 1,
\]

\[
R^n_{m_0} f(x) = \int_0^t dt_1 \int_0^{t_1} dt_2 \ldots \int_0^{t_{m_0-1}} dt_{m_0} \prod_{i=0}^{m_0-1} (P^n_{t_i-t_{i+1}} \Delta_n) P^n_{t_{m_0}} f(x).
\]

In order to analyze \( I^n_m f \) we use Lemma 3.9 for the semigroup \( S_t = P^n_t \) and for the operators \( U_i = \Delta_n = L - L_n \) (the same for each \( i \)), with \( t_i = t_{i-1} + 1, i = 0, \ldots, m \) (with \( t_{m+1} = 0 \)). So the hypotheses (3.15) and (3.16) in Assumption 3.5 coincide with the requests (2.14) and (2.15) in Assumption 2.1. And we have \( C_{q,\kappa,\infty}(U) = C_{q,\kappa,p}(U) = C\varepsilon_n \). Moreover the hypotheses (3.17) and (3.18) in Assumption 3.6 coincide with the hypotheses (2.16) and (2.17) in Assumption 2.2. And we have \( C_{q,\kappa,\infty}(P^n) = C_{q,\kappa,p}(P^n) = \Lambda_n \). Hence,

\[
C_{q,\kappa,\infty,p}(\Delta_n, P^n) = C \varepsilon_n \times \Lambda_n,
\]

Finally, the hypothesis (3.23) in Assumption 3.7 coincides with (2.20) in Assumption 2.3. So, we can apply Lemma 3.9: by using (3.26) we obtain

\[
I^n_m f(x) = \int_0^t dt_1 \ldots \int_0^{t_{m-1}} dt_m \int_{\mathbb{R}^d} p^n_{t-t_1-t_2-\ldots-t_m}(x, y) f(y) dy.
\]
We denote
\[ \phi_t^{n_m}(x, y) = p_t^n(x, y) + \sum_{m=1}^{m_0-1} \int_0^t dt_1 \ldots \int_0^{t_{m-1}} dt_m p_t^{n_m}(x, y) \]
so that (4.3) reads
\[ \int f(y) P_t(x, dy) = \int f(y) \phi_t^{n_m}(x, y) dy + R_{n_0} f(x). \]

We recall that \( \Psi_{n,\kappa} \) is defined in (2.24) and we define the measures on \( \mathbb{R}^d \times \mathbb{R}^d \) defined by
\[ \mu^{n,\kappa}(dx, dy) = \Psi_{n,\kappa}(x, y) P_t(dx, dy) \quad \text{and} \quad \mu_{n,m}^{n,\kappa}(dx, dy) = \Psi_{n,\kappa}(x, y) \phi_t^{n,m}(x, y) dx dy. \]

So, the proof consists in applying Lemma 3.4 to \( \mu = \mu^{n,\kappa} \) and \( \mu_n = \mu_{n,m}^{n,\kappa}. \)

**Step 2: analysis of the principal term.** We study here the estimates for \( f_n(x, y) = \Psi_{n,\kappa} \phi_t^{n,m}(x, y) \) which are required in (3.7).

We first use (3.27) in order to get estimates for \( p_t^{n,m}(x, y) \). We fix \( q_1, q_2 \in \mathbb{N}, \kappa \geq 0, p > 1 \) and we recall that in Lemma 3.9 we introduced \( \bar{q} = q_1 + q_2 + (a+b)(m_0-1) \). Moreover in Lemma 3.9 one produces \( \chi \) such that (3.27) holds true: for every multi-index \( \beta \) with \( |\beta| \leq q_2 \)
\[ \| \psi_n \partial_x^\beta p_t^{n,m}(x, \cdot) \|_{q_1,p} \leq C \left( \frac{1}{\lambda_n t} \right)^{\theta q_1 q_2 + \theta a + \theta b} \times \left( \varepsilon_n A_n \left( \frac{1}{\lambda_n t} \right)^{\theta a + b} \right)^m \psi_\chi(x). \]

We recall the constant defined in (2.22):
\[ \Phi_n(\delta) = \varepsilon_n A_n \times \frac{1}{\lambda_n^{\theta q_1 q_2 + \theta a + b}}. \]

Denote
\[ \xi_1(q) = q + d + 2\theta_1 + m_0(a + b), \quad \omega_1(q) = q + d + 2\theta_1. \]

With this notation, if \( |\beta| \leq q_2 \) we have
\[ \| \psi_n \partial_x^\beta \phi_t^{n,m}(x, \cdot) \|_{q_1,p} \leq C \left( \frac{1}{\lambda_n t} \right)^{\theta q_1 q_2 + \theta a + b} \times \left( \varepsilon_n A_n \left( \frac{1}{\lambda_n t} \right)^{\theta a + b} \right)^m \psi_\chi(x) \]
\[ = C t^{-\theta q_1(1 + q_1)} \lambda_n^{\theta q_1 q_2(1 + q_2)} \Phi_n^{m_0}(0) \psi_\chi(x). \]

We take \( l = 2h + q, l' = 2h \) and we take \( q(l) = l + (a+b)m_0. \) Moreover we fix \( q_1 \) and \( q_2 \) (so \( q = q_1 + q_2 \leq l \)) and we take \( \chi \) to be the one in (4.5). Moreover we take \( \eta \) is sufficiently large in order to have \( p\eta - 2h - p\chi \geq d + 1. \) This guarantees that
\[ \int_{\mathbb{R}^d} \frac{dx}{\psi_{p\eta - p\chi}} = C < \infty. \]
By (2.6) and (4.5)

\[
\| \Psi_{\eta, \kappa}^{\phi_t} \|_{L_{\kappa\omega}^{m_0}} \leq C \sum_{|\alpha| + |\beta| \leq l} \int_{\mathbb{R}^d} \int_{\mathbb{R}^d} \Psi_{\eta, \kappa}^p(x, y) \left| \partial_x^\alpha \partial_y^\beta \phi_t^{\eta, \kappa, m_0}(x, y) \right|^p \psi_t(x) \psi_t(y) dy dx
\]

\[
= C \sum_{|\alpha| + |\beta| \leq l} \int_{\mathbb{R}^d} \psi_{\eta, \kappa}^p(y) \int_{\mathbb{R}^d} \left| \psi_{\eta, \kappa}^p(y) \partial_x^\alpha \partial_y^\beta \phi_t^{\eta, \kappa, m_0}(x, y) \right|^p dy dx
\]

\[
\leq C \sum_{|\alpha| + |\beta| \leq l} \int_{\mathbb{R}^d} \psi_{\eta, \kappa}^p(y) \left| \psi_{\eta, \kappa}^p(y) \partial_x^\alpha \partial_y^\beta \phi_t^{\eta, \kappa, m_0}(x, y) \right|^p dx
\]

\[
\leq C \left( t^{-\theta_0 \xi(l)} \lambda^{-\theta_0 \omega(l)} \phi_n(0) \right)^{m_0} \int_{\mathbb{R}^d} \frac{dx}{\psi_{\eta, \kappa}^p(x)}.
\]

