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A PALEY-WIENER THEOREM FOR HARISH-CHANDRA MODULES

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Abstract. We formulate and prove a Paley-Wiener theorem for Harish-Chandra modules for a real reductive group. As a corollary we obtain a new and elementary proof of the Helgason conjecture.
1. Introduction

Let $G$ be a real reductive algebraic group and $K \subset G$ a maximal compact subgroup. Let $V$ be a Harish-Chandra module for $(g, K)$ where $g = \text{Lie}(G)$.

Every Harish-Chandra module admits a completion (globalization) to a representation of $G$. Such a completion is in general not unique. First and foremost is the smooth completion $V^\infty$ of moderate growth, due to Casselman-Wallach, which is unique up to isomorphism, see [5], [22, Sect. 11] and [2]. Another completion is the $G$-module $V^\omega$ of analytic vectors in $V^\infty$ with its natural compact-open topology.

Define the minimal completion of $V$ by the convolution product

$$V_{\min} := C^\infty_c(G) \ast V \subset V^\infty$$

and endow it with a topology as follows: take a finite dimensional subspace $V_f \subset V$ which generates $V$, and consider the surjective map

$$C_c^\infty(G) \otimes V_f \to V_{\min}.$$  

The quotient topology on $V_{\min}$ does not depend on the choice of the finite dimensional generating subspace $V_f$ and thus induces a natural quotient Hausdorff locally convex topology on $V_{\min}$. It is inherent in the construction that $V_{\min}$ embeds equivariantly and continuously into every completion of $V$, hence the terminology.

Next we review Schmid’s interpretation [20] of the Helgason conjecture. The conjecture was stated in [9] and first proven in [12]. Let $\chi$ be a character of the algebra $\mathcal{D}(G/K)$ of $G$-invariant differential operators on $G/K$. The Helgason conjecture states that the Poisson transform for $G/K$ is an isomorphism between the space of hyperfunction sections of a line bundle over the minimal boundary of $G/K$ and the space $C^\infty(G/K) \chi$ of joint eigenfunctions of $\mathcal{D}(G/K)$ with eigencharacter $\chi$. Then Schmid’s interpretation and extension of the Helgason conjecture is

$$V_{\min} = V^\omega$$  \hspace{1cm} (1.1)

as topological vector spaces, for all Harish-Chandra modules $V$. The equality (1.1) was stated in [20] Theorem on p. 317] and [13 Theorem 2.12].

The objective of this work is to understand the equality (1.1) quantitatively. For that let $G = KAN$ be an Iwasawa decomposition of $G$ and $G = KAK$ the associated Cartan decomposition. Let $\| \cdot \|$ be a Cartan-Killing norm on $g$, and define balls $A_R \subset A$ for any $R > 0$ by $A_R = \text{exp}(a_R)$ and $a_R := \{ X \in a \mid \|X\| \leq R \}$. This gives us a family of balls $B_R := KA_R K \subset G$, and we write $C^\infty_c(G) \subset C^\infty_c(G)$ for the subspace of functions with support in $B_R$. We define

$$V^\min_R := C^\infty_c(G) \ast V$$

and endow it with the quotient topology. Note that

$$V_{\min} = \lim_{R \to \infty} V^\min_R$$  \hspace{1cm} (1.2)

as inductive limit of Fréchet spaces.

Next we consider the analytic filtration of $V^\omega$. We recall that a vector $v \in V^\infty$ is analytic if and only if it is $K$-analytic, i.e. the restricted orbit map

$$f_v : K \to V^\infty, \ k \mapsto k \cdot v$$
is analytic (see Lemma 4.1). Now for any $r > 0$ we define a $K$-bi-invariant domain of $K\mathbb{C}$ by $K(r) := K \exp(it_r)$, where
\[ t_r = \{ X \in \mathfrak{t} \mid \|X\| < r \}. \]
We define $V^\omega_r \subset V^\omega$ to be the subspace of those $v$ for which $f_v$ extends holomorphically to $K\mathbb{C}(r)$ and endow it with the topology of uniform convergence on compacta in $K\mathbb{C}(r)$. We then obtain the analytic filtration as inductive limit of Fréchet spaces

\[ V^\omega = \lim_{r \to 0} V^\omega_r. \tag{1.3} \]

By (1.1) and the Grothendieck factorization theorem [8, Ch. 4, Sect. 5, Th. 1] (see also [19, Corollary 24.35]) the two filtrations (1.2) and (1.3) are continuously sandwiched into each other, i.e.:

**Geometric inclusion:** For all $R > 0$ there exists $r = r(R) > 0$ with $V^\omega_{r}^{\min} \subset V^\omega_r$.

**Analytic inclusion:** For all $r > 0$ there exists $R = R(r) > 0$ with $V^\omega_r \subset V^\omega_{r}^{\min}$.

Observe that the equality (1.1) is a consequence of the analytic inclusion.

By a Paley-Wiener type theorem for a Harish-Chandra module $V$ we understand the existence of the geometric and analytic inclusions together with bounds on the numbers $r(R)$ and $R(r)$. In this article we prove such a theorem.

To explain the terminology, we consider the following algebraic type of Fourier transform

\[ \mathcal{F} = \bigoplus_{V \in \mathcal{H}C} \mathcal{F}_V : C^\infty_c(G) \to \bigoplus_{V \in \mathcal{H}C} \text{Hom}_{(g,K)}(V, V^\omega), \]

that is given by
\[ \mathcal{F}_V \phi(v) = \phi * v \quad (V \in \mathcal{H}C, v \in V). \]

Here $\mathcal{H}C$ is the category of Harish-Chandra modules. A complete Paley-Wiener theorem would be a description of the image under $\mathcal{F}$ of the filtration of $C^\infty_c(G)$. A step towards that is the localized version, i.e. for a fixed $V \in \mathcal{H}C$ a description for the image under $\mathcal{F}_V$ of the filtration of $C^\infty_c(G)$ in terms of the filtration on $\text{Hom}_{(g,K)}(V, V^\omega)$ induced from $V^\omega$. Optimal estimates of $r(R)$ and $R(r)$ determining the geometric and analytic inclusions are an interesting open problem, even for groups of rank 1.

### 1.1. Geometric inclusion.

What we termed geometric inclusion has a straightforward relation to a problem concerning the complex geometry of the $G$-invariant crown domain $\Xi \subset Z\mathbb{C} = G\mathbb{C}/K\mathbb{C}$ of the attached Riemannian symmetric space $Z = G/K$. The crown domain $\Xi$ was first defined in [1] as in (3.1)-(3.2) below and characterized as the largest $G$-domain $Z \subset \Xi \subset Z\mathbb{C}$ on which $G$ acts properly. If $z_0 = K\mathbb{C}$ is the standard base point, then the crown domain can alternatively be defined as the connected component of the intersection

\[ \bigcap_{g \in G} gN\mathbb{C}A_G : z_0 = \bigcap_{k \in K} kN\mathbb{C}A_G : z_0 \]

which contains $z_0$. The latter can also be rephrased by $\Xi \subset Z\mathbb{C}$ being the maximal $G$-invariant domain containing $Z$ such that for every $K$-spherical principal series
representation $V = V_\lambda$ with $\lambda \in \mathfrak{a}_C^*$ and non-zero $K$-spherical vector $v_K = v_{K,\lambda}$ the orbit map 

$$f_\lambda : G/K \to V_\lambda^\infty, \quad gK \mapsto \pi_\lambda(g)v_{K,\lambda}$$

extends as a holomorphic map to $\Xi \to V_\lambda^\infty$. (See [18] and [17] for the fact that every $f_\lambda$ extends holomorphically to $\Xi$, and [16, Sect. 4] for the fact that $\Xi$ is maximal with respect to this property.)

Given $R > 0$ we define an Ad$(K)$-invariant open subset in $k$ by 

$$k(R) := \{ X \in k \mid \exp(iX)B_R \cdot z_0 \subset \Xi \}$$

with the subscript indicating the connected component which contains $0 \in k$.

**Proposition 1.1.** The following assertions hold.

(i) For any $r > 0$ with $k_r \subset k(R)$ we have a continuous embedding $V_R^{\min} \subset V_r^\omega$.

(ii) There exist constants $c, C > 0$ so that 

$$k_r \subset k(R) \quad \text{if} \quad r < Ce^{-cR}.$$  \hspace{1cm} (1.4)

Assertion (i) is Proposition 5.1; assertion (ii) is Proposition 3.1.

It is an interesting problem to determine $k(R)$ explicitly, and we do so for two examples in Appendix A. The results in the appendix suggest that the bound (1.4) is sharp modulo the constants $c, C > 0$.

1.2. Analytic inclusion. We now address the more interesting and much more difficult part, namely the analytic inclusion, i.e. to find for given $r > 0$ an $R = R(r) > 0$ such that $V_r^\omega \subset V_R^{\min}$. The main theorem of this paper is (see Theorem 10.1 with Remark 10.2):

**Theorem 1.2.** Let $G$ be a real reductive group and $V$ be a Harish-Chandra module. Then there exist constants $c > 0$ and $R_0 > 0$, only depending on $G$, with the following property: Given $r > 0$, then for all $R > R_0$ satisfying 

$$\frac{(\log R)^2}{R^2} < cr$$

one has a continuous embedding 

$$V_r^\omega \subset V_R^{\min}.$$ 

As a corollary of this theorem we obtain Schmid’s identity (1.1), and we can view Theorem 1.2 as a new quantitative version of it. In Appendix B we give a short derivation of the Helgason conjecture from (1.1). Finally, in Appendix C we give an application of our quantitative version to the factorization of analytic eigenfunctions in terms of the Harish-Chandra spherical function.

Let us now explain the idea of the proof. Standard techniques reduce matters quickly to the case when $V = V_\lambda$ is a principal series for which the $K$-spherical vector is cyclic (see Lemma 4.4). Our approach is based on the Paley-Wiener theorem of Helgason for the Fourier transform on $G/K$. Let us briefly recall the statement. Let $\text{PW}(\mathfrak{a}_C^*, C^\infty(K/M))_R$ be the $C^\infty(K/M)$-valued Paley-Wiener space of holomorphic functions on the complexification $\mathfrak{a}_C^*$ of the Euclidean space $\mathfrak{a}$ with growth rate $R$, see (6.1) for the formal definition. We realize $V_\lambda$ in the compact picture, where $V_\lambda^\infty = C^\infty(K/M)$ as $K$-modules, and denote by $v_{K,\lambda} = 1_{K/M}$ the constant indicator function of $K/M$. It is then easy to see that the spherical Fourier transform
\[ \mathcal{F} : C^\infty_c(G) \to \mathcal{O}(a^*_c, C^\infty(K/M)), \quad f \mapsto (\lambda \mapsto \pi(\lambda) f_{V_{K,\lambda}}) \]

satisfies
\[ \mathcal{F}(C^\infty_c(G)) \subset \text{PW}(a^*_c, C^\infty(K/M))_R. \]

Let \( W \) be the Weyl group of \( \Sigma(\mathfrak{g}, \mathfrak{a}) \). For \( w \in W \) we denote by
\[ J_{w,\lambda} : V^\infty_\lambda \simeq C^\infty(K/M) \to V^\infty_{w\lambda} \simeq C^\infty(K/M) \]
the normalized (i.e. fixing \( 1_{K/M} \)) intertwining operator and recall that \( \lambda \mapsto J_{w,\lambda} \) is meromorphic. With that we obtain an action of \( W \) on the space of \( C^\infty(K/M) \)-valued meromorphic functions,
\[ W \times \mathcal{M}(a^*_c, C^\infty(K/M)) \to \mathcal{M}(a^*_c, C^\infty(K/M)), \quad (w, f) \mapsto w \circ f, \]
\[ (w \circ f)(\lambda) = J_{w,w^{-1}\lambda} f(w^{-1}\lambda) \quad (\lambda \in a^*_c). \]

In this framework Helgason’s Paley-Wiener theorem [10] asserts that
\[ \mathcal{F}(C^\infty_R(G)) = \text{PW}_W(a^*_c, C^\infty(K/M))_R, \]
where the subscript \( W \) refers to invariant functions for the action defined above. However, from the geometric inclusion it follows that \( \mathcal{F}(C^\infty_R(G))(\lambda) \subset C^\infty_R(G) \ast V_\lambda \subset V^\omega_\lambda \). Thus we observe that the intertwining relations force analyticity, i.e. we have
\[ \text{PW}_W(a^*_c, C^\infty(K/M))_R = \text{PW}_W(a^*_c, C^\infty(K/M))_R, \]
and this observation was the motivation for our approach to the analytic inclusion.

