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ON THE GREEN FUNCTION AND POISSON INTEGRALS OF THE DUNKL LAPLACIAN

PIOTR GRACZYK, TOMASZ LUKS, AND MARGIT RÖSLER

ABSTRACT. We prove the existence and study properties of the Green function of the unit ball for the Dunkl Laplacian Δ_k in \mathbb{R}^d . As applications we derive the Poisson-Jensen formula for Δ_k -subharmonic functions and Hardy-Stein identities for the Poisson integrals of Δ_k . We also obtain sharp estimates of the Newton potential kernel, Green function and Poisson kernel in the rank one case in \mathbb{R}^d . These estimates contrast sharply with the well-known results in the potential theory of the classical Laplacian.

1. INTRODUCTION

Dunkl operators are differential reflection operators associated with finite reflection groups which generalize the usual partial derivatives as well as the invariant differential operators of Riemannian symmetric spaces. They play an important role in harmonic analysis and the study of special functions of several variables. Among other applications, Dunkl operators are employed in the description of quantum integrable models of Calogero-Moser type, see e.g. [8]. Also, there are stochastic processes associated with Dunkl Laplacians which generalize Dyson's Brownian motion model, see e.g. [15, 28]. Recently, the potential theory of the Dunkl Laplacian Δ_k has found increasing attention in view of many interesting open problems and the need of developing new techniques, as many standard methods known from the case of diffusion operators do not apply, see, e.g., [14, 23, 24]. In the present paper we study the properties of one of the fundamental objects in the potential theory of Δ_k : the Green function $G_k(x, y)$ of the unit ball \mathbb{B} in \mathbb{R}^d . The behavior and estimates of this function and its generalizations for bounded smooth domains were intensively studied in the case of the classical Laplacian [3, 31, 32, 33], more general diffusion operators [1, 2, 7, 16, 20, 22], as well as nonlocal operators [5, 6, 17, 19, 21].

Our first result, Theorem 3.1, establishes the existence and an integral formula for $G_k(x, y)$. A more convenient two-sided bound of $G_k(x, y)$ is given in Theorem 3.2. We also prove a standard relation between $G_k(x, y)$ and the Poisson kernel $P_k(x, y)$ of \mathbb{B} for Δ_k , see Proposition 3.5. As applications of Theorem 3.1 we obtain the Poisson-Jensen formula for Δ_k -subharmonic functions and Hardy-Stein identities for Δ_k -harmonic functions on \mathbb{B} , see Theorem 4.2 and Theorem 4.5. This leads to an equivalent characterization of the Hardy spaces of Δ_k on \mathbb{B} in the spirit of [4]. We remark that the general integral representation (3.4) of $G_k(x, y)$ and the estimate of Theorem 3.2

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involve the representing measure for the intertwining operator whose structure depends strongly on the underlying root system. Note that explicit formulas for the representing measure are known only in a few particular cases, and the question whether it always admits a Lebesgue density is a challenging open problem. However, the available results together with Theorem 3.2 allow us to derive explicit two-sided bounds of the Newton kernel $N_k(x, y)$, the Green function $G_k(x, y)$ and the Poisson kernel $P_k(x, y)$ for Δ_k in the rank one case in \mathbb{R}^d , see Theorem 5.1, Theorem 5.4, and Corollary 5.7. The obtained estimates contrast sharply with the classical results in the potential theory of the Laplacian Δ or more general diffusion operators. The main novelties in the present setting are additional singularities of $N_k(x, y)$ and $G_k(x, y)$ in $x = gy$ in dimensions higher than 3 (g is in the associated reflection group W) and the dependence of the estimate of $N_k(x, y)$, $G_k(x, y)$ and $P_k(x, y)$ on the distance to the boundary of the Weyl chamber. This makes the obtained asymptotics more complex than in the case of diffusion operators, in particular these for the Green function $G_k(x, y)$. Deriving analogous two-sided bounds in the setting of any other root system is an interesting open problem, and available informations about the representing measure for the intertwining operator are in this case essential. We should note that the existence of singularities of the Newton kernel $N_k(\cdot, y)$ on the orbit $W.y$ has recently been discussed in the case of an orthogonal root system, see [24, Proposition 2.59].

The paper is organized as follows. In Section 2 we give basic definitions and list some useful facts in the theory of Dunkl operators. In Section 3 we prove the existence and study properties of $G_k(x, y)$. In Section 4 we prove the Poisson-Jensen formula and Hardy-Stein identities. In Section 5 we derive sharp estimates of $N_k(x, y)$, $G_k(x, y)$ and $P_k(x, y)$ in the rank one case in \mathbb{R}^d .

2. PRELIMINARIES

For details on the following, see [10], [11], [25] and, for a general overview, [12] or [27]. Let R be a root system in \mathbb{R}^d (equipped with the usual scalar product and Euclidean norm $|\cdot|$), and let W be the associated finite reflection group. The root system R needs not be crystallographic and W is not required to be effective, i.e. $\text{span}_{\mathbb{R}}R$ may be a proper subspace of \mathbb{R}^d . The dimension of $\text{span}_{\mathbb{R}}R$ is called the rank of R . An important example is $R = A_{d-1} = \{\pm(e_i - e_j) : 1 \leq i < j \leq d\} \subset \mathbb{R}^d$ with $W = S_d$, the symmetric group in d elements. We fix a nonnegative multiplicity function k on R , i.e. $k : R \rightarrow [0, \infty)$ is W -invariant. The (rational) Dunkl operators associated with R and k are given by

$$T_{\xi}f(x) = \partial_{\xi}f(x) + \sum_{\alpha \in R_+} k(\alpha) \langle \alpha, \xi \rangle \frac{f(x) - f(\sigma_{\alpha}x)}{\langle \alpha, x \rangle}, \quad \xi \in \mathbb{R}^d,$$

where R_+ denotes an (arbitrary) positive subsystem of R . For fixed R and k , these operators commute. Moreover, there is a unique linear isomorphism V_k on the space of polynomial functions in d variables, called the intertwining operator, which preserves the degree of homogeneity, is normalized by $V_k(1) = 1$ and intertwines the Dunkl operators with the usual partial derivatives:

$$T_{\xi}V_k = V_k\partial_{\xi} \quad \text{for all } \xi \in \mathbb{R}^d.$$

The Dunkl Laplacian is defined by

$$\Delta_k := \sum_{i=1}^d T_{\xi_i}^2$$

with an (arbitrary) orthonormal basis $(\xi_i)_{1 \leq i \leq d}$ of \mathbb{R}^d . In explicit form,

$$\Delta_k f(x) = \Delta f(x) + \sum_{\alpha \in R_+} k(\alpha) \left(\frac{\langle \nabla f(x), \alpha \rangle}{\langle \alpha, x \rangle} - \frac{f(x) - f(\sigma_\alpha(x))}{\langle \alpha, x \rangle^2} \right),$$

where Δ is the usual Laplacian on \mathbb{R}^d . For $x \in \mathbb{R}^d$ denote by $C(x)$ the convex hull of the Weyl group orbit $W.x$ of x in \mathbb{R}^d . The intertwining operator V_k has the integral representation

$$(2.1) \quad V_k f(x) = \int_{C(x)} f(z) d\mu_x^k(z),$$

where μ_x^k is a probability measure on $C(x)$. The measures μ_x^k satisfy

$$\mu_{rx}^k(A) = \mu_x^k(r^{-1}A)$$

for all $r > 0$ and Borel sets $A \subseteq \mathbb{R}^d$. In [30], it was deduced from formula (2.1) that V_k establishes a homeomorphism of $C^\infty(\mathbb{R}^d)$ with its usual Fréchet space topology.

In the rank one case $R = \{\pm 1\} \subset \mathbb{R}$, the representation (2.1) is explicitly known ([11, Theorem 5.1]); it is given by

$$(2.2) \quad V_k f(x) = c_k \int_{-1}^1 f(tx) (1-t)^{k-1} (1+t)^k dt \quad \text{with } c_k = \frac{\Gamma(k+1/2)}{\sqrt{\pi} \Gamma(k)}.$$

We shall employ the Dunkl-type generalized translation on $C^\infty(\mathbb{R}^d)$ which was defined in [30] by

$$\tau_y f(x) := V_k^x V_k^y (V_k^{-1} f)(x+y), \quad x, y \in \mathbb{R}^d.$$

Here the superscript denotes the relevant variable. This translation satisfies $\tau_y f(x) = \tau_x f(y)$, and we shall use the notation $f(x *_k y) := \tau_y f(x)$.

Lemma 2.1. (i) *The representing measures μ_x^k satisfy $\mu_{-x}^k(-A) = \mu_x^k(A)$.*
(ii) *Let $f \in C^\infty(\mathbb{R}^d)$ and write $f^-(x) := f(-x)$. Then $f(-x *_k -y) = f^-(x *_k y)$.*

Proof. It is immediate that the Dunkl operators satisfy $T_\xi(f^-) = (T_{-\xi} f)^-$. By the characterization of V_k , it follows that $V_k(f^-) = (V_k f)^-$. This implies both assertions. \square

Of particular importance in our context will be translates of functions f on \mathbb{R}^d which are radial, that is $f(x) = \tilde{f}(|x|)$ with $\tilde{f} : [0, \infty) \rightarrow \mathbb{C}$. We recall from [26] that for each $x, y \in \mathbb{R}^d$ there exists a unique compactly supported radial probability measure $\rho_{x,y}^k$ on \mathbb{R}^d such that

$$(2.3) \quad f(x *_k y) = \int_{\mathbb{R}^d} f d\rho_{x,y}^k$$

for all $f \in C^\infty(\mathbb{R}^d)$. This can be written explicitly as

$$(2.4) \quad f(x *_k y) = \int_{C(y)} \tilde{f}(\sqrt{|x|^2 + |y|^2 + 2\langle x, z \rangle}) d\mu_y^k(z).$$

Notice that Dunkl translates of non-negative, smooth radial functions are again non-negative. Formula (2.3) allows to extend the generalized translation to measurable radial functions which are either complex-valued and bounded or have values in $[0, \infty]$. We maintain the notations $\tau_y f(x)$ and $f(x *_k y)$ for functions from these classes. In particular, for radial f we have

$$(2.5) \quad f(-x *_k -y) = f(x *_k y).$$

We put

$$\gamma := \sum_{\alpha \in R_+} k_\alpha$$

and define the weight function ω_k on \mathbb{R}^d by

$$\omega_k(x) := \prod_{\alpha \in R_+} |\langle \alpha, x \rangle|^{2k_\alpha}.$$

Let $\mathbb{B} = \{x \in \mathbb{R}^d : |x| < 1\}$ denote the open unit ball in \mathbb{R}^d and let $\mathbb{S} = \partial\mathbb{B}$ denote the unit sphere. The Poisson kernel $P_k(x, y)$ of \mathbb{B} for the Dunkl Laplacian Δ_k was defined in [11] as a reproducing kernel for Δ_k -harmonic polynomials. It can be written as

$$(2.6) \quad P_k(x, y) = V_k \left[\frac{1 - |x|^2}{(1 - 2\langle x, \cdot \rangle + |x|^2)^{\gamma+d/2}} \right] (y), \quad x \in \mathbb{B}, y \in \mathbb{S}.$$

In view of identity (2.5) with $f(x) = |x|^{-2\gamma-d}$, we obtain

$$(2.7) \quad \begin{aligned} P_k(x, y) &= \int_{C(y)} \frac{1 - |x|^2}{(1 - 2\langle x, z \rangle + |x|^2)^{\gamma+d/2}} d\mu_y(z) = (1 - |x|^2) \cdot f(-x *_k y) \\ &= (1 - |x|^2) \cdot \tau_{-y}(|x|^{-2\gamma-d}). \end{aligned}$$

The notation $f \asymp g$ will always mean that there is a constant $C > 0$ depending on k and d only (unless stated otherwise) such that $C^{-1}g \leq f \leq Cg$.