We conclude that

\[
\| \Psi_{\eta, \kappa}^{\phi_t} \|_{L_{\kappa\omega}^{m_0}} \leq C t^{-\theta_0 \xi(l + 2h)} \times \lambda^{-\theta_0 \omega(l + 2h)} \phi_n(0) =: \theta(n).
\]

By (2.23) \( \theta(n) \uparrow +\infty \) and \( \Theta \theta(n) \geq \theta(n + 1) \) with

\[\Theta = \gamma^{\theta_0(a+b)m_0 + q + 2h + d + 2\theta_1} m_0 \geq 1.\]

In the following we will choose \( h \) sufficiently large, depending on \( \delta, m_0, q, d \) and \( p \). So \( \Theta \) is a constant depending on \( \delta, m_0, q, d, a, b, \gamma \) and \( p \), as the constants considered in the statement of our theorem.

**Step 3: analysis of the remainder.** We study here \( d_{m_0}(n) := d_{(a+b)m_0}(\mu^{\eta, \kappa}, \mu^{\eta, \kappa, m_0}) \) as required in (3.8): we prove that, if \( \eta \geq \kappa + d + 1 \), then

\[
d_{m_0}(n) \leq C(\Lambda_n \varepsilon_n)^{m_0} \leq \lambda_{n}^{\theta_0(a+b+d)(m_0)} \Phi_{n}^{m_0}(\delta_n).
\]

Using first (A1) and (A2) (see (2.14) and (2.16)) and then (A4) (see (2.21)) we obtain

\[
\left\| \prod_{i=0}^{m_0-1} (P_{l+1}^{i} \Lambda_n) P_{l+m_0} f \right\|_{0, -\kappa, \infty} \leq C \| f \|_{(a+b)m_0, -\kappa, \infty} (\Lambda_n \varepsilon_n)^{m_0}
\]

which gives

\[
\| R_{m_0} f \|_{0, -\kappa, \infty} \leq C \| f \|_{(a+b)m_0, -\kappa, \infty} (\Lambda_n \varepsilon_n)^{m_0}.
\]

Using now the equivalence between (2.11) and (2.12) we obtain

\[
\left\| \frac{1}{\psi_{\kappa}} R_{m_0}^{m_0}(\psi_{\kappa} f) \right\|_{\infty} \leq C \| f \|_{(a+b)m_0, \infty} (\Lambda_n \varepsilon_n)^{m_0}.
\]

We take now \( g \in C^\infty(\mathbb{R}^d \times \mathbb{R}^d) \), we denote \( g_x(y) = g(x, y) \), and we write

\[
\left\| \int_{\mathbb{R}^d \times \mathbb{R}^d} g(x, y) (\mu^{\eta, \kappa} - \mu^{\eta, \kappa, m_0})(dx, dy) \right\|
\]

\[
\leq \int_{\mathbb{R}^d} dx \left\| \int_{\mathbb{R}^d} g_x(y) \psi_{\kappa}(y) (P_r(x, dy) - \phi_t^{\eta, \kappa, m_0}(x, y)) dy \right\|
\]

\[
\leq \int_{\mathbb{R}^d} dx \left\| \frac{1}{\psi_{\kappa}(x)} R_{m_0}^{m_0}(\psi_{\kappa} g_x)(x) \right\| dx
\]

\[
\leq C \sup_{x \in \mathbb{R}^d} \| g_x \|_{(a+b)m_0, \infty} (\Lambda_n \varepsilon_n)^{m_0}
\]

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the last inequality being a consequence of (4.10) and of \( \eta - \kappa \geq d + 1 \). Now (4.9) is proved because
\[
\sup_{x \in \mathbb{R}^d} \| g_x \|_{(a+b)m_0, \infty} \leq \| g \|_{(a+b)m_0, \infty}.
\]