Fix \( \lambda_0 \in a^*_c \) such that \( V_{\lambda_0} \) is cyclic for the \( K \)-spherical vector. We explicitly construct for any given analytic vector \( v \in V^\omega_{\lambda_0}(r) \) a holomorphic function
\[ f_v : a^*_c \to C^\infty(K/M) \]
such that its average
\[ \mathcal{A}(f_v) := \sum_{w \in W} w \circ f_v \]
lies in the Paley-Wiener space for a certain \( R > 0 \) and such that \( \mathcal{A}(f_v)(\lambda_0) = v \).

The Paley-Wiener theorem then yields that \( v \in C^\infty_R(G) \ast V_{\lambda_0} \), proving the theorem.

We point out that our proof is in essence an \( \text{SL}(2, \mathbb{R}) \)-proof. More precisely, in Section 8 we provide a variety of estimates for products of \( \Gamma \)-functions, which lie at the core of the construction for \( G = \text{SL}(2, \mathbb{R}) \). Given the framework provided by Kostant in [14], the general case of a reductive group \( G \) is then a consequence of the one-variable estimates in Section 8.

2. Preliminaries

Let \( G \) be the real points of a connected algebraic reductive group defined over \( \mathbb{R} \) and let \( \mathfrak{g} \) be its Lie algebra. Subgroups of \( G \) are denoted by capitals. The corresponding subalgebras are denoted by the corresponding fraktur letter. The unitary dual of a subgroup \( S \) of \( G \) we denote by \( \hat{S} \).

We denote by \( \mathfrak{g}_\mathbb{C} = \mathfrak{g} \otimes_{\mathbb{R}} \mathbb{C} \) the complexification of \( \mathfrak{g} \) and by \( G_\mathbb{C} \) the group of complex points. We fix a Cartan involution \( \theta \) and write \( K \) for the maximal compact subgroup that is fixed by \( \theta \). We also write \( \theta \) for the derived automorphism of \( \mathfrak{g} \). We
write $K_C$ for the complexification of $K$, i.e. $K_C$ is the subgroup of $G_C$ consisting of the fixed points for the analytic extension of $\theta$.

The Cartan involution induces the infinitesimal Cartan decomposition $g = \mathfrak{k} \oplus \mathfrak{s}$. Let $a \subset s$ be a maximal abelian subspace. Diagonalize $g$ under $\text{ad} a$ to obtain the familiar root space decomposition

$$g = a \oplus m \oplus \bigoplus_{\alpha \in \Sigma} g^\alpha,$$

with $m = z_\mathfrak{k}(a)$ as usual. Let $A$ be the connected subgroup of $G$ with Lie algebra $a$ and let $M = Z_K(a)$. We fix an Iwasawa decomposition $G = KAN$ of $G$. We define the projections $k : G \to K$ and $a : G \to A$ by

$$g \in k(g) a(g) N \quad (g \in G).$$

The set of restricted roots of $a$ in $g$ we denote by $\Sigma$ and the positive system determined by the Iwasawa decomposition by $\Sigma^+$. We write $W$ for the Weyl group of $\Sigma$.

Let $\kappa$ be the Killing form on $g$ and let $\tilde{\kappa}$ be a non-degenerate $\text{Ad}(G)$-invariant symmetric bilinear form on $g$ such that its restriction to $[g, g]$ coincides with the restriction of $\kappa$ and $-\tilde{\kappa}( \cdot, \theta \cdot )$ is positive definite. We write $\| \cdot \|$ for the corresponding norm on $g$.

3. **The complex crown of a Riemannian symmetric space**

The Riemannian symmetric space $Z = G/K$ can be realized as a totally real subvariety of the Stein symmetric space $Z_C = G_C/K_C$:

$$Z = G/K \hookrightarrow Z_C, \quad gK \mapsto gK_C.$$

In the following we view $Z \subset Z_C$ and write $z_0 = K \in Z$ for the standard base point.

We define the subgroups $A_C = \exp(a_C)$ and $N_C = \exp(n_C)$ of $G_C$. We note that $N_C A_C K_C$ is a Zariski-open subset of $G_C$. The maximal $G \times K_C$-invariant domain in $G_C$ containing $e$ and contained in $N_C A_C K_C$ is given by

$$\tilde{\Xi} = G \exp(i \Omega) K_C,$$

where $\Omega = \{ Y \in a \mid (\forall \alpha \in \Sigma) \alpha(Y) < \pi/2 \}$. Taking right cosets by $K_C$, we obtain the $G$-domain

$$\Xi := \tilde{\Xi}/K_C \subset Z_C = G_C/K_C,$$

commonly referred to as the *crown domain*. See [7] for the origin of the notion, [17, Cor. 3.3] for the inclusion $\tilde{\Xi} \subset N_C A_C K_C$ and [16, Th. 4.3] for the maximality.

We recall that $\Xi$ is a contractible space. To be more precise, let $\hat{\Omega} = \text{Ad}(K)\Omega$ and note that $\hat{\Omega}$ is an open convex subset of $s$. As a consequence of the Kostant convexity theorem it satisfies $\hat{\Omega} \cap a = \Omega$ and $p_a \hat{\Omega} = \Omega$, where $p_a$ is the orthogonal projection $s \to a$. The fiber map

$$G \times K \hat{\Omega} \to \Xi; \quad [g, X] \mapsto g \exp(iX) \cdot K_C,$$

is a diffeomorphism by [1] Prop. 4, 5 and 7. Since $G/K \simeq s$ and $\hat{\Omega}$ are both contractible, also $\Xi$ is contractible. In particular, $\Xi$ is simply connected.
We denote by \( \mathbf{a} : G \to A \) the middle projection of the Iwasawa decomposition \( G = KAN \) and note that \( \mathbf{a} \) extends holomorphically to
\[
\Xi^{-1} := \{ g^{-1} : g \in \Xi \}.
\]
Here the simply connectedness of \( \Xi \) plays a role to achieve \( \mathbf{a} : \Xi^{-1} \to A_C \) uniquely: A priori \( \mathbf{a} \) is only defined as a map to \( A_C/T_2 \), where \( T_2 := A_C \cap K_C \) is the 2-torsion subgroup of group \( A_C \). We denote the extension by the same symbol.

Likewise one defines \( \mathbf{k} : G \to K \), which extends holomorphically to \( \Xi^{-1} \) as well.

For \( R > 0 \) we define a ball in \( A \) by
\[
A_R := \{ \exp(Y) \mid Y \in \mathbf{a}, \|Y\| \leq R \}.
\]
Related to that we define the ball \( B_R \subset G \) by
\[
B_R = K A_R K.
\]
We consider the following subset of \( \mathbf{k} \):
\[
\mathcal{K}(R) := \{ Y \in \mathbf{k} \mid \exp(iY) K A_R \subset \Xi \}.
\]
Note that \( \mathcal{K}(R) \) is open, because \( K A_R \subset G \) is compact. Moreover, \( \mathcal{K}(R) \) is \( \text{Ad}(K) \)-invariant. Hence it is uniquely determined by its intersection with a Cartan subalgebra \( \mathfrak{t} \) of \( \mathfrak{k} \), i.e. \( \mathcal{K}(R) \) is determined by
\[
\mathfrak{t}(R) := \mathfrak{t} \cap \mathfrak{t}(R).
\]
Actually, it is sufficient to consider the intersection with a closed chamber of \( \mathfrak{t} \), say \( \mathfrak{t}^+ \):
\[
\mathfrak{t}(R)^+ := \mathfrak{t}^+ \cap \mathfrak{t}(R).
\]
For \( r > 0 \) let \( \mathfrak{t}_r := \{ X \in \mathfrak{t} \mid \|X\| < r \} \) and define the domains in \( K_C \)
\[
K_C(r) := K \exp(\mathfrak{t}_r).
\]
Note that \( K_C(r) \) is \( K \)-biinvariant, as \( \mathfrak{t}_r \) is \( \text{Ad}(K) \)-invariant. Note further that \( K_C(r) = (K_C(r))^{-1} \), since \( \mathfrak{t}_r = -\mathfrak{t}_r \).

In general it is an interesting problem to determine \( \mathfrak{t}(R) \) explicitly. We do this in Appendix \( \ref{app} \) for two cases, namely \( \mathfrak{g} = \mathfrak{so}(1,n) \) and \( \mathfrak{g} = \mathfrak{su}(1,1) \), the latter being treated in a way so that the generalization to Hermitian symmetric spaces becomes apparent.

As a precise description of \( \mathfrak{t}(R) \) may be difficult to obtain in general, one could instead determine the best possible \( r = r(R) > 0 \) with \( \mathfrak{t}_r \subset \mathfrak{t}(R) \). The following proposition gives a first bound which, given the results in Appendix \( \ref{app} \) appears to be sharp up to constants.

**Proposition 3.1.** There exist constants \( C, c > 0 \) such that for all \( r, R > 0 \) one has
\[
\mathfrak{t}_r \subset \mathfrak{t}(R) \quad (r < Ce^{-cR}).
\]

**Proof.** Let \( G = \text{GL}(n, \mathbb{R}) \). We consider the standard Iwasawa decomposition of \( G \), i.e. \( K = O(n, \mathbb{R}) \), \( A = \text{diag}(n, \mathbb{R}_{>0}) \) and \( N \) is the group of unipotent upper triangular matrices. It suffices to consider this case, as any real reductive group can be embedded into \( G = \text{GL}(n, \mathbb{R}) \) with compatible Iwasawa decompositions. Here we remark that the possible incompatibility of the Cartan-Killing norms is taken care of by the presence of the constants \( C \) and \( c \).
We recall that 
\[ Z = G/K \to \text{Sym}(n, \mathbb{R})^+, \quad gK \mapsto gg^t, \]
identifies \( Z \) with the positive definite symmetric matrices. In this matrix picture \( Z_{\mathbb{C}} \) is identified with \( \text{Sym}(n, \mathbb{C})_{\det \neq 0}^+ \), the invertible symmetric matrices. In case \( n \geq 3 \), the crown domain \( \Xi \subset \text{Sym}(n, \mathbb{C})_{\det \neq 0}^+ \) is not explicitly known. However, \( \Xi \) contains the so-called square root domain
\[ \Xi^\frac{1}{2} = \text{Sym}(n, \mathbb{R})^+ + i\text{Sym}(n, \mathbb{R}) \subset \text{Sym}(n, \mathbb{C})_{\det \neq 0}^+, \tag{3.4} \]
see \[18\, \text{Sect. 8}\]. Let \( m = \begin{bmatrix} n \end{bmatrix} \) and define for \( x \in \mathbb{R}^m \)
\[ D(x) = \begin{pmatrix} D_1(x) \\ \vdots \\ D_m(x) \end{pmatrix}, \]
with
\[ D_j(x) = \begin{pmatrix} \cos x_j & -\sin x_j \\ \sin x_j & \cos x_j \end{pmatrix}. \]
In case \( n \) is even we have \( D(x) \in O(n, \mathbb{R}) \), and in case of \( n \) odd we view \( D(x) \in O(n, \mathbb{R}) \) by means of the embedding
\[ D(x) \mapsto \begin{pmatrix} D(x) \\ 1 \end{pmatrix}. \]

Our choice of maximal torus \( T \subset K \) then is \( T = \{ D(x) \mid x \in \mathbb{R}^m \} \).

