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► **To cite this version:**

Marie-Françoise Bidaut-Véron, Giang Hoang, Quoc-Hung Nguyen, Laurent Véron. An elliptic semilinear equation with source term and boundary measure data: the supercritical case. 2014. hal-01096025v3

HAL Id: hal-01096025

<https://hal.science/hal-01096025v3>

Preprint submitted on 20 Dec 2014 (v3), last revised 9 Sep 2015 (v5)

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An elliptic semilinear equation with source term and boundary measure data: the supercritical case

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Abstract

We give new criteria for the existence of weak solutions to equation with source term

$$-\Delta u = u^q \text{ in } \Omega, \quad u = \sigma \text{ on } \partial\Omega$$

where $q > 1$, Ω is either a bounded smooth domain or \mathbb{R}_+^N and $\sigma \in \mathfrak{M}^+(\partial\Omega)$ is a nonnegative Radon measure on $\partial\Omega$. In particular, one of the criteria is expressed in terms of some Bessel capacities on $\partial\Omega$. We also give a sufficient condition for the existence of weak solutions to equation with source mixed terms.

$$-\Delta u = |u|^{q_1-1}u|\nabla u|^{q_2} \text{ in } \Omega, \quad u = \sigma \text{ on } \partial\Omega$$

where $q_1, q_2 \geq 0$, $q_1 + q_2 > 1$, $q_2 < 2$, $\sigma \in \mathfrak{M}(\partial\Omega)$ is a Radon measure on $\partial\Omega$.

1 Introduction and main results

Let Ω be a bounded smooth domain in \mathbb{R}^N or $\Omega = \mathbb{R}_+^N := \mathbb{R}^{N-1} \times (0, \infty)$, $N \geq 3$, and $g : \mathbb{R} \times \mathbb{R}^N \mapsto \mathbb{R}$ be a continuous function. In this paper, we study the solvability of the problem

$$\begin{aligned} -\Delta u &= g(u, \nabla u) && \text{in } \Omega, \\ u &= \sigma && \text{on } \partial\Omega, \end{aligned} \tag{1.1}$$

where $\sigma \in \mathfrak{M}(\partial\Omega)$ is a Radon measure on $\partial\Omega$. All solutions are understood in the usual very weak sense: $u \in L^1(\Omega)$, $g(u, \nabla u) \in L_\rho^1(\Omega)$, where $\rho(x)$ is the distance from x to $\partial\Omega$ when Ω is bounded, or $u \in L^1(\mathbb{R}_+^N \cap B)$, $g(u, \nabla u) \in L_\rho^1(\mathbb{R}_+^N \cap B)$ for any ball B if $\Omega = \mathbb{R}_+^N$, and

$$\int_\Omega u(-\Delta \xi) dx = \int_\Omega g(u, \nabla u) \xi dx - \int_{\partial\Omega} \frac{\partial \xi}{\partial n} d\sigma \tag{1.2}$$

for any $\xi \in C^2(\overline{\Omega}) \cap C_c(\mathbb{R}^N)$ with $\xi = 0$ on $\partial\Omega$, where $\rho(x) = \text{dist}(x, \partial\Omega)$, n is the outward unit vector on $\partial\Omega$. It is well-known that such a solution u satisfies

$$u = \mathbf{G}[g(u, \nabla u)] + \mathbf{P}[\sigma] \text{ a. e. in } \Omega.$$

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where $\mathbf{G}[\cdot], \mathbf{P}[\cdot]$, respectively the Green and the Poisson potentials of $-\Delta$ in Ω , are defined from the Green and the Poisson kernels by

$$\mathbf{P}[\sigma](y) = \int_{\partial\Omega} \mathbf{P}(y, z) d\sigma(z), \quad \mathbf{G}[g(u, \nabla u)](y) = \int_{\Omega} \mathbf{G}(y, x) g(u, \nabla u)(x) dx,$$

see [14].

Our main goal is to establish necessary and sufficient conditions for the existence of weak solutions of (1.1) with boundary data measures, together with sharp pointwise estimates of the solutions. In the sequel we study two cases for problem (1.1):

1- The pure power case

$$\begin{aligned} -\Delta u &= |u|^{q-1}u && \text{in } \Omega, \\ u &= \sigma && \text{on } \partial\Omega, \end{aligned} \tag{1.3}$$

with $u \geq 0$, $q > 1$ and $\sigma \geq 0$.

2- The mixed gradient-power case

$$\begin{aligned} -\Delta u &= |\nabla u|^{q_2} |u|^{q_1-1}u && \text{in } \Omega, \\ u &= \sigma && \text{on } \partial\Omega, \end{aligned} \tag{1.4}$$

with $q_1, q_2 > 0$, $q_1 + q_2 > 1$ and $q_2 \geq 2$.

Problem (1.3) has been first studied by Bidaut-Véron and Vivier [2] in the subcritical case $1 < q < \frac{N+1}{N-1}$ with Ω bounded. They proved that (1.3) admits a nonnegative solution provided $\sigma(\partial\Omega)$ is small enough. They also proved that for any $\sigma \in \mathfrak{M}^+(\partial\Omega)$ there holds

$$\mathbf{G}[(\mathbf{P}[\sigma])^q] \leq c\sigma(\partial\Omega)\mathbf{P}[\sigma] \tag{1.5}$$

for some $c = c(N, p, q) > 0$. Then Bidaut-Véron and Yarur [3] have considered again problem (1.3) in a bounded domain in a more general situation since they allowed both interior and boundary data measures, giving a complete description of the solutions in the subcritical case, and sufficient conditions for existence in the supercritical case. In particular they showed that problem (1.3) has a solution if and only if

$$(\mathbf{G}[\mathbf{P}[\sigma]])^q \leq c\mathbf{P}[\sigma] \tag{1.6}$$

for some $c = c(N, q, \Omega) > 0$, see [3, Th 3.12-3.13, Remark 3.12].

The absorption case, i.e. $g(u, \nabla u) = -|u|^{q-1}u$ has been studied by Gmira and Véron [8] in the subcritical case (again $1 < q < \frac{N+1}{N-1}$) and by Marcus and Véron in the supercritical case [12], [13], [14]. The case $g(u, \nabla u) = -|\nabla u|^q$ was studied by Nguyen Phuoc and Véron [15] and extended recently to the case $g(u, \nabla u) = -|\nabla u|^{q_2} |u|^{q_1-1}u$ by Marcus and Nguyen Phuoc [10]. To our knowledge, problem (1.4) has not yet been studied.

To state our results, let us introduce some notations. We denote $A \lesssim (\gtrsim) B$ if $A \leq (\geq) CB$ for some C depending on some structural constants, $A \asymp B$ if $A \lesssim B \lesssim A$. Various capacities will be used throughout the paper. Among them are the Riesz and Bessel capacities in \mathbb{R}^{N-1} defined respectively by

$$\begin{aligned} \text{Cap}_{I_\gamma, s}(O) &= \inf \left\{ \int_{\mathbb{R}^{N-1}} f^s dy : f \geq 0, I_\gamma * f \geq \chi_O \right\}, \\ \text{Cap}_{G_\gamma, s}(O) &= \inf \left\{ \int_{\mathbb{R}^{N-1}} f^s dy : f \geq 0, G_\gamma * f \geq \chi_O \right\}, \end{aligned}$$

for any Borel set $O \subset \mathbb{R}^{N-1}$, where $s > 1$, I_γ, G_γ are the Riesz and the Bessel kernels in \mathbb{R}^{N-1} with order $\gamma \in (0, N-1)$. We remark that

$$\text{Cap}_{G_\gamma, s}(O) \geq \text{Cap}_{I_\gamma, s}(O) \geq C|O|^{1-\frac{\gamma s}{N-1}} \quad (1.7)$$

for any Borel set $O \subset \mathbb{R}^{N-1}$ where $\gamma s < N-1$ and C is a positive constant. When we consider equations in a bounded smooth domain Ω in \mathbb{R}^N we use a specific capacity that we define as follows: there exist open sets O_1, \dots, O_m in \mathbb{R}^N , diffeomorphisms $T_i : O_i \mapsto B_1(0)$ and compact sets K_1, \dots, K_m in $\partial\Omega$ such that

- a. $K_i \subset O_i$, $\partial\Omega \subset \bigcup_{i=1}^m K_i$
- b. $T_i(O_i \cap \partial\Omega) = B_1(0) \cap \{x_N = 0\}$, $T_i(O_i \cap \Omega) = B_1(0) \cap \{x_N > 0\}$.
- c. for any $x \in O_i \cap \Omega$, $\exists y \in O_i \cap \partial\Omega$, $\rho(x) = |x - y|$.