**Step 4: use of Lemma 3.4 and proof of A. and B.** We recall that \( \rho_h \) is defined in (4.2) and we estimate
\[
d_{m_0}(n) \times \theta(n)^{\rho_h} \leq Ct^{-\theta_0\xi_2(h)} \chi_0^{\theta_0\omega_2(h)} \Phi_n^{m_0(1+\rho_h)}(\delta_*)
\]
with
\[
\xi_2(h) = \rho_h \xi_1(q + 2h) = \rho_h (q + 2h + d + 2\theta_1 + m_0(a + b))
\]
and
\[
\omega_2(h) = (a + b + \delta_*)m_0 - \rho_h (q + 2h + d + 2\theta_1) = \delta_*m_0 - \frac{(a + b)m_0 + q + 2d/p_*}{2h} (q + d + 2\theta_1) - (q + 2d/p_*)
\]
By our choice of \( m_0 \) we have
\[
\delta_*m_0 > q + 2d/p_*
\]
so, taking \( h \) sufficiently large we get \( \omega_2(h) > 0 \). And we also have \( \xi_2(h) \leq \xi_3 := (a + b)m_0 + q + \frac{2d}{p_*} + \varepsilon_* \) and \( \rho_h \leq \varepsilon_* \). So we finally get
\[
d_{m_0}(n) \times \theta(n)^{\rho_h} \leq Ct^{-\theta_0\xi_3} \Phi_n^{m_0(1+\varepsilon_*)}(\delta_*) \tag{4.11}
\]
The above inequality guarantees that (3.8) holds so that we may use Lemma 3.4. We take \( \eta > \kappa + d \) and, using \((A_4)\) (see (2.21)) we obtain
\[
|\mu^{n,\kappa}| = \int_{\mathbb{R}^2} \frac{\psi_\eta(x)}{\psi_\kappa(y)} P_t(x, dy) dx \leq C \int_{\mathbb{R}} \frac{dx}{\psi_{\kappa-\eta}(x)} < \infty.
\]
Then, \( A(\delta) < C \) (see (3.9)). One also has \( B(\varepsilon) < \infty \) (see (3.10)) and finally (see (3.11))
\[
C_{h,m_*}(\varepsilon) \leq Ct^{-\theta_0\xi_3} \Phi_n^{m_0(1+\varepsilon_*)}(\delta_*)
\]
We have used here (4.11). For large \( h \) we also have
\[
\theta(n)^{\rho_h} \leq C(\lambda_n)_{\theta_0((a+b)m_0+q+\frac{2d}{p_*})}(1+\varepsilon_*) \Phi_n^{\varepsilon_*}(0).
\]
Now (3.12) gives (2.27). So \( A \) and \( B \) are proved.
Step 5: proof of C. We apply B. with q replaced by \( \bar{q} = q+1 \), so \( \Psi_{\eta,\kappa}p_t \in W^{\bar{q},p}(\mathbb{R}^d \times \mathbb{R}^d) = W^{\bar{q},p}(\mathbb{R}^{2d}) \). Since \( \bar{q} > 2d/p \) (here the dimension is 2d), we can use the Morrey’s inequality: for every \( \alpha, \beta \) with \( |\alpha| + |\beta| \leq \lfloor \bar{q} - 2d/p \rfloor = q \), then \( |\partial_x^\alpha \partial_y^\beta (\Psi_{\eta,\kappa}p_t)(x, y)| \leq C \| \Psi_{\eta,\kappa}p_t \|_{\bar{q},p} \). By (2.27), one has (with \( m = 1 + \frac{\bar{q}+2d/p_*}{\delta_*} \))

\[
|\partial_x^\alpha \partial_y^\beta (\Psi_{\eta,\kappa}p_t)(x, y)| \leq C \left( 1 + \left( \frac{1}{\lambda_n t} \right)^{(a+b)m+\bar{q}+2d/p_*} \right) + \Phi_{t,n,r}^\delta(\delta_*) \right) \left( 1 + \frac{1}{\Psi_{\eta,\kappa}(x, y)} \right)
\]

i.e. (using (2.6)),

\[
|\partial_x^\alpha \partial_y^\beta p_t(x, y)| \leq C \left( 1 + \left( \frac{1}{\lambda_n t} \right)^{(a+b)m+\bar{q}+2d/p_*} \right) + \Phi_{t,n,r}^\delta(\delta_*) \right) \left( 1 + \frac{1}{\Psi_{\eta,\kappa}(x, y)} \right)
\]

Now, by a standard calculus, \( \Psi_{\eta,\kappa}(x, y) \geq C_\kappa \frac{\psi_\kappa(x-y)}{\psi_{\eta+\kappa}(x)} \) (use that \( \psi_\kappa(x-y) \leq C_\kappa \psi_\kappa(x) \psi_\kappa(-y) = C_\kappa \psi_\kappa(x) \psi_\kappa(y) \)), so (2.29) follows. □

4.2 Proof of Theorem 2.7

By applying Theorem 2.5, \( P_t(x, dy) = p_t(x, y)dy \) and \( p_t \) satisfies (2.27), which we rewrite here as

\[
\| \Psi_{\eta,\kappa}p_t \|_{q,p} \leq Ct^{-\theta_1 q + \theta_1},
\]

where \( \theta_* = \theta_0(1 + \frac{a+b}{\delta} + 1 + \varepsilon) \) and \( \theta_1 \) is computed from (2.27) (the precise value is not important here). The constant \( C \) in the above inequality depends on \( \kappa, \eta, \varepsilon, \delta, q \). Moreover, by choosing \( \eta > \kappa + d \),

\[
\int_{\mathbb{R}^d} \Psi_{\eta,\kappa}(x, y)p_t(x, y)dx = \int_{\mathbb{R}^d} \frac{1}{\psi_\eta(x)} \times P_t \psi_\kappa(x) dx \leq \int_{\mathbb{R}^d} \frac{1}{\psi_{\eta-\kappa}(x)} dx = m < \infty.
\]

So, Lemma 3.3 (recall that we are working here with \( \mathbb{R}^d \times \mathbb{R}^d = \mathbb{R}^{2d} \)) gives

\[
\| \Psi_{\eta,\kappa}p_t \|_{q,p} \leq C_* t^{-\theta_1 (q+2d/p_*)}.
\]

We choose now \( p > 2d \) and by Morrey’s inequality,

\[
\| \Psi_{\eta,\kappa}p_t \|_{q,\infty} \leq C \| \Psi_{\eta,\kappa}p_t \|_{q+1,p} \leq C t^{-\theta_1 (q+1+2d/p_*)}.
\]

By taking \( p = 2d/(1-\varepsilon) \), we get

\[
\| \Psi_{\eta,\kappa}p_t \|_{r,\infty} \leq C t^{-\theta_1 (r+2d+\varepsilon)},
\]

where \( C \) denotes here a constant depending on \( \kappa, \eta, \varepsilon \). This gives that, for every \( x, y \in \mathbb{R}^d \) and for every multi-index \( \alpha \) and \( \beta \),

\[
|\partial_x^\alpha \partial_y^\beta p_t(x, y)| \leq C \times t^{-\theta_1 (|\alpha| + |\beta| + 2d + \varepsilon)} \frac{\psi_\eta(x)}{\psi_\kappa(y)}.
\]

The statement now follows from (2.4). □
4.3 Proof of Theorem 2.11

In this section we give the proof of Theorem 2.11.

