Limit transition between hypergeometric functions of type BC and type A

Rösler, M.; Koornwinder, T.; Voit, M.

DOI
10.1112/S0010437X13007045

Publication date
2013

Document Version
Accepted author manuscript

Published in
Compositio Mathematica

Citation for published version (APA):
https://doi.org/10.1112/S0010437X13007045
LIMIT TRANSITION BETWEEN HYPERGEOMETRIC
FUNCTIONS OF TYPE BC AND TYPE A

MARGIT RÖSLER, TOM KOORNWINDER, AND MICHAEL VOIT

ABSTRACT. Let $F_{BC}(\lambda, k; t)$ be the Heckman-Opdam hypergeometric function of type BC with multiplicities $k = (k_1, k_2, k_3)$ and weighted half sum $\rho(k)$ of positive roots. We prove that $F_{BC}(\lambda + \rho(k), k; t)$ converges for $k_1 + k_2 \to \infty$ and $k_1/k_2 \to \infty$ to a function of type A for $t \in \mathbb{R}^n$ and $\lambda \in \mathbb{C}^n$. This limit is obtained from a corresponding result for Jacobi polynomials of type BC, which is proven for a slightly more general limit behavior of the multiplicities, using an explicit representation of Jacobi polynomials in terms of Jack polynomials.

Our limits include limit transitions for the spherical functions of non-compact Grassmann manifolds over one of the fields $\mathbb{F} = \mathbb{R}, \mathbb{C}, \mathbb{H}$ when the rank is fixed and the dimension tends to infinity. The limit functions turn out to be exactly the spherical functions of the corresponding infinite dimensional Grassmann manifold in the sense of Olshanski.

1. Introduction

Consider the Heckman-Opdam hypergeometric functions $F_R(\lambda, k; t)$ for the root systems $R = BC_n = \{\pm e_i, \pm 2e_i, \pm e_i \pm e_j, 1 \leq i < j \leq n\}$ and $A_{n-1} = \{\pm(e_i - e_j) : 1 \leq i < j \leq n\}$ with multiplicities $k = (k_1, k_2, k_3)$ and $k = \kappa$ respectively as studied e.g. in [BO], [H1], [H2], [H3], [HS], [O1], [O2]. Fix a positive subsystem $R_+$ in each case and denote by $\rho_R(k) = \frac{1}{2} \sum_{\alpha \in R_+} k_\alpha \alpha$ the weighted half-sum of positive roots.

The Jacobi polynomials of type $BC_n$ are indexed by the cone of dominant weights $P_{+} = \{(\lambda_1, \ldots, \lambda_n) \in \mathbb{Z}^n_+ : \lambda_1 \geq \ldots \geq \lambda_n\}$ and can be written as

$$P^{BC}_\lambda(k; t) = \frac{1}{c(\lambda + \rho_{BC}(k), k)} F_{BC}(\lambda + \rho_{BC}(k), k; t)$$

where $c$ is the generalized $c$-function. The Jacobi polynomials of type $A_{n-1}$ are indexed by the set $\pi(P_+)$, where $\pi$ denotes the orthogonal projection of $\mathbb{R}^n$ onto $\mathbb{R}^n_0$. They can be written as monic Jack polynomials,

$$P^{A}_{\pi(\lambda)}(k; t) = J^k_\lambda(e^t), \quad t \in \mathbb{R}^n_0;$$

see Section 4 for the precise notation.

In this paper, we shall prove the following limit for the Jacobi polynomials of type $BC_n$:

$$\lim_{k_1 + k_2 \to \infty, k_1/k_2 \to a} P^{BC}_\lambda(k; t) = 4^{|\lambda|} J^{k_3}_\lambda(x(t)) \quad (1.1)$$

2010 Mathematics Subject Classification. Primary 33C67; Secondary 33C52, 43A90, 33C80, 53C35.

Key words and phrases. Hypergeometric functions associated with root systems, limit transitions, Heckman-Opdam theory, spherical functions, Grassmann manifolds, Olshanski spherical pairs.
for \( a \in [0, \infty) \), with the transform
\[
\mathbb{R}^n \to \mathbb{R}^n_t, \quad t \mapsto x(t) \quad \text{with} \quad x_i(t) = \gamma_a + \sinh^2\left( \frac{t_i}{2} \right), \quad \gamma_a = \frac{a + 1}{a + 2}.
\]

This result was already stated in [K2] without proof. A proof different from the one in the present paper was given by R. J. Beerends and the second author in an unpublished manuscript.

Restricting to the case \( a = \infty \) we shall next extend the limit with respect to the spectral variable \( \lambda \) and prove that
\[
\lim_{k_1, k_2 \to \infty \atop k_1, k_2 \to \infty} F_{BC}(\lambda + \rho_{BC}(k), k; t) = \prod_{i=1}^{n} \left( \cosh^2 \frac{t_i}{2} \sum_{l=1}^{n} \lambda_l \cdot F_A \left( \pi(\lambda) + \rho_A(k_3), k; \pi(\log \cosh \frac{t}{2}) \right) \right)
\]
for all \( t \in \mathbb{R}^n \), locally uniformly in \( \lambda \in \mathbb{C}^n \).

Let us briefly discuss the above limits for the rank one case \( n = 1 \) where \( k_3 \) does not appear, the functions \( F_{BC}(\lambda, k; t) \) are essentially Jacobi functions
\[
\varphi_{\lambda, k}^{(\alpha, \beta)}(t) = 2F_1 \left( \frac{1}{2} (\alpha + \beta + i\lambda), \frac{1}{2} (\alpha + \beta + 1 - i\lambda); \alpha + 1; -\sinh^2 t \right),
\]
for which we refer to [K1], and where \( F_A \) reduces to the constant function 1. More precisely, comparing the examples on p. 89 of [O1] and [K1], we have
\[
F_{BC,1}(\lambda, k; t) = \varphi_{-2\lambda}^{(\alpha, \beta)} \left( \frac{t}{2} \right) \quad \text{with} \quad \alpha = k_1 + k_2 - 1/2, \quad \beta = k_2 - 1/2,
\]
and (1.2) becomes the limit
\[
\lim_{\alpha \to \infty, \alpha/\beta \to \infty} \varphi_{\lambda + \pi(\alpha + \beta + 1)}^{(\alpha, \beta)}(t) = (\cosh t)^{-i\lambda} \quad (\lambda \in \mathbb{C}).
\]

This limit is easily seen from
\[
\varphi_{\lambda + \pi(\alpha + \beta + 1)}^{(\alpha, \beta)}(t) = 2F_1 \left( \frac{1}{2} i\lambda, \alpha + \beta + 1 - \frac{1}{2} i\lambda; \alpha + 1; -\sinh^2 t \right)
= (\cosh t)^{-1/2} F_1 \left( \frac{1}{2} i\lambda, -\beta + \frac{1}{2} i\lambda; \alpha + 1; \tanh^2 t \right).
\]

Moreover, the Heckman-Opdam polynomials in rank one are related to the monic Jacobi polynomials \( p_n^{(\alpha, \beta)} \) by
\[
P_n^{BC}(k; it) = 2^n p_n^{\lambda}((\alpha, \beta))(\cos t), \quad n \in \mathbb{Z}^+.
\]

Limit (1.1) means that for \( c = a + 1 \in [1, \infty) \) and \( x = \cos t \in [-1, 1] \),
\[
\lim_{\alpha \to \infty, \alpha/\beta \to \infty} p_n^{\lambda}((\alpha, \beta))(x) = \left( x + \frac{c - 1}{c + 1} \right)^n.
\]

This limit is easily seen from
\[
p_n^{(\alpha, \beta)}(x) = \frac{2^n (\alpha + 1)_n}{(n + \alpha + \beta + 1)_n} \sum_{l=0}^{n} \frac{(n + \alpha + \beta + 1)_l}{(\alpha + 1)_l} \left( \frac{x - 1}{2} \right)^l.
\]

We shall obtain (1.1) by means of an explicit representation of \( P_n^{BC} \) in terms of Jack polynomials which goes back to ideas of [SK] and to [Ha]. The limit (1.2) for the hypergeometric function is then obtained from (1.1) by Phragmén-Lindelöf principles and sharp explicit estimates for general hypergeometric functions which
slightly improve estimates by Opdam [O1] and Schapira [S]. Our limit transition \( \text{(1.2)} \) includes a limit result for the spherical functions of the Grassmannians \( SO_0(p, n)/SO(p) \times SO(n), SU(p, n)/SU(p) \times U(n) \) and \( Sp(p, n)/Sp(p) \times Sp(n) \), where \( Sp(p, n) \) denotes the pseudo-unitary group of index \((p, n)\) over \( \mathbb{H} \). As \( p \to \infty \) (and the rank \( n \) is fixed), the spherical functions of these Grassmannians converge to (restrictions of) the spherical functions of the reductive symmetric space \( GL_+(n, \mathbb{R})/SO(n), GL(n, \mathbb{C})/U(n) \) and \( GL(n, \mathbb{H})/Sp(n) \), respectively. We shall also show that the obtained limits are exactly the spherical functions of the corresponding infinite dimensional Grassmannians in the sense of Olshanski. Our results for infinite dimensional Grassmannians are also of interest in comparison with the recent results of [DOW]. There it is shown that under natural conditions on an infinite dimensional symmetric space \( G_{\infty}/K_{\infty} = \lim G_n/K_n \) where \( G_n/K_n \) are Riemannian symmetric of compact type, spherical functions of \( G_n/K_n \) can have a limit which is \( K_{\infty} \)-spherical only if the \( G_n/K_n \) are Grassmannians.

