

ANALYSIS & PDE

Volume 8

No. 5

2015

JUAN DÁVILA, MANUEL DEL PINO,
SERENA DIPIERRO AND ENRICO VALDINOCI

**CONCENTRATION PHENOMENA
FOR THE NONLOCAL SCHRÖDINGER EQUATION
WITH DIRICHLET DATUM**



CONCENTRATION PHENOMENA FOR THE NONLOCAL SCHRÖDINGER EQUATION WITH DIRICHLET DATUM

JUAN DÁVILA, MANUEL DEL PINO, SERENA DIPIERRO AND ENRICO VALDINOCI

For a smooth, bounded domain Ω , $s \in (0, 1)$, $p \in (1, (n + 2s)/(n - 2s))$ we consider the nonlocal equation

$$\varepsilon^{2s}(-\Delta)^s u + u = u^p \quad \text{in } \Omega$$

with zero Dirichlet datum and a small parameter $\varepsilon > 0$. We construct a family of solutions that concentrate as $\varepsilon \rightarrow 0$ at an interior point of the domain in the form of a scaling of the ground state in entire space. Unlike the classical case $s = 1$, the leading order of the associated reduced energy functional in a variational reduction procedure is of polynomial instead of exponential order on the distance from the boundary, due to the nonlocal effect. Delicate analysis is needed to overcome the lack of localization, in particular establishing the rather unexpected asymptotics for the Green function of $\varepsilon^{2s}(-\Delta)^s + 1$ in the expanding domain $\varepsilon^{-1}\Omega$ with zero exterior datum.

1. Introduction	1165
2. Estimates on the Robin function H_ε and on the leading term of the energy functional	1169
3. Estimates on \bar{u}_ε and first approximation of the solution	1177
4. Energy estimates and functional expansion in \bar{u}_ε	1181
5. Decay of the ground state w	1185
6. Some regularity estimates	1190
7. The Lyapunov–Schmidt reduction	1194
8. Proof of Theorem 1.1	1228
Appendix: Some physical motivation	1230
Acknowledgements	1234
References	1234

1. Introduction

Given $s \in (0, 1)$, $n \in \mathbb{N}$ with $n > 2s$, $p \in (1, (n + 2s)/(n - 2s))$ and a bounded smooth domain $\Omega \subset \mathbb{R}^n$, we consider the fractional Laplacian problem

$$\begin{cases} \varepsilon^{2s}(-\Delta)^s U + U = U^p & \text{in } \Omega, \\ U = 0 & \text{in } \mathbb{R}^n \setminus \Omega, \end{cases} \quad (1-1)$$

where $\varepsilon > 0$ is a small parameter.

MSC2010: 35R11.

Keywords: nonlocal quantum mechanics, Green functions, concentration phenomena.

As usual, the operator $(-\Delta)^s$ is the fractional Laplacian, defined at any point $x \in \mathbb{R}^n$ as

$$(-\Delta)^s U(x) := c(n, s) \int_{\mathbb{R}^n} \frac{2U(x) - U(x+y) - U(x-y)}{|y|^{n+2s}} dy$$

for a suitable positive normalizing constant $c(n, s)$. We refer to [Landkof 1972; Silvestre 2005; Di Nezza et al. 2012] for an introduction to the fractional Laplacian operator.

We provide in the Appendix a heuristic physical motivation of the problem considered and of the relevance of our results in the light of a nonlocal quantum mechanics theory.

The goal of this paper is to construct solutions of problem (1-1) that concentrate at interior points of the domain for sufficiently small values of ε . More precisely, we shall establish the existence of a solution U_ε that at main order looks like

$$U_\varepsilon(x) \approx w\left(\frac{x - \tilde{\xi}_\varepsilon}{\varepsilon}\right). \tag{1-2}$$

Here $\tilde{\xi}_\varepsilon$ is a point lying at a uniformly positive distance from the boundary $\partial\Omega$ and w designates the unique radial positive *least energy solution* of the problem

$$(-\Delta)^s w + w = w^p, \quad w \in H^s(\mathbb{R}^n). \tag{1-3}$$

See, for instance, [Felmer et al. 2012] for the existence of such a solution and its basic properties. See [Amick and Toland 1991; Frank and Lenzmann 2013; Fall and Valdinoci 2014] for the (delicate) proof of uniqueness in special situations and [Frank et al. 2015] for the general case. The solution w is smooth and has the asymptotic behavior

$$\alpha|x|^{-(n+2s)} \leq w(x) \leq \beta|x|^{-(n+2s)} \quad \text{for } |x| \geq 1 \tag{1-4}$$

for some positive constants α, β ; see Theorem 1.5 of [Felmer et al. 2012] and the lower bound in formula (IV.6) of [Carmona et al. 1990].

Our main result is the following:

Theorem 1.1. *If ε is sufficiently small, there exist a point $\tilde{\xi}_\varepsilon \in \Omega$ and a solution U_ε of problem (1-1) such that*

$$\left| U_\varepsilon(x) - w\left(\frac{x - \tilde{\xi}_\varepsilon}{\varepsilon}\right) \right| \leq C\varepsilon^{n+2s} \tag{1-5}$$

and $\text{dist}(\tilde{\xi}_\varepsilon, \partial\Omega) \geq c$. Here, c and C are positive constants independent of ε and Ω .

Further, the point $\xi_\varepsilon := \tilde{\xi}_\varepsilon/\varepsilon$ is such that

$$\mathcal{H}_\varepsilon(\xi_\varepsilon) = \min_{\xi \in \Omega_\varepsilon} \mathcal{H}_\varepsilon(\xi) + O(\varepsilon^{n+4s}) \tag{1-6}$$

for the functional $\mathcal{H}_\varepsilon(\xi)$ defined in (1-17) below, where

$$\Omega_\varepsilon := \frac{\Omega}{\varepsilon} = \left\{ \frac{x}{\varepsilon} \mid x \in \Omega \right\}. \tag{1-7}$$

The basic idea of the proof, which also leads to the characterization (1-6) of the location of the point $\tilde{\xi}_\varepsilon$ goes as follows. Letting $u(x) := U(\varepsilon x)$, problem (1-1) becomes

$$\begin{cases} (-\Delta)^s u + u = u^p & \text{in } \Omega_\varepsilon, \\ u = 0 & \text{in } \mathbb{R}^n \setminus \Omega_\varepsilon, \end{cases} \tag{1-8}$$

where Ω_ε is as defined in (1-7).

For a given $\xi \in \Omega_\varepsilon$, a first approximation \bar{u}_ξ for the solution of problem (1-8) consistent with the desired form (1-2) and the Dirichlet exterior condition can be taken as the solution of the linear problem

$$\begin{cases} (-\Delta)^s \bar{u}_\xi + \bar{u}_\xi = w_\xi^p & \text{in } \Omega_\varepsilon, \\ \bar{u}_\xi = 0 & \text{in } \mathbb{R}^n \setminus \Omega_\varepsilon, \end{cases} \tag{1-9}$$

where

$$w_\xi(x) := w(x - \xi).$$

The actual solution will be obtained as a small perturbation from \bar{u}_ξ for a suitable point $\xi = \xi_\varepsilon$. Problem (1-8) is variational. It corresponds to the Euler–Lagrange equation for the functional

$$I_\varepsilon(u) = \frac{1}{2} \int_{\Omega_\varepsilon} ((-\Delta)^s u(x)u(x) + u^2(x)) dx - \frac{1}{p+1} \int_{\Omega_\varepsilon} u^{p+1}(x) dx, \quad u \in H_0^s(\Omega_\varepsilon), \tag{1-10}$$

where

$$H_0^s(\Omega_\varepsilon) = \{u \in H^s(\mathbb{R}^n) \mid u = 0 \text{ a.e. in } \mathbb{R}^n \setminus \Omega_\varepsilon\}.$$

Since the solution we look for should be close to \bar{u}_ξ for $\xi = \xi_\varepsilon$, the functional $\xi \mapsto I_\varepsilon(\bar{u}_\xi)$ should have a critical point near $\xi = \xi_\varepsilon$. We shall next argue that this functional actually has a global minimizer located at distance $\sim 1/\varepsilon$ from $\partial\Omega_\varepsilon$.

The expansion of $I_\varepsilon(\bar{u}_\xi)$ involves the regular part of the Green function for the operator $(-\Delta)^s + 1$ in Ω_ε , which we define next. In \mathbb{R}^n the operator $(-\Delta)^s + 1$ has a unique decaying fundamental solution Γ , which solves

$$(-\Delta)^s \Gamma + \Gamma = \delta_0. \tag{1-11}$$

The function Γ is radially symmetric, positive and satisfies

$$\frac{\alpha}{|x|^{n+2s}} \leq \Gamma(x) \leq \frac{\beta}{|x|^{n+2s}} \tag{1-12}$$

for $|x| \geq 1$ and $\alpha, \beta > 0$; see for instance Lemma C.1 in [Frank et al. 2015].

The Green function G_ε for $(-\Delta)^s + 1$ in Ω_ε solves

$$\begin{cases} (-\Delta)^s G_\varepsilon(x, y) + G_\varepsilon(x, y) = \delta_y & \text{if } x \in \Omega_\varepsilon, \\ G_\varepsilon(x, y) = 0 & \text{if } x \in \mathbb{R}^n \setminus \Omega_\varepsilon. \end{cases} \tag{1-13}$$

In other words,

$$G_\varepsilon(x, y) := \Gamma(x - y) - H_\varepsilon(x, y), \tag{1-14}$$

where $H_\varepsilon(x, y)$, the regular part, satisfies, for fixed $y \in \mathbb{R}^n$,

$$\begin{cases} (-\Delta)^s H_\varepsilon(x, y) + H_\varepsilon(x, y) = 0 & \text{if } x \in \Omega_\varepsilon, \\ H_\varepsilon(x, y) = \Gamma(x - y) & \text{if } x \in \mathbb{R}^n \setminus \Omega_\varepsilon. \end{cases} \tag{1-15}$$

We will show in Theorem 4.1 that, for $\text{dist}(\xi, \partial\Omega_\varepsilon) \geq \delta/\varepsilon$, with $\delta > 0$ fixed and appropriately small, we have that

$$I_\varepsilon(\bar{u}_\xi) = I_0 + \frac{1}{2}\mathcal{H}_\varepsilon(\xi) + o(\varepsilon^{n+4s}), \tag{1-16}$$

where I_0 is the energy of w computed in \mathbb{R}^n and $\mathcal{H}_\varepsilon(\xi)$ is given by

$$\mathcal{H}_\varepsilon(\xi) := \int_{\Omega_\varepsilon} \int_{\Omega_\varepsilon} H_\varepsilon(x, y) w_\xi^p(x) w_\xi^p(y) dx dy. \tag{1-17}$$

We will show that \mathcal{H}_ε satisfies

$$\frac{\alpha}{\text{dist}(\xi, \partial\Omega_\varepsilon)^{n+4s}} \leq \mathcal{H}_\varepsilon(\xi) \leq \frac{\beta}{\text{dist}(\xi, \partial\Omega_\varepsilon)^{n+4s}}, \tag{1-18}$$

where $\alpha, \beta > 0$, for all points $\xi \in \Omega_\varepsilon$ such that $\text{dist}(\xi, \partial\Omega_\varepsilon) \in [5, \bar{\delta}/\varepsilon]$ for $\bar{\delta} > 0$ fixed, suitably small, and $\varepsilon \ll \bar{\delta}$.

From (1-18) and estimate (1-16), we deduce the existence of a global minimizer ξ_ε for the functional $I_\varepsilon(\bar{u}_\xi)$ for all small $\varepsilon > 0$, which is located at distance $\sim 1/\varepsilon$ from $\partial\Omega_\varepsilon$. The actual proof *reduces* the problem of finding a solution close to w_ξ via a Lyapunov–Schmidt procedure to that of finding a critical point ξ_ε of a functional with a similar expansion to (1-16), as we will see in Section 7.

In the classical case (i.e., when $s = 1$ and the operator boils down to the classical Laplacian), there is a broad literature on concentration phenomena; we recall here the seminal papers [Ni and Wei 1995; Li and Nirenberg 1998] and we refer to [Ambrosetti and Malchiodi 2006] for detailed discussions and more precise references. In particular, we recall that [Ni and Wei 1995; Li and Nirenberg 1998; del Pino and Felmer 1999; del Pino et al. 2000] construct solutions of the classical Dirichlet problem that concentrate at points which maximize the distance from the boundary; in this sense, Theorem 1.1 may be seen as the nonlocal counterpart of these results. In our case, the determination of the concentrating point is less explicit than in the classical case, due to the nonlocal behavior of the energy expansion. More precisely, for $s = 1$ one gets the expansion parallel to (1-16),

$$I_\varepsilon(\bar{u}_\xi) = I_0 + \frac{1}{2}\mathcal{H}_\varepsilon(\xi) + O(e^{-(2+\sigma)\text{dist}(\xi, \partial\Omega_\varepsilon)/\varepsilon}),$$

where now

$$\mathcal{H}_\varepsilon(\xi) \approx e^{-2\text{dist}(\xi, \partial\Omega_\varepsilon)/\varepsilon}; \tag{1-19}$$

see for instance Y. Li and L. Nirenberg [1998] (compare (1-19) with (1-18)).

In the nonlocal case, much less is known. Multipole solutions of a fractional Schrödinger equation set in the whole of \mathbb{R}^n were considered recently in [Dávila et al. 2014]. The analysis needed in this paper is considerably more involved. Concentrating solutions for fractional problems involving critical or almost critical exponents were considered in [Choi et al. 2014]. See also [Chen and Zheng 2014] for some

concentration phenomena in particular cases, and also [Secchi 2013] and references therein for related problems about Schrödinger-type equations in a fractional setting.

The paper is organized as follows. The rather delicate analysis of the behavior of the regular part of Green’s function is contained in Section 2. We estimate the function \bar{u}_ξ in Section 3, thus obtaining a first approximation of the energy expansion in Section 4.

The remainders of this expansion need to be carefully estimated; for this, we provide some decay and regularity estimates in Sections 5 and 6.

The Lyapunov–Schmidt method will be resumed in Section 7, where we discuss the linear theory and the bifurcation from it. A key ingredient is the linear nondegeneracy of the least energy solution w ; this is an important result that was completely achieved only recently in [Frank et al. 2015], after preliminary works in particular cases discussed in [Amick and Toland 1991; Frank and Lenzmann 2013; Fall and Valdinoci 2014]. Then we complete the proof of Theorem 1.1 in Section 8.

2. Estimates on the Robin function H_ϵ and on the leading term of the energy functional

Given $\xi \in \Omega_\epsilon$ and $x \in \mathbb{R}^n$, we define

$$\beta_\xi(x) := \int_{\mathbb{R}^n \setminus \Omega_\epsilon} \Gamma(z - \xi)\Gamma(x - z) dz.$$

Notice that, for any $x \in \Omega_\epsilon$ and $z \in \mathbb{R}^n \setminus \Omega_\epsilon$, we have

$$((-\Delta)^s + 1)\Gamma(x - z) = \delta_0(x - z) = 0, \tag{2-1}$$

and so

$$((-\Delta)^s + 1)\beta_\xi(x) = \int_{\mathbb{R}^n \setminus \Omega_\epsilon} \Gamma(z - \xi)((-\Delta)^s + 1)\Gamma(x - z) dz = 0 \tag{2-2}$$

for any $x \in \Omega_\epsilon$. Our purpose is to use $\beta_\xi(x)$ as a barrier, from above and below, for the Robin function $H_\epsilon(x, \xi)$, using (1-15), (2-2) and the comparison principle. For this scope, we estimate the behavior of β_ξ outside Ω_ϵ :

Lemma 2.1. *There exists $c \in (0, 1)$ such that*

$$cH_\epsilon(x, \xi) \leq \beta_\xi(x) \leq c^{-1}H_\epsilon(x, \xi) \tag{2-3}$$

for any $x \in \mathbb{R}^n \setminus \Omega_\epsilon$ and $\xi \in \Omega_\epsilon$ with

$$\text{dist}(\xi, \partial\Omega_\epsilon) \geq 1. \tag{2-4}$$

Proof. First we observe that, for any $x \in \mathbb{R}^n \setminus \Omega_\epsilon$,

$$|B_{1/2}(x) \setminus \Omega_\epsilon| \geq c_\star \tag{2-5}$$

for a suitable $c_\star > 0$. For concreteness, one can take c_\star as the measure of the spherical segment

$$\Sigma := \left\{ z = (z', z_n) \in \mathbb{R}^{n-1} \times \mathbb{R} \mid |z| < \frac{1}{2} \text{ and } z_n \geq \frac{1}{4} \right\}.$$

To prove (2-5), we argue as follows. If $B_{1/2}(x) \subseteq (\mathbb{R}^n \setminus \Omega_\varepsilon)$ we are done. If not, let $p \in (\partial\Omega_\varepsilon) \cap B_{1/2}(x)$ with $\text{dist}(x, \partial\Omega_\varepsilon) = |x - p|$. Notice that the ball centered at x of radius $|x - p|$ is tangent to Ω_ε from the outside at p , and $|x - p| \leq \frac{1}{2}$.

Up to a rigid motion, we suppose that $p = 0$ and $x = |x|e_n$. By scaling back, the ball of radius $|\hat{x}|$ centered at $\hat{x} := \varepsilon x = \varepsilon|x|e_n$ is tangent to Ω from the outside at the origin, and $|\hat{x}| = \varepsilon|x| = \varepsilon|x - p| \leq \varepsilon/2$.

From the regularity of Ω , we have that there exists a ball of universal radius $r_o > 0$ touching Ω from the outside at any point, so in particular $B_{r_o}(r_o e_n)$ touches Ω from the outside at the origin, hence

$$B_{r_o}(r_o e_n) \subseteq \mathbb{R}^n \setminus \Omega. \tag{2-6}$$

We observe that

$$\hat{x} + \varepsilon\Sigma \subseteq B_{r_o}(r_o e_n). \tag{2-7}$$

Indeed, if $z = (z', z_n) \in \hat{x} + \varepsilon\Sigma$ then $\varepsilon\Sigma \ni z - \hat{x} = (z', z_n - |\hat{x}|)$ and so $z_n - |\hat{x}| \in [\varepsilon/4, \varepsilon/2]$ and $|z'| \leq |z| \leq \varepsilon/2$. Hence, for small ε , we have that $r_o - z_n \geq r_o - |\hat{x}| - \varepsilon/2 \geq r_o - \varepsilon \geq 0$ and $r_o - z_n \leq r_o - |\hat{x}| - \varepsilon/4 \leq r_o - \varepsilon/4$, and so

$$|z_n - r_o| = r_o - z_n \leq r_o - \frac{\varepsilon}{4},$$

which gives

$$|z - r_o e_n|^2 = |z'|^2 + |z_n - r_o|^2 \leq \left(\frac{\varepsilon}{2}\right)^2 + \left(r_o - \frac{\varepsilon}{4}\right)^2 = r_o^2 + \frac{\varepsilon^2}{16} + \frac{\varepsilon^2}{4} - \frac{2r_o\varepsilon}{2} < r_o$$

if ε is sufficiently small. This proves (2-7).

As a consequence of (2-6) and (2-7), we conclude that $\hat{x} + \varepsilon\Sigma \subseteq \mathbb{R}^n \setminus \Omega$, that is, by scaling back, $x + \Sigma \subseteq \mathbb{R}^n \setminus \Omega_\varepsilon$. Accordingly,

$$(B_{1/2}(x) \setminus \Omega_\varepsilon) \supseteq B_{1/2}(x) \cap (x + \Sigma) = x + \Sigma$$

and this ends the proof of (2-5).

Now we observe that if $a, b \in \mathbb{R}^n$ satisfy $|a - b| \leq |b - \xi|/2$ and $\min\{|a - \xi|, |b - \xi|\} \geq 1$ then

$$\Gamma(a - \xi) \leq C\Gamma(b - \xi) \tag{2-8}$$

for some $C > 0$. Indeed,

$$|a - \xi| \geq |b - \xi| - |a - b| \geq \frac{|b - \xi|}{2}$$

and so, from (1-12),

$$\Gamma(a - \xi) \leq \frac{C}{|a - \xi|^{n+2s}} \leq \frac{2^{n+2s}C}{|b - \xi|^{n+2s}} \leq 2^{n+2s}C^2\Gamma(b - \xi).$$

This proves (2-8), up to relabeling the constants. As a consequence, given $x \in \mathbb{R}^n \setminus \Omega_\varepsilon$, we apply (2-8) with $a := x$ and $b := z \in B_{1/2}(x) \setminus \Omega_\varepsilon$, we recall (2-4) and (2-5), and we obtain that

$$\begin{aligned} \beta_\xi(x) &\geq \int_{B_{1/2}(x) \setminus \Omega_\varepsilon} \Gamma(z - \xi)\Gamma(x - z) dz \geq C^{-1} \int_{B_{1/2}(x) \setminus \Omega_\varepsilon} \Gamma(x - \xi)\Gamma(x - z) dz \\ &\geq C^{-1}\Gamma(x - \xi) \inf_{y \in B_{1/2}} \Gamma(y) |B_{1/2}(x) \setminus \Omega_\varepsilon| \geq c_* C^{-1}\Gamma(x - \xi) \inf_{y \in B_{1/2}} \Gamma(y). \end{aligned}$$

This proves the first inequality in (2-3), since $x \in \mathbb{R}^n \setminus \Omega_\varepsilon$ and so

$$\Gamma(x - \xi) = H_\varepsilon(x, \xi). \tag{2-9}$$

Now we prove the second inequality in (2-3). For this, we use (2-8) once again (applied here with $a := z$, $b := x$ and recalling (2-4)) and the fact that

$$\int_{\mathbb{R}^n} \Gamma(z) dz = 1 \tag{2-10}$$

to see that

$$I_1 := \int_{B_{|x-\xi|/2}(x) \setminus \Omega_\varepsilon} \Gamma(z - \xi) \Gamma(x - z) dz \leq C \int_{B_{|x-\xi|/2}(x)} \Gamma(x - \xi) \Gamma(x - z) dz \leq C \Gamma(x - \xi). \tag{2-11}$$

On the other hand, if $z \notin B_{|x-\xi|/2}(x)$, we have that $|x - z| \geq |x - \xi|/2$ and so, by (1-12),

$$\Gamma(x - z) \leq \frac{C}{|x - z|^{n+2s}} \leq \frac{2^{n+2s} C}{|x - \xi|^{n+2s}} \leq 2^{n+2s} C^2 \Gamma(x - \xi).$$

Consequently,

$$I_2 := \int_{\mathbb{R}^n \setminus B_{|x-\xi|/2}(x)} \Gamma(z - \xi) \Gamma(x - z) dz \leq C' \int_{\mathbb{R}^n \setminus B_{|x-\xi|/2}(x)} \Gamma(z - \xi) \Gamma(x - \xi) dz \leq C' \Gamma(x - \xi)$$

for some $C' > 0$, thanks to (2-10). From this and (2-11) we obtain that

$$\beta_\xi(x) \leq I_1 + I_2 \leq C'' \Gamma(x - \xi)$$

for some $C'' > 0$. This, together with (2-9), completes the proof of (2-3). □

Corollary 2.2. *There exists $c \in (0, 1)$ such that*

$$c H_\varepsilon(x, \xi) \leq \beta_\xi(x) \leq c^{-1} H_\varepsilon(x, \xi)$$

for any $x \in \mathbb{R}^n$ and $\xi \in \Omega_\varepsilon$ with $\text{dist}(\xi, \partial\Omega_\varepsilon) \geq 1$.

Proof. The desired estimate holds true outside Ω_ε , thanks to (2-3). Then it holds true inside Ω_ε as well, in virtue of (2-2), (1-15) and the comparison principle. □

The above result implies an interesting lower bound on the symmetric version of the Robin function $H_\varepsilon(\xi, \xi)$, and in general for the values of the Robin function sufficiently close to the diagonal, according to the following:

Proposition 2.3. *Let $\delta \in (0, 1)$. Let $\xi \in \Omega_\varepsilon$ with*

$$d := \text{dist}(\xi, \partial\Omega_\varepsilon) \in \left[2, \frac{\delta}{\varepsilon} \right].$$

Let $x, y \in B_{d/2}(\xi)$. Then

$$H_\varepsilon(x, y) \geq \frac{c_o}{d^{n+4s}}$$

for a suitable $c_o \in (0, 1)$, as long as δ is sufficiently small.

Proof. Let $z \in \mathbb{R}^n \setminus \Omega_\varepsilon$. Notice that

$$|\xi - y| \leq \frac{d}{2} \leq \frac{|z - \xi|}{2} \tag{2-12}$$

and so

$$|z - y| \leq |z - \xi| + |\xi - y| \leq \frac{3}{2}|z - \xi|. \tag{2-13}$$

Similarly,

$$|z - x| \leq \frac{3}{2}|z - \xi|. \tag{2-14}$$

Another consequence of (2-12) is that

$$|z - y| \geq |z - \xi| - |\xi - y| \geq \frac{|z - \xi|}{2} \geq \frac{d}{2} \geq 1, \tag{2-15}$$

hence $\text{dist}(y, \partial\Omega_\varepsilon) \geq 1$ (as a matter of fact, till now we only exploited that $d \geq 2$). Notice that in the same way, one has that

$$|z - x| \geq 1. \tag{2-16}$$

Therefore we can use Corollary 2.2 with ξ replaced by y and so, recalling (1-12), (2-15), (2-16), (2-13) and (2-14), we conclude that

$$\begin{aligned} H_\varepsilon(x, y) &\geq c\beta_y(x) \\ &= c \int_{\mathbb{R}^n \setminus \Omega_\varepsilon} \Gamma(z - y)\Gamma(x - z) dz \\ &\geq \frac{c}{C^2} \int_{\mathbb{R}^n \setminus \Omega_\varepsilon} \frac{1}{|y - z|^{n+2s}|x - z|^{n+2s}} dz \\ &\geq c' \int_{\mathbb{R}^n \setminus \Omega_\varepsilon} \frac{1}{|z - \xi|^{2n+4s}} dz \end{aligned} \tag{2-17}$$

for a suitable $c' > 0$.

Now we introduce some geometric considerations. By the smoothness of the domain, we can touch Ω from the outside at any point with balls of universal radius, say $r_o > 0$. By scaling, we can touch Ω_ε from the exterior by balls of radius $r_o\varepsilon^{-1}$, and so of radius d (notice indeed that $d \leq \delta\varepsilon^{-1} \leq r_o\varepsilon^{-1}$ if δ is small enough). Let $\eta \in \partial\Omega_\varepsilon$ be such that $|\xi - \eta| = d$. By the above considerations, we can touch Ω_ε from the outside at η with a ball \mathcal{B} of radius d (i.e., of diameter $2d$). We stress that $\mathcal{B} \subseteq \mathbb{R}^n \setminus \Omega_\varepsilon$, that $|\mathcal{B}| \geq \bar{c}d^n$ for some $\bar{c} > 0$, and that if $z \in \mathcal{B}$ then

$$|z - \xi| \leq |z - \eta| + |\eta - \xi| \leq 2d + d = 3d.$$

These observations and (2-17) yield that

$$H_\varepsilon(x, y) \geq c' \int_{\mathcal{B}} \frac{1}{|z - \xi|^{2n+4s}} dz \geq c'(3d)^{-(2n+4s)}|\mathcal{B}| = c'3^{-(2n+4s)}\bar{c}d^{-(n+4s)},$$

as desired. □

There is also an upper bound similar to the lower bound obtained in Proposition 2.3:

Proposition 2.4. *Let $\xi \in \Omega_\varepsilon$ with $d := \text{dist}(\xi, \partial\Omega_\varepsilon) \geq 2$, and $x, y \in B_{d/2}(\xi)$. Then*

$$H_\varepsilon(x, y) \leq \frac{C_o}{d^{n+4s}}$$

for a suitable $C_o > 0$.

Proof. As noticed in the proof of Proposition 2.3, we can use Corollary 2.2 with ξ replaced by y . Then, since $B_d(\xi) \subseteq \Omega_\varepsilon$, we have $(\mathbb{R}^n \setminus \Omega_\varepsilon) \subseteq (\mathbb{R}^n \setminus B_d(\xi))$, and therefore we obtain that

$$H_\varepsilon(x, y) \leq c^{-1} \beta_y(x) \leq c^{-1} \int_{\mathbb{R}^n \setminus B_d(\xi)} \Gamma(z - \xi) \Gamma(x - z) dz.$$

Also, if $z \in \mathbb{R}^n \setminus B_d(\xi)$, we have that

$$|z - x| \geq |z - \xi| - |\xi - x| \geq d - |\xi - x| \geq \frac{d}{2},$$

hence, by (1-12),

$$H_\varepsilon(x, y) \leq c^{-1} C^2 \int_{\mathbb{R}^n \setminus B_d(\xi)} \frac{1}{|z - \xi|^{n+2s} |z - x|^{n+2s}} dz \leq c^{-1} C^2 \left(\frac{2}{d}\right)^{n+2s} \int_{\mathbb{R}^n \setminus B_d(\xi)} \frac{1}{|z - \xi|^{n+2s}} dz.$$

By computing the latter integral in polar coordinates, we obtain the desired result. □

It will be convenient to define, for any $\xi \in \Omega_\varepsilon$,

$$\Pi_\varepsilon(x, \xi) := \int_{\Omega_\varepsilon} H_\varepsilon(x, y) w_\xi^p(y) dy. \tag{2-18}$$

As a consequence of Proposition 2.4, we have:

Lemma 2.5. *Let $\xi \in \Omega_\varepsilon$ with $d := \text{dist}(\xi, \partial\Omega_\varepsilon) \geq 2$. Let $x \in B_{d/8}(\xi)$. Then*

$$\Pi_\varepsilon(x, \xi) \leq \frac{C}{d^{n+4s}}$$

for some $C > 0$, where $\Pi_\varepsilon(x, \xi)$ is as defined in (2-18).

Proof. We split the integral into two contributions, one in $B_{d/4}(\xi)$ and one outside such ball.

We can use Proposition 2.4 to obtain that, for $y \in \Omega_\varepsilon \cap B_{d/4}(\xi)$, it holds that $H_\varepsilon(x, y) \leq C_o d^{-n-4s}$ and so

$$\pi_1 := \int_{\Omega_\varepsilon \cap B_{d/4}(\xi)} H_\varepsilon(x, y) w_\xi^p(y) dy \leq C_o d^{-n-4s} \int_{\mathbb{R}^n} w_\xi^p(y) dy \leq C_1 d^{-n-4s},$$

for some $C_1 > 0$.

Now we consider the case in which $y \in \Omega_\varepsilon \setminus B_{d/4}(\xi)$. We use (1-4) to see that $w_\xi^p(y) \leq C_2 |y - \xi|^{-p(n+2s)}$ for some $C_2 > 0$. Also, in this case,

$$|y - x| \geq |y - \xi| - |x - \xi| \geq \frac{d}{4} - \frac{d}{8} = \frac{d}{8};$$

hence, by the maximum principle,

$$H_\varepsilon(x, y) \leq \Gamma(x - y) \leq \frac{C_3}{|x - y|^{n+2s}} \leq \frac{C_4}{d^{n+2s}} \tag{2-19}$$

for some $C_3, C_4 > 0$. As a consequence,

$$\pi_2 := \int_{\Omega_\varepsilon \setminus B_{d/4}(\xi)} H_\varepsilon(x, y) w_\xi^p(y) dy \leq \frac{C_2 C_4}{d^{n+2s}} \int_{\mathbb{R}^n \setminus B_{d/4}(\xi)} |y - \xi|^{-p(n+2s)} dz = \frac{C_5}{d^{2s+p(n+2s)}}$$

for some $C_5 > 0$. In particular, since $d \geq 1$ and $p > 1$, we see that $\pi_2 \leq C_5 d^{-n-4s}$ and therefore, recalling (2-18), we conclude that $\Pi_\varepsilon(x, \xi) \leq \pi_1 + \pi_2 \leq (C_1 + C_5) d^{-n-4s}$. \square

The function \mathcal{H}_ε defined in (1-17) will represent the first interesting order in the expansion of the reduced energy functional (see Theorem 4.1 for a precise statement). To show that this reduced energy functional has a local minimum, we will show that \mathcal{H}_ε (and so the reduced energy functional itself) attains, in a certain domain, values that are smaller than the ones attained at the boundary (concretely, this domain will be given by the subset of Ω_ε with points of distance δ/ε from the boundary for some $\delta \in (0, 1)$ fixed suitably small, possibly dependent on n, s and Ω).

To this extent, a detailed statement will be given in Proposition 2.8 and the necessary bounds on \mathcal{H}_ε will be given in Corollaries 2.6 and 2.7, which in turn follow from Propositions 2.3 and 2.4, respectively.

Corollary 2.6. *Let $\delta \in (0, 1)$. Let $\xi \in \Omega_\varepsilon$ with*

$$d := \text{dist}(\xi, \partial\Omega_\varepsilon) \in \left[2, \frac{\delta}{\varepsilon}\right].$$

Then

$$\mathcal{H}_\varepsilon(\xi) \geq \frac{c}{d^{n+4s}}$$

for a suitable $c > 0$ as long as δ is sufficiently small.