3. THE GREEN FUNCTION OF THE BALL

From now on, it is always assumed that $d + 2\gamma > 2$. Following [24], we introduce the Newton kernel in the Dunkl setting by

$$N_k(x, y) = \int_0^\infty \Gamma_k(t, x, y) dt \quad (x, y \in \mathbb{R}^d),$$

with the heat kernel

$$\Gamma_k(t, x, y) = \frac{M_k}{t^{\gamma+d/2}} e^{-(|x|^2+|y|^2)/4t} E_k\left(\frac{x}{\sqrt{2t}}, \frac{y}{\sqrt{2t}}\right),$$

where

$$M_k = 2^{-\gamma-d/2} \left(\int_{\mathbb{R}^d} e^{-|x|^2/2} \omega_k(x) dx \right)^{-1}.$$

Notice that $N_k(x, y) = N_k(y, x)$. According to the results in [24, Section 2.7], the Newton kernel can be written as

$$(3.1) \quad N_k(x, y) = C_k \int_{C(y)} (|x|^2 + |y|^2 - 2\langle x, z \rangle)^{1-\gamma-d/2} d\mu_y(z)$$

where

$$(3.2) \quad C_k = \frac{1}{d_k(d + 2\gamma - 2)} \quad \text{and} \quad d_k = \int_{\mathbb{S}} \omega_k(x) d\sigma(x).$$

Here σ denotes the surface measure on \mathbb{S} . Formula (3.1) is also easily obtained by translations. Recall that

$$\Gamma_k(t, x, y) = \tau_{-y}g_t(x) \quad \text{with} \quad g_t(x) = \frac{M_k}{t^{\gamma+d/2}} e^{-|x|^2/4t},$$

which follows from [26, Lemma 2.2. and (3.2)] (see also [28]). As

$$\int_0^\infty g_t(\xi) dt = M_k \Gamma(\gamma + \frac{d}{2} - 1) \cdot \left(\frac{2}{|\xi|}\right)^{d-2+2\gamma} = \frac{C_k}{|\xi|^{d-2+2\gamma}},$$

it follows that

$$N_k(x, y) = \int_0^\infty \int_{\mathbb{R}^d} g_t(\xi) d\rho_{x,-y}^k(\xi) dt = C_k \cdot \tau_{-y}(|x|^{2-2\gamma-d}).$$

In view of identity (2.5), this equals the right-hand side of (3.1). Furthermore, the Newton kernel $N_k(\cdot, y)$ is Δ_k -harmonic on $\mathbb{R}^d \setminus W.y$ for fixed $y \in \mathbb{R}^d$ (see [24, Proposition 2.64]). It can be regarded as the global Green function for the Dunkl Laplacian Δ_k .

The goal of this section is to introduce and study the Green function of the ball \mathbb{B} for Δ_k . For this, we recall from [13] the Kelvin transform associated with the Dunkl Laplacian, which is given by

$$K_k[u](x) = |x|^{2-2\gamma-d} u(x^*)$$

for functions u on $\mathbb{R}^d \setminus \{0\}$, where $x^* = x/|x|^2$ is the inversion with respect to the unit sphere in \mathbb{R}^d . By [13, Theorem 3.1], K_k preserves Δ_k -harmonic functions on $\mathbb{R}^d \setminus \{0\}$. Following the classical case $k = 0$ (cf. [9, 29]), we define

$$(3.3) \quad G_k(x, y) := N_k(x, y) - K_k[N_k(\cdot, y)](x)$$

for $x, y \in \overline{\mathbb{B}} \times \overline{\mathbb{B}}$ with $x \neq 0$, where $K_k[N_k(\cdot, y)](x) = |x|^{2-2\gamma-d} N_k(x^*, y)$.

Theorem 3.1. *The kernel G_k is the Green function of \mathbb{B} for Δ_k , that is, G_k extends to a $[0, \infty]$ -valued function on $\overline{\mathbb{B}} \times \overline{\mathbb{B}}$ which is uniquely characterized by the following conditions:*

- (i) $G_k(x, y) > 0$ for all $x, y \in \mathbb{B}$ and $G_k(x, y) = 0$ for $x \in \mathbb{S}$ and $y \in \mathbb{B}$.
- (ii) $G_k(\cdot, y)$ is continuous on $\overline{\mathbb{B}} \setminus W.y$ for any fixed $y \in \mathbb{B}$.
- (iii) $N_k(\cdot, y) - G_k(\cdot, y)$ is Δ_k -harmonic on \mathbb{B} for any fixed $y \in \mathbb{B}$.

Moreover, the Green function G_k can be written as

$$(3.4) \quad G_k(x, y) = C_k \int_{C(y)} \left[(|x|^2 + |y|^2 - 2\langle x, z \rangle)^{1-\gamma-d/2} - (1 + |x|^2|y|^2 - 2\langle x, z \rangle)^{1-\gamma-d/2} \right] d\mu_y(z).$$

It satisfies $G_k(x, y) = G_k(y, x)$ for all $x, y \in \overline{\mathbb{B}}$, and $G_k(\cdot, y)$ is Δ_k -harmonic on $\mathbb{B} \setminus W.y$ for any fixed $y \in \mathbb{B}$.

Proof. As $N_k(\cdot, y)$ is Δ_k -harmonic on $\mathbb{R}^d \setminus W.y$ for fixed $y \in \mathbb{R}^d$, its Kelvin transform $K_k[N_k(\cdot, y)]$ is Δ_k -harmonic on $\mathbb{B} \setminus \{0\}$ and continuous on $\overline{\mathbb{B}} \setminus \{0\}$ for any fixed $y \in \mathbb{B}$. By (3.1) we have

$$(3.5) \quad K_k[N_k(\cdot, y)](x) = C_k \int_{C(y)} (1 + |x|^2|y|^2 - 2\langle x, z \rangle)^{1-\gamma-d/2} d\mu_y(z),$$

and from this representation it is immediate by the dominated convergence theorem that $K_k[N_k(\cdot, y)]$ has a removable singularity at 0 for fixed $y \in \mathbb{B}$. Employing [14, Theorem 5.1], we conclude that $K_k[N_k(\cdot, y)]$ extends to a Δ_k -harmonic function on \mathbb{B} . Furthermore, $K_k[N_k(\cdot, y)]$ solves the Δ_k -Dirichlet

problem on $\overline{\mathbb{B}}$ with the boundary values of $N_k(\cdot, y)$. Therefore, $G_k(\cdot, y)$ vanishes continuously at \mathbb{S} and is Δ_k -harmonic on $\mathbb{B} \setminus W.y$. Formula (3.5) immediately gives the claimed identity (3.4). As $1 + |x|^2|y|^2 - 2\langle x, z \rangle > |x|^2 + |y|^2 - 2\langle x, z \rangle \geq 0$ for all $x, y \in \mathbb{B}$ and $z \in C(y)$, it follows from (3.4) that $G_k(x, y) > 0$ for all $x, y \in \mathbb{B}$. For the symmetry of G_k , it suffices to prove that $K_k[N_k(\cdot, y)](x)$ is symmetric in x and y for $x \neq 0$. Using the symmetry of N_k and the fact that for any $r > 0$, the representing measure μ_{rx} is just the image measure of μ_x under the dilation $z \mapsto rz$ of \mathbb{R}^d , we obtain

$$\begin{aligned} K_k[N_k(\cdot, y)](x) &= |x|^{2-2\gamma-d} N_k(y, x^*) \\ &= |x|^{2-2\gamma-d} \cdot C_k \int_{\mathbb{R}^d} (|y|^2 + |x^*|^2 - 2\langle y, z \rangle)^{1-\gamma-d/2} d\mu_{x/|x|^2}(z) \\ &= |x|^{2-2\gamma-d} \cdot C_k \int_{\mathbb{R}^d} (|y|^2 + |x^*|^2 - 2\langle y, \frac{z}{|x|^2} \rangle)^{1-\gamma-d/2} d\mu_x(z) \\ &= C_k \int_{\mathbb{R}^d} (|x|^2|y|^2 + 1 - 2\langle y, z \rangle)^{1-\gamma-d/2} d\mu_x(z) \\ &= K_k[N_k(\cdot, x)](y). \end{aligned}$$

Further, [24, Proposition 2.58] gives $G_k(x, x) = +\infty$. Finally, the uniqueness of the function G_k subject to the conditions (i) – (iii) follows from the uniqueness of solutions to the Δ_k -Dirichlet problem on \mathbb{B} , see [23]. \square

According to [24, Proposition 2.64], $-N_k(x, \cdot)$ provides a fundamental solution for Δ_k on \mathbb{R}^d in the sense that $\Delta_k(-N_k(x, \cdot)\omega_k) = \delta_x$ in $\mathcal{D}'(\mathbb{R}^d)$. This implies that $-G_k(x, \cdot)$ provides a fundamental solution for Δ_k in \mathbb{B} :

$$\Delta_k(-G_k(x, \cdot)\omega_k) = \delta_x \quad \text{in } \mathcal{D}'(\mathbb{B}).$$

Our next result provides sharp two-sided bounds for $G_k(x, y)$ which are more convenient to deal with rather than (3.4). For $x \in \mathbb{B}$ denote $\delta(x) := 1 - |x|$.

Theorem 3.2. *The two-sided bound of $G_k(x, y)$ on $\mathbb{B} \times \mathbb{B}$ is given by*

$$\begin{aligned} G_k(x, y) &\asymp \int_{C(y)} \frac{(1 - |x|^2)(1 - |y|^2)d\mu_y(z)}{(1 + |x|^2|y|^2 - 2\langle x, z \rangle)(|x|^2 + |y|^2 - 2\langle x, z \rangle)^{\gamma+d/2-1}} \\ &\asymp \int_{C(y)} \frac{\delta(x)\delta(y)d\mu_y(z)}{(\delta(x)\delta(y) + |x|^2 + |y|^2 - 2\langle x, z \rangle)(|x|^2 + |y|^2 - 2\langle x, z \rangle)^{\gamma+d/2-1}}. \end{aligned}$$

Proof. Note that for $x, y \in \mathbb{B}$ we have

$$1 + |x|^2|y|^2 - |x|^2 - |y|^2 = (1 - |x|^2)(1 - |y|^2) \asymp \delta(x)\delta(y).$$

Hence, the estimate is a direct consequence of Theorem 3.1 and Lemma 3.3 below. \square

Lemma 3.3. *Fix $p > 0$. There exists a constant $C_p > 0$ depending only on p such that for all $0 < a < b < \infty$ we have*

$$\frac{b-a}{C_p b a^p} \leq \frac{1}{a^p} - \frac{1}{b^p} \leq \frac{C_p(b-a)}{b a^p}.$$

Proof. Assume first $p > 1$. Then by [4, Lemma 6, (11)] (see also (4.5)) we get

$$\begin{aligned} b^p - a^p &\leq C(b-a)^2 b^{p-2} + p a^{p-1}(b-a) \\ &\leq C(b-a)(b^{p-1} - ab^{p-2} + a^{p-1}) \\ &= C b^{p-1}(b-a) \left(1 + (a/b)^{p-1} - a/b\right), \end{aligned}$$

and the lower bound obtains analogously. Furthermore, since $p > 1$, we have

$$\sup_{x \in [0,1]} |x^{p-1} - x| < 1.$$

Hence $b^p - a^p \asymp b^{p-1}(b-a)$ and

$$\frac{1}{a^p} - \frac{1}{b^p} = \frac{b^p - a^p}{(ab)^p} \asymp \frac{b-a}{ba^p}.$$