This paper is organized as follows: In Section 2 we recapitulate some basic notions and facts on the Cherednik kernel and Heckman-Opdam hypergeometric functions. We need the Cherednik kernel because we improve in Section 3 estimates of Opdam [O1] and Schapira [S] for this function. This results in an estimate for the Heckman-Opdam hypergeometric functions which is uniform in the multiplicity parameters. The Cherednik kernel will not be further used in the main part of the paper, starting in Section 4, where the limit \( \text{(1.2)} \) for Jacobi polynomials of type BC is proved. This result, the estimates of Section 3, and Phragmén-Lindelöf principles are combined in Section 5, leading to the limit \( \text{(1.2)} \). In Section 6 we briefly discuss this limit in terms of spherical functions for non-compact Grassmann manifolds of growing dimension and fixed rank. Finally, in Section 7 the Olshanski spherical functions of the associated infinite dimensional Grassmannians are characterized.

2. Notation and Preliminaries

Let \( a \) be a finite-dimensional Euclidean space with inner product \( \langle \cdot, \cdot \rangle \) which is extended to a complex bilinear form on the complexification \( a_c \) of \( a \). We identify \( a \) with its dual space \( a^* = \text{Hom}(a, \mathbb{R}) \) via the given inner product. Let \( R \subset a \) be a (not necessarily reduced) crystallographic root system and let \( W \) be the Weyl group of \( R \). For \( \alpha \in R \) we write \( \alpha^\vee = 2\alpha/\langle \alpha, \alpha \rangle \) and denote by \( \sigma_\alpha(t) = t - \langle t, \alpha^\vee \rangle \alpha \) the orthogonal reflection in the hyperplane perpendicular to \( \alpha \). We denote by \( K \) the vector space of multiplicity functions \( k = (k_\alpha)_{\alpha \in R} \), satisfying \( k_\alpha = k_\beta \) if \( \alpha \) and \( \beta \) are in the same \( W \)-orbit. We shall write \( k \geq 0 \) \((k > 0)\) if \( k_\alpha \geq 0 \) \((k_\alpha > 0)\) for all \( \alpha \in R \). For \( k \in K \) let

\[
\rho = \rho(k) := \frac{1}{2} \sum_{\alpha \in R_+} k_\alpha \alpha \tag{2.1}
\]

be the weighted half-sum of positive roots, where \( R_+ \) is some fixed positive subsystem of \( R \). Let

\[
a_+ := \{ t \in a : \langle t, \alpha \rangle > 0 \ \forall \alpha \in R_+ \}
\]

be the positive Weyl chamber associated with \( R_+ \). If \( k \geq 0 \), then \( \rho(k) \in a_+ \), and if \( k > 0 \), then \( \rho(k) \in a_+ \). This follows from the fact that for a simple system \( \{ \alpha_i \} \subset R_+ \) (with indivisible roots \( \alpha_i \)), the reflection \( \sigma_{\alpha_i} \) leaves \( R_+ \setminus \{ \alpha_i \} \) invariant, and hence

\[
\langle \rho(k), \alpha^\vee_i \rangle = k_{\alpha_i} + 2k_{2\alpha_i}.
\]
(with the understanding that $k_{2\alpha_i} = 0$ if $2\alpha_i \not\in R$), c.f. [M1], Section 11.
For fixed $k \in K$, the Cherednik operator in direction $\xi \in a$ is defined by

$$T_\xi = T_\xi(k) := \partial_\xi + \sum_{\alpha \in R_+} k_\alpha \langle \alpha, \xi \rangle \frac{1}{1 - e^{-\alpha}} (1 - \sigma_\alpha) - \langle \rho(k), \xi \rangle$$

where $\partial_\xi$ is the usual directional derivative and

$$e^\lambda(t) := e^{(\lambda, t)} \quad \forall \lambda, t \in a_C.$$ 

For fixed $k$, the operators $\{T_\xi(k), \xi \in a\}$ commute. According to Theorem 3.15 of [O1], there exist a $W$-invariant tubular neighborhood $U$ of $a$ in $a_C$ and a unique holomorphic function $G$ on $a_C \times K^reg \times U$ which satisfies

(i) $\forall \xi \in a, \lambda \in a_C : T_\xi(k) G(\lambda, k; \cdot) = \langle \lambda, \xi \rangle G(\lambda, k; \cdot)$

(ii) $G(\lambda, k; 0) = 1$. 

(2.2) 

The function $G$ is called the Cherednik-Opdam kernel. We shall mainly be concerned with the hypergeometric function associated with $R$, which is given by

$$F(\lambda, k; t) := \frac{1}{|W|} \sum_{w \in W} G(\lambda, k; w^{-1}t).$$

It is actually $W$-invariant both in $\lambda$ and $t$. The functions $F(\lambda, k; \cdot)$ generalize the spherical functions of Riemannian symmetric spaces of the non-compact type, which occur for specific values of the multiplicity parameter $k \geq 0$.

In order to interpret the main results below in the geometric context, we shall use the following scaling property:

**Lemma 2.1.** Let $R$ be a root system in a Euclidean space $a$ with multiplicity function $k$. For a constant $c > 0$ consider the rescaled root system $\bar{R} := cR := \{c\alpha, \alpha \in R\}$ and define $\bar{k}$ on $\bar{R}$ by $\bar{k}_\alpha := k_\alpha$. Then the associated Cherednik kernels are related via

$$G_\lambda(\bar{k}; t) = G_{\lambda/c}(k; ct).$$

A corresponding result holds also for the associated hypergeometric functions.

**Proof.** Write $f(t) = f(ct)$ for functions $f$ on $a$. Then

$$(T_\xi(\bar{k}) \bar{f})(t) = (T_\xi(k)f)(ct).$$

In view of characterization (2.2), this implies the assertion. \qed

In this paper, we shall always assume that $k \geq 0$ and we often write

$$G(\lambda, k; t) = G_\lambda(k; t), \quad F(\lambda, k; t) = F_\lambda(k; t).$$

For certain spectral variables $\lambda$, the hypergeometric functions $F_\lambda$ are actually exponential polynomials, called Heckman-Opdam Jacobi polynomials. To introduce these, let $P = \{\lambda \in a : \langle \lambda, \alpha^\vee \rangle \in \mathbb{Z} \forall \alpha \in R\}$ denote the weight lattice of $R$ and $P_+ = \{\lambda \in P : \langle \lambda, \alpha^\vee \rangle \geq 0 \forall \alpha \in R_+\}$ the set of dominant weights associated with $R_+$. We equip $P_+$ with the usual dominance order, that is, $\mu < \lambda$ iff $\lambda - \mu$ is a sum of positive roots. Let

$$\mathcal{T} := \text{span}_C \{e^\lambda, \lambda \in P\}$$
denote the space of exponential polynomials associated with $R$. The monomial symmetric functions
\[ M_\lambda = \sum_{\mu \in W_\lambda} e^\mu, \quad \lambda \in P_+ \quad (2.3) \]
form a basis of the subspace $T^W$ of $W$-invariant elements from $T$.

**Definition 2.2.** The Jacobi polynomials $\{P_\lambda(k), \lambda \in P_+\}$ associated with $R$ are uniquely characterized by the following two conditions:

(i) $P_\lambda(k) = M_\lambda + \sum_{\mu < \lambda} c_{\lambda\mu}(k) M_\mu$, $(c_{\lambda\mu}(k) \in \mathbb{C})$;

(ii) $L_k P_\lambda(k) = \langle \lambda, \lambda + 2\rho(k) \rangle P_\lambda(k)$, where
\[ L_k = \Delta_a + \sum_{\alpha \in R_+} k_\alpha \coth \frac{\langle \alpha, t \rangle}{2} \partial_{\alpha}. \quad (2.4) \]

Note that (2.4) just gives the $W$-invariant part of the Heckman-Opdam Laplacian, which is given by restriction to $W$-invariant functions of
\[ \sum_{i=1}^n T_\xi_i(k)^2 - |\rho(k)|^2, \]
with an arbitrary orthonormal basis $\{\xi_1, \ldots, \xi_n\}$ of $a$. The operator $L_k$ generalizes the radial part of the Laplace-Beltrami operator on a Riemannian symmetric space of the non-compact type.

Let us point out that in the definition of the Jacobi polynomials, condition (ii) is frequently replaced by an orthogonality condition. As remarked in Proposition 8.1 of [H1], both sets of conditions are equivalent. Note also that in [H1], the Jacobi polynomials are indexed by $-P_+$ instead of $P_+$, which leads to a different sign in (ii).