Clearly, $\rho(T_i^{-1}(z)) \asymp |z_N|$ for any $z = (z', z_N) \in B_1(0) \cap \{x_N > 0\}$ and $|\mathbf{J}_{T_i}(x)| \asymp 1$ for any $x \in O_i \cap \Omega$, here \mathbf{J}_{T_i} is the Hessian matrix of T_i .

Definition 1.1 Let $\gamma \in (0, N-1)$, $s > 1$. We denote the $\text{Cap}_{\gamma, s}^{\partial\Omega}$ -capacity of a compact set $E \subset \partial\Omega$ by

$$\text{Cap}_{\gamma, s}^{\partial\Omega}(E) = \sum_{i=1}^m \text{Cap}_{G_\gamma, s}(T_i(E \cap K_i)),$$

where $T_i(E \cap K_i) = \tilde{T}_i(E \cap K_i) \times \{x_N = 0\}$.

Notice that, if $\gamma s > N-1$ then there exists $C = C(N, \gamma, s, \Omega) > 0$ such that

$$\text{Cap}_{\gamma, s}^{\partial\Omega}(\{x\}) \geq C \quad (1.8)$$

for all $x \in \partial\Omega$. Also the definition does not depend on the choice of the sets O_i .

Our first two theorems give criteria for the solvability of problem (1.1) in \mathbb{R}_+^N .

Theorem 1.2 Let $q > 1$ and $\sigma \in \mathfrak{M}_b^+(\mathbb{R}^{N-1})$. Then, the following statements are equivalent

1. The inequality

$$\sigma(K) \leq C \text{Cap}_{I_{\frac{2}{q}}, q'}(K) \quad (1.9)$$

holds for any compact set $K \subset \mathbb{R}^{N-1}$.

2. The inequality

$$\mathbf{G}[(\mathbf{P}[\sigma])^q] \leq C\mathbf{P}[\sigma] < \infty \quad \text{a.e in } \mathbb{R}_+^N \quad (1.10)$$

holds.

3. The problem

$$\begin{aligned} -\Delta u &= u^q & \text{in } \mathbb{R}_+^N, \\ u &= \varepsilon\sigma & \text{in } \partial\mathbb{R}_+^N, \end{aligned} \quad (1.11)$$

has a positive solution for $\varepsilon > 0$ small enough.

Moreover, there is a constant $C_0 > 0$ such that if any one of the two statement 1 and 2 holds with $C \leq C_0$, then equation (1.11) admits a solution u with $\varepsilon = 1$ which satisfies

$$u \asymp \mathbf{P}[\sigma]. \quad (1.12)$$

Conversely, if (1.11) has a solution u with $\varepsilon = 1$, then the two statement 1. and 2. hold for some $C > 0$.

As a consequence of Theorem 1.2 when $g(u, \nabla u) = |u|^{q-1}u$ ($q > 1$) and $\Omega = \mathbb{R}_+^N$, we prove that if (1.3) has a nonnegative solution u with $\sigma \in \mathfrak{M}_b^+(\mathbb{R}^{N-1})$, then

$$\sigma(B_r'(y')) \leq Cr^{N-\frac{q+1}{q-1}} \quad (1.13)$$

for any ball $B_r'(y')$ in \mathbb{R}^{N-1} where $C = C(q, N)$ and $q > \frac{N+1}{N-1}$; if $1 < q \leq \frac{N+1}{N-1}$, then $\sigma \equiv 0$. Conversely, if $q > \frac{N+1}{N-1}$, $d\sigma = fdz$ for some $f \geq 0$ which satisfies

$$\int_{B_r'(y')} f^{1+\varepsilon} dz \leq r^{N-1-\frac{2(\varepsilon+1)}{q-1}} \quad (1.14)$$

for some $\varepsilon > 0$, then there exists a constant $C_0 = C_0(N, q)$ such that (1.1) has a nonnegative solution if $C \leq C_0$. The above inequality is an analogue of the classical Fefferman-Phong condition [5]. In particular, (1.14) holds if f belongs to the Lorentz space $L^{\frac{(N-1)(q-1)}{2}, \infty}(\mathbb{R}^{N-1})$.

We give sufficient conditions for the existence of weak solutions to (1.1) when $g(u, \nabla u) = |u|^{q_1-1}u|\nabla u|^{q_2}$, $q_1, q_2 \geq 0$, $q_1 + q_2 > 1$ and $q_2 < 2$.

Theorem 1.3 *Let $q_1, q_2 \geq 0, q_1 + q_2 > 1, q_2 < 2$ and $\sigma \in \mathfrak{M}_b^+(\mathbb{R}^{N-1})$. Assume that*

$$|\sigma|(K) \leq C \text{Cap}_{L^{\frac{2-q_2}{q_1+q_2}, (q_1+q_2)'}}(K) \quad (1.15)$$

for some $C > 0$ holds for any Borel set $K \subset \mathbb{R}^{N-1}$; then the problem

$$\begin{aligned} -\Delta u &= |u|^{q_1-1}u|\nabla u|^{q_2} && \text{in } \mathbb{R}_+^N, \\ u &= \varepsilon\sigma && \text{in } \partial\mathbb{R}_+^N, \end{aligned} \quad (1.16)$$

has a solution for $\varepsilon > 0$ small enough and it satisfies

$$|u| \lesssim \mathbf{P}[|\sigma|], \quad |\nabla u| \lesssim \rho^{-1}\mathbf{P}[|\sigma|]. \quad (1.17)$$

Remark 1.4 1- We define the subcritical range by

$$(N-1)q_1 + Nq_2 < N+1 \quad \text{or equivalently} \quad \frac{2-q_2}{q_1+q_2-1} > N-1. \quad (1.18)$$

In that case problem (1.16) has a solution for any measure $\sigma \in \mathfrak{M}_b^+(\mathbb{R}^{N-1})$ and $\varepsilon > 0$ small enough.

2- In any case and in view of (1.7), if $f \in L^{\frac{(N-1)(q_1+q_2-1)}{2-q_2}, \infty}(\mathbb{R}^{N-1})$ and $\frac{(N-1)(q_1+q_2-1)}{2-q_2} > 1$ then (1.15) holds for some $C > 0$ and problem (1.16) has a solution for $\varepsilon > 0$ small enough.

In a bounded domain Ω we obtain existence results analogous to Theorem (1.2) and 1.3 provided the specific capacities on $\partial\Omega$ are used instead of the Riesz capacities.

Theorem 1.5 *Let $q > 1$, $\Omega \subset \mathbb{R}^N$ be a bounded domain with a C^2 boundary and $\sigma \in \mathfrak{M}^+(\partial\Omega)$. Then, the following statements are equivalent:*

1. *The inequality*

$$\sigma(K) \leq C \text{Cap}_{\frac{2}{q}, q'}^{\partial\Omega}(K) \quad (1.19)$$

for some $C > 0$ holds for any Borel set $K \subset \partial\Omega$.

2. *The inequalities*

$$\mathbf{G}[(\mathbf{P}[\sigma])^q] \leq C\mathbf{P}[\sigma] < \infty \quad \text{a.e in } \Omega. \quad (1.20)$$

holds.

3. *The problem*

$$\begin{aligned} -\Delta u &= u^q && \text{in } \Omega, \\ u &= \varepsilon\sigma && \text{on } \partial\Omega, \end{aligned} \quad (1.21)$$

admits a positive solution for $\varepsilon > 0$ small enough.

Moreover, there is a constant $C_0 > 0$ such that if any one of the two statement 1. and 2. holds with $C \leq C_0$, then equation 1.21 has a solution u with $\varepsilon = 1$ which satisfies

$$u \asymp \mathbf{P}[\sigma]. \quad (1.22)$$

Conversely, if (1.21) has a solution u with $\varepsilon = 1$, then the two statements 1. and 2. hold for some $C > 0$.

From (1.8), we see that if $\sigma \in \mathfrak{M}^+(\partial\Omega)$ and $1 < q < \frac{N+1}{N-1}$, then (1.19) holds for some constant $C > 0$. Hence, in this case, problem (1.21) has a positive solution for $\varepsilon > 0$ small enough.