Here \asymp means two-sided estimates with constants depending only on p . For $0 < p \leq 1$ we let $q = p + 1$. We have

$$\frac{1}{a^p} - \frac{1}{b^p} = \frac{a}{a^q} - \frac{b}{b^q} = \frac{ab^q - ba^q}{(ab)^q}.$$

Let $c = b^{1/q}a$, $d = a^{1/q}b$. Then $0 < c < d < \infty$ and applying the estimate obtained previously we get

$$\begin{aligned} ab^q - ba^q &= d^q - c^q \asymp d^{q-1}(d-c) \\ &= a^{(q-1)/q} b^{q-1} \left(a^{1/q}b - b^{1/q}a\right) \\ &= ab^{q-1} \left(b - b^{1/q}a^{1-1/q}\right). \end{aligned}$$

Since $a < b$, we obtain

$$b - b^{1/q}a^{1-1/q} = b - (b/a)^{1/q}a \leq b - a$$

and the upper bound follows. To get the lower bound define $f(x) = b^{1/q}x^{1-1/q}$ for $x \in [a, b]$. Then $f'(x) = (1-1/q)(b/x)^{1/q}$ and by the mean value theorem, for some $\xi \in (a, b)$ we have

$$b - b^{1/q}a^{1-1/q} = f(b) - f(a) = (1-1/q)(b/\xi)^{1/q}(b-a) \geq (1-1/q)(b-a).$$

Therefore

$$\frac{ab^q - ba^q}{(ab)^q} \asymp \frac{ab^{q-1}(b-a)}{(ab)^q} = \frac{b-a}{ba^p}.$$

□

A simple consequence of Theorem 3.2 is the following estimate.

Corollary 3.4. *Let $y_0 \in \mathbb{B}$ be fixed. There is a constant $C > 0$ depending on d, k and y_0 only, such that*

$$C^{-1}\delta(x)N_k(x, y_0) \leq G_k(x, y_0) \leq C\delta(x)N_k(x, y_0).$$

The following classical formula relates the Poisson kernel $P_k(x, y)$ to the Green function $G_k(x, y)$.

Proposition 3.5. *For all $x \in \mathbb{B}$ and $y \in \mathbb{S}$ we have*

$$P_k(x, y) = -d_k \langle y, \nabla_y G_k(x, y) \rangle.$$

Proof. We use the symmetry $G_k(x, y) = G_k(y, x)$. By the dominated convergence, we can differentiate under the integral sign in (3.4) to see that for all $x \in \mathbb{B}$ and $y \in \mathbb{S}$,

$$-d_k \langle y, \nabla_y G_k(x, y) \rangle = (1 - |x|^2) \int_{C(x)} (|x|^2 + 1 - 2 \langle y, z \rangle)^{-\gamma-d/2} d\mu_x(z).$$

With $f(x) = |x|^{-2\gamma-d}$ and in view of (2.5) and representation (2.7) for the kernel P_k we obtain

$$-d_k \langle y, \nabla_y G_k(x, y) \rangle = (1 - |x|^2) f(x *_{k} -y) = P_k(x, y).$$

□

4. POISSON-JENSEN FORMULA AND HARDY-STEIN IDENTITIES

Our first goal in this section is to prove the so-called *Poisson-Jensen formula* for Δ_k -subharmonic functions on $\overline{\mathbb{B}}$. The corresponding result for classical subharmonic functions may be found in [18]. We will next use the formula to derive the *Hardy-Stein identities* for Δ_k -harmonic functions on \mathbb{B} , which equivalently characterize the Hardy spaces of Δ_k in the spirit of [4].

All functions in this section are assumed to be real-valued. Let $\Omega \subset \mathbb{R}^d$ be a W -invariant open set. We will say that a function $u \in C^2(\Omega)$ is Δ_k -subharmonic on Ω if $\Delta_k u(x) \geq 0$ for all $x \in \Omega$. We refer to [24] for basic properties and other characterizations of Δ_k -subharmonic functions. We will further say that a function u is Δ_k -harmonic (resp. Δ_k -subharmonic) on $\overline{\mathbb{B}}$ if there exists $\varepsilon > 0$ such that u extends to a Δ_k -harmonic (resp. Δ_k -subharmonic) function on $\mathbb{B}_\varepsilon := \{x : |x| < 1 + \varepsilon\}$. For $r > 0$ we define the dilation of a function u by $u_r(x) := u(rx)$.

The Riesz decomposition theorem [24, Theorem 2.74, see also Ex. 2.47 and Corollary 2.53] implies that for every $\varepsilon > 0$ and every function u which is Δ_k -subharmonic on $\mathbb{B}_\varepsilon := \{x : |x| < 1 + \varepsilon\}$ there exists a unique Δ_k -harmonic function h_ε on $\mathbb{B}_{\varepsilon/2} \subset \overline{\mathbb{B}_{\varepsilon/2}} \subset \mathbb{B}_\varepsilon$ such that

$$(4.1) \quad u(x) = - \int_{\mathbb{B}_{\varepsilon/2}} N_k(x, y) \Delta_k u(x) \omega_k(x) dx + h_\varepsilon(x), \quad x \in \mathbb{B}_{\varepsilon/2}.$$

As in the previous section, we denote by σ the surface measure on \mathbb{S} and let $\omega_k \sigma$ denote the measure on \mathbb{S} given by $d\omega_k \sigma(x) = \omega_k(x) d\sigma(x)$. For $f \in L^1(\mathbb{S}, \omega_k \sigma)$ we define the Poisson integral of f by

$$P_k[f](x) := \frac{1}{d_k} \int_{\mathbb{S}} P_k(x, z) f(z) \omega_k(z) d\sigma(z), \quad x \in \mathbb{B}.$$

Our first result is the following property of the Newton kernel of Δ_k .

Lemma 4.1. *For all $x \in \mathbb{B}$ we have*

$$P_k[N_k(\cdot, y)](x) = \begin{cases} N_k(x, y) - G_k(x, y), & y \in \mathbb{B}, \\ N_k(x, y), & y \notin \mathbb{B}. \end{cases}$$

Proof. For $y \in \mathbb{B}$ the statement follows from (3.3). Clearly, $K_k[N_k(\cdot, y)]$ is Δ_k -harmonic on \mathbb{B} and continuous on $\overline{\mathbb{B}}$ with $K_k[N_k(\cdot, y)](x) = N_k(x, y)$ for all $x \in \mathbb{S}$. By the uniqueness of the solution to the Δ_k -Dirichlet problem [23] we have $K_k[N_k(\cdot, y)] = P_k[N_k(\cdot, y)]$ on \mathbb{B} . When $y \in (\overline{\mathbb{B}})^c$, then $N_k(\cdot, y)$ is Δ_k -harmonic on $\overline{\mathbb{B}}$, and hence $N_k(\cdot, y) = P_k[N_k(\cdot, y)]$ on \mathbb{B} in this case.

Finally, let $y \in \mathbb{S}$. Since $N_k(\cdot, y)$ is Δ_k -harmonic on \mathbb{B} , the dilation $N_k(\cdot, y)_r$ is Δ_k -harmonic on $\overline{\mathbb{B}}$ for any $0 < r < 1$. Hence

$$N_k(rx, y) = \frac{1}{d_k} \int_{\mathbb{S}} P_k(x, z) N_k(rz, y) \omega_k(z) d\sigma(z),$$

and it is enough to show that the right-hand side above tends to $P_k[N_k(\cdot, y)](x)$ as $r \rightarrow 1$. First note that Fatou's lemma gives $P_k[N_k(\cdot, y)](x) \leq N_k(x, y)$. By (3.1), for $z, y \in \mathbb{S}$ we have

$$N_k(rz, y) = C_k \int_{C(y)} (|rz|^2 + |y|^2 - 2\langle rz, v \rangle)^{1-\gamma-d/2} d\mu_y(v).$$

For $v \in C(y)$ write $v = \sum_{g \in W} \lambda_g(v) gy$, where $\lambda_g(v) \geq 0$ for all $g \in W$ and $\sum_{g \in W} \lambda_g(v) = 1$. This gives

$$|rz|^2 + |y|^2 - 2\langle rz, v \rangle = \sum_{g \in W} \lambda_g(v) |rz - gy|^2.$$

Furthermore, since $|z| = |gy| = 1$, we have $|rz - gy| \geq |rz - rgy|$ for any $0 < r < 1$. Consequently,

$$|rz|^2 + |y|^2 - 2\langle rz, v \rangle \geq r^2(|z|^2 + |y|^2 - 2\langle z, v \rangle),$$

and $N_k(rz, y) \leq r^{2-2\gamma-d} N_k(z, y)$. Therefore, $N_k(rz, y) \leq C N_k(z, y)$ for all $1/2 < r < 1$ and $P_k[N_k(\cdot, y)](x) \leq N_k(x, y) < \infty$. The dominated convergence theorem gives the result. \square

As a consequence of (4.1) and Lemma 4.1 we obtain the following Poisson-Jensen formula.

Theorem 4.2. *Let u be Δ_k -subharmonic on $\overline{\mathbb{B}}$. Then for every $x \in \mathbb{B}$ we have*

$$u(x) = \frac{1}{d_k} \int_{\mathbb{S}} P_k(x, y) u(y) \omega_k(y) d\sigma(y) - \int_{\mathbb{B}} G_k(x, y) \Delta_k u(y) \omega_k(y) dy.$$

Proof. Choose $\varepsilon > 0$ such that u extends to a Δ_k -subharmonic function on \mathbb{B}_ε . By (4.1),

$$u(x) = - \int_{\mathbb{B}_{\varepsilon/2}} N_k(x, y) \Delta_k u(y) \omega_k(y) dy + h_\varepsilon(x), \quad x \in \mathbb{B}_{\varepsilon/2},$$

where h_ε is Δ_k -harmonic on $\mathbb{B}_{\varepsilon/2}$. Evaluating the Poisson integral of both sides and applying Fubini's theorem and Lemma 4.1 we get

$$\begin{aligned} P_k[u](x) &= \frac{1}{d_k} \int_{\mathbb{S}} P_k(x, y) u(y) \omega_k(y) d\sigma(y) \\ &= \frac{1}{d_k} \int_{\mathbb{S}} P_k(x, y) \left(- \int_{\mathbb{B}_{\varepsilon/2}} N_k(y, z) \Delta_k u(z) \omega_k(z) dz + h_\varepsilon(y) \right) \omega_k(y) d\sigma(y) \\ &= - \int_{\mathbb{B}_{\varepsilon/2}} \left(\frac{1}{d_k} \int_{\mathbb{S}} P_k(x, y) N_k(y, z) \omega_k(y) d\sigma(y) \right) \Delta_k u(z) \omega_k(z) dz + h_\varepsilon(x) \\ &= \int_{\mathbb{B}} (G_k(x, z) - N_k(x, z)) \Delta_k u(z) \omega_k(z) dz \\ &\quad - \int_{\mathbb{B}_{\varepsilon/2} \setminus \mathbb{B}} N_k(x, z) \Delta_k u(z) \omega_k(z) dz + h_\varepsilon(x) \\ &= \int_{\mathbb{B}} G_k(x, z) \Delta_k u(z) \omega_k(z) dz + u(x). \end{aligned}$$

□

Let $1 \leq p \leq \infty$. The Hardy space $H_k^p(\mathbb{B})$ is defined as the family of those Δ_k -harmonic functions on \mathbb{B} which satisfy

$$\|u\|_{H^p} := \sup_{0 \leq r < 1} \|u_r\|_{L^p(\omega_k \sigma)} < \infty.$$

By [23, Theorem 2.2 and Theorem 2.3], $u \in H_k^p(\mathbb{B})$ for a given $1 < p \leq \infty$ if and only if $u = P_k[f]$ for some $f \in L^p(\mathbb{S}, \omega_k \sigma)$, and in this case $\|u\|_{H^p} = \|f\|_{L^p(\omega_k \sigma)}$. This implies that

$$(4.2) \quad \|u\|_{H^p} = \lim_{r \rightarrow 1} \|u_r\|_{L^p(\omega_k \sigma)}$$

for any Δ_k -harmonic function u on \mathbb{B} . As an application of Theorem 4.2, we will give an equivalent characterization of the spaces $H_k^p(\mathbb{B})$, $1 < p < \infty$, in terms of the Hardy-Stein identities. The approach is inspired by [4], where similar description was obtained for Hardy spaces of the classical Laplacian Δ and the fractional Laplacian $\Delta^{\alpha/2}$.