According to equation (4.4.10) of [HS], the $P_\lambda(k)$ can be expressed in terms of the hypergeometric function via
\[ F_{\lambda + \rho}(k; t) = c(\lambda + \rho, k) P_\lambda(k; t), \quad (2.5) \]
where $c(\lambda, k)$ is the generalized $c$-function as defined in [HS], Definition 3.4.2. As the polynomial $P_0(k)$ is a constant, it follows that
\[ F_{\rho}(k; t) = 1. \quad (2.6) \]

### 3. Some estimates for $G$ and $F$

The growth behavior and asymptotic properties of the Cherednik kernel $G$ and the hypergeometric function $F$ have been studied in detail in [O1] as well as in [S], where the precise asymptotic behavior in the space variable was determined. We recall the following results:

**Lemma 3.1.** ([O1]) Let $k \geq 0$. Then for all $\lambda \in aC$ and all $t \in a$,
\[ |G_\lambda(k; t)| \leq \sqrt{|W|} \cdot e^{\max_{w \in W} Re(w\lambda, t)}. \quad (3.1) \]

**Lemma 3.2.** ([S]) Let $k \geq 0$. Then

1. For $\lambda \in a$, the kernel $G_\lambda(k; \cdot)$ is real and strictly positive on $a$.
2. $|G_\lambda(k; t)| \leq G_{Re\lambda}(k; t)$ for all $\lambda \in aC$ and $t \in a$. 


By symmetrization over the Weyl group, one obtains the same properties and estimates for the hypergeometric function $F$.

In [S], Opdam’s estimate (3.1) was substantially improved. In fact, it is shown there that for all $\lambda \in \mathfrak{a}$ and all $t \in \mathfrak{a}$,

$$G_\lambda(k; t) \leq G_0(k; t) \cdot e^{\max_{w \in W} \langle w\lambda, t \rangle}$$

(3.2)

and that for fixed $k > 0$, the kernel $G_0$ has the asymptotic behavior

$$G_0(k; t) \asymp \prod_{\alpha \in R_0^+ \mid \langle \alpha, t \rangle \geq 0} (1 + \langle \alpha, t \rangle) e^{-\langle \rho, t+ \rangle}$$

where $R_0^+$ denotes the set of indivisible positive roots and $t_+$ is the unique element from the orbit $Wt$ which is contained in $\overline{\mathfrak{a}_+}$.

The following result generalizes Schapira’s estimate (3.2).

**Theorem 3.3.** Let $k \geq 0$. Then for all $\lambda \in \mathfrak{a}$, all $\mu \in \overline{\mathfrak{a}_+}$ and all $t \in \mathfrak{a}$,

$$G_{\lambda+\mu}(k; t) \leq G_\mu(k; t) \cdot e^{\max_{w \in W} \langle w\lambda, t \rangle}.$$ 

The same estimate holds for the hypergeometric function $F$ instead of $G$.

For $\mu = \rho \in \overline{\mathfrak{a}_+}$ we obtain, in view of identity (2.6) and of Lemma 3.2, the following

**Corollary 3.4.** Let $k \geq 0$. Then for all $\lambda \in \mathfrak{a}_C$ and all $t \in \mathfrak{a}$,

$$|F_{\lambda+\rho}(k; t)| \leq e^{\max_{w \in W} \text{Re} \langle w\lambda, t \rangle}.$$ 

(3.3)

**Remarks.**

1. While the proof of (3.2) is by real-analytic methods and uses the Cherednik operators, we shall present a different approach, based on methods from complex analysis.
2. Remark 3.1 of [S] implies the following asymptotics for $t \in \overline{\mathfrak{a}_+}$, when $k > 0$ and some real $\lambda \in \overline{\mathfrak{a}_+}$ are fixed:

$$F_{\lambda+\rho}(k; t) \asymp e^{\langle \lambda, t \rangle}.$$ 

For our purposes, it will however be important to have an estimate which is uniform in $k$.

For the proof of Theorem 3.3 we shall use the Phragmén-Lindelöf principle, see e.g. Theorem 5.61 of [T].

**Lemma 3.5.** (Phragmén-Lindelöf). Let $f$ be holomorphic in an open neighborhood of the right half plane $H = \{ z \in \mathbb{C} : \text{Re} z \geq 0 \}$, and suppose that $f$ satisfies

$$|f(iy)| \leq M \quad \forall y \in \mathbb{R}$$

and, as $|z| = r \to \infty$,

$$f(z) = O(e^{r^\beta})$$

for some $\beta < 1$, uniformly in $H$. Then actually $|f(z)| \leq M$ for all $z \in H$. 

Proof of Theorem 3.3. Fix \( t \in a \) and denote again by \( t^+ \) the unique element from the orbit \( Wt \) which is contained in \( \overline{a^+} \). Further, put
\[
S := \{ \lambda \in a_C : \Re \lambda \in a^+ \}.
\]
The geometry of root systems implies that for \( \lambda \in S \) and all \( w \in W \),
\[
\langle w \Re \lambda, t \rangle \leq \langle \Re \lambda, t^+ \rangle.
\]
Fix now \( w \in W \) and consider the function
\[
f(\lambda) := e^{-\langle \lambda, t^+ \rangle} \cdot \frac{G_{w\lambda + \mu}(k; t)}{G_{\mu}(k; t)}
\]
which is holomorphic on \( a_C \). We shall investigate \( f \) on the closure \( \overline{S} \) of \( S \). By part (2) of Lemma 3.2 we have
\[
|f(\lambda)| \leq f(\Re \lambda).
\]
Hence for \( \lambda \in \overline{S} \), Lemma 3.1 leads to the estimate
\[
|f(\lambda)| \leq e^{-\langle \Re \lambda, t^+ \rangle} \cdot \frac{G_{w\Re \lambda + \mu}(k; t)}{G_{\mu}(k; t)} \leq \sqrt{|W|} \cdot \frac{e^{\langle \mu, t^+ \rangle}}{G_{\mu}(k; t)}.
\]
Note that the right side is independent of \( \lambda \). Again by Lemma 3.2 we further obtain for real \( \lambda \in a \) the uniform estimate
\[
|f(i\lambda)| = \frac{|G_{iw\lambda + \mu}(k; t)|}{G_{\mu}(k; t)} \leq 1.
\]
We claim that \( |f| \leq 1 \) on \( \overline{S} \). For this, fix a basis \( \{\lambda_1, \ldots, \lambda_n\} \subseteq P_+ \) of fundamental weights. Then each \( \lambda \in S \) has a unique expansion \( \lambda = \sum_{i=1}^n z_i \lambda_i \) with \( z_i \in H = \{z \in \mathbb{C} : \Re z \geq 0\} \). Consider first \( \lambda = z_1 \lambda_1 \) with \( z_1 \in H \). In view of estimates (3.5) and (3.4), we may apply Lemma 3.5 with \( \beta = 0 \), thus obtaining
\[
|f(z_1 \lambda_1)| \leq 1 \quad \forall z_1 \in H.
\]
We proceed by induction: Suppose, for \( 1 \leq m < n \), that
\[
|f(z_1 \lambda_1 + \ldots + z_m \lambda_m)| \leq 1 \quad \forall z_1, \ldots, z_m \in H.
\]
Consider \( h(z_{m+1}) := f(z_1 \lambda_1 + \ldots + z_m \lambda_m + z_{m+1} \lambda_{m+1}) \) for \( z_{m+1} \in H \). This function is uniformly bounded on \( H \) according to (3.4), and for purely imaginary \( z_{m+1} \in i\mathbb{R} \) we have
\[
|h(z_{m+1})| \leq |f(\Re(z_1 \lambda_1 + \ldots + z_m \lambda_m + z_{m+1} \lambda_{m+1}))| = |f(\Re z_1 \lambda_1 + \ldots + \Re z_m \lambda_m)|
\]
which is less or equal to 1 by our induction hypothesis. By Lemma 3.3 we conclude that \( |h(z)| \leq 1 \) for all \( z \in H \). Thus, induction shows that \( |f(\lambda)| \leq 1 \) for all \( \lambda \in S \), and in particular for all \( \lambda \in \overline{a^+} \). If \( \lambda \in a \) is arbitrary, just use the fact that \( \lambda = w \lambda' \) with some \( w \in W \) and \( \lambda' \in \overline{a^+} \). This implies the assertion.