Step 1. Let

\[ \omega_t(dt_1, ..., dt_m) = \frac{m!}{t^m} 1_{\{0 < t_1 < ... < t_m < t\}} dt_1 \ldots dt_m \]

and (with \( t_{m+1} = t \))

\[ I_m(f)(x) = E \left( 1 \{N(t) = m\} \int_{R^m} \left( \prod_{i=0}^{m-1} P_{t_{m-i+1} - t_{m-i}} U_{Z_{m-i}} \right) P_t f(x) \omega_t(dt_1, ..., dt_m) \right), \]

Since, conditionally to \( N(t) = m \), the law of \( (T_1, ..., T_m) \) is given by \( \omega_t(dt_1, ..., dt_m) \), it follows that

\[ P_t f(x) = \sum_{m=0}^{\infty} I_m(f)(x) = \sum_{m=0}^{m_0} I_m(f)(x) + R_{m_0} f(x) \]

with

\[ R_{m_0} f(x) = \sum_{m=m_0+1}^{\infty} I_m(f)(x). \]

Step 2. We analyze first the regularity of \( I_n(f) \). We apply Lemma 3.9. Here \( S_t = P_t \), so assumptions 3.6 and 3.7 hold due to assumptions 2.8 and 2.9 respectively. Moreover, here \( U_i = U_{m-Z_i} \), so Assumption 3.5 is satisfied uniformly in \( \omega \) as observed in Remark 2.10. Notice that \( a = b = 0 \) in our case. Then Lemma 3.9 gives

\[ \left( \prod_{i=0}^{m-1} P_{t_{m-i+1} - t_{m-i}} U_{Z_{m-i}} \right) P_t f(x) = \int p_{t_1, t_2-t_1, ..., t_m}(x, y) f(y) dy \]

and, for \( q, q_2 \in \mathbb{N}, \kappa \geq 0, p > 1 \) and \( |\beta| \leq q_2 \) we have

\[ \left\| \partial_x^\beta p_{t_1, t_2-t_1, ..., t_m}(x, \cdot) \right\|_{q_1, \kappa, p} \leq \theta_{q,t}(m) \times \psi_\chi(x). \quad (4.12) \]

with

\[ \theta_{q,t}(m) = \frac{C \times m^{q+d+2\theta_1}}{(\lambda t)^{\theta_0(q+d+2\theta_1)} \times C_{q,\chi,p,\infty}^{m-1}(P,U)}. \]

Here \( C \) and \( \chi \) are constants which depend on \( q, q_2, \kappa, p \) and \( \delta \). We notice that

\[ \theta_{q,t}(m+1) \leq C \times C_{q,\chi,p,\infty}(P,U) \times \theta_{q,t}(m). \]

We summarize: for each fixed \( q, \chi, \kappa, p \) and each \( \delta > 0 \) there exists some constants \( \Theta \geq 1 \) and \( Q \geq 1 \) (depending on \( q, \chi, \kappa, p \) and \( \delta \) but not on \( m \) and on \( t \)) such that for every \( m \in \mathbb{N} \)

\[ \theta_{q,t}(m+1) \leq \Theta \times \theta_{q,t}(m), \quad \text{and} \quad \theta_{q,t}(m) \leq \frac{Q}{(\lambda t)^{\theta_0(q+d+2\theta_1)}}. \quad (4.13) \]

We define now

\[ \phi_t^{m_0}(x, y) = \sum_{m=0}^{m_0} \int p_{t_1, t_2-t_1, ..., t_m}(x, y) \omega_t(dt_m \ldots dt_1). \]

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Using (4.12), standard computations give: for every $l, l' \in \mathbb{N}$, $p > 1$ and $\kappa \in \mathbb{N}$ there exists $\eta_0 \in \mathbb{N}$ such that for every $\eta > \eta_0$,

$$\|\Psi_{\eta,\kappa,\phi_t^{m_0}}\|_{l,l'} \leq \theta_{l,t}(m_0). \quad (4.15)$$

**Step 3.** We fix $\eta > \eta_0$ and $\eta > \kappa + d$ and we define the measures

$$\mu_{\eta,\kappa}^m(dx, dy) = \Psi_{\eta,\kappa}(x, y)\mathcal{P}_t(x, dy)dx \quad \text{and} \quad \mu_{\eta,\kappa,m_0}^m(dx, dy) = \Psi_{\eta,\kappa}(x, y)\phi_t^{m_0}(x, y)dxdy.$$

Let $g = g(x, y)$ be a bounded function and set $g_x(y) = g(x, y)$. We have,

$$\left| \int gd\mu_{\eta,\kappa}^m - \int gd\mu_{\eta,\kappa,m_0}^m \right| \leq \int \frac{1}{\psi_{\eta,\kappa}(x)} \left\| \frac{1}{\psi_{\kappa}} R_{m_0}(\psi_{\kappa}g_x) \right\|_\infty \, dx \leq \sum_{m \geq m_0+1} \int \frac{1}{\psi_{\eta,\kappa}(x)} \left\| \frac{1}{\psi_{\kappa}} I_m(\psi_{\kappa}g_x) \right\|_\infty \, dx.$$

We deal with the norm in the integral above. By iterating (2.31) and (2.39) (with $q = 0$) we get

$$\left\| \left( \prod_{i=0}^{m-1} P_{t_{m-i+1},t_{m-i}} U_{Z_{m-i}} \right) P_{t_{1}}(\psi_{\kappa}g_x) \right\|_{0,-\kappa,\infty} \leq c^m_{\kappa} \|\psi_{\kappa}g_x\|_{0,-\kappa,\infty} \leq c^m_{\kappa} \|g\|_\infty,$$

where $c_{\kappa} > 0$ is a constant depending on the constants appearing in (2.31) and (2.39). Therefore, we obtain

$$\left\| \frac{1}{\psi_{\kappa}} I_m(\psi_{\kappa}g_x) \right\|_\infty \leq c^m_{\kappa} P(N(t) = m) \|g\|_\infty.$$

Since $\eta - \kappa > d$, it follows that for every $m_0 \geq 1$ (recall that $t < 1$),

$$d_0(\mu_{\eta,\kappa}^m, \mu_{\eta,\kappa,m_0}^m) \leq \sum_{m \geq m_0 + 1} \frac{(c_{\kappa}t_0)^m}{m!} \leq \frac{(c_{\kappa}t_0)^{m_0}}{m_0!} e^{c_{\kappa}t_0}.$$