Let $1 < p < \infty$. For $a, b \in \mathbb{R}$ we set

$$(4.3) \quad F(a, b) = |b|^p - |a|^p - pa|a|^{p-2}(b-a).$$

Here $F(a, b) = |b|^p$ if $a = 0$, and $F(a, b) = (p-1)|a|^p$ if $b = 0$. For instance, if $p = 2$, then $F(a, b) = (b-a)^2$. Generally, $F(a, b)$ is the second-order Taylor remainder of $\mathbb{R} \ni x \mapsto |x|^p$, therefore by convexity, $F(a, b) \geq 0$. Furthermore, for $1 < p < \infty$ and $\varepsilon \in \mathbb{R}$ we define

$$(4.4) \quad F_\varepsilon(a, b) = (b^2 + \varepsilon^2)^{p/2} - (a^2 + \varepsilon^2)^{p/2} - pa(a^2 + \varepsilon^2)^{(p-2)/2}(b-a).$$

Since $F_\varepsilon(a, b)$ is the second-order Taylor remainder of $\mathbb{R} \ni x \mapsto (x^2 + \varepsilon^2)^{p/2}$, by convexity, $F_\varepsilon(a, b) \geq 0$. Of course, $F_\varepsilon(a, b) \rightarrow F_0(a, b) = F(a, b)$ as $\varepsilon \rightarrow 0$. The next result is proved in [4, Lemma 6].

Lemma 4.3. *For every $p > 1$ there is a constant $C > 0$ depending on p only such that*

$$(4.5) \quad C^{-1}(b-a)^2(|b| \vee |a|)^{p-2} \leq F(a, b) \leq C(b-a)^2(|b| \vee |a|)^{p-2}, \quad a, b \in \mathbb{R}.$$

If $p \in (1, 2)$, then

$$(4.6) \quad 0 \leq F_\varepsilon(a, b) \leq \frac{1}{p-1} F(a, b), \quad \varepsilon, a, b \in \mathbb{R}.$$

The following explicit formulas shed some light on the meaning of the function F .

Lemma 4.4. *Let u be of class C^2 in the neighborhood of $x \in \mathbb{R}^d$. Then for $2 \leq p < \infty$ we have*

$$(4.7) \quad \begin{aligned} \Delta_k |u(x)|^p &= p(p-1)|u(x)|^{p-2} |\nabla u(x)|^2 + 2 \sum_{\alpha \in R_+} k(\alpha) \frac{F(u(x), u(\sigma_\alpha(x)))}{\langle \alpha, x \rangle^2} \\ &\quad + pu(x)|u(x)|^{p-2} \Delta_k u(x). \end{aligned}$$

When $1 < p < \infty$ and $\varepsilon > 0$, then

$$(4.8) \quad \begin{aligned} \Delta_k |u(x) + i\varepsilon|^p &= p|u(x) + i\varepsilon|^{p-4} [(p-1)u(x)^2 + \varepsilon^2] |\nabla u(x)|^2 \\ &\quad + 2 \sum_{\alpha \in R_+} k(\alpha) \frac{F_\varepsilon(u(x), u(\sigma_\alpha(x)))}{\langle \alpha, x \rangle^2} + pu(x)|u(x) + i\varepsilon|^{p-2} \Delta_k u(x). \end{aligned}$$

Proof. When $2 \leq p < \infty$ or $u(x) \neq 0$ we write $|u(x)|^p = (u(x)^2)^{p/2}$ and a straightforward calculation gives

$$\begin{aligned}\nabla|u(x)|^p &= pu(x)|u(x)|^{p-2}\nabla u(x), \\ \Delta|u(x)|^p &= p(p-1)|u(x)|^{p-2}|\nabla u(x)|^2 + pu(x)|u(x)|^{p-2}\Delta u(x).\end{aligned}$$

Note that

$$|u(\sigma_\alpha(x))|^p - |u(x)|^p = F(u(x), u(\sigma_\alpha(x))) + pu(x)|u(x)|^{p-2}(u(\sigma_\alpha(x)) - u(x)).$$

Hence

$$\begin{aligned}\Delta_k|u(x)|^p &= \Delta|u(x)|^p + 2 \sum_{\alpha \in R_+} k(\alpha) \left(\frac{\langle \nabla|u(x)|^p, \alpha \rangle}{\langle \alpha, x \rangle} + \frac{|u(\sigma_\alpha(x))|^p - |u(x)|^p}{\langle \alpha, x \rangle^2} \right) \\ &= p(p-1)|u(x)|^{p-2}|\nabla u(x)|^2 + pu(x)|u(x)|^{p-2}\Delta u(x) \\ &\quad + 2pu(x)|u(x)|^{p-2} \sum_{\alpha \in R_+} k(\alpha) \left(\frac{\langle \nabla u(x), \alpha \rangle}{\langle \alpha, x \rangle} + \frac{(u(\sigma_\alpha(x)) - u(x))}{\langle \alpha, x \rangle^2} \right) \\ &\quad + 2 \sum_{\alpha \in R_+} k(\alpha) \frac{F(u(x), u(\sigma_\alpha(x)))}{\langle \alpha, x \rangle^2},\end{aligned}$$

and (4.7) follows. For $1 < p < \infty$ and $\varepsilon > 0$ we have

$$\begin{aligned}\nabla|u(x) + i\varepsilon|^p &= pu(x)|u(x) + i\varepsilon|^{p-2}\nabla u(x), \\ \Delta|u(x) + i\varepsilon|^p &= p|u(x) + i\varepsilon|^{p-4} [(p-1)u(x)^2 + \varepsilon^2] |\nabla u(x)|^2 \\ &\quad + p|u(x) + i\varepsilon|^{p-2}u(x)\Delta u(x),\end{aligned}$$

and

$$\begin{aligned}|u(\sigma_\alpha(x)) + i\varepsilon|^p - |u(x) + i\varepsilon|^p &= F_\varepsilon(u(x), u(\sigma_\alpha(x))) \\ &\quad + pu(x)|u(x) + i\varepsilon|^{p-2}(u(\sigma_\alpha(x)) - u(x)).\end{aligned}$$

The rest of the proof is similar to the previous case. \square

We are now ready to prove the Hardy-Stein identities.

Theorem 4.5. *Let $1 < p < \infty$. Then for any $u \in H_k^p(\mathbb{B})$ we have*

$$\begin{aligned}\|u\|_{H^p}^p &= |u(0)|^p + C_k \int_{\mathbb{B}} (|y|^{2-2\gamma-d} - 1) [p(p-1)|u(y)|^{p-2}|\nabla u(y)|^2 \\ &\quad + 2 \sum_{\alpha \in R_+} k(\alpha) \frac{F(u(y), u(\sigma_\alpha(y)))}{\langle \alpha, y \rangle^2}] \omega_k(y) dy.\end{aligned}$$

In fact, a Δ_k -harmonic function u on \mathbb{B} belongs to $H_k^p(\mathbb{B})$ if and only if the integral above is finite.

Proof. Suppose v is Δ_k -subharmonic on \mathbb{B} . Then v_r is Δ_k -subharmonic on $\overline{\mathbb{B}}$ for any $0 < r < 1$. By Theorem 4.2,

$$(4.9) \quad v(0) = \frac{1}{d_k} \int_{\mathbb{S}} v_r(y) \omega_k(y) d\sigma(y) - \int_{\mathbb{B}} G_k(0, y) (\Delta_k v_r)(y) \omega_k(y) dy.$$

Since $(\Delta_k v_r)(x) = r^2 (\Delta_k v)_r(x)$, by (3.4) we have

$$\begin{aligned}(4.10) \quad &\int_{\mathbb{B}} G_k(0, y) (\Delta_k v_r)(y) \omega_k(y) dy = C_k r^2 \int_{\mathbb{B}} (|y|^{2-2\gamma-d} - 1) (\Delta_k v)(ry) \omega_k(y) dy \\ &= C_k \int_{B(0,r)} (|z|^{2-2\gamma-d} - r^{2-2\gamma-d}) \Delta_k v(z) \omega_k(z) dz,\end{aligned}$$

where $B(0, r) := \{x \in \mathbb{R}^d : |x| < r\}$. Let now u be Δ_k -harmonic on \mathbb{B} and suppose first $2 \leq p < \infty$. Then $|u|^p$ is of class C^2 on \mathbb{B} and by (4.7) we have

$$\Delta_k |u(x)|^p = p(p-1)|u(x)|^{p-2} |\nabla u(x)|^2 + 2 \sum_{\alpha \in R_+} k(\alpha) \frac{F(u(x), u(\sigma_\alpha(x)))}{\langle \alpha, x \rangle^2}.$$

In particular, $\Delta_k |u|^p \geq 0$ on \mathbb{B} so (4.9) and (4.10) apply to $v = |u|^p$. Let $r \rightarrow 1$. By (4.2),

$$\frac{1}{d_k} \int_{\mathbb{S}} |u(ry)|^p \omega_k(y) d\sigma(y) \rightarrow \|u\|_{H^p}^p,$$

and by the monotone convergence,

$$\begin{aligned} C_k \int_{B(0,r)} (|y|^{2-2\gamma-d} - r^{2-2\gamma-d}) \Delta_k |u(z)|^p \omega_k(z) dz \\ \rightarrow \int_{\mathbb{B}} G_k(0, z) \Delta_k |u(z)|^p \omega_k(z) dz. \end{aligned}$$

This gives the result for $p \geq 2$. Assume now $1 < p < 2$ and let $\varepsilon > 0$. Then $|u + i\varepsilon|^p$ is of class C^2 on \mathbb{B} and by (4.8) we have

$$\begin{aligned} \Delta_k |u(x) + i\varepsilon|^p &= p|u(x) + i\varepsilon|^{p-4} [(p-1)u(x)^2 + \varepsilon^2] |\nabla u(x)|^2 \\ &+ 2 \sum_{\alpha \in R_+} k(\alpha) \frac{F_\varepsilon(u(x), u(\sigma_\alpha(x)))}{\langle \alpha, x \rangle^2}. \end{aligned}$$

Since $\Delta_k |u + i\varepsilon|^p \geq 0$ on \mathbb{B} , we can apply (4.9) and (4.10) to $v = |u + i\varepsilon|^p$. This gives

$$\begin{aligned} |u(0) + i\varepsilon|^p &= \frac{1}{d_k} \int_{\mathbb{S}} |u(ry) + i\varepsilon|^p \omega_k(y) d\sigma(y) \\ &- C_k \int_{B(0,r)} (|y|^{2-2\gamma-d} - r^{2-2\gamma-d}) \Delta_k |u(y) + i\varepsilon|^p \omega_k(y) dy. \end{aligned}$$

Let $\varepsilon \rightarrow 0$. Then

$$\Delta_k |u(x) + i\varepsilon|^p \rightarrow p(p-1)|u(x)|^{p-2} |\nabla u(x)|^2 + 2 \sum_{\alpha \in R_+} k(\alpha) \frac{F(u(x), u(\sigma_\alpha(x)))}{\langle \alpha, x \rangle^2}$$

for a.e. $x \in \mathbb{B}$, and

$$\int_{\mathbb{S}} |u(ry) + i\varepsilon|^p \omega_k(y) d\sigma(y) \rightarrow \int_{\mathbb{S}} |u(ry)|^p \omega_k(y) d\sigma(y).$$

Fatou's lemma, (4.6) and dominated convergence give

$$\begin{aligned} |u(0)|^p &= \frac{1}{d_k} \int_{\mathbb{S}} |u(ry)|^p \omega_k(y) d\sigma(y) - C_k \int_{B(0,r)} (|y|^{2-2\gamma-d} - r^{2-2\gamma-d}) \\ &\times [p(p-1)|u(x)|^{p-2} |\nabla u(x)|^2 + 2 \sum_{\alpha \in R_+} k(\alpha) \frac{F(u(x), u(\sigma_\alpha(x)))}{\langle \alpha, x \rangle^2}] \omega_k(y) dy. \end{aligned}$$

Let $r \rightarrow 1$. The final conclusion follows from (4.2) and monotone convergence. \square

An immediate consequence of Theorem 4.5 and [23, Theorem 2.2 and Theorem 2.3] is the following identity.