\[\square\]
4. Limit transition for Jacobi polynomials of type BC

Let $a = \mathbb{R}^n$ with the usual Euclidian scalar product and denote by $(e_i)_{i=1,\ldots,n}$ the standard basis of $\mathbb{R}^n$. We consider the root system $BC_n$ in $\mathbb{R}^n$ with the positive subsystem

$$BC_n^+ = \{e_i, 2e_i, 1 \leq i \leq n\} \cup \{e_i \pm e_j, 1 \leq i < j \leq n\},$$

as well as the root system $A_{n-1}$ in the linear subspace

$$\mathbb{R}_{n}^0 := \{t \in \mathbb{R}^n : t_1 + \ldots + t_n = 0\}$$

with the positive subsystem

$$A_{n-1}^+ = \{e_i - e_j, 1 \leq i < j \leq n\}.$$

The Jacobi polynomials associated with these root systems (following Definition 2.2) as well as their relationship have been widely studied; see in particular [BO], [BF], [H1] and [H2]. We recall the fundamental facts: Let

$$\pi(t) := t - \frac{1}{n}(t, \omega_n)\omega_n$$

with

$$\omega_n = e_1 + \ldots + e_n$$

denote the orthogonal projection of $\mathbb{R}^n$ onto $\mathbb{R}_{n}^0$. The cone of dominant weights of $BC_n$ is

$$P_{BC}^+ = \{(\lambda_1, \ldots, \lambda_n) \in \mathbb{Z}_+^n : \lambda_1 \geq \ldots \geq \lambda_n\},$$

and the dominant weights of $A_{n-1}$ are given by

$$P_{A}^+ = \pi(P_{BC}^+).$$

For abbreviation, we write $P_+ := P_{BC}^+$, which is just the set of partitions of length $n$. The dominance order and inclusion order on $P_+$ are respectively given by

$$\lambda \leq \mu \iff \sum_{j=1}^i \lambda_j \leq \sum_{j=1}^i \mu_j, \quad i = 1, \ldots, n,$$

$$\lambda \subseteq \mu \iff \lambda_i \leq \mu_i, \quad i = 1, \ldots, n.$$

For the $A_{n-1}$-case, we take a real parameter $\kappa \geq 0$ and consider the monic Jack polynomials $j_\lambda^\kappa$ in $n$ variables which are indexed by partitions $\lambda \in P_+$ and are uniquely characterized by the following conditions:

1. $j_\lambda^\kappa$ is homogeneous of degree $|\lambda|$ and of the form

$$j_\lambda^\kappa = m_\lambda + \sum_{\mu < \lambda} c_{\lambda\mu}(\kappa) m_\mu$$

where $\mu < \lambda$ refers to the dominance order on $P_+$ and the $m_\lambda, \lambda \in P_+$, are the monomial symmetric polynomials

$$m_\lambda(x) = \sum_{\mu \in S_n, \lambda} x^\mu \quad (x \in \mathbb{R}^n).$$

2. $j_\lambda^\kappa$ is an eigenfunction of the operator

$$D_\kappa = \sum_{i=1}^n x_i^2 \frac{\partial^2}{\partial x_i^2} + 2\kappa \sum_{i \neq j} \frac{x_i^2}{x_i - x_j} \frac{\partial}{\partial x_i}.$$
In fact, the Jack polynomials satisfy
\[ D_{\kappa} j_{\lambda}^\kappa = d_{\lambda}(\kappa) j_{\lambda}^\kappa \quad \text{with} \quad d_{\lambda}(\kappa) = \sum_{i=1}^{n} \lambda_i (\lambda_i - 1 + 2\kappa(n - i)), \]
see [Ha] or [St]. For \( \kappa = 0 \), we have \( j_{\lambda}^0 = m_{\lambda} \), while for \( \kappa > 0 \), the polynomial \( j_{\lambda}^\kappa(x) \) coincides up to constant positive factor with the Jack polynomial \( J_{\lambda}(x; 1/\kappa) \) in standard normalization as introduced in [St].

The Heckman-Opdam Jacobi polynomials of type \( A_{n-1} \) with multiplicity parameter \( \kappa \geq 0 \) are essentially Jack polynomials; according to Proposition 3.3. of [BO], the two types of polynomials are related by
\[ P_{\pi(\lambda)}^A(\kappa; t) = j_{\lambda}^\kappa(e^t) \quad \text{where} \quad e^t = (e^{t_1}, \ldots, e^{t_n}), \quad t = (t_1, \ldots, t_n) \in \mathbb{R}_0^n. \]

Notice that the homogeneity of the Jack polynomials implies that for arbitrary \( t \in \mathbb{R}^n \),
\[ j_{\lambda}^\kappa(e^t) = e^{\lambda|t_1 + \cdots + t_n|/n} \cdot j_{\lambda}^\kappa(e^{\pi(t)}). \quad (4.2) \]

The Heckman-Opdam Jacobi polynomials of type \( BC_n \) are parameterized by a multiplicity function \( k = (k_1, k_2, k_3) \geq 0 \) on \( BC_n \), where \( k_1 \) stands for the parameter on \( e_i, k_2 \) for the parameter on \( 2e_i \) and \( k_3 \) for the parameter on \( e_i \pm e_j \). Let \( L_{k}^{BC} \) be the associated operator (2.4) of type \( BC_n \). The corresponding eigenvalue (see [Ha]) is
\[ e_\lambda(k) := d_{\lambda}(k_3) + (k_1 + 2k_2 + 1)|\lambda|, \]
with \( d_{\lambda} \) as above. We then obtain from [Ha] the following representation of the \( BC_n \)-type Jacobi polynomials \( P_{\lambda}^{BC}(k) \) in terms of the Jack polynomials \( j_{\lambda}^{k_3} \):

**Proposition 4.1.** For all \( \lambda, k, t \) as above,
\[ P_{\lambda}^{BC}(k; t) = 4|\lambda| \prod_{\mu \subset \lambda} \frac{L_{k}^{BC} - e_\mu(k)}{e_\lambda(k) - e_\mu(k)} j_{\lambda}^{k_3}(-\sinh^2(t/2)). \quad (4.3) \]

Here \( \sinh^2(t/2) \) is understood component-wise, and \( \mu \subset \lambda \) means that \( \mu \neq \lambda \) and \( \mu_i \leq \lambda_i \) for all \( i \).

**Proof.** Denote the right hand side of (4.3) by \( \tilde{P}_{\lambda}^{BC}(k; t) \). It follows from relation (13) of [Ha] that \( \tilde{P}_{\lambda}^{BC}(k; t) \) is equal to \( P_{\lambda}^{BC}(k; t) \) up to a multiplicative constant. In order to identify this constant, we compare the leading terms of both polynomials in the expansion with respect to the monomial symmetric functions \( M_{\mu}^{BC} \) of type \( BC \) as defined in (2.3). In fact,
\[ 4|\lambda| m_{\lambda}(\sinh^2(t/2)) = M_{\lambda}^{BC}(t) + \sum_{\mu < \lambda} b_{\lambda \mu} M_{\mu}^{BC}(t) \]
with certain constants \( b_{\lambda \mu} \) (see [SK], the last displayed formula on p. 383 with \( t = i\theta \)). Next we use the characterization of the Jack polynomials \( j_{\lambda}^\kappa \) given above and also, from p. 1580 of [Ha], the first part of the characterization of the \( \tilde{P}_{\lambda}^{BC}(k; t) \) and the definition of \( t_i \). Then we conclude that
\[ \tilde{P}_{\lambda}^{BC}(k; t) = M_{\lambda}^{BC}(t) + \sum_{\mu < \lambda} d_{\lambda \mu} M_{\mu}^{BC}(t) \]
(4.4)
with certain coefficients \( d_{\lambda \mu} \). Therefore \( \tilde{P}_{\lambda}^{BC}(k; t) = P_{\lambda}^{BC}(k; t) \) as claimed. \( \square \)
We notice that representations such as (1.3) were already observed by Macdonald [M1] and were used in [SK] for limit transitions between different families of orthogonal polynomials.

From (1.3), we shall deduce the following limit result.

**Theorem 4.2.** Fix a parameter $0 \leq a \leq \infty$ and consider $k = (k_1, k_2, k_3)$ where $k_3 \geq 0$ is fixed. Then

$$\lim_{k_1 + k_2 \to \infty} P^{BC}_\lambda(k; t) = 4^{\lambda} \cdot j_\lambda^{k_3}(x(t)), \quad (4.5)$$

where the transform $t \mapsto x(t), \mathbb{R}^n \to \mathbb{R}^n_+$ is given by

$$x_i(t) = \gamma_a + \sinh^2(\frac{t_i}{2}), \quad \gamma_a = \frac{a + 1}{a + 2}$$

with the understanding that $\gamma_\infty = 1$. The convergence in (4.5) is locally uniform in $t \in \mathbb{R}^n$. Especially if $a = \infty$, then

$$\lim_{k_1 + k_2 \to \infty} P^{BC}_\lambda(k; t) = 4^{\lambda} \cdot j_\lambda^{k_3}\left(\cosh^2\left(\frac{t}{2}\right)\right)$$

$$= \left(\prod_{i=1}^{n} 4 \cosh^2\left(\frac{t_i}{2}\right)^{\lambda_i/n}\cdot P^{A}_{\lambda}(k_3; \pi(\log \cosh^2\frac{t}{2}))\right) \quad (4.6)$$

The case $a = \infty$ occurs for instance if $k_2, k_3 \geq 0$ are fixed and $k_1 \to \infty$.