Let now \( R > 0 \) and \( Y \in \text{Sym}(n, \mathbb{R})^+ \) with \( \text{spec}(Y) \subset \mathbb{R}^{-R, R} \). We then seek an \( r > 0 \) such that for all \( x \in \mathbb{R}^m \) with \( \|x\| < r \) and \( Y \) as above we have \( D(ix)YD(ix)^t \in \Xi^\frac{1}{2} \). If we decompose \( D(ix) = U(x) + iV(x) \) into real and imaginary parts, this amounts to
\[ U(x)YU(x) - V(x)YV(x)^t \in \text{Sym}(n, \mathbb{R})^+, \]
by \[3.4\]. With
\[ S(x) = \begin{pmatrix} 0 & -\tanh x_1 \\ \tanh x_1 & 0 \\ \vdots & \vdots \\ 0 & -\tanh x_m \\ \tanh x_m & 0 \end{pmatrix}, \]
we can rewrite this as
\[ Y - S(x)YS(x)^t \in \text{Sym}(n, \mathbb{R})^+. \tag{3.5} \]
Now note that
\[ \|S(x)YS(x)^t\|_{\text{op}} \leq [\tanh r]^2 \|Y\|_{\text{op}} \leq [\tanh r]^2 e^R. \]
On the other hand, the smallest eigenvalue of \( Y \) is at least \( e^{-R} \). Hence \[3.5\] is satisfied, provided \( [\tanh r]^2 e^{2R} < 1 \). As \( \tanh r \leq r \), \[3.5\] is implied by \( r^2 < e^{-2R} \), and the assertion of the proposition follows. \[\square\]
4. Generalities on the analytic filtration

4.1. Filtration by holomorphic extension. Let $V$ be a Harish-Chandra module. The analytic vectors $V^\omega$ of $V$ are defined as the analytic vectors in $V^\infty$, i.e. $V^\omega := (V^\infty)^\omega$. In the following we provide various standard descriptions of $V^\omega$.

The first one is in terms of holomorphic extensions. For $r > 0$ we define

$$V^\omega_r := \{ v \in V^\infty | K \ni k \mapsto k \cdot v \in V^\infty \text{ extends holomorphically to } K_C(r) \}.$$

Lemma 4.1. For any Harish-Chandra module $V$ every $K$-analytic vector is analytic. Moreover,

$$V^\omega = \lim_{r \to 0} V^\omega_r$$

as topological vector spaces.

Proof. From the definition it is easily checked that $\lim_{r \to 0} V^\omega_r$ describes the space of analytic vectors for the representation on $V^\infty$ restricted to $K$ with the topology of uniform convergence on $K$.

We recall the notion of $\Delta$-analytic vectors from [6, Sect. 5] and that the space of $\Delta$-analytic vectors coincides with the space of analytic vectors for any $F$-representation of a Lie group, and in particular for $V^\infty$. Let $C$ be the Casimir element and let $\Delta_K$ and $\Delta_G$ be the standard Laplace elements in $U(\mathfrak{t})$ and $U(\mathfrak{g})$, respectively. Then $\Delta_G = C + 2\Delta_K$. As $\Delta_G$ differs from $2\Delta_K$ by $C$, which acts finitely on $V$, it follows that any $\Delta_K$-analytic vector is $\Delta_G$-analytic, and vice versa. This proves the first assertion.

The identity map from the space of $G$-analytic vectors to the space of $K$-analytic vectors is continuous. The second assertion now follows from the open mapping theorem (see [19, Theorem 24.30 and Remark 24.36]).

4.2. Filtration by $K$-type decay. The next description of analytic vectors is by exponential decay of $K$-types. A norm $p$ on $V$ is called $G$-continuous provided that the completion $V_p$ of the normed space $(V, p)$ gives rise to a Banach-representation of $G$. We choose a $G$-continuous norm $p$ on $V$. Let $V^\infty$ be the up to isomorphism unique smooth completion of $V$ with moderate growth, see [5], [22, Ch. 11] or [2]. We write a vector $v \in V^\infty$ as a convergent sum

$$v = \sum_{\tau \in \hat{K}} v_\tau,$$

where $v_\tau$ is contained in the $K$-isotypical component $V[\tau]$ of $V$. For any $\tau \in \hat{K}$ we denote by $|\tau|$ the norm of the highest weight of $\tau$.

For $r > 0$ let us define

$$V^\omega(r) := \{ v \in V^\infty | (\forall 0 < r' < r) \sum_{\tau \in \hat{K}} e^{r'|\tau|} p(v_\tau) < \infty \}$$

and endow it with the Fréchet topology induced by the seminorms

$$v \mapsto \sum_{\tau \in \hat{K}} e^{r'|\tau|} p(v_\tau) \quad (0 < r' < r).$$

The space $V^\omega(r)$ is independent of the choice of the $G$-continuous norm $p$, as all these norms are polynomially comparable on the $K$-types, i.e. given two $G$
Lemma 4.2. For every Harish-Chandra module $V$ we have

$$V^\omega_r = V^\omega(r) \quad (r > 0)$$

as topological vector spaces.

Proof. Let $r > 0$. We first prove the inclusion $V^\omega_r \subset V^\omega$. For this let $v \in V^\omega(r)$ and $0 < r' < r$. Recall that $K_C(r') = K \exp(it_r)K$ with $t_r = \{X \in t \mid \|X\| < r'\}$. Since the space $V^\omega(r)$ is independent of the choice of the $G$-continuous norm $p$, we may assume that $p$ is Hermitian and $K$-unitary. Any element $t \in \exp(it_r)$ acts semisimply on $V[\tau]$ with eigenvalues bounded by $e^{r'r}$. As $p$ is $K$-unitary, it follows that

$$\sup_{k \in K_C(r')} p(k \cdot v_r) \leq e^{r'r}p(v_r) \quad (\tau \in \hat{K}). \quad (4.1)$$

We recall that $V_p$ is the Hilbert completion of $V$ with respect to $p$ and that $V_p$ is a Hilbert representation of $G$. Because $v \in V^\omega(r)$, inequality (4.1) and the fact that $\dim V[\tau]$ is polynomially bounded in $|\tau|$ imply that the orbit map

$$f_v : K \to V_p, \quad k \mapsto k \cdot v,$$

extends holomorphically to $K_C(r')$. Since this holds for all $r' < r$, the function $f_v$ in fact extends holomorphically to $K_C(r)$. The image of $f_v$ is not only in $V_p$, but in the $K$-smooth vectors of $V_p$. Since the Fréchet spaces of $K$-smooth and $G$-smooth vectors in $V_p$ are identical (see [2 Corollary 3.10]), we obtain that $f_v$ is a holomorphic map with values in $V_p^\infty = V^\infty$. Thus we have shown that $V^\omega_r \subset V^\omega$. The embedding is continuous in view of (4.1).

For the converse inclusion $V^\omega \subset V^\omega_r$, we note that for an irreducible Harish-Chandra module $V$ the representation $V^\infty$ can be embedded into the space of smooth vectors of a minimal principal series module $V_{\sigma,\lambda}$. The latter can be realized as the space of smooth functions $f : G \to V_p$ satisfying

$$f(g \text{man}) = a^{-i\lambda - \rho} \sigma(m)^{-1} f(g) \quad (g \in G, \text{man} \in MAN).$$

Note that $V_{\sigma,\lambda}^\infty$ is naturally a $G$-module, with $G$ acting on $V_{\sigma,\lambda}^\infty$ by left displacements in the arguments, in symbols $\pi_{\sigma,\lambda}(g)(f) = f(g^{-1})$. We write $\mathcal{H}$ for $C^\infty(K)$ equipped with the $G$-representation $\pi_\lambda$ given by

$$(\pi_\lambda(g)f)(k) = a(g^{-1}k)^{-i\lambda - \rho} f(k(g^{-1}k)) \quad (f \in \mathcal{H}, g \in G, k \in K).$$

We may embed $V^\infty$ equivariantly into $\mathcal{H} \otimes V_\sigma$. It therefore suffices to prove that $\mathcal{H}^\omega \subset \mathcal{H}^\omega_r$.

We let $p$ be the $L^2$-norm on $\mathcal{H}$, which is $G$-continuous. Note that $K$ acts also from the right on smooth functions on $K$, and therefore $\mathcal{H}$ carries a representation of $K \times K$. From now on we consider $\mathcal{H}$ as a $K \times K$ module. For $0 < r' < r$ we define a $K \times K$-invariant Hermitian norm on $\mathcal{H}^\omega_r$ by

$$q_r^\omega(v) := \left[ \int_{K_C(r')} |v(k)|^2 \, d\mu(k) \right]^{1/2} \quad (v \in \mathcal{H}^\omega_r).$$
Here $d\mu$ is the measure on $K_\mathbb{C}$ which in the polar decomposition $K_\mathbb{C} = K \exp(it^+)K$ is given by

$$d\mu(k_1 \exp(it)k_2) = dk_1 \ dt \ dk_2,$$

with $dk_{1,2}$ the Haar measure on $K$ and $dt$ the Lebesgue measure on $t^+$. For $\tau \in \hat{K}$ we define $\mathcal{H}[\tau]$ to be the $\tau \otimes \tau^\vee$-isotypical component of $\mathcal{H}$ and denote the restriction of $p$ and $q_{r',\tau}$ to $\mathcal{H}[\tau]$ by $p_\tau$ and $q_{r',\tau}$, respectively. Since $\mathcal{H}[\tau]$ is $K \times K$-irreducible, there exists a constant $c_{r',\tau} > 0$, so that $q_{r',\tau} = c_{r',\tau} \cdot p_\tau$.

We will estimate the constant from below by estimating $q_{r',\tau}(v)$ for a matrix coefficient

$$v = m_{w_1,w_2} : k \mapsto \langle w_1, \tau(k)w_2 \rangle,$$

where $w_1, w_2 \in V_\tau$. Using the Schur-Weyl orthogonality relations we obtain

$$q_{r',\tau}(v)^2 = \frac{\|w_1\|^2}{\dim \tau} \int_K \int_{t^+} \|\tau(\exp(it)) w_2\|^2 \ d\mu \ dt.$$ 

Next we pick an orthonormal basis of weight vectors $v_1, \ldots, v_n \in V_\tau$ and expand the integrand. We thus obtain that the right-hand side is equal to

$$\frac{\|w_1\|^2}{\dim \tau} \sum_{j=1}^n \int_{t^+} \|\tau(\exp(it)) v_j\|^2 \ dt.$$ 

Now we apply Schur-Weyl once more. This yields

$$\frac{\|w_1\|^2}{\dim(\tau)^2} \sum_{j=1}^n \int_{t^+} \|\tau(\exp(it)) v_j\|^2 \ dt.$$ 

Again by Schur-Weyl we note

$$\frac{\|w_1\|^2}{\dim(\tau)} = p_\tau(v)^2.$$ 

Let $\mu_\tau$ be the highest weight of $\tau$, and assume that $v_1$ is a highest weight vector with weight $\mu_\tau$. Then for all $r'' < r'$ there exists a constant $c$, independent of $\tau$, so that

$$q_{r',\tau}(v)^2 \geq \frac{p_\tau(v)^2}{\dim(\tau)} \int_{t^+} e^{2\mu_\tau(it)} \ dt \geq c^2 e^{2\|\mu_\tau\|_{r''} p_\tau(v)^2}.$$ 

As $\|\mu_\tau\| = |\tau|$, we conclude that for every $r'' < r'$ there exists a constant $c_{r',\tau} > 0$, so that

$$c_{r',\tau} \geq c_{r''} e^{r''|\tau|} \quad (\tau \in \hat{K}).$$ 

If $v = \sum_{\tau \in \hat{K}} v_\tau \in \mathcal{H}_r^{\omega}$, then for all $0 < r'' < r' < r$

$$\sum_{\tau \in \hat{K}} e^{r''|\tau|} p_\tau(v_\tau) \leq \frac{1}{c_{r''}} \sum_{\tau \in \hat{K}} q_{r',\tau}(v_\tau) = \frac{1}{c_{r''}} q_{r'}(v) < \infty.$$ 

It follows that $v \in \mathcal{H}_r^{\omega}$ implies $v \in \mathcal{H}_r^{\omega}(r)$. Moreover, the embedding is continuous. \qed
4.3. Reduction to spherical principal series. It is our intention to show for a given Harish-Chandra module $V$ and $r > 0$ that there is a continuous embedding

$$V^\omega(r) \subset V_R^{\min}$$

for some $R = R(r) > 0$. For $\lambda \in a_c^*$, we write $V_\lambda$ for the spherical principal series representation $\text{Ind}^G_r(C_{i\lambda})$. We will first reduce the problem to the case in which $V = V_\lambda$ for some $\lambda \in a_c^*$.