Corollary 4.6. *Let $1 < p < \infty$, $f \in L^p(\mathbb{S}, \omega_k \sigma)$ and set $u = P_k[f]$. Then*

$$\begin{aligned} \int_{\mathbb{S}} |f(x)|^p \omega_k(x) d\sigma(x) &= |u(0)|^p + C_k \int_{\mathbb{B}} (|y|^{2-2\gamma-d} - 1) \\ &\times [p(p-1)|u(y)|^{p-2} |\nabla u(y)|^2 + 2 \sum_{\alpha \in R_+} k(\alpha) \frac{F(u(y), u(\sigma_\alpha(y)))}{\langle \alpha, y \rangle^2}] \omega_k(y) dy. \end{aligned}$$

5. SHARP ESTIMATES OF THE GREEN FUNCTION AND POISSON KERNEL IN RANK ONE

In this part we consider the rank one case. The basic situation is that of the root system $A_1 = \{\pm(e_1 - e_2)\}$ in \mathbb{R}^2 , where e_1, e_2 denote the standard basis vectors. We choose $\alpha = e_1 - e_2$ as positive root and let $\sigma_\alpha(x_1, x_2) = (x_2, x_1)$ denote the reflection corresponding to α . To simplify formulas, it will be convenient to switch to the orthonormal basis

$$(e'_1, e'_2) = \left(\frac{1}{\sqrt{2}}(e_1 - e_2), \frac{1}{\sqrt{2}}(e_1 + e_2) \right)$$

and write $x \in \mathbb{R}^2$ as $x = (x_1, x_2)$ with coordinates x_1, x_2 with respect to the basis (e'_1, e'_2) . The reflection σ writes $\sigma(x_1, x_2) = (-x_1, x_2)$. By formula (2.2) we obtain

$$V_k f(y) = c_k \int_{-1}^1 f(ty_1, y_2) (1-t)^{k-1} (1+t)^k dt.$$

This case has a nice motivation, namely the potential theory of a 2-dimensional k -Dyson Brownian Motion, which corresponds to the W -invariant Dunkl process in this case.

More generally, we will consider the rank one case with root system A_1 in \mathbb{R}^d , with the intertwining operator given by

$$(5.1) \quad V_k f(y) = c_k \int_{-1}^1 f(ty_1, y_2, \dots, y_d) (1-t)^{k-1} (1+t)^k dt.$$

Though this generalization seems elementary from the algebraic point of view, it reveals nontrivial analytic phenomena which are strongly dependent on the underlying dimension. Note that in the rank one case we have $\gamma = k$, and as before we work under the assumption $d + 2k > 2$.

The Newton kernel (3.1) can be written as

$$(5.2) \quad N_k(x, y) = \tilde{C}_k \int_{-1}^1 \frac{(1-t)^{k-1} (1+t)^k dt}{(|x|^2 + |y|^2 - 2(tx_1y_1 + x_2y_2 + \dots + x_dy_d))^{k+d/2-1}},$$

where $\tilde{C}_k = c_k C_k$ and the constants c_k, C_k were defined in (2.2) and (3.2). The reflection σ writes

$$\sigma(x_1, x_2, \dots, x_d) = (-x_1, x_2, \dots, x_d).$$

We then have

$$(5.3) \quad \begin{aligned} |x|^2 + |y|^2 - 2(tx_1y_1 + x_2y_2 + \dots + x_dy_d) &= |x - y|^2 + 2x_1y_1(1-t) \\ &= |x - \sigma y|^2 - 2x_1y_1(1+t). \end{aligned}$$

Our first result in this section characterizes the asymptotic behaviour of the Newton kernel $N_k(x, y)$.

Theorem 5.1. *Let $\Phi(x, y) := |x - y| \vee |x - \sigma y|$. The two-sided bound of $N_k(x, y)$ on $\mathbb{R}^d \times \mathbb{R}^d$ is the following.*

1. If $d = 2$, then

$$(5.4) \quad N_k(x, y) \asymp \frac{1}{\Phi(x, y)^{2k}} \left[1 \vee \log \left(\frac{|x_1 y_1|}{|x - y|^2} \right) \right].$$

2. If $d = 3$, then

$$(5.5) \quad N_k(x, y) \asymp \frac{1}{\Phi(x, y)^{2k} |x - y|}.$$

3. If $d = 4$, then

$$(5.6) \quad N_k(x, y) \asymp \frac{1}{\Phi(x, y)^{2k} |x - y|^2} \left[1 \vee \log \left(\frac{|x_1 y_1|}{|x - \sigma y|^2} \right) \right].$$

4. If $d \geq 5$, then

$$(5.7) \quad N_k(x, y) \asymp \frac{1}{\Phi(x, y)^{2k} |x - y|^2 (|x - y| \wedge |x - \sigma y|)^{d-4}}.$$

Theorem 5.1 is a direct consequence of Lemma 5.2 and Lemma 5.3 below.

Lemma 5.2. *The two-sided bound of $N_k(x, y)$ on $\{(x, y) \in \mathbb{R}^d \times \mathbb{R}^d : x_1 y_1 \geq 0\}$ is as follows.*

1. If $d = 2$, then

$$(5.8) \quad N_k(x, y) \asymp \frac{1}{|x - \sigma y|^{2k}} \left[1 \vee \log \left(\frac{x_1 y_1}{|x - y|^2} \right) \right].$$

2. If $d \geq 3$, then

$$(5.9) \quad N_k(x, y) \asymp \frac{1}{|x - \sigma y|^{2k} |x - y|^{d-2}}.$$

Proof. Denote $\zeta = |x - y|^2$ and $\eta = x_1 y_1$. Since $x_1 y_1 \geq 0$ we have $\zeta + \eta \asymp |x - \sigma y|^2$. By (5.2) and (5.3) we have

$$(5.10) \quad N_k(x, y) = C_k \int_{-1}^1 \frac{(1-t)^{k-1} (1+t)^k dt}{(\zeta + 2\eta(1-t))^{k+d/2-1}} = C_k \int_0^2 \frac{s^{k-1} (2-s)^k ds}{(\zeta + 2\eta s)^{k+d/2-1}}.$$

We write $N_k(x, y) = C_k(I_1 + I_2)$, where

$$I_1 = \int_0^1 \frac{s^{k-1} (2-s)^k ds}{(\zeta + 2\eta s)^{k+d/2-1}} \asymp \int_0^1 \frac{s^{k-1} ds}{(\zeta + \eta s)^{k+d/2-1}},$$

and

$$I_2 = \int_1^2 \frac{s^{k-1} (2-s)^k ds}{(\zeta + 2\eta s)^{k+d/2-1}} \asymp \int_1^2 \frac{(2-s)^k ds}{(\zeta + \eta s)^{k+d/2-1}} \asymp (\zeta + \eta)^{1-k-d/2}.$$

For $\eta = 0$ the estimates of the lemma are obvious, so assume $\eta > 0$. Using the change of variables $s = u\zeta$ we get

$$\begin{aligned} I_1 &\asymp \int_0^{1/\zeta} \frac{\zeta^k u^{k-1} du}{(\zeta + \zeta \eta u)^{k+d/2-1}} = \zeta^{1-d/2} \int_0^{1/\zeta} \frac{u^{k-1} du}{(1 + \eta u)^{k+d/2-1}} \\ &= \zeta^{1-d/2} \int_0^{1/\zeta} \frac{du}{u^{d/2} (1/u + \eta)^{k+d/2-1}} = \zeta^{1-d/2} \int_\zeta^\infty \frac{w^{d/2-2} dw}{(w + \eta)^{k+d/2-1}}. \end{aligned}$$

Let $d = 2$ and assume first $\eta \leq \zeta$. Then

$$I_1 \asymp \int_\zeta^\infty \frac{dw}{w(w \vee \eta)^k} = \int_\zeta^\infty w^{-k-1} dw = \zeta^{-k}/k \asymp (\zeta + \eta)^{-k},$$

and note that the same two-sided estimate holds also for I_2 . Assume $\eta > \zeta$. We have

$$\begin{aligned} I_1 &\asymp \int_{\zeta}^{\infty} \frac{dw}{w(w \vee \eta)^k} = \int_{\zeta}^{\eta} \frac{dw}{w\eta^k} + \int_{\eta}^{\infty} \frac{dw}{w^{k+1}} = \eta^{-k} \log(\eta/\zeta) + \eta^{-k}/k \\ &\asymp (\zeta + \eta)^{-k} [1 \vee \log(\eta/\zeta)]. \end{aligned}$$

It is clear that the estimate above holds also for $I_1 + I_2$, and combining it with the previous case we get (5.8).