Proof. Notice that $B_1(\xi) \subseteq B_{d/2}(\xi) \subseteq \Omega_\varepsilon$. So, by Proposition 2.3, $H_\varepsilon(x, y) \geq c_o d^{-(n+4s)}$ if $x, y \in B_1(\xi)$ and

$$\mathcal{H}_\varepsilon(\xi) \geq \int_{B_1(\xi)} \int_{B_1(\xi)} H_\varepsilon(x, y) w_\xi^p(x) w_\xi^p(y) dx dy \geq c_o d^{-(n+4s)} \left(\int_{B_1} w^p(z) dz \right)^2. \quad \square$$

Corollary 2.7. *Let $\xi \in \Omega_\varepsilon$ with $d := \text{dist}(\xi, \partial\Omega_\varepsilon) \geq 5$. Then*

$$\mathcal{H}_\varepsilon(\xi) \leq \frac{C}{d^{n+4s}}$$

for a suitable $C > 0$.

Proof. We split the integral in (1-17) into three contributions: first we treat the case in which $x, y \in B_{d/2}(\xi)$, then the case in which $x, y \in \mathbb{R}^n \setminus B_{d/2}(\xi)$, and finally the case in which $x \in B_{d/2}(\xi)$ and $y \in \mathbb{R}^n \setminus B_{d/2}(\xi)$ (the case in which $y \in B_{d/2}(\xi)$ and $x \in \mathbb{R}^n \setminus B_{d/2}(\xi)$ is, of course, symmetrical to this one).

In the first case, we use Proposition 2.4, obtaining that

$$\begin{aligned} \int_{B_{d/2}(\xi)} dx \int_{B_{d/2}(\xi)} dy H_\varepsilon(x, y) w_\xi^p(x) w_\xi^p(y) &\leq C_o d^{-(n+4s)} \left(\int_{B_{d/2}} w^p(z) dz \right)^2 \\ &\leq C_o d^{-(n+4s)} \left(\int_{\mathbb{R}^n} w^p(z) dz \right)^2. \end{aligned} \quad (2-20)$$

In the second case, we twice use the decay of w given in (1-4), (2-19) and (2-10), obtaining that

$$\begin{aligned}
 & \int_{\mathbb{R}^n \setminus B_{d/2}(\xi)} dx \int_{\mathbb{R}^n \setminus B_{d/2}(\xi)} dy H_\varepsilon(x, y) w_\xi^p(x) w_\xi^p(y) \\
 & \leq C^{2p} \int_{\mathbb{R}^n \setminus B_{d/2}(\xi)} dx \int_{\mathbb{R}^n \setminus B_{d/2}(\xi)} dy |x - \xi|^{-p(n+2s)} |y - \xi|^{-p(n+2s)} \Gamma(x - y) \\
 & \leq C^{2p} (d/2)^{-p(n+2s)} \int_{\mathbb{R}^n \setminus B_{d/2}(\xi)} dx \int_{\mathbb{R}^n \setminus B_{d/2}(\xi)} dy |x - \xi|^{-p(n+2s)} \Gamma(x - y) \\
 & \leq C^{2p} (d/2)^{-p(n+2s)} \int_{\mathbb{R}^n \setminus B_{d/2}} d\eta \int_{\mathbb{R}^n} d\theta |\eta|^{-p(n+2s)} \Gamma(\theta) \\
 & \leq C' d^{-2p(n+2s)+n} \\
 & \leq C' d^{-(n+4s)}
 \end{aligned} \tag{2-21}$$

for some $C' > 0$.

As for the third case, we take $x \in B_{d/2}(\xi)$ and $y \in \mathbb{R}^n \setminus B_{d/2}(\xi)$ and we distinguish two subcases: either $|x - y| \leq d/6$ or $|x - y| > d/6$.

In the first subcase, we use a translated version of Proposition 2.4. If $x \in B_{d/2}(\xi)$, $y \in \mathbb{R}^n \setminus B_{d/2}(\xi)$ and $|x - y| \leq d/6$, we take $\hat{\xi} := (x + y)/2$. Notice that

$$|\xi - y| \leq |\xi - x| + |x - y| \leq \frac{d}{2} + \frac{d}{6}$$

and therefore

$$2|\hat{\xi} - \xi| = |(x + y) - 2\xi| \leq |x - \xi| + |y - \xi| \leq \frac{d}{2} + \left(\frac{d}{2} + \frac{d}{6}\right) = \frac{7d}{6}.$$

As a consequence,

$$\hat{d} := \text{dist}(\hat{\xi}, \partial\Omega_\varepsilon) \geq \text{dist}(\xi, \partial\Omega_\varepsilon) - |\hat{\xi} - \xi| \geq d - \frac{7d}{12} = \frac{5d}{12}. \tag{2-22}$$

In particular,

$$\hat{d} \geq 2. \tag{2-23}$$

Also, by construction, $x - \hat{\xi} = \hat{\xi} - y = (x - y)/2$, and so

$$|x - \hat{\xi}| = |\hat{\xi} - y| = \frac{1}{2}|x - y| \leq \frac{d}{12}.$$

This and (2-22) say that

$$x, y \in B_{d/12}(\hat{\xi}) \subseteq B_{\hat{d}/2}(\hat{\xi}). \tag{2-24}$$

Thanks to (2-23) and (2-24), we can now use Proposition 2.4 with ξ and d replaced by $\hat{\xi}$ and \hat{d} , respectively. So we obtain that, in this case,

$$H_\varepsilon(x, y) \leq \frac{C_o}{\hat{d}^{n+4s}} \leq \frac{\hat{C}}{d^{n+4s}} \tag{2-25}$$

for some $\hat{C} > 0$, where (2-22) was used again in the last inequality.

So, we make use of (1-4) and (2-25) to obtain that

$$\begin{aligned}
 \int_{B_{d/2}(\xi)} dx \int_{B_{d/6}(x) \setminus B_{d/2}(\xi)} dy H_\varepsilon(x, y) w_\xi^p(x) w_\xi^p(y) \\
 \leq C^p \hat{C} d^{-(n+4s)} \int_{B_{d/2}(\xi)} dx \int_{B_{d/6}(x) \setminus B_{d/2}(\xi)} dy w_\xi^p(x) |y - \xi|^{-p(n+2s)} \\
 \leq C^p \hat{C} d^{-(n+4s)} \int_{\mathbb{R}^n} dx \int_{\mathbb{R}^n \setminus B_{d/2}} dz w_\xi^p(x) |z|^{-p(n+2s)} \\
 \leq \tilde{C} d^{-4s-p(n+2s)} \\
 \leq \tilde{C} d^{-(n+4s)}.
 \end{aligned} \tag{2-26}$$

Finally, we consider the subcase in which $x \in B_{d/2}(\xi)$, $y \in \mathbb{R}^n \setminus B_{d/2}(\xi)$ and $|x - y| > d/6$. In this circumstance we use (1-4), (2-19) and (1-12) to conclude that

$$\begin{aligned}
 \int_{B_{d/2}(\xi)} dx \int_{\substack{\mathbb{R}^n \setminus B_{d/2}(\xi) \\ \{|x-y|>d/6\}}} dy H_\varepsilon(x, y) w_\xi^p(x) w_\xi^p(y) \\
 \leq C^p \int_{B_{d/2}(\xi)} dx \int_{\substack{\mathbb{R}^n \setminus B_{d/2}(\xi) \\ \{|x-y|>d/6\}}} dy \Gamma(x - y) w_\xi^p(x) |y - \xi|^{-p(n+2s)} \\
 \leq \underline{C} \int_{B_{d/2}(\xi)} dx \int_{\substack{\mathbb{R}^n \setminus B_{d/2}(\xi) \\ \{|x-y|>d/6\}}} dy |x - y|^{-(n+2s)} w_\xi^p(x) |y - \xi|^{-p(n+2s)} \\
 \leq \underline{C} (d/6)^{-(n+2s)} \int_{\mathbb{R}^n} dx \int_{\mathbb{R}^n \setminus B_{d/2}(\xi)} dy w_\xi^p(x) |y - \xi|^{-p(n+2s)} \\
 \leq \bar{C} d^{-2s-p(n+2s)} \\
 \leq \bar{C} d^{-(n+4s)}
 \end{aligned} \tag{2-27}$$

for suitable $\underline{C}, \bar{C} > 0$. From (2-26) and (2-27) we complete the third case, namely when $x \in B_{d/2}(\xi)$ and $y \in \mathbb{R}^n \setminus B_{d/2}(\xi)$, by obtaining that

$$\int_{B_{d/2}(\xi)} dx \int_{\mathbb{R}^n \setminus B_{d/2}(\xi)} dy H_\varepsilon(x, y) w_\xi^p(x) w_\xi^p(y) \leq (\tilde{C} + \bar{C}) d^{-(n+4s)}. \tag{2-28}$$

The desired result follows from (1-17), (2-20), (2-21) and (2-28). □

For concreteness, we summarize the results of Corollaries 2.6 and 2.7 in the following:

Proposition 2.8. *Let $\delta > 0$ be suitably small and*

$$\Omega_{\varepsilon, \delta} := \{x \in \Omega_\varepsilon \mid \text{dist}(x, \partial\Omega_\varepsilon) > \delta/\varepsilon\}. \tag{2-29}$$

Then \mathcal{H}_ε attains an interior minimum in $\Omega_{\varepsilon, \delta}$, namely there exist $c_1, c_2 > 0$ such that

$$\min_{\Omega_{\varepsilon, \delta}} \mathcal{H}_\varepsilon \leq c_1 \varepsilon^{n+4s} < c_2 \left(\frac{\varepsilon}{\delta}\right)^{n+4s} \leq \min_{\partial\Omega_{\varepsilon, \delta}} \mathcal{H}_\varepsilon.$$

Proof. Let δ_\star be the maximal distance that a point of Ω may attain from the boundary of Ω . By scaling, the maximal distance that a point of Ω_ε may attain from the boundary of Ω_ε is δ_\star/ε . Let ξ_\star be such a point, i.e.,

$$d_\star := \text{dist}(\xi_\star, \partial\Omega_\varepsilon) = \frac{\delta_\star}{\varepsilon}.$$

For δ sufficiently small we have that $\xi_\star \in \Omega_{\varepsilon,\delta}$. So, by Corollary 2.7,

$$\min_{\Omega_{\varepsilon,\delta}} \mathcal{H}_\varepsilon \leq \mathcal{H}_\varepsilon(\xi_\star) \leq \frac{C}{d_\star^{n+4s}} = \frac{C\varepsilon^{n+4s}}{\delta_\star^{n+4s}} = c_1\varepsilon^{n+4s}$$

for a suitable $c_1 > 0$. On the other hand, by Corollary 2.6,

$$\min_{\partial\Omega_{\varepsilon,\delta}} \mathcal{H}_\varepsilon \geq \frac{c\varepsilon^{n+4s}}{\delta^{n+4s}},$$

which implies the desired result for δ appropriately small. □

3. Estimates on \bar{u}_ξ and first approximation of the solution

Now we make some estimates on the function \bar{u}_ξ introduced in (1-9), by using in particular the auxiliary function Π_ε in (2-18). For this, we define, for any $\xi \in \Omega_\varepsilon$,

$$\Lambda_\xi(x) := \int_{\mathbb{R}^n \setminus \Omega_\varepsilon} w_\xi^p(y) \Gamma(x-y) dy. \tag{3-1}$$

We have the following estimate for Λ_ξ :

Lemma 3.1. *Let $x, \xi \in \Omega_\varepsilon$. Assume that $d := \text{dist}(\xi, \partial\Omega_\varepsilon) \geq 1$. Then*

$$0 \leq \Lambda_\xi(x) \leq \frac{C}{d^{(n+2s)p}},$$

where $C > 0$ depends on n, p, s and Ω .

Proof. If $y \in \mathbb{R}^n \setminus \Omega_\varepsilon$ then $|y - \xi| \geq \text{dist}(\xi, \partial\Omega_\varepsilon) \geq 1$; therefore, by (1-4),

$$|w_\xi(y)| = |w(y - \xi)| \leq C|y - \xi|^{-(n+2s)} \leq Cd^{-(n+2s)}.$$

As a consequence of this, and recalling (2-10), we deduce that

$$\int_{\mathbb{R}^n \setminus \Omega_\varepsilon} w_\xi^p(y) \Gamma(x-y) dy \leq (Cd^{-(n+2s)})^p \int_{\mathbb{R}^n \setminus \Omega_\varepsilon} \Gamma(x-y) dy \leq (Cd^{-(n+2s)})^p. \tag{3-2}$$

Lemma 3.2. *Let $x, \xi \in \Omega_\varepsilon$. Assume that $d := \text{dist}(\xi, \partial\Omega_\varepsilon) \geq 1$. Then*

$$\bar{u}_\xi(x) = w_\xi(x) - \Lambda_\xi(x) - \Pi_\varepsilon(x, \xi) \tag{3-2}$$

and

$$0 \leq w_\xi(x) - \bar{u}_\xi(x) - \Pi_\varepsilon(x, \xi) \leq \frac{C}{d^{(n+2s)p}} \tag{3-3}$$

for a suitable $C > 0$ that depends on n, p, s and Ω .

Proof. First of all, notice that $w = w^p * \Gamma$, since they both satisfy (1-3), thanks to (1-11), and uniqueness holds. As a consequence

$$w_\xi(x) = w(x - \xi) = \int_{\mathbb{R}^n} w^p(x - \xi - y)\Gamma(y) dy = \int_{\mathbb{R}^n} w_\xi^p(y)\Gamma(x - y) dy. \tag{3-4}$$

Similarly, recalling (1-9), (1-13) and the symmetry of G_ε , we see that

$$\begin{aligned} \bar{u}_\xi(x) &= \int_{\Omega_\varepsilon} \bar{u}_\xi(z)\delta_x(z) dz \\ &= \int_{\Omega_\varepsilon} \bar{u}_\xi(z)((-\Delta)^s + 1)G_\varepsilon(z, x) dz \\ &= \int_{\Omega_\varepsilon} w_\xi^p(z)G_\varepsilon(x, z) dz \\ &= \int_{\Omega_\varepsilon} w_\xi^p(z)\Gamma(x - z) dz - \int_{\Omega_\varepsilon} w_\xi^p(z)H_\varepsilon(x, z) dz \\ &= \int_{\mathbb{R}^n} w_\xi^p(z)\Gamma(x - z) dz - \int_{\mathbb{R}^n \setminus \Omega_\varepsilon} w_\xi^p(z)\Gamma(x - z) dz - \int_{\Omega_\varepsilon} w_\xi^p(z)H_\varepsilon(x, z) dz. \end{aligned}$$

This, (2-18), (3-1) and (3-4) imply (3-2), which, together with Lemma 3.1, implies (3-3). □

Lemma 3.3. *Let $\xi \in \Omega_\varepsilon$. Assume that $d := \text{dist}(\xi, \partial\Omega_\varepsilon) \geq 2$. Then*

$$\int_{\Omega_\varepsilon} w_\xi^{p-1}(x)\Lambda_\xi(x)\Pi_\varepsilon(x, \xi) dx \leq \frac{C}{d^{(n+2s)p+2s}}$$

for a suitable $C > 0$ that depends on n, p, s and Ω .

Proof. First of all, we notice that for $y \in \mathbb{R}^n \setminus \Omega_\varepsilon$ we have $|y - \xi| \geq d > 1$, and therefore, thanks to (1-4),

$$|w_\xi(y)| = |w(y - \xi)| \leq C|y - \xi|^{-(n+2s)} \leq Cd^{-(n+2s)}.$$

Hence, recalling (3-1),

$$\begin{aligned} \int_{\Omega_\varepsilon} w_\xi^{p-1}(x)\Lambda_\xi(x)\Pi_\varepsilon(x, \xi) dx &= \int_{\Omega_\varepsilon} w_\xi^{p-1}(x) \left(\int_{\mathbb{R}^n \setminus \Omega_\varepsilon} w_\xi^p(y)\Gamma(x - y) dy \right) \Pi_\varepsilon(x, \xi) dx \\ &\leq Cd^{-(n+2s)p} \int_{\Omega_\varepsilon} dx \int_{\mathbb{R}^n \setminus \Omega_\varepsilon} dy w_\xi^{p-1}(x)\Gamma(x - y)\Pi_\varepsilon(x, \xi) \\ &\leq Cd^{-(n+2s)p} \int_{\{|x-\xi| \leq d/4\}} dx \int_{\mathbb{R}^n \setminus \Omega_\varepsilon} dy w_\xi^{p-1}(x)\Gamma(x - y)\Pi_\varepsilon(x, \xi) \\ &\quad + Cd^{-(n+2s)p} \int_{\{|x-\xi| > d/4\}} dy w_\xi^{p-1}(x)\Gamma(x - y)\Pi_\varepsilon(x, \xi) \\ &=: I_1 + I_2. \end{aligned} \tag{3-5}$$

Now, thanks to (3-3), we have that $\Pi_\varepsilon(x, \xi) \leq w_\xi(x)$, and so

$$w_\xi^{p-1}(x)\Pi_\varepsilon(x, \xi) \leq w_\xi^p(x). \tag{3-6}$$

Therefore, I_1 can be estimated as follows:

$$\begin{aligned} I_1 &\leq C d^{-(n+2s)p} \int_{\{|x-\xi|\leq d/4\}} dx \int_{\mathbb{R}^n \setminus \Omega_\varepsilon} dy w_\xi^p(x) \Gamma(x-y) \\ &\leq C d^{-(n+2s)p} \int_{\{|x-\xi|\leq d/4\}} dx \int_{\mathbb{R}^n \setminus B_{d/2}(\xi)} dy w_\xi^p(x) \Gamma(x-y). \end{aligned}$$

We notice that, in the above domain,

$$|x-y| \geq |y-\xi| - |x-\xi| \geq \frac{d}{2} - \frac{d}{4} = \frac{d}{4},$$

hence

$$\Gamma(x-y) \leq \frac{C}{|x-y|^{n+2s}}.$$

Now, we can compute in polar coordinates the following integral:

$$\int_{\mathbb{R}^n \setminus B_{d/2}(\xi)} \frac{1}{|x-y|^{n+2s}} dy \leq \frac{C}{d^{2s}},$$

up to renaming the constant C . This and the fact that w_ξ^p is integrable give

$$\begin{aligned} I_1 &\leq C_1 d^{-(n+2s)p} \int_{\{|x-\xi|\leq d/4\}} dx \int_{\mathbb{R}^n \setminus B_{d/2}(\xi)} dy \frac{w_\xi^p(x)}{|x-y|^{n+2s}} \leq C_2 d^{-(n+2s)p} d^{-2s} \int_{\{|x-\xi|\leq d/4\}} w_\xi^p(x) dx \\ &\leq C_3 d^{-(n+2s)p} d^{-2s}, \end{aligned} \tag{3-7}$$

for suitable $C_1, C_2, C_3 > 0$. Now, if $|x-\xi| > d/4$ then, thanks to (1-4),

$$|w_\xi(x)| = |w(x-\xi)| \leq C|x-\xi|^{-(n+2s)}.$$

This, together with (3-6) and (2-10), implies that

$$\begin{aligned} I_2 &\leq C d^{-(n+2s)p} \int_{\{|x-\xi|>d/4\}} dx \int_{\mathbb{R}^n \setminus \Omega_\varepsilon} dy w_\xi^p(x) \Gamma(x-y) \\ &\leq C' d^{-(n+2s)p} \int_{\{|x-\xi|>d/4\}} dx \int_{\mathbb{R}^n \setminus \Omega_\varepsilon} dy \frac{\Gamma(x-y)}{|x-\xi|^{(n+2s)p}} \\ &\leq C'' d^{-(n+2s)p} d^{-(n+2s)p+n} \end{aligned} \tag{3-8}$$

for suitable $C', C'' > 0$, where in the last inequality we have computed the integral in dx in polar coordinates and used (2-10). Putting together (3-7) and (3-8) and recalling (3-5), we get the desired estimate. \square

Lemma 3.4. *Let $\xi \in \Omega_\varepsilon$ and $\tilde{p} := \min\{p, 2\}$. Assume that $d := \text{dist}(\xi, \partial\Omega_\varepsilon) \geq 2$. Then*

$$\int_{\Omega_\varepsilon} w_\xi^{p-1}(x) \Pi_\varepsilon^2(x, \xi) dx \leq \frac{C}{d^{\tilde{p}(n+2s)+2s}}$$

for a suitable $C > 0$ that depends on n, p, s and Ω .

Proof. First we observe that

$$\begin{aligned}
 2(n + 4s) &\geq \tilde{p}(n + 4s) = \tilde{p}(n + 2s + 2s) > \tilde{p}(n + 2s) + 2s && \text{if } p \geq 2, \\
 p(n + 4s) &\geq \tilde{p}(n + 4s) = \tilde{p}(n + 2s + 2s) > \tilde{p}(n + 2s) + 2s && \text{if } 1 < p < 2, \\
 (n + 2s)(p + 1) - n &= p(n + 2s) + 2s \geq \tilde{p}(n + 2s) + 2s.
 \end{aligned}
 \tag{3-9}$$

Now, we can write the integral that we want to estimate as

$$\begin{aligned}
 \int_{\Omega_\varepsilon} w_\xi^{p-1}(x) \Pi_\varepsilon^2(x, \xi) dx &= \int_{\{|x-\xi| \leq d/8\}} w_\xi^{p-1}(x) \Pi_\varepsilon^2(x, \xi) dx + \int_{\{|x-\xi| > d/8\}} w_\xi^{p-1}(x) \Pi_\varepsilon^2(x, \xi) dx \\
 &=: I_1 + I_2.
 \end{aligned}
 \tag{3-10}$$

If $p \geq 2$, then to estimate I_1 we use Lemma 2.5 together with the fact that w_ξ^{p-1} is integrable to get

$$I_1 \leq \frac{C}{d^{2(n+4s)}}.
 \tag{3-11}$$

If $1 < p < 2$, we notice that, thanks to (3-3), $\Pi_\varepsilon(x, \xi) \leq w_\xi(x)$ and so

$$w_\xi^{p-1}(x) \Pi_\varepsilon^2(x, \xi) = w_\xi^{p-1}(x) \Pi_\varepsilon^{2-p}(x, \xi) \Pi_\varepsilon^p(x, \xi) \leq w_\xi^{p-1}(x) w_\xi^{2-p}(x) \Pi_\varepsilon^p(x, \xi) = w_\xi(x) \Pi_\varepsilon^p(x, \xi).$$

Therefore, again using Lemma 2.5 and the fact that w_ξ is integrable, we obtain

$$I_1 \leq \int_{\{|x-\xi| \leq d/8\}} w_\xi(x) \Pi_\varepsilon^p(x, \xi) dx \leq \frac{C}{d^{p(n+4s)}} \int_{\{|x-\xi| \leq d/8\}} w_\xi(x) dx \leq \frac{C}{d^{p(n+4s)}}.
 \tag{3-12}$$

To estimate I_2 , we use (3-3) to obtain that $\Pi_\varepsilon(x, \xi) \leq w_\xi(x)$, and so $w_\xi^{p-1}(x) \Pi_\varepsilon^2(x, \xi) \leq w_\xi^{p+1}(x)$. This implies that

$$I_2 \leq \int_{\{|x-\xi| > d/8\}} w_\xi^{p+1}(x) dx.$$

Since $|x - \xi| > d/8$, thanks to (1-4) we have that

$$|w_\xi(x)| = |w(x - \xi)| \leq C|x - \xi|^{-(n+2s)}.$$

Therefore, computing the integral in polar coordinates,

$$I_2 \leq \int_{\{|x-\xi| > d/8\}} \frac{C}{|x - \xi|^{(n+2s)(p+1)}} dx \leq \frac{C}{d^{(n+2s)(p+1)-n}}.
 \tag{3-13}$$

Putting together (3-11), (3-12) and (3-13) and recalling (3-10), we obtain the result (one can use (3-9) to obtain a simpler common exponent). □

Lemma 3.5. *Let $\delta \in (0, 1)$. Let $\xi \in \Omega_\varepsilon$ be such that $d := \text{dist}(\xi, \partial\Omega_\varepsilon) \geq \delta/\varepsilon$. Then*

$$\int_{\Omega_\varepsilon} w_\xi^{p-1}(x) \Lambda_\xi^2(x) dx \leq C\varepsilon^{2p(n+2s)-n}$$

for a suitable $C > 0$ that depends on n, p, s, δ and Ω .

Proof. We use Lemma 3.1 and the fact that Ω is bounded to obtain that

$$\int_{\Omega_\varepsilon} w_\xi^{p-1}(x) \Lambda_\xi^2(x) dx \leq \frac{C}{d^{2p(n+2s)}} \int_{\Omega_\varepsilon} w_\xi^{p-1}(x) dx \leq \frac{C'}{d^{2p(n+2s)}} |\Omega_\varepsilon| \leq \frac{C''}{d^{2p(n+2s)} \varepsilon^n} \leq \frac{C'' \varepsilon^{2p(n+2s)}}{\delta^{2p(n+2s)} \varepsilon^n}$$

for suitable $C', C'' > 0$. This implies the desired estimate. □

4. Energy estimates and functional expansion in \bar{u}_ξ

In this section we make some estimates for the energy functional (1-10). For this, we consider the functional associated to problem (1-3):

$$I(u) = \frac{1}{2} \int_{\mathbb{R}^n} ((-\Delta)^s u(x)u(x) + u^2(x)) dx - \frac{1}{p+1} \int_{\mathbb{R}^n} u^{p+1}(x) dx, \quad u \in H^s(\mathbb{R}^n). \quad (4-1)$$

Theorem 4.1. Fix $\delta \in (0, 1)$ and $\xi \in \Omega_\varepsilon$ such that $d := \text{dist}(\xi, \partial\Omega_\varepsilon) \geq \delta/\varepsilon$. Then, we have

$$I_\varepsilon(\bar{u}_\xi) = I(w) + \frac{1}{2} \mathcal{H}_\varepsilon(\xi) + o(\varepsilon^{n+4s}) \quad (4-2)$$

as $\varepsilon \rightarrow 0$, where I is given by (4-1), w is the solution to (1-3) and $\mathcal{H}_\varepsilon(\xi)$ is defined in (1-17), as long as δ is sufficiently small.

The following simple observation will be used often in the sequel:

Lemma 4.2. Let $\delta \geq 1$ and $q > 1$. Then

$$\int_{\mathbb{R}^n \setminus B_\delta(\xi)} w_\xi^q(z) dz \leq \frac{C}{\delta^{n(q-1)+2sq}}$$

for some $C > 0$.

Proof. First of all, we observe that

$$n - 1 - (n + 2s)q < n - 1 - (n + 2s) = -1 - 2s < -1$$

and therefore

$$\int_\delta^{+\infty} \rho^{n-1-(n+2s)q} d\rho = \frac{\delta^{n-(n+2s)q}}{(n+2s)q - n}. \quad (4-3)$$

Now, we use (1-4) to see that

$$\int_{\mathbb{R}^n \setminus B_\delta(\xi)} w_\xi^q(z) dz \leq \int_{\mathbb{R}^n \setminus B_\delta(\xi)} \frac{C}{|x - \xi|^{(n+2s)q}} dz = C' \int_\delta^{+\infty} \rho^{n-1-(n+2s)q} d\rho$$

for some $C' > 0$. This and (4-3) imply the desired result. □

Corollary 4.3. Let $\xi \in \Omega_\varepsilon$, with $d := \text{dist}(\xi, \partial\Omega_\varepsilon) \geq 1$. Then

$$\int_{\mathbb{R}^n \setminus \Omega_\varepsilon} w_\xi^{p+1}(z) dz \leq \frac{C}{d^{np+2s(p+1)}}$$

for some $C > 0$.

Proof. Notice that $(\mathbb{R}^n \setminus \Omega_\varepsilon) \subseteq (\mathbb{R}^n \setminus B_d(\xi))$ and exploit Lemma 4.2. □

Proof of Theorem 4.1. Using (1-9) and (3-2), we have

$$\begin{aligned}
 I_\varepsilon(\bar{u}_\xi) &= \frac{1}{2} \int_{\Omega_\varepsilon} ((-\Delta)^s \bar{u}_\xi(x) + \bar{u}_\xi(x)) \bar{u}_\xi(x) dx - \frac{1}{p+1} \int_{\Omega_\varepsilon} \bar{u}_\xi^{p+1}(x) dx \\
 &= \frac{1}{2} \int_{\Omega_\varepsilon} w_\xi^p(x) \bar{u}_\xi(x) dx - \frac{1}{p+1} \int_{\Omega_\varepsilon} \bar{u}_\xi^{p+1}(x) dx \\
 &= \frac{1}{2} \int_{\Omega_\varepsilon} w_\xi^p(x) (w_\xi(x) - \Lambda_\xi(x) - \Pi_\varepsilon(x, \xi)) dx \\
 &\quad - \frac{1}{p+1} \int_{\Omega_\varepsilon} (w_\xi(x) - \Lambda_\xi(x) - \Pi_\varepsilon(x, \xi))^{p+1} dx \\
 &= \left(\frac{1}{2} - \frac{1}{p+1}\right) \int_{\Omega_\varepsilon} w_\xi^{p+1}(x) dx - \frac{1}{2} \int_{\Omega_\varepsilon} w_\xi^p(x) (\Lambda_\xi(x) + \Pi_\varepsilon(x, \xi)) dx \\
 &\quad + \frac{1}{p+1} \int_{\Omega_\varepsilon} [w_\xi^{p+1}(x) - (w_\xi(x) - \Lambda_\xi(x) - \Pi_\varepsilon(x, \xi))^{p+1}] dx. \tag{4-4}
 \end{aligned}$$

We note that the first term in the right-hand side of (4-4) can be written as

$$\begin{aligned}
 \left(\frac{1}{2} - \frac{1}{p+1}\right) \int_{\Omega_\varepsilon} w_\xi^{p+1}(x) dx &= \left(\frac{1}{2} - \frac{1}{p+1}\right) \int_{\mathbb{R}^n} w_\xi^{p+1}(x) dx - \left(\frac{1}{2} - \frac{1}{p+1}\right) \int_{\mathbb{R}^n \setminus \Omega_\varepsilon} w_\xi^{p+1}(x) dx \\
 &= I(w) - \left(\frac{1}{2} - \frac{1}{p+1}\right) \int_{\mathbb{R}^n \setminus \Omega_\varepsilon} w_\xi^{p+1}(x) dx,
 \end{aligned}$$

since w is a solution to (1-3). Therefore,

$$\begin{aligned}
 I_\varepsilon(\bar{u}_\xi) &= I(w) - \left(\frac{1}{2} - \frac{1}{p+1}\right) \int_{\mathbb{R}^n \setminus \Omega_\varepsilon} w_\xi^{p+1}(x) dx - \frac{1}{2} \int_{\Omega_\varepsilon} w_\xi^p(x) (\Lambda_\xi(x) + \Pi_\varepsilon(x, \xi)) dx \\
 &\quad + \frac{1}{p+1} \int_{\Omega_\varepsilon} [w_\xi^{p+1}(x) - (w_\xi(x) - \Lambda_\xi(x) - \Pi_\varepsilon(x, \xi))^{p+1}] dx \\
 &= I(w) - \left(\frac{1}{2} - \frac{1}{p+1}\right) J_1 - \frac{1}{2} J_2 + \frac{1}{p+1} J_3, \tag{4-5}
 \end{aligned}$$

where

$$\begin{aligned}
 J_1 &:= \int_{\mathbb{R}^n \setminus \Omega_\varepsilon} w_\xi^{p+1}(x) dx, \\
 J_2 &:= \int_{\Omega_\varepsilon} w_\xi^p(x) (\Lambda_\xi(x) + \Pi_\varepsilon(x, \xi)) dx \\
 \text{and } J_3 &:= \int_{\Omega_\varepsilon} [w_\xi^{p+1}(x) - (w_\xi(x) - \Lambda_\xi(x) - \Pi_\varepsilon(x, \xi))^{p+1}] dx.
 \end{aligned}$$

Now, we estimate separately J_1 , J_2 and J_3 . Thanks to Corollary 4.3, we have that

$$J_1 = \int_{\mathbb{R}^n \setminus \Omega_\varepsilon} w_\xi^{p+1}(x) dx \leq \frac{C}{d^{np+2s(p+1)}} \leq \frac{C}{\delta^{np+2s(p+1)}} \varepsilon^{np+2s(p+1)}. \tag{4-6}$$

Concerning J_2 , we write it as

$$J_2 = J_{21} + J_{22},$$

where

$$\begin{aligned}
 J_{21} &:= \int_{\Omega_\varepsilon} w_\xi^p(x) \Lambda_\xi(x) dx, \\
 J_{22} &:= \int_{\Omega_\varepsilon} w_\xi^p(x) \Pi_\varepsilon(x, \xi) dx.
 \end{aligned}
 \tag{4-7}$$