Theorem 1.6 *Let $q_1, q_2 \geq 0, q_1 + q_2 > 1, q_2 < 2, \Omega \subset \mathbb{R}^N$ be a bounded domain with a C^2 boundary and $\sigma \in \mathfrak{M}(\partial\Omega)$. Assume that*

$$|\sigma|(K) \leq C \text{Cap}_{\frac{2-q_2}{q_1+q_2}, (q_1+q_2)'}^{\partial\Omega}(K) \quad (1.23)$$

for some $C > 0$ holds for any Borel set $K \subset \partial\Omega$, then problem

$$\begin{aligned} -\Delta u &= |u|^{q_1-1}u|\nabla u|^{q_2} && \text{in } \Omega, \\ u &= \varepsilon\sigma && \text{on } \partial\Omega, \end{aligned} \quad (1.24)$$

has a solution for $\varepsilon > 0$ small enough which satisfies (1.17).

Remark 1.7 *As above, if (1.18) holds, then problem (1.24) has a solution for any $\sigma \in \mathfrak{M}(\partial\Omega)$ and $\varepsilon > 0$ small enough.*

2 Integral equations

Let Ω be either $\mathbb{R}^{N-1} \times (0, \infty)$ or Ω a bounded domain in \mathbb{R}^N with a C^2 boundary $\partial\Omega$. For $0 \leq \alpha \leq \beta < N$, we denote

$$\mathbf{N}_{\alpha, \beta}(x, y) = \frac{1}{|x-y|^{N-\beta} \max\{|x-y|, \rho(x), \rho(y)\}^\alpha} \quad \forall (x, y) \in \bar{\Omega} \times \bar{\Omega}. \quad (2.1)$$

We set

$$\mathbf{N}_{\alpha, \beta}[\nu](x) = \int_{\bar{\Omega}} \mathbf{N}_{\alpha, \beta}(x, y) d\nu(y) \quad \forall \nu \in \mathfrak{M}^+(\bar{\Omega})$$

and $\mathbf{N}_{\alpha, \beta}[f] := \mathbf{N}_{\alpha, \beta}[f dx]$ if $f \in L^1_{loc}(\Omega)$, $f \geq 0$.

In this section, we are interested in the solvability of the following integral equations

$$U = \mathbf{N}_{\alpha,\beta} [U^q(\rho(\cdot))^{\alpha_0}] + \mathbf{N}_{\alpha,\beta}[\omega] \quad (2.2)$$

where $\alpha_0 \geq 0$ and $\omega \in \mathfrak{M}^+(\bar{\Omega})$.

We follow the ideas developed by Kalton and Verbitsky in [9] who expressed a PDE problem under the form of an integral equation. They proved a certain number of properties of this integral equation which are essential for our study and we recall them here. Let X be a metric space and $\nu \in \mathfrak{M}^+(X)$. Let \mathbf{K} be a Borel positive kernel function $\mathbf{K} : X \times X \mapsto (0, \infty]$ such that \mathbf{K} is symmetric and satisfies a quasi-metric inequality, i.e there is a constant $C \geq 1$ such that for all $x, y, z \in X$ we have

$$\frac{1}{\mathbf{K}(x, y)} \leq C \left(\frac{1}{\mathbf{K}(x, z)} + \frac{1}{\mathbf{K}(z, y)} \right).$$

Under these conditions, we can define the quasi-metric d by

$$d(x, y) = \frac{1}{\mathbf{K}(x, y)},$$

and by $\mathbb{B}_r(x) = \{y \in X : d(x, y) < r\}$ the open d -ball of radius $r > 0$ and center x . Note that this set can be empty.

For $\omega \in \mathfrak{M}^+(X)$, we define the potentials $\mathbf{K}\omega$ and $\mathbf{K}^\nu f$ by

$$\mathbf{K}\omega(x) = \int_X \mathbf{K}(x, y) d\omega(y), \quad \mathbf{K}^\nu f(x) = \int_X \mathbf{K}(x, y) f(y) d\nu(y),$$

and for $q > 1$, the capacity $\text{Cap}_{\mathbf{K}, q}^\nu$ in X by

$$\text{Cap}_{\mathbf{K}, q}^\nu(E) = \inf \left\{ \int_X g^{q'} d\nu : g \geq 0, \mathbf{K}^\nu g \geq \chi_E \right\}$$

for any Borel set $E \subset X$.

Theorem 2.1 ([9]) *Let $q > 1$ and $\nu, \omega \in \mathfrak{M}^+(X)$ such that*

$$\int_0^{2r} \frac{\nu(\mathbb{B}_s(x))}{s} \frac{ds}{s} \leq C \int_0^r \frac{\nu(\mathbb{B}_s(x))}{s} \frac{ds}{s}, \quad (2.3)$$

$$\sup_{y \in \mathbb{B}_r(x)} \int_0^r \frac{\nu(\mathbb{B}_s(y))}{s} \frac{ds}{s} \leq C \int_0^r \frac{\nu(\mathbb{B}_s(x))}{s} \frac{ds}{s}, \quad (2.4)$$

for any $r > 0, x \in X$, where $C > 0$ is a constant. Then the following statements are equivalent:

1. The equation $u = \mathbf{K}^\nu u^q + \varepsilon \mathbf{K}\omega$ has a solution for some $\varepsilon > 0$.
2. The inequality

$$\int_E (\mathbf{K}\omega_E)^q d\sigma \leq C\omega(E) \quad (2.5)$$

holds for any Borel set $E \subset X$, $\omega_E = \chi_E \omega$.

3. For any Borel set $E \subset X$, there holds

$$\omega(E) \leq C \text{Cap}_{\mathbf{K}, q}^\nu(E). \quad (2.6)$$

4. The inequality

$$\mathbf{K}^\nu(\mathbf{K}\omega)^q \leq C\mathbf{K}\omega < \infty \quad \nu - a.e. \quad (2.7)$$

holds.

We check below that $N_{\alpha,\beta}$ satisfies all assumptions of \mathbf{K} in Theorem 2.1.

Lemma 2.2 $N_{\alpha,\beta}$ is symmetric and satisfies the quasi-metric inequality.

Proof. Clearly, $N_{\alpha,\beta}$ is symmetric. Now we check the quasi-metric inequality associated to $N_{\alpha,\beta}$ and $X = \bar{\Omega}$. For any $x, z, y \in \bar{\Omega}$ such that $x \neq y \neq z$, we have

$$\begin{aligned} |x - y|^{N-\beta+\alpha} &\lesssim |x - z|^{N-\beta+\alpha} + |z - y|^{N-\beta+\alpha} \\ &\lesssim \frac{1}{N_{\alpha,\beta}(x, z)} + \frac{1}{N_{\alpha,\beta}(z, y)}. \end{aligned}$$

Since $|\rho(x) - \rho(y)| \leq |x - y|$, so

$$\begin{aligned} |x - y|^{N-\beta}(\rho(x))^\alpha + |x - y|^{N-\beta}(\rho(y))^\alpha &\lesssim |x - y|^{N-\beta}(\min\{\rho(x), \rho(y)\})^\alpha + |x - y|^{N-\beta+\alpha} \\ &\lesssim (|x - z|^{N-\beta} + |z - y|^{N-\beta})(\min\{\rho(x), \rho(y)\})^\alpha + |x - z|^{N-\beta+\alpha} + |z - y|^{N-\beta+\alpha} \\ &= ((\rho(x))^\alpha |x - z|^{N-\beta} + |x - z|^{N-\beta+\alpha}) + ((\rho(y))^\alpha |z - y|^{N-\beta} + |z - y|^{N-\beta+\alpha}) \\ &\lesssim \frac{1}{N_{\alpha,\beta}(x, z)} + \frac{1}{N_{\alpha,\beta}(z, y)}, \end{aligned}$$

Thus,

$$\frac{1}{N_{\alpha,\beta}(x, y)} \lesssim \frac{1}{N_{\alpha,\beta}(x, z)} + \frac{1}{N_{\alpha,\beta}(z, y)}.$$

■

Next we give sufficient conditions for (2.3), (2.3) to hold, in view of the applications that we develop in Sections 3 and 4.

Lemma 2.3 If $d\nu(x) = \chi_\Omega(\rho(x))^{\alpha_0} dx$ with $\alpha_0 \geq 0$, then (2.3) and (2.4) hold.