Assume $d \geq 3$. For $\eta \leq \zeta$ we get

$$\begin{aligned} I_1 &\asymp \zeta^{1-d/2} \int_{\zeta}^{\infty} \frac{w^{d/2-2} dw}{(w \vee \eta)^{k+d/2-1}} = \zeta^{1-d/2} \int_{\zeta}^{\infty} w^{-k-1} dw \\ &= \zeta^{1-k-d/2}/k \asymp (\zeta + \eta)^{-k} \zeta^{1-d/2}. \end{aligned}$$

When $\eta > \zeta$, then a similar reasoning as before gives

$$\begin{aligned} I_1 &\asymp \zeta^{1-d/2} \left(\int_{\zeta}^{\eta} \frac{w^{d/2-2} dw}{\eta^{k+d/2-1}} + \int_{\eta}^{\infty} \frac{dw}{w^{k+1}} \right) \\ &= \zeta^{1-d/2} \left[\frac{2}{(d-2)\eta^{k+d/2-1}} \left(\eta^{d/2-1} - \zeta^{d/2-1} \right) + \frac{1}{k\eta^k} \right] \\ &= \frac{1}{\eta^{k+d/2-1}\zeta^{d/2-1}} \left[\frac{2}{d-2} \left(\eta^{d/2-1} - \zeta^{d/2-1} \right) + \frac{\eta^{d/2-1}}{k} \right]. \end{aligned}$$

Since $0 < \eta^{d/2-1} - \zeta^{d/2-1} \leq \eta^{d/2-1}$, we obtain

$$I_1 \asymp \eta^{-k} \zeta^{1-d/2} \asymp (\zeta + \eta)^{-k} \zeta^{1-d/2}.$$

Finally,

$$I_2 \asymp (\zeta + \eta)^{1-k-d/2} \leq (\zeta + \eta)^{-k} \zeta^{1-d/2},$$

and hence $I_1 + I_2 \asymp I_1$. This proves (5.9). \square

Lemma 5.3. *The two-sided bound of $N_k(x, y)$ on $\{(x, y) \in \mathbb{R}^d \times \mathbb{R}^d : x_1 y_1 < 0\}$ is as follows.*

1. If $2 \leq d \leq 3$, then

$$(5.11) \quad N_k(x, y) \asymp \frac{1}{|x - y|^{2k+d-2}}.$$

2. If $d = 4$, then

$$(5.12) \quad N_k(x, y) \asymp \frac{1}{|x - y|^{2k+2}} \left[1 \vee \log \left(\frac{|x_1 y_1|}{|x - \sigma y|^2} \right) \right].$$

3. If $d \geq 5$, then

$$(5.13) \quad N_k(x, y) \asymp \frac{1}{|x - y|^{2k+2} |x - \sigma y|^{d-4}}.$$

Proof. Denote $\zeta = |x - \sigma y|^2$ and $\eta = |x_1 y_1|$. Since $x_1 y_1 < 0$ we have $\zeta + \eta \asymp |x - y|^2$. By (5.2) and (5.3) we have

$$(5.14) \quad N_k(x, y) = C_k \int_{-1}^1 \frac{(1-t)^{k-1} (1+t)^k dt}{(\zeta + 2\eta(1+t))^{k+d/2-1}} = C_k \int_0^2 \frac{(2-s)^{k-1} s^k ds}{(\zeta + 2\eta s)^{k+d/2-1}}.$$

We write $N_k(x, y) = C_k(I_1 + I_2)$, where

$$I_1 = \int_0^1 \frac{(2-s)^{k-1} s^k ds}{(\zeta + 2\eta s)^{k+d/2-1}} \asymp \int_0^1 \frac{s^k ds}{(\zeta + \eta s)^{k+d/2-1}},$$

and

$$I_2 = \int_1^2 \frac{(2-s)^{k-1} s^k ds}{(\zeta + 2\eta s)^{k+d/2-1}} \asymp \int_1^2 \frac{(2-s)^{k-1} ds}{(\zeta + \eta s)^{k+d/2-1}} \asymp (\zeta + \eta)^{1-k-d/2}.$$

As in the proof of Lemma 5.2, we apply the change of variables $s = u\zeta$ and get

$$\begin{aligned} I_1 &\asymp \zeta^{2-d/2} \int_0^{1/\zeta} \frac{u^k du}{(1 + \eta u)^{k+d/2-1}} = \zeta^{2-d/2} \int_0^{1/\zeta} \frac{du}{u^{d/2-1} (1/u + \eta)^{k+d/2-1}} \\ &= \zeta^{2-d/2} \int_\zeta^\infty \frac{w^{d/2-3} dw}{(w + \eta)^{k+d/2-1}}. \end{aligned}$$

Assume $\eta \leq \zeta$. Then

$$(5.15) \quad I_1 \asymp \zeta^{2-d/2} \int_\zeta^\infty w^{-k-2} dw \asymp \zeta^{1-k-d/2} \asymp (\zeta + \eta)^{1-k-d/2}.$$

When $\eta > \zeta$ we have

$$\begin{aligned} I_1 &\asymp \zeta^{2-d/2} \int_\zeta^\infty \frac{w^{d/2-3} dw}{(w \vee \eta)^{k+d/2-1}} = \zeta^{2-d/2} \left(\int_\zeta^\eta \frac{w^{d/2-3} dw}{\eta^{k+d/2-1}} + \int_\eta^\infty \frac{dw}{w^{k+2}} \right) \\ &= \zeta^{2-d/2} \left(\frac{1}{\eta^{k+d/2-1}} \int_\zeta^\eta w^{d/2-3} dw + \frac{1}{(k+1)\eta^{k+1}} \right). \end{aligned}$$

Assume first $2 \leq d \leq 3$. We obtain

$$\begin{aligned} I_1 &\asymp \zeta^{2-d/2} \left[\frac{2}{(4-d)\eta^{k+d/2-1}} \left(\frac{1}{\zeta^{2-d/2}} - \frac{1}{\eta^{2-d/2}} \right) + \frac{1}{(k+1)\eta^{k+1}} \right] \\ &= \frac{2}{(4-d)\eta^{k+d/2-1}} \left[1 - \left(1 - \frac{(4-d)}{2(k+1)} \right) \frac{\zeta^{2-d/2}}{\eta^{2-d/2}} \right]. \end{aligned}$$

Since $0 < (4-d)/(2k+2) < 1$ and $\zeta^{2-d/2} \leq \eta^{2-d/2}$, we get

$$I_1 \asymp \eta^{1-k-d/2} \asymp (\zeta + \eta)^{1-k-d/2}.$$

Note that the same estimate holds for I_1 when $\eta \leq \zeta$ and for I_2 for all x, y with $x_1 y_1 < 0$. This gives (5.11).

For $d = 4$ and $\eta > \zeta$ we have

$$I_1 \asymp \eta^{-k-1} \log(\eta/\zeta) + \eta^{-k-1}/(k+1) \asymp (\zeta + \eta)^{-k-1} [1 \vee \log(\eta/\zeta)].$$

The last two-sided estimate remains valid for I_1 also when $\eta \leq \zeta$ and the upper bound dominates I_2 . This proves (5.12).

Finally, assume $d \geq 5$ and $\eta > \zeta$. Then

$$\begin{aligned} I_1 &\asymp \zeta^{2-d/2} \left[\frac{2(\eta^{d/2-2} - \zeta^{d/2-2})}{(d-4)\eta^{k+d/2-1}} + \frac{1}{(k+1)\eta^{k+1}} \right] \\ &\asymp \eta^{-k-1} \zeta^{2-d/2} \left(\frac{\eta^{d/2-2} - \zeta^{d/2-2}}{\eta^{d/2-2}} + 1 \right) \asymp (\zeta + \eta)^{-k-1} \zeta^{2-d/2}. \end{aligned}$$

For $\eta \leq \zeta$ we have $\zeta + \eta \asymp \zeta$, and by (5.15) we get

$$I_1 \asymp (\zeta + \eta)^{1-k-d/2} \asymp (\zeta + \eta)^{-k-1} \zeta^{2-d/2}.$$

Since $d \geq 5$, the upper bound of the last estimate also dominates I_2 . The proof of (5.13) is complete. \square

We will next give sharp two-sided estimates of $G_k(x, y)$ in the rank one case.

Theorem 5.4. *Let $\Phi(x, y) := |x - y| \vee |x - \sigma y|$. The two-sided bound of $G_k(x, y)$ on $\mathbb{B} \times \mathbb{B}$ is the following.*

1. *If $d = 2$, then*

$$(5.16) \quad G_k(x, y) \asymp \frac{1}{\Phi(x, y)^{2k}} \left(1 \wedge \frac{\delta(x)\delta(y)}{|x - y|^2} \right) \left[1 \vee \log \left(\frac{|x_1 y_1| \wedge \delta(x)\delta(y)}{|x - y|^2} \right) \right] \\ \times \left[1 \vee \log \left(\frac{|x_1 y_1|}{\delta(x)\delta(y) \vee |x - \sigma y|^2} \right) \right].$$

2. *If $d = 3$, then*

$$(5.17) \quad G_k(x, y) \asymp \frac{1}{\Phi(x, y)^{2k}|x - y|} \left(1 \wedge \frac{\sqrt{\delta(x)\delta(y)}}{|x - y|} \right) \\ \times \left(1 \wedge \frac{\sqrt{\delta(x)\delta(y)}}{|x - y| \wedge |x - \sigma y|} \right).$$

3. *If $d = 4$, then*

$$(5.18) \quad G_k(x, y) \asymp \frac{1}{\Phi(x, y)^{2k}|x - y|^2} \left(1 \wedge \frac{\delta(x)\delta(y)}{|x - y|^2 \wedge |x - \sigma y|^2} \right) \\ \times \left[1 \vee \log \left(\frac{|x_1 y_1| \wedge \delta(x)\delta(y)}{|x - \sigma y|^2} \right) \right].$$

4. *If $d \geq 5$, then*

$$(5.19) \quad G_k(x, y) \asymp \frac{1}{\Phi(x, y)^{2k}(|x - y| \wedge |x - \sigma y|)^{d-4}|x - y|^2} \\ \times \left(1 \wedge \frac{\delta(x)\delta(y)}{|x - y|^2 \wedge |x - \sigma y|^2} \right).$$

Theorem 5.4 is a direct consequence of Lemma 5.5 and Lemma 5.6 below.

Lemma 5.5. *The two-sided bound of $G_k(x, y)$ on $\{(x, y) \in \mathbb{B} \times \mathbb{B} : x_1 y_1 \geq 0\}$ is the following.*

1. *If $d = 2$, then*

$$(5.20) \quad G_k(x, y) \asymp \frac{1}{|x - \sigma y|^{2k}} \left(1 \wedge \frac{\delta(x)\delta(y)}{|x - y|^2} \right) \\ \times \left[1 \vee \log \left(\frac{x_1 y_1 \wedge \delta(x)\delta(y)}{|x - y|^2} \right) \right].$$

2. *If $d \geq 3$, then*

$$(5.21) \quad G_k(x, y) \asymp \frac{1}{|x - \sigma y|^{2k}|x - y|^{d-2}} \left(1 \wedge \frac{\delta(x)\delta(y)}{|x - y|^2} \right).$$

Proof. Let $\zeta = |x - y|^2$, $\eta = x_1 y_1$, and $\xi = \delta(x)\delta(y)$. By Theorem 3.2, (5.1), and (5.3) we have

$$(5.22) \quad G_k(x, y) \asymp \int_{-1}^1 \frac{\xi(1-t)^{k-1}(1+t)^k dt}{(\xi + \zeta + \eta(1-t))(\zeta + \eta(1-t))^{k+d/2-1}}.$$

Assume first $\xi \leq \zeta$. Then by (5.22),

$$G_k(x, y) \asymp \int_{-1}^1 \frac{\xi(1-t)^{k-1}(1+t)^k dt}{(\zeta + \eta(1-t))^{k+d/2}},$$

and observe that the same integral appears in (5.10) with $d' = d + 2$ instead of d . Hence, by (5.9) we get

$$(5.23) \quad G_k(x, y) \asymp \frac{\xi}{(\zeta + \eta)^k \zeta^{d/2}}.$$

Assume $\xi > \zeta$. Using (5.22) and the substitution $s = 1 - t$ we obtain

$$G_k(x, y) \asymp \int_0^2 \frac{\xi s^{k-1}(2-s)^k ds}{(\xi + \eta s)(\zeta + \eta s)^{k+d/2-1}} = I_1 + I_2,$$

where

$$(5.24) \quad I_1 \asymp \int_0^1 \frac{\xi s^{k-1} ds}{(\xi + \eta s)(\zeta + \eta s)^{k+d/2-1}},$$

and

$$(5.25) \quad I_2 \asymp \int_1^2 \frac{\xi(2-s)^k ds}{(\xi + \eta s)(\zeta + \eta s)^{k+d/2-1}} \asymp \frac{\xi}{(\xi + \eta)(\zeta + \eta)^{k+d/2-1}}.$$

In order to estimate I_1 we consider two cases. Assume first $d = 2$.