So, for $m \geq 1$ we have, for every $l$

$$\sup_{m \geq 1} d_0(\mu_{\eta,\kappa}^l, \mu_{\eta,\kappa,m}^l) \times \theta_{l,t}(m) \leq \frac{1}{(\lambda t)^{\frac{d}{2} + d/2 + 2\delta}} \times \sup_{m \geq 1} \frac{(c_{\kappa}t_0)^m}{m!} e^{c_{\kappa}t_0} \leq \frac{e^{c_{\kappa}t_0(1+Q^\kappa)}}{(\lambda t)^{\frac{d}{2} + d/2 + 2\delta}}, \quad (4.16)$$

We now use Lemma 3.4 and we get $\mu_{\eta,\kappa}^l(dx, dy) = \rho_{\eta,\kappa}^l(x, y)dxdy$ with $\rho_{\eta,\kappa}^l \in C^\infty(\mathbb{R}^d \times \mathbb{R}^d)$. And one concludes that in (3.6) we have defined $\rho_h = (q + 2d/p_\kappa)/2h$ (in our case $k = 0$ and we work on $R^d \times R^d \sim R^{2d}$). So, with the notation from (3.11) (with $n_\kappa = 1$)

$$C_{h,1}(\varepsilon) = \frac{e^{c_{\kappa}t_0(1+Q^\kappa)}}{(\lambda t)^{\frac{d}{2} + d/2 + 2\delta}(1/\rho_\kappa + \varepsilon)}.$$

We have used here (4.16) with $l = 2h + q$ and $r = \rho_h + \varepsilon$. Then by (3.12) with $n_\kappa = 1$, for every $\delta > 0$

$$\|\rho_{\eta,\kappa}^l\|_{q,p} \leq C(\Theta + \theta_{2h+q,t}^\kappa(1 + C_{h,1}(\varepsilon))).$$
Taking $h$ sufficiently large we have
\[ C_{h,1}(\varepsilon) \leq \frac{e^{2c_k \rho}}{(\lambda t)^{q_0(q+2d/p_*)(1+\delta)}}. \]

and, for $\delta > 0$,
\[ \theta_{\rho h}^{\rho h(1+\delta)}(c(r_h)\rho) \leq \frac{Q^{\rho h + \varepsilon}}{(\lambda t)^{(2h+q+d/p_*)(1+\delta)}} \leq C \times \frac{e^{2c_k \rho}}{(\lambda t)^{(q+2d/p_*)(1+\delta)}}. \]

Since $\rho \geq 1$ we conclude that
\[ \|p^{\eta,\kappa}\|_{q,p} \leq C \times \frac{e^{2c_k \rho}}{(\lambda t)^{(q+2d/p_*)(1+\delta)}}, \]

$C$ denoting a constant which is independent of $\rho$. We take now $p = 2d + \varepsilon$ and, using now Morrey’s inequality
\[ \|p^{\eta,\kappa}\|_{q,\infty} \leq \|p^{\eta,\kappa}\|_{q+1,p} \leq C \times \frac{e^{2c_k \rho}}{(\lambda t)^{(q+2d)(1+\delta)}}. \]

This proves (2.43). □

A Appendix

A.1 Weights

We denote
\[ \psi_k(x) = (1 + |x|^2)^k. \]  

Lemma A.1 For every multi-index $\alpha$ there exists a constant $C_\alpha$ such that
\[ \left| \partial^\alpha \left( \frac{1}{\psi_k} \right) \right| \leq \frac{C_\alpha}{\psi_k}. \]  

Moreover, for every $q$ there is a constant $C_q \geq 1$ such that for every $f \in C^\infty_b(\mathbb{R}^d)$
\[ \frac{1}{C_q} \sum_{0 \leq |\alpha| \leq q} \left| \partial^\alpha \left( \frac{f}{\psi_k} \right) \right| \leq \sum_{0 \leq |\alpha| \leq q} \frac{1}{\psi_k} \left| \partial^\alpha f \right| \leq C_q \sum_{0 \leq |\alpha| \leq q} \left| \partial^\alpha \left( \frac{f}{\psi_k} \right) \right|. \]  

Proof. One checks by recurrence that
\[ \partial^\alpha \left( \frac{1}{\psi_k} \right) = \sum_{q=1}^{\left| \alpha \right|} \frac{P_{\alpha,q}}{\psi_k^q} \]
where $P_{\alpha,q}$ is a polynomial of order $q$. And since
\[ \frac{(1 + |x|^q)^q}{(1 + |x|^2)^{q+k}} \leq \frac{C}{(1 + |x|^2)^k} \]

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the proof (A.2) is completed. In order to prove (A.3) we write
\[ \partial^\alpha \left( \frac{f}{\psi_k} \right) = \frac{1}{\psi_k} \partial^\alpha f + \sum_{(\beta, \gamma) = \alpha \atop |\beta| \geq 1 \atop (\beta, \gamma) \neq (\alpha, 0)} c(\beta, \gamma) \partial^\beta \left( \frac{1}{\psi_k} \right) \partial^\gamma f. \]

This, together with (A.2) implies
\[ \left| \partial^\alpha \left( \frac{f}{\psi_k} \right) \right| \leq C \sum_{0 \leq |\gamma| \leq |\alpha|} \frac{1}{\psi_k} |\partial^\gamma f| \]
so the first inequality in (A.3) is proved. In order to prove the second inequality we proceed by recurrence on \( q \). The inequality is true for \( q = 0 \). Suppose that it is true for \( q - 1 \). Then we write
\[ \frac{1}{\psi_k} \partial^\alpha f = \partial^\alpha \left( \frac{f}{\psi_k} \right) - \sum_{(\beta, \gamma) = \alpha \atop |\beta| \geq 1 \atop (\beta, \gamma) \neq (\alpha, 0)} c(\beta, \gamma) \partial^\beta \left( \frac{1}{\psi_k} \right) \partial^\gamma f \]
and we use again (A.2) in order to obtain
\[ \frac{1}{\psi_k} |\partial^\alpha f| \leq \left| \partial^\alpha \left( \frac{f}{\psi_k} \right) \right| + C \sum_{|\gamma| < |\alpha|} \frac{1}{\psi_k} |\partial^\gamma f| \leq C \sum_{0 \leq |\beta| \leq q} \left| \partial^\beta \left( \frac{f}{\psi_k} \right) \right| \]
the second inequality being a consequence of the recurrence hypothesis. □

**Remark A.2** The assertion is false if we define \( \psi_k(x) = (1 + |x|)^k \) because \( \partial_i \partial_j |x| = \frac{\delta_{ij}}{|x|} - \frac{x_i x_j}{|x|^2} \) blows up in zero.