Proof. It is easy to see that for any $x \in \bar{\Omega}$, $s > 0$

$$B_{2^{-\frac{\alpha_0+1}{N-\beta}}s}(x) \cap \bar{\Omega} \subset \mathbb{B}_s(x) \subset B_S(x) \cap \bar{\Omega}, \quad (2.8)$$

with $S = \min\{s^{\frac{1}{N-\beta+\alpha}}, s^{\frac{1}{N-\beta}}(\rho(x))^{-\frac{\alpha_0}{N-\beta}}\}$ and $\mathbb{B}_s(x) = \bar{\Omega}$ when $s > 2^{\frac{\alpha_0 N}{N-\alpha}}(\text{diam}(\Omega))^N$. We show that for any $0 \leq s < 8\text{diam}(\Omega)$, $x \in \bar{\Omega}$

$$\nu(B_s(x)) \asymp (\max\{\rho(x), s\})^{\alpha_0} s^N. \quad (2.9)$$

Indeed, take $0 \leq s < 8\text{diam}(\Omega)$, $x \in \bar{\Omega}$. There exists $\varepsilon = \varepsilon(\Omega) \in (0, 1)$ and $x_s \in \Omega$ such that $B_{\varepsilon s}(x_s) \subset B_s(x) \cap \Omega$ and $d(x_s, \partial\Omega) > \varepsilon s$.

(a) If $0 \leq s \leq \frac{\rho(x)}{4}$, so for any $y \in B_s(x)$, $\rho(y) \asymp \rho(x)$. Thus, $\nu(B_s(x)) \asymp (\rho(x))^{\alpha_0} |B_s(x) \cap \Omega| \asymp (d(x, \partial\Omega))^{\alpha_0} s^N$.

(b) If $s > \frac{\rho(x)}{4}$. Since $\rho(y) \leq \rho(x) + |x - y| < 5s$ for any $y \in B_s(x)$, $\nu(B_s(x)) \lesssim s^{N+\alpha_0}$

(b.1) If $s \leq 4\rho(x)$, we have

$$\nu(B_s(x)) \gtrsim \nu(B_{\frac{\rho(x)}{4}}(x)) \asymp (\rho(x))^{\alpha_0+N} \gtrsim s^{N+\alpha_0}.$$

(b.2) If $s \geq 4\rho(x)$. We have for any $y \in B_{\varepsilon s/2}(x_s)$, $\rho(y) \geq -|y - x_s| + \rho(x_s) > \varepsilon s/2$. It follows

$$\nu(B_s(x)) \gtrsim \nu(B_{\varepsilon s/2}(x_s)) \gtrsim s^{N+\alpha_0}.$$

Thus, for any $0 \leq s < 2^{\frac{(\alpha+1)(N-\beta+\alpha)}{N-\beta}} (\text{diam}(\Omega))^{N-\beta+\alpha}$, $x \in \bar{\Omega}$ we have

$$\begin{aligned} \nu(\mathbb{B}_s(x)) &\asymp (\max\{\rho(x), \min\{s^{\frac{1}{N-\beta+\alpha}}, s^{\frac{1}{N-\beta}} (\rho(x))^{-\frac{\alpha}{N-\beta}}\}\})^{\alpha_0} \\ &\quad \times \left(\min\{s^{\frac{1}{N-\beta+\alpha}}, s^{\frac{1}{N-\beta}} (\rho(x))^{-\frac{\alpha}{N-\beta}}\} \right)^N \\ &\asymp \begin{cases} s^{\frac{\alpha_0+N}{N-\beta+\alpha}} & \text{if } \rho(x) \leq s^{\frac{1}{N-\beta+\alpha}}, \\ (\rho(x))^{\alpha_0 - \frac{\alpha N}{N-\beta}} s^{\frac{N}{N-\beta}} & \text{if } \rho(x) \geq s^{\frac{1}{N-\beta+\alpha}}, \end{cases} \end{aligned}$$

and $\nu(\mathbb{B}_s(x)) = \nu(\bar{\Omega}) \asymp (\text{diam}(\Omega))^{\alpha_0+N}$ if $s > 2^{\frac{(\alpha+1)(N-\beta+\alpha)}{N-\beta}} (\text{diam}(\Omega))^{N-\beta+\alpha}$. We get,

$$\int_0^r \frac{\nu(\mathbb{B}_s(x))}{s} \frac{ds}{s} \asymp \begin{cases} (\text{diam}(\Omega))^{\alpha_0+\beta-\alpha} & \text{if } r > (\text{diam}(\Omega))^{N-\beta+\alpha}, \\ r^{\frac{\alpha_0+\beta-\alpha}{N-\beta+\alpha}} & \text{if } r \in ((\rho(x))^{N-\beta+\alpha}, (\text{diam}(\Omega))^{N-\beta+\alpha}], \\ (\rho(x))^{\alpha_0 - \frac{\alpha N}{N-\beta}} r^{\frac{\beta}{N-\beta}} & \text{if } r \in (0, (\rho(x))^{N-\beta+\alpha}]. \end{cases}$$

So, (2.3) holds. It remains to check (2.4). For any $x \in \bar{\Omega}$ and $r > 0$, clearly, if $r > \frac{1}{2}(\rho(x))^{N-\beta+\alpha}$ we have

$$\sup_{y \in \mathbb{B}_r(x)} \int_0^r \frac{\nu(\mathbb{B}_s(y))}{s} \frac{ds}{s} \lesssim \min\{r^{\frac{\alpha_0+\beta-\alpha}{N-\beta+\alpha}}, (\text{diam}(\Omega))^{\alpha_0+\beta-\alpha}\},$$

we obtain

$$\sup_{y \in \mathbb{B}_r(x)} \int_0^r \frac{\nu(\mathbb{B}_s(y))}{s} \frac{ds}{s} \lesssim \int_0^r \frac{\nu(\mathbb{B}_s(x))}{s} \frac{ds}{s}.$$

If $0 < r \leq \frac{1}{2}(\rho(x))^{N-\beta+\alpha}$, we have $\mathbb{B}_r(x) \subset B_{r^{\frac{1}{N-\beta}} (\rho(x))^{-\frac{\alpha}{N-\beta}}}(x)$ and $\rho(x) \asymp \rho(y)$ for all $y \in B_{r^{\frac{1}{N-\beta}} (\rho(x))^{-\frac{\alpha}{N-\beta}}}(x)$, thus

$$\begin{aligned} \sup_{y \in \mathbb{B}_r(x)} \int_0^r \frac{\nu(\mathbb{B}_s(y))}{s} \frac{ds}{s} &\leq \sup_{|y-x| < r^{\frac{1}{N-\beta}} (\rho(x))^{-\frac{\alpha}{N-\beta}}} \int_0^r \frac{\nu(\mathbb{B}_s(y))}{s} \frac{ds}{s} \\ &\asymp \sup_{|y-x| < r^{\frac{1}{N-\beta}} (\rho(x))^{-\frac{\alpha}{N-\beta}}} (\rho(y))^{\alpha_0 - \frac{\alpha N}{N-\beta}} r^{\frac{\beta}{N-\beta}} \\ &\asymp (\rho(x))^{\alpha_0 - \frac{\alpha N}{N-\beta}} r^{\frac{\beta}{N-\beta}} \\ &\asymp \int_0^r \frac{\nu(\mathbb{B}_s(x))}{s} \frac{ds}{s}. \end{aligned}$$

Therefore, (2.4) holds. ■

Definition 2.4 For $\alpha_0 \geq 0, 0 \leq \alpha \leq \beta < N$ and $s > 1$, we define $\text{Cap}_{\mathbf{N}_{\alpha,\beta,s}}^{\alpha_0}$ by

$$\text{Cap}_{\mathbf{N}_{\alpha,\beta,s}}^{\alpha_0}(E) = \inf \left\{ \int_{\bar{\Omega}} g^s(\rho(x))^{\alpha_0} dx : g \geq 0, \mathbf{N}_{\alpha,\beta}[g(\rho(\cdot))^{\alpha_0}] \geq \chi_E \right\}$$

for any Borel set $E \subset \bar{\Omega}$.

Clearly, we have

$$\text{Cap}_{\mathbf{N}_{\alpha,\beta,s}}^{\alpha_0}(E) = \inf \left\{ \int_{\bar{\Omega}} g^s(\rho(x))^{-\alpha_0(s-1)} dx : g \geq 0, \mathbf{N}_{\alpha,\beta}[g] \geq \chi_E \right\}$$

for any Borel set $E \subset \bar{\Omega}$. Furthermore we have by [1, Theorem 2.5.1],

$$\left(\text{Cap}_{\mathbf{N}_{\alpha,\beta,s}}^{\alpha_0}(E) \right)^{1/s} = \sup \left\{ \omega(E) : \omega \in \mathfrak{M}_b^+(E), \|\mathbf{N}_{\alpha,\beta}[\omega]\|_{L^{s'}(\Omega, (\rho(\cdot))^{\alpha_0} dx)} \leq 1 \right\} \quad (2.10)$$

for any compact set $E \subset \bar{\Omega}$, where s' is the conjugate exponent of s .