- (a) $\xi \geq \eta$. Then, by (5.24) and the estimates from the proof of Lemma 5.2 we get

$$I_1 \asymp \int_0^1 \frac{s^{k-1} ds}{(\zeta + \eta s)^k} \asymp \frac{1}{(\zeta + \eta)^k} \left(1 \vee \log \frac{\eta}{\zeta}\right).$$

In view of (5.25), we also have $I_1 + I_2 \asymp I_1$.

- (b) $\xi < \eta$. Then $\zeta < \xi < \eta$, and by (5.24) we have $I_1 \asymp I_1^{(1)} + I_1^{(2)}$, where

$$\begin{aligned} I_1^{(1)} &= \int_0^{\xi/\eta} \frac{\xi s^{k-1} ds}{(\xi + \eta s)(\zeta + \eta s)^k} \asymp \int_0^{\xi/\eta} \frac{s^{k-1} ds}{(\zeta + \eta s)^k} \\ &= \eta^{-k} \left(\int_0^{\zeta/\eta} \frac{s^{k-1} ds}{(\zeta/\eta + s)^k} + \int_{\zeta/\eta}^{\xi/\eta} \frac{s^{k-1} ds}{(\zeta/\eta + s)^k} \right) \\ &\asymp \eta^{-k} \left((\eta/\zeta)^k \int_0^{\zeta/\eta} s^{k-1} ds + \int_{\zeta/\eta}^{\xi/\eta} \frac{ds}{s} \right) \\ &= \eta^{-k} (1/k + \log(\xi/\eta) - \log(\zeta/\eta)) \\ &\asymp \eta^{-k} (1 \vee \log(\xi/\zeta)) \asymp (\zeta + \eta)^{-k} (1 \vee \log(\xi/\zeta)), \end{aligned}$$

and

$$\begin{aligned} I_1^{(2)} &= \int_{\xi/\eta}^1 \frac{\xi s^{k-1} ds}{(\xi + \eta s)(\zeta + \eta s)^k} \asymp \int_{\xi/\eta}^1 \frac{\xi ds}{\eta^{k+1} s^2} = (\eta - \xi)/\eta^{k+1} \\ &\leq \eta^{-k} \asymp (\zeta + \eta)^{-k} \leq (\zeta + \eta)^{-k} (1 \vee \log(\xi/\zeta)). \end{aligned}$$

Hence

$$I_1 \asymp I_1^{(1)} + I_1^{(2)} \asymp I_1^{(1)} \asymp (\zeta + \eta)^{-k} (1 \vee \log(\xi/\zeta)).$$

This and (5.25) give $I_1 + I_2 \asymp I_1$.

Altogether, for $\xi > \zeta$ we have

$$G_k(x, y) \asymp \frac{1}{(\zeta + \eta)^k} \left[1 \vee \log \left(\frac{\eta \wedge \xi}{\zeta} \right) \right],$$

and (5.23) with $d = 2$ otherwise. Hence (5.20) follows.

It remains to estimate I_1 for $d \geq 3$.

(a) $\xi \geq \eta$. By (5.24) and the estimates from the proof of Lemma 5.2 we have

$$I_1 \asymp \int_0^1 \frac{s^{k-1} ds}{(\zeta + \eta s)^{k+d/2-1}} \asymp (\zeta + \eta)^{-k} \zeta^{1-d/2}.$$

Combining this with (5.25) give $I_1 + I_2 \asymp I_1$.

(b) $\zeta < \xi < \eta$. By (5.24) we have $I_1 \asymp I_1^{(1)} + I_1^{(2)}$, where

$$\begin{aligned} I_1^{(1)} &= \int_0^{\xi/\eta} \frac{\xi s^{k-1} ds}{(\xi + \eta s)(\zeta + \eta s)^{k+d/2-1}} \asymp \int_0^{\xi/\eta} \frac{s^{k-1} ds}{(\zeta + \eta s)^{k+d/2-1}} \\ &= \eta^{1-k-d/2} \left(\int_0^{\zeta/\eta} \frac{s^{k-1} ds}{(\zeta/\eta + s)^{k+d/2-1}} + \int_{\zeta/\eta}^{\xi/\eta} \frac{s^{k-1} ds}{(\zeta/\eta + s)^{k+d/2-1}} \right) \\ &\asymp \eta^{1-k-d/2} \left((\eta/\zeta)^{k+d/2-1} \int_0^{\zeta/\eta} s^{k-1} ds + \int_{\zeta/\eta}^{\xi/\eta} s^{-d/2} ds \right) \\ &= \eta^{1-k-d/2} \left(\frac{(\eta/\zeta)^{d/2-1}}{k} + \frac{2}{d-2} \left[(\eta/\zeta)^{d/2-1} - (\eta/\xi)^{d/2-1} \right] \right) \\ &\asymp \eta^{1-k-d/2} (\eta/\zeta)^{d/2-1} \asymp (\zeta + \eta)^{-k} \zeta^{1-d/2}, \end{aligned}$$

and

$$\begin{aligned} I_1^{(2)} &= \int_{\xi/\eta}^1 \frac{\xi s^{k-1} ds}{(\xi + \eta s)(\zeta + \eta s)^{k+d/2-1}} \asymp \int_{\xi/\eta}^1 \frac{\xi ds}{\eta^{k+d/2} s^{d/2+1}} \\ &= \frac{2\xi}{d\eta^{k+d/2}} \left[(\eta/\xi)^{d/2} - 1 \right] \leq \eta^{-k} \xi^{1-d/2} \asymp (\zeta + \eta)^{-k} \zeta^{1-d/2}. \end{aligned}$$

Hence

$$I_1 = I_1^{(1)} + I_1^{(2)} \asymp I_1^{(1)} \asymp (\zeta + \eta)^{-k} \zeta^{1-d/2}.$$

This and (5.25) give $I_1 + I_2 \asymp I_1$.

Altogether, $G_k(x, y) \asymp (\zeta + \eta)^{-k} \zeta^{1-d/2}$ for $\xi > \zeta$, and (5.23) otherwise. This proves (5.21). \square

Lemma 5.6. *The two-sided bound of $G_k(x, y)$ on $\{(x, y) \in \mathbb{B} \times \mathbb{B} : x_1 y_1 < 0\}$ is the following.*

1. If $d = 2$, then

$$(5.26) \quad G_k(x, y) \asymp \frac{1}{|x - y|^{2k}} \left(1 \wedge \frac{\delta(x)\delta(y)}{|x - y|^2} \right) \times \left[1 \vee \log \left(\frac{|x_1 y_1|}{\delta(x)\delta(y) \vee |x - \sigma y|^2} \right) \right].$$

2. If $d = 3$, then

$$(5.27) \quad G_k(x, y) \asymp \frac{1}{|x - y|^{2k+1}} \left(1 \wedge \frac{\sqrt{\delta(x)\delta(y)}}{|x - \sigma y|} \right) \left(1 \wedge \frac{\sqrt{\delta(x)\delta(y)}}{|x - y|} \right).$$

3. If $d = 4$, then

$$(5.28) \quad G_k(x, y) \asymp \frac{1}{|x - y|^{2k+2}} \left(1 \wedge \frac{\delta(x)\delta(y)}{|x - \sigma y|^2} \right) \times \left[1 \vee \log \left(\frac{|x_1 y_1| \wedge \delta(x)\delta(y)}{|x - \sigma y|^2} \right) \right].$$

4. If $d \geq 5$, then

$$(5.29) \quad G_k(x, y) \asymp \frac{1}{|x - y|^{2k+2}|x - \sigma y|^{d-4}} \left(1 \wedge \frac{\delta(x)\delta(y)}{|x - \sigma y|^2} \right).$$

Proof. Denote $\zeta = |x - \sigma y|^2$, $\eta = |x_1 y_1|$, and $\xi = \delta(x)\delta(y)$. By Theorem 3.2, (5.1), and (5.3) we have

$$(5.30) \quad G_k(x, y) \asymp \int_{-1}^1 \frac{\xi(1-t)^{k-1}(1+t)^k dt}{(\xi + \zeta + \eta(1+t))(\zeta + \eta(1+t))^{k+d/2-1}}.$$

Assume first $\xi \leq \zeta$. Then by (5.30),

$$G_k(x, y) \asymp \int_{-1}^1 \frac{\xi(1-t)^{k-1}(1+t)^k dt}{(\zeta + \eta(1+t))^{k+d/2}}.$$

Let $d = 2$. Using the estimate derived for (5.14) with $d' = 4$ instead of d , we get by (5.12) that

$$(5.31) \quad G_k(x, y) \asymp \frac{\xi}{(\zeta + \eta)^{k+1}} \left(1 \vee \log \frac{\eta}{\zeta} \right).$$

If $d \geq 3$, then (5.13) with $d' = d + 2$ instead of d gives

$$(5.32) \quad G_k(x, y) \asymp \frac{\xi}{(\zeta + \eta)^{k+1} \zeta^{d/2-1}}.$$

Assume $\xi > \zeta$. Using (5.30) and substituting $s = t + 1$ we get

$$G_k(x, y) \asymp \int_0^2 \frac{\xi(2-s)^{k-1} s^k ds}{(\xi + \eta s)(\zeta + \eta s)^{k+d/2-1}} = I_1 + I_2,$$

where

$$(5.33) \quad I_1 \asymp \int_0^1 \frac{\xi s^k ds}{(\xi + \eta s)(\zeta + \eta s)^{k+d/2-1}},$$

and

$$(5.34) \quad I_2 \asymp \int_1^2 \frac{\xi(2-s)^{k-1} ds}{(\xi + \eta s)(\zeta + \eta s)^{k+d/2-1}} \asymp \frac{\xi}{(\xi + \eta)(\zeta + \eta)^{k+d/2-1}}.$$

In order to estimate I_1 we need to consider several cases.

(a) $\xi \geq \eta$. Then the estimate depends on the dimension as follows.

(i) $2 \leq d \leq 3$. (5.33) and the estimates derived in the proof of Lemma 5.3 give

$$I_1 \asymp \int_0^1 \frac{s^k ds}{(\zeta + \eta s)^{k+d/2-1}} \asymp \frac{1}{(\zeta + \eta)^{k+d/2-1}}.$$

In view of (5.34), we also have $I_1 + I_2 \asymp I_1$.

(ii) $d = 4$. The same arguments as above give

$$I_1 \asymp \int_0^1 \frac{s^k ds}{(\zeta + \eta s)^{k+1}} \asymp \frac{1}{(\zeta + \eta)^{k+1}} \left(1 \vee \log \frac{\eta}{\zeta} \right),$$

and $I_1 + I_2 \asymp I_1$.

(iii) $d \geq 5$. We get

$$I_1 + I_2 \asymp I_1 \asymp \frac{1}{(\zeta + \eta)^{k+1} \zeta^{d/2-2}}.$$

(b) $\xi < \eta$. Then $\zeta < \xi < \eta$. By (5.33), for any $d \geq 2$ we have $I_1 \asymp I_1^{(1)} + I_1^{(2)}$, where

$$\begin{aligned} I_1^{(1)} &= \int_0^{\xi/\eta} \frac{\xi s^k ds}{(\xi + \eta s)(\zeta + \eta s)^{k+d/2-1}} \asymp \int_0^{\xi/\eta} \frac{s^k ds}{(\zeta + \eta s)^{k+d/2-1}} \\ &= \eta^{1-k-d/2} \left(\int_0^{\zeta/\eta} \frac{s^k ds}{(\zeta/\eta + s)^{k+d/2-1}} + \int_{\zeta/\eta}^{\xi/\eta} \frac{s^k ds}{(\zeta/\eta + s)^{k+d/2-1}} \right) \\ (5.35) \quad &\asymp \eta^{1-k-d/2} \left((\eta/\zeta)^{k+d/2-1} \int_0^{\zeta/\eta} s^k ds + \int_{\zeta/\eta}^{\xi/\eta} s^{1-d/2} ds \right), \end{aligned}$$

and

$$(5.36) \quad I_1^{(2)} = \int_{\xi/\eta}^1 \frac{\xi s^k ds}{(\xi + \eta s)(\zeta + \eta s)^{k+d/2-1}} \asymp \frac{\xi}{\eta^{k+d/2}} \int_{\xi/\eta}^1 s^{-d/2} ds.$$

At this point we need to consider different values of d separately.