Recalling the definition of Λ_ξ in (3-1) and the estimate in (1-4), we have that

$$\begin{aligned}
 J_{21} &= \int_{\Omega_\varepsilon} dx \int_{\mathbb{R}^n \setminus \Omega_\varepsilon} dy w_\xi^p(x) w_\xi^p(y) \Gamma(x-y) \\
 &\leq C \int_{\Omega_\varepsilon} dx \int_{\mathbb{R}^n \setminus \Omega_\varepsilon} dy w_\xi^p(x) \frac{\Gamma(x-y)}{|y-\xi|^{(n+2s)p}} \\
 &\leq \frac{C}{d^{(n+2s)p}} \int_{\Omega_\varepsilon} dx \int_{\mathbb{R}^n \setminus \Omega_\varepsilon} dy w_\xi^p(x) \Gamma(x-y) \\
 &= \frac{C}{d^{(n+2s)p}} \left(\int_{\Omega_\varepsilon} dx \int_{\substack{\mathbb{R}^n \setminus \Omega_\varepsilon \\ \{|x-y| \leq d/2\}}} dy w_\xi^p(x) \Gamma(x-y) + \int_{\Omega_\varepsilon} dx \int_{\substack{\mathbb{R}^n \setminus \Omega_\varepsilon \\ \{|x-y| > d/2\}}} dy w_\xi^p(x) \Gamma(x-y) \right).
 \end{aligned}
 \tag{4-8}$$

We notice that, if $x \in \Omega_\varepsilon$ and $y \in \mathbb{R}^n \setminus \Omega_\varepsilon$ with $|x - y| \leq d/2$, then

$$|x - \xi| \geq |y - \xi| - |x - y| \geq d - \frac{d}{2} = \frac{d}{2}.$$

Therefore, using (1-4), (2-10) and the fact that Ω is bounded, we have

$$\begin{aligned}
 \int_{\Omega_\varepsilon} dx \int_{\substack{\mathbb{R}^n \setminus \Omega_\varepsilon \\ \{|x-y| \leq d/2\}}} dy w_\xi^p(x) \Gamma(x-y) &\leq C' \int_{\Omega_\varepsilon} dx \int_{\substack{\mathbb{R}^n \setminus \Omega_\varepsilon \\ \{|x-y| \leq d/2\}}} dy \frac{\Gamma(x-y)}{|x-\xi|^{(n+2s)p}} \\
 &\leq C' \int_{\Omega_\varepsilon} dx \int_{\mathbb{R}^n} d\tilde{y} \frac{\Gamma(\tilde{y})}{|x-\xi|^{(n+2s)p}} \\
 &\leq C'' (1/d)^{(n+2s)p} |\Omega_\varepsilon| \\
 &\leq \frac{C'''}{d^{(n+2s)p} \varepsilon^n} \\
 &\leq \frac{C'''}{\delta^{(n+2s)p}} \varepsilon^{(n+2s)p-n}
 \end{aligned}
 \tag{4-9}$$

for suitable constants $C', C'', C''' > 0$. Moreover, if $|x - y| > d/2$, we use (1-12) to get

$$\int_{\Omega_\varepsilon} dx \int_{\substack{\mathbb{R}^n \setminus \Omega_\varepsilon \\ \{|x-y| > d/2\}}} dy w_\xi^p(x) \Gamma(x-y) \leq C \int_{\mathbb{R}^n} dx \int_{\substack{\mathbb{R}^n \setminus \Omega_\varepsilon \\ \{|x-y| > d/2\}}} dy \frac{w_\xi^p(x)}{|x-y|^{n+2s}} \leq \tilde{C} d^{-2s} \leq \frac{\tilde{C}}{\delta^{2s}} \varepsilon^{2s}
 \tag{4-10}$$

for some $\tilde{C} > 0$. Putting together (4-9) and (4-10) and recalling (4-8), we obtain

$$\begin{aligned}
 J_{21} &\leq \frac{C}{d^{(n+2s)p}} \left(\frac{C'''}{\delta^{(n+2s)p}} \varepsilon^{(n+2s)p-n} + \frac{\tilde{C}}{\delta^{2s}} \varepsilon^{2s} \right) \\
 &\leq \frac{C}{\delta^{(n+2s)p}} \varepsilon^{(n+2s)p} \left(\frac{C'''}{\delta^{(n+2s)p}} \varepsilon^{(n+2s)p-n} + \frac{\tilde{C}}{\delta^{2s}} \varepsilon^{2s} \right) \leq \hat{C} \varepsilon^{np+2s(p+1)}
 \end{aligned}
 \tag{4-11}$$

for suitable $\hat{C} > 0$. Therefore,

$$J_2 = J_{22} + o(\varepsilon^{n+4s}) = \int_{\Omega_\varepsilon} w_\xi^p(x) \Pi_\varepsilon(x, \xi) dx + o(\varepsilon^{n+4s}). \tag{4-12}$$

To estimate J_3 we expand $w_\xi^{p+1}(x)$ in the following way:

$$w_\xi^{p+1}(x) = \bar{u}_\xi^{p+1}(x) + (p+1)w_\xi^p(x)(w_\xi(x) - \bar{u}_\xi(x)) + c_p \alpha_\xi^{p-1}(x)(w_\xi(x) - \bar{u}_\xi(x))^2,$$

where $0 \leq \bar{u}_\xi \leq \alpha_\xi \leq w_\xi$ and c_p is a positive constant depending only on p . Therefore, recalling (3-2) and (4-7),

$$\begin{aligned} J_3 &= \int_{\Omega_\varepsilon} [w_\xi^{p+1}(x) - (w_\xi(x) - \Lambda_\xi(x) - \Pi_\varepsilon(x, \xi))^{p+1}] dx \\ &= \int_{\Omega_\varepsilon} [w_\xi^{p+1}(x) - \bar{u}_\xi^{p+1}(x)] dx \\ &= (p+1) \int_{\Omega_\varepsilon} w_\xi^p(x)(\Lambda_\xi(x) + \Pi_\varepsilon(x, \xi)) dx + c_p \int_{\Omega_\varepsilon} \alpha_\xi^{p-1}(x)(\Lambda_\xi(x) + \Pi_\varepsilon(x, \xi))^2 dx \\ &= (p+1)(J_{21} + J_{22}) + c_p \int_{\Omega_\varepsilon} \alpha_\xi^{p-1}(x)(\Lambda_\xi(x) + \Pi_\varepsilon(x, \xi))^2 dx. \end{aligned} \tag{4-13}$$

Since $\alpha_\xi(x) \leq w_\xi(x)$, we have that

$$\begin{aligned} &\int_{\Omega_\varepsilon} \alpha_\xi^{p-1}(x)(\Lambda_\xi(x) + \Pi_\varepsilon(x, \xi))^2 dx \\ &\leq \int_{\Omega_\varepsilon} w_\xi^{p-1}(x)(\Lambda_\xi(x) + \Pi_\varepsilon(x, \xi))^2 dx \\ &= \int_{\Omega_\varepsilon} w_\xi^{p-1}(x)\Lambda_\xi^2(x) dx + \int_{\Omega_\varepsilon} w_\xi^{p-1}(x)\Pi_\varepsilon^2(x, \xi) dx + 2 \int_{\Omega_\varepsilon} w_\xi^{p-1}(x)\Lambda_\xi(x)\Pi_\varepsilon(x, \xi) dx. \end{aligned}$$

Hence, from Lemmata 3.3, 3.4 and 3.5 (together with the fact that $d \geq \delta/\varepsilon$) we deduce that

$$\int_{\Omega_\varepsilon} \alpha_\xi^{p-1}(x)(\Lambda_\xi(x) + \Pi_\varepsilon(x, \xi))^2 dx \leq C_\delta(\varepsilon^{2p(n+2s)-n} + \varepsilon^{(n+2s)\tilde{p}+2s} + \varepsilon^{(n+2s)p+2s})$$

for some C_δ , where $\tilde{p} = \min\{p, 2\}$. The last estimate, (4-11) and (4-13) give

$$J_3 = (p+1)J_{22} + o(\varepsilon^{n+4s}) = (p+1) \int_{\Omega_\varepsilon} w_\xi^p(x) \Pi_\varepsilon(x, \xi) dx + o(\varepsilon^{n+4s}). \tag{4-14}$$

Putting together (4-6), (4-12) and (4-14) and using (4-5), we get

$$I_\varepsilon(\bar{u}_\xi) = I(w) + \frac{1}{2} \int_{\Omega_\varepsilon} w_\xi^p(x) \Pi_\varepsilon(x, \xi) dx + o(\varepsilon^{n+4s}).$$

Thus, recalling the definitions of Π_ε and \mathcal{H}_ε in (2-18) and (1-17), respectively, we obtain (4-2). □

5. Decay of the ground state w

In this section we recall some basic (though not optimal) decay properties of the ground state and of its derivatives.

For this, we start with a general convolution result:

Lemma 5.1. *Let $a, b > n, C_a, C_b > 0$ and $f, g \in L^\infty(\mathbb{R}^n)$ with*

$$|f(x)| \leq C_a(1 + |x|)^{-a} \quad \text{and} \quad |g(x)| \leq C_b(1 + |x|)^{-b}.$$

Then there exists $C > 0$ such that

$$|(f * g)(x)| \leq C(1 + |x|)^{-c}$$

with $c := \min\{a, b\}$.

Proof. Fix $x \in \mathbb{R}^n$ and $r := |x|/2$, and observe that if $y \in B_r(x)$ then

$$|y| \geq |x| - |x - y| \geq |x| - r = \frac{|x|}{2}.$$

As a consequence,

$$\begin{aligned} \int_{B_r(x)} \frac{C_a}{(1 + |x - y|)^a} \frac{C_b}{(1 + |y|)^b} dy &\leq \int_{B_r(x)} \frac{C_a}{(1 + |x - y|)^a} \frac{C_b}{(1 + (|x|/2))^b} dy \\ &\leq \frac{C}{(1 + |x|)^b} \int_{\mathbb{R}^n} \frac{1}{(1 + |x - y|)^a} dy \leq \frac{C}{(1 + |x|)^b}, \end{aligned} \tag{5-1}$$

up to renaming constants. On the other hand, if $y \in \mathbb{R}^n \setminus B_r(x)$ then $|x - y| \geq r = |x|/2$, thus

$$\begin{aligned} \int_{\mathbb{R}^n \setminus B_r(x)} \frac{C_a}{(1 + |x - y|)^a} \frac{C_b}{(1 + |y|)^b} dy &\leq \int_{\mathbb{R}^n \setminus B_r(x)} \frac{C_a}{(1 + (|x|/2))^a} \frac{C_b}{(1 + |y|)^b} dy \\ &\leq \frac{C}{(1 + |x|)^a} \int_{\mathbb{R}^n} \frac{1}{(1 + |y|)^b} dy \leq \frac{C}{(1 + |x|)^a}. \end{aligned} \tag{5-2}$$

Putting together (5-1) and (5-2), we obtain the desired result. □

Now we fix $\xi \in \Omega_\varepsilon$ and we define, for any $i \in \{1, \dots, n\}$,

$$Z_i := \frac{\partial w_\xi}{\partial x_i}, \tag{5-3}$$

where w_ξ is the ground state solution centered at ξ . Moreover, we denote by \mathcal{Z} the linear space spanned by the functions Z_i .

We prove first the following lemmata:

Lemma 5.2. *There exists a positive constant C such that, for any $i = 1, \dots, n$,*

$$|Z_i| \leq C|x - \xi|^{-\nu_1} \quad \text{for any } |x - \xi| \geq 1,$$

where $\nu_1 := \min\{(n + 2s + 1), p(n + 2s)\}$.

Proof. Given $R > 0$, we take $\Gamma_{1,R} \in C^\infty(\mathbb{R}^n)$, with $0 \leq \Gamma_{1,R} \leq \Gamma$ in \mathbb{R}^n and $\Gamma_{1,R} = \Gamma$ outside B_R , and we define $\Gamma_{2,R} := \Gamma - \Gamma_{1,R}$. We use (1-11) to write

$$w = \Gamma * w^p = \Gamma_{1,R} * w^p + \Gamma_{2,R} * w^p. \tag{5-4}$$

We assume, up to translation, that $\xi = 0$. Then, our goal is to prove that, for any $k \in \mathbb{N}$, we have that

$$\left| \frac{\partial w}{\partial x_i}(x) \right| \leq C_k(1 + |x|)^{-\nu(k)}, \tag{5-5}$$

where

$$\nu(k) := \min\{(n + 2s + 1), p(n + 2s), k(p - 1)(n + 2s)\} = \min\{\nu_1, k(p - 1)(n + 2s)\}$$

for some $C_k > 0$. Indeed, the desired claim would follow from (5-5) simply by taking the smallest k for which $k(p - 1) > p$.

To prove (5-5) we perform an inductive argument. So, we first check (5-5) when $k = 0$. For this, we use the fact that $w \in L^\infty(\mathbb{R}^n)$ and that $\Gamma \in L^1(\mathbb{R}^n)$ to find $R > 0$ sufficiently small that

$$\int_{B_R} \Gamma(y) dy \leq \frac{1}{2p\|w\|_{L^\infty(\mathbb{R}^n)}}.$$

This fixes R once and for all for the proof of (5-5) when $k = 0$. Hence, we use the sign of $\Gamma_{1,R}$ and the fact that $\Gamma_{2,R} = 0$ outside B_R to obtain that

$$\int_{\mathbb{R}^n} \Gamma_{2,R}(y) dy = \int_{B_R} \Gamma_{2,R}(y) dy \leq \int_{B_R} \Gamma_{1,R}(y) + \Gamma_{2,R}(y) dy \leq \frac{1}{2p\|w\|_{L^\infty(\mathbb{R}^n)}}. \tag{5-6}$$

Then, for any $t \in (0, 1)$, we define $D_t w(x) := (w(x + te_i) - w(x))/t$ and we infer from (5-4) that

$$D_t w = (D_t \Gamma_{1,R}) * w^p + \Gamma_{2,R} * (D_t w^p). \tag{5-7}$$

Also, from formula (3.2) of [Felmer et al. 2012] we know that

$$|\nabla \Gamma(x)| \leq C|x|^{-(n+2s+1)} \quad \text{for any } |x| \geq 1. \tag{5-8}$$

As a consequence, if $|x| > 2$ and $\eta \in B_1(x)$, we have that

$$|\eta| \geq |x| - |x - \eta| \geq \frac{|x|}{2} > 1;$$

hence,

$$|\Gamma(x + te_1) - \Gamma(x)| \leq t \sup_{\eta \in B_1(x)} |\nabla \Gamma(\eta)| \leq Ct|x|^{-(n+2s+1)},$$

up to renaming C . This gives that $|D_t \Gamma(x)| \leq C(1 + |x|)^{-(n+2s+1)}$, so $|D_t \Gamma_{1,R}(x)| \leq C(1 + |x|)^{-(n+2s+1)}$. Accordingly, we have that

$$|(D_t \Gamma_{1,R}) * w^p| \leq \|w\|_{L^\infty(\mathbb{R}^n)}^p \int_{\mathbb{R}^n} |D_t \Gamma_{1,R}(y)| dy \leq C. \tag{5-9}$$

Also,

$$|w^p(x + te_i) - w^p(x)| \leq p\|w\|_{L^\infty(\mathbb{R}^n)}^{p-1} |w(x + te_i) - w(x)|.$$

This says that

$$|D_t w^p(x)| \leq p \|w\|_{L^\infty(\mathbb{R}^n)}^{p-1} |D_t w(x)|.$$

Moreover,

$$|D_t w(x)| \leq \frac{2 \|w\|_{L^\infty(\mathbb{R}^n)}}{t};$$

hence we can define

$$M(t) := \sup_{x \in \mathbb{R}^n} |D_t w(x)|,$$

so we obtain that

$$|D_t w^p(x)| \leq p \|w\|_{L^\infty(\mathbb{R}^n)}^{p-1} M(t)$$

for every $x \in \mathbb{R}^n$, and thus

$$|\Gamma_{2,R} * (D_t w^p)(x)| \leq \int_{\mathbb{R}^n} \Gamma_{2,R}(y) |D_t w^p(x-y)| dy \leq p \|w\|_{L^\infty(\mathbb{R}^n)}^{p-1} M(t) \int_{\mathbb{R}^n} \Gamma_{2,R}(y) dy \leq \frac{M(t)}{2},$$

thanks to (5-6). Using this and (5-9) in (5-7), we conclude that

$$D_t w \leq C + \frac{M(t)}{2}.$$

By taking the supremum, we obtain that

$$M(t) \leq C + \frac{M(t)}{2},$$

and this gives, up to renaming C , that $M(t) \leq C$. By sending $t \searrow 0$, we complete the proof of (5-5) when $k = 0$.

Now we suppose that (5-5) holds true for some k and we prove it for $k + 1$. The proof is indeed similar to the case $k = 0$: here we take $R := 1$ and use the shorthand notation $\Gamma_1 := \Gamma_{1,R}$ and $\Gamma_2 := \Gamma_{2,R}$. By (5-5) for $k = 0$ and the regularity theory (applied to the equation for $D_t w$), we know that $w \in C^1(\mathbb{R})$; hence, we can differentiate (5-4) and obtain that

$$\frac{\partial w}{\partial x_i} = \frac{\partial \Gamma_1}{\partial x_i} * w^p + \Gamma_2 * \left(p w^{p-1} \frac{\partial w}{\partial x_i} \right). \tag{5-10}$$

So, we use (1-4), (5-8) and Lemma 5.1 to obtain

$$\left| \frac{\partial \Gamma_1}{\partial x_i} * w^p(x) \right| \leq C(1 + |x|)^{-\min\{(n+2s+1), p(n+2s)\}}. \tag{5-11}$$

Moreover, we notice that

$$\begin{aligned} (p-1)(n+2s) + \nu(k) &= \min\{(p-1)(n+2s) + \nu_1, (k+1)(p-1)(n+2s)\} \\ &\geq \min\{\nu_1, (k+1)(p-1)(n+2s)\} = \nu(k+1). \end{aligned}$$

Hence, using (5-5) for k and (1-4) we see that

$$\left| p w^{p-1} \frac{\partial w}{\partial x_i}(x) \right| \leq C(1 + |x|)^{-(p-1)(n+2s) - \nu(k)} \leq C(1 + |x|)^{-\nu(k+1)}, \tag{5-12}$$

up to renaming constants (possibly depending on p). Now, we observe that

$$1 + |x - y| \geq \frac{1}{3}(1 + |x|) \quad \text{if } x \in \mathbb{R}^n \text{ and } |y| < 1. \tag{5-13}$$

Indeed, if $|x| \geq 2$ and $|y| < 1$, then

$$|x - y| \geq |x| - |y| \geq \frac{|x|}{2},$$

which implies (5-13) in this case. If instead $|x| < 2$ and $|y| < 1$, we have that

$$1 + |x| < 3 < 3(1 + |x - y|),$$

and this finishes the proof of (5-13).

Therefore, since Γ_2 vanishes outside B_1 , using (5-12) and (5-13) we have

$$\begin{aligned} \left| \Gamma_2 * \left(pw^{p-1} \frac{\partial w}{\partial x_i} \right) (x) \right| &\leq C \int_{B_1} \frac{\Gamma_2(y)}{(1 + |x - y|)^{\nu(k+1)}} dy \\ &\leq C \int_{B_1} \frac{\Gamma_2(y)}{(1 + |x|)^{\nu(k+1)}} dy \leq \frac{C}{(1 + |x|)^{\nu(k+1)}} \int_{\mathbb{R}^n} \Gamma(y) dy = \frac{C}{(1 + |x|)^{\nu(k+1)}}. \end{aligned}$$

This and (5-11) establish (5-5) for $k + 1$, thus completing the inductive argument. □

Lemma 5.3. *There exists a positive constant C such that, for any $i = 1, \dots, n$,*

$$|\nabla Z_i| \leq C|x - \xi|^{-\nu_2} \quad \text{for any } |x - \xi| \geq 1,$$

where $\nu_2 := \min\{(n + 2s + 2), p(n + 2s)\}$.

Proof. From formula (3.2) of [Felmer et al. 2012], we know that

$$|D^2 \Gamma(x)| \leq C|x|^{-(n+2s+2)}, \quad |x| \geq 1. \tag{5-14}$$

Hence the proof of Lemma 5.3 follows as that of Lemma 5.2, by using (5-14) instead of (5-8). □

Lemma 5.4. *For any $k \in \mathbb{N}$ there exists a positive constant C_k such that, for any $i = 1, \dots, n$,*

$$|D^k Z_i| \leq C_k|x - \xi|^{-n} \quad \text{for any } |x - \xi| \geq 1.$$

Proof. From Lemma C.1(ii) of [Frank et al. 2015], we have that

$$|D^{k+1} \Gamma(x)| \leq C_k|x|^{-n}, \quad |x| \geq 1. \tag{5-15}$$

The proof of Lemma 5.4 follows as that of Lemma 5.2 by using (5-15) instead of (5-8). □

We note that

$$\int_{\mathbb{R}^n} Z_i^2 dx = \int_{\mathbb{R}^n} Z_j^2 dx \quad \text{for any } i, j = 1, \dots, n. \tag{5-16}$$

We set

$$\alpha := \int_{\mathbb{R}^n} Z_1^2 dx, \tag{5-17}$$

and so, thanks to (5-16), we observe that

$$\int_{\mathbb{R}^n} Z_i^2 dx = \alpha \quad \text{for any } i = 1, \dots, n. \tag{5-18}$$

Lemma 5.5. *The Z_i satisfy the following condition:*

$$\int_{\mathbb{R}^n} Z_i Z_j dx = \alpha \delta_{ij}. \tag{5-19}$$

Also, if $\tau_o \in L^\infty([0, +\infty))$, $\tau(x) := \tau_o(|x - \xi|)$ for any $x \in \mathbb{R}^n$ and $\tilde{Z}_i := \tau Z_i$, then

$$\int_{\mathbb{R}^n} \tilde{Z}_i Z_j dx = \tilde{\alpha} \delta_{ij}, \tag{5-20}$$

where¹

$$\tilde{\alpha} := \int_{\mathbb{R}^n} \tilde{Z}_1 Z_1 dx. \tag{5-21}$$

Proof. We first observe that the function w is radial (see, for instance, [Felmer et al. 2012]) and therefore, recalling the definition of Z_i in (5-3), we have that

$$Z_i = \frac{\partial w}{\partial x_i}(x - \xi) = w'_\xi(|x - \xi|) \frac{x_i - \xi_i}{|x - \xi|}.$$

Hence, using the change of variable $y = x - \xi$, for any $i, j = 1, \dots, n$, we have

$$\begin{aligned} \int_{\mathbb{R}^n} \tilde{Z}_i Z_j dx &= \int_{\mathbb{R}^n} \tau_o(|x - \xi|) |w'(|x - \xi|)|^2 \frac{(x_i - \xi_i)(x_j - \xi_j)}{|x - \xi|^2} dx \\ &= \int_{\mathbb{R}^n} \tau_o(|y|) |w'(|y|)|^2 \frac{y_i y_j}{|y|^2} dy. \end{aligned} \tag{5-22}$$

Therefore, if $i \neq j$,

$$\int_{\mathbb{R}^n} \tilde{Z}_i Z_j dx = \int_{\mathbb{R}^{n-1}} y_j \left(\int_{\mathbb{R}} \tau_o(|y|) |w'(|y|)|^2 \frac{y_i}{|y|^2} dy_i \right) dy' = 0,$$

since the function $\tau_o(|y|) |w'(|y|)|^2 y_i / |y|^2$ is odd. This proves (5-20) when $i \neq j$. On the other hand, if $i = j$, formula (5-22) becomes

$$\int_{\mathbb{R}^n} \tilde{Z}_i Z_i dx = \int_{\mathbb{R}^n} \tau_o(|y|) |w'(|y|)|^2 \frac{y_i^2}{|y|^2} dy.$$

We observe that the latter integral is invariant under rotation; hence,

$$\int_{\mathbb{R}^n} \tilde{Z}_i Z_i dx = \int_{\mathbb{R}^n} \tau_o(|y|) |w'(|y|)|^2 \frac{y_1^2}{|y|^2} dy = \tilde{\alpha}.$$

This establishes (5-20) also when $i = j$. Then, (5-19) follows from (5-20) by choosing $\tau_o := 1$ and comparing (5-18) and (5-21). □

¹In particular, we note that, if τ_o has a sign and does not vanish identically then $\tilde{\alpha} \neq 0$ (and we will often implicitly assume that this is so in the sequel).

Corollary 5.6. *The Z_i satisfy the condition*

$$\int_{\Omega_\varepsilon} Z_i Z_j \, dx = \alpha \delta_{ij} + O(\varepsilon^\nu)$$

with $\nu > n + 4s$.

Proof. From Lemma 5.5, we have that

$$\int_{\Omega_\varepsilon} Z_i Z_j \, dx = \int_{\mathbb{R}^n} Z_i Z_j \, dx - \int_{\mathbb{R}^n \setminus \Omega_\varepsilon} Z_i Z_j \, dx = \alpha \delta_{ij} - \int_{\mathbb{R}^n \setminus \Omega_\varepsilon} Z_i Z_j \, dx.$$

Moreover, from Lemma 5.2, we obtain that

$$\int_{\mathbb{R}^n \setminus \Omega_\varepsilon} Z_i Z_j \, dx \leq C \int_{\mathbb{R}^n \setminus \Omega_\varepsilon} \frac{1}{|x - \xi|^{2\nu_1}} \, dx \leq C \varepsilon^{2\nu_1 - n},$$

which implies the desired result. □

6. Some regularity estimates

Here we perform some uniform estimates on the solutions of our differential equations. For this, we introduce some notation: given $\xi \in \Omega_\varepsilon$ with

$$\text{dist}(\xi, \partial\Omega_\varepsilon) \geq \frac{c}{\varepsilon} \quad \text{for some } c \in (0, 1), \tag{6-1}$$

and $n/2 < \mu < n + 2s$, we define, for any $x \in \mathbb{R}^n$,

$$\rho_\xi(x) := \frac{1}{(1 + |x - \xi|)^\mu}. \tag{6-2}$$

Moreover, we set

$$\|\psi\|_{\star, \xi} := \|\rho_\xi^{-1} \psi\|_{L^\infty(\mathbb{R}^n)}.$$

Lemma 6.1. *Let $g \in L^2(\mathbb{R}^n) \cap L^\infty(\mathbb{R}^n)$ and let $\psi \in H^s(\mathbb{R}^n)$ be a solution to the problem*

$$\begin{cases} (-\Delta)^s \psi + \psi + g = 0 & \text{in } \Omega_\varepsilon, \\ \psi = 0 & \text{in } \mathbb{R}^n \setminus \Omega_\varepsilon. \end{cases} \tag{6-3}$$

Then, there exists a positive constant C such that

$$\|\psi\|_{L^\infty(\mathbb{R}^n)} + \sup_{x \neq y} \frac{|\psi(x) - \psi(y)|}{|x - y|^s} \leq C(\|g\|_{L^\infty(\mathbb{R}^n)} + \|g\|_{L^2(\mathbb{R}^n)}).$$

Proof. From Theorem 8.2 in [Dipierro et al. 2014], we have that $\psi \in L^\infty(\mathbb{R}^n)$ and there exists a constant $C > 0$ such that

$$\|\psi\|_{L^\infty(\mathbb{R}^n)} \leq C(\|g\|_{L^\infty(\mathbb{R}^n)} + \|\psi\|_{L^2(\mathbb{R}^n)}). \tag{6-4}$$

Now, we show that

$$\|\psi\|_{L^2(\mathbb{R}^n)} \leq \|g\|_{L^2(\mathbb{R}^n)}. \tag{6-5}$$

Indeed, we multiply the equation in (6-3) by ψ and we integrate over Ω_ε , obtaining that

$$\int_{\Omega_\varepsilon} (-\Delta)^s \psi \psi + \psi^2 + g \psi \, dx = 0. \tag{6-6}$$

We notice that, thanks to formula (1.5) in [Ros-Oton and Serra 2014b],

$$\int_{\Omega_\varepsilon} (-\Delta)^s \psi \psi \, dx = \int_{\Omega_\varepsilon} |(-\Delta)^s \psi|^2 \, dx \geq 0.$$

Hence, from (6-6) we have

$$\int_{\Omega_\varepsilon} \psi^2 \, dx \leq \int_{\Omega_\varepsilon} -g \psi \, dx.$$

So, using Hölder’s inequality, we get

$$\int_{\Omega_\varepsilon} \psi^2 \, dx \leq \left(\int_{\Omega_\varepsilon} g^2 \, dx \right)^{\frac{1}{2}} \left(\int_{\Omega_\varepsilon} \psi^2 \, dx \right)^{\frac{1}{2}},$$

and therefore, dividing by $(\int_{\Omega_\varepsilon} \psi^2 \, dx)^{1/2}$, we obtain (6-5).

From (6-4) and (6-5), we have that

$$\|\psi\|_{L^\infty(\mathbb{R}^n)} \leq C(\|g\|_{L^\infty(\mathbb{R}^n)} + \|g\|_{L^2(\mathbb{R}^n)}).$$

Now, since both ψ and g are bounded, from the regularity results in [Silvestre 2007] we have that ψ is C^α in the interior of Ω_ε for some $\alpha \in (0, 2s)$.

It remains to prove that ψ is C^α near the boundary of Ω_ε . For this, we fix a point $p \in \partial\Omega_\varepsilon$ and we look at the equation in the ball $B_1(p)$.

We notice that $|(-\Delta)^s \psi|$ is bounded, since both ψ and g are in $L^\infty(\mathbb{R}^n)$, and therefore we can apply Proposition 3.5 in [Ros-Oton and Serra 2014a], obtaining that, for any $x, y \in B_1(p) \cap \Omega_\varepsilon$,

$$\frac{\psi(x)}{d^s(x)} - \frac{\psi(y)}{d^s(y)} \leq C_1(\|\psi\|_{L^\infty(\mathbb{R}^n)} + \|g\|_{L^\infty(\mathbb{R}^n)}), \tag{6-7}$$

where $d(x) := \text{dist}(x, \partial\Omega_\varepsilon)$. In particular, we can fix $y \in B_1(p) \cap \Omega_\varepsilon$ such that $d(y) = \frac{1}{2}$. Since ψ is bounded, from (6-7) we have that

$$\frac{\psi(x)}{d^s(x)} \leq C_2(\|\psi\|_{L^\infty(\mathbb{R}^n)} + \|g\|_{L^\infty(\mathbb{R}^n)}),$$

which gives that

$$\psi(x) \leq C_2(\|\psi\|_{L^\infty(\mathbb{R}^n)} + \|g\|_{L^\infty(\mathbb{R}^n)})d^s(x).$$

This implies that ψ is C^s also near the boundary and concludes the proof of the lemma. □

Lemma 6.2. *Let $\xi \in \Omega_\varepsilon$, \mathcal{B} be a bounded subset of \mathbb{R}^n , and $R_0 > 0$ be such that*

$$B_{R_0}(\xi) \supseteq \mathcal{B}. \tag{6-8}$$

Let $\mathcal{W} \in L^\infty(\mathbb{R}^n)$ be such that

$$m := \inf_{\mathbb{R}^n \setminus \mathcal{B}} \mathcal{W} > 0. \tag{6-9}$$

Let also $g \in L^2(\mathbb{R}^n)$, with $\|g\|_{\star,\xi} < +\infty$, and let $\psi \in H^s(\mathbb{R}^n)$ be a solution to

$$\begin{cases} (-\Delta)^s \psi + \mathcal{W}\psi + g = 0 & \text{in } \Omega_\varepsilon, \\ \psi = 0 & \text{in } \mathbb{R}^n \setminus \Omega_\varepsilon. \end{cases}$$

Then, there exists a positive constant C , possibly depending on m, R_0 and $\|\mathcal{W}\|_{L^\infty(\mathbb{R}^n)}$ (and also on n, s , and Ω), such that²

$$\|\psi\|_{\star,\xi} \leq C(\|\psi\|_{L^\infty(\mathcal{B})} + \|g\|_{\star,\xi}). \tag{6-10}$$

Proof. We define

$$W := m\chi_{\mathcal{B}} + \mathcal{W}\chi_{\mathbb{R}^n \setminus \mathcal{B}} \quad \text{and} \quad G := (m - \mathcal{W})\chi_{\mathcal{B}}\psi - g. \tag{6-11}$$

We observe that

$$\begin{aligned} \|G\|_{\star,\xi} &\leq \sup_{x \in \mathcal{B}} (1 + |x - \xi|)^\mu (m + \mathcal{W}(x))\psi(x) + \|g\|_{\star,\xi} \\ &\leq 2(1 + R_0)^\mu \|\mathcal{W}\|_{L^\infty(\mathbb{R}^n)} \|\psi\|_{L^\infty(\mathcal{B})} + \|g\|_{\star,\xi} \\ &\leq C_0 \|\psi\|_{L^\infty(\mathcal{B})} + \|g\|_{\star,\xi} \end{aligned} \tag{6-12}$$

for a suitable $C_0 > 0$ possibly depending on R_0 and $\|\mathcal{W}\|_{L^\infty(\mathbb{R}^n)}$ (notice that (6-8) was used here). Also, ψ is a solution of

$$(-\Delta)^s \psi + W\psi = (W - \mathcal{W})\psi - g = (W - \mathcal{W}\chi_{\mathbb{R}^n \setminus \mathcal{B}} - \mathcal{W}\chi_{\mathcal{B}})\psi - g = (m\chi_{\mathcal{B}} - \mathcal{W}\chi_{\mathcal{B}})\psi - g = G \tag{6-13}$$

and, in virtue of (6-9),

$$W \geq m\chi_{\mathcal{B}} + m\chi_{\mathbb{R}^n \setminus \mathcal{B}} = m. \tag{6-14}$$

We let $\rho_0 := (1 + |x|)^{-\mu}$ and take $\eta \in H^s(\mathbb{R}^n)$ to be a solution of

$$(-\Delta)^s \eta + m\eta = \rho_0. \tag{6-15}$$

We refer to formula (2.4) in [Dávila et al. 2014] for the existence of such solution and to Lemma 2.2 there for the following estimate:

$$\sup_{x \in \mathbb{R}^n} (1 + |x|)^\mu \eta(x) \leq C_1 \sup_{x \in \mathbb{R}^n} (1 + |x|)^\mu \rho_0(x) = C_1 \tag{6-16}$$

for some $C_1 > 0$, possibly depending on m . Also, by Lemma 2.4 in [Dávila et al. 2014], we have that $\eta \geq 0$, and so, recalling (6-14), we obtain that

$$(W(x) - m)\eta(x - \xi) \geq 0. \tag{6-17}$$

Now we define $\eta_\xi(x) := \eta(x - \xi)$,

$$C_\star := \|G\|_{\star,\xi} \tag{6-18}$$

and $\omega := C_\star \eta_\xi \pm \psi$. We remark that the quantity C_\star plays a different role from the other constants C_0, C_1 and C_2 : indeed, while C_0, C_1 and C_2 depend only on m, R_0 and $\|\mathcal{W}\|_{L^\infty(\mathbb{R}^n)}$ (as well on n, s and Ω), the quantity C_\star also depends on G , and this will be made explicit at the end of the proof.