**Proof.** We split the coordinate transform $t \mapsto x(t)$ and consider first the transform

$$y_i = -\sinh^2\left(\frac{t_i}{2}\right)$$

which is frequently used in the $BC$-setting. In $y$-coordinates, the operator $L^{BC}_k$ becomes

$$\tilde{L}^{BC}_k = \sum_{i=1}^{n} y_i(y_i - 1) \frac{\partial^2}{\partial y_i^2} - \sum_{i=1}^{n} (k_1 + k_2 + 1/2) - (k_1 + 2k_2 + 1)y_i \frac{\partial}{\partial y_i}$$

$$+ 2k_3 \sum_{i \neq j} \frac{y_i(y_i - 1)}{y_i - y_j} \frac{\partial}{\partial y_i},$$

see Section 4 of [BO] (or also [Ha], Section 2.3). Next, we carry out the linear transform $x_i = \gamma_a - y_i$, under which $\tilde{L}^{BC}_k$ becomes

$$\tilde{L}^{BC}_k = \sum_{i=1}^{n} (\gamma_a - x_i)(\gamma_a - 1 - x_i) \frac{\partial^2}{\partial x_i^2} + 2k_3 \sum_{i \neq j} (\gamma_a - x_i)(\gamma_a - 1 - x_i) \frac{\partial}{\partial x_i}$$

$$+ \sum_{i=1}^{n} (k_1 + k_2 + 1/2) - (k_1 + 2k_2 + 1)(\gamma_a - x_i) \frac{\partial}{\partial x_i}.$$

Equation (1.3) thus writes

$$P^{BC}_\lambda(k; t) = 4^{\lambda} \left(\prod_{\mu \subseteq \lambda} \tilde{L}^{BC}_k - e_\lambda(k) \cdot e_\lambda(k)\right) j_\lambda^{k_3}(x(t)) \quad (4.7)$$

with $x = x(t)$. As $k_1 + k_2 \to \infty$, we have

$$e_\lambda(k) \sim \lambda(k_1 + 2k_2).$$
If in addition \( k_1/k_2 \to a \), then
\[
\frac{k_1 + k_2}{k_1 + 2k_2} \to \gamma_a.
\]
Now let \( \mu \subset \lambda \). Then \(|\mu| < |\lambda|\) and for \( f \in C^\infty(\mathbb{R}^n)\) we obtain, as \((k_1, k_2) \to \infty\) in the required way,
\[
\frac{\hat{L}_k^{BC} - e_\mu(k)}{e_\lambda(k) - e_\mu(k)} f(x) \to \frac{1}{|\lambda| - |\mu|} \left( \sum_{i=1}^n x_i \frac{\partial}{\partial x_i} - |\mu| \right) f(x).
\]
For \( f \) a symmetric polynomial, the convergence is locally uniform in \( x \in \mathbb{R}^n \). In our case, \( f = j_\lambda^{k_3} \) is homogeneous of degree \(|\lambda|\). Thus
\[
\sum_{i=1}^n x_i \frac{\partial}{\partial x_i} j_\lambda^{k_3}(x) = |\lambda| \cdot j_\lambda^{k_3}(x)
\]
and therefore
\[
\frac{\hat{L}_k^{BC} - e_\mu(k)}{e_\lambda(k) - e_\mu(k)} j_\lambda^{k_3} \to j_\lambda^{k_3}
\]
locally uniformly, for each \( \mu \subset \lambda \). Iteration according to formula (4.7) yields
\[
P_\lambda^{BC}(k; t) \to 4^{|\lambda|} \cdot j_\lambda^{k_3}(x(t)),
\]
locally uniformly in \( t \) which completes the proof of relation (4.5). Finally, in the setting of relation (4.6) we have \( \gamma_a = 1 \), and the claimed limit result follows from formula (4.2). \(\square\)

Remark. Theorem 4.2 was already stated without proof as Theorem 1 in [K2]. There it was based on an unpublished manuscript of R. J. Beerends and Koornwinder. The proof given in this manuscript uses the coefficients \( c_{\lambda,\mu} \) in
\[
P_\lambda(k) = \sum_{\mu \leq \lambda} c_{\lambda,\mu}(k) e^\mu
\]
with \( c_{\lambda,\lambda} = 1 \) and \( c_{\lambda,w\mu} = c_{\lambda,\mu} \) \((w \in W)\) (which is equivalent to Definition 2.2(i)). By (2.4) and (ii) of this Definition there follows a recurrence relation for the \( c_{\lambda,\mu} \) which determines them uniquely with the given initial value \( c_{\lambda,\lambda} = 1 \). Then it is shown that the coefficients in the recurrence relation for the \( c_{\lambda,\mu} \) in case \( BC \) tend in the limit under consideration to the corresponding coefficients in the recurrence relation for the Jack case. This essentially involves the asymptotics of the operator \( L_k^{BC} \) and the eigenvalue \( e_\lambda(k) \), just as we used in the proof of Theorem 4.2.

Remark. It follows from Macdonald [M0] (see also [BO] (5.3), [La] Théorème 3] and [Ha] p.1580) that from Definition 2.2 an equivalent definition is obtained by replacing condition (i) by
\[
(i)' \quad P_\lambda^{BC}(k; t) = \sum_{\mu \leq \lambda} u_{\lambda\mu} j_\lambda^{k_3}(-\sinh^2(\frac{1}{2} t)), \quad u_{\lambda\lambda} = (-4)^{|\lambda|}.
\]
Macdonald [M0] also obtained a recurrence relation for the coefficients \( u_{\lambda\mu} \). This can be used in order to give a third proof of Theorem 4.2. Furthermore, in combination with the homogeneity of the Jack polynomials, (i)’ yields another limit from \( BC_n \) type Jacobi polynomials to Jack polynomials:
\[
\lim_{r \to \infty} e^{-|\lambda| r(t, \omega)} P_\lambda^{BC}(k; t + r\omega) = j_\lambda^{k_3}(e^t).
\]
(4.8)
This can be further specialized as a limit to $A_{n-1}$ type Jacobi polynomials. Then it is the $q = 1$ analogue of a limit from Macdonald-Koornwinder polynomials to $A_{n-1}$ type Macdonald polynomials given by van Diejen [vD, Section 5.2].

5. LIMIT TRANSITION FOR HYPERGEOMETRIC FUNCTIONS OF TYPE BC

We now extend the above limit transition to the associated hypergeometric functions, where we restrict our attention to the case $a = \infty$.

For abbreviation, we write $C_B$ for the closed Weyl chamber associated with the positive system $BC_n^+$, i.e.

$$C_B = \{ t \in \mathbb{R}^n : t_1 \geq \ldots \geq t_n \geq 0 \}.$$ 

Observe that under the projection $\pi : \mathbb{R}^n \to \mathbb{R}_0^+$, the chamber $C_B$ is mapped onto the closed Weyl chamber associated with the positive subsystem $A_{n-1}^+$ of $A_{n-1}$.

Again, we consider $k = (k_1, k_2, k_3)$ where $k_3 \geq 0$ is fixed. We also recapitulate that the half-sums $[2.1]$ of positive roots for $BC_n$ and $A_{n-1}$ are given by

$$\rho_{BC}(k) = \sum_{i=1}^{n} (k_1 + 2k_2 + 2k_3(n-i)) e_i \quad \text{and} \quad \rho_A(k_3) = k_3 \sum_{i=1}^{n} (n+1-2i) e_i. \quad (5.1)$$

**Theorem 5.1.** For each $t \in \mathbb{R}^n$ and $\lambda \in \mathbb{C}^n$,

$$\lim_{k_1, k_2 \to \infty \atop k_1 / k_2 \to \infty} F_{BC}(\lambda + \rho_{BC}(k), k; t) = \prod_{i=1}^{n} \left( \frac{1}{2} \sum_{i=1}^{n} (\lambda_i - \omega_i) e_i \right)^{\lambda_i / n} \cdot F_A(\pi(\lambda + \rho_A(k_3)), k_3; \pi(\log \cosh \frac{t}{2})). \quad (5.2)$$

The convergence is locally uniform with respect to $\lambda$.

Notice that in this situation, $\rho_{BC}(k) \to \infty$. The proof of Theorem 5.1 will be based on Theorem 4.3 above and the following well-known theorem of Carlson (see e.g. [T], Theorem 5.81):

**Theorem 5.2.** (Carlson’s Theorem) Let $f$ be a function which is holomorphic in a neighborhood of $\{ z \in \mathbb{C} : \Re z \geq 0 \}$ and satisfies $f(z) = O(e^{c|z|})$ for some constant $c < \pi$. Suppose that $f(n) = 0$ for all $n \in \mathbb{N}_0$. Then $f$ is identically zero.