Thanks to Lemma 2.2 and 2.3, we can apply Theorem 2.1 to obtain.

Theorem 2.5 Let $\omega \in \mathfrak{M}^+(\overline{\Omega})$, $\alpha_0 \geq 0$, $0 \leq \alpha \leq \beta < N$ and $q > 1$. Then the following statements are equivalent:

1. The equation $u = \mathbf{N}_{\alpha,\beta}[u^q(\rho(\cdot))^{\alpha_0}] + \varepsilon \mathbf{N}_{\alpha,\beta}[\omega]$ has a solution for $\varepsilon > 0$ small enough.
2. The inequality

$$\int_{E \cap \Omega} (\mathbf{N}_{\alpha,\beta}[\omega_E])^q (\rho(x))^{\alpha_0} dx \leq C\omega(E) \quad (2.11)$$

holds for some $C > 0$ and any Borel set $E \subset \overline{\Omega}$, $\omega_E = \omega \chi_E$.

3. The inequality

$$\omega(K) \leq C \text{Cap}_{\mathbf{N}_{\alpha,\beta,q}^{\alpha_0}}(K) \quad (2.12)$$

holds for some $C > 0$ and any compact set $K \subset \overline{\Omega}$.

4. The inequality

$$\mathbf{N}_{\alpha,\beta}[(\mathbf{N}_{\alpha,\beta}[\omega])^q (\rho(\cdot))^{\alpha_0}] \leq C \mathbf{N}_{\alpha,\beta}[\omega] < \infty \quad \text{a.e in } \Omega \quad (2.13)$$

holds for some $C > 0$.

To apply the previous theorem we need the following result.

Proposition 2.6 Let $q > 1$, $\nu, \omega \in \mathfrak{M}^+(X)$. Suppose that $A_1, A_2, B_1, B_2 : X \times X \mapsto [0, +\infty)$ are Borel positive Kernel functions with $A_1 \asymp A_2, B_1 \asymp B_2$. Then, the following statements are equivalent:

1. The equation $u = A_1^\nu u^q + \varepsilon B_1 \omega$ ν -a.e has a solution for $\varepsilon > 0$ small enough.
2. The equation $u = A_2^\nu u^q + \varepsilon B_2 \omega$ ν -a.e has a solution for $\varepsilon > 0$ small enough.
3. The problem $u \asymp A_1^\nu u^q + \varepsilon B_1 \omega$ ν -a.e has a solution for $\varepsilon > 0$ small enough.
4. The equation $u \gtrsim A_1^\nu u^q + \varepsilon B_1 \omega$ ν -a.e has a solution for $\varepsilon > 0$ small enough.

Proof. We only prove that 4 implies 2. Suppose that there exist $c_1 > 0, \varepsilon_0 > 0$ and a position Borel function u such that

$$A_1^\nu u^q + \varepsilon_0 B_1 \omega \leq c_1 u.$$

Taken $c_2 > 0$ with $A_2 \leq c_2 A_1, B_2 \leq c_2 B_1$. We consider $u_{n+1} = A_2^\nu u_n^q + \varepsilon_0 (c_1 c_2)^{-\frac{q}{q-1}} B_2 \omega$ and $u_0 = 0$ for any $n \geq 0$. Clearly, $u_n \leq (c_1 c_2)^{-\frac{1}{q-1}} u$ for any n and $\{u_n\}$ is nondecreasing. Thus, $U = \lim_{n \rightarrow \infty} u_n$ is a solution of $U = A_2^\nu U^q + \varepsilon_0 (c_1 c_2)^{-\frac{q}{q-1}} B_2 \omega$. ■

The following results provide some relations between the capacities $\text{Cap}_{\mathbf{N}_{\alpha,\beta,s}^{\alpha_0}}$ and the Riesz capacities on \mathbb{R}^{N-1} which allow to define the capacities on $\partial\Omega$.

Proposition 2.7 Assume that $\Omega = \mathbb{R}^{N-1} \times (0, \infty)$ and let $\alpha_0 \geq 0$ such that $-1 + s'(1 + \alpha - \beta) < \alpha_0 < -1 + s'(N - \beta + \alpha)$. There holds

$$\text{Cap}_{\mathbf{N}_{\alpha,\beta,s}^{\alpha_0}}(K \times \{0\}) \asymp \text{Cap}_{I_{\beta-\alpha+\frac{\alpha_0+1}{s}-1}, s'}(K) \quad (2.14)$$

for any compact set $K \subset \mathbb{R}^{N-1}$,

Proof. The proof relies on an idea of [16, Corollary 4.20]. Thanks to [1, Theorem 2.5.1] and (2.10), we get (2.14) from the following estimate: for any $\mu \in \mathfrak{M}_b^+(\mathbb{R}^{N-1})$

$$\|\mathbf{N}_{\alpha,\beta}[\mu \otimes \delta_{\{x_N=0\}}]\|_{L^{s'}(\Omega,(\rho(\cdot))^{\alpha_0} dx)} \asymp \|I_{\beta-\alpha+\frac{\alpha_0+1}{s'}-1}[\mu]\|_{L^{s'}(\mathbb{R}^{N-1})}, \quad (2.15)$$

where $I_\gamma[\mu]$ is the Riesz potential of μ in \mathbb{R}^{N-1} , i.e

$$I_\gamma[\mu](y) = \int_0^\infty \frac{\mu(B'_r(y))}{r^{N-1-\gamma}} \frac{dr}{r} \quad \forall y \in \mathbb{R}^{N-1},$$

with $B'_r(y)$ is a ball in \mathbb{R}^{N-1} . We have

$$\begin{aligned} \|\mathbf{N}_{\alpha,\beta}[\mu \otimes \delta_{\{x_N=0\}}]\|_{L^{s'}(\Omega,(\rho(\cdot))^{\alpha_0} dx)}^{s'} &= \int_{\mathbb{R}^{N-1}} \int_0^\infty \left(\int_{\mathbb{R}^{N-1}} \frac{d\mu(z)}{(|x'-z|^2 + x_N^2)^{\frac{N-\beta+\alpha}{2}}} \right)^{s'} x_N^{\alpha_0} dx_N dx' \\ &\asymp \int_{\mathbb{R}^{N-1}} \int_0^\infty \left(\int_{x_N}^\infty \frac{\mu(B'_r(x'))}{r^{N-\beta+\alpha}} \frac{dr}{r} \right)^{s'} x_N^{\alpha_0} dx_N dx'. \end{aligned}$$

Notice that

$$\begin{aligned} \int_0^\infty \left(\int_{x_N}^\infty \frac{\mu(B'_r(x'))}{r^{N-\beta+\alpha}} \frac{dr}{r} \right)^{s'} x_N^{\alpha_0} dx_N &\geq \int_0^\infty \left(\int_{x_N}^{2x_N} \frac{\mu(B'_r(x'))}{r^{N-\beta+\alpha}} \frac{dr}{r} \right)^{s'} x_N^{\alpha_0} dx_N \\ &\gtrsim \int_0^\infty \left(\frac{\mu(B'_{x_N}(x'))}{x_N^{N-\beta+\alpha-\frac{\alpha_0+1}{s'}}} \right)^{s'} \frac{dx_N}{x_N}. \end{aligned}$$

Thus, using Hölder's inequality and Fubini's Theorem, we obtain

$$\begin{aligned} \int_0^\infty \left(\int_{x_N}^\infty \frac{\mu(B'_r(x'))}{r^{N-\beta+\alpha}} \frac{dr}{r} \right)^{s'} x_N^{\alpha_0} dx_N &\leq \int_0^\infty \left(\int_{x_N}^\infty r^{-\frac{s'}{2s'}} \frac{dr}{r} \right)^{\frac{s'}{s}} \int_{x_N}^\infty \left(\frac{\mu(B'_r(x'))}{r^{N-\beta+\alpha-\frac{1}{2s'}}} \right)^{s'} \frac{dr}{r} x_N^{\alpha_0} dx_N \\ &= C \int_0^\infty \int_{x_N}^\infty \left(\frac{\mu(B'_r(x'))}{r^{N-\beta+\alpha-\frac{1}{2s'}}} \right)^{s'} \frac{dr}{r} x_N^{\alpha_0-\frac{1}{2}} dx_N \\ &= C \int_0^\infty \int_0^r x_N^{\alpha_0-\frac{1}{2}} dx_N \left(\frac{\mu(B'_r(x'))}{r^{N-\beta+\alpha-\frac{1}{2s'}}} \right)^{s'} \frac{dr}{r} \\ &= C \int_0^\infty \left(\frac{\mu(B'_r(x'))}{r^{N-\beta+\alpha-\frac{\alpha_0+1}{s'}}} \right)^{s'} \frac{dr}{r}. \end{aligned}$$