²In (6-10) we use the standard convention that $\|\psi\|_{L^\infty(\mathcal{B})} := 0$ when $\mathcal{B} := \emptyset$ (equivalently, if $\mathcal{B} = \emptyset$, the term $\|\psi\|_{L^\infty(\mathcal{B})}$ can be neglected in the proof of Lemma 6.2, since, in this case, G and g are the same from (6-11) on).

Notice also that $\rho_0(x - \xi) = \rho_\xi(x)$, due to the definition in (6-2), and

$$C_\star \rho_\xi(x) \pm G(x) \geq \rho_\xi(x) (C_\star - \rho_\xi^{-1}(x) |G(x)|) \geq \rho_\xi(x) (C_\star - \|G\|_{\star, \xi}) \geq 0. \tag{6-19}$$

Thus we infer that

$$(-\Delta)^s \omega + W\omega = C_\star ((-\Delta)^s \eta_\xi + W\eta_\xi) \pm ((-\Delta)^s \psi + W\psi) = C_\star \rho_\xi + C_\star (W - m)\eta_\xi \pm G \geq 0 \tag{6-20}$$

in Ω_ε , thanks to (6-13), (6-15), (6-17) and (6-19). Furthermore, in $\mathbb{R}^n \setminus \Omega_\varepsilon$ we have that $\omega = C_\star \eta_\xi \geq 0$. As a consequence of this, (6-20) and the maximum principle (see, e.g., Lemma 6 in [Servadei and Valdinoci 2014]), we conclude that $\omega \geq 0$ in the whole of \mathbb{R}^n .

Accordingly, for any $x \in \mathbb{R}^n$,

$$\begin{aligned} \mp \rho_\xi^{-1}(x) \psi(x) &= \rho_\xi^{-1}(x) (C_\star \eta_\xi(x) - \omega(x)) \\ &\leq C_\star \rho_\xi^{-1}(x) \eta_\xi(x) \\ &\leq C_\star \sup_{y \in \mathbb{R}^n} \rho_\xi^{-1}(y) \eta_\xi(y) \\ &= C_\star \sup_{y \in \mathbb{R}^n} \rho_\xi^{-1}(y + \xi) \eta_\xi(y + \xi) \\ &= C_\star \sup_{y \in \mathbb{R}^n} (1 + |y|)^\mu \eta(y) \\ &\leq C_1 C_\star, \end{aligned}$$

where (6-16) was used in the last step. Hence, recalling (6-18) and (6-12),

$$|\rho_\xi^{-1}(x) \psi(x)| \leq C_1 \|G\|_{\star, \xi} \leq C_1 (C_0 \|\psi\|_{L^\infty(B)} + \|g\|_{\star, \xi}),$$

which implies (6-10). □

As a consequence of Lemma 6.2, we obtain the following two corollaries:

Corollary 6.3. *Let $g \in L^2(\mathbb{R}^n)$, with $\|g\|_{\star, \xi} < +\infty$, and let $\psi \in H^s(\mathbb{R}^n)$ be a solution to*

$$\begin{cases} (-\Delta)^s \psi + \psi - pw_\xi^{p-1} \psi + g = 0 & \text{in } \Omega_\varepsilon, \\ \psi = 0 & \text{in } \mathbb{R}^n \setminus \Omega_\varepsilon. \end{cases}$$

Then, there exist positive constants C and R such that

$$\|\psi\|_{\star, \xi} \leq C (\|\psi\|_{L^\infty(B_R(\xi))} + \|g\|_{\star, \xi}). \tag{6-21}$$

Proof. We apply Lemma 6.2 with $\mathcal{W} := 1 - pw_\xi^{p-1}$ and $\mathcal{B} := B_R(\xi)$ (notice that, with this notation, (6-21) would follow from (6-10)). So, we only need to check that (6-9) holds true with a suitable choice of R . For this, we use that w decays at infinity (recall (1-4)); hence we can fix R large enough that

$$pw^{p-1}(x) \leq \frac{1}{2} \quad \text{for every } x \in \mathbb{R}^n \setminus B_R.$$

Accordingly, $\mathcal{W} \geq 1 - \frac{1}{2} = \frac{1}{2}$, which establishes (6-9) with $m := \frac{1}{2}$. □

Corollary 6.4. *Let $g \in L^2(\mathbb{R}^n)$, with $\|g\|_{\star,\xi} < +\infty$, and let $\psi \in H^s(\mathbb{R}^n)$ be a solution to*

$$\begin{cases} (-\Delta)^s \psi + \psi + g = 0 & \text{in } \Omega_\varepsilon, \\ \psi = 0 & \text{in } \mathbb{R}^n \setminus \Omega_\varepsilon. \end{cases}$$

Then, there exists a positive constant C such that

$$\|\psi\|_{\star,\xi} \leq C \|g\|_{\star,\xi}.$$

Proof. For this we use Lemma 6.2 with $\mathcal{W} := 1$ and $\mathcal{B} := \emptyset$ (recall the footnote on page 1192). □

7. The Lyapunov–Schmidt reduction

In this section we deal with the linear theory associated to the scaled problem (1-8). For this, we introduce the functional space

$$\Psi := \left\{ \psi \in H^s(\mathbb{R}^n) \mid \psi = 0 \text{ in } \mathbb{R}^n \setminus \Omega_\varepsilon \text{ and } \int_{\Omega_\varepsilon} \psi Z_i dx = 0 \text{ for any } i = 1, \dots, n \right\},$$

where the Z_i were introduced in (5-3). We remark that the condition

$$\int_{\Omega_\varepsilon} \psi Z_i dx = 0 \quad \text{for any } i = 1, \dots, n$$

means that ψ is orthogonal to the space \mathcal{Z} (that is the space spanned by Z_i) with respect to the scalar product in $L^2(\Omega_\varepsilon)$.

We look for a solution to (1-8) of the form

$$u = u_\xi := \bar{u}_\xi + \psi, \tag{7-1}$$

where \bar{u}_ξ is the solution to (1-9) and ψ is a small function (for ε sufficiently small) which belongs to Ψ .

Inserting u (given in (7-1)) into (1-8) and recalling that \bar{u}_ξ is a solution to (1-9), we have that, in order to obtain a solution to (1-8), ψ must satisfy

$$(-\Delta)^s \psi + \psi - pw_\xi^{p-1} \psi = E(\psi) + N(\psi) \quad \text{in } \Omega_\varepsilon, \tag{7-2}$$

where³

$$E(\psi) := (\bar{u}_\xi + \psi)^p - (w_\xi + \psi)^p \quad \text{and} \quad N(\psi) := (w_\xi + \psi)^p - w_\xi^p - pw_\xi^{p-1} \psi. \tag{7-3}$$

Instead of solving (7-2), we will consider a projected version of the problem. Namely we will look for a solution $\psi \in H^s(\mathbb{R}^n)$ of the equation

$$(-\Delta)^s \psi + \psi - pw_\xi^{p-1} \psi = E(\psi) + N(\psi) + \sum_{i=1}^n c_i Z_i \quad \text{in } \Omega_\varepsilon \tag{7-4}$$

³As a matter of fact, one should write the positive parts in (7-3), namely set $E(\psi) := (\bar{u}_\xi + \psi)_+^p - (w_\xi + \psi)_+^p$ and $N(\psi) := (w_\xi + \psi)_+^p - w_\xi^p - pw_\xi^{p-1} \psi$, but, a posteriori, this is the same by maximum principle. So, we preferred, with a slight abuse of notation, to drop the positive parts for simplicity of notation.

for some coefficients $c_i \in \mathbb{R}, i \in \{1, \dots, n\}$. Moreover, we require that ψ satisfies the conditions

$$\psi = 0 \quad \text{in } \mathbb{R}^n \setminus \Omega_\varepsilon \tag{7-5}$$

and

$$\int_{\Omega_\varepsilon} \psi Z_i \, dx = 0 \quad \text{for any } i = 1, \dots, n. \tag{7-6}$$

We will prove that problem (7-4)–(7-6) admits a unique solution, which is small if ε is sufficiently small, and then we will show that the coefficients c_i are equal to zero for every $i \in \{1, \dots, n\}$ for a suitable ξ . This will give us a solution $\psi \in \Psi$ to (7-2), and therefore a solution u of (1-8), thanks to the definition in (7-1).

Linear theory. In this subsection we develop a general theory that will give us the existence result for the linear problem (7-4)–(7-6).

Theorem 7.1. *Let $g \in L^2(\mathbb{R}^n)$ with $\|g\|_{\star, \xi} < +\infty$. If $\varepsilon > 0$ is sufficiently small, there exist a unique $\psi \in \Psi$ and numbers $c_i \in \mathbb{R}$ for any $i \in \{1, \dots, n\}$ such that*

$$(-\Delta)^s \psi + \psi - pw_\xi^{p-1} \psi + g = \sum_{i=1}^n c_i Z_i \quad \text{in } \Omega_\varepsilon. \tag{7-7}$$

Moreover, there exists a constant $C > 0$ such that

$$\|\psi\|_{\star, \xi} \leq C \|g\|_{\star, \xi}. \tag{7-8}$$

Before proving Theorem 7.1 we need some preliminary lemmata. In the next lemma we show that we can uniquely determine the coefficients c_i in (7-7) in terms of ψ and g . Actually, we will show that the estimate on the c_i holds in a more general case; that is, we do not need the orthogonality condition in (7-6).

Lemma 7.2. *Let $g \in L^2(\mathbb{R}^n)$ with $\|g\|_{\star, \xi} < +\infty$. Suppose that $\psi \in H^s(\mathbb{R}^n)$ satisfies*

$$\begin{cases} (-\Delta)^s \psi + \psi - pw_\xi^{p-1} \psi + g = \sum_{i=1}^n c_i Z_i & \text{in } \Omega_\varepsilon, \\ \psi = 0 & \text{in } \mathbb{R}^n \setminus \Omega_\varepsilon, \end{cases} \tag{7-9}$$

for some $c_i \in \mathbb{R}, i = 1, \dots, n$.

Then, for $\varepsilon > 0$ sufficiently small and for any $i \in \{1, \dots, n\}$, the coefficient c_i is given by

$$c_i = \frac{1}{\alpha} \int_{\mathbb{R}^n} g Z_i \, dx + f_i, \tag{7-10}$$

where α is as defined in (5-17), for a suitable $f_i \in \mathbb{R}$ that satisfies

$$|f_i| \leq C \varepsilon^{n/2} (\|\psi\|_{L^2(\mathbb{R}^n)} + \|g\|_{L^2(\mathbb{R}^n)}) \tag{7-11}$$

for some positive constant C .

Proof. We start with some considerations in Fourier space on a function $T \in C^2(\mathbb{R}^n) \cap H^2(\mathbb{R}^n)$. First of all, for any $j \in \{1, \dots, n\}$,

$$\|\partial_j^2 T\|_{L^2(\mathbb{R}^n)}^2 = \|\mathcal{F}(\partial_j^2 T)\|_{L^2(\mathbb{R}^n)}^2 = \|\xi_j^2 \hat{T}\|_{L^2(\mathbb{R}^n)}^2 = \int_{\mathbb{R}^n} \xi_j^4 |\hat{T}(\xi)|^2 d\xi.$$

Moreover, by convexity,

$$|\xi|^4 = \left(\sum_{j=1}^n \xi_j^2 \right)^2 \leq 2 \sum_{j=1}^n \xi_j^4,$$

and therefore

$$2\|D^2 T\|_{L^2(\mathbb{R}^n)}^2 = \sum_{j=1}^n 2\|\partial_j^2 T\|_{L^2(\mathbb{R}^n)}^2 \geq \int_{\mathbb{R}^n} |\xi|^4 |\hat{T}(\xi)|^2 d\xi.$$

As a consequence,

$$\begin{aligned} \|(-\Delta)^s T\|_{L^2(\mathbb{R}^n)}^2 &= \|\mathcal{F}((-\Delta)^s T)\|_{L^2(\mathbb{R}^n)}^2 = \|\xi^{2s} \hat{T}\|_{L^2(\mathbb{R}^n)}^2 \\ &= \int_{\mathbb{R}^n} |\xi|^{4s} |\hat{T}(\xi)|^2 d\xi \leq \int_{\mathbb{R}^n} (1 + |\xi|^4) |\hat{T}(\xi)|^2 d\xi \\ &\leq \|T\|_{L^2(\mathbb{R}^n)}^2 + 2\|D^2 T\|_{L^2(\mathbb{R}^n)}^2 \leq C\|T\|_{H^2(\mathbb{R}^n)} \end{aligned} \tag{7-12}$$

for some $C > 0$.

Now, without loss of generality, we may suppose that

$$B_{c/\varepsilon}(\xi) \subseteq \Omega_\varepsilon \tag{7-13}$$

for some $c > 0$. Fix $\varepsilon > 0$, and choose $\tau_\varepsilon \in C^\infty(\mathbb{R}^n, [0, 1])$ with $\tau_\varepsilon = 1$ in $B_{(c/\varepsilon)-1}(\xi)$, $\tau_\varepsilon = 0$ outside $B_{c/\varepsilon}(\xi)$ and $|\nabla \tau_\varepsilon| \leq C$. We set $T_{\varepsilon,j} := Z_j \tau_\varepsilon$. Hence, from (7-12) and Lemmata 5.3 and 5.4,

$$\|(-\Delta)^s T_{\varepsilon,j}\|_{L^2(\mathbb{R}^n)}^2 \leq C \tag{7-14}$$

for some $C > 0$, independent of ε and j .

Moreover, the function $T_{\varepsilon,j}$ belongs to $H^s(\mathbb{R}^n)$ and vanishes outside $B_{c/\varepsilon}(\xi)$, and so in particular outside Ω_ε , thanks to (7-13).

Thus (see, e.g., formula (1.5) in [Ros-Oton and Serra 2014b]),

$$\int_{\Omega_\varepsilon} (-\Delta)^s \psi T_{\varepsilon,j} dx = \int_{\Omega_\varepsilon} (-\Delta)^{s/2} \psi (-\Delta)^{s/2} T_{\varepsilon,j} dx = \int_{\Omega_\varepsilon} \psi (-\Delta)^s T_{\varepsilon,j} dx. \tag{7-15}$$

As a consequence, recalling (7-14),

$$\left| \int_{\Omega_\varepsilon} (-\Delta)^s \psi T_{\varepsilon,j} dx \right| \leq \|\psi\|_{L^2(\Omega_\varepsilon)} \|(-\Delta)^s T_{\varepsilon,j}\|_{L^2(\Omega_\varepsilon)} \leq C\|\psi\|_{L^2(\mathbb{R}^n)}. \tag{7-16}$$

Now, we fix $j \in \{1, \dots, n\}$, we multiply the equation in (7-9) by $T_{\varepsilon,j}$ and we integrate over Ω_ε . We obtain

$$\sum_{i=1}^n c_i \int_{\Omega_\varepsilon} Z_i T_{\varepsilon,j} dx = \int_{\Omega_\varepsilon} T_{\varepsilon,j} ((-\Delta)^s \psi + \psi - p w_\xi^{p-1} \psi + g) dx. \tag{7-17}$$

Now, we observe that, thanks to (7-15), we can write

$$\int_{\Omega_\varepsilon} (-\Delta)^s \psi T_{\varepsilon,j} dx = \int_{\Omega_\varepsilon} \psi (-\Delta)^s T_{\varepsilon,j} dx = \int_{\Omega_\varepsilon} \psi (-\Delta)^s (T_{\varepsilon,j} - Z_j) dx + \int_{\Omega_\varepsilon} \psi (-\Delta)^s Z_j dx. \tag{7-18}$$

Using Hölder’s inequality and (7-12), we have that

$$\begin{aligned} \left| \int_{\Omega_\varepsilon} \psi (-\Delta)^s (T_{\varepsilon,j} - Z_j) dx \right| &\leq \| \psi \|_{L^2(\mathbb{R}^n)} \| (-\Delta)^s (T_{\varepsilon,j} - Z_j) \|_{L^2(\mathbb{R}^n)} \\ &\leq C \| \psi \|_{L^2(\mathbb{R}^n)} \| T_{\varepsilon,j} - Z_j \|_{H^2(\mathbb{R}^n)}. \end{aligned} \tag{7-19}$$

Let us estimate the H^2 -norm of $T_{\varepsilon,j} - Z_j$. First, we have that

$$\| T_{\varepsilon,j} - Z_j \|_{L^2(\mathbb{R}^n)}^2 = \int_{\mathbb{R}^n} (\tau_\varepsilon - 1)^2 Z_j^2 dx \leq \int_{B_{(c/\varepsilon)-1}^c(\xi)} Z_j^2 dx,$$

since $\tau_\varepsilon = 1$ in $B_{c/\varepsilon-1}(\xi)$ and takes values in $(0, 1)$. Hence, from Lemma 5.2, we deduce that

$$\| T_{\varepsilon,j} - Z_j \|_{L^2(\mathbb{R}^n)}^2 \leq C \int_{B_{c/\varepsilon-1}^c(\xi)} \frac{1}{|x - \xi|^{2\nu_1}} dx \leq C \varepsilon^n,$$

up to renaming C . Therefore,

$$\| T_{\varepsilon,j} - Z_j \|_{L^2(\mathbb{R}^n)} \leq C \varepsilon^{n/2}. \tag{7-20}$$

Moreover, we have that

$$\begin{aligned} \| \nabla (T_{\varepsilon,j} - Z_j) \|_{L^2(\mathbb{R}^n)}^2 &= \int_{\mathbb{R}^n} |(\tau_\varepsilon - 1) \nabla Z_j + \nabla \tau_\varepsilon Z_j|^2 dx \\ &= \int_{\mathbb{R}^n} (\tau_\varepsilon - 1)^2 |\nabla Z_j|^2 + |\nabla \tau_\varepsilon|^2 Z_j^2 + 2(\tau_\varepsilon - 1) Z_j \nabla Z_j \cdot \nabla \tau_\varepsilon dx. \end{aligned}$$

Using the fact that both $\tau_\varepsilon - 1$ and $\nabla \tau_\varepsilon$ have support outside $B_{c/\varepsilon-1}(\xi)$, and Lemmata 5.2 and 5.3, we obtain that

$$\| \nabla (T_{\varepsilon,j} - Z_j) \|_{L^2(\mathbb{R}^n)} \leq C \varepsilon^{n/2}. \tag{7-21}$$

Finally, using again the fact that $\tau_\varepsilon - 1$, $\nabla \tau_\varepsilon$ and $D^2 \tau_\varepsilon$ have support outside $B_{c/\varepsilon-1}(\xi)$, and Lemmata 5.2, 5.3 and 5.4, we obtain that

$$\| D^2 (T_{\varepsilon,j} - Z_j) \|_{L^2(\mathbb{R}^n)} \leq C \varepsilon^{n/2}.$$

Using this, (7-20) and (7-21) we have that

$$\| T_{\varepsilon,j} - Z_j \|_{H^2(\mathbb{R}^n)} \leq C \varepsilon^{n/2},$$

and so, from (7-19), we obtain

$$\left| \int_{\Omega_\varepsilon} \psi (-\Delta)^s (T_{\varepsilon,j} - Z_j) dx \right| \leq C \varepsilon^{n/2} \| \psi \|_{L^2(\mathbb{R}^n)}. \tag{7-22}$$

Now, using (7-18), we have that

$$\begin{aligned} \int_{\Omega_\varepsilon} T_{\varepsilon,j}((-\Delta)^s \psi + \psi - pw_\xi^{p-1} \psi) dx \\ = \int_{\Omega_\varepsilon} \psi(-\Delta)^s Z_j + T_{\varepsilon,j} \psi - pw_\xi^{p-1} \psi T_{\varepsilon,j} dx + \int_{\Omega_\varepsilon} \psi(-\Delta)^s (T_{\varepsilon,j} - Z_j) dx. \end{aligned}$$

Since w_ξ is a solution to (1-3), we have that Z_j solves

$$(-\Delta)^s Z_j + Z_j = pw_\xi^{p-1} Z_j,$$

and this implies that

$$\begin{aligned} \int_{\Omega_\varepsilon} T_{\varepsilon,j}((-\Delta)^s \psi + \psi - pw_\xi^{p-1} \psi) dx \\ = \int_{\Omega_\varepsilon} \psi(T_{\varepsilon,j} - Z_j) - pw_\xi^{p-1} \psi(T_{\varepsilon,j} - Z_j) dx + \int_{\Omega_\varepsilon} \psi(-\Delta)^s (T_{\varepsilon,j} - Z_j) dx. \end{aligned}$$

Hence, using the fact that w_ξ is bounded (see (1-4)) and Hölder’s inequality, we have that

$$\begin{aligned} \left| \int_{\Omega_\varepsilon} T_{\varepsilon,j}((-\Delta)^s \psi + \psi - pw_\xi^{p-1} \psi) dx \right| \\ \leq C \left(\|\psi\|_{L^2(\mathbb{R}^n)} \|T_{\varepsilon,j} - Z_j\|_{L^2(\mathbb{R}^n)} + \left| \int_{\Omega_\varepsilon} \psi(-\Delta)^s (T_{\varepsilon,j} - Z_j) dx \right| \right) \\ \leq C\varepsilon^{n/2} \|\psi\|_{L^2(\mathbb{R}^n)}, \end{aligned} \tag{7-23}$$

where we have used (7-20) and (7-22) in the last step.

Now, we can write

$$\begin{aligned} \int_{\Omega_\varepsilon} T_{\varepsilon,j} g dx &= \int_{\Omega_\varepsilon} (T_{\varepsilon,j} - Z_j) g dx + \int_{\Omega_\varepsilon} Z_j g dx \\ &= \int_{\Omega_\varepsilon} (T_{\varepsilon,j} - Z_j) g dx + \int_{\mathbb{R}^n} Z_j g dx - \int_{\mathbb{R}^n \setminus \Omega_\varepsilon} Z_j g dx. \end{aligned} \tag{7-24}$$

Using Hölder’s inequality and (7-20), we can estimate

$$\left| \int_{\Omega_\varepsilon} (T_{\varepsilon,j} - Z_j) g dx \right| \leq \|T_{\varepsilon,j} - Z_j\|_{L^2(\mathbb{R}^n)} \|g\|_{L^2(\mathbb{R}^n)} \leq C\varepsilon^{n/2} \|g\|_{L^2(\mathbb{R}^n)}.$$

Moreover, from Hölder’s inequality and Lemma 5.2 (and recalling that $\text{dist}(\xi, \partial\Omega_\varepsilon) \geq c/\varepsilon$), we obtain that

$$\left| \int_{\mathbb{R}^n \setminus \Omega_\varepsilon} Z_j g dx \right| \leq \|g\|_{L^2(\mathbb{R}^n)} \left(\int_{\mathbb{R}^n \setminus \Omega_\varepsilon} \frac{C}{|x - \xi|^{2\nu_1}} dx \right)^{\frac{1}{2}} \leq C\varepsilon^{n/2} \|g\|_{L^2(\mathbb{R}^n)}.$$

The last two estimates and (7-24) imply that

$$\int_{\Omega_\varepsilon} T_{\varepsilon,j} g dx = \int_{\mathbb{R}^n} Z_j g dx + \tilde{f}_j,$$

where

$$|\tilde{f}_j| \leq C \varepsilon^{n/2} \|g\|_{L^2(\mathbb{R}^n)}.$$

From this, (7-17) and (7-23), we have that

$$\sum_{i=1}^n c_i \int_{\Omega_\varepsilon} Z_i T_{\varepsilon,j} dx = \int_{\mathbb{R}^n} g Z_j dx + \tilde{f}_j, \tag{7-25}$$

where

$$|\tilde{f}_j| \leq C \varepsilon^{n/2} (\|\psi\|_{L^2(\mathbb{R}^n)} + \|g\|_{L^2(\mathbb{R}^n)}), \tag{7-26}$$

up to renaming the constants.

On the other hand, we can write

$$\int_{\Omega_\varepsilon} Z_i T_{\varepsilon,j} dx = \int_{\Omega_\varepsilon} Z_i (T_{\varepsilon,j} - Z_j) dx + \int_{\Omega_\varepsilon} Z_i Z_j dx. \tag{7-27}$$

From Hölder’s inequality, (7-20) and Lemma 5.2, we have that

$$\left| \int_{\Omega_\varepsilon} Z_i (T_{\varepsilon,j} - Z_j) dx \right| \leq \left(\int_{\Omega_\varepsilon} Z_i^2 dx \right)^{\frac{1}{2}} \|T_{\varepsilon,j} - Z_j\|_{L^2(\mathbb{R}^n)} \leq C \varepsilon^{n/2}.$$

Using this and Corollary 5.6 in (7-27), we obtain that

$$\int_{\Omega_\varepsilon} Z_i T_{\varepsilon,j} dx = \alpha \delta_{ij} + O(\varepsilon^{n/2}). \tag{7-28}$$

So, we consider the matrix $A \in \text{Mat}(n \times n)$ defined as

$$A_{ji} := \int_{\Omega_\varepsilon} Z_i T_{\varepsilon,j} dx. \tag{7-29}$$

Thanks to (7-28), the matrix $\alpha^{-1}A$ is a perturbation of the identity and so it is invertible for ε sufficiently small, with inverse equal to the identity plus a smaller order term of size $\varepsilon^{n/2}$. Hence, the matrix A is invertible too, with inverse

$$(A^{-1})_{ji} = \alpha^{-1} \delta_{ij} + O(\varepsilon^{n/2}). \tag{7-30}$$

So we consider the vector $d = (d_1, \dots, d_n)$ defined by

$$d_j := \int_{\mathbb{R}^n} g Z_j dx + \tilde{f}_j. \tag{7-31}$$

We observe that

$$\left| \int_{\mathbb{R}^n} g Z_j dx \right| \leq \|g\|_{L^2(\mathbb{R}^n)} \|Z_j\|_{L^2(\mathbb{R}^n)} \leq C \|g\|_{L^2(\mathbb{R}^n)},$$

thanks to Lemma 5.2. As a consequence, recalling (7-26), we obtain that

$$|d| \leq C (\|\psi\|_{L^2(\mathbb{R}^n)} + \|g\|_{L^2(\mathbb{R}^n)}), \tag{7-32}$$

up to renaming C .

With the setting above, (7-25) reads

$$\sum_{i=1}^n c_i A_{ji} = \int_{\mathbb{R}^n} g Z_j dx + \bar{f}_j = d_j;$$

that is, in matrix notation, $Ac = d$. We can invert this relation using (7-30) and write

$$c = A^{-1}d = \alpha^{-1}d + f^\sharp$$

with

$$|f^\sharp| \leq C\varepsilon^{n/2}|d| \leq C\varepsilon^{n/2}(\|\psi\|_{L^2(\mathbb{R}^n)} + \|g\|_{L^2(\mathbb{R}^n)}), \tag{7-33}$$

in virtue of (7-32). So, using (7-31),

$$c_i = \alpha^{-1}d_i + f_i^\sharp = \alpha^{-1} \int_{\mathbb{R}^n} g Z_i dx + \alpha^{-1} \bar{f}_i + f_i^\sharp.$$

This proves (7-10) with

$$f_i := \alpha^{-1} \bar{f}_i + f_i^\sharp,$$

and then (7-11) follows from (7-26) and (7-33). □

Now, we show that solutions to (7-7) satisfy an a priori estimate. We remark that the result in the following lemma is different from the one in Corollary 6.4, since here also a combination of Z_i for $i = 1, \dots, n$ appears in the equation satisfied by ψ .

Lemma 7.3. *Let $g \in L^2(\mathbb{R}^n)$ with $\|g\|_{\star, \xi} < +\infty$. Let $\psi \in \Psi$ be a solution to (7-7) for some coefficients $c_i \in \mathbb{R}$, $i = 1, \dots, n$, and for ε sufficiently small.*

Then,

$$\|\psi\|_{\star, \xi} \leq C \|g\|_{\star, \xi}.$$

Proof. Suppose by contradiction that there exists a sequence $\varepsilon_j \searrow 0$ as $j \rightarrow +\infty$ such that, for any $j \in \mathbb{N}$, the function ψ_j satisfies

$$\begin{cases} (-\Delta)^s \psi_j + \psi_j - p w_{\xi_j}^{p-1} \psi_j + g_j = \sum_{i=1}^n c_i^j Z_i^j & \text{in } \Omega_{\varepsilon_j}, \\ \psi_j = 0 & \text{in } \mathbb{R}^n \setminus \Omega_{\varepsilon_j}, \\ \int_{\Omega_{\varepsilon_j}} \psi_j Z_i^j dx = 0 & \text{for any } i = 1, \dots, n, \end{cases} \tag{7-34}$$

for suitable $g_j \in L^2(\mathbb{R}^n)$ and $\xi_j \in \Omega_{\varepsilon_j}$, where

$$Z_i^j := \frac{\partial w_{\xi_j}}{\partial x_i}.$$

Moreover,

$$\|\psi_j\|_{\star, \xi_j} = 1 \quad \text{for any } j \in \mathbb{N} \tag{7-35}$$

$$\text{and } \|g_j\|_{\star, \xi_j} \searrow 0 \quad \text{as } j \rightarrow +\infty. \tag{7-36}$$

Notice that the fact that the equation in (7-34) is linear with respect to ψ_j , g_j and Z_i^j allows us to take the sequences ψ_j and g_j as in (7-35) and (7-36).

We claim that, for any given $R > 0$,

$$\|\psi_j\|_{L^\infty(B_R(\xi_j))} \rightarrow 0 \quad \text{as } j \rightarrow +\infty. \tag{7-37}$$

For this, we argue by contradiction and we assume that there exists $\delta > 0$ and $j_0 \in \mathbb{N}$ such that, for any $j \geq j_0$, we have that $\|\psi_j\|_{L^\infty(B_R(\xi_j))} \geq \delta$.

Thanks to Lemmata 7.2 and 5.2, we have that

$$|c_i^j| \leq \frac{C_1}{\alpha_i} \|g_j\|_{\star, \xi_j} + C_2 \varepsilon_j^{n/2}$$

for suitable positive constants C_1 and C_2 . Hence, from (7-36), we obtain that

$$c_i^j \searrow 0 \quad \text{as } j \rightarrow +\infty \text{ for any } i \in \{1, \dots, n\}. \tag{7-38}$$

Now, from Lemma 6.1, we have that

$$\begin{aligned} & \sup_{x \neq y} \frac{|\psi_j(x) - \psi_j(y)|}{|x - y|^s} \\ & \leq C \left(\left\| g_j + \sum_{i=1}^n c_i^j Z_i^j + p w_{\xi_j}^{p-1} \psi_j \right\|_{L^\infty(\mathbb{R}^n)} + \left\| g_j + \sum_{i=1}^n c_i^j Z_i^j + p w_{\xi_j}^{p-1} \psi_j \right\|_{L^2(\mathbb{R}^n)} \right). \end{aligned} \tag{7-39}$$

We observe that

$$\left\| g_j + \sum_{i=1}^n c_i^j Z_i^j + p w_{\xi_j}^{p-1} \psi_j \right\|_{L^\infty(\mathbb{R}^n)} \leq C \left(\|g\|_{\star, \xi_j} + \sum_{i=1}^n |c_i^j| + \|\psi_j\|_{\star, \xi_j} \right),$$

thanks to the decay of Z_i^j in Lemma 5.2 and the fact that $w_{\xi_j}^{p-1}$ is bounded (recall (1-4)). So, from (7-36), (7-38) and (7-35), we obtain that

$$\left\| g_j + \sum_{i=1}^n c_i^j Z_i^j + p w_{\xi_j}^{p-1} \psi_j \right\|_{L^\infty(\mathbb{R}^n)} \leq C \tag{7-40}$$

for a suitable constant $C > 0$ independent of j .