**Proof of Theorem 5.1.** Let $K_+ := \{ k = (k_1, k_2, k_3) \in \mathbb{R}^3 : k_i \geq 0 \ \forall \ i \}$ and fix some $t \in \mathbb{R}^n$. By the $BC$-symmetry of both sides, we may assume that $t \in C_B$. For $k \in K_+$ define

$$f_k(\lambda) := e^{-(\lambda, t)} \cdot F_{BC}(\lambda + \rho_{BC}(k), k; t)$$

and

$$g(\lambda) := e^{-(\lambda, t)} \cdot \prod_{i=1}^{n} \left( \frac{1}{2} \sum_{i=1}^{n} (\lambda_i - \omega_i) e_i \right)^{\lambda_i / n} \cdot F_A(\pi(\lambda + \rho_A(k_3)), k_3; \pi(\log \cosh \frac{t}{2})).$$

The functions $f_k$ and $g$ are holomorphic on $\mathbb{C}^n$. Corollary 3.3 readily implies that the family $\{f_k : k \in K_+\}$ is locally bounded on $\mathbb{C}^n$ and uniformly bounded on the set $S := \{ \lambda \in \mathbb{C}^n : \Re \lambda \in C_B \}$; indeed, as $t \in C_B$ we obtain

$$|f_k(\lambda)| \leq 1 \quad \forall \lambda \in S. \quad (5.2)$$
Now let \((k(j))_{j \in \mathbb{N}} \subset \mathcal{K}_+\) be a sequence of multiplicities such that \(k(j)_1 = k_3\) with fixed \(k_3 \geq 0\) and \(k(j)_1 + k(j)_2 \to +\infty, k(j)_1/k(j)_2 \to +\infty\). For abbreviation, we write

\[
f_j := f_{k(j)}, \quad j \in \mathbb{N}.
\]

We have to show that \(f_j \to g\) locally uniformly on \(\mathbb{C}^q\). By Montel’s theorem in several complex variables (see for instance [3]), each locally bounded sequence of holomorphic functions on \(\mathbb{C}^q\) has a subsequence which converges locally uniformly to some limit function which is again holomorphic on \(\mathbb{C}^q\). It therefore suffices to verify the following condition:

(M) If \((f_{j_\nu})\) is a subsequence of \((f_j)\) such that \(f_{j_\nu} \to h\) locally uniformly on \(\mathbb{C}^q\) for some \(h\), then \(h = g\) on \(\mathbb{C}^q\).

Suppose that \((f_{j_\nu})\) is a subsequence with \(f_{j_\nu} \to h\) locally uniformly on \(\mathbb{C}^q\). According to Theorem 4.2 together with (2.5) and \(F_{\lambda + \rho}(k;0) = 1\), we have

\[
f_{j_\nu}(\lambda) \to g(\lambda)
\]

for all dominant weights \(\lambda \in P_+\). Therefore \(h(\lambda) = g(\lambda)\) for all \(\lambda \in P_+\). Consider again the set \(S\). We claim that

\[
h(\lambda) = g(\lambda) \quad \forall \lambda \in S. \quad (5.3)
\]

Once this is shown, the identity theorem will imply that \(h = g\) on \(\mathbb{C}^q\), and the verification of condition (M) will be accomplished. For the proof of (5.3) we shall apply Carlson’s theorem to \(g - h\) on \(S\), which requires suitable growth bounds on the involved functions. First, \(h\) is the locally uniform limit of the sequence \(f_{j_\nu}\) which is uniformly bounded on \(S\) according to (5.2). Hence

\[
|h(\lambda)| \leq 1 \quad \forall \lambda \in S.
\]

For an estimate of \(g\) on \(S\), note that \(\text{Re} \pi(\lambda)\) is contained in the closed positive chamber associated with \(A^{+}_{n-1}\) for each \(\lambda \in S\). Application of Corollary 3.4 therefore yields

\[
\left| e^{-\langle \pi(\lambda), \pi(\log(\cosh^2 t/2)) \rangle} \cdot F_{\lambda}(\pi(\lambda) + \rho(3), \lambda; \pi(\log(\cosh^2 t/2))) \right| \leq 1
\]

for all \(\lambda \in S\). Let us call the function on the left \(E(\lambda)\) and write

\[
|g(\lambda)| = \left| e^{-\langle \lambda, t \rangle} \cdot e^{\langle \pi(\lambda), \pi(\log(\cosh^2 t/2)) \rangle} \cdot \prod_{i=1}^n (\cosh^2 t_i)(\lambda, \omega_n)/n \right| \cdot E(\lambda).
\]

As

\[
\langle \pi(x), \pi(y) \rangle = \langle x, y \rangle - \frac{1}{n} \langle x, \omega_n \rangle \langle y, \omega_n \rangle \quad \forall x, y \in \mathbb{R}^n,
\]

we obtain

\[
|g(\lambda)| = \left| e^{-\langle \lambda, t \rangle} \cdot e^{\langle \lambda, \log(\cosh^2 t/2) \rangle} \right| \cdot E(\lambda) \leq \prod_{i=1}^n \left(e^{-t_i} \cosh^2 t_i\right)^{\text{Re} \lambda_i}
\]

and therefore

\[
|g(\lambda)| \leq 1 \quad \forall \lambda \in S.
\]

Summing up, we have

\[
|g - h| \leq 2 \quad \text{on} \ S \quad \text{and} \quad (g - h)(\lambda) = 0 \quad \forall \lambda \in P_+.
\]

As in the proof of Theorem 3.3 we fix a set of fundamental weights \(\{\lambda_1, \ldots, \lambda_n\} \subset P_+\) and write \(\lambda \in S\) as \(\lambda = \sum_{i=1}^n z_i \lambda_i\) with coefficients \(z_i \in \{z \in \mathbb{C} : \text{Re} \ z \geq 0\}\).
Then successive use of Carlson’s Theorem with respect to the variables \(z_1, \ldots, z_n\) shows that actually \(g - h = 0\) on \(S\).

\[
\begin{array}{c}
\text{6. LIMIT TRANSITION FOR SPHERICAL FUNCTIONS OF NONCOMPACT GRASSMANNIANS}
\end{array}
\]

6.1. Spherical functions of non-compact Grassmannians. For specific multiplicities, hypergeometric functions of type \(BC\) occur as spherical functions of non-compact Grassmann manifolds. This was the starting point for the construction of hypergroup convolution algebras with hypergeometric functions as characters in \([R]\). Let us recall this connection. For each of the fields \(\mathbb{F} = \mathbb{R}, \mathbb{C}, \mathbb{H}\) we consider the Grassmann manifolds \(G_{p,q}(\mathbb{F}) = G/K\) where \(G\) is one of the groups \(SO_0(p,q), SU(p,q)\) or \(Sp(p,q)\) with maximal compact subgroup \(K = SO(p) \times SO(q), SU(p \times U(q))\) or \(Sp(p) \times Sp(q)\), where we assume that \(p > q\). We regard \(G\) and \(K\) as subgroups of the indefinite unitary group \(U(p,q; \mathbb{F})\) over \(\mathbb{F}\). The Lie algebra \(g\) of \(G\) has the Cartan decomposition \(g = t \oplus p\) where \(t\) is the Lie algebra of \(K\) and \(p\) consists of the \((p + q)\)-block matrices

\[
\begin{pmatrix}
0 & X \\
X^t & 0
\end{pmatrix}, \quad X \in M_{p,q}(\mathbb{F}).
\]

As a maximal abelian subspace of \(p\) we choose

\[
a = \left\{ H_t = \begin{pmatrix}
0_{p \times p} & \mathbb{I} \\
\mathbb{I} & 0_{(p-q) \times q}
\end{pmatrix}, \quad t \in \mathbb{R}^q \right\}
\]

where \(\mathbb{I} := \text{diag}(t_1, \ldots, t_q)\) is the \(q \times q\) diagonal matrix corresponding to \(t\).

The restricted root system \(\Delta = \Delta(g,a)\) is of type \(BC_q\) with the understanding that zero is allowed as a multiplicity on the long roots. We identify \(a^*\) with \(a\) via the Killing form and \(a\) with \(\mathbb{R}^q\) via the mapping \(H_t \mapsto t\). Under this identification, the Killing form corresponds to a constant multiple of the Euclidean scalar product on \(\mathbb{R}^q\), and

\[
\Delta = BC_q = \{ \pm e_i, \pm 2e_i, \pm e_i \pm e_j, \quad 1 \leq i < j \leq q\} \subset \mathbb{R}^q.
\]

The geometric multiplicities of the roots are given by

\[
m_\alpha = \begin{cases}
d(p-q) & \text{for } \alpha = \pm e_i \\
d-1 & \text{for } \alpha = \pm 2e_i \\
d & \text{for } \alpha = \pm e_i \pm e_j.
\end{cases}
\]

where \(d = \dim g_{\mathbb{F}}\). We consider the spherical functions of \(G/K\) as functions on \(A = \exp a\). Let \(F_{BC}\) denote the hypergeometric function associated with \(R = BC_q\) and multiplicity \(k_\alpha = \frac{1}{2}m_\alpha\) \((m_\alpha\) as above\), and denote by \(\tilde{F}_{BC}\) the hypergeometric function associated with the rescaled root system \(\tilde{R} = 2BC_q\) and multiplicity \(\tilde{k}_\alpha = k_\alpha\). Then according to Remark 2.3 of [HR] and Lemma 2.1 the spherical functions of the Grassmannian \(G_{p,q}(\mathbb{F})\) are given by

\[
\varphi_\lambda(a_t) = \tilde{F}_{BC}(\lambda, \tilde{k}; t) = F_{BC}(\lambda/2, k; 2t), \quad \lambda \in \mathbb{C}^q,
\]

(6.1)
where
\[ t \in \mathbb{R}^q \quad \text{and} \quad a_t = e^{Ht} = \begin{pmatrix} \cosh t & 0 & \sinh t \\ 0 & I_n & 0 \\ \sinh t & 0 & \cosh t \end{pmatrix}. \]

The limit \( k_1 \to \infty \) in Theorem 5.1 here corresponds to \( p \to \infty \). In order to identify the limit in this case, we recapitulate some facts on spherical functions of type A.