Thus,

$$\|\mathbf{N}_{\alpha,\beta}[\mu \otimes \delta_{\{x_N=0\}}]\|_{L^{s'}(\Omega,(\rho(\cdot))^{\alpha_0} dx)} \asymp \left(\int_{\mathbb{R}^{N-1}} \int_0^\infty \left(\frac{\mu(B'_r(y))}{r^{N-\beta+\alpha-\frac{\alpha_0+1}{s'}}} \right)^{s'} \frac{dr}{r} dy \right)^{1/s'}. \quad (2.16)$$

It implies (2.15) from [4, Theorem 2.3]. \blacksquare

Proposition 2.8 *Let $\Omega \subset \mathbb{R}^N$ be a bounded domain a C^2 boundary. Assume $\alpha_0 \geq 0$ and $-1 + s'(1 + \alpha - \beta) < \alpha_0 < -1 + s'(N - \beta + \alpha)$. Then there holds*

$$\text{Cap}_{\mathbf{N}_{\alpha,\beta,s}}^{\alpha_0}(E) \asymp \text{Cap}_{\beta-\alpha+\frac{\alpha_0+1}{s'}-1,s}^{\partial\Omega}(E) \quad (2.17)$$

for any compact set $E \subset \partial\Omega \subset \mathbb{R}^N$.

Proof. Let K_1, \dots, K_m be as in definition 1.1. We have

$$\text{Cap}_{\mathbf{N}_{\alpha, \beta, s}}^{\alpha_0}(E) \asymp \sum_{i=1}^m \text{Cap}_{\mathbf{N}_{\alpha, \beta, s}}^{\alpha_0}(E \cap K_i),$$

for any compact set $E \subset \partial\Omega$. By definition 1.1, we need to prove that

$$\text{Cap}_{\mathbf{N}_{\alpha, \beta, s}}^{\alpha_0}(E \cap K_i) \asymp \text{Cap}_{G_{\beta-\alpha+\frac{\alpha_0+1}{s'}-1}, s}(\tilde{T}_i(E \cap K_i)) \quad \forall i = 1, 2, \dots, m. \quad (2.18)$$

We can show that for any $\omega \in \mathfrak{M}_b^+(\partial\Omega)$ and $i = 1, \dots, m$, there exists $\omega_i \in \mathfrak{M}_b^+(\tilde{T}_i(K_i))$ with $T_i(K_i) = \tilde{T}_i(K_i) \times \{x_N = 0\}$ such that

$$\omega_i(O) = \omega(T_i^{-1}(O \times \{0\}))$$

for all Borel set $O \subset \tilde{T}_i(K_i)$, its proof can be found in [1, Proof of Lemma 5.2.2]. Thanks to [1, Theorem 2.5.1], it is enough to show that for any $i \in \{1, 2, \dots, m\}$ there holds

$$\|\mathbf{N}_{\alpha, \beta}[\chi_{K_i}\omega]\|_{L^{s'}(\Omega, (\rho(\cdot))^{\alpha_0} dx)} \asymp \|G_{\beta-\alpha+\frac{\alpha_0+1}{s'}-1}[\omega_i]\|_{L^{s'}(\mathbb{R}^{N-1})}, \quad (2.19)$$

where $G_\gamma[\omega_i]$ ($0 < \gamma < N-1$) is the Bessel potential of ω_i in \mathbb{R}^{N-1} , i.e

$$G_\gamma[\omega_i](x) = \int_{\mathbb{R}^{N-1}} G_\gamma(x-y) d\omega_i(y).$$

Indeed, we have

$$\begin{aligned} \|\mathbf{N}_{\alpha, \beta}[\omega\chi_{K_i}]\|_{L^{s'}(\Omega, (\rho(\cdot))^{\alpha_0} dx)} &= \int_{\Omega} \left(\int_{K_i} \frac{d\omega(z)}{|x-z|^{N-\beta+\alpha}} \right)^{s'} (\rho(x))^{\alpha_0} dx \\ &= \int_{O_i \cap \Omega} \left(\int_{K_i} \frac{d\omega(z)}{|x-z|^{N-\beta+\alpha}} \right)^{s'} (\rho(x))^{\alpha_0} dx + \int_{\Omega \setminus O_i} \left(\int_{K_i} \frac{d\omega(z)}{|x-z|^{N-\beta+\alpha}} \right)^{s'} (\rho(x))^{\alpha_0} dx \\ &\asymp \int_{O_i \cap \Omega} \left(\int_{K_i} \frac{d\omega(z)}{|x-z|^{N-\beta+\alpha}} \right)^{s'} (\rho(x))^{\alpha_0} dx + (\omega(K_i))^{s'}. \end{aligned}$$

Here we used $|x-z| \asymp 1$ for any $x \in \Omega \setminus O_i, z \in K_i$.

By a standard change of variable

$$\begin{aligned} &\int_{O_i \cap \Omega} \left(\int_{K_i} \frac{d\omega(z)}{|x-z|^{N-\beta+\alpha}} \right)^{s'} (\rho(x))^{\alpha_0} dx + (\omega(K_i))^{s'} \\ &= \int_{T_i(O_i \cap \Omega)} \left(\int_{K_i} \frac{d\omega(z)}{|T_i^{-1}(y)-z|^{N-\beta+\alpha}} \right)^{s'} (\rho(T_i^{-1}(y)))^{\alpha_0} |\mathbf{J}_{T_i}(T_i^{-1}(y))|^{-1} dy + (\omega(K_i))^{s'} \\ &\asymp \int_{B_1(0) \cap \{x_N > 0\}} \left(\int_{K_i} \frac{d\omega(z)}{|y-T_i(z)|^{N-\beta+\alpha}} \right)^{s'} y_N^{\alpha_0} dy + (\omega(K_i))^{s'} \quad \text{with } y = (y', y_N), \end{aligned}$$

since $|T_i^{-1}(y) - z| \asymp |y - T_i(z)|$, $|\mathbf{J}_{T_i}(T_i^{-1}(y))| \asymp 1$ and $\rho(T_i^{-1}(y)) \asymp y_N$ for all $(y, z) \in T_i(O_i \cap \Omega) \times K_i$. From the definition of ω_i , we have

$$\begin{aligned} &\int_{B_1(0) \cap \{x_N > 0\}} \left(\int_{K_i} \frac{1}{|y-T_i(z)|^{N-\beta+\alpha}} d\omega(z) \right)^{s'} y_N^{\alpha_0} dy + (\omega(K_i))^{s'} \\ &= \int_{B_1(0) \cap \{x_N > 0\}} \left(\int_{\tilde{T}_i(K_i)} \frac{1}{(|y'-\xi|^2 + y_N^2)^{\frac{N-\beta+\alpha}{2}}} d\omega_i(\xi) \right)^{s'} y_N^{\alpha_0} dy_N dy' + (\omega(K_i))^{s'} \\ &\asymp \int_{\mathbb{R}^{N-1}} \int_0^\infty \left(\int_{\min\{y_N, R\}}^{2R} \frac{\omega_i(B'_r(y'))}{r^{N-\beta+\alpha}} \frac{dr}{r} \right)^{s'} y_N^{\alpha_0} dy_N dy' \quad \text{with } R = \text{diam}(\Omega). \end{aligned}$$

As in the proof of Proposition 2.7, we also obtain

$$\begin{aligned} & \int_{\mathbb{R}^{N-1}} \int_0^\infty \left(\int_{\min\{y_N, R\}}^{2R} \frac{\omega_i(B'_r(y'))}{r^{N-\beta+\alpha}} \frac{dr}{r} \right)^{s'} y_N^{\alpha_0} dy_N dy' \\ & \asymp \int_{\mathbb{R}^{N-1}} \int_0^{2R} \left(\frac{\omega_i(B'_r(y'))}{r^{N-\beta+\alpha-\frac{\alpha_0+1}{s'}}} \right)^{s'} \frac{dr}{r} dy'. \end{aligned}$$