We claim that

$$\left\| g_j + \sum_{i=1}^n c_i^j Z_i^j + p w_{\xi_j}^{p-1} \psi_j \right\|_{L^2(\mathbb{R}^n)} \leq C, \tag{7-41}$$

where $C > 0$ does not depend on j . Indeed,

$$\begin{aligned} \|g_j\|_{L^2(\mathbb{R}^n)} &= \left(\int_{\mathbb{R}^n} g_j^2 dx \right)^{\frac{1}{2}} \leq \|g_j\|_{\star, \xi_j} \left(\int_{\mathbb{R}^n} \rho_{\xi_j}^2 dx \right)^{\frac{1}{2}} \\ &\leq \|g_j\|_{\star, \xi_j} \left(\int_{\mathbb{R}^n} \frac{1}{(1 + |x - \xi_j|)^{2\mu}} dx \right)^{\frac{1}{2}} \leq C \|g_j\|_{\star, \xi_j} \leq C, \end{aligned}$$

since $2\mu > n$ and (7-36) holds. Moreover,

$$\left\| \sum_{i=1}^n c_i^j Z_i^j \right\|_{L^2(\mathbb{R}^n)} \leq \sum_{i=1}^n |c_i^j| \|Z_i^j\|_{L^2(\mathbb{R}^n)} \leq C,$$

thanks to (7-38) and Lemma 5.2. Finally, using (1-4), the fact that $2\mu > n$, and (7-35), we have that

$$\begin{aligned} \left\| pw_{\xi_j}^{p-1} \psi_j \right\|_{L^2(\mathbb{R}^n)} &\leq p \|\psi_j\|_{\star, \xi_j} \left(\int_{\mathbb{R}^n} w_{\xi_j}^{2(p-1)} \rho_{\xi_j}^2 dx \right)^{\frac{1}{2}} \\ &\leq C \|\psi_j\|_{\star, \xi_j} \left(\int_{\mathbb{R}^n} \frac{1}{(1 + |x - \xi_j|)^{2(p-1)(n+2s)+2\mu}} dx \right)^{\frac{1}{2}} \leq C. \end{aligned}$$

Putting together the above estimates, we obtain (7-41).

Hence, from (7-39), (7-40) and (7-41), we have that the ψ_j are equicontinuous.

For any $j = 1, \dots, n$, we define the function

$$\tilde{\psi}_j(x) := \psi_j(x + \xi_j)$$

and the set

$$\tilde{\Omega}_j := \{x = y - \xi_j \mid y \in \Omega_{\varepsilon_j}\}.$$

We notice that $\tilde{\psi}_j$ satisfies

$$(-\Delta)^s \tilde{\psi}_j + \tilde{\psi}_j - pw^{p-1} \tilde{\psi}_j + \tilde{g}_j = \sum_{i=1}^n c_i^j \tilde{Z}_i \quad \text{in } \tilde{\Omega}_j, \tag{7-42}$$

where $\tilde{g}_j(x) := g(x + \xi_j)$ and $\tilde{Z}_i := \partial w / \partial x_i$. Moreover,

$$\tilde{\psi}_j = 0 \quad \text{in } \mathbb{R}^n \setminus \tilde{\Omega}_j. \tag{7-43}$$

Now, thanks to (6-1), we have that $B_{c/\varepsilon_j}(\xi_j) \subset \Omega_{\varepsilon_j}$. Hence, $B_{c/\varepsilon_j} \subset \tilde{\Omega}_j$, which means that $\tilde{\Omega}_j$ converges to \mathbb{R}^n when $j \rightarrow +\infty$.

Furthermore, we have that

$$\|\tilde{\psi}_j\|_{L^\infty(B_R)} \geq \delta \quad \text{and} \quad \|(1 + |x|)^\mu \tilde{\psi}_j\|_{L^\infty(\mathbb{R}^n)} = 1. \tag{7-44}$$

Now, since the ψ_j are equicontinuous, the $\tilde{\psi}_j$ are equicontinuous too, and therefore there exists a function $\bar{\psi}$ such that, up to subsequences, the $\tilde{\psi}_j$ converge to $\bar{\psi}$ uniformly on compact sets.

The function $\bar{\psi}$ is in $L^2(\mathbb{R}^n)$. Indeed, by Fatou's Theorem and (7-35), and recalling that $2\mu > n$, we have

$$\int_{\mathbb{R}^n} \bar{\psi}^2 dx \leq \liminf_{j \rightarrow +\infty} \int_{\mathbb{R}^n} \psi_j^2 dx \leq \liminf_{j \rightarrow +\infty} \|\psi_j\|_{\star, \xi_j}^2 \int_{\mathbb{R}^n} \frac{1}{(1 + |x - \xi_j|)^{2\mu}} dx \leq C.$$

Moreover, $\bar{\psi}$ satisfies the conditions

$$\|\bar{\psi}\|_{L^\infty(B_R)} \geq \delta \tag{7-45}$$

$$\text{and} \quad \|(1 + |x|)^\mu \bar{\psi}\|_{L^\infty(\mathbb{R}^n)} \leq 1. \tag{7-46}$$

We prove that $\bar{\psi}$ solves the equation

$$(-\Delta)^s \bar{\psi} + \bar{\psi} = pw^{p-1} \bar{\psi} \quad \text{in } \mathbb{R}^n. \tag{7-47}$$

Indeed, we multiply the equation in (7-42) by a function $\eta \in C_0^\infty(\tilde{\Omega}_j)$ and we integrate over \mathbb{R}^n . We notice that both η and $\tilde{\psi}_j$ are equal to zero outside $\tilde{\Omega}_j$ (recall (7-43)), and therefore we can use formula (1.5) in [Ros-Oton and Serra 2014b], and we get

$$\int_{\mathbb{R}^n} ((-\Delta)^s \eta + \eta - pw^{p-1} \eta) \tilde{\psi}_j \, dx + \int_{\mathbb{R}^n} \tilde{g}_j \eta \, dx = \sum_{i=1}^n c_i^j \int_{\mathbb{R}^n} \tilde{Z}_i \eta \, dx. \tag{7-48}$$

Now, we have that

$$\|\tilde{g}_j\|_{\star,0} = \|g_j\|_{\star,\xi_j} \searrow 0 \quad \text{as } j \rightarrow +\infty.$$

Moreover,

$$\left| \int_{\mathbb{R}^n} \tilde{g}_j \eta \, dx \right| \leq \|\tilde{g}_j\|_{\star,0} \int_{\mathbb{R}^n} \rho_0 \eta \, dx \leq C \|\tilde{g}_j\|_{\star,0},$$

since $2\mu > n$, which implies that

$$\int_{\mathbb{R}^n} \tilde{g}_j \eta \, dx \rightarrow 0 \quad \text{as } j \rightarrow +\infty. \tag{7-49}$$

Also,

$$\left| \sum_{i=1}^n c_i^j \int_{\mathbb{R}^n} \tilde{Z}_i \eta \, dx \right| \leq C \sum_{i=1}^n |c_i^j|,$$

and so, thanks to (7-38), we obtain that

$$\sum_{i=1}^n c_i^j \int_{\mathbb{R}^n} \tilde{Z}_i \eta \, dx \rightarrow 0 \quad \text{as } j \rightarrow +\infty. \tag{7-50}$$

Finally, we fix $r > 0$ and we estimate

$$\begin{aligned} & \left| \int_{\mathbb{R}^n} ((-\Delta)^s \eta + \eta - pw^{p-1} \eta) \tilde{\psi}_j \, dx - \int_{\mathbb{R}^n} ((-\Delta)^s \eta + \eta - pw^{p-1} \eta) \bar{\psi} \, dx \right| \\ & \leq \int_{\mathbb{R}^n} |(-\Delta)^s \eta + \eta - pw^{p-1} \eta| |\tilde{\psi}_j - \bar{\psi}| \, dx \\ & = \int_{B_r} |(-\Delta)^s \eta + \eta - pw^{p-1} \eta| |\tilde{\psi}_j - \bar{\psi}| \, dx + \int_{\mathbb{R}^n \setminus B_r} |(-\Delta)^s \eta + \eta - pw^{p-1} \eta| |\tilde{\psi}_j - \bar{\psi}| \, dx. \end{aligned} \tag{7-51}$$

We define the function

$$\tilde{\eta} := (-\Delta)^s \eta + \eta - pw^{p-1} \eta$$

and we notice that it satisfies the decay

$$|\tilde{\eta}(x)| \leq \frac{C_1}{(1 + |x|)^{n+2s}}. \tag{7-52}$$

Hence,

$$\begin{aligned} \int_{B_r} |(-\Delta)^s \eta + \eta - pw^{p-1} \eta| |\tilde{\psi}_j - \bar{\psi}| dx &\leq C_1 \|\tilde{\psi}_j - \bar{\psi}\|_{L^\infty(B_r)} \int_{B_r} \frac{1}{(1+|x|)^{n+2s}} dx \\ &\leq C_2 \|\tilde{\psi}_j - \bar{\psi}\|_{L^\infty(B_r)}, \end{aligned}$$

which implies that

$$\int_{B_r} |(-\Delta)^s \eta + \eta - pw^{p-1} \eta| |\tilde{\psi}_j - \bar{\psi}| dx \searrow 0 \quad \text{as } j \rightarrow +\infty \quad (7-53)$$

due to the uniform convergence of $\tilde{\psi}_j$ to $\bar{\psi}$ on compact sets. On the other hand, from (7-44), (7-46) and (7-52), we have that

$$\begin{aligned} \int_{\mathbb{R}^n \setminus B_r} |(-\Delta)^s \eta + \eta - pw^{p-1} \eta| |\tilde{\psi}_j - \bar{\psi}| dx &\leq 2C_1 \int_{\mathbb{R}^n \setminus B_r} \frac{1}{(1+|x|)^{n+2s}} dx \\ &\leq 2C_1 \int_{\mathbb{R}^n \setminus B_r} \frac{1}{|x|^{n+2s}} dx \\ &\leq C_3 r^{-2s}. \end{aligned}$$

Hence, sending $r \rightarrow +\infty$, we obtain that

$$\int_{\mathbb{R}^n \setminus B_r} |(-\Delta)^s \eta + \eta - pw^{p-1} \eta| |\tilde{\psi}_j - \bar{\psi}| dx \searrow 0. \quad (7-54)$$

Putting together (7-51), (7-53) and (7-54), we obtain that

$$\int_{\mathbb{R}^n} ((-\Delta)^s \eta + \eta - pw^{p-1} \eta) \tilde{\psi}_j dx \rightarrow \int_{\mathbb{R}^n} ((-\Delta)^s \eta + \eta - pw^{p-1} \eta) \bar{\psi} dx \quad \text{as } j \rightarrow +\infty.$$

This, (7-49), (7-50) and (7-48) imply that

$$\int_{\mathbb{R}^n} ((-\Delta)^s \eta + \eta - pw^{p-1} \eta) \bar{\psi} dx = 0$$

for any $\eta \in C_0^\infty(\mathbb{R}^n)$. This means that $\bar{\psi}$ is a weak solution to (7-47), and so a strong solution, thanks to [Servadei and Valdinoci 2014].

Hence, recalling the nondegeneracy result in [Frank et al. 2015], we have that

$$\bar{\psi} = \sum_{i=1}^n \beta_i \frac{\partial w}{\partial x_i} \quad (7-55)$$

for some coefficients $\beta_i \in \mathbb{R}$.

On the other hand, the orthogonality condition in (7-34) passes to the limit, that is,

$$\int_{\mathbb{R}^n} \bar{\psi} \tilde{Z}_i dx = 0 \quad \text{for any } i = 1, \dots, n. \quad (7-56)$$

Indeed, we fix $r > 0$ and we compute

$$\int_{\mathbb{R}^n} (\bar{\psi} - \tilde{\psi}_j) \tilde{Z}_i dx = \int_{B_r} (\bar{\psi} - \tilde{\psi}_j) \tilde{Z}_i dx + \int_{\mathbb{R}^n \setminus B_r} (\bar{\psi} - \tilde{\psi}_j) \tilde{Z}_i dx. \quad (7-57)$$

Concerning the first term on the right-hand side, we use the uniform convergence of $\tilde{\psi}_j$ to $\bar{\psi}$ on compact sets together with the fact that \tilde{Z}_i is bounded to obtain that

$$\int_{B_r} (\bar{\psi} - \tilde{\psi}_j) \tilde{Z}_i \, dx \rightarrow 0 \quad \text{as } j \rightarrow +\infty.$$

As for the second term, we use (7-44), (7-46) and Lemma 5.2 and we get

$$\int_{\mathbb{R}^n \setminus B_r} (\bar{\psi} - \tilde{\psi}_j) \tilde{Z}_i \, dx \leq C \int_{\mathbb{R}^n \setminus B_r} \frac{1}{|x|^{n+2s}} \, dx \leq \bar{C} r^{-2s},$$

which tends to zero as $r \rightarrow +\infty$. Using the above two formulas in (7-57) we obtain that

$$0 = \int_{\mathbb{R}^n} \tilde{\psi}_j \tilde{Z}_i \, dx \rightarrow \int_{\mathbb{R}^n} \bar{\psi} \tilde{Z}_i \, dx,$$

which implies (7-56).

Therefore, recalling (5-3) also, (7-55) and (7-56) imply that $\bar{\psi} \equiv 0$, thus contradicting (7-45). This proves (7-37).

Now, from Corollary 6.3 (notice that we can take R sufficiently big in order to apply the corollary), we have that

$$\begin{aligned} \|\psi_j\|_{\star, \xi_j} &\leq C \left(\|\psi_j\|_{L^\infty(B_R(\xi_j))} + \left\| g_j + \sum_{i=1}^n c_i^j Z_i^j \right\|_{\star, \xi_j} \right) \\ &\leq C \left(\|\psi_j\|_{L^\infty(B_R(\xi_j))} + \|g_j\|_{\star, \xi_j} + \left\| \sum_{i=1}^n |c_i^j| Z_i^j \right\|_{\star, \xi_j} \right) \\ &= C \left(\|\psi_j\|_{L^\infty(B_R(\xi_j))} + \|g_j\|_{\star, \xi_j} + \left\| \sum_{i=1}^n |c_i^j| \rho_{\xi_j}^{-1} Z_i^j \right\|_{L^\infty(\mathbb{R}^n)} \right) \\ &\leq C \left(\|\psi_j\|_{L^\infty(B_R(\xi_j))} + \|g_j\|_{\star, \xi_j} + \sum_{i=1}^n |c_i^j| \right), \end{aligned}$$

up to renaming C , where we have used the decay of Z_i^j (see Lemma 5.2) and the fact that $\mu < n + 2s$. Therefore, (7-36), (7-37) and (7-38) imply that

$$\|\psi_j\|_{\star, \xi_j} \rightarrow 0 \quad \text{as } j \rightarrow +\infty,$$

which contradicts (7-35) and concludes the proof. □

Now we consider an auxiliary problem: we look for a solution $\psi \in \Psi$ of

$$(-\Delta)^s \psi + \psi + g = \sum_{i=1}^n c_i Z_i \quad \text{in } \Omega_\varepsilon, \tag{7-58}$$

and we prove the following:

Proposition 7.4. *Let $g \in L^2(\mathbb{R}^n)$ with $\|g\|_{\star, \xi} < +\infty$. Then, there exists a unique solution $\psi \in \Psi$ to (7-58).*

Furthermore, there exists a constant $C > 0$ such that

$$\|\psi\|_{\star, \xi} \leq C \|g\|_{\star, \xi}. \tag{7-59}$$

Proof. We first prove the existence of a solution to (7-58).

First of all, we notice that formula (1.5) in [Ros-Oton and Serra 2014b] implies that, for any $\psi, \varphi \in \Psi$,

$$\int_{\mathbb{R}^n} (-\Delta)^s \psi \varphi \, dx = \int_{\mathbb{R}^n} (-\Delta)^{s/2} \psi (-\Delta)^{s/2} \varphi \, dx = \int_{\mathbb{R}^n} \psi (-\Delta)^s \varphi \, dx.$$

Now, given $g \in L^2(\mathbb{R}^n)$, we look for a solution $\psi \in \Psi$ of the problem

$$\int_{\mathbb{R}^n} (-\Delta)^{s/2} \psi (-\Delta)^{s/2} \varphi \, dx + \int_{\mathbb{R}^n} \psi \varphi \, dx + \int_{\mathbb{R}^n} g \varphi \, dx = 0 \tag{7-60}$$

for any $\varphi \in \Psi$. Subsequently we will show that ψ is a solution to the original problem (7-58).

We observe that

$$\langle \psi, \varphi \rangle := \int_{\mathbb{R}^n} (-\Delta)^{s/2} \psi (-\Delta)^{s/2} \varphi \, dx + \int_{\mathbb{R}^n} \psi \varphi \, dx$$

defines an inner product in Ψ , and that

$$F(\varphi) := - \int_{\mathbb{R}^n} g \varphi \, dx$$

is a linear and continuous functional on Ψ . Hence, from Riesz’s theorem, we have that there exists a unique function $\psi \in \Psi$ which solves (7-60).

We claim that

$$\psi \text{ is a strong solution to (7-58).} \tag{7-61}$$

For this, we take a radial cutoff $\tau \in C_0^\infty(\Omega_\varepsilon)$ of the form $\tau(x) = \tau_\circ(|x - \xi|)$ for some smooth and compactly supported real function, and we use Lemma 5.5. So, for any $\phi \in H^s(\mathbb{R}^n)$ such that $\phi = 0$ outside Ω_ε , we define

$$\tilde{\phi} := \phi - \sum_{i=1}^n \lambda_i(\phi) \tilde{Z}_i,$$

where

$$\lambda_i(\phi) := \tilde{\alpha}^{-1} \int_{\mathbb{R}^n} \phi Z_i \, dx, \tag{7-62}$$

and \tilde{Z}_i and $\tilde{\alpha}$ are as in Lemma 5.5. We remark that \tilde{Z}_i vanishes outside Ω_ε , hence so does $\tilde{\phi}$. Furthermore, for any $j \in \{1, \dots, n\}$,

$$\begin{aligned} \int_{\Omega_\varepsilon} \tilde{\phi} Z_j \, dx &= \int_{\mathbb{R}^n} \tilde{\phi} Z_j \, dx = \int_{\mathbb{R}^n} \phi Z_j \, dx - \sum_{i=1}^n \lambda_i(\phi) \int_{\mathbb{R}^n} \tilde{Z}_i Z_j \, dx = \int_{\mathbb{R}^n} \phi Z_j \, dx - \sum_{i=1}^n \lambda_i(\phi) \tilde{\alpha} \delta_{ij} \\ &= \int_{\mathbb{R}^n} \phi Z_j \, dx - \lambda_j(\phi) \tilde{\alpha} \\ &= 0, \end{aligned}$$

thanks to Lemma 5.5 and (7-62). This shows that $\tilde{\phi} \in \Psi$.

As a consequence, we can use $\tilde{\phi}$ as a test function in (7-60) and conclude that

$$\int_{\mathbb{R}^n} (-\Delta)^{s/2} \psi (-\Delta)^{s/2} \left(\phi - \sum_{i=1}^n \lambda_i(\phi) \tilde{Z}_i \right) dx + \int_{\mathbb{R}^n} \psi \left(\phi - \sum_{i=1}^n \lambda_i(\phi) \tilde{Z}_i \right) dx + \int_{\mathbb{R}^n} g \left(\phi - \sum_{i=1}^n \lambda_i(\phi) \tilde{Z}_i \right) dx = 0,$$

that is,

$$\begin{aligned} \int_{\mathbb{R}^n} (-\Delta)^{s/2} \psi (-\Delta)^{s/2} \phi dx + \int_{\mathbb{R}^n} \psi \phi dx + \int_{\mathbb{R}^n} g \phi dx \\ = \int_{\mathbb{R}^n} (\psi + g) \sum_{i=1}^n \lambda_i(\phi) \tilde{Z}_i dx + \int_{\mathbb{R}^n} (-\Delta)^s \psi \sum_{i=1}^n \lambda_i(\phi) \tilde{Z}_i dx \\ = \sum_{i=1}^n \lambda_i(\phi) \int_{\mathbb{R}^n} (\psi + g + (-\Delta)^s \psi) \tilde{Z}_i dx. \end{aligned} \tag{7-63}$$

Now, we define

$$b_i := \tilde{\alpha}^{-1} \int_{\mathbb{R}^n} (\psi + g + (-\Delta)^s \psi) \tilde{Z}_i dx,$$

we recall (7-62) and we write (7-63) as

$$\int_{\mathbb{R}^n} (-\Delta)^{s/2} \psi (-\Delta)^{s/2} \phi dx + \int_{\mathbb{R}^n} \psi \phi dx + \int_{\mathbb{R}^n} g \phi dx = \sum_{i=1}^n \lambda_i(\phi) \tilde{\alpha} b_i = \sum_{i=1}^n b_i \int_{\mathbb{R}^n} \phi Z_i dx.$$

Since ϕ is any test function, this means that ψ is a solution of

$$(-\Delta)^s \psi + \psi + g = \sum_{i=1}^n b_i Z_i$$

in a weak sense, and therefore in a strong sense, thanks to [Servadei and Valdinoci 2014], thus proving (7-61).

Now, we prove the uniqueness of the solution to (7-58). For this, suppose by contradiction that there exist ψ_1 and ψ_2 in Ψ that solve (7-58). We set

$$\tilde{\psi} := \psi_1 - \psi_2,$$

and we observe that $\tilde{\psi}$ is in Ψ and solves

$$(-\Delta)^s \tilde{\psi} + \tilde{\psi} = \sum_{i=1}^n a_i Z_i \quad \text{in } \Omega_\varepsilon \tag{7-64}$$

for suitable coefficients $a_i \in \mathbb{R}$, $i = 1, \dots, n$.

We multiply the equation in (7-64) by $\tilde{\psi}$ and we integrate over Ω_ε , obtaining that

$$\int_{\Omega_\varepsilon} (-\Delta)^s \tilde{\psi} \tilde{\psi} + \tilde{\psi}^2 dx = 0,$$

since $\tilde{\psi} \in \Psi$ (and so it is orthogonal to Z_i in $L^2(\Omega_\varepsilon)$ for any $i = 1, \dots, n$). Since $\tilde{\psi} = 0$ outside Ω_ε , we can apply formula (1.5) in [Ros-Oton and Serra 2014b] and we obtain that

$$\int_{\mathbb{R}^n} |(-\Delta)^{s/2} \tilde{\psi}|^2 + \tilde{\psi}^2 dx = 0,$$

that is,

$$\|\tilde{\psi}\|_{H^s(\mathbb{R}^n)} = 0,$$

which implies that $\tilde{\psi} = 0$. Thus $\psi_1 = \psi_2$ and this concludes the proof of the uniqueness.

It remains to establish (7-59). Thanks to (7-58) and Corollary 6.4, we have that

$$\|\psi\|_{\star, \xi} \leq C \left\| g - \sum_{i=1}^n c_i Z_i \right\|_{\star, \xi} \leq C \left(\|g\|_{\star, \xi} + \left\| \sum_{i=1}^n c_i Z_i \right\|_{\star, \xi} \right). \quad (7-65)$$

First, we observe that, for any $i = 1, \dots, n$,

$$\|Z_i\|_{\star, \xi} = \sup_{\mathbb{R}^n} |\rho_\xi^{-1} Z_i| \leq C_1,$$

due to Lemma 5.2 and the fact that $\mu < n + 2s$ (recall also (6-2)). Hence,

$$\left\| \sum_{i=1}^n c_i Z_i \right\|_{\star, \xi} \leq \sum_{i=1}^n |c_i| \|Z_i\|_{\star, \xi} \leq C_1 \sum_{i=1}^n |c_i|. \quad (7-66)$$

Now, we claim that

$$\left\| \sum_{i=1}^n c_i Z_i \right\|_{\star, \xi} \leq C_2 (\|\psi\|_{L^2(\mathbb{R}^n)} + \|g\|_{L^2(\mathbb{R}^n)}). \quad (7-67)$$

Indeed, we recall Lemma 5.5, we multiply (7-58) by \tilde{Z}_j for $j \in \{1, \dots, n\}$, and we integrate over \mathbb{R}^n , obtaining that

$$\int_{\mathbb{R}^n} (-\Delta)^s \psi \tilde{Z}_j + \psi \tilde{Z}_j + g \tilde{Z}_j dx = \tilde{\alpha} c_j, \quad (7-68)$$

where \tilde{Z}_j and $\tilde{\alpha}$ are as in Lemma 5.5. Thanks to formula (1.5) in [Ros-Oton and Serra 2014b], we have that

$$\left| \int_{\mathbb{R}^n} (-\Delta)^s \psi \tilde{Z}_j dx \right| = \left| \int_{\mathbb{R}^n} \psi (-\Delta)^s \tilde{Z}_j dx \right| \leq \|(-\Delta)^s \tilde{Z}_j\|_{L^2(\mathbb{R}^n)} \|\psi\|_{L^2(\mathbb{R}^n)},$$

where we have used Hölder's inequality. Therefore, this and (7-68) give that

$$\tilde{\alpha} |c_j| \leq \|(-\Delta)^s \tilde{Z}_j\|_{L^2(\mathbb{R}^n)} \|\psi\|_{L^2(\mathbb{R}^n)} + \|\tilde{Z}_j\|_{L^2(\mathbb{R}^n)} \|\psi\|_{L^2(\mathbb{R}^n)} + \|\tilde{Z}_j\|_{L^2(\mathbb{R}^n)} \|g\|_{L^2(\mathbb{R}^n)},$$

which, together with (7-66), implies (7-67), since both $\|(-\Delta)^s \tilde{Z}_j\|_{L^2(\mathbb{R}^n)}$ and $\|\tilde{Z}_j\|_{L^2(\mathbb{R}^n)}$ are bounded (recall Lemma 5.4).

Now, we observe that

$$\|\psi\|_{L^2(\mathbb{R}^n)} \leq \|g\|_{L^2(\mathbb{R}^n)}. \tag{7-69}$$

Indeed, we multiply (7-58) by ψ and we integrate over Ω_ε : we obtain

$$\int_{\Omega_\varepsilon} (-\Delta)^s \psi \psi + \psi^2 + g \psi \, dx = 0,$$

since $\psi \in \Psi$. We notice that the first term in the above formula is quadratic, and so, using Hölder’s inequality, we have that

$$\int_{\Omega_\varepsilon} \psi^2 \, dx \leq \int_{\Omega_\varepsilon} (-g) \psi \, dx \leq \|g\|_{L^2(\mathbb{R}^n)} \|\psi\|_{L^2(\mathbb{R}^n)},$$

which implies (7-69).

Therefore, from (7-67) and (7-69), we deduce that

$$\left\| \sum_{i=1}^n c_i Z_i \right\|_{\star, \xi} \leq 2C_3 \|g\|_{L^2(\mathbb{R}^n)}.$$

Moreover,

$$\|g\|_{L^2(\mathbb{R}^n)} \leq \|g\|_{\star, \xi} \left(\int_{\mathbb{R}^n} \rho_\xi^2 \, dx \right)^{\frac{1}{2}} = \|g\|_{\star, \xi} \left(\int_{\mathbb{R}^n} \frac{1}{(1 + |x - \xi|)^{2\mu}} \, dx \right)^{\frac{1}{2}} \leq C \|g\|_{\star, \xi},$$

since $2\mu > n$. The above two formulas give that

$$\left\| \sum_{i=1}^n c_i Z_i \right\|_{\star, \xi} \leq C_4 \|g\|_{\star, \xi}.$$

This and (7-65) show (7-59), and conclude the proof. □

Now, for any $g \in L^2(\mathbb{R}^n)$ with $\|g\|_{\star, \xi} < +\infty$, we denote by $\mathcal{A}[g]$ the unique solution to (7-58). We notice that Proposition 7.4 implies that the operator \mathcal{A} is well defined and that

$$\|\mathcal{A}[g]\|_{\star, \xi} \leq C \|g\|_{\star, \xi}.$$

We also remark that \mathcal{A} is a linear operator.

We consider the Banach space

$$Y_\star := \{ \psi : \mathbb{R}^n \rightarrow \mathbb{R} \mid \|\psi\|_{\star, \xi} < +\infty \} \tag{7-70}$$

endowed with the norm $\|\cdot\|_{\star, \xi}$.

With this notation we can prove the main theorem of the linear theory, Theorem 7.1.

Proof of Theorem 7.1. We notice that solving (7-7) is equivalent to finding a function $\psi \in \Psi$ such that

$$\psi - \mathcal{A}[-pw_\xi^{p-1}\psi] = \mathcal{A}[g]. \tag{7-71}$$

For this, we set

$$\mathcal{B}[\psi] := \mathcal{A}[-pw_\xi^{p-1}\psi]. \tag{7-72}$$

Recalling the definition of Y_\star given in (7-70), we observe that

$$\text{if } \psi \in Y_\star \text{ then } \mathcal{B}[\psi] \in Y_\star. \quad (7-73)$$

Indeed, from Proposition 7.4 we deduce that $\mathcal{B}[\psi] \in \Psi$ solves (7-58) with $g := -pw_\xi^{p-1}\psi$, and so

$$\|\mathcal{B}[\psi]\|_{\star, \xi} \leq C \| -pw_\xi^{p-1}\psi \|_{\star, \xi} \leq \tilde{C} \|\psi\|_{\star, \xi}$$

for some $\tilde{C} > 0$ (recall that w_ξ is bounded thanks to (1-4)), which proves (7-73).

We claim that

$$\mathcal{B} \text{ defines a compact operator in } Y_\star \text{ with respect to the norm } \|\cdot\|_{\star, \xi}. \quad (7-74)$$

Indeed, let $(\psi_j)_j$ a bounded sequence in Y_\star with respect to the norm $\|\cdot\|_{\star, \xi}$. Then, thanks to Lemma 6.1, the fact that w_ξ^{p-1} and Z_i^j are bounded and $w_\xi^{p-1}\rho_\xi$ and Z_i^j belong to $L^2(\mathbb{R}^n)$, and Lemma 7.2, we have that

$$\begin{aligned} & \sup_{x \neq y} \frac{|\mathcal{B}[\psi_j](x) - \mathcal{B}[\psi_j](y)|}{|x - y|^s} \\ & \leq C_1 \left(\left\| -pw_\xi^{p-1}\psi_j + \sum_{i=1}^n c_i^j Z_i^j \right\|_{L^\infty(\mathbb{R}^n)} + \left\| -pw_\xi^{p-1}\psi_j + \sum_{i=1}^n c_i^j Z_i^j \right\|_{L^2(\mathbb{R}^n)} \right) \\ & \leq C_2 \left(\|\psi_j\|_{L^\infty(\mathbb{R}^n)} + \sum_{i=1}^n |c_i^j| \|Z_i^j\|_{L^\infty(\mathbb{R}^n)} + \|\psi_j\|_{\star, \xi} \|w_\xi^{p-1}\rho_\xi\|_{L^2(\mathbb{R}^n)} + \sum_{i=1}^n |c_i^j| \|Z_i^j\|_{L^2(\mathbb{R}^n)} \right) \\ & \leq C_3 \left(\|\psi_j\|_{\star, \xi} + \sum_{i=1}^n |c_i^j| \right) \\ & \leq C_4 \end{aligned}$$

for suitable positive constants C_1, C_2, C_3 and C_4 . This gives the equicontinuity of the sequence $\mathcal{B}[\psi_j]$, and so it converges to a function \bar{b} uniformly on compact sets. Hence, for any $R > 0$, we have

$$\|\mathcal{B}[\psi_j] - \bar{b}\|_{L^\infty(B_R(\xi))} \rightarrow 0 \text{ as } j \rightarrow +\infty. \quad (7-75)$$

On the other hand, for any $x \in \mathbb{R}^n \setminus B_R(\xi)$, we have the estimate

$$\begin{aligned} |w_\xi^{p-1}(x)\psi_j(x)| & \leq \|\psi_j\|_{\star, \xi} |w_\xi^{p-1}(x)\rho_\xi(x)| \\ & \leq C_5 \|\psi_j\|_{\star, \xi} \left| \frac{1}{(1 + |x - \xi|)^{(n+2s)(p-1)}} \rho_\xi(x) \right| \\ & \leq C_5 \|\psi_j\|_{\star, \xi} \rho_\xi^{1+(n+2s)(p-1)/\mu}(x) \end{aligned}$$

for some $C_5 > 0$, where we have used the decay of w_ξ in (1-4) and the expression of ρ_ξ given in (6-2). This implies that

$$\sup_{x \in \mathbb{R}^n \setminus B_R(\xi)} |\rho_\xi^{-1} w_\xi^{p-1} \psi_j| \leq C_5 \|\psi_j\|_{\star, \xi} \sup_{x \in \mathbb{R}^n \setminus B_R(\xi)} \rho_\xi^\sigma(x),$$

where

$$\sigma := \frac{(n+2s)(p-1)}{\mu} > 0. \quad (7-76)$$

Hence, since ψ_j is a uniformly bounded sequence with respect to the norm $\|\cdot\|_{\star, \xi}$, we obtain that

$$\sup_{x \in \mathbb{R}^n \setminus B_R(\xi)} |\rho_\xi^{-1} \mathcal{B}[\psi_j]| \leq C_6 \sup_{x \in \mathbb{R}^n \setminus B_R(\xi)} \rho_\xi^\sigma(x). \quad (7-77)$$

It follows that

$$\sup_{x \in \mathbb{R}^n \setminus B_R(\xi)} |\rho_\xi^{-1} \bar{b}| \leq C_6 \sup_{x \in \mathbb{R}^n \setminus B_R(\xi)} \rho_\xi^\sigma(x). \quad (7-78)$$

We observe that

$$\begin{aligned} \sup_{x \in \mathbb{R}^n} |\rho_\xi^{-1} (\mathcal{B}[\psi_j] - \bar{b})| &= \sup_{x \in \mathbb{R}^n} |\rho_\xi^{-1} (\mathcal{B}[\psi_j] - \bar{b}) \chi_{B_R(\xi)} + \rho_\xi^{-1} (\mathcal{B}[\psi_j] - \bar{b}) \chi_{\mathbb{R}^n \setminus B_R(\xi)}| \\ &\leq \sup_{x \in \mathbb{R}^n} (|\rho_\xi^{-1} (\mathcal{B}[\psi_j] - \bar{b}) \chi_{B_R(\xi)}| + |\rho_\xi^{-1} (\mathcal{B}[\psi_j] - \bar{b}) \chi_{\mathbb{R}^n \setminus B_R(\xi)}|) \\ &\leq \sup_{x \in \mathbb{R}^n} |\rho_\xi^{-1} (\mathcal{B}[\psi_j] - \bar{b}) \chi_{B_R(\xi)}| + \sup_{x \in \mathbb{R}^n} |\rho_\xi^{-1} (\mathcal{B}[\psi_j] - \bar{b}) \chi_{\mathbb{R}^n \setminus B_R(\xi)}| \\ &= \sup_{x \in B_R(\xi)} |\rho_\xi^{-1} (\mathcal{B}[\psi_j] - \bar{b})| + \sup_{x \in \mathbb{R}^n \setminus B_R(\xi)} |\rho_\xi^{-1} (\mathcal{B}[\psi_j] - \bar{b})|. \end{aligned}$$

Therefore, we obtain that

$$\begin{aligned} \|\mathcal{B}[\psi_j] - \bar{b}\|_{\star, \xi} &= \sup_{x \in \mathbb{R}^n} |\rho_\xi^{-1} (\mathcal{B}[\psi_j] - \bar{b})| \\ &\leq \sup_{x \in B_R(\xi)} |\rho_\xi^{-1} (\mathcal{B}[\psi_j] - \bar{b})| + \sup_{x \in \mathbb{R}^n \setminus B_R(\xi)} |\rho_\xi^{-1} (\mathcal{B}[\psi_j] - \bar{b})| \\ &\leq \sup_{x \in B_R(\xi)} |\rho_\xi^{-1} (\mathcal{B}[\psi_j] - \bar{b})| + C_7 \sup_{x \in \mathbb{R}^n \setminus B_R(\xi)} \rho_\xi^\sigma(x), \end{aligned} \quad (7-79)$$

where we have also used (7-77) and (7-78). Concerning the first term in the right-hand side, we have

$$\begin{aligned} \sup_{x \in B_R(\xi)} |\rho_\xi^{-1} (\mathcal{B}[\psi_j] - \bar{b})| &= \sup_{x \in B_R(\xi)} |(1 + |x - \xi|)^\mu (\mathcal{B}[\psi_j] - \bar{b})| \\ &\leq (1 + R)^\mu \|\mathcal{B}[\psi_j] - \bar{b}\|_{L^\infty(B_R(\xi))}. \end{aligned}$$

Therefore, sending $j \rightarrow +\infty$ and recalling (7-75), we obtain that

$$\sup_{x \in B_R(\xi)} |\rho_\xi^{-1} (\mathcal{B}[\psi_j] - \bar{b})| \rightarrow 0 \quad \text{as } j \rightarrow +\infty. \quad (7-80)$$

Now, we send $R \rightarrow +\infty$ and, recalling (7-76), we get

$$\sup_{x \in \mathbb{R}^n \setminus B_R(\xi)} \rho_\xi^\sigma(x) \rightarrow 0 \quad \text{as } R \rightarrow +\infty. \quad (7-81)$$

Putting together (7-79), (7-80) and (7-81), we obtain that

$$\|\mathcal{B}[\psi_j] - \bar{b}\|_{\star, \xi} \rightarrow 0 \quad \text{as } j \rightarrow +\infty,$$

and this shows (7-74).