6.2. Spherical functions of type A. Consider the symmetric spaces \( G/K \) where \( G \) is one of the connected reductive groups \( GL_+(q, \mathbb{R}), GL(q, \mathbb{C}), GL(q, \mathbb{H}) \) with maximal compact subgroup \( K = SO(q), U(q) \) and \( Sp(q) \), respectively. We have the Cartan decomposition \( G = KAK \) with
\[ A = \exp a, \quad a = \{ t = \text{diag}(t_1, \ldots, t_q), \ t = (t_1, \ldots, t_q) \in \mathbb{R}^q \}. \]

For the moment, we consider the spherical functions of \( G/K \) as functions on \( a \), where we identify \( a \cong \mathbb{R}^q \) via \( t \mapsto t \). The spherical functions of \( G/K \) are then characterized as the continuous functions on \( \mathbb{R}^q \) which are symmetric and satisfy the product formula
\[ \psi(t)\psi(s) = \int_K \psi(\log(\sigma_{\text{sing}}(e^{t} e^{s}))) dk; \]

here \( \sigma_{\text{sing}}(M) = (\sigma_1, \ldots, \sigma_q) \in \mathbb{R}^q \) denotes the singular values of \( M \in M_q(\mathbb{F}) \) ordered by size: \( \sigma_1 \geq \ldots \geq \sigma_q \). The spherical functions of \( G/K = GL(q, \mathbb{F})/U(q, \mathbb{F}) \) are closely related to those of \( G_1/K_1 \) where \( G_1 \) is the corresponding semisimple group \( SL(q, \mathbb{F}) \) and \( K_1 = SU(q, \mathbb{F}) \). Indeed, consider the orthogonal projection \( \pi : \mathbb{R}^q \to \mathbb{R}^q_0 \) as in (6.1). In the same way as above, the spherical functions of \( G_1/K_1 \) may be characterized as the symmetric functions \( \psi \) on \( \mathbb{R}^q_0 \) which satisfy the same product formula (6.3). Now suppose that \( \psi \) is a spherical function of \( G/K \). Then for \( t \in \mathbb{R}^q \), we have
\[ \psi(t) = \psi(t - \pi(t) + \pi(t)) = \psi(t - \pi(t)) \cdot \psi(\pi(t)) \]
because \( t - \pi(t) \) corresponds to the scalar matrix \( \exp(\sum_{i=1}^q t_i/q) \cdot I_q \) which belongs to the subgroup \( Z_R := \{ a \cdot I_q : a > 0 \} \) of the center of \( G \). As the restriction of \( \psi \) to \( Z_R \) is multiplicative on \( Z_R \), we have \( \psi(a \cdot I_q) = a^m \) with some exponent \( m \in \mathbb{C} \).

Therefore
\[ \psi(t) = \exp\left( m \cdot \sum_{i=1}^q t_i/q \right) \cdot \psi(\pi(t)) \]

where the restriction \( \psi|_{\mathbb{R}^q_0} \) corresponds to a spherical function of \( G_1/K_1 \). Conversely, it is easily checked that for a given spherical function \( \psi \) of \( G_1/K_1 \), formula (6.4) defines an extension to a spherical function \( \psi \) of \( G/K \).

We now return to the usual convention and consider spherical functions as functions on the group. For \( G_1/K_1 \), the geometric multiplicity on the restricted root system \( \Delta = A_{q-1} \) is given by \( m = d \). Therefore, again according to Remark 2.3 of [4] and Lemma 2.1 the spherical functions of \( G_1/K_1 \) can be identified as
\[ \psi_\lambda(e^{t}) = F_A(\lambda/2, d/2; 2t), \quad t \in \mathbb{R}^q_0, \]

with \( \lambda \in \mathbb{C}^q_0 := \{ \lambda \in \mathbb{C}^q : \sum_{i=1}^q \lambda_i = 0 \} \). For \( \lambda \in \mathbb{C}^q \), put \( m = \sum_{i=1}^q \lambda_i \). Then
\[ (t - \pi(t), \lambda) = m \cdot \sum_{i=1}^q t_i/q. \]
This shows that we can parameterize the spherical functions of \( G/K \) according to
\[
\psi_\lambda (e^t) = e^{\left(t - \pi i t, \lambda \right)} : F_A (\pi (\lambda / 2), d/2; \pi (2t)), \quad \lambda \in \mathbb{C}^q. \tag{6.7}
\]
With the notions of \eqref{eq:6.1} and \eqref{eq:6.7}, Theorem \ref{thm:5.1} now implies the following limit relation.

**Corollary 6.1.** The spherical functions \( \varphi_\lambda \) of \( G_{p,q} (\mathbb{F}) \) and \( \psi_\lambda \) of \( GL(q, \mathbb{F})/U(q, \mathbb{F}) \) satisfy
\[
\lim_{p \to \infty} \varphi_{\lambda + \rho_{BC}^{geo}}(a_1) = \psi_{\lambda + \rho_{BC}^{geo}}(\cosh t)
\]
for all \( \lambda \in \mathbb{C}^q \) and \( t \in \mathbb{R}^q \), with the “geometric” constants \( \rho_{BC}^{geo} = 2 \rho_B (k) \) given by
\[
\rho_{BC}^{geo} = \sum_{i=1}^q (d(p + q + 2 - 2i) - 2) e_i \quad \text{and} \quad \rho_{A}^{geo} = \sum_{i=1}^q d(q + 1 - 2i) e_i.
\]

**Proof.** From relation \eqref{eq:6.1}, Theorem \ref{thm:5.1} and identity \eqref{eq:6.6} we obtain
\[
\lim_{p \to \infty} \varphi_{\lambda + \rho_{BC}^{geo}}(a_1) = \lim_{k_1 \to \infty} F_{BC} (\lambda/2 + \rho_{BC} (k); 2t)
\]
\[
= \prod_{i=1}^q (\cosh^2 t_i) (\lambda, \omega_q)^/2q \cdot F_A (\pi (\lambda/2) + \rho_A (k_3), d/2; \pi (\ln \cosh^2 t))
\]
\[
eq e^{(\ln \cosh^2 t - \pi (\ln \cosh^2 t), \lambda/2 + \rho_A (k_3))} \cdot F_A (\pi (\lambda/2) + \rho_A (k_3), d/2; \pi (\ln \cosh^2 t))
\]
\[
= \psi_{\lambda + \rho_{BC}^{geo}}(\cosh t)
\]
as claimed. \( \square \)

We finally mention that Corollary \ref{cor:6.1} can be also obtained by sharp estimates on the order of convergence, by comparing explicit versions of the Harish-Chandra integral representations of the involved spherical functions. This is work in progress. We also remark that our limit transition for hypergeometric functions has a counterpart in the Euclidean case, namely the convergence of (suitably scaled) Dunkl-Bessel functions of type B to such of type A, which was obtained in \cite{RV1} by completely different methods.

### 7. Spherical functions of infinite-dimensional Grassmannians

We now discuss an interpretation of the preceding limit results in the context of infinite dimensional symmetric spaces and Olshanski spherical pairs. For the general background on this subject we refer to Faraut \cite{F} and Olshanski \cite{Ol}, \cite{Ol2}. In order to be in agreement with standard terminology, we slightly change our notation. We consider the Grassmannian manifolds \( G_n / K_n \) with \( G_n = SO_0 (n + q, q) \), \( SU(n+q,q) \) or \( Sp(n+q,q) \) and maximal compact subgroup \( K_n = SO(n+q) \times SO(q) \), \( SU(n+q) \times U(q) \) or \( Sp(n+q) \times Sp(q) \). In all three cases, \( G_n \) is regarded as a closed subgroup of \( G_{n+1} \) with \( K_n = G_n \cap K_{n+1} \). Consider the inductive limits \( G_\infty = \lim_{\to} G_n \) and \( K_\infty := \lim_{\to} K_n \). Then \((G_\infty, K_\infty)\) is an Olshanski spherical pair, and \( G_\infty / K_\infty \) is one of the infinite-dimensional Grassmannians \( SO_0 (\infty, q) / SO(\infty) \times SO(q), SU(\infty, q) / SU(\infty) \times U(q) \), \( Sp(\infty, q) / Sp(\infty) \times Sp(q) \). A continuous function
\( \phi : G_\infty \to \mathbb{C} \) is called an Olshanski spherical function of \((G_\infty, K_\infty)\) if \( \phi \) is \( K_\infty \)-biinvariant and satisfies the product formula

\[
\phi(g) \cdot \phi(h) = \lim_{n \to \infty} \int_{K_n} \phi(ghk) \, dk \quad \text{for} \quad g, h \in G_\infty.
\]

We shall now classify the Olshanski spherical functions of \((G_\infty, K_\infty)\) without representation theory.