Therefore, we get (2.19) from [4, Theorem 2.3]. ■

3 Proof of the main results

We denote

$$\mathbf{P}[\sigma](x) = \int_{\partial\Omega} \mathbf{P}(x, z) d\sigma(z), \quad \mathbf{G}[f](x) = \int_{\Omega} \mathbf{G}(x, y) f(y) dy$$

for any $\sigma \in \mathfrak{M}(\partial\Omega)$, $f \in L^1_\rho(\Omega)$, $f \geq 0$. Then the unique weak solution of

$$\begin{aligned} -\Delta u &= f && \text{in } \Omega, \\ u &= \sigma && \text{on } \partial\Omega, \end{aligned}$$

can be represented by

$$u(x) = \mathbf{G}[f](x) + \mathbf{P}[\sigma](x) \quad \forall x \in \Omega.$$

We recall below some classical estimates for the Green and the Poisson kernels.

$$\begin{aligned} \mathbf{G}(x, y) &\asymp \min \left\{ \frac{1}{|x-y|^{N-2}}, \frac{\rho(x)\rho(y)}{|x-y|^N} \right\}, \\ \mathbf{P}(x, z) &\asymp \frac{\rho(x)}{|x-z|^N}, \end{aligned}$$

and

$$|\nabla_x \mathbf{G}(x, y)| \lesssim \frac{\rho(y)}{|x-y|^N} \min \left\{ 1, \frac{|x-y|}{\sqrt{\rho(x)\rho(y)}} \right\}, \quad |\nabla_x \mathbf{P}(x, z)| \lesssim \frac{1}{|x-z|^N},$$

for any $(x, y, z) \in \Omega \times \Omega \times \partial\Omega$, see [2]. Since $|\rho(x) - \rho(y)| \leq |x - y|$ we have

$$\max \{ \rho(x)\rho(y), |x-y|^2 \} \asymp \max \{ |x-y|, \rho(x), \rho(y) \}^2.$$

Thus,

$$\min \left\{ 1, \left(\frac{|x-y|}{\sqrt{\rho(x)\rho(y)}} \right)^\gamma \right\} \asymp \frac{|x-y|^\gamma}{(\max \{ |x-y|, \rho(x), \rho(y) \})^\gamma} \quad \text{for } \gamma > 0. \quad (3.1)$$

Therefore,

$$\mathbf{G}(x, y) \asymp \rho(x)\rho(y)\mathbf{N}_{2,2}(x, y), \quad \mathbf{P}(x, z) \asymp \rho(x)\mathbf{N}_{\alpha,\alpha}(x, z) \quad (3.2)$$

and

$$|\nabla_x \mathbf{G}(x, y)| \lesssim \rho(y)\mathbf{N}_{1,1}(x, y), \quad |\nabla_x \mathbf{P}(x, z)| \lesssim \mathbf{N}_{\alpha,\alpha}(x, z) \quad (3.3)$$

for all $(x, y, z) \in \bar{\Omega} \times \bar{\Omega} \times \partial\Omega$, $\alpha \geq 0$.

Proof of Theorem 1.2 and Theorem 1.5. By (3.2), the following equivalence holds

$$\mathbf{G}[(\mathbf{P}[\sigma])^q] \lesssim \mathbf{P}[\sigma] < \infty \text{ a.e in } \Omega. \iff \mathbf{N}_{2,2}[(\mathbf{N}_{2,2}[\sigma])^q \rho^{q+1}] \lesssim \mathbf{N}_{2,2}[\sigma] < \infty \text{ a.e in } \Omega.$$

Furthermore

$$U \asymp \mathbf{G}[U^q] + \mathbf{P}[\sigma] \iff U \asymp \rho \mathbf{N}_{2,2}[\rho U^q] + \rho \mathbf{N}_{2,2}[\sigma],$$

which in turn is equivalent to

$$V \asymp \mathbf{N}_{2,2}[\rho^{q+1} V^q] + \mathbf{N}_{2,2}[\sigma] \text{ with } V = U \rho^{-1}.$$

By Proposition 2.7 and 2.8 we have:

$$\text{Cap}_{I_{\frac{2}{q}, q'}}(K) \asymp \text{Cap}_{\mathbf{N}_{2,2}, q'}^{q+1}(K \times \{0\}) \quad \forall K \subset \mathbb{R}^{N-1}, K \text{ compact.}$$

if $\Omega = \mathbb{R}_+^N$, and

$$\text{Cap}_{\frac{\partial\Omega}{q}, q'}^{\partial\Omega}(K) \asymp \text{Cap}_{\mathbf{N}_{2,2}, q'}^{q+1}(K) \quad \forall K \subset \partial\Omega, K \text{ compact.}$$

if Ω is a bounded domain. Thanks to Theorem (2.5) with $\omega = \sigma$, $\alpha = 2, \beta = 2, \alpha_0 = q + 1$ and proposition 2.6, we get the results. ■

Proof of Theorem 1.3 and 1.6. By (3.2) and (3.3), we have

$$\mathbf{G}(x, y) \leq C\rho(x)\rho(y)\mathbf{N}_{1,1}(x, y), \quad |\nabla_x \mathbf{G}(x, y)| \leq C\rho(y)\mathbf{N}_{1,1}(x, y), \quad (3.4)$$

$$\mathbf{P}(x, y) \leq C\rho(y)\mathbf{N}_{1,1}(x, z), \quad |\nabla_x \mathbf{P}(x, z)| \leq C\mathbf{N}_{1,1}(x, z), \quad (3.5)$$

for all $(x, y, z) \in \Omega \times \Omega \times \partial\Omega$ for some constant $C > 0$.

For any $u \in W_{loc}^{1,1}(\Omega)$, we set

$$\mathbf{F}(u)(x) = \int_{\Omega} \mathbf{G}(x, y)|u(y)|^{q_1-1}u(y)|\nabla u(y)|^{q_2} dy + \int_{\partial\Omega} \mathbf{P}(x, z)d\sigma(z).$$

Using (3.4) and (3.5), we have

$$\begin{aligned} |\mathbf{F}(u)| &\leq C\rho(\cdot)\mathbf{N}_{1,1}[|u|^{q_1}|\nabla u|^{q_2}\rho(\cdot)] + C\rho(\cdot)\mathbf{N}_{1,1}[|\sigma|], \\ |\nabla \mathbf{F}(u)| &\leq C\mathbf{N}_{1,1}[|u|^{q_1}|\nabla u|^{q_2}\rho(\cdot)] + C\mathbf{N}_{1,1}[|\sigma|]. \end{aligned}$$

Therefore, we can easily see that if

$$\mathbf{N}_{1,1}\left[\left(\mathbf{N}_{1,1}[|\sigma|]\right)^{q_1+q_2}(\rho(\cdot))^{q_1+1}\right] \leq \frac{(q_1+q_2-1)^{q_1+q_2-1}}{(C(q_1+q_2))^{q_1+q_2}}\mathbf{N}_{1,1}[|\sigma|] < \infty \text{ a.e in } \Omega \quad (3.6)$$

holds then \mathbf{F} is the map from \mathbf{E} to \mathbf{E} , where

$$\mathbf{E} = \left\{ u \in W_{loc}^{1,1}(\Omega) : |u| \leq \lambda\rho(\cdot)\mathbf{N}_{1,1}[|\sigma|], |\nabla u| \leq \lambda\mathbf{N}_{1,1}[|\sigma|] \text{ a.e in } \Omega \right\}$$

with $\lambda = \frac{C(q_1+q_2)}{q_1+q_2-1}$.

Assume that (3.6) holds. We denote \mathcal{S} by the subspace of functions $f \in W_{loc}^{1,1}(\Omega)$ with norm

$$\|f\|_{\mathcal{S}} = \|f\|_{L^{q_1+q_2}(\Omega, (\rho(\cdot))^{1-q_2} dx)} + \|\nabla f\|_{L^{q_1+q_2}(\Omega, (\rho(\cdot))^{1+q_2} dx)} < \infty.$$

Clearly, $\mathbf{E} \subset \mathcal{S}$, \mathbf{E} is closed under the strong topology of \mathcal{S} and convex.