(i) $d = 2$. By (5.35) we have

$$I_1^{(1)} \asymp \eta^{-k} \left(\frac{\zeta}{(k+1)\eta} + \frac{\xi - \zeta}{\eta} \right) \asymp \frac{\xi}{\eta^{k+1}},$$

and by (5.36),

$$I_1^{(2)} \asymp \frac{\xi}{\eta^{k+1}} \log \frac{\eta}{\xi}.$$

Therefore,

$$I_1 \asymp I_1^{(1)} + I_1^{(2)} \asymp \frac{\xi}{\eta^{k+1}} \left(1 \vee \log \frac{\eta}{\xi} \right).$$

Since $\zeta < \xi < \eta$, the last estimate of I_1 and (5.34) give

$$I_1 + I_2 \asymp I_1 \asymp \frac{\xi}{(\zeta + \eta)^{k+1}} \left(1 \vee \log \frac{\eta}{\xi} \right).$$

Combining this with (a)(i) and (5.31) we get (5.26).

(ii) $d = 3$. Then (5.35) gives

$$I_1^{(1)} \asymp \frac{1}{\eta^{k+1/2}} \left[\frac{1}{k+1} \sqrt{\zeta/\eta} + 2 \left(\sqrt{\xi/\eta} - \sqrt{\zeta/\eta} \right) \right] \asymp \frac{\sqrt{\xi}}{\eta^{k+1}},$$

and by (5.36),

$$I_1^{(2)} \asymp \frac{\xi}{\eta^{k+3/2}} \left(\sqrt{\eta/\xi} - 1 \right) \leq \frac{\sqrt{\xi}}{\eta^{k+1}} \asymp \frac{\sqrt{\xi}}{(\zeta + \eta)^{k+1}}.$$

Therefore, $I_1 \asymp I_1^{(1)} + I_1^{(2)} \asymp I_1^{(1)}$. Furthermore, by (5.34) we have

$$I_2 \leq \left(\frac{\xi}{\xi + \eta} \right)^{1/2} \frac{1}{(\zeta + \eta)^{k+1/2}} \leq \frac{\sqrt{\xi}}{(\zeta + \eta)^{k+1}}.$$

Hence

$$I_1 + I_2 \asymp I_1 \asymp \frac{\sqrt{\xi}}{(\zeta + \eta)^{k+1}}.$$

This, (a)(i) and (5.32) give (5.27).

(iii) $d = 4$. By (5.35),

$$I_1^{(1)} \asymp \eta^{-k-1} \left(\frac{1}{k+1} + \log \frac{\xi}{\zeta} \right) \asymp \frac{1}{(\zeta + \eta)^{k+1}} \left(1 \vee \log \frac{\xi}{\zeta} \right),$$

and by (5.36),

$$I_1^{(2)} \asymp \frac{\xi}{\eta^{k+2}} \left(\frac{\eta}{\xi} - 1 \right) \leq \frac{1}{\eta^{k+1}} \asymp \frac{1}{(\zeta + \eta)^{k+1}}.$$

Hence $I_1 \asymp I_1^{(1)} + I_1^{(2)} \asymp I_1^{(1)}$. Combining this with (5.34) we get

$$I_1 + I_2 \asymp I_1 \asymp \frac{1}{(\zeta + \eta)^{k+1}} \left(1 \vee \log \frac{\xi}{\zeta} \right).$$

The last estimate, (a)(ii) and (5.32) give (5.28).

(iv) $d \geq 5$. By (5.35),

$$I_1^{(1)} \asymp \frac{1}{\eta^{k+d/2-1}} \left[2 \left(\frac{\eta}{\zeta} \right)^{d/2-2} - \left(\frac{\eta}{\xi} \right)^{d/2-2} \right] \asymp \frac{1}{\eta^{k+1} \zeta^{d/2-2}},$$

and by (5.36),

$$I_1^{(2)} \asymp \frac{\xi}{\eta^{k+d/2}} \left[\left(\frac{\eta}{\xi} \right)^{d/2-1} - 1 \right] \leq \frac{1}{\eta^{k+1} \xi^{d/2-2}} \leq \frac{1}{\eta^{k+1} \zeta^{d/2-2}}.$$

It follows that $I_1 \asymp I_1^{(1)} + I_1^{(2)} \asymp I_1^{(1)}$. Furthermore, by (5.34),

$$I_2 \leq \frac{1}{(\zeta + \eta)^{k+d/2-1}} \leq \frac{1}{(\zeta + \eta)^{k+1} \zeta^{d/2-2}}.$$

Hence

$$I_1 + I_2 \asymp I_1 \asymp \frac{1}{\eta^{k+1} \zeta^{d/2-2}} \asymp \frac{1}{(\zeta + \eta)^{k+1} \zeta^{d/2-2}}.$$

The same estimate holds also in (a)(iii). Combining this with (5.32) we obtain (5.29). \square

By (2.7) and (5.1), the Poisson kernel in the rank one case in \mathbb{R}^d can be written as

$$(5.37) \quad P_k(x, y) = c_k \int_{-1}^1 \frac{(1 - |x|^2)(1 - t)^{k-1}(1 + t)^k dt}{(|x|^2 + 1 - 2(tx_1y_1 + x_2y_2 + \dots + x_dy_d))^{k+d/2}}.$$

As a consequence of the two-sided bounds of the Newton kernel obtained in Theorem 5.1 we get the following two-sided estimates of $P_k(x, y)$.

Corollary 5.7. *Let $\Phi(x, y) := |x - y| \vee |x - \sigma y|$. The two-sided bound of $P_k(x, y)$ on $\mathbb{B} \times \mathbb{S}$ is the following.*

1. If $d = 2$, then

$$(5.38) \quad P_k(x, y) \asymp \frac{1 - |x|^2}{\Phi(x, y)^{2k} |x - y|^2} \left[1 \vee \log \left(\frac{|x_1 y_1|}{|x - \sigma y|^2} \right) \right].$$

2. If $d \geq 3$, then

$$(5.39) \quad P_k(x, y) \asymp \frac{1 - |x|^2}{\Phi(x, y)^{2k} |x - y|^2 (|x - y| \wedge |x - \sigma y|)^{d-2}}.$$

Proof. In view of the formulas (5.2) and (5.37), we can apply Theorem 5.1 with $d' = d + 2$ instead of d . Hence, (5.38) follows from (5.6), and (5.39) follows from (5.7). \square

Remark 5.8. When $d = 1$, the condition $k > 1/2$ guarantees that $N_k(x, y)$ is well defined and finite, and hence also $G_k(x, y)$ and $P_k(x, y)$. Using the methods of this section one can derive the following two-sided estimates.

$$\begin{aligned} N_k(x, y) &\asymp (|x| + |y|)^{1-2k}, \quad x, y \in \mathbb{R}, \\ G_k(x, y) &\asymp \frac{\sqrt{\delta(x)\delta(y)}}{(|x| + |y|)^{2k-1}} \left(1 \wedge \frac{\sqrt{\delta(x)\delta(y)}}{|x - y|} \right), \quad x, y \in (-1, 1), \\ P_k(x, y) &\asymp 1 - |x|, \quad x \in (-1, 1), y \in \{-1, 1\}. \end{aligned}$$

Remark 5.9. It is noteworthy that the explicit formulas for $N_k(x, y)$, $G_k(x, y)$ and $P_k(x, y)$ can be obtained in some particular cases, e.g., for $k \in \mathbb{N}$ and $d \in 2\mathbb{N}$ the integrands in formulas (5.2) and (5.37) are rational functions of t . For instance, when $k = 1$ and $d = 2$ (i.e. for the root system A_1 in \mathbb{R}^2), we can derive the following explicit expressions

$$(5.40) \quad \begin{aligned} N_1(x, y) &= \frac{1}{4\pi} \left[\frac{|x - \sigma y|^2}{2x_1^2 y_1^2} \log \left(\frac{|x - \sigma y|}{|x - y|} \right) - \frac{1}{x_1 y_1} \right], \\ P_1(x, y) &= \frac{1 - |x|^2}{4x_1^2 y_1^2} \left[\frac{2x_1 y_1}{|x - y|^2} + \log \left(\frac{|x - y|}{|x - \sigma y|} \right) \right], \\ G_1(x, y) &= \frac{|x - \sigma y|^2}{8\pi x_1^2 y_1^2} \log \left(\frac{|x - \sigma y|}{|x - y|} \right) - \frac{|x|^2 |x^* - \sigma y|^2}{8\pi x_1^2 y_1^2} \log \left(\frac{|x^* - \sigma y|}{|x^* - y|} \right). \end{aligned}$$

Remark 5.10. W -radial case and applications to the Dyson Brownian Motion. The results of this paper can be applied to the W -invariant part of the Dunkl Laplacian,

$$\Delta_k^W f(x) = \Delta f(x) + \sum_{\alpha \in R_+} k(\alpha) \frac{\partial_\alpha f(x)}{\langle \alpha, x \rangle}.$$

Notice that for $k = 1$ and $W = S_{d-1}$ this is just the generator of the d -dimensional Dyson Brownian motion. In fact, for all integral kernels $K(x, y)$ for Δ_k considered in the paper, the following formula holds

$$(5.41) \quad K^W(x, y) = \sum_{g \in W} K(x, gy),$$

where K^W is the corresponding kernel for the operator Δ_k^W . In the rank one case with $k = 1$ and $d = 2$, formulas (5.40) and (5.41) give

$$\begin{aligned} N_1^W(x, y) &= \frac{1}{2\pi x_1 y_1} \log \left(\frac{|x - \sigma y|}{|x - y|} \right), \\ P_1^W(x, y) &= \frac{2(1 - |x|^2)}{|x - y|^2 |x - \sigma y|^2}, \\ G_1^W(x, y) &= \frac{1}{2\pi x_1 y_1} \log \left(\frac{|x^* - y| |x - \sigma y|}{|x - y| |x^* - \sigma y|} \right). \end{aligned}$$

Furthermore, by multiplying the above formulas by $\omega_1(y) = y_1^2$ and going back to the initial form $A_1 = \{\pm(e_1 - e_2)\}$ with the standard basis vectors e_1, e_2 one obtains the Newton kernel, Poisson kernel and Green function of the unit ball in the setting of the potential theory of 2-dimensional Dyson Brownian motion:

$$\begin{aligned} N_1^{Dys}(x, y) &= \frac{1}{2\pi} \frac{\pi(y)}{\pi(x)} \log \left(\frac{|x - \sigma_\alpha y|}{|x - y|} \right), \\ P_1^{Dys}(x, y) &= \frac{2\pi(y)^2(1 - |x|^2)}{|x - y|^2 |x - \sigma_\alpha y|^2}, \\ G_1^{Dys}(x, y) &= \frac{1}{2\pi} \frac{\pi(y)}{\pi(x)} \log \left(\frac{|x^* - y| |x - \sigma_\alpha y|}{|x - y| |x^* - \sigma_\alpha y|} \right), \end{aligned}$$

where x, y are in the positive Weyl chamber $C^+ = \{(z_1, z_2) : z_1 > z_2\}$, $\pi(z) = z_1 - z_2$, and $\sigma_\alpha(z_1, z_2) = (z_2, z_1)$.

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