Every irreducible Harish-Chandra module $V$ is a quotient

$$V_\lambda \otimes F \twoheadrightarrow V$$

for some spherical principal series $V_\lambda$ and finite dimensional representation $F$ of $G$, see [21 Sect. 2]. We first recall how this arises. By the Casselman embedding theorem every irreducible Harish-Chandra module $V$ is a quotient of some minimal principal series module $V_{\sigma,\lambda} = \text{Ind}^G_r(V_\sigma \otimes C_{i\lambda})$ with $(\sigma, V_\sigma) \in \hat{M}$ and $\lambda \in a_c^*$, i.e.

$$V_{\sigma,\lambda} \twoheadrightarrow V.$$

Now, by op. cit. the $M$-representation $(\sigma, V_\sigma)$ can be realized as the quotient $F/\mathfrak{n}F$ of a finite dimensional module $F$ of $G$, i.e. $V_\sigma = F/\mathfrak{n}F$. By the Mackey isomorphism we have

$$V_\lambda \otimes F = \text{Ind}^G_r(C_{i\lambda}) \otimes F \simeq \text{Ind}^G_r(C_{i\lambda} \otimes F|_R).$$

Hence the $P$-morphism $C_{i\lambda} \otimes F|_P \rightarrow C_{i\lambda} \otimes F/\mathfrak{n}F \simeq C_{i\lambda} \otimes V_\sigma$ gives rise to the chain of quotients

$$V_\lambda \otimes F \twoheadrightarrow V_{\sigma,\lambda} \twoheadrightarrow V.$$

This proves (4.2).

Lemma 4.3. Let $\lambda \in a_c^*$ and $F$ a finite dimensional representation of $G$. The following assertions hold.

(i) Let $r, R > 0$. If $V_\lambda^\omega(r)$ embeds continuously into $C^\infty_r(G) * V_\lambda$, then also $(V_\lambda \otimes F)^\omega(r)$ embeds continuously into $C^\infty_r(G) * (V_\lambda \otimes F)$.

(ii) Let $V$ be a Harish-Chandra module so that there exists a quotient map $\omega : V_\lambda \otimes F \twoheadrightarrow V$. Then for every $r > 0$

$$V^\omega(r) = \omega((V_\lambda \otimes F)^\omega(r)),$$

where the symbol $\omega$ is also used for its the globalization to $(V_\lambda \otimes F)^\infty$.

Proof. First note that $(V_\lambda \otimes F)^\omega(r) = V_\lambda^\omega(r) \otimes F$, as $F$ is in fact a $G_C$-module. To prove (i), it thus suffices to show that $(C^\infty_r(G) * V_\lambda) \otimes F$ continuously embeds into $C^\infty_r(G) * (V_\lambda \otimes F)$. The proof for this is analogous to [2 Lemma 9.4].

We move on to (ii). Let $p$ be a $K$-invariant $G$-continuous Hermitian norm on $V_\lambda \otimes F$. Let $q$ be the corresponding quotient norm on $V$. Then $q$ is $G$-continuous and $K$-invariant. Note that the definition of $V^\omega(r)$ does not depend on the choice of the $G$-continuous norm on $V$. Assertion (ii) now follows, because $V^\omega(r)$ as a $K$-module is a direct summand of $(V_\lambda \otimes F)^\omega(r)$. \qed
4.4. Kostant’s condition. We would like to be more restrictive on the parameter \( \lambda \) of the quotient \( V_{\lambda} \otimes F \to V \).

Lemma 4.4. Every irreducible Harish-Chandra module \( V \) admits a quotient \( V_{\lambda} \otimes F \to V \), where \( F \) is an irreducible finite dimensional representation of \( G \) and \( \lambda \in a_\mathbb{C}^* \) satisfies the Kostant condition

\[
\Re(i\lambda)(\alpha^\vee) \geq 0 \quad (\alpha \in \Sigma^+) .
\]

If (4.3) is satisfied, then \( V_{\lambda} = \mathcal{U}(\mathfrak{g})v_{K,\lambda} \) is \( \mathcal{U}(\mathfrak{g}) \)-cyclic for the \( K \)-fixed vector \( v_{K,\lambda} \).

Proof. In view of (4.2), \( V \) admits a quotient \( V_{\lambda} \otimes F \to V \), where \( F \) is a finite dimensional representation of \( G \). Let \( F' \) be a \( K \)-spherical finite dimensional representation of lowest weight \( -\mu \in a^* \), where \( \mu \) is dominant. Then \( M \) acts trivially on the \( MA \)-module \( F'/nF' \cong \mathbb{C}_{-\mu} \) with \( A \)-weight \( -\mu \). In particular, we obtain a quotient

\[ V_{\lambda-\mu} \otimes F' \to V_{\lambda} . \]

It follows that \( V \) admits a quotient \( V_{\lambda-\mu} \otimes F \otimes F' \to V \). The first assertion now follows by taking \( \mu \) sufficiently large. The last assertion is [11] Th. 8. \( \square \)

5. The geometric inclusion

The goal of this section is to show that \( V_R^{\min} = C_R^\infty(G) * V \) embeds into \( V^\omega(r) \) for any \( r > 0 \) with \( \mathfrak{t}_r \subset \mathfrak{t}(R) \). This reduces to the case where \( V = V_{\lambda} \) is the spherical principal series representation with parameter \( \lambda \in a_\mathbb{C}^* \). Elements in \( V_{\lambda}^\infty \) are uniquely determined by their restriction to \( K \). This gives rise to the compact model, in which

- \( V_{\lambda}^\infty = C^\infty(K/M) \),
- \( V_{\lambda}^\omega = C^\omega(K/M) \),
- \( V_{\lambda} = \mathbb{C}[K_C/M_C] \)

as \( K \)-modules. The main result of this section is the following.

Proposition 5.1. Let \( V \) be a Harish-Chandra module, and \( R > 0 \). Let \( r \) be such that \( \mathfrak{t}_r \subset \mathfrak{t}(R) \). Then we have the continuous embedding

\[ V_R^{\min} \subset V^\omega(r) . \]

Proof. We first reduce to the case where \( V = V_{\lambda} \) is a spherical principal series. We recall from Section 4.3 that \( V \) is a quotient of some \( V_{\lambda} \otimes F \), with \( F \) a finite dimensional representation. Now all matrix coefficients of \( F \) extend holomorphically to \( G_C \), and this completes the reduction to \( V = V_{\lambda} \).

We work in the compact model of \( V_{\lambda} \). Let \( v = \pi(f)w \) for some \( w \in V \) and \( f \in C_R^\infty(G) \). Then we note that for \( k \in K \)

\[ v(k) = \pi(f)(w)(k) = \int_{B_R} f(g)w(g^{-1}k) \, dg . \quad (5.1) \]

Observe that \( w(g^{-1}k) = w(k^{-1}g^{-1})a(g^{-1})^{-i\lambda-\rho} \). As \( w \in \mathbb{C}[K_C/M_C] \), \( w \) is a holomorphic function on \( K_C/M_C \). Thus with \( B_RK_C(r) \subset \tilde{G}^{-1} \subset K_CA_CN_C \), we conclude that \( a \) and \( k \) are defined on \( B_RK_C(r) \) and holomorphic. Thus \( v \) extends to the holomorphic function on \( K_C(r) \) given by (5.1). This shows the continuous embedding for this case. \( \square \)
6. Preliminaries on the analytic inclusion

6.1. $K$-type expansion of functions on $K/M$. In the following we view functions on $K/M$ as right $M$-invariant functions on $K$. For any $\tau \in \hat{K}$ we fix a model (finite dimensional) Hilbert space $V_{\tau}$. For $\tau \in \hat{K}$ we write $\tau^{\vee}$ for the dual representation. We then obtain for each $\tau \in \hat{K}$ a $K \times K$-equivariant realization of $V_{\tau} \otimes V_{\tau^{\vee}}$ as polynomial functions on $K$:

$$V_{\tau} \otimes V_{\tau^{\vee}} \rightarrow \mathbb{C}[K], \quad v \otimes v^{\vee} \mapsto m_{v,v^{\vee}}; \quad m_{v,v^{\vee}}(k) := v^{\vee}(k^{-1}v),$$

where $K \times K$ acts on $\mathbb{C}[K]$ by the left-right regular representation. We arrive at the $K \times K$-isomorphism of $K \times K$-modules

$$\mathbb{C}[K] = \bigoplus_{\tau \in \hat{K}} V_{\tau} \otimes V_{\tau^{\vee}},$$

and taking right $M$-invariants at the $K$-isomorphism of $K$-modules

$$\mathbb{C}[K_C/M_C] = \bigoplus_{\tau \in \hat{K}_M} V_{\tau} \otimes V_{\tau^{\vee}},$$

where $\hat{K}_M \subset \hat{K}$ is the $M$-spherical part of $\hat{K}$. Fix $\tau$ and identify $V_{\tau^{\vee}} \simeq V_{\tau}^{\ast}$. In particular, the unitary norm on $V_{\tau}$ induces the unitary dual norm on $V_{\tau^{\vee}}$ and we write $\| \cdot \|_{\tau}$ for the Hilbert-Schmidt norm on $V_{\tau} \otimes V_{\tau^{\vee}}$. We recall that $\| \cdot \|_{\tau}$ is independent of the particular unitary norm on $V_{\tau}$ (which is unique up to positive scalar by Schur’s Lemma) and is thus intrinsically defined. Any function on $f \in \mathbb{C}[K_C]$ we now expand into $K$-types $f = \sum_{\tau \in \hat{K}} f_{\tau}$ with $f_{\tau} \in V_{\tau} \otimes V_{\tau^{\vee}}$. With that we record the well known Fourier characterizations of $C^\infty(K)$ and $C^\omega(K)$ as

$$C^\infty(K) = \{ f = \sum_{\tau \in \hat{K}} f_{\tau} \mid (\forall N \in \mathbb{N}) \sum_{\tau \in \hat{K}} (1 + |\tau|)^N \| f_{\tau} \|_{\tau} < \infty \}$$

and

$$C^\omega(K) = \{ f = \sum_{\tau \in \hat{K}} f_{\tau} \mid (\exists r > 0) \sum_{\tau \in \hat{K}} e^{r|\tau|} \| f_{\tau} \|_{\tau} < \infty \}.$$

Taking right $M$-invariants, we obtain corresponding Fourier characterizations of $C^\infty(K/M)$ and $C^\omega(K/M)$.