We look now to \( \psi_k \) itself.

**Lemma A.3** For every multi-index \( \alpha \) there exists a constant \( C_\alpha \) such that
\[ |\partial^\alpha \psi_k| \leq C_\alpha \psi_k. \tag{A.4} \]
Moreover, for every \( q \) there is a constant \( C_q \geq 1 \) such that for every \( f \in C^\infty_0 (\mathbb{R}^d) \)
\[ \frac{1}{C_q} \sum_{0 \leq |\alpha| \leq q} |\partial^\alpha (\psi_k f)| \leq \sum_{0 \leq |\alpha| \leq q} \psi_k |\partial^\alpha f| \leq C_q \sum_{0 \leq |\alpha| \leq q} |\partial^\alpha (\psi_k f)|. \tag{A.5} \]

**Proof.** One proves by recurrence that, if \( |\alpha| \geq 1 \) then \( \partial^\alpha \psi_k = \sum_{q=1}^{[\alpha]} \psi_{k-q} P_q \) with \( P_q \) a polynomial of order \( q \). Since \( 1 + |x| \leq 2(1 + |x|^2) \) it follows that \( |P_q| \leq C \psi_q \) and (A.4) follows. Now we write
\[ \psi_k \partial^\alpha f = \partial^\alpha (\psi_k f) - \sum_{(\beta, \gamma) = \alpha \atop |\beta| \geq 1} c(\beta, \gamma) \partial^\beta \psi_k \partial^\gamma f \]
and the same arguments as in the proof of (A.3) give (A.5).
A.2 Semigroup estimates

We consider a semigroup $P_t$ on $C^\infty(\mathbb{R}^d)$ such that $P_tf(x) = \int f(y)P_t(x,dy)$ where $P_t(x,dy)$ is a probability transition kernel and we denote by $P_t^*$ its formal adjoint.

Assumption A.4 There exists $Q \geq 1$ such that for every $t \leq T$ and every $f \in C^\infty(\mathbb{R}^d)$

$$\|P_t f\|_1 \leq Q \|f\|_1.$$  \hfill (A.6)

Moreover, for every $k \in \mathbb{N}$ there exists $K_k \geq 1$ such that for every $x \in \mathbb{R}^d$

$$|P_t(\psi_k)(x)| \leq K_k \psi_k(x).$$  \hfill (A.7)

Lemma A.5 Under Assumption A.4, one has

$$\|\psi_k P_t^*(f/\psi_k)\|_p \leq K_k^{1/p} Q^{1/p^*} \|f\|_p.$$  \hfill (A.8)

Proof. Using Hölder’s inequality, the identity $\psi_k^p = \psi_{kp}$, and (A.7)

$$|P_t(\psi_k g)(x)| \leq |P_t(\psi_k^p)(x)|^{1/p} |P_t(|g|^{p^*})(x)|^{1/p^*} \leq K_k p \psi_k(x) |P_t(|g|^{p^*})(x)|^{1/p^*}.$$

Then, using (A.6)

$$\left\| \frac{1}{\psi_k} P_t(\psi_k g) \right\|_{p^*} \leq K_k^{1/p} \left\| P_t(|g|^{p^*}) \right\|_{1/p^*} = K_k^{1/p} \left( \left\| P_t(|g|^{p^*}) \right\|_1 \right)^{1/p^*} \leq K_k^{1/p} Q^{1/p^*} \left( \left\| g \right\|_{p^*} \right)^{1/p^*} = K_k^{1/p} Q^{1/p^*} \|g\|_{p^*}.$$

Using Hölder’s inequality first and the above inequality we obtain

$$\langle g, \psi_k P_t^*(f/\psi_k) \rangle = \left\langle \frac{1}{\psi_k} P_t(g\psi_k), f \right\rangle \leq \|f\|_p \left\| \frac{1}{\psi_k} P_t(g\psi_k) \right\|_{p^*} \leq K_k^{1/p} Q^{1/p^*} \|g\|_{p^*} \|f\|_p.$$  \hfill \Box

We consider also the following hypothesis.

Assumption A.6 There exists $\rho > 1$ such that for every $q \in \mathbb{N}$ there exists $D_{(q)}^\rho(p) \geq 1$ such that for every $x \in \mathbb{R}^d$

$$\sum_{|\alpha| \leq q} |\partial^\alpha P_t^* f(x)| \leq D_{(q)}^\rho(\rho) \sum_{|\alpha| \leq q} (P_t^*(|\partial^\alpha f|^{\rho})(x))^{1/p}.$$  \hfill (A.9)

Proposition A.7 Suppose that Assumption A.4 and A.6 hold. Then for every $k, q \in \mathbb{N}$ and $p > \rho$ there exists a universal constant $C$ (depending on $k$ and $q$ only) such that