From (7-59) in Proposition 7.4, we deduce that if $g = 0$ then $\psi = \mathcal{A}[g] = 0$ is the unique solution to (7-58), and so by Fredholm's alternative we obtain that, for any $g \in Y_\star$, there exists a unique ψ that solves (7-71) (recall (7-72) and (7-74)). This gives existence and uniqueness of the solution to (7-7), while the estimate (7-8) follows from Lemma 7.3. This concludes the proof of Theorem 7.1. \square

In the next proposition we deal with the differentiability of the solution ψ to (7-7) with respect to the parameter ξ (we recall Theorem 7.1 for the existence and uniqueness of the solution).

For this, we denote by \mathcal{T}_ξ the operator that associates to any $g \in L^2(\mathbb{R}^n)$ with $\|g\|_{\star, \xi} < +\infty$ the solution to (7-7), that is,

$$\psi := \mathcal{T}_\xi[g] \text{ is the unique solution to (7-7) in } Y_\star, \quad (7-82)$$

where Y_\star is as given in (7-70).

We notice that, thanks to Theorem 7.1, \mathcal{T}_ξ is a linear and continuous operator from Y_\star to Y_\star endowed with the norm $\|\cdot\|_{\star, \xi}$, and we will write $\mathcal{T}_\xi \in \mathcal{L}(Y_\star)$.

Proposition 7.5. *The map $\xi \mapsto \mathcal{T}_\xi$ on Ω_ε is continuously differentiable. Moreover, there exists a positive constant C such that*

$$\left\| \frac{\partial \mathcal{T}_\xi[g]}{\partial \xi} \right\|_{\star, \xi} \leq C \left(\|g\|_{\star, \xi} + \left\| \frac{\partial g}{\partial \xi} \right\|_{\star, \xi} \right). \quad (7-83)$$

Proof. First, let us prove (7-83) assuming the differentiability of $\xi \mapsto \mathcal{T}_\xi$. Given $\xi \in \Omega_\varepsilon$, $|t| < 1$ with $t \neq 0$ and a function f , we let $\xi_j^t := \xi + te_j$ and

$$D_j^t f := \frac{f(\xi_j^t) - f(\xi)}{t}$$

for any $j = 1, \dots, n$.

Also, we set

$$\varphi_j^t := D_j^t \psi \quad \text{and} \quad d_{i,j}^t := D_j^t c_i. \quad (7-84)$$

Using the fact that ψ is a solution to (7-7), we have that φ_j^t solves

$$(-\Delta)^s \varphi_j^t + \varphi_j^t - p w_\xi^{p-1} \varphi_j^t = p (D_j^t w_\xi^{p-1}) \psi - D_j^t g + \sum_{i=1}^n c_i D_j^t Z_i + \sum_{i=1}^n d_{i,j}^t Z_i \quad \text{in } \Omega_\varepsilon. \quad (7-85)$$

Moreover, we have that $\varphi_j^t \in H^s(\mathbb{R}^n)$ and $\varphi_j^t = 0$ outside Ω_ε .

Now, for the fixed index j , for any $i \in \{1, \dots, n\}$ we define

$$\lambda_i(\varphi_j^t) := \tilde{\alpha}^{-1} \int_{\mathbb{R}^n} \varphi_j^t Z_i \, dx, \quad (7-86)$$

where $\tilde{\alpha}$ is as defined in (5-21), and

$$\tilde{\varphi}_j^t := \varphi_j^t - \sum_{i=1}^n \lambda_i(\varphi_j^t) \tilde{Z}_i, \quad (7-87)$$

where the \tilde{Z}_i are the ones in Lemma 5.5. We remark that φ_j^t and \tilde{Z}_i vanish outside Ω_ε by construction. Hence $\tilde{\varphi}_j^t$ vanishes outside Ω_ε as well. Moreover,

$$\begin{aligned} \int_{\mathbb{R}^n} \tilde{\varphi}_j^t Z_k dx &= \int_{\mathbb{R}^n} \varphi_j^t Z_k dx - \sum_{i=1}^n \lambda_i(\varphi_j^t) \int_{\mathbb{R}^n} \tilde{Z}_i Z_k dx = \int_{\mathbb{R}^n} \varphi_j^t Z_k dx - \sum_{i=1}^n \lambda_i(\varphi_j^t) \tilde{\alpha} \delta_{ik} \\ &= \int_{\mathbb{R}^n} \varphi_j^t Z_k dx - \lambda_k(\varphi_j^t) \tilde{\alpha} \\ &= 0, \end{aligned}$$

thanks to Lemma 5.5 and (7-86). This yields that

$$\tilde{\varphi}_j^t \in \Psi. \tag{7-88}$$

By plugging (7-87) into (7-85), we obtain that

$$(-\Delta)^s \tilde{\varphi}_j^t + \tilde{\varphi}_j^t - p w_\xi^{p-1} \tilde{\varphi}_j^t = \tilde{g}_j + \sum_{i=1}^n d_{i,j}^t Z_i, \tag{7-89}$$

where

$$\tilde{g}_j := -(-\Delta)^s \sum_{i=1}^n \lambda_i(\tilde{\varphi}_j^t) \tilde{Z}_i - \sum_{i=1}^n \lambda_i(\tilde{\varphi}_j^t) \tilde{Z}_i + p w_\xi^{p-1} \sum_{i=1}^n \lambda_i(\tilde{\varphi}_j^t) \tilde{Z}_i + p(D_j^t w_\xi^{p-1})\psi - D_j^t g + \sum_{i=1}^n c_i D_j^t Z_i. \tag{7-90}$$

From (7-89), (7-88) and Lemma 7.3, we obtain that

$$\|\tilde{\varphi}_j^t\|_{\star, \xi} \leq C \|\tilde{g}_j\|_{\star, \xi}. \tag{7-91}$$

Now we observe that

$$\left\| \sum_{i=1}^n \lambda_i(\tilde{\varphi}_j^t) \tilde{Z}_i \right\|_{\star, \xi} \leq C \|g\|_{\star, \xi}. \tag{7-92}$$

To prove this, we notice that the orthogonality condition $\psi \in \Psi$ implies that

$$\int_{\Omega_\varepsilon} \varphi_j^t Z_k dx = - \int_{\Omega_\varepsilon} \psi D_j^t Z_k dx$$

for any $k \in \{1, \dots, n\}$. Hence, recalling (7-87), (7-88) and Lemma 5.5,

$$\begin{aligned} - \int_{\Omega_\varepsilon} \psi D_j^t Z_k dx &= \int_{\Omega_\varepsilon} \left(\tilde{\varphi}_j^t + \sum_{i=1}^n \lambda_i(\tilde{\varphi}_j^t) \tilde{Z}_i \right) Z_k dx = \sum_{i=1}^n \lambda_i(\tilde{\varphi}_j^t) \int_{\Omega_\varepsilon} \tilde{Z}_i Z_k dx \\ &= \sum_{i=1}^n \lambda_i(\tilde{\varphi}_j^t) \tilde{\alpha} \delta_{ik} \\ &= \lambda_k(\tilde{\varphi}_j^t) \tilde{\alpha}. \end{aligned}$$

Therefore,

$$\begin{aligned} |\lambda_k(\tilde{\varphi}_j^t)| &= |\tilde{\alpha}^{-1}| \left| \int_{\Omega_\varepsilon} \psi D_j^t Z_k dx \right| \leq |\tilde{\alpha}^{-1}| \int_{\Omega_\varepsilon} \rho_\xi^{-1} |\psi| \rho_\xi |D_j^t Z_k| dx \\ &\leq |\tilde{\alpha}^{-1}| \|\psi\|_{\star, \xi} \int_{\mathbb{R}^n} \rho_\xi |D_j^t Z_k| dx \\ &\leq C \|\psi\|_{\star, \xi}, \end{aligned}$$

thanks to Lemma 5.3. Using this and Lemma 5.2, and possibly renaming the constants, we obtain that

$$\left\| \sum_{i=1}^n \lambda_i(\tilde{\varphi}_j^t) \tilde{Z}_i \right\|_{\star, \xi} \leq \sum_{i=1}^n |\lambda_i(\tilde{\varphi}_j^t)| \|\tilde{Z}_i\|_{\star, \xi} \leq C \sum_{i=1}^n |\lambda_i(\tilde{\varphi}_j^t)| \leq C \|\psi\|_{\star, \xi}.$$

On the other hand, by Lemma 7.3, we have that $\|\psi\|_{\star, \xi} \leq C \|g\|_{\star, \xi}$, so the above estimate implies (7-92), as desired.

Now we claim that

$$\left\| (-\Delta)^s \sum_{i=1}^n \lambda_i(\tilde{\varphi}_j^t) \tilde{Z}_i \right\|_{\star, \xi} \leq C \|g\|_{\star, \xi}. \tag{7-93}$$

Indeed, \tilde{Z}_i is compactly supported in a neighborhood of ξ , hence $(-\Delta)^s \tilde{Z}_i$ decays like $|x - \xi|^{-n-2s}$ at infinity. Accordingly, $\|(-\Delta)^s \tilde{Z}_i\|_{\star, \xi}$ is finite, and then we obtain

$$\begin{aligned} \left\| (-\Delta)^s \sum_{i=1}^n \lambda_i(\tilde{\varphi}_j^t) \tilde{Z}_i \right\|_{\star, \xi} &= \left\| \sum_{i=1}^n \lambda_i(\tilde{\varphi}_j^t) (-\Delta)^s \tilde{Z}_i \right\|_{\star, \xi} \\ &\leq \sum_{i=1}^n |\lambda_i(\tilde{\varphi}_j^t)| \|(-\Delta)^s \tilde{Z}_i\|_{\star, \xi} \\ &\leq C \sum_{i=1}^n |\lambda_i(\tilde{\varphi}_j^t)| \\ &\leq C \|g\|_{\star, \xi}, \end{aligned}$$

due to (7-92), and this establishes (7-93).

Now we claim that

$$|D_j^t w_\xi^{p-1}| \leq C \tag{7-94}$$

with C independent of t . Indeed,

$$\begin{aligned} D_j^t w_\xi^{p-1}(x) &= \frac{1}{t} (w^{p-1}(x - \xi - te_j) - w^{p-1}(x - \xi)) \\ &= \frac{1}{t} \int_0^t \frac{d}{d\tau} w^{p-1}(x - \xi - \tau e_j) d\tau \\ &= \frac{p-1}{t} \int_0^t w^{p-2}(x - \xi - \tau e_j) \frac{d}{d\tau} w(x - \xi - \tau e_j) d\tau \\ &= -\frac{p-1}{t} \int_0^t w^{p-2}(x - \xi - \tau e_j) \nabla w(x - \xi - \tau e_j) \cdot e_j d\tau. \end{aligned}$$

Also, by formulas (IV.2) and (IV.6) of [Carmona et al. 1990], we know that

$$w(x) \text{ is bounded both from above and from below by a constant times } \frac{1}{1 + |x|^{n+2s}}. \tag{7-95}$$

Thus, supposing without loss of generality that $t > 0$, and recalling Lemma 5.2, we have that

$$\begin{aligned} |D_j^t w_\xi^{p-1}(x)| &\leq \frac{p-1}{t} \int_0^t w^{p-2}(x - \xi - \tau e_j) |\nabla w(x - \xi - \tau e_j)| d\tau \\ &\leq \frac{C}{t} \int_0^t (1 + |x - \xi - \tau e_j|)^{-(p-2)(n+2s)} (1 + |x - \xi - \tau e_j|)^{-(n+2s)} d\tau \\ &= \frac{C}{t} \int_0^t (1 + |x - \xi - \tau e_j|)^{-(p-1)(n+2s)} d\tau \\ &\leq \frac{C}{t} \int_0^t 1 d\tau \\ &= C, \end{aligned}$$

and this proves (7-94).

From (7-94) and Lemma 7.3 we obtain that

$$\|(D_j^t w_\xi^{p-1})\psi\|_{\star, \xi} \leq C \|\psi\|_{\star, \xi} \leq C \|g\|_{\star, \xi}. \tag{7-96}$$

Now we use Lemmata 5.3, 7.2 and 7.3 to see that

$$\begin{aligned} \left\| \sum_{i=1}^n c_i D_j^t Z_i \right\|_{\star, \xi} &\leq \sum_{i=1}^n |c_i| \|D_j^t Z_i\|_{\star, \xi} \leq C \sum_{i=1}^n |c_i| = C \sum_{i=1}^n \left| \frac{1}{\alpha} \int_{\mathbb{R}^n} g Z_i dx + f_i \right| \\ &\leq C \left(\|g\|_{L^2(\mathbb{R}^n)} + \sum_{i=1}^n |f_i| \right) \leq C (\|\psi\|_{L^2(\mathbb{R}^n)} + \|g\|_{L^2(\mathbb{R}^n)}) \\ &\leq C (\|\psi\|_{\star, \xi} + \|g\|_{\star, \xi}) \leq C \|g\|_{\star, \xi}. \end{aligned} \tag{7-97}$$

By plugging (7-92), (7-93), (7-96) and (7-97) into (7-90), we obtain that

$$\|\tilde{g}_j\|_{\star, \xi} \leq C (\|g\|_{\star, \xi} + \|D_j^t g\|_{\star, \xi}).$$

Therefore, by (7-91),

$$\|\tilde{\varphi}_j^t\|_{\star, \xi} \leq C (\|g\|_{\star, \xi} + \|D_j^t g\|_{\star, \xi}).$$

This and (7-92) imply that

$$\|\varphi_j^t\|_{\star, \xi} \leq \|\tilde{\varphi}_j^t\|_{\star, \xi} + \left\| \sum_{i=1}^n \lambda_i (\tilde{\varphi}_j^t) \tilde{Z}_i \right\|_{\star, \xi} \leq C (\|g\|_{\star, \xi} + \|D_j^t g\|_{\star, \xi}).$$

Hence, we send $t \searrow 0$ and we obtain

$$\left\| \frac{\partial \psi}{\partial \xi} \right\|_{\star, \xi} \leq C \left(\|g\|_{\star, \xi} + \left\| \frac{\partial g}{\partial \xi} \right\|_{\star, \xi} \right),$$

which implies that

$$\left\| \frac{\partial \mathcal{T}_\xi[g]}{\partial \xi} \right\|_{\star, \xi} \leq C \left(\|g\|_{\star, \xi} + \left\| \frac{\partial g}{\partial \xi} \right\|_{\star, \xi} \right).$$

Using the previous computation and the implicit function theorem, a standard argument shows that $\xi \mapsto \mathcal{T}_\xi$ is continuously differentiable (see, e.g., Section 2.2.1 in [Ambrosetti and Malchiodi 2006], and in particular Lemma 2.11 there, or [Dávila et al. 2014] below formula (4.20)). \square

The nonlinear projected problem. In this subsection we solve the nonlinear projected problem

$$\begin{cases} (-\Delta)^s \psi + \psi - pw_\xi^{p-1} \psi = E(\psi) + N(\psi) + \sum_{i=1}^n c_i Z_i & \text{in } \Omega_\varepsilon, \\ \psi = 0 & \text{in } \mathbb{R}^n \setminus \Omega_\varepsilon, \\ \int_{\Omega_\varepsilon} \psi Z_i dx = 0 & \text{for any } i = 1, \dots, n, \end{cases} \quad (7-98)$$

where $E(\psi)$ and $N(\psi)$ are as given in (7-3).

Theorem 7.6. *If $\varepsilon > 0$ is sufficiently small, there exists a unique solution $\psi \in H^s(\mathbb{R}^n)$ to (7-98) for suitable real coefficients $c_i, i = 1, \dots, n$, such that there exists a positive constant C such that*

$$\|\psi\|_{\star, \xi} \leq C\varepsilon^{n+2s}. \quad (7-99)$$

Before proving Theorem 7.6, we show some estimates for the error terms $E(\psi)$ and $N(\psi)$.

Lemma 7.7. *There exists a positive constant C such that*

$$|\bar{u}_\xi - w_\xi| \leq C\varepsilon^{n+2s}. \quad (7-100)$$

Proof. To prove (7-100), we define $\eta_\xi := \bar{u}_\xi - w_\xi$, and we observe that η_ξ satisfies

$$\begin{cases} (-\Delta)^s \eta_\xi + \eta_\xi = 0 & \text{in } \Omega_\varepsilon, \\ \eta_\xi = -w_\xi & \text{in } \mathbb{R}^n \setminus \Omega_\varepsilon, \end{cases} \quad (7-101)$$

due to (1-3) and (1-9).

We have

$$|\eta_\xi| = |w_\xi| \leq C\varepsilon^{n+2s} \quad \text{outside } \Omega_\varepsilon,$$

thanks to (1-4). Hence, this together with (7-101) and the maximum principle give

$$|\eta_\xi| \leq C\varepsilon^{n+2s} \quad \text{in } \mathbb{R}^n,$$

which implies the thesis (recall the definition of η_ξ). \square

Moreover, we can prove the following:

Lemma 7.8. *There exists a positive constant C such that*

$$\left| \frac{\partial \bar{u}_\xi}{\partial \xi} - \frac{\partial w_\xi}{\partial \xi} \right| \leq C\varepsilon^{v_1} \quad (7-102)$$

with $v_1 := \min\{(n + 2s + 1), p(n + 2s)\}$.

Proof. We set $\eta_\xi := \bar{u}_\xi - w_\xi$. From (1-3) and (1-9), we have that η_ξ solves

$$(-\Delta)^s \eta_\xi + \eta_\xi = 0 \quad \text{in } \Omega_\varepsilon.$$

Therefore, the derivative of η_ξ with respect to ξ satisfies

$$(-\Delta)^s \frac{\partial \eta_\xi}{\partial \xi} + \frac{\partial \eta_\xi}{\partial \xi} = 0 \quad \text{in } \Omega_\varepsilon. \tag{7-103}$$

Moreover, since $\bar{u}_\xi = 0$ outside Ω_ε , we have that

$$\eta_\xi = \bar{u}_\xi - w_\xi = -w_\xi \quad \text{in } \mathbb{R}^n \setminus \Omega_\varepsilon,$$

which implies

$$\frac{\partial \eta_\xi}{\partial \xi} = -\frac{\partial w_\xi}{\partial \xi} = \frac{\partial w_\xi}{\partial x} \quad \text{in } \mathbb{R}^n \setminus \Omega_\varepsilon.$$

Therefore, from Lemma 5.2 (recall also (5-3)), we have that

$$\left| \frac{\partial \eta_\xi}{\partial \xi} \right| \leq C \varepsilon^{\nu_1} \quad \text{outside } \Omega_\varepsilon.$$

From this, (7-103) and the maximum principle, we deduce that

$$\left| \frac{\partial \eta_\xi}{\partial \xi} \right| \leq C \varepsilon^{\nu_1} \quad \text{in } \mathbb{R}^n,$$

which gives the desired estimate (recall the definition of η_ξ). □

In the next lemma we estimate the \star -norm of the error term $E(\psi)$. For this, we recall the definition of the space Y_\star given in (7-70).

Lemma 7.9. *Let $\psi \in Y_\star$ with $\|\psi\|_{\star, \xi} \leq 1$. Then, there exists a positive constant \bar{C} such that*

$$\|E(\psi)\|_{\star, \xi} \leq \bar{C} \varepsilon^{n+2s}.$$

Proof. Using (7-100) and Lemma 2.1 in [Dipierro et al. ≥ 2015] with $a := w_\xi + \psi$ and $b := \bar{u}_\xi - w_\xi$, we obtain that

$$|E(\psi)| = |(\bar{u}_\xi - w_\xi + w_\xi + \psi)^p - (w_\xi + \psi)^p| \leq C_1 (w_\xi + \psi)^{p-1} |\bar{u}_\xi - w_\xi| \leq C_2 \varepsilon^{n+2s} (w_\xi + \psi)^{p-1}.$$

Hence, since $\|w_\xi\|_{\star, \xi}$ and $\|\psi\|_{\star, \xi}$ are bounded, we have

$$\|E(\psi)\|_{\star, \xi} \leq C_3 \varepsilon^{n+2s},$$

which gives the desired result. □

Now, we give a bound for the \star -norm of the error term $N(\psi)$.

Lemma 7.10. *Let $\psi \in Y_\star$. Then, there exists a positive constant C such that*

$$\|N(\psi)\|_{\star, \xi} \leq C (\|\psi\|_{\star, \xi}^2 + \|\psi\|_{\star, \xi}^p).$$

Proof. We take $\psi \in Y_\star$ and we estimate

$$|N(\psi)| = |(w_\xi + \psi)^p - w_\xi^p - pw_\xi^{p-1}\psi| \leq C(|\psi|^2 + |\psi|^p)$$

for some positive constant C (see, for instance, Corollary 2.2 in [Dipierro et al. \geq 2015], applied here with $a := w_\xi$ and $b := \psi$). Hence,

$$\rho_\xi^{-1}|N(\psi)| \leq C\rho_\xi^{-1}(|\psi|^2 + |\psi|^p) \leq C(\rho_\xi^{-2}|\psi|^2 + \rho_\xi^{-p}|\psi|^p) \leq C(\|\psi\|_{\star, \xi}^2 + \|\psi\|_{\star, \xi}^p),$$

which implies the desired estimate. \square

For further reference, we now recall an estimate of elementary nature:

Lemma 7.11. *Fixed $\kappa > 0$, there exists a constant $C_\kappa > 0$ such that, for any $a, b \in [0, \kappa]$, we have*

$$|a^{p-1} - b^{p-1}| \leq C_\kappa |a - b|^q, \quad (7-104)$$

where

$$q := \min\{1, p - 1\}. \quad (7-105)$$

Proof. Fixing $\alpha \in (0, 1)$, for any $t > 0$ we define

$$h(t) := \frac{(t+1)^\alpha - 1}{t^\alpha}.$$

Using l'Hospital's rule, we see that

$$\lim_{t \searrow 0} h(t) = \lim_{t \searrow 0} \frac{t^{1-\alpha}}{(t+1)^{1-\alpha}} = 0;$$

hence we can extend h to a continuous function on $[0, +\infty)$ with $h(0) := 0$. Moreover,

$$\lim_{t \rightarrow +\infty} h(t) = 1;$$

hence there exists

$$M_0 := \sup_{t \in [0, +\infty)} h(t) < +\infty. \quad (7-106)$$

Now we prove (7-104). For this, we may and do assume that $a > b$. If $p \geq 2$, we have that

$$a^{p-1} - b^{p-1} = (p-1) \int_b^a \tau^{p-2} d\tau \leq (p-1)a^{p-2}(a-b) \leq (p-1)\kappa^{p-2}(a-b),$$

that is, (7-104) in this case. On the other hand, if $p \in (1, 2)$ we take $t := a/b - 1 > 0$ and $\alpha := p - 1$, so

$$M_0 \geq h(t) = \frac{(a/b)^{p-1} - 1}{(a/b - 1)^{p-1}} = \frac{a^{p-1} - b^{p-1}}{(a-b)^{p-1}},$$

thanks to (7-106), and this establishes (7-104) also in this case. \square

Now we are ready to complete the proof of Theorem 7.6.

Proof of Theorem 7.6. Recalling the definition of the operator \mathcal{T}_ξ in (7-82), we can write

$$\psi = \mathcal{T}_\xi[E(\psi) + N(\psi)].$$

We will prove Theorem 7.6 by a contraction argument. To do this, we set

$$\mathcal{K}_\xi(\psi) := \mathcal{T}_\xi[E(\psi) + N(\psi)]. \tag{7-107}$$

Moreover, we take a constant $C_0 > 0$ and $\varepsilon > 0$ small (we will specify the choice of C_0 and ε in (7-118)), and we define the set

$$B := \{ \psi \in Y_\star \mid \|\psi\|_{\star,\xi} \leq C_0 \varepsilon^{n+2s} \},$$

where Y_\star was introduced in (7-70).

We claim that

$$\mathcal{K}_\xi \text{ as in (7-107) is a contraction mapping from } B \text{ into itself with respect to the norm } \|\cdot\|_{\star,\xi}. \tag{7-108}$$

First, we prove that

$$\text{if } \psi \in B \text{ then } \mathcal{K}_\xi(\psi) \in B. \tag{7-109}$$

Indeed, if $\psi \in B$, we have that

$$\|N(\psi)\|_{\star,\xi} \leq C_1(\|\psi\|_{\star,\xi}^2 + \|\psi\|_{\star,\xi}^p), \tag{7-110}$$

thanks to Lemma 7.10.

Now, thanks to (7-8), we have that

$$\|\mathcal{K}_\xi(\psi)\|_{\star,\xi} = \|\mathcal{T}_\xi[E(\psi) + N(\psi)]\|_{\star,\xi} \leq C\|E(\psi) + N(\psi)\|_{\star,\xi}.$$

This, Lemma 7.9 and (7-110) give that

$$\begin{aligned} \|\mathcal{K}_\xi(\psi)\|_{\star,\xi} &\leq C(\|E(\psi)\|_{\star,\xi} + \|N(\psi)\|_{\star,\xi}) \\ &\leq C(\|E(\psi)\|_{\star,\xi} + C_1(\|\psi\|_{\star,\xi}^2 + \|\psi\|_{\star,\xi}^p)) \\ &\leq C(\bar{C}\varepsilon^{n+2s} + C_1C_0^2\varepsilon^{2(n+2s)} + C_1C_0^p\varepsilon^{p(n+2s)}) \\ &= C_0\varepsilon^{n+2s} \left(\frac{C\bar{C}}{C_0} + CC_1C_0\varepsilon^{n+2s} + CC_1C_0^{p-1}\varepsilon^{(p-1)(n+2s)} \right), \end{aligned} \tag{7-111}$$

since $\psi \in B$. We assume

$$C_0 > 2C\bar{C} \tag{7-112}$$

and

$$\varepsilon < \varepsilon_1 := \begin{cases} (2CC_1(C_0 + C_0^{p-1}))^{-1/(n+2s)} & \text{if } p \geq 2, \\ (2CC_1(C_0 + C_0^{p-1}))^{-1/(p-1)(n+2s)} & \text{if } 1 < p < 2. \end{cases} \tag{7-113}$$

With this choice of C_0 and ε , (7-111) implies that

$$\|\mathcal{K}_\xi(\psi)\|_{\star,\xi} \leq C_0\varepsilon^{n+2s},$$

which proves (7-109).

Now, we take $\psi_1, \psi_2 \in B$. Then,

$$\begin{aligned} |N(\psi_1) - N(\psi_2)| &= |(w_\xi + \psi_1)^p - (w_\xi + \psi_2)^p - pw_\xi^{p-1}(\psi_1 - \psi_2)| \\ &\leq C_2(|\psi_1| + |\psi_2| + |\psi_1|^{p-1} + |\psi_2|^{p-1})|\psi_1 - \psi_2|. \end{aligned}$$

This and the fact that $\psi_1, \psi_2 \in B$ give that

$$\begin{aligned} \|N(\psi_1) - N(\psi_2)\|_{\star, \xi} &\leq C_2(\|\psi_1\|_{\star, \xi} + \|\psi_2\|_{\star, \xi} + \|\psi_1\|_{\star, \xi}^{p-1} + \|\psi_2\|_{\star, \xi}^{p-1})\|\psi_1 - \psi_2\|_{\star, \xi} \\ &\leq C_2(2C_0\varepsilon^{n+2s} + 2C_0^{p-1}\varepsilon^{(p-1)(n+2s)})\|\psi_1 - \psi_2\|_{\star, \xi} \\ &\leq 2C_2(C_0 + C_0^{p-1})\varepsilon^{q(n+2s)}\|\psi_1 - \psi_2\|_{\star, \xi}, \end{aligned} \tag{7-114}$$

where q is as defined in (7-105).

We claim that

$$|E(\psi_1) - E(\psi_2)| \leq C|\bar{u}_\xi - w_\xi|^q|\psi_1 - \psi_2|, \tag{7-115}$$

where q is as given in (7-105).

Fixing $x \in \Omega_\varepsilon$, given τ in a bounded subset of \mathbb{R} we consider the function

$$e(\tau) := (\bar{u}_\xi(x) + \tau)^p - (w_\xi(x) + \tau)^p.$$

We have that

$$|e'(\tau)| = p|(\bar{u}_\xi(x) + \tau)^{p-1} - (w_\xi(x) + \tau)^{p-1}| \leq C|\bar{u}_\xi - w_\xi|^q,$$

where we used (7-104) with $a := \bar{u}_\xi(x) + \tau$ and $b := w_\xi(x) + \tau$. This gives that

$$|e(\tau_1) - e(\tau_2)| \leq C|\bar{u}_\xi - w_\xi|^q|\tau_1 - \tau_2|. \tag{7-116}$$

Now we take $\tau_1 := \psi_1(x)$ and $\tau_2 := \psi_2(x)$; we remark that τ_1 and τ_2 range in a bounded set, by our definition of B , and that $e(\tau_i) = E(\psi_i)$. Thus (7-115) follows from (7-116)

Hence, from (7-115) and (7-100), we obtain that

$$\|E(\psi_1) - E(\psi_2)\|_{\star, \xi} \leq \tilde{C}\varepsilon^{q(n+2s)}\|\psi_1 - \psi_2\|_{\star, \xi}.$$

This, (7-114) and (7-8) give that

$$\begin{aligned} \|\mathcal{K}_\xi(\psi_1) - \mathcal{K}_\xi(\psi_2)\|_{\star, \xi} &\leq C(\|E(\psi_1) - E(\psi_2)\|_{\star, \xi} + \|N(\psi_1) - N(\psi_2)\|_{\star, \xi}) \\ &\leq C(2C_2(C_0 + C_0^{p-1})\varepsilon^{q(n+2s)} + \tilde{C}\varepsilon^{q(n+2s)})\|\psi_1 - \psi_2\|_{\star, \xi}. \end{aligned} \tag{7-117}$$

Now, we let

$$\varepsilon_2 := \left(\frac{1}{C(2C_2(C_0 + C_0^{p-1}) + \tilde{C})} \right)^{\frac{1}{q(n+2s)}}.$$

Therefore, recalling also (7-112) and (7-113), we obtain that if

$$C_0 > 2C\bar{C} \quad \text{and} \quad \varepsilon < \min\{\varepsilon_1, \varepsilon_2\} \tag{7-118}$$

then, from (7-117), we have that

$$\|\mathcal{K}_\xi(\psi_1) - \mathcal{K}_\xi(\psi_2)\|_{\star, \xi} < \|\psi_1 - \psi_2\|_{\star, \xi},$$

which concludes the proof of (7-108).