6.2. The Helgason Paley-Wiener Theorem. We begin with a short review of the Fourier transform on $Z = G/K$ and recollect some notation. For $\lambda \in \mathfrak{a}_C^\ast$ we denote by $V_{\lambda}$ the Harish-Chandra module of the $K$-spherical principal series with parameter $\lambda$ as defined before. Recall that $V_{\lambda}^\infty = C^\infty(K/M)$ as $K$-module. We denote by $v_{K_{\lambda}} = 1_{K/M} \in V_{\lambda}$ the constant function.

For every $R > 0$ we let $\text{PW}(\mathfrak{a}_C^\ast, C^\infty(K/M))_R$ be the space of holomorphic functions $f : \mathfrak{a}_C^\ast \rightarrow C^\infty(K/M)$, so that for every continuous semi-norm $q$ on $C^\infty(K/M)$ and $N \in \mathbb{N}$ one has

$$\sup_{\lambda \in \mathfrak{a}_C^\ast} q(f(\lambda))(1 + \|\lambda\|)^N e^{-R\|\text{Im}\lambda\|} < \infty. \tag{6.1}$$

Further we denote

$$\text{PW}(\mathfrak{a}_C^\ast, C^\infty(K/M)) = \bigcup_{R > 0} \text{PW}(\mathfrak{a}_C^\ast, C^\infty(K/M))_R.$$
and refer to it as the Paley-Wiener space on $a_C^*$ with values in $C^\infty(K/M)$.

The Fourier transform on $Z$ is then defined by

$$F : C^\infty_c(Z) \to PW(a_C^*, C^\infty(K/M)),$$

$$f \mapsto F(f); \quad F(f)(\lambda) := \pi_\lambda(f) v_{K,\lambda}.$$  

Note that

$$F(f)(\lambda)(kM) = \int_Z f(gK) a(g^{-1}k)^{-i\lambda - \rho} \, d(gK) \quad (k \in K).$$

It is convenient to write $F(f)(\lambda)(kM)$ for $F(f)(\lambda)(kM)$.

In order to describe the image of $F$, we recall the Weyl group $W$ of the restricted root system $\Sigma = \Sigma(a, g)$. Attached to $w \in W$ there is a meromorphic family of standard intertwining operators

$$I_{w,\lambda} : V^\infty_\lambda \to V^\infty_{w\lambda}.$$  

Further we recall that $I_{w,\lambda}(v_{K,\lambda}) = c_w(\lambda) v_{K,w\lambda}$ for a meromorphic and explicit function $c_w$ ($w$-partial Harish-Chandra $c$-function, calculated by Gindikin-Karpelevic).

We define the normalized intertwining operator by $J_{w,\lambda} := \frac{1}{c_w(\lambda)} I_{w,\lambda}$. We recall that $\lambda \mapsto J_{w,\lambda}$ is meromorphic on $a_C^*$, and holomorphic on an open neighborhood of the cone

$$\{ \lambda \in a_C^* : \Re (i\lambda(\alpha^\vee)) \geq 0 \text{ for all } \alpha \in \Sigma^+ \cap w^{-1} \Sigma^- \}.$$  

It is clear from the definitions that every Fourier transform $\phi = F(f)$ satisfies the intertwining relations

$$J_{w,\lambda}(\phi(\lambda)) = \phi(w\lambda) \quad (w \in W, \lambda \in a_C^*). \quad (6.2)$$

Let $PW_W(a_C^*, C^\infty(K/M))$ be the subspace of $PW(a_C^*, C^\infty(K/M))$ of Paley-Wiener functions that satisfy all intertwining relations (6.2). Then Helgason’s Paley-Wiener theorem [10, Theorem 8.3] states that

$$F(C^\infty_c(Z)) = PW_W(a_C^*, C^\infty(K/M))_R \quad (R > 0). \quad (6.3)$$

6.3. Intertwining relations on $K$-types. For any $\tau \in \hat{K}$ and $\lambda \in a_C^*$ we have

$$V_\lambda[\tau] = C^\infty(K/M)[\tau] = V_\tau \otimes V^M_\tau \quad (6.4)$$

as $K$-modules, where $V^*_\tau = V^M_\tau$. We denote by $J_{w,\lambda}[\tau]$ the restriction of $J_{w,\lambda}$ to $V_\lambda[\tau]$ and observe that $J_{w,\lambda}[\tau] : V_\lambda[\tau] \to V_{w\lambda}[\tau]$. Within the identification (6.4) we then obtain

$$J_{w,\lambda}[\tau] \in \End_K(V_\tau \otimes V^M_\tau) \simeq \End(V^M_\tau).$$

Next we recall Kostant’s factorization of $J_{w,\lambda}[\tau]$. In general, if $\mathfrak{c} \subset \mathfrak{g}$ is a subspace, we denote by $S(\mathfrak{c})$ the symmetric algebra and by $S^*(\mathfrak{c})$ the image of $S(\mathfrak{c})$ in $U(\mathfrak{g})$ under the symmetrization map. From the Cartan decomposition $\mathfrak{g} = \mathfrak{s} + \mathfrak{k}$ and the PBW-theorem we thus obtain the direct sum decomposition

$$U(\mathfrak{g}) = S^*(\mathfrak{s}) \oplus U(\mathfrak{g})\mathfrak{k}.$$  

Next, according to [15] Th. 15 we have $S(\mathfrak{s}) = \mathcal{H}(\mathfrak{s}) \otimes \mathcal{I}(\mathfrak{s})$, where $\mathcal{H}(\mathfrak{s})$ denotes the harmonic polynomials on $\mathfrak{s}_C^*$ and $\mathcal{I}(\mathfrak{s})$ the $K$-invariant polynomials on $\mathfrak{s}_C^*$. We derive the refined decomposition

$$U(\mathfrak{g}) = \mathcal{H}^*(\mathfrak{s})\mathcal{I}^*(\mathfrak{s}) \oplus U(\mathfrak{g})\mathfrak{k}. \quad (6.5)$$
Consequently we have for all $\lambda \in \mathfrak{a}^*_C$ that
\[
d_{\pi_\lambda}(U(\mathfrak{g}))v_{K,\lambda} = d_{\pi_\lambda}(H^*(\mathfrak{s}))v_{K,\lambda}.
\]
We recall from Lemma 4.4 that in case $\lambda$ satisfies the Kostant condition (4.3), the vector $v_{K,\lambda}$ is cyclic in $V_\lambda$ for $U(\mathfrak{g})$. In general we have for each $\tau \in \hat{K}$ the $K$-equivariant maps
\[
Q_\tau(\lambda) : H^*(\mathfrak{s})[\tau] \to V_\lambda[\tau] = V_\tau \otimes V^M_{\tau}, \quad D \mapsto d_{\pi_\lambda}(D)v_{K,\lambda},
\]
which are isomorphisms if $\lambda$ satisfies (4.3), see [14, Cor. to Prop. 4 and Cor. to Th. 7]. (In [14] the polynomials $Q_\tau$ are denoted by $P^\tau$. Compared to the polynomials defined in [11, p. 238] there is a sign difference in the argument.)

For fixed $\tau \in \hat{K}_M$ we recall that the assignment
\[
a^*_C \ni \lambda \mapsto Q_\tau(\lambda) \in \text{Hom}_K(H^*(\mathfrak{s})[\tau], V_\tau \otimes V^M_{\tau})
\]
is polynomial. Since $J_{w,\lambda}v_{K,\lambda} = v_{K,w\lambda}$, we obtain the relation
\[
J_{w,\lambda}[\tau] \circ Q_\tau(\lambda) = Q_\tau(w\lambda),
\]
and as a consequence Kostant’s factorization
\[
J_{w,\lambda}[\tau] = Q_\tau(w\lambda) \circ Q_\tau(\lambda)^{-1}, \quad (6.6)
\]
which exhibits $J_{w,\lambda}[\tau]$ for fixed $\tau \in \hat{K}_M$ as a rational vector-valued function
\[
a^*_C \ni \lambda \mapsto J_{w,\lambda}[\tau] \in \text{End}(V^M_{\tau}).
\]

**Remark 6.1.** To understand the polynomial dependence of $\lambda \mapsto Q_\tau(\lambda)$ better, it proves useful to introduce a normalization. Set
\[
\tilde{Q}_\tau(\lambda) := Q_\tau(\lambda) \circ Q_\tau(0)^{-1} \in \text{End}_K(V_\tau \otimes V^M_{\tau}) \simeq \text{End}(V^M_{\tau}).
\]
Hence $\tilde{Q}_\tau(0) = \text{id}$ and we can, upon fixing a basis of the vector space $V^M_{\tau}$, view $\tilde{Q}_\tau$ as a polynomial function on $a^*_C$ with values in the space of $l(\tau) \times l(\tau)$-matrices, where $l(\tau) := \dim V^M_{\tau}$.

**Remark 6.2.** In case $G$ has real rank one, the subgroup $M \subset K$ is symmetric and thus $V^M_{\tau}$ is one-dimensional for all $\tau \in \hat{K}_M$. In this case, for fixed $\tau \in \hat{K}_M$ the map
\[
\lambda \mapsto \tilde{Q}_\tau(\lambda)
\]
is an explicitly computable polynomial in $\lambda$ (see [11, Ch. III, Cor. 11.3]), and consequently $\lambda \mapsto J_{w,\lambda}[\tau]$ is a scalar-valued rational function.

Specifically, let now $G = \text{SL}(2, \mathbb{R})$ with $K = \text{SO}(2, \mathbb{R})$ and $A$ as before. We identify $\hat{K}_M$ with $\mathbb{Z}$ and $a^*_C$ with $\mathbb{C}$ via $\mathbb{C} \ni \lambda \mapsto \lambda \rho$. Then for $n = \tau \in \mathbb{Z}$
\[
\tilde{Q}_n(\lambda) = \frac{\Gamma\left(\frac{1}{2}(i\lambda + \rho)(\alpha^\vee) + |n|\right) \Gamma\left(\frac{1}{2}\rho(\alpha^\vee)\right)}{\Gamma\left(\frac{1}{2}(i\lambda + \rho)(\alpha^\vee)\right) \Gamma\left(\frac{1}{2}\rho(\alpha^\vee) + |n|\right)}
\]

\[
= \frac{\Gamma\left(\frac{1}{2}(i\lambda + 1) + |n|\right) \Gamma\left(\frac{1}{2}\right)}{\Gamma\left(\frac{1}{2}(i\lambda + 1)\right) \Gamma\left(\frac{1}{2} + |n|\right)}
\]

\[
= \frac{(1 + i\lambda)(3 + i\lambda) \ldots (2|n| - 1 + i\lambda)}{1 \cdot 3 \cdot \ldots \cdot (2|n| - 1)}.
\]
Then, for all \( n \in \mathbb{Z} = \hat{K}_M \) and \( \lambda \in \mathbb{C} = a_\mathbb{C}^* \) and \( w \in W \) the non trivial element, the map \( J_{w,\lambda}[n] \) is given by the scalar

\[
J_{w,\lambda}[n] = \frac{(1 - i\lambda)(3 - i\lambda) \cdots (2|n| - 1 - i\lambda)}{(1 + i\lambda)(3 + i\lambda) \cdots (2|n| - 1 + i\lambda)}.
\]

7. Strategy of proof

In this section we describe the general strategy of proof for the analytic inclusion. The approach is simpler when \( G/K \) has rank one, and therefore we give a separate proof for that. The strategy for rank one is described through the following Ansatz 1. The general case is treated in Ansatz 2.