On the other hand, it is not difficult to show that \mathbf{F} is continuous and $\mathbf{F}(\mathbf{E})$ is precompact in \mathcal{S} . Consequently, by Schauder's fixed point theorem, there exist $u \in \mathbf{E}$ such that $\mathbf{F}(u) = u$. Hence, u is a solution of (1.16)-(1.24) and it satisfies

$$|u| \leq \lambda\rho(\cdot)\mathbf{N}_{1,1}[|\sigma|], \quad |\nabla u| \leq \lambda\mathbf{N}_{1,1}[|\sigma|].$$

Thanks to Theorem 2.5 and Proposition 2.7, 2.8, we verify that assumptions (1.15) and (1.24) in Theorem 1.3 and 1.6 are equivalent to (3.6). This completes the proof of the Theorems. ■

4 Extension to Schrödinger operators with Hardy potentials

We can apply Theorem 2.5 to solve the problem

$$\begin{aligned} -\Delta u - \frac{\kappa}{\rho^2} u &= u^q & \text{in } \Omega, \\ u &= \sigma & \text{on } \partial\Omega, \end{aligned}$$

where $\kappa \in [0, \frac{1}{4}]$ and $\sigma \in \mathfrak{M}^+(\partial\Omega)$.

Let G_κ, P_κ be the Green kernel and Poisson kernel of $-\Delta - \frac{\kappa}{(\rho(\cdot))^2}$ in Ω with $\kappa \in [0, \frac{1}{4}]$. We have

$$\begin{aligned} G_\kappa(x, y) &\asymp \min \left\{ \frac{1}{|x-y|^{N-2}}, \frac{(\rho(x)\rho(y))^{\frac{1+\sqrt{1-4\kappa}}{2}}}{|x-y|^{N-1+\sqrt{1-4\kappa}}} \right\}, \\ P_\kappa(x, z) &\asymp \frac{(\rho(x))^{\frac{1+\sqrt{1-4\kappa}}{2}}}{|x-z|^{N-1+\sqrt{1-4\kappa}}}, \end{aligned}$$

for all $(x, y, z) \in \bar{\Omega} \times \bar{\Omega} \times \partial\Omega$, see [6, 11, 7]. Therefore, from (3.1) we get

$$G_\kappa(x, y) \asymp (\rho(x)\rho(y))^{\frac{1+\sqrt{1-4\kappa}}{2}} \mathbf{N}_{1+\sqrt{1-4\kappa}, 2}(x, y), \quad (4.1)$$

$$P_\kappa(x, z) \asymp (\rho(x))^{\frac{1+\sqrt{1-4\kappa}}{2}} \mathbf{N}_{\alpha, 1-\sqrt{1-4\kappa}+\alpha}(x, z), \quad (4.2)$$

for all $(x, y, z) \in \bar{\Omega} \times \bar{\Omega} \times \partial\Omega$, $\alpha \geq 0$. We denote

$$\mathbf{P}_\kappa[\sigma](x) = \int_{\partial\Omega} P_\kappa(x, z) d\sigma(z), \quad \mathbf{G}_\kappa[f](x) = \int_{\Omega} G_\kappa(x, y) f(y) dy$$

for any $\sigma \in \mathfrak{M}^+(\partial\Omega)$, $f \in L^1(\Omega, \rho^{\frac{1+\sqrt{1-4\kappa}}{2}} dx)$, $f \geq 0$. Then the unique weak solution of

$$\begin{aligned} -\Delta u - \frac{\kappa}{\rho^2} u &= f & \text{in } \Omega, \\ u &= \sigma & \text{on } \partial\Omega, \end{aligned}$$

satisfies the following integral equation [7]

$$u = \mathbf{G}_\kappa[f] + \mathbf{P}_\kappa[\sigma] \quad \text{a.e. in } \Omega.$$

As in the proofs of Theorem 1.2 and Theorem 1.5 the relation

$$\mathbf{G}_\kappa[(\mathbf{P}_\kappa[\sigma])^q] \lesssim \mathbf{P}_\kappa[\sigma] < \infty \quad \text{a.e. in } \Omega,$$

is equivalent to

$$\mathbf{N}_{1+\sqrt{1-4\kappa}, 2} \left[\left(\mathbf{N}_{1+\sqrt{1-4\kappa}, 2}[\sigma] \right)^q \rho^{\frac{(q+1)(1+\sqrt{1-4\kappa})}{2}} \right] \lesssim \mathbf{N}_{1+\sqrt{1-4\kappa}, 2}[\sigma] < \infty \quad \text{a.e. in } \Omega,$$

and the relation

$$U \asymp \mathbf{G}_\kappa[U^q] + \mathbf{P}_\kappa[\sigma],$$

is equivalent to

$$V \asymp \mathbf{N}_{1+\sqrt{1-4\kappa}, 2} \left[\rho^{\frac{(q+1)(1+\sqrt{1-4\kappa})}{2}} V^q \right] + \mathbf{N}_{1+\sqrt{1-4\kappa}, 2}[\sigma] \quad \text{with } V = U \rho^{-\frac{1+\sqrt{1-4\kappa}}{2}}.$$

Thanks to Theorem 2.5 with $\omega = \sigma$, $\alpha = 1 + \sqrt{1-4\kappa}$, $\beta = 2$, $\alpha_0 = \frac{(q+1)(1+\sqrt{1-4\kappa})}{2}$ and proposition 2.6, 2.7, 2.8, we obtain.

Theorem 4.1 Let $q > 1, 0 \leq \kappa \leq \frac{1}{4}$ and $\sigma \in \mathfrak{M}^+(\partial\Omega)$. Then, the following statements are equivalent

1. There exists $C > 0$ such that the following inequalities hold

$$\sigma(O) \leq C \text{Cap}_{I_{\frac{q+3-(q-1)\sqrt{1-4\kappa}}{2q}, q'}}(O) \quad (4.3)$$

for any Borel set $O \subset \mathbb{R}^{N-1}$ if $\Omega = \mathbb{R}_+^N$ and

$$\sigma(O) \leq C \text{Cap}_{\frac{\partial\Omega}{\frac{q+3-(q-1)\sqrt{1-4\kappa}}{2q}, q'}}(O) \quad (4.4)$$

for any Borel set $O \subset \partial\Omega$ if Ω is a bounded domain.

2. There exists $C > 0$ such that the inequality

$$\mathbf{G}_\kappa [(\mathbf{P}_\kappa[\sigma])^q] \leq C \mathbf{P}_\kappa[\sigma] < \infty \quad \text{a.e in } \Omega, \quad (4.5)$$

holds.

3. Problem

$$\begin{aligned} -\Delta u - \frac{\kappa}{\rho^2} u &= u^q & \text{in } \Omega, \\ u &= \varepsilon \sigma & \text{on } \partial\Omega, \end{aligned} \quad (4.6)$$

has a positive solution for $\varepsilon > 0$ small enough.

Moreover, there is a constant $C_0 > 0$ such that if any one of the two statements 1 and 2 holds with $C \leq C_0$, then equation 4.6 has a solution u with $\varepsilon = 1$ which satisfies

$$u \asymp \mathbf{P}_\kappa[\sigma]. \quad (4.7)$$

Conversely, if (4.6) has a solution u with $\varepsilon = 1$, then the two statement 1. and 2. hold for some $C > 0$.

Remark 4.2 Problem (4.6) admits a subcritical range

$$1 < q < \frac{N + \frac{\alpha_+}{2}}{N + \frac{\alpha_+}{2} - 2}.$$

If the above inequality, the problem can be solved with any positive measure provided $\sigma(\partial\Omega)$ is small enough. The role of this critical exponent has been pointed out in [11] and [7] for the removability of boundary isolated singularities of solutions of

$$-\Delta u - \frac{\kappa}{\rho^2} u + u^q = 0 \text{ in } \Omega$$

i.e. solutions which vanish on the boundary except at one point. Furthermore the complete study of the problem

$$\begin{aligned} -\Delta u - \frac{\kappa}{\rho^2} u + u^q &= 0 & \text{in } \Omega, \\ u &= \sigma & \text{on } \partial\Omega, \end{aligned} \quad (4.8)$$

is performed in [7] in the supercritical range

$$q \geq \frac{N + \frac{1+\sqrt{1-4\kappa}}{2}}{N + \frac{1+\sqrt{1-4\kappa}}{2} - 2}.$$

The necessary and sufficient condition is therein expressed in terms of the absolute continuity of σ with respect to the $\text{Cap}_{I_{\frac{q+3-(q-1)\sqrt{1-4\kappa}}{2q}, q'}}$ -capacity.

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