From (7-108), we obtain the existence of a unique solution to (7-98) which belongs to B . This shows (7-99) and concludes the proof of Theorem 7.6. \square

For any $\xi \in \Omega_\varepsilon$, we say that

$$\Psi(\xi) \text{ is the unique solution to (7-98).} \quad (7-119)$$

Arguing as the proof of Proposition 5.1 in [Dávila et al. 2014], one can also prove the following:

Proposition 7.12. *The map $\xi \mapsto \Psi(\xi)$ is of class C^1 , and*

$$\left\| \frac{\partial \Psi(\xi)}{\partial \xi} \right\|_{\star, \xi} \leq C \left(\|E(\Psi(\xi))\|_{\star, \xi} + \left\| \frac{\partial E(\Psi(\xi))}{\partial \xi} \right\|_{\star, \xi} \right)$$

for some constant $C > 0$.

Derivative estimates. Here we deal with the derivatives of the solution $\psi = \Psi(\xi)$ to (7-98) with respect to ξ . This will also imply derivative estimates for the error term $\xi \mapsto E(\Psi(\xi))$.

We first show the following:

Lemma 7.13. *Let $\psi \in \Psi$ be a solution⁴ to (7-98) with $\|\psi\|_{\star, \xi} \leq C\varepsilon^{n+2s}$. Then, there exist positive constants C and γ such that*

$$\left\| \frac{\partial E(\psi)}{\partial \xi} \right\|_{\star, \xi} \leq C \left(\varepsilon^{q(n+2s)} \left\| \frac{\partial \psi}{\partial \xi} \right\|_{\star, \xi} + \varepsilon^\gamma \right),$$

where q is as defined in (7-105).

Proof. First of all, we observe that, thanks to Proposition 7.5 (applied here with $g := -(E(\psi) + N(\psi))$), the function $\partial\psi/\partial\xi$ is well defined.

We make the following computations: from (7-3) we have that

$$\begin{aligned} \frac{\partial E(\psi)}{\partial \xi} &= p(\bar{u}_\xi + \psi)^{p-1} \left(\frac{\partial \bar{u}_\xi}{\partial \xi} + \frac{\partial \psi}{\partial \xi} \right) - p(w_\xi + \psi)^{p-1} \left(\frac{\partial w_\xi}{\partial \xi} + \frac{\partial \psi}{\partial \xi} \right) \\ &= p \frac{\partial \psi}{\partial \xi} [(\bar{u}_\xi + \psi)^{p-1} - (w_\xi + \psi)^{p-1}] + p(\bar{u}_\xi + \psi)^{p-1} \frac{\partial \bar{u}_\xi}{\partial \xi} - p(w_\xi + \psi)^{p-1} \frac{\partial w_\xi}{\partial \xi} \\ &= p \frac{\partial \psi}{\partial \xi} [(\bar{u}_\xi + \psi)^{p-1} - (w_\xi + \psi)^{p-1}] + p(\bar{u}_\xi + \psi)^{p-1} \left(\frac{\partial \bar{u}_\xi}{\partial \xi} - \frac{\partial w_\xi}{\partial \xi} \right) \\ &\quad + p[(\bar{u}_\xi + \psi)^{p-1} - (w_\xi + \psi)^{p-1}] \frac{\partial w_\xi}{\partial \xi}. \end{aligned}$$

⁴We remark that a solution that fulfils the assumptions of Lemma 7.13 is provided by Theorem 7.6, as long as ε is sufficiently small.

Thus, recalling (7-104), (7-100) and (7-102), we infer that

$$\begin{aligned} \left| \frac{\partial E(\psi)}{\partial \xi} \right| &\leq Cp \left| \frac{\partial \psi}{\partial \xi} \right| |\bar{u}_\xi - w_\xi|^q + p(|\bar{u}_\xi| + |\psi|)^{p-1} \left| \frac{\partial \bar{u}_\xi}{\partial \xi} - \frac{\partial w_\xi}{\partial \xi} \right| + Cp |\bar{u}_\xi - w_\xi|^q \left| \frac{\partial w_\xi}{\partial \xi} \right| \\ &\leq C \left| \frac{\partial \psi}{\partial \xi} \right| \varepsilon^{q(n+2s)} + C(|\bar{u}_\xi| + |\psi|)^{p-1} \varepsilon^{v_1} + C \varepsilon^{q(n+2s)} \left| \frac{\partial w_\xi}{\partial \xi} \right| \end{aligned} \quad (7-120)$$

for some $C > 0$. Now, we claim that

$$\sup_{x \in \mathbb{R}^n} (1 + |x - \xi|)^\mu |\bar{u}_\xi(x)|^{p-1} \varepsilon^{v_1} \leq C \varepsilon^\gamma \quad \text{and} \quad \sup_{x \in \mathbb{R}^n} (1 + |x - \xi|)^\mu |\psi(x)|^{p-1} \varepsilon^{v_1} \leq C \varepsilon^\gamma \quad (7-121)$$

for suitable $C > 0$ and $\gamma > 0$. Let us prove the first inequality in (7-121). For this, we use that \bar{u}_ξ vanishes outside Ω_ε , together with (7-100) and (1-4), to see that

$$\begin{aligned} \sup_{x \in \mathbb{R}^n} (1 + |x - \xi|)^\mu |\bar{u}_\xi(x)|^{p-1} \varepsilon^{v_1} &= \sup_{x \in \Omega_\varepsilon} (1 + |x - \xi|)^\mu |\bar{u}_\xi(x)|^{p-1} \varepsilon^{v_1} \\ &\leq \sup_{x \in \Omega_\varepsilon} (1 + |x - \xi|)^\mu \varepsilon^{(p-1)(n+2s)} \varepsilon^{v_1} + \sup_{x \in \Omega_\varepsilon} (1 + |x - \xi|)^\mu |w_\xi(x)|^{p-1} \varepsilon^{v_1} \\ &\leq C \varepsilon^{-\mu} \varepsilon^{(p-1)(n+2s)} \varepsilon^{v_1} + \sup_{x \in \Omega_\varepsilon} (1 + |x - \xi|)^{\mu(p-1)} |w_\xi(x)|^{p-1} (1 + |x - \xi|)^{\mu(2-p)} \varepsilon^{v_1} \\ &\leq C \varepsilon^{-\mu} \varepsilon^{(p-1)(n+2s)} \varepsilon^{v_1} + \|w_\xi\|_{\star, \xi}^{p-1} \varepsilon^{-\mu(2-p)_+} \varepsilon^{v_1} \\ &\leq C \varepsilon^{-\mu} \varepsilon^{(p-1)(n+2s)} \varepsilon^{v_1} + C \varepsilon^{-\mu(2-p)_+} \varepsilon^{v_1}. \end{aligned} \quad (7-122)$$

Now we observe that

$$\begin{aligned} -\mu + (p-1)(n+2s) + v_1 &= \min\{-\mu + (p-1)(n+2s) + n + 2s + 1, -\mu + (p-1)(n+2s) + p(n+2s)\} \\ &> \min\{-(n+2s) + (p-1)(n+2s) + n + 2s + 1, -(n+2s) + (p-1)(n+2s) + p(n+2s)\} \\ &= \min\{(p-1)(n+2s) + 1, (2p-2)(n+2s)\} > 0. \end{aligned} \quad (7-123)$$

Moreover, if $p \geq 2$, then

$$-\mu(2-p)_+ + v_1 = v_1 > 0,$$

while, if $1 < p < 2$, then

$$\begin{aligned} -\mu(2-p)_+ + v_1 &= \min\{-\mu(2-p) + n + 2s + 1, -\mu(2-p) + p(n+2s)\} \\ &> \min\{-(n+2s)(2-p) + n + 2s + 1, -(n+2s)(2-p) + p(n+2s)\} \\ &= \min\{(p-1)(n+2s) + 1, (2p-2)(n+2s)\} > 0. \end{aligned}$$

Using this and (7-123) in (7-122), we obtain the first formula in (7-121). Now, we focus on the second inequality: From the assumptions on ψ we have

$$\begin{aligned} \sup_{x \in \mathbb{R}^n} (1 + |x - \xi|)^\mu |\psi(x)|^{p-1} \varepsilon^{v_1} &= \sup_{x \in \Omega_\varepsilon} (1 + |x - \xi|)^\mu |\psi(x)|^{p-1} \varepsilon^{v_1} \\ &= \sup_{x \in \Omega_\varepsilon} (1 + |x - \xi|)^{\mu(p-1)} |\psi(x)|^{p-1} (1 + |x - \xi|)^{\mu(2-p)} \varepsilon^{v_1} \\ &\leq \|\psi\|_{\star, \xi}^{p-1} \varepsilon^{-\mu(2-p)_+} \varepsilon^{v_1} \\ &\leq C \varepsilon^{(p-1)(n+2s)} \varepsilon^{-\mu(2-p)_+} \varepsilon^{v_1}. \end{aligned} \tag{7-124}$$

If $p \geq 2$ we get the second inequality in (7-121), as desired, hence we focus on the case $1 < p < 2$. For this, we notice that

$$\begin{aligned} &(p-1)(n+2s) - \mu(2-p)_+ + v_1 \\ &= \min\{(p-1)(n+2s) - \mu(2-p) + n + 2s + 1, (p-1)(n+2s) - \mu(2-p) + p(n+2s)\} \\ &> \min\{(p-1)(n+2s) - (2-p)(n+2s) + n + 2s + 1, (p-1)(n+2s) - (2-p)(n+2s) + p(n+2s)\} \\ &= \min\{(2p-2)(n+2s) + 1, (3p-3)(n+2s)\} > 0, \end{aligned}$$

and this, together with (7-124), implies the second inequality in (7-121) also in this case. Hence the proof of (7-121) is finished.

Exploiting (7-121) and Lemma 5.2, we infer from (7-120) that

$$\left\| \frac{\partial E(\psi)}{\partial \xi} \right\|_{\star, \xi} \leq C \varepsilon^{q(n+2s)} \left\| \frac{\partial \psi}{\partial \xi} \right\|_{\star, \xi} + C \varepsilon^\gamma \tag{7-125}$$

for suitable $C > 0$ and $\gamma > 0$, and this concludes the proof of Lemma 7.13, up to renaming the constants. \square

Lemma 7.14. *Let $\psi \in \Psi$ be a solution to (7-98) with $\|\psi\|_{\star, \xi} \leq C \varepsilon^{n+2s}$. Then, there exists a positive constant C such that*

$$\left\| \frac{\partial \psi}{\partial \xi} \right\|_{\star, \xi} \leq C.$$

Proof. We observe that, thanks to Proposition 7.5 (applied here with $g := -(E(\psi) + N(\psi))$),

$$\left\| \frac{\partial \psi}{\partial \xi} \right\|_{\star, \xi} \leq C \left(\|E(\psi)\|_{\star, \xi} + \|N(\psi)\|_{\star, \xi} + \left\| \frac{\partial E(\psi)}{\partial \xi} \right\|_{\star, \xi} + \left\| \frac{\partial N(\psi)}{\partial \xi} \right\|_{\star, \xi} \right).$$

Therefore, from Lemmata 7.9, 7.10 and 7.13, we obtain that

$$\left\| \frac{\partial \psi}{\partial \xi} \right\|_{\star, \xi} \leq C \left(1 + \varepsilon^{q(n+2s)} \left\| \frac{\partial \psi}{\partial \xi} \right\|_{\star, \xi} + \left\| \frac{\partial N(\psi)}{\partial \xi} \right\|_{\star, \xi} \right). \tag{7-126}$$

Now we observe that, from (7-3),

$$\begin{aligned} \frac{\partial N(\psi)}{\partial \xi} &= p(w_\xi + \psi)^{p-1} \left(\frac{\partial w_\xi}{\partial \xi} + \frac{\partial \psi}{\partial \xi} \right) - p w_\xi^{p-1} \frac{\partial w_\xi}{\partial \xi} - p(p-1) w_\xi^{p-2} \frac{\partial w_\xi}{\partial \xi} \psi - p w_\xi^{p-1} \frac{\partial \psi}{\partial \xi} \\ &= p[(w_\xi + \psi)^{p-1} - w_\xi^{p-1}] \frac{\partial \psi}{\partial \xi} + p[(w_\xi + \psi)^{p-1} - w_\xi^{p-1}] \frac{\partial w_\xi}{\partial \xi} - p(p-1) w_\xi^{p-2} \frac{\partial w_\xi}{\partial \xi} \psi. \end{aligned}$$

As a consequence, using (7-104) once again,

$$\left| \frac{\partial N(\psi)}{\partial \xi} \right| \leq C |\psi|^q \left[\left| \frac{\partial \psi}{\partial \xi} \right| + \left| \frac{\partial w_\xi}{\partial \xi} \right| \right] + C w_\xi^{p-2} \left| \frac{\partial w_\xi}{\partial \xi} \right| |\psi|. \tag{7-127}$$

Now we claim that

$$w_\xi^{p-2} \left| \frac{\partial w_\xi}{\partial \xi} \right| \leq C \tag{7-128}$$

for some $C > 0$. When $p \geq 2$, (7-128) follows from (1-4) and Lemma 5.2, hence we focus on the case $p \in (1, 2)$. In this case, we take ν_1 as in Lemma 5.2 and we notice that

$$\begin{aligned} \tilde{\nu} &:= \nu_1 - (2 - p)(n + 2s) = \min\{n + 2s + 1 + (p - 2)(n + 2s), (2p - 2)(n + 2s)\} \\ &= \min\{(p - 1)(n + 2s) + 1, (2p - 2)(n + 2s)\} > 0. \end{aligned}$$

Then we use (7-95) and we obtain that

$$w_\xi^{p-2} \left| \frac{\partial w_\xi}{\partial \xi} \right| \leq C |x - \xi|^{(2-p)(n+2s)} |x - \xi|^{-\nu_1} = C |x - \xi|^{-\tilde{\nu}}.$$

Since w_ξ is positive and smooth in the vicinity of ξ , this proves (7-128).

Now, using (7-128) into (7-127), we obtain that

$$\left| \frac{\partial N(\psi)}{\partial \xi} \right| \leq C |\psi|^q \left[\left| \frac{\partial \psi}{\partial \xi} \right| + \left| \frac{\partial w_\xi}{\partial \xi} \right| \right] + C |\psi|. \tag{7-129}$$

We claim that

$$\left\| \frac{\partial N(\psi)}{\partial \xi} \right\|_{\star, \xi} \leq C \|\psi\|_{\star, \xi}^q \left[\left\| \frac{\partial \psi}{\partial \xi} \right\|_{\star, \xi} + \left\| \frac{\partial w_\xi}{\partial \xi} \right\|_{\star, \xi} \right] + C \|\psi\|_{\star, \xi}. \tag{7-130}$$

Indeed, the claim plainly follows from (7-129) if $q = 1$ (that is, $p \geq 2$), hence we focus on the case $q = p - 1$ (that is, $1 < p < 2$). In this case, we observe that

$$\begin{aligned} (1 + |x - \xi|)^\mu |\psi|^q \left[\left| \frac{\partial \psi}{\partial \xi} \right| + \left| \frac{\partial w_\xi}{\partial \xi} \right| \right] &= (1 + |x - \xi|)^{\mu q} |\psi|^q (1 + |x - \xi|)^\mu \left[\left| \frac{\partial \psi}{\partial \xi} \right| + \left| \frac{\partial w_\xi}{\partial \xi} \right| \right] (1 + |x - \xi|)^{-\mu q} \\ &\leq C \|\psi\|_{\star, \xi}^q \left[\left\| \frac{\partial \psi}{\partial \xi} \right\|_{\star, \xi} + \left\| \frac{\partial w_\xi}{\partial \xi} \right\|_{\star, \xi} \right], \end{aligned}$$

and this implies (7-130) also in this case.

Hence, using our assumptions on ψ , we deduce that

$$\left\| \frac{\partial N(\psi)}{\partial \xi} \right\|_{\star, \xi} \leq C \varepsilon^{q(n+2s)} \left[\left\| \frac{\partial \psi}{\partial \xi} \right\|_{\star, \xi} + 1 \right] + C,$$

up to renaming constants. By inserting this into (7-126) we conclude that

$$\left\| \frac{\partial \psi}{\partial \xi} \right\|_{\star, \xi} \leq C + \frac{1}{2} \left\| \frac{\partial \psi}{\partial \xi} \right\|_{\star, \xi}$$

as long as ε is sufficiently small. By reabsorbing one term into the left-hand side, we obtain the desired result. □

Lemma 7.15. *Let $\psi \in \Psi$ be a solution to (7-98) with $\|\psi\|_{\star,\xi} \leq C\varepsilon^{n+2s}$. Then, there exist positive constants \tilde{C} and γ such that*

$$\left\| \frac{\partial E(\psi)}{\partial \xi} \right\|_{\star,\xi} \leq \tilde{C}\varepsilon^\gamma.$$

Proof. The proof easily follows from Lemmata 7.13 and 7.14, up to renaming the constants. □

The variational reduction. We seek for solutions to (1-8) of the form (7-1), that is, recalling also (7-119),

$$u_\xi = \bar{u}_\xi + \Psi(\xi). \tag{7-131}$$

We observe that, thanks to (1-9) and (7-98), the function u_ξ satisfies the equation

$$(-\Delta)^s u_\xi + u_\xi = u_\xi^p + \sum_{i=1}^n c_i Z_i \quad \text{in } \Omega_\varepsilon. \tag{7-132}$$

Notice that if $c_i = 0$ for any $i = 1, \dots, n$ then we will have a solution to (1-8). Hence, the aim of this subsection is to find a suitable point $\xi \in \Omega_\varepsilon$ such that all the coefficients $c_i, i = 1, \dots, n$, in (7-132) vanish.

In order to do this, we define the functional $J_\varepsilon : \Omega_\varepsilon \rightarrow \mathbb{R}$ as

$$J_\varepsilon(\xi) := I_\varepsilon(\bar{u}_\xi + \Psi(\xi)) = I_\varepsilon(u_\xi) \quad \text{for any } \xi \in \Omega_\varepsilon, \tag{7-133}$$

where I_ε was introduced in (1-10). We have the following characterization:

Lemma 7.16. *If $\varepsilon > 0$ is sufficiently small, the coefficients $c_i, i = 1, \dots, n$, in (7-132) are equal to zero if and only if ξ satisfies the condition*

$$\frac{\partial J_\varepsilon}{\partial \xi}(\xi) = 0.$$

Proof. We first write $\xi = (\xi_1, \dots, \xi_n)$ and, for any $j = 1, \dots, n$, we take the derivative of u_ξ with respect to ξ_j .

We observe that

$$\frac{\partial u_\xi}{\partial \xi_j} = \frac{\partial \bar{u}_\xi}{\partial \xi_j} + \frac{\partial \Psi(\xi)}{\partial \xi_j}. \tag{7-134}$$

Thanks to (7-102), we have that

$$\frac{\partial \bar{u}_\xi}{\partial \xi_j} = \frac{\partial w_\xi}{\partial \xi_j} + O(\varepsilon^{\nu_1}). \tag{7-135}$$

Moreover, from Proposition 7.12 and Lemmata 7.9 and 7.15, we obtain that

$$\frac{\partial \Psi(\xi)}{\partial \xi_j} = O(\varepsilon^\gamma), \tag{7-136}$$

where $\gamma > 0$. Hence, (7-134), (7-135) and (7-136) imply that

$$\frac{\partial u_\xi}{\partial \xi_j} = \frac{\partial w_\xi}{\partial \xi_j} + O(\varepsilon^\gamma),$$

which means, recalling (5-3) and using the fact that $\partial w_\xi / \partial \xi_j = -\partial w_\xi / \partial x_j$, that

$$\frac{\partial u_\xi}{\partial \xi_j} = -Z_j + O(\varepsilon^\gamma). \tag{7-137}$$

In particular,

$$\int_{\Omega_\varepsilon} Z_i \frac{\partial u_\xi}{\partial \xi_j} dx = \int_{\Omega_\varepsilon} Z_i (-Z_j + O(\varepsilon^\gamma)) dx = - \int_{\Omega_\varepsilon} Z_i Z_j dx + O(\varepsilon^\gamma) \tag{7-138}$$

and, from Lemma 5.2, we deduce that

$$\left| \frac{\partial u_\xi}{\partial \xi_j} \right| \leq C_1 (|Z_j| + \varepsilon^\gamma) \leq C_2. \tag{7-139}$$

With this, we introduce the matrix $M \in \text{Mat}(n \times n)$ whose entries are given by

$$M_{ji} := \int_{\Omega_\varepsilon} Z_i \frac{\partial u_\xi}{\partial \xi_j} dx. \tag{7-140}$$

We claim that

$$M \text{ is invertible.} \tag{7-141}$$

To prove this, we use (7-138), Corollary 5.6 and the fact that $\alpha > 0$ (recall (5-17)); namely, we compute

$$M_{ji} = - \int_{\Omega_\varepsilon} Z_i Z_j dx + O(\varepsilon^\gamma) = -\alpha \delta_{ij} + O(\varepsilon^\gamma).$$

This says that the matrix $-\alpha^{-1}M$ is a perturbation of the identity and therefore it is invertible for ε sufficiently small, hence (7-141) readily follows.

Now, we multiply (7-132) by $\partial u_\xi / \partial \xi$, obtaining that

$$((-\Delta)^s u_\xi + u_\xi - u_\xi^p) \frac{\partial u_\xi}{\partial \xi} = \sum_{i=1}^n c_i Z_i \frac{\partial u_\xi}{\partial \xi} \quad \text{in } \Omega_\varepsilon,$$

and therefore

$$\left| ((-\Delta)^s u_\xi + u_\xi - u_\xi^p) \frac{\partial u_\xi}{\partial \xi} \right| \leq \sum_{i=1}^n |c_i| |Z_i| \left| \frac{\partial u_\xi}{\partial \xi} \right|.$$

This, together with (7-139) and Lemma 5.2, implies that the function $((-\Delta)^s u_\xi + u_\xi - u_\xi^p) \partial u_\xi / \partial \xi$ is in $L^\infty(\Omega_\varepsilon)$, and so in $L^1(\Omega_\varepsilon)$ uniformly with respect to ξ .

This allows us to compute the derivative of J_ε with respect to ξ_j as follows:

$$\begin{aligned} \frac{\partial J_\varepsilon}{\partial \xi_j}(\xi) &= \frac{\partial}{\partial \xi_j} I_\varepsilon(u_\xi) = \frac{\partial}{\partial \xi_j} \left(\int_{\Omega_\varepsilon} \frac{1}{2} (-\Delta)^s u_\xi u_\xi + \frac{1}{2} u_\xi^2 - \frac{1}{p+1} u_\xi^{p+1} dx \right) \\ &= \int_{\Omega_\varepsilon} \frac{1}{2} (-\Delta)^s \frac{\partial u_\xi}{\partial \xi_j} u_\xi + \frac{1}{2} (-\Delta)^s u_\xi \frac{\partial u_\xi}{\partial \xi_j} + \frac{\partial u_\xi}{\partial \xi_j} u_\xi - u_\xi^p \frac{\partial u_\xi}{\partial \xi_j} dx \\ &= \int_{\Omega_\varepsilon} ((-\Delta)^s u_\xi + u_\xi - u_\xi^p) \frac{\partial u_\xi}{\partial \xi_j} dx = \sum_{i=1}^n c_i \int_{\Omega_\varepsilon} Z_i \frac{\partial u_\xi}{\partial \xi_j} dx, \end{aligned} \tag{7-142}$$

where we have used (7-132) in the last step. Thus, recalling (7-140), we can write

$$\frac{\partial J_\varepsilon}{\partial \xi_j}(\xi) = \sum_{i=1}^n c_i M_{ji}$$

for any $j \in \{1, \dots, n\}$, that is, the vector

$$\frac{\partial J_\varepsilon}{\partial \xi}(\xi) := \left(\frac{\partial J_\varepsilon}{\partial \xi_1}(\xi), \dots, \frac{\partial J_\varepsilon}{\partial \xi_n}(\xi) \right)$$

is equal to the product between the matrix M and the vector $c := (c_1, \dots, c_n)$. From (7-141) we obtain that $\partial J_\varepsilon(\xi)/\partial \xi$ is equal to zero if and only if c is equal to zero, as desired. \square

Thanks to Lemma 7.16, the problem of finding a solution to (1-8) reduces to the one of finding critical points of the functional defined in (7-133). To this end, we obtain an expansion of J_ε :

Theorem 7.17. *We have the following expansion of the functional J_ε :*

$$J_\varepsilon(\xi) = I_\varepsilon(\bar{u}_\xi) + o(\varepsilon^{n+4s}).$$

Proof. We know that

$$J_\varepsilon(\xi) = I_\varepsilon(\bar{u}_\xi + \Psi(\xi)).$$

Hence, we can Taylor expand in the vicinity of \bar{u}_ξ , obtaining

$$\begin{aligned} J_\varepsilon(\xi) &= I_\varepsilon(\bar{u}_\xi) + I'_\varepsilon(\bar{u}_\xi)[\Psi(\xi)] + I''(\bar{u}_\xi)[\Psi(\xi), \Psi(\xi)] + O(|\Psi(\xi)|^3) \\ &= I_\varepsilon(\bar{u}_\xi) + \int_{\Omega_\varepsilon} (-\Delta)^s \bar{u}_\xi \Psi(\xi) + \bar{u}_\xi \Psi(\xi) - \bar{u}_\xi^p \Psi(\xi) dx \\ &\quad + \int_{\Omega_\varepsilon} (-\Delta)^s \Psi(\xi) \Psi(\xi) + \Psi^2(\xi) - p \bar{u}_\xi^{p-1} \Psi^2(\xi) dx + O(|\Psi(\xi)|^3) \\ &= I_\varepsilon(\bar{u}_\xi) + \int_{\Omega_\varepsilon} ((-\Delta)^s u_\xi + u_\xi - u_\xi^p) \Psi(\xi) dx - \int_{\Omega_\varepsilon} ((-\Delta)^s (u_\xi - \bar{u}_\xi) + u_\xi - \bar{u}_\xi - u_\xi^p + \bar{u}_\xi^p) \Psi(\xi) dx \\ &\quad + \int_{\Omega_\varepsilon} (-\Delta)^s \Psi(\xi) \Psi(\xi) + \Psi^2(\xi) - p \bar{u}_\xi^{p-1} \Psi^2(\xi) dx + O(|\Psi(\xi)|^3). \end{aligned}$$

Therefore, using (7-131), we have that

$$J_\varepsilon(\xi) = I_\varepsilon(\bar{u}_\xi) + \int_{\Omega_\varepsilon} ((-\Delta)^s u_\xi + u_\xi - u_\xi^p) \Psi(\xi) dx + \int_{\Omega_\varepsilon} (u_\xi^p - \bar{u}_\xi^p - p \bar{u}_\xi^{p-1} \Psi(\xi)) \Psi(\xi) dx + O(|\Psi(\xi)|^3). \tag{7-143}$$

We notice that

$$\int_{\Omega_\varepsilon} ((-\Delta)^s u_\xi + u_\xi - u_\xi^p) \Psi(\xi) dx = 0,$$

thanks to (7-132) and the fact that $\Psi(\xi)$ is orthogonal in $L^2(\Omega_\varepsilon)$ to any function in the space \mathcal{Z} .

Hence, (7-143) becomes

$$J_\varepsilon(\xi) = I_\varepsilon(\bar{u}_\xi) + \int_{\Omega_\varepsilon} (u_\xi^p - \bar{u}_\xi^p - p \bar{u}_\xi^{p-1} \Psi(\xi)) \Psi(\xi) dx + O(|\Psi(\xi)|^3). \tag{7-144}$$

Now, we observe that

$$|u_\xi^p - \bar{u}_\xi^p - p\bar{u}_\xi^{p-1}\Psi(\xi)| \leq |u_\xi^p - \bar{u}_\xi^p| + p|\bar{u}_\xi^{p-1}\Psi(\xi)| \leq C|\bar{u}_\xi^{p-1}\Psi(\xi)|$$

for a positive constant C , and so, also using (7-100), we have

$$\begin{aligned} & \left| \int_{\Omega_\varepsilon} (u_\xi^p - \bar{u}_\xi^p - p\bar{u}_\xi^{p-1}\Psi(\xi))\Psi(\xi) dx \right| \\ & \leq C \int_{\Omega_\varepsilon} |\bar{u}_\xi|^{p-1} |\Psi(\xi)|^2 dx \\ & \leq C \|\Psi(\xi)\|_{\star, \xi}^2 \int_{\Omega_\varepsilon} |\bar{u}_\xi|^{p-1} \rho_\xi^2 dx \\ & \leq C \|\Psi(\xi)\|_{\star, \xi}^2 \int_{\Omega_\varepsilon} |w_\xi + O(\varepsilon^{n+2s})|^{p-1} \rho_\xi^2 dx \\ & \leq C \|\Psi(\xi)\|_{\star, \xi}^2 \int_{\Omega_\varepsilon} |w_\xi|^{p-1} \rho_\xi^2 dx + C\varepsilon^{(p-1)(n+2s)} \|\Psi(\xi)\|_{\star, \xi}^2 \int_{\Omega_\varepsilon} \rho_\xi^2 dx. \end{aligned} \tag{7-145}$$

Recalling the definition of ρ_ξ in (6-2) and the fact that $\mu > n/2$, we have that

$$\int_{\Omega_\varepsilon} \rho_\xi^2 dx \leq C_1 \tag{7-146}$$

for a suitable constant $C_1 > 0$. Moreover, thanks to (7-99) (recall also (7-119)), we obtain

$$\varepsilon^{(p-1)(n+2s)} \|\Psi(\xi)\|_{\star, \xi}^2 \leq C_2 \varepsilon^{(p-1)(n+2s)} \varepsilon^{2(n+2s)} = C_2 \varepsilon^{(p+1)(n+2s)},$$

which, together with (7-146), says that

$$C\varepsilon^{(p-1)(n+2s)} \|\Psi(\xi)\|_{\star, \xi}^2 \int_{\Omega_\varepsilon} \rho_\xi^2 dx = o(\varepsilon^{n+4s}). \tag{7-147}$$

Also, using (1-4), we have that

$$\int_{\Omega_\varepsilon} |w_\xi|^{p-1} \rho_\xi^2 dx \leq C_3 \int_{\Omega_\varepsilon} \frac{1}{(1 + |x - \xi|)^{(p-1)(n+2s)}} \frac{1}{(1 + |x - \xi|)^{2\mu}} dx \leq C_4,$$

and so, using also (7-99) we have that

$$C \|\Psi(\xi)\|_{\star, \xi}^2 \int_{\Omega_\varepsilon} |w_\xi|^{p-1} \rho_\xi^2 dx = o(\varepsilon^{n+4s}).$$

This, (7-144), (7-145) and (7-147) give the desired claim in Theorem 7.17. □

8. Proof of Theorem 1.1

In this section we complete the proof of Theorem 1.1. For this, we notice that, thanks to Theorems 4.1 and 7.17, we have that, for any $\xi \in \Omega_\varepsilon$ with $\text{dist}(\xi, \partial\Omega_\varepsilon) \geq \delta/\varepsilon$ (for some $\delta \in (0, 1)$),

$$J_\varepsilon(\xi) = I(w) + \frac{1}{2} \mathcal{H}_\varepsilon(\xi) + o(\varepsilon^{n+4s}), \tag{8-1}$$

where J_ε and I are as defined in (7-133) and (4-1), respectively (see also (7-119)) and \mathcal{H}_ε is given by (1-17).