7.1. Ansatz 1. We consider a module \( V_{\lambda_0} \), where \( \lambda_0 \) satisfies (4.3). Let \( r > 0 \) and \( v \in V_{\lambda_0}(r) \), i.e. \( v = \sum_{\tau \in \hat{K}_M} v_\tau \) with \( v_\tau \in V_{\lambda_0}[\tau] = V_\tau \otimes V_\lambda^M \), so that

\[
\sum_{\tau \in \hat{K}_M} e^{r' |\tau|} \| v_\tau \|_\tau < \infty \quad (0 < r' < r).
\]

We make the following ansatz. First, let

\[
F(\lambda) = F_v(\lambda) = \sum_{\tau \in \hat{K}_M} u_\tau(\lambda),
\]

where

\[
a_\mathbb{C}^* \ni \lambda \mapsto u_\tau(\lambda) \in V_\tau \otimes V_\lambda^M
\]

is a certain holomorphic function such that \( u_\tau(\lambda_0) = v_\tau \). Specifically, we set

\[
u_\tau(\lambda) = \phi_\tau(\lambda)Q_\tau(\lambda) \circ Q_\tau(\lambda_0)^{-1} v_\tau,
\]

where \( \phi_\tau \in \mathcal{O}(a_\mathbb{C}^*)^W \) is a \( W \)-invariant holomorphic function with \( \phi_\tau(\lambda_0) = 1 \). Suppose that the series defining \( F(\lambda) \) converges locally uniformly, so that \( F_v \in \mathcal{O}(a_\mathbb{C}^*, C^\infty(K/M)) \). Then we observe with (6.6) and the \( W \)-invariance of \( \lambda \mapsto \phi_\tau(\lambda) \) that

\[
J_{w,\lambda} F(\lambda) = \sum_{\tau \in \hat{K}_M} \phi_\tau(\lambda)J_{w,\lambda}[\tau] \circ Q_\tau(\lambda) \circ Q_\tau(\lambda_0)^{-1} v_\tau
\]

\[
= \sum_{\tau \in \hat{K}_M} \phi_\tau(\lambda)Q_\tau(w\lambda) \circ Q_\tau(\lambda_0)^{-1} v_\tau = F(\lambda)w(\lambda).
\]

In other words \( \lambda \mapsto F(\lambda) \) satisfies the intertwining relations. If we can now construct the \( \phi_\tau \) in such a way that \( F \in \text{PW}(a_\mathbb{C}^*, C^\infty(K/M))_R \) for some \( R = R(r) \), then the Paley-Wiener theorem (6.3) implies the existence of an \( f \in C_R^\infty(Z) \) such that \( F(f) = F \). In particular, we obtain \( v = \pi_{\lambda_0}(f)v_{K,\lambda_0} \), that is

\[
V_{\lambda_0}(r) \subset C_R^\infty(\mathbb{G}^*) \ast V_{\lambda_0}.
\]

We follow this ansatz for the rank 1 spaces in Section 9.
7.2. Ansatz 2. For the second ansatz we need some terminology. We denote by $\mathfrak{M}(\mathfrak{a}_C^*, C^\infty(K/M))$ the space of $C^\infty(K/M)$-valued meromorphic functions on $\mathfrak{a}_C^*$. We recall that a vector-valued function $f$ on $\mathfrak{a}_C^*$ is called meromorphic provided that for all $\lambda_0 \in \mathfrak{a}_C^*$ there exists an open neighborhood $U$ of $\lambda_0$ and a polynomial $p(\lambda)$ so that $\lambda \mapsto p(\lambda)f(\lambda)$ extends to a holomorphic function on $U$. In this regard we recall that $\mathcal{H}_\infty^K = C^\infty(K/M)$ as $K$-modules for every $\lambda \in \mathfrak{a}_C^*$. We then view an element $f \in \mathfrak{M}(\mathfrak{a}_C^*, C^\infty(K/M))$ as a section of the bundle $\prod_{\lambda \in \mathfrak{a}_C^*} \mathcal{H}_\infty^K \to \mathfrak{a}_C^*$, i.e. we consider $f(\lambda) \in \mathcal{H}_\infty^K$. The key observation is that the prescription

$$W \times \mathfrak{M}(\mathfrak{a}_C^*, C^\infty(K/M)) \to \mathfrak{M}(\mathfrak{a}_C^*, C^\infty(K/M)), \quad (w, f) \mapsto w \circ f;$$

defines an action of $W$ and, moreover, a meromorphic function $f$ satisfies the intertwining relations if and only if it is $W$-invariant for this action.

Now we come to the ansatz proper. Fix $\lambda_0 \in \mathfrak{a}_C^*$ which satisfies the Kostant condition \cite{1,3}, and let $W_{\lambda_0} \subset W$ be the stabilizer of $\lambda_0$. As $\lambda_0$ satisfies \cite{1,3}, it follows that $J_{w,w^{-1}\lambda_0} = J_{w,\lambda_0}$ is defined for all $w \in W_{\lambda_0}$ and constitutes an intertwining operator $J_{w,\lambda_0} : V_{\lambda_0}^w \to V_{\lambda_0}^w$ with $J_{w,\lambda_0}(v_{K,\lambda_0}) = v_{K,\lambda_0}$. The fact that $v_{K,\lambda_0}$ is fixed by $J_{w,\lambda_0}$ and that $v_{K,\lambda_0}$ is cyclic for $V_{\lambda_0}$ (see Lemma \cite{4,3}) implies that $J_{w,\lambda_0}$ is equal to the identity on $V_{\lambda_0}$ and hence also on $V_{\lambda_0}^\infty$.

Let now $v \in V_{\lambda_0}^\infty(r)$. Let further $f_v : \mathfrak{a}_C^* \to C^\infty(K/M)$ be a holomorphic function satisfying the properties

- $f_v(\lambda_0) = \frac{1}{|W_{\lambda_0}|}v$,
- $f_v(w\lambda_0) = 0$ if $w \in W \setminus W_{\lambda_0}$.

Given a choice for $f_v$, we define a meromorphic function by $A(f_v) := \sum_{w \in W} w \circ f_v$, and note that $A(f_v)$ automatically satisfies the intertwining relations. Moreover,

$$A(f_v)(\lambda_0) = \sum_{w \in W} J_{w,w^{-1}\lambda_0} f_v(w^{-1}\lambda_0) = \sum_{w \in W_{\lambda_0}} J_{w,\lambda_0} f_v(\lambda_0) = v, \quad (7.1)$$

i.e. $A(f_v)$ interpolates $v$ at $\lambda = \lambda_0$.

The difficulty is that the operators $J_{w,w^{-1}\lambda}$ have poles and the function $f_v$ has to be chosen carefully, so that $A(f_v)$ is indeed holomorphic and satisfies the Paley-Wiener condition for some $R = R(r) > 0$. The overall strategy is to start with a simple minded function $f_v(\lambda) = p_{\lambda_0}(\lambda)v$ for some polynomial $p_{\lambda_0}$ and then modify $f_v$ along its $K$-isotypical components, i.e. for each $\tau \in \hat{K}$ we replace $p_{\lambda_0}(\lambda)v_\tau$ by $\phi_\tau(\lambda)p_{\lambda_0}(\lambda)v_\tau$ for some appropriate holomorphic function $\phi_\tau$.

This ansatz is used for the general case in Section \cite{10}

Remark 7.1. Compared to the first ansatz this approach is computationally more complex, as we have to average over the Weyl group $W$, and in addition the functions $\phi_\tau$ have to be such that the poles of the rational functions $J_{w,\lambda}$ are canceled. However, the advantage of this ansatz is that intertwining operators, in contrast to the $Q$-polynomials, factor into rank one intertwiners, which can be explicitly computed and estimated.
7.3. **An application of Helgason’s Paley-Wiener theorem.** The following proposition will be used in the implementation of both ansatzes.

We define $\mathcal{H}$ to be the $K$ representation $L^2(K/M)$. Accordingly, we write $\mathcal{H}^\infty$ and $\mathcal{H}^{\omega}$ for $C^\infty(K/M)$ and $C^{\omega}(K/M)$, respectively. For each $r > 0$ we define a Fréchet space by

$$\mathcal{H}^\omega(r) := \{v \in \mathcal{H}^\omega \mid \forall 0 < r' < r \sum_{\tau \in \hat{K}_M} e^{r' |\tau|} \|v_\tau\| < \infty\}$$

with the indicated seminorms. We write $\mathcal{H}_r$ for the $r$-component of $\mathcal{H}$.

**Proposition 7.2.** Let $r, R > 0$ and $\lambda_0 \in a_\mathbb{C}^\ast$. Consider a family $(F_\tau)_{\tau \in \hat{K}_M}$ of holomorphic functions $F_\tau : a_\mathbb{C}^\ast \to \text{End}(\mathcal{H}_r)$ satisfying the following conditions.

(i) For every $\tau \in \hat{K}_M$ we have $F_\tau(\lambda_0) = \text{id}$.

(ii) For every $\tau \in \hat{K}_M$, $w \in W$ and $\lambda \in a_\mathbb{C}^\ast$ the intertwining relation holds

$$F_\tau(w \cdot \lambda) = J_{w,\lambda} \circ F_\tau(\lambda).$$

(iii) There exist a real number $0 < r' < r$, integers $j, l \in \mathbb{N}_0$, and a constant $C' > 0$ so that for all $\tau \in \hat{K}_M$ and $\lambda \in a_\mathbb{C}^\ast$

$$\|F_\tau(\lambda)\|_{\text{op}} \leq C'(1 + |\tau|)^j e^{r' |\tau|} (1 + \|\lambda\|)^l e^{R \|\text{Im}\lambda\|}.$$

Then for every $\epsilon > 0$ there exists a continuous linear map $\varphi : \mathcal{H}^\omega(r) \to C^{\infty}_{R+\epsilon}(G/K)$ so that

$$v = \varphi(v) \ast v_{K,\lambda_0} \quad (v \in \mathcal{H}^\omega(r)).$$

**Proof.** For $k \in \mathbb{N}_0$, let $p_k$ be the continuous seminorm on $\mathcal{H}^\infty$ given by

$$p_k(u) = \sum_{\tau \in \hat{K}_M} (1 + |\tau|)^k \|u_\tau\| \quad (u \in \mathcal{H}^\infty).$$

Note that this family of seminorms determines the topology of $\mathcal{H}^\infty$.

Let $r' < r'' < r$. It follows from (iii) that for $\lambda \in a_\mathbb{C}^\ast$, $k \in \mathbb{N}_0$ and $v \in \mathcal{H}^\omega(r)$

$$\sum_{\tau \in \hat{K}_M} (1 + |\tau|)^k \|F_\tau(\lambda)(v)\| \leq C''(1 + \|\lambda\|)^l e^{R \|\text{Im}\lambda\|} \sum_{\tau \in \hat{K}_M} e^{r'' |\tau|} \|v_\tau\|,$$

where

$$C'' := C' \sup_{\tau \in \hat{K}_M} (1 + |\tau|)^{j+k} e^{(r' - r'')|\tau|} < \infty.$$  

By definition $\sum_{\tau \in \hat{K}_M} e^{r'' |\tau|} \|v_\tau\| < \infty$ for each $v \in \mathcal{H}^\omega(r)$. It follows from (7.2) that for every $v \in \mathcal{H}^\omega(r)$ the series

$$F_v(\lambda) := \sum_{\tau \in \hat{K}_M} F_\tau(\lambda)(v_\tau) \quad (\lambda \in a_\mathbb{C}^\ast)$$

converges in $\mathcal{H}^\infty$. The convergence is uniform for $\lambda$ in compacta, and hence $F_v$ is a holomorphic $\mathcal{H}^\infty$-valued function depending linearly on $v$.