$$\|\psi_k P_t^*(f/\psi_k)\|_{q,p} \leq C K_k^{1/p} Q^{(p-\rho)/\rho p} D_{(q)}^\rho(\rho) \|f\|_{q,p}.$$  \hfill (A.10)
Proof. We will prove (A.10) first. Let $\alpha$ with $|\alpha| \leq q$. By (A.9)
\[
|\partial^\alpha (\psi_k P_t^* (f/\psi_k)(x))| \leq C \psi_k(x) \sum_{|\gamma| \leq q} |\partial^\gamma (P_t^* (f/\psi_k)(x))|
\]
\[
\leq CD_{(q)}(\rho) \psi_k(x) \sum_{|\delta| \leq q} (P_t^* (|\partial^\delta (f/\psi_k)|^\rho))(x)^{1/\rho}
\]
\[
= CD_{(q)}(\rho) \sum_{|\delta| \leq q} (\psi_{pk}(x) P_t^* (|\partial^\delta (f/\psi_k)|^\rho))(x)^{1/\rho}
\]
\[
= CD_{(q)}(\rho) \sum_{|\delta| \leq q} (\psi_{pk}(x) P_t^* (g/\psi_{pk})(x))^{1/\rho}
\]
with
\[
g(x) = \psi_{pk}(x) |\partial^\delta (f/\psi_k)(x)|^\rho = |\psi_k(x) \partial^\delta (f/\psi_k)(x)|^\rho.
\]
Using (A.8)
\[
\left\| (\psi_{pk} P_t^* (g/\psi_{pk}))^{1/\rho} \right\|_p = \left\| \psi_{pk} P_t^* (g/\psi_{pk}) \right\|_{p/p}^{1/\rho} \leq K_{kpp}^p Q(p-\rho)/\rho \|g\|^{1/\rho}_{p/p}.
\]
And we have
\[
\|g\|^{1/\rho}_{p/p} = (\int |\psi_k(x) \partial^\delta (f/\psi_k)(x)|^p dx)^{1/\rho} \leq C \sum_{|\gamma| \leq q} (\int |\partial^\gamma f(x)|^p dx)^{1/\rho} = C \|f\|_{q,p}.
\]
We conclude that
\[
\|\psi_k P_t^* (f/\psi_k)\|_{q,p} \leq CK_{kpp}^1 Q(p-\rho)/\rho D_{(q)}^r (\rho) \|f\|_{q,p}.
\]
\[\square\]

A.3 Integration by parts

We consider a function $\phi \in C^\infty(\mathbb{R}^d, \mathbb{R}^d)$ such that $\partial_j \phi \in C^\infty_b(\mathbb{R}^d, \mathbb{R}^d)$, $j = 1, \ldots, d$. We denote $\nabla \phi$ the $d \times d$ matrix field whose $(i,j)$ entry is $\partial_j \phi^i$ and $\sigma(\phi) = \nabla \phi(\nabla \phi)^t$.

Lemma A.8 We suppose that $\sigma(\phi)$ is invertible and we denote $\gamma(\phi) = \sigma^{-1}(\phi)$. Then
\[
\int (\partial_i f)(\phi(x)) g(x) dx = \int f(\phi(x)) H_i (\phi, g)(x) dx \quad (A.11)
\]
with
\[
H_i (\phi, g) = -\sum_{k=1}^d \partial_k \left( g \sum_{j=1}^d \gamma^{i,j}(\phi) \partial_k \phi^j \right). \quad (A.12)
\]
Moreover, for a multi-index $\alpha = (\alpha_1, \ldots, \alpha_m)$ we define
\[
H_\alpha (\phi, g) = H_{\alpha_m} (\phi, H_{(\alpha_1, \ldots, \alpha_{m-1})}(\phi, g)) \quad (A.13)
\]
and we obtain
\[
\int (\partial^\alpha f)(\phi(x)) g(x) dx = \int f(\phi(x)) H_\alpha (\phi, g)(x) dx \quad (A.14)
\]
Proof. The proof is standard: we use the chain rule and we obtain $\nabla (f(\phi)) = (\nabla \phi)^{\ast} (\nabla f)(\phi)$. By multiplying with $\nabla \phi$ first and with $\gamma(\phi)$ then, we get $(\nabla f)(\phi) = \gamma(\phi) \nabla \phi \nabla (f(\phi))$. Using standard integration by parts, (A.11) and (A.12) hold. And (A.13) follows by iteration. □

Our aim now is to give estimates of $|H_\alpha(\phi,g)(x)|_q$. We use the notation introduced in (2.1) and for $q \in \mathbb{N}$, we denote

$$C_q(\phi)(x) = \frac{1 \lor |\phi(x)|^{2d-1}_{1,q+2}}{1 \land (\det \sigma(\phi)(x))^{q+1}}.$$  \hspace{1cm} (A.15)

Lemma A.9  \hspace{1cm} For every multi index $\alpha$ and every $q \in \mathbb{N}$ there exists a universal constant $C \geq 1$ such that

$$|H_\alpha(\phi,g)(x)|_q \leq C |g(x)|_{q+|\alpha|} \times C^{[\alpha]}_{q+|\alpha|}(\phi)(x).$$  \hspace{1cm} (A.16)

Proof. We begin with some simple computational rules:

$$|f(x)g(x)|_q \leq C \sum_{k_1+k_2=q} |f(x)|_{k_1} \times |g(x)|_{k_2},$$  \hspace{1cm} (A.17)

$$|\langle \nabla f(x), \nabla g(x) \rangle|_q \leq C \sum_{k_1+k_2=q} |f(x)|_{1,k_1+1} \times |g(x)|_{1,k_2+1},$$  \hspace{1cm} (A.18)

$$\left| \frac{1}{|g(x)|} \right|_q \leq \frac{C}{|g(x)|} \sum_{l=0}^{q} \frac{|g(x)|^l_q}{|g(x)|^l}.$$  \hspace{1cm} (A.19)

We denote by $\tilde{\gamma}^{i,j}(\phi)$ the algebraic complement and write $\gamma^{i,j}(\phi) = \tilde{\gamma}^{i,j}(\phi)/\det \sigma(\phi)$. Then, using the above computational rules we obtain

$$|\gamma^{i,j}(\phi)(x)|_q \leq C \times \frac{|\phi(x)|^{2(d-1)}_{1,q+1}}{1 \land (\det \sigma(\phi)(x))^{q+1}}$$

and moreover

$$|H_i(\phi,g)(x)|_q \leq C |g(x)|_{q+1} \times |\phi(x)|_{1,q+2} \times \frac{|\phi(x)|^{2(d-1)}_{1,q+2}}{1 \land (\det \sigma(\phi)(x))^{q+1}} \leq C |g(x)|_{q+1} \times C_q(\phi)(x).$$

Let $\alpha = (\beta,i)$. Iterating the above estimate we obtain

$$|H_\alpha(\phi,g)(x)|_q = |H_i(\phi,H_\beta(\phi,g))(x)|_q \leq C |H_\beta(\phi,g)(x)|_{q+1} \times C_q(\phi)(x) \leq C |g(x)|_{q+|\alpha|} \times C^{[\alpha]}_{q+|\alpha|}(\phi)(x).$$