Also, we recall the definition of the set $\Omega_{\varepsilon,\delta}$ given in (2-29), and we claim that J_ε has an interior minimum, namely

$$\text{there exists } \bar{\xi} \in \Omega_{\varepsilon,\delta} \text{ such that } J_\varepsilon(\bar{\xi}) = \min_{\xi \in \bar{\Omega}_{\varepsilon,\delta}} J_\varepsilon(\xi). \tag{8-2}$$

For this, we observe that J_ε is a continuous functional, and therefore

$$J_\varepsilon \text{ admits a minimizer } \bar{\xi} \in \bar{\Omega}_{\varepsilon,\delta}. \tag{8-3}$$

We have that

$$\bar{\xi} \in \Omega_{\varepsilon,\delta}. \tag{8-4}$$

Indeed, suppose by contradiction that $\bar{\xi} \in \partial\Omega_{\varepsilon,\delta}$. Then, from (8-1), we have that

$$J_\varepsilon(\bar{\xi}) = I(w) + \frac{1}{2}\mathcal{H}_\varepsilon(\bar{\xi}) + o(\varepsilon^{n+4s}) \geq I(w) + \frac{1}{2} \min_{\partial\Omega_{\varepsilon,\delta}} \mathcal{H}_\varepsilon + o(\varepsilon^{n+4s}). \tag{8-5}$$

On the other hand, by Proposition 2.8, we know that \mathcal{H}_ε has a strict interior minimum: more precisely, there exists $\xi_o \in \Omega_{\varepsilon,\delta}$ such that

$$\mathcal{H}_\varepsilon(\xi_o) = \min_{\Omega_{\varepsilon,\delta}} \mathcal{H}_\varepsilon \leq c_1 \varepsilon^{n+4s} \tag{8-6}$$

and

$$\min_{\partial\Omega_{\varepsilon,\delta}} \mathcal{H}_\varepsilon \geq c_2 \left(\frac{\varepsilon}{\delta}\right)^{n+4s} \tag{8-7}$$

for suitable $c_1, c_2 > 0$. Also, the minimality of $\bar{\xi}$ and (8-1) say that

$$J_\varepsilon(\bar{\xi}) = \min_{\xi \in \bar{\Omega}_{\varepsilon,\delta}} J_\varepsilon(\xi) \leq J_\varepsilon(\xi_o) = I(w) + \frac{1}{2}\mathcal{H}_\varepsilon(\xi_o) + o(\varepsilon^{n+4s}).$$

By comparing this with (8-5), and using (8-6) and (8-7), we obtain

$$\frac{c_2 \varepsilon^{n+4s}}{2\delta^{n+4s}} + o(\varepsilon^{n+4s}) \leq \frac{1}{2} \min_{\partial\Omega_{\varepsilon,\delta}} \mathcal{H}_\varepsilon + o(\varepsilon^{n+4s}) \leq J_\varepsilon(\bar{\xi}) - I(w) \leq \frac{1}{2}\mathcal{H}_\varepsilon(\xi_o) + o(\varepsilon^{n+4s}) \leq \frac{1}{2}c_1 \varepsilon^{n+4s} + o(\varepsilon^{n+4s}).$$

So, a division by ε^{n+4s} and a limit argument give that

$$\frac{c_2}{2\delta^{n+4s}} \leq \frac{c_1}{2}.$$

This is a contradiction when δ is sufficiently small, thus (8-4) is proved. Hence (8-2) follows from (8-3) and (8-4).

From (8-2), since $\Omega_{\varepsilon,\delta}$ is open, we conclude that

$$\frac{\partial J_\varepsilon}{\partial \xi}(\bar{\xi}) = 0.$$

Therefore, from Lemma 7.16 we obtain the existence of a solution to (1-1) that satisfies (1-5) for ε sufficiently small, and this concludes the proof of Theorem 1.1.

Appendix: Some physical motivation

Equation (1-1) is a particular case of the fractional Schrödinger equation

$$i\hbar\partial_t\psi = \hbar^{2s}(-\Delta)^s\psi + V\psi, \quad (\text{A-1})$$

when the wave function ψ is a standing wave (i.e., $\psi(x, t) = U(x)e^{it/\hbar}$) and the potential V is a suitable power of the density function (i.e., $V = V(|\psi|) = -|\psi|^{p-1}$). As usual, \hbar is the Planck's constant (then we write $\varepsilon := \hbar$ in (1-1)) and $\psi = \psi(x, t)$ is the quantum mechanical probability amplitude for a given particle (of unit mass, for simplicity) to have position x at time t (the corresponding probability density is $|\psi|^2$).

In this setting our Theorem 1.1 describes the confinement of a particle inside a given domain Ω : for small values of \hbar the wave function concentrates to a material particle well inside the domain.

Equation (A-1) is now quite popular (enough to have its own Wikipedia page: see [Wikipedia 2009–2015]) and it is based on the classical Schrödinger equation (corresponding to the case $s = 1$) in which the Brownian motion of the quantum paths is replaced by a Lévy flight. We refer to [Laskin 2000; 2002; 2012] for a throughout physical discussion and detailed motivation of equation (A-1) (see in particular formula (18) in [Laskin 2000]), but here we sketch some heuristics about it.

The idea is that the evolution of the wave function $\psi(x, t)$ from its initial state $\psi_0(x) := \psi(x, 0)$ is run by a quantum mechanics kernel (or amplitude) K which produces the forthcoming values of the wave function by integration with the initial state, that is,

$$\psi(x, t) = \int_{\mathbb{R}^n} dy K(x, y, t)\psi_0(y). \quad (\text{A-2})$$

The main assumption is that this amplitude $K(x, y, t)$ is modulated by an action functional S_t via the contributions of all the possible paths γ that join x to y in time t , that is,

$$K(x, y, t) = \int_{\mathcal{F}(x, y, t)} d\gamma e^{-iS_t(\gamma)/\hbar}. \quad (\text{A-3})$$

The above integral denotes the Feynman path integral over “all possible histories of the system”, that is, over “all possible” continuous paths $\gamma : [0, t] \rightarrow \mathbb{R}^n$ with $\gamma(0) = y$ and $\gamma(t) = x$; see [Feynman 1948]. We remark that this integral is indeed a functional integral, that is, the domain of integration $\mathcal{F}(x, y, t)$ is not a region of a finite-dimensional space, but a space of functions. The mathematical treatment of Feynman path integrals is by no means trivial; as a matter of fact, the convergence must rely on the highly oscillatory behavior of the system, which produces the necessary cancellations. In some cases, a rigorous justification can be provided by the theory of Wiener spaces, but a complete treatment of this topic is far beyond the scopes of this appendix (see, e.g., [Cameron 1960; Cameron and Storvick 1983; Grosche and Steiner 1998; Albeverio et al. 2008]).

The next structural ansatz we take is that the action functional S_t is the superposition of a (complex) diffusive operator H_0 and a potential term V .

Though the diffusion and the potential operate “simultaneously”, with some approximation we may suppose that, at each tiny time step, they operate just one at a time, interchanging their action⁵ at a very high frequency. Namely, we discretize a path γ into N adjacent paths of time range t/N , say $\gamma_1, \dots, \gamma_N : [0, t/N] \rightarrow \mathbb{R}^n$, with $\gamma_1(0) = y$ and $\gamma_N(t/N) = x$, and we suppose that along each γ_j the action reduces to the subsequent nonoverlapping superpositions of diffusion and potential terms, according to the formula

$$e^{-iS_t(\gamma)/\hbar} = \lim_{N \rightarrow +\infty} (e^{-itH_0/(\hbar N)} e^{-itV/(\hbar N)})^N. \tag{A-4}$$

Once more, we do not indulge into a rigorous mathematical discussion of such a limit and we just plug (A-3) and (A-4) into (A-2). We obtain

$$\begin{aligned} \psi(x, t) &= \int_{\mathbb{R}^n} dy \int_{\mathcal{F}(x, y, t)} d\gamma e^{-iS_t(\gamma)/\hbar} \psi_0(y) \\ &= \lim_{N \rightarrow +\infty} \int_{\mathbb{R}^n} dy \int_{\mathcal{F}(x, y, t)} d\gamma (e^{-itH_0/(\hbar N)} e^{-itV/(\hbar N)})^N \psi_0(y). \end{aligned} \tag{A-5}$$

Therefore, if we formally⁶ apply the time derivative to (A-5), we obtain that

⁵In a sense, this is the quantum mechanics version of the Lie–Trotter product formula

$$e^{A+B} = \lim_{N \rightarrow +\infty} (e^{A/N} e^{B/N})^N$$

for $A, B \in \text{Mat}(n \times n)$. The procedure of disentangling mixed exponentials is indeed crucial in quantum mechanics computations; see, e.g., [Feynman 1951]. In our computation, a more rigorous approximation scheme lies in explicitly writing $S_t(\gamma)$ as an integral from 0 to t of the Lagrangian along the path γ , then splitting the integral in N time steps of size t/N by supposing that in each of these time steps the Lagrangian is approximately constant. One may also suppose that the Lagrangian involved in the action is a classical one, i.e., it is the sum of a kinetic term and the potential V . Then the effect of taking the integral over all possible paths averages out the kinetic part, reducing it to a diffusive operator. Since here we are not aiming at a rigorous justification of all these delicate procedures (such as infinite-dimensional integrals, limit exchanges, and so on), for simplicity we are just taking H_0 to be a diffusive operator from the beginning. In this spirit, it is also convenient to suppose that the potential is an operator, that is, we identify V with the operation of multiplying a function by V .

⁶The disentangling procedure allows us to take the derivative of the exponentials of the operators “as if they were commuting ones”. Namely, the Zassenhaus formula,

$$e^{t(A+B)} = e^{tA} e^{tB} e^{O(t^2)} = e^{tA} e^{tB} (1 + O(t^2)),$$

in our case gives

$$e^{-itH_0/(\hbar N)} e^{-itV/(\hbar N)} = e^{-it(H_0+V)/(\hbar N)} (1 + O(t^2/N^2))$$

and so

$$(e^{-itH_0/(\hbar N)} e^{-itV/(\hbar N)})^N = e^{-it(H_0+V)/\hbar} (1 + O(t^2/N^2)).$$

Hence,

$$\lim_{N \rightarrow +\infty} \partial_t (e^{-itH_0/(\hbar N)} e^{-itV/(\hbar N)})^N = \lim_{N \rightarrow +\infty} -\frac{i(H_0+V)}{\hbar} e^{-it(H_0+V)/\hbar} (1 + O(t^2/N^2)) + O(t/N^2) = -\frac{i(H_0+V)}{\hbar}.$$

Moreover, we point out that a couple of additional approximations are likely to be hidden in the computation in (A-6). Namely, first of all, we do not differentiate the functional domain of the Feynman integral. This is consistent with the ansatz that the set of the paths joining two points at a macroscopic scale in time t “does not vary much” for small variations of t . Furthermore, we replace the action of H_0 and V along the infinitesimal paths with their effective action after averaging, so that we can take $(H_0 + V)$ outside the integral.

$$\begin{aligned}
 i\hbar\partial_t\psi(x,t) &= \lim_{N\rightarrow+\infty} \int_{\mathbb{R}^n} dy \int_{\mathcal{F}(x,y,t)} d\gamma N \left(\frac{H_0}{N} e^{-itH_0/(\hbar N)} e^{-itV/(\hbar N)} + \frac{V}{N} e^{-itH_0/(\hbar N)} e^{-itV/(\hbar N)} \right) \\
 &\quad \cdot (e^{-itH_0/(\hbar N)} e^{-itV/(\hbar N)})^{N-1} \psi_0(y) \\
 &= \lim_{N\rightarrow+\infty} \int_{\mathbb{R}^n} dy \int_{\mathcal{F}(x,y,t)} d\gamma (H_0 e^{-itH_0/(\hbar N)} e^{-itV/(\hbar N)} + V e^{-itH_0/(\hbar N)} e^{-itV/(\hbar N)}) \\
 &\quad \cdot (e^{-itH_0/(\hbar N)} e^{-itV/(\hbar N)})^{N-1} \psi_0(y) \\
 &= (H_0 + V) \int_{\mathbb{R}^n} dy \int_{\mathcal{F}(x,y,t)} d\gamma e^{-iS_t(\gamma)/\hbar} \psi_0(y) \\
 &= (H_0 + V)\psi
 \end{aligned} \tag{A-6}$$

by (A-2), (A-3) and (A-4). The classical Schrödinger equation follows by taking $H_0 := -\hbar^2\Delta$, that is, the Gaussian diffusive process, while (A-1) follows by taking $H_0 := \hbar^{2s}(-\Delta)^s$, that is, the $2s$ -stable diffusive process with polynomial tail.

Having given a brief justification of (A-1), we also recall that the fractional Schrödinger case presents interesting differences with respect to the classical one. For instance, the energy of a particle of unit mass is proportional to $|p|^{2s}$ (instead of $|p|^2$; see, e.g., formula (12) in [Laskin 2000]). Also the space/time scaling of the process gives that the fractal dimension of the Lévy paths is $2s$ (differently from the classical Brownian case, in which it is 2); see pages 300–301 of [Laskin 2000].

Now, for completeness, we discuss a nonlocal notion of canonical quantization, together with the associated Heisenberg uncertainty principle (see, for example, pages 17–28 of [Giulini 2003] for the classical canonical quantization and related issues).

For this, we introduce the canonical operators, for $k \in \{1, \dots, n\}$,

$$P_k := -i\hbar^s \partial_k (-\Delta)^{(s-1)/2} \quad \text{and} \quad Q_k := x_k. \tag{A-7}$$

Notice that Q_k is the classical position operator, namely the multiplication by the k -th space coordinate. On the other hand, P_k is a fractional momentum operator, that reduces⁷ to the classical momentum $-i\hbar\partial_k$ when $s = 1$. In this setting, our goal is to check that the commutator

$$[Q, P] := \sum_{k=1}^n [Q_k, P_k]$$

does not vanish. For this, we suppose $0 < \sigma < n/2$ and use the Riesz potential representation of the inverse of the fractional Laplacian of order σ , that is,

$$(-\Delta)^{-\sigma} \psi(x) = c(n, s) \int_{\mathbb{R}^n} \frac{\psi(x-y)}{|y|^{n-2\sigma}} dy = c(n, s) \int_{\mathbb{R}^n} \frac{\psi(y)}{|x-y|^{n-2\sigma}} dy \tag{A-8}$$

for a suitable $c(n, s) > 0$, see [Landkof 1972].

⁷Of course, the fractional momentum is not a momentum, since it has physical dimension $[\text{Planck constant}]^s/[\text{length}]^s$, while the classical momentum has physical dimension $[\text{Planck constant}]/[\text{length}]$. Namely, the physical dimension of the fractional momentum is a fractional power of the physical dimension of the classical momentum. Clearly, the same phenomenon occurs for the physical dimension of the fractional Laplace operators in terms of the usual Laplacian.

In our case we use (A-8) with $\sigma := (1 - s)/2 \in (0, \frac{1}{2}) \subseteq (0, n/2)$. Then

$$P_k \psi(x) = -c(n, s) i \hbar^s \partial_k \int_{\mathbb{R}^n} \frac{\psi(y)}{|x - y|^{n+s-1}} dy = c(n, s) i \hbar^s (n + s - 1) \int_{\mathbb{R}^n} \frac{(x_k - y_k) \psi(y)}{|x - y|^{n+s+1}} dy$$

and so

$$P_k Q_k \psi(x) = P_k(x_k \psi(x)) = c(n, s) i \hbar^s (n + s - 1) \int_{\mathbb{R}^n} \frac{(x_k - y_k) y_k \psi(y)}{|x - y|^{n+s+1}} dy.$$

This gives that

$$\begin{aligned} Q_k P_k \psi - P_k Q_k \psi &= c(n, s) i \hbar^s (n + s - 1) \left[\int_{\mathbb{R}^n} \frac{x_k(x_k - y_k) \psi(y)}{|x - y|^{n+s+1}} dy - \int_{\mathbb{R}^n} \frac{(x_k - y_k) y_k \psi(y)}{|x - y|^{n+s+1}} dy \right] \\ &= c(n, s) i \hbar^s (n + s - 1) \int_{\mathbb{R}^n} \frac{(x_k - y_k)^2 \psi(y)}{|x - y|^{n+s+1}} dy, \end{aligned}$$

and so, by summing up⁸ and recalling (A-8), we conclude that

$$[Q, P] \psi = c(n, s) i \hbar^s (n + s - 1) \int_{\mathbb{R}^n} \frac{\psi(y)}{|x - y|^{n+s-1}} dy = i(n + s - 1) \hbar^s (-\Delta)^{(s-1)/2} \psi.$$

Notice that, as $s \rightarrow 1$, this formula reduces to the classical Heisenberg uncertainty principle.

We also point out that a similar computation shows that, differently from the local quantum momentum, the k -th fractional quantum momentum does not commute with the m -th spatial coordinates even when $k \neq m$; namely, $[Q_m, P_k] \psi(x)$ is, up to normalizing constants,

$$i \hbar^s \int_{\mathbb{R}^n} \frac{(x_m - y_m)(x_k - y_k) \psi(y)}{|x - y|^{n+s+1}} dy.$$

This Heisenberg uncertainty principle is also compatible with (A-1), in the sense that the diffusive operator H_0 is exactly the one obtained by the canonical quantization in (A-7); indeed,

$$\begin{aligned} \sum_{k=1}^n P_k^2 &= \sum_{k=1}^n (-i \hbar^s \partial_k (-\Delta)^{(s-1)/2}) (-i \hbar^s \partial_k (-\Delta)^{(s-1)/2}) = -\hbar^{2s} \sum_{k=1}^n \partial_k^2 (-\Delta)^{s-1} \\ &= -\hbar^{2s} \Delta (-\Delta)^{s-1} = \hbar^{2s} (-\Delta)^s = H_0. \end{aligned}$$

Moreover, we mention that the fractional Laplace operator also arises naturally in the high energy Hamiltonians of relativistic theories. For further motivation of the fractional Laplacian in modern physics see, for example, [Chen 2004] and the references therein.

⁸Alternatively, one can perform the commutator calculation in Fourier space and then reduce to the original variable by an inverse Fourier transform. This computation can be done easily by using the facts that the Fourier transform sends products into convolutions and that (up to constants)

$$\begin{aligned} (\hat{x}_k * g)(\xi) &= \mathcal{F}(x_k \mathcal{F}^{-1} g(x))(\xi) = \int_{\mathbb{R}^n} dx \int_{\mathbb{R}^n} dy e^{ix \cdot (y - \xi)} x_k g(y) = i^{-1} \int_{\mathbb{R}^n} dx \int_{\mathbb{R}^n} dy \partial_{y_k} e^{ix \cdot (y - \xi)} g(y) \\ &= i \int_{\mathbb{R}^n} dx \int_{\mathbb{R}^n} dy e^{ix \cdot (y - \xi)} \partial_k g(y) = i \int_{\mathbb{R}^n} dx e^{-ix \cdot \xi} \mathcal{F}^{-1}(\partial_k g)(x) = i \mathcal{F}(\mathcal{F}^{-1}(\partial_k g))(\xi) = i \partial_k g(\xi). \end{aligned}$$

Then we leave to the reader the computation of $\mathcal{F}([Q, P] \psi)(\xi)$.

Acknowledgements

This work has been supported by Millennium Nucleus CAPDE NC130017, Fondecyt grants 1150066, 1130360, Fondo Basal CMM-Chile, EPSRC grant EP/K024566/1 “Monotonicity formula methods for nonlinear PDEs” and ERC grant 277749 “EPSILON Elliptic PDEs and Symmetry of Interfaces and Layers for Odd Nonlinearities”.

References

- [Albeverio et al. 2008] S. A. Albeverio, R. J. Høegh-Krohn, and S. Mazzucchi, *Mathematical theory of Feynman path integrals: an introduction*, 2nd ed., Lecture Notes in Mathematics **523**, Springer, Berlin, 2008. MR 2010e:58008 Zbl 1222.46001
- [Ambrosetti and Malchiodi 2006] A. Ambrosetti and A. Malchiodi, *Perturbation methods and semilinear elliptic problems on \mathbb{R}^n* , Progress in Mathematics **240**, Birkhäuser, Basel, 2006. MR 2007k:35005 Zbl 1115.35004
- [Amick and Toland 1991] C. J. Amick and J. F. Toland, “Uniqueness and related analytic properties for the Benjamin–Ono equation—a nonlinear Neumann problem in the plane”, *Acta Math.* **167**:1–2 (1991), 107–126. MR 92i:35099 Zbl 0755.35108
- [Cameron 1960] R. H. Cameron, “A family of integrals serving to connect the Wiener and Feynman integrals”, *J. Math. and Phys.* **39** (1960), 126–140. MR 23 #B821 Zbl 0096.06901
- [Cameron and Storvick 1983] R. H. Cameron and D. A. Storvick, “A simple definition of the Feynman integral, with applications”, *Mem. Amer. Math. Soc.* **46**:288 (1983), iv+46. MR 86c:81029 Zbl 0527.28015
- [Carmona et al. 1990] R. Carmona, W. C. Masters, and B. Simon, “Relativistic Schrödinger operators: asymptotic behavior of the eigenfunctions”, *J. Funct. Anal.* **91**:1 (1990), 117–142. MR 91i:35139 Zbl 0716.35006
- [Chen 2004] W. Chen, “Soft matter and fractional mathematics: insights into mesoscopic quantum and time-space structures”, preprint, 2004. arXiv cond-mat/0405345
- [Chen and Zheng 2014] G. Chen and Y. Zheng, “Concentration phenomenon for fractional nonlinear Schrödinger equations”, *Commun. Pure Appl. Anal.* **13**:6 (2014), 2359–2376. MR 3248394
- [Choi et al. 2014] W. Choi, S. Kim, and K.-A. Lee, “Asymptotic behavior of solutions for nonlinear elliptic problems with the fractional Laplacian”, *J. Funct. Anal.* **266**:11 (2014), 6531–6598. MR 3192461 Zbl 1297.35268
- [Dávila et al. 2014] J. Dávila, M. del Pino, and J. Wei, “Concentrating standing waves for the fractional nonlinear Schrödinger equation”, *J. Differential Equations* **256**:2 (2014), 858–892. MR 3121716 Zbl 06447081
- [Di Nezza et al. 2012] E. Di Nezza, G. Palatucci, and E. Valdinoci, “Hitchhiker’s guide to the fractional Sobolev spaces”, *Bull. Sci. Math.* **136**:5 (2012), 521–573. MR 2944369 Zbl 1252.46023
- [Dipierro et al. 2014] S. Dipierro, A. Figalli, and E. Valdinoci, “Strongly nonlocal dislocation dynamics in crystals”, *Comm. Partial Differential Equations* **39**:12 (2014), 2351–2387. MR 3259559 Zbl 1304.35731
- [Dipierro et al. \geq 2015] S. Dipierro, F. Mahmoudi, and A. Malchiodi, “Singularly perturbed PDEs and patterns with periodic profiles”, in progress.
- [Fall and Valdinoci 2014] M. M. Fall and E. Valdinoci, “Uniqueness and nondegeneracy of positive solutions of $(-\Delta)^s u + u = u^p$ in \mathbb{R}^N when s is close to 1”, *Comm. Math. Phys.* **329**:1 (2014), 383–404. MR 3207007 Zbl 1304.35746
- [Felmer et al. 2012] P. Felmer, A. Quaas, and J. Tan, “Positive solutions of the nonlinear Schrödinger equation with the fractional Laplacian”, *Proc. Roy. Soc. Edinburgh Sect. A* **142**:6 (2012), 1237–1262. MR 3002595 Zbl 1290.35308
- [Feynman 1948] R. P. Feynman, “Space-time approach to non-relativistic quantum mechanics”, *Rev. Modern Physics* **20** (1948), 367–387. MR 10,224b
- [Feynman 1951] R. P. Feynman, “An operator calculus having applications in quantum electrodynamics”, *Physical Rev. (2)* **84** (1951), 108–128. MR 13,410e Zbl 0044.23304
- [Frank and Lenzmann 2013] R. L. Frank and E. Lenzmann, “Uniqueness of non-linear ground states for fractional Laplacians in \mathbb{R}^n ”, *Acta Math.* **210**:2 (2013), 261–318. MR 3070568 Zbl 1307.35315
- [Frank et al. 2015] R. L. Frank, E. Lenzmann, and L. Silvestre, “Uniqueness of radial solutions for the fractional Laplacian”, preprint, 2015. To appear in *Comm. Pure Appl. Math.*

- [Giulini 2003] D. Giulini, “That strange procedure called quantisation”, pp. 17–40 in *Quantum gravity*, edited by D. Giulini et al., Lecture Notes in Phys. **631**, Springer, Berlin, 2003. MR 2206994 Zbl 1052.83019
- [Grosche and Steiner 1998] C. Grosche and F. Steiner, *Handbook of Feynman path integrals*, Springer Tracts in Modern Physics **145**, Springer, Berlin, 1998. MR 2000f:81103 Zbl 1029.81045
- [Landkof 1972] N. S. Landkof, *Foundations of modern potential theory*, Grundlehren der Math. Wissenschaften **180**, Springer, Heidelberg, 1972. MR 50 #2520 Zbl 0253.31001
- [Laskin 2000] N. Laskin, “Fractional quantum mechanics and Lévy path integrals”, *Phys. Lett. A* **268**:4–6 (2000), 298–305. MR 2000m:81097 Zbl 0948.81595
- [Laskin 2002] N. Laskin, “Fractional Schrödinger equation”, *Phys. Rev. E* (3) **66**:5 (2002), 056108, 7. MR 2003k:81043
- [Laskin 2012] N. Laskin, “Principles of fractional quantum mechanics”, pp. 393–427 in *Fractional dynamics*, edited by J. Klafter et al., World Sci. Publ., Hackensack, NJ, 2012. MR 2932616 Zbl 1297.81070
- [Li and Nirenberg 1998] Y. Li and L. Nirenberg, “The Dirichlet problem for singularly perturbed elliptic equations”, *Comm. Pure Appl. Math.* **51**:11–12 (1998), 1445–1490. MR 99g:35014 Zbl 0933.35083
- [Ni and Wei 1995] W.-M. Ni and J. Wei, “On the location and profile of spike-layer solutions to singularly perturbed semilinear Dirichlet problems”, *Comm. Pure Appl. Math.* **48**:7 (1995), 731–768. MR 96g:35077 Zbl 0838.35009
- [del Pino and Felmer 1999] M. del Pino and P. L. Felmer, “Spike-layered solutions of singularly perturbed elliptic problems in a degenerate setting”, *Indiana Univ. Math. J.* **48**:3 (1999), 883–898. MR 2001b:35027 Zbl 0932.35080
- [del Pino et al. 2000] M. del Pino, P. L. Felmer, and J. Wei, “On the role of distance function in some singular perturbation problems”, *Comm. Partial Differential Equations* **25**:1–2 (2000), 155–177. MR 2000m:35017 Zbl 0949.35054
- [Ros-Oton and Serra 2014a] X. Ros-Oton and J. Serra, “The Dirichlet problem for the fractional Laplacian: regularity up to the boundary”, *J. Math. Pures Appl.* (9) **101**:3 (2014), 275–302. MR 3168912 Zbl 1285.35020
- [Ros-Oton and Serra 2014b] X. Ros-Oton and J. Serra, “The Pohozaev identity for the fractional Laplacian”, *Arch. Ration. Mech. Anal.* **213**:2 (2014), 587–628. MR 3211861 Zbl 06343915
- [Secchi 2013] S. Secchi, “Ground state solutions for nonlinear fractional Schrödinger equations in \mathbb{R}^N ”, *J. Math. Phys.* **54**:3 (2013), 031501, 17. MR 3059423 Zbl 1281.81034
- [Servadei and Valdinoci 2014] R. Servadei and E. Valdinoci, “Weak and viscosity solutions of the fractional Laplace equation”, *Publ. Mat.* **58**:1 (2014), 133–154. MR 3161511 Zbl 1292.35315
- [Silvestre 2005] L. E. Silvestre, *Regularity of the obstacle problem for a fractional power of the Laplace operator*, Ph.D. thesis, The University of Texas at Austin, 2005, available at <http://search.proquest.com/docview/305384256>. MR 2707618
- [Silvestre 2007] L. Silvestre, “Regularity of the obstacle problem for a fractional power of the Laplace operator”, *Comm. Pure Appl. Math.* **60**:1 (2007), 67–112. MR 2008a:35041 Zbl 1141.49035
- [Wikipedia 2009–2015] Wikipedia, “Fractional Schrödinger equation”, 2009–2015, available at http://en.wikipedia.org/wiki/Fractional_Schrödinger_equation.

Received 19 Nov 2014. Accepted 30 Apr 2015.

JUAN DÁVILA: jdavila@dim.uchile.cl

Departamento de Ingeniería Matemática and Centro de Modelamiento Matemático, Universidad de Chile, Casilla 170 Correo 3, 8370459 Santiago, Chile

MANUEL DEL PINO: delpino@dim.uchile.cl

Universidad de Chile, 8370459 Santiago, Chile

SERENA DIPIERRO: serena.dipierro@ed.ac.uk

School of Mathematics, University of Edinburgh, Peter Guthrie Tait Road, Edinburgh, EH9 3FD, United Kingdom

ENRICO VALDINOCI: enrico.valdinoci@wias-berlin.de

Weierstrass Institut für Angewandte Analysis und Stochastik, Mohrenstrasse 39, D-10117 Berlin, Germany

Analysis & PDE

msp.org/apde

EDITORS

EDITOR-IN-CHIEF

Maciej Zworski
zworski@math.berkeley.edu
University of California
Berkeley, USA

BOARD OF EDITORS

Nicolas Burq	Université Paris-Sud 11, France nicolas.burq@math.u-psud.fr	Yuval Peres	University of California, Berkeley, USA peres@stat.berkeley.edu
Sun-Yung Alice Chang	Princeton University, USA chang@math.princeton.edu	Gilles Pisier	Texas A&M University, and Paris 6 pisier@math.tamu.edu
Michael Christ	University of California, Berkeley, USA mchrist@math.berkeley.edu	Tristan Rivière	ETH, Switzerland riviere@math.ethz.ch
Charles Fefferman	Princeton University, USA cf@math.princeton.edu	Igor Rodnianski	Princeton University, USA irod@math.princeton.edu
Ursula Hamenstaedt	Universität Bonn, Germany ursula@math.uni-bonn.de	Wilhelm Schlag	University of Chicago, USA schlag@math.uchicago.edu
Vaughan Jones	U.C. Berkeley & Vanderbilt University vaughan.f.jones@vanderbilt.edu	Sylvia Serfaty	New York University, USA serfaty@cims.nyu.edu
Herbert Koch	Universität Bonn, Germany koch@math.uni-bonn.de	Yum-Tong Siu	Harvard University, USA siu@math.harvard.edu
Izabella Laba	University of British Columbia, Canada ilaba@math.ubc.ca	Terence Tao	University of California, Los Angeles, USA tao@math.ucla.edu
Gilles Lebeau	Université de Nice Sophia Antipolis, France lebeau@unice.fr	Michael E. Taylor	Univ. of North Carolina, Chapel Hill, USA met@math.unc.edu
László Lempert	Purdue University, USA lempert@math.purdue.edu	Gunther Uhlmann	University of Washington, USA gunther@math.washington.edu
Richard B. Melrose	Massachusetts Institute of Technology, USA rbm@math.mit.edu	András Vasy	Stanford University, USA andras@math.stanford.edu
Frank Merle	Université de Cergy-Pontoise, France Frank.Merle@u-cergy.fr	Dan Virgil Voiculescu	University of California, Berkeley, USA dvv@math.berkeley.edu
William Minicozzi II	Johns Hopkins University, USA minicozz@math.jhu.edu	Steven Zelditch	Northwestern University, USA zelditch@math.northwestern.edu
Werner Müller	Universität Bonn, Germany mueller@math.uni-bonn.de		

PRODUCTION

production@msp.org

Silvio Levy, Scientific Editor

See inside back cover or msp.org/apde for submission instructions.

The subscription price for 2015 is US \$205/year for the electronic version, and \$390/year (+\$55, if shipping outside the US) for print and electronic. Subscriptions, requests for back issues from the last three years and changes of subscribers address should be sent to MSP.

Analysis & PDE (ISSN 1948-206X electronic, 2157-5045 printed) at Mathematical Sciences Publishers, 798 Evans Hall #3840, c/o University of California, Berkeley, CA 94720-3840, is published continuously online. Periodical rate postage paid at Berkeley, CA 94704, and additional mailing offices.

APDE peer review and production are managed by EditFLOW[®] from MSP.

PUBLISHED BY

 **mathematical sciences publishers**
nonprofit scientific publishing

<http://msp.org/>

© 2015 Mathematical Sciences Publishers

ANALYSIS & PDE

Volume 8 No. 5 2015

Partial collapsing and the spectrum of the Hodge–de Rham operator COLETTE ANNÉ and JUNYA TAKAHASHI	1025
Sharp L^p bounds for the wave equation on groups of Heisenberg type DETLEF MÜLLER and ANDREAS SEEGER	1051
Global well-posedness on the derivative nonlinear Schrödinger equation YIFEI WU	1101
On the boundary value problem for the Schrödinger equation: compatibility conditions and global existence CORENTIN AUDIARD	1113
On estimates for fully nonlinear parabolic equations on Riemannian manifolds BO GUAN, SHUJUN SHI and ZHENAN SUI	1145
Concentration phenomena for the nonlocal Schrödinger equation with Dirichlet datum JUAN DÁVILA, MANUEL DEL PINO, SERENA DIPIERRO and ENRICO VALDINOCI	1165
Local spectral asymptotics for metric perturbations of the Landau Hamiltonian TOMÁS LUNGENSTRASS and GEORGI RAIKOV	1237
Hilbert transform along measurable vector fields constant on Lipschitz curves: L^2 boundedness SHAOMING GUO	1263



2157-5045(2015)8:5;1-9