Let $\epsilon > 0$. We claim that there exists a $\theta \in C^{\infty}_c(K \setminus G/K)$ so that $\theta \ast v_{K,\lambda_0} = v_{K,\lambda_0}$. To see this, first note that

$$C^{\infty}_c(K \setminus G/K) \ast v_{K,\lambda_0} \subseteq C v_{K,\lambda_0}.$$
Consider now a Dirac sequence \((\theta_n)_{n \in \mathbb{N}}\) of functions \(\theta_n \in C_{1/n}^\infty(K \setminus G/K)\). Since \(\theta_n \ast v_{K,\lambda_0}\) converges to \(v_{K,\lambda_0}\) for \(n \to \infty\), there exists an \(m \in \mathbb{N}\) so that \(\theta_n \ast v_{K,\lambda_0} \neq 0\) for all \(n > m\). Let now \(n > m\) be so large that \(\frac{1}{n} < \epsilon\). After a rescaling of \(\theta_n\) we obtain a function with the claimed property.

Since \(\theta\) is \(K\)-invariant, its Fourier transform \(\hat{\theta} = F(\theta)\) is a \(W\)-invariant scalar-valued holomorphic function on \(a^*_\mathbb{C}\), and by the Paley-Wiener Theorem (6.3) it satisfies for every \(N \in \mathbb{N}_0\) the estimate

\[
\sup_{\lambda \in a^*_\mathbb{C}} |\hat{\theta}(\lambda)|((1 + \|\lambda\|)^N e^{-\epsilon\|\Im \lambda\|} < \infty \quad (7.3)
\]

Moreover, since \(\theta \ast v_{K,\lambda_0} = v_{K,\lambda_0}\) we have

\[
\hat{\theta}(\lambda_0) = 1. \quad (7.4)
\]

For \(\lambda \in a^*_\mathbb{C}\) and \(v \in \mathcal{H}^\omega(\tau)\) we define \(f_v(\lambda) := \hat{\theta}(\lambda) F_v(\lambda) \in \mathcal{H}^\infty\). The function \(f_v : a^*_\mathbb{C} \to \mathcal{H}^\infty\) thus obtained is holomorphic. It follows from (7.4) and assumption (\(H\)) that \(f_v(\lambda_0) = F_v(\lambda_0) = v\). In view of assumption (\(H\)) the function \(f_v\) satisfies the intertwining relations (6.2). Finally, it follows from the estimates (7.2) and (7.3) that there exist for every \(N \in \mathbb{N}_0\) and \(k \in \mathbb{N}_0\) a constant \(C_{N,k} > 0\), so that for every \(\lambda \in a^*_\mathbb{C}\) and \(v \in \mathcal{H}^\omega(\tau)\)

\[
p_k(f_v(\lambda)) \leq C_{N,k}(1 + \|\lambda\|)^{-N}(\|\lambda\|/c(\lambda))^2 \sum_{\tau \in \hat{K}_M} e^{\epsilon \|\tau\|} \|v_\tau\|, \quad (7.5)
\]

Now it follows from the Paley-Wiener theorem (6.3) that \(f_v = F(\varphi'_v)\) for some \(\varphi'_v \in C_{R^+2k}^\infty(G/K)\). Set \(\varphi_v = \varphi'_v \ast \theta \in C_{R^+2k}^\infty(G/K)\). Note that \(\varphi_v\) depends linearly on \(v\) and satisfies

\[
\varphi_v \ast v_{K,\lambda_0} = \varphi_v \ast v_{K,\lambda_0} = F(\varphi'_v)(\lambda_0) = f_v(\lambda_0) = v. \quad (7.2)
\]

It remains to show continuity from \(\mathcal{H}^\omega(\tau)\) to \(C_{R^+2k}^\infty(G/K)\) of the map \(v \mapsto \varphi_v\). The Paley-Wiener space \(\text{PW}(a^*_\mathbb{C}, \mathcal{H}^\infty)_{R^+\ell}\) is a subspace of \(L^2(a^*, \mathcal{H}, \frac{d\lambda}{|c(\lambda)|})\). By the Plancherel theorem for \(G/K\) and (7.5) we have

\[
\|\varphi'_v\|_{L^2} = \int_{a^*} \|f_v(\lambda)\|^2 \frac{d\lambda}{|c(\lambda)|^2} \leq \int_{a^*} p_0(f_v(\lambda)) \frac{d\lambda}{|c(\lambda)|^2} \leq c_0 \left( \sum_{\tau \in \hat{K}_M} e^{\epsilon \|\tau\|} \|v_\tau\| \right)^2,
\]

with

\[
c_0 = C_{N,0}^2 \int_{a^*} (1 + \|\lambda\|)^{-2N} \frac{d\lambda}{|c(\lambda)|^2} < \infty
\]

for a sufficiently large \(N \in \mathbb{N}\). Finally for every continuous seminorm \(q\) on \(C_{R^+2k}^\infty(G/K)\) there exists a constant \(c' > 0\), only depending on \(\theta\), so that

\[
q(\varphi_v) \leq c' \|\varphi'_v\|_{L^2}.
\]

The continuity follows. \(\square\)
PALEY-WIENER THEOREM

8. AN EXPLICIT CONSTRUCTION IN ONE VARIABLE

For every \( n \in \mathbb{N}_0 \) and \( R > 0 \) we define an entire function \( f_{n,R} \) on \( \mathbb{C} \) by

\[
 f_{n,R}(z) := \frac{\sin(zR\pi)}{zR\pi \prod_{j=1}^{n} \left(1 - \left(\frac{Rz}{j}\right)^2\right)} = \prod_{j=n+1}^{\infty} \left(1 - \left(\frac{Rz}{j}\right)^2\right) \quad (z \in \mathbb{C}),
\]

invoking the product expansion of the sine function. Next we define for \( n \in \mathbb{N}_0 \) a polynomial function \( q_n \) on \( \mathbb{C} \) by

\[
 q_n(z) := \prod_{j=1}^{n} \left(1 + \frac{z}{j}\right) \quad (z \in \mathbb{C}).
\]

**Proposition 8.1.** There exist \( c, R_0 > 0 \) and for every \( r > 0 \) a constant \( C_r > 0 \) so that the following assertion holds for every \( n \in \mathbb{N}_0 \).

Let \( r > 0 \) and \( R > R_0 \) with

\[
 \frac{(\log R)^2}{R^2} < cr.
\]

Let \( V \) be a finite dimensional inner product space and \( P : \mathbb{C} \to \text{End}(V) \) a polynomial map such that

\[
 \|P(z)\|_{\text{op}} \leq q_n(|z|)^k \quad (z \in \mathbb{C})
\]

for some \( k \in \mathbb{N} \). Then

\[
 \|f_{n,R}(z)^k P(z)\|_{\text{op}} \leq \left[C_r e^{rn} e^{R\pi |\text{Im } z|}\right]^k
\]

for all \( z \in \mathbb{C} \).

The proof is divided into several lemmas. Let

\[
 F_{n,R}(z) := f_{n,R}(z)^k P(z).
\]

The first two lemmas contain estimates of the function defined by

\[
 \tilde{F}_{n,R}(z) := f_{n,R}(z)q_n(|z|),
\]

for which we have

\[
 \|F_{n,R}(z)\|_{\text{op}} \leq |\tilde{F}_{n,R}(z)|^k \quad (z \in \mathbb{C}).
\]

**Lemma 8.2.** There exists a constant \( C > 0 \), so that for all \( R > 3 \), \( n \in \mathbb{N}_0 \) and \( z \in \mathbb{C} \) with \( |z| \geq \frac{R}{n} \) we have

\[
 |\tilde{F}_{n,R}(z)| \leq C e^{R\pi |\text{Im } z|}.
\]

**Proof.** By symmetry, we may assume without loss of generality that \( \text{Re } z \geq 0 \). Note that

\[
 \tilde{F}_{n,R}(z) = \frac{(1 + |z|) \cdots (n + |z|)}{(1 + Rz) \cdots (n + Rz)} \cdot \frac{1 \cdot 2 \cdots n}{(1 - Rz) \cdots (n - Rz)} \cdot \frac{\sin(\pi Rz)}{\pi Rz}.
\]

We claim that

\[
 \frac{(1 + |z|) \cdots (n + |z|)}{(1 + Rz) \cdots (n + Rz)} \leq 1.
\]

To prove the claim it suffices to show that for all \( 1 \leq j \leq n \) we have

\[
 j + |z| \leq |j + Rz|.
\]
Since \( \text{Re} z \geq 0 \), we have
\[
|j + Rz|^2 = R^2|z|^2 + 2Rj \text{Re} z + j^2 \geq R^2|z|^2 + j^2.
\]
For \( R \geq 3 \) and \( |z| \geq \frac{n}{R} \) the condition \( R^2|z|^2 \geq |z|^2 + 2n|z| \) is satisfied, and hence
\[
R^2|z|^2 + j^2 \geq |z|^2 + 2n|z| + j^2 \geq (j + |z|)^2.
\]
This proves the claim.
We further claim that
\[
\left| \frac{1 \cdot 2 \cdots (n - 1)}{(1 - Rz) \cdots (n - 1 - Rz)} \right| \leq 1
\]
if \( R|z| \geq n \). This is a direct consequence of the inequality \( |j - Rz| \geq R|z| - j \geq n - j \).
Altogether, we obtain the estimate
\[
\left| \tilde{F}_{n,R}(z) \right| \leq \frac{n}{n - Rz} \cdot \left| \frac{\sin(\pi Rz)}{\pi Rz} \right| \leq \frac{\sin \left( \frac{\pi (n - Rz)}{n - Rz} \right)}{\pi (n - Rz)} \leq Ce^{R|z| \Im z}.
\]
\[ \square \]

**Lemma 8.3.** There exists a constant \( c > 0 \) such that the following holds: For all \( r > 0 \) there exists \( C > 0 \), so that for all \( n \in \mathbb{N}_0 \) and \( R > e \) with
\[
\frac{(\log R)^2}{R^2} < cr,
\]
we have
\[
\left| \tilde{F}_{n,R}(z) \right| \leq Ce^{rn} \quad (0 \leq z \leq \frac{n}{R}).
\]

**Proof.** Let \( n \in \mathbb{N}_0 \), \( R > 1 \) and \( z \geq 0 \). We shall estimate \( \tilde{F}_{n,R}(z) \) using Stirling’s approximation. Euler’s reflection identity \( \Gamma(1 - x)\Gamma(x) = \frac{\pi}{\sin \pi x} \) and the functional equation of the Gamma function yield
\[
\left( \prod_{j=1}^{n} (j + Rz) \right) \left( \prod_{j=1}^{n} (j - Rz) \right) \frac{\pi Rz}{\sin \pi Rz} = \Gamma(n + 1 - Rz)\Gamma(n + 1 + Rz).
\]
This allows to rewrite (8.5) and express \( \tilde{F}_{n,R} \) in terms of Gamma functions:
\[
\tilde{F}_{n,R}(z) = \frac{\Gamma(n + 1 + z)\Gamma(n + 1)}{\Gamma(1 + z)\Gamma(n + 1 + Rz)\Gamma(n + 1 - Rz)}.
\]
We recall Stirling’s approximation
\[
\Gamma(x) = \sqrt{\frac{2\pi}{x}} e^{-x} x^x \left( 1 + O(1/x) \right)
\]
for \( x \to \infty \). Applying Stirling to \( \tilde{F}_{n,R} \), we obtain that there exists a constant \( c' > 0 \), independent of \( n \) and \( R \), so that for all \( z \in [0, \frac{n}{R}] \)
\[
\tilde{F}_{n,R}(z) \leq c' \sqrt{1 + \frac{n}{R} e^{h_{n,R}(z)}},
\]
where
\[
h_{n,R}(z) = \frac{1 \cdot 2 \cdots (n - 1)}{(1 - Rz) \cdots (n - 1 - Rz)}.
\]
where
\[ h_{n,R}(z) := (n + 1 + z) \log(n + 1 + z) + (n + 1) \log(n + 1) - (1 + z) \log(1 + z) - (n + 1 + Rz) \log(n + 1 + Rz) - (n + 1 - Rz) \log(n + 1 - Rz). \]

Here we used the straightforward estimate for \( z \in [0, \frac{n}{R}] \)
\[
\frac{(1 + z)(n + 1 + Rz)(n + 1 - Rz)}{(n + 1 + z)(n + 1)} = \frac{(1 + z)((n + 1)^2 - R^2z^2)}{(n + 1 + z)(n + 1)} \leq 1 + \frac{n}{R}
\]
to estimate the square roots in (8.6).