□

We define now the operator $V_\phi : C_b^\infty(\mathbb{R}^d) \rightarrow C_b^\infty(\mathbb{R}^d)$ by

$$V_\phi f(x) = f(\phi(x)).$$  \hspace{1cm} (A.20)

Lemma A.10  \hspace{1cm} A.  One has

$$\left\| \frac{1}{\psi_\kappa} V_\phi(\psi_\kappa f) \right\|_{q,\infty} \leq C \psi_\kappa(\phi(0)) \|\phi\|^{q+2\kappa}_{1,q,\infty} \|f\|_{q,\infty}.$$  \hspace{1cm} (A.21)
B. Suppose that \[
\inf_{x \in \mathbb{R}^d} \det \sigma(\phi)(x) \geq \varepsilon(\phi) > 0 \tag{A.22}
\]
Then, for \(\kappa, q \in \mathbb{N}\) and \(p > 1\),
\[
\left\| \psi_\kappa V_\phi^* \left( \frac{1}{\psi_\kappa} f \right) \right\|_{q,p} \leq C \psi_\kappa(0) \times \frac{1 \vee \|\phi\|_{1,q+2,\infty}^{2d+2+2\kappa}}{\varepsilon(\phi)^{q(q+1)+1/p^*}} \times \|f\|_{q+1,p}. \tag{A.23}
\]

**Proof.** We notice first that
\[
|g(\phi(x))|_q \leq C(1 \vee |\phi(x)|_{1,q})^{q+1} \sum_{|\alpha| \leq q} |(\partial^\alpha g)(\phi(x))|. \tag{A.24}
\]
Using (2.6) and the above inequality we obtain
\[
\left| \frac{1}{\psi_\kappa(x)} V_\phi(\psi_\kappa f)(x) \right|_q \leq \frac{C V_\phi(\psi_\kappa f)(x)}{\psi_\kappa(x)} \sum_{|\alpha| \leq q} |(\partial^\alpha(\psi_\kappa f))(\phi(x))| \leq \frac{C(1 \vee |\phi(x)|_{1,q})^q}{\psi_\kappa(x)} \sum_{|\alpha| \leq q} |(\partial^\alpha f)(\phi(x))|.
\]
And using (2.5) this gives (A.21).

B. We take now \(\alpha\) with \(|\alpha| \leq q\) and we write
\[
\left\langle \partial^\alpha(\psi_\kappa V_\phi^* \left( \frac{1}{\psi_\kappa} f \right)), g \right\rangle = (-1)^{|\alpha|} \left\langle \frac{f}{\psi_\kappa}, V_\phi(\psi_\kappa \partial^\alpha g) \right\rangle
= (-1)^{|\alpha|} \int_{\mathbb{R}^d} \frac{f}{\psi_\kappa}(x)(\psi_\kappa \partial^\alpha g)(\phi(x))dx
= (-1)^{|\alpha|} \int_{\mathbb{R}^d} g(\phi(x))H_\alpha \left( \phi, \frac{f}{\psi_\kappa} \right) \times \psi_\kappa(\phi)(x)dx.
\]
It follows that
\[
\left\| \left\langle \partial^\alpha(\psi_\kappa V_\phi^* \left( \frac{1}{\psi_\kappa} f \right)), g \right\rangle \right\| \leq \|g(\phi)\|_p \left\| H_\alpha \left( \phi, \frac{f}{\psi_\kappa} \right) \times \psi_\kappa(\phi) \right\|_p.
\]
Using (A.16) and (A.22) we obtain (recall that \(|\alpha| \leq q\))
\[
\left| H_\alpha \left( \phi, \frac{f}{\psi_\kappa} \times \psi_\kappa(\phi) \right)(x) \right| \leq C \left| \left( \frac{f}{\psi_\kappa} \times \psi_\kappa(\phi) \right)(x) \right|_{q+1} \times C_q^q(\phi(x)) \leq C |f(x)|_{q+1} \left| \frac{1}{\psi_\kappa} \times \psi_\kappa(\phi)(x) \right|_{q+1} \times \left( \frac{1 \vee |\phi(x)|_{1,q+1}^{2d-1}}{\varepsilon(\phi)^{q+2}} \right)^q
\]
By (A.24) we have
\[
|\psi_\kappa(\phi)(x)|_{q+1} \leq C(1 \vee |\phi(x)|_{1,q+1}^{q+1}) \sum_{|\alpha| \leq k+1} |(\partial^\alpha \psi_\kappa)(\phi(x))| \leq C(1 \vee |\phi(x)|_{1,q+1}^{q+1}) \times \psi_\kappa(\phi(x)) \leq C(1 \vee |\phi(x)|_{1,q+1}^{q+1}) \times \psi_\kappa(\phi(0))(1 \vee \|\nabla \phi\|_{\infty}^{2\kappa}) \psi_\kappa(x).
\]

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Finally

\[ |H_\alpha(\phi, \frac{f}{\psi_\kappa} \times \psi_\kappa(\phi))(x)| \leq C |f(x)|_q + \psi_\kappa(\phi(0)) (1 \vee \|\nabla \phi\|_\infty^{2\kappa}) \times \frac{1 \vee \|\phi\|_{1,q+2}^{2d+1}}{\varepsilon(\phi)^q(q+1)} \]

\[ \leq C |f(x)|_q + \psi_\kappa(\phi(0)) \times \frac{1 \vee \|\phi\|_{1,q+2,\infty}^{2d+1+2\kappa}}{\varepsilon(\phi)^q(q+1)} \]

and this gives

\[ \left\| H_\alpha(\phi, \frac{f}{\psi_\kappa} \times \psi_\kappa(\phi)) \right\|_p \leq C\psi_\kappa(\phi(0)) \times \frac{1 \vee \|\phi\|_{1,q+2,\infty}^{2d+1+2\kappa}}{\varepsilon(\phi)^q(q+1)} \times \|f\|_{q+1,p} \]

Using a change of variable and (A.22) \( \|g(\phi)\|_{p_*} \leq \varepsilon(\phi)^{-1/p_*} \|g\|_{p_*} \). These two inequalities prove (A.23). □

References