For this we use the decomposition \( G_n = K_n A_n^+ K_n \)

\[
A_n^+ := \left\{ \begin{pmatrix} \cosh t & 0 & \sinh t \\ 0 & I_n & 0 \\ \sinh t & 0 & \cosh t \end{pmatrix} : t \in C_B \right\}
\]

of representatives of the \( K_n \)-double cosets in \( G_n \), where again

\[
C_B := \{ t = (t_1, \ldots, t_q) \in \mathbb{R}^q : t_1 \geq t_2 \geq \cdots \geq t_q \geq 0 \}
\]
denotes the closed Weyl chamber of type \( BC \). Therefore, independently of \( n \), we identify \( A_n^+ \) with the set of diagonal matrices

\[
D := \{ \cosh \frac{t}{2} := \text{diag}(\cosh t_1, \ldots, \cosh t_q) : t \in C_B \}.
\]

This gives the topological identification \( G_\infty//K_\infty \simeq A_\infty^+ \simeq D \). Notice that the elements of \( D \) are just the lower right \( q \times q \)-blocks of the matrices from \( A_n^+ \). In the same way,

\[
G_\infty//K_\infty \simeq A_\infty^+ := \left\{ \tilde{a}_i^\infty := \begin{pmatrix} \cosh \frac{t}{2} & 0 & \sinh \frac{t}{2} \\ 0 & I_\infty & 0 \\ \sinh \frac{t}{2} & 0 & \cosh \frac{t}{2} \end{pmatrix} : t \in C_B \right\} \simeq D.
\]

By definition of the inductive limit topology, a function \( \phi : G_\infty \to \mathbb{C} \) is continuous and \( K_\infty \)-biinvariant iff for all \( n \in \mathbb{N} \), \( \phi|_{G_n} \) is continuous and \( K_n \)-biinvariant. The space of all continuous, \( K_\infty \)-biinvariant functions on \( G_\infty \) may thus be identified with the space of all continuous functions on \( D \). Using this convention, the Olshanski spherical functions of \((G_\infty, K_\infty)\) can be characterized as follows:

**Lemma 7.1.** A continuous \( K_\infty \)-biinvariant function \( \phi : G_\infty \to \mathbb{C} \) is an Olshanski spherical function if and only if there is a continuous function \( \tilde{\phi} : D \to \mathbb{C} \) with \( \phi(a^\infty_i) = \tilde{\phi}(\cosh t_i) \) for \( t \in C_B \) such that \( \tilde{\phi} \) satisfies the product formula

\[
\tilde{\phi}(a) \cdot \tilde{\phi}(b) = \int_{U(q, \mathbb{R})} \tilde{\phi}(\sigma_{\text{sing}}(akb)) \, dk, \quad a, b \in D. \tag{7.1}
\]

Here the vector \( \sigma_{\text{sing}}(\cdots) \in \mathbb{R}^q \) is identified with the corresponding diagonal matrix.

**Proof.** Let \( \phi \) be a continuous \( K_\infty \)-biinvariant function on \( G_\infty \). By the preceding discussion, \( \phi \) is Olshanski spherical if and only if there is a continuous function \( \phi : D \to \mathbb{C} \) with \( \phi(a^\infty_i) = \tilde{\phi}(\cosh t_i) \) for \( t \in C_B \) such that \( \tilde{\phi} \) satisfies

\[
\tilde{\phi}(\cosh t_i) \cdot \tilde{\phi}(\cosh t_s) = \lim_{n \to \infty} \int_{K_n} \phi(a^\infty_i k a^\infty_s) \, dk = \lim_{n \to \infty} \int_{K_n} \phi(a^\infty_i k a^\infty_s) \, dk \tag{7.2}
\]

for \( s, t \in C_B \). We shall use Proposition 2.2 of [R] to rewrite the integrals on the right hand side. Let \( B_q := \{ w \in M_q(\mathbb{R}) : w^*w < 1 \} \) and

\[
c_n := \int_{B_q} \Delta(I - w^*w)^{(n+q)d/2-\gamma} \, dw \quad \text{with} \quad \gamma := d(q - 1/2) + 1,
\]
where $\Delta$ denotes the determinant and $dw$ means integration with respect to Lebesgue measure. Then
\[
\int_{K_n} \phi(a_n^u b a_n^u) \, dk = c_n^{-1} \int_{B_n} \int_{U_0(q,F)} \phi(\sigma_{\text{sing}}(\sinh t w \sinh s + \cosh t k \cosh s) \cdot \Delta(I - w^* w)^{(n+q)d/2 - \gamma}) \, dk \, dw
\]
where $U_0(q,F)$ is the connected component of $U(q,F)$. The probability measures
\[
c_n^{-1} \cdot \Delta(I - w^* w)^{(n+q)d/2 - \gamma} \, dw
\]
are compactly supported in $B_q$ and tend weakly to the point measure $\delta_0$ for $n \to \infty$. Therefore (7.2) is equivalent to
\[
\phi(\cosh t \cdot \phi(\cosh s) = \int_{U_0(q,F)} \phi(\sigma_{\text{sing}}(\cosh t k \cosh s)) \, dk.
\]

Finally, is easily checked that the group $U_0(q,F)$ may be replaced by $U(q,F)$ in the integral, which completes the proof. \hfill $\Box$

We consider the reductive symmetric spaces $G/K = GL(q,F)/U(q,F)$ of sub-section 6.2 and resume the notation from there. We introduce the set of diagonal matrices
\[
D_0 := \{ \epsilon \in M_q(\mathbb{R}) : t = (t_1, \ldots, t_q) \in \mathbb{R}^q \text{ with } t_1 \geq \ldots \geq t_q \}.
\]
Then $G//K \cong D_0$, and a spherical function $\psi$ of $G/K$ may be characterized as a continuous function on $D_0$ satisfying the product formula
\[
\psi(a) \cdot \psi(b) = \int_{U(q,F)} \psi(\sigma_{\text{sing}}(k ab)) \, dk, \quad a, b \in D_0.
\]

Comparison with Lemma 7.1 gives

**Theorem 7.2.** A continuous $K_\infty$-biinvariant function $\phi : G_\infty \to \mathbb{C}$ is an Olshanski spherical function if and only if the function $\phi : D \to \mathbb{C}$ with $\phi(a_\kappa^\infty) = \tilde{\phi}(\cosh t)$ for $t \in C_B$ is the restriction to $D$ of a spherical function $\psi$ of $G/K$. Each spherical function $\psi$ of $G/K$ is uniquely determined by its restriction to $D$, and the Olshanski spherical functions therefore correspond in a bijective way to the spherical functions of $G/K$.

**Proof.** The if-part is clear from Lemma 7.2. The converse direction follows from Lemma 7.1 together with the following lemma. \hfill $\Box$

**Lemma 7.3.** Each continuous function $\varphi$ on $D$ which satisfies product formula (7.1) admits a unique extension to a continuous function $\psi$ on $D_0$ satisfying product formula (7.5).

**Proof.** Assume first that $\psi : D_0 \to \mathbb{C}$ is such an extension of $\varphi$. Consider first a scalar matrix $a = r I_q$ with $r \geq 1$. Then $a \in D$ and hence $\psi(a) = \varphi(a)$. Moreover, as $\psi(a^{-1}) = 1/\psi(a)$ for $a$ as above, the function $\psi$ is uniquely determined by $\varphi$ on the set of scalar matrices $Z = \{ r I_q, r > 0 \}$. Now let $a \in D_0$. We then find $r > 0$ and a matrix $b \in D$ such that $a = rb$. Using Product formula (7.5) we obtain
\[
\psi(r I_q) \psi(b) = \int_{U(q,F)} \psi(\sigma_{\text{sing}}(r k b)) \, dk = \psi(r b) = \psi(a).
\]
Therefore, $\psi$ is determined uniquely by $\varphi$. \hfill $\Box$
Conversely, it is easily checked that for given \( \varphi \), the definition of \( \psi \) first on \( Z \) as above and then on \( D_0 \) via \((7.6)\) leads to a well-defined continuous function \( \psi \) on \( D_0 \) which satisfies the product formula. \( \square \)

We notice at this point that our proof of Theorem \(7.2\) relies only on the explicit product formula \((7.3)\) and does not require the results of the preceding sections. On the other hand, Corollary \(6.1\) and Theorem \(7.2\) imply the following

**Corollary 7.4.** All Olshanski spherical functions of the infinite-dimensional Grassmannians \( G_\infty/K_\infty \) appear as limits of the spherical functions of the Grassmannians \( G_n/K_n \).

Let us finally remark that further Olshanski spherical pairs with fixed rank may be treated in a similar way, for example pairs related to the Cartan motion groups of Grassmann manifolds with growing dimension, see \( [RV2] \).

**References**