The term \((1 + z) \log(1 + z)\) in \(h_{n,R}(z)\) can be estimated below by \(z \log(z)\). With the substitution \(z = (n + 1)x\) we then obtain
\[ h_{n,R}(z) \leq (n + 1)H_R(x) \tag{8.8} \]
where
\[ H_R(x) := (1 + x) \log(1 + x) - x \log(x) - (1 + Rx) \log(1 + Rx) - (1 - Rx) \log(1 - Rx). \]

We will show
\[ H_R(x) \leq 4\left(\frac{\log R}{R^2}\right)^2, \quad x \in (0, \frac{1}{R}), \tag{8.9} \]
for all \(R \geq e\). We estimate the first two terms of \(H_R(x)\) in a separate lemma.

**Lemma 8.4.** For every \(b \geq e^2\) and \(0 < x \leq 1\)
\[(1 + x) \log(1 + x) - x \log x \leq \frac{(\log b)^2}{b} + bx^2.\]

**Proof.** Since \((1 + x) \log(1 + x) \leq 2x\) for \(0 < x \leq 1\) it suffices to show
\[ 2x - x \log x =: \phi(x) \leq \psi(x) := \frac{(\log b)^2}{b} + bx^2. \]

The functions \(\phi\) and \(\psi\) are concave and convex, respectively. We will prove the inequality by exhibiting a separating line of slope \(\log b\).

We have \(\phi'(x) = 1 - \log x\) and hence \(\phi'(x) = \log b\) for \(x = \frac{\epsilon}{b}\). Then
\[ \phi(x) \leq \phi\left(\frac{\epsilon}{b}\right) + \log(b)(x - \frac{\epsilon}{b}) = \frac{\epsilon}{b} + \log(b)x. \]

On the other hand \(\psi'(x) = 2bx = \log b\) for \(x = \frac{\log b}{2b}\) and therefore
\[ \psi(x) \geq \psi\left(\frac{\log b}{2b}\right) + \log(b)\left(x - \frac{\log b}{2b}\right) = \frac{3(\log b)^2}{4b} + \log(b)x. \]

Hence \(\psi \geq \phi\) if \(\frac{3}{4}(\log b)^2 \geq e\) and in particular if \(b \geq e^2\). \(\square\)

We proceed with the proof of (8.9). Let
\[ \varphi(t) = (1 + t) \log(1 + t) + (1 - t) \log(1 - t) \]
for \(0 \leq t < 1\). Then \(\varphi(0) = \varphi'(0) = 0\) and \(\varphi''(t) = \frac{1}{1+t} + \frac{1}{1-t} \geq 2\). Hence
\[ \varphi(t) \geq t^2. \]
Then for \( x \in (0, \frac{1}{R}) \)

\[
H_R(x) \leq (1 + x) \log(1 + x) - x \log x - R^2 x^2.
\]

We obtain \([8.9]\) from Lemma \([8.4]\) with \( b = R^2 \).

We can now finish the proof of Lemma \([8.3]\). Let \( 0 < c < \frac{1}{R} \). If \( r > 0 \), \( R \geq e \) and \( \frac{\log(r^2)}{R^2} \leq cr \), then

\[
|F_n^R(z)| \leq c e^r \sqrt{1 + n e^{4rn}} \leq C e^{rn}, \quad n \in \mathbb{N}_0, z \in [0, \frac{R}{r}],
\]

by \([8.7]\) and \([8.8]\), with a constant \( C > 0 \) depending only on \( c \) and \( r \).

\[\square\]

**Proof of Proposition \([8.7]\).** By Lemma \([8.2]\) and \([8.4]\) we have for all \( R > 3, n \in \mathbb{N}_0 \) and \( z \in \mathbb{C} \) with \( |z| \geq \frac{R}{r} \)

\[
\|F_n^R(z)\|_{\text{op}} \leq \left[ C e^{R^2 |\text{Im} z|} \right]^k.
\]

(8.10)

It therefore suffices to estimate \( F_n^R(z) \) for \( z \) in the disk \( D = \{ z \in \mathbb{C} : |z| \leq \frac{R}{r} \} \).

Note that

\[
\|F_n^R(z)\|_{\text{op}} = \sup_{v,w \in V \atop |v| = |w| = 1} |\langle F_n^R(z)v, w \rangle|,
\]

and that the matrix coefficients \( \langle F_n^R(z)v, w \rangle \) depend holomorphically on \( z \in \mathbb{C} \).

Let \( D_+ = D \cap \mathbb{C}_+ \) where \( \mathbb{C}_+ \) denotes the closed upper/lower half plane. By the maximum modulus principle a holomorphic function in \( D_\pm \) assumes its maximum modulus on \( \partial D_\pm \), i.e. on the union of the semicircle \( \partial D \cap \mathbb{C}_\pm \) and the segment \( D \cap \mathbb{R} = [-\frac{R}{r}, \frac{R}{r}] \). We apply the principle to the holomorphic function

\[
\langle F_n^R(z)v, w \rangle e^{\pm i R k \pi z}
\]

on \( D_\pm \), which by \([8.10]\) is bounded in absolute value by \( C^k \) on \( \partial D \cap \mathbb{C}_\pm \).

On the other hand, with \( c \) as in Lemma \([8.3]\) it follows that for all \( r \) satisfying \([8.3]\) there exists a constant \( C_r \) such that \( |\langle F_n^R(z)v, w \rangle e^{\pm i R k \pi z}| \) is bounded by \( [C_r e^{rn}]^k \) for \( z \in [-\frac{R}{r}, \frac{R}{r}] \). Assuming as we may that \( C_r \geq C \), we obtain

\[
|\langle F_n^R(z)v, w \rangle e^{\pm i R k \pi z}| \leq [C_r e^{rn}]^k
\]

for all \( z \in D_\pm \). This implies the proposition. \[\square\]

The following lemma will be used in the next two sections.

**Lemma 8.5.** Let \( R > 0 \) and \( z_0 \in \mathbb{C} \). Assume \( R z_0 \notin \mathbb{Z}\setminus\{0\} \). Then

\[
\inf_{n \in \mathbb{N}_0} |f_n^R(z_0)| > 0.
\]

**Proof.** With \([8.1]\) we observe that \( f_n^R(z) = 0 \) if and only if \( Rz \in \mathbb{Z} \) and \( |z| > \frac{R}{R} \).

In particular the assumption on \( z_0 \) implies \( f_n^R(z_0) \neq 0 \) for all \( n \in \mathbb{N}_0 \).

If \( n \geq N := \lceil R|z_0| \rceil \) then

\[
|f_n^R(z_0)| \geq \prod_{j=n+1}^{\infty} \left( 1 - \left( \frac{R|z_0|}{j} \right)^2 \right) \geq \prod_{j=N+1}^{\infty} \left( 1 - \left( \frac{R|z_0|}{j} \right)^2 \right) = f_{N,R}(|z_0|).
\]

Hence

\[
\inf_{n \in \mathbb{N}_0} |f_n^R(z_0)| \geq \min \{ |f_0^R(z_0)|, \ldots, |f_{N-1,R}(z_0)|, f_{N,R}(|z_0|) \} > 0
\]
by the first observation in the proof. □

We end this section with a remark that will be useful when Proposition 8.1 is applied in Sections 9 and 10.

**Remark 8.6.** Let \( P(R, r) \) be any proposition depending on two variables \( R, r > 0 \). Then the proposition
\[
\exists c, R_0 > 0 \forall r > 0, R > R_0 : \left( \frac{(\log R)^2}{R^2} < cr \Rightarrow P(R, r) \right)
\]
possesses a scaling invariance. Let \( a, A > 0 \) and \( B \in \mathbb{R} \). Then
\[
\exists d, S_0 > 0 \forall s > 0, S > S_0 : \left( \frac{(\log S)^2}{S^2} < ds \Rightarrow P(AS + B, as) \right)
\]
is an equivalent proposition. This follows from the observation that there exist constants \( C_0, C_1, C_2 > 0 \) so that for all \( R > C_0 \)
\[
C_1 \frac{\log R}{R} \leq \frac{\log(AR + B)}{AR + B} \leq C_2 \frac{\log R}{R}.
\]

9. **The rank one cases**

Using the construction from the previous section we can now complete the argument in case \( G \) is of real rank one. Let \( \alpha \in \Sigma^+ \) be the indivisible root. Then
\[
g = g^{2\alpha} + g^\alpha + a + m + g^{-\alpha} + g^{-2\alpha}
\]
with \( a = R\alpha \). We set \( m_\alpha := \dim g^\alpha \) and \( m_{2\alpha} = \dim g^{2\alpha} \). Then
\[
\rho = \frac{1}{2}(m_\alpha + 2m_{2\alpha})\alpha.
\]
The goal of this section is to prove the following

**Theorem 9.1.** Let \( G \) be a group of real rank one and \( V_{\lambda_0} \) a representation of the \( K \)-spherical principal series with \( \lambda_0 \) satisfying (4.3). Then there exist positive constants \( c, R_0 > 0 \) independent of \( \lambda_0 \), such that for all \( R, r > 0 \) with \( R > R_0 \) and \( \frac{(\log R)^2}{R^2} < cr \), we have a continuous embedding
\[
V_{\lambda_0}^\omega(r) \subset C_\infty^\omega(G) * v_{K,\lambda_0} = (V_{\lambda_0})_{R}^{\min}.
\]

**Remark 9.2.** With the theorem above we can prove Theorem 1.2 for groups of real rank one. Let \( c \) and \( R_0 \) be as above. Then Theorem 9.1 and Lemma 4.2 imply that the conclusion of Theorem 1.2 is valid for \( V = V_{\lambda_0} \). For a general irreducible Harish-Chandra module \( V \) the conclusion then follows from Lemmas 4.3 and 4.4.

In order to prepare for the proof of Theorem 9.1 we introduce some new notation and collect a few facts about real rank one groups which will be used in the sequel. A special feature of this case is that \( K/M \) is a compact symmetric space of rank one. In particular we have \( \dim V^\tau_M = 1 \) for all \( \tau \in \hat{K}_M \). Consequently, the \( \hat{Q} \)-matrices from Remark 6.1 are just scalar-valued polynomials. These polynomials can be read off from [11, Ch. III, Th. 11.2]. We recall from op. cit. the non-negative integers \( 0 \leq r \leq s \) attached to a fixed \( \tau \in \hat{K}_M \). From the proof of the cited theorem it follows that \( r \) and \( s \) have the same parity if \( m_{2\alpha} \neq 0 \). It further follows from the
equation for $s$ and $r$ on page 346 in op. cit. that there exists an $m > 0$, independent of $\tau$, such that
\[ s \leq m|\tau|. \]
We may and will take $m \in \mathbb{N}$. In order to express the $\tilde{Q}_\tau(\lambda)$ in an efficient way, we introduce some new notation.

For elements $0 < a \leq b$ with $b - a \in \mathbb{N}_0$, we define polynomials in the complex plane by
\[
\Gamma_{a,b}(z) := \frac{\Gamma(z + b)\Gamma(a)}{\Gamma(z + a)\Gamma(b)} = \frac{(z + a)(z + a + 1) \cdots (z + b - 1)}{a(a + 1) \cdots (b - 1)}.
\]

For later reference we note the following estimates by the polynomials introduced in (8.2):
\[
|\Gamma_{a,b}(z)| \leq \Gamma_{a,b}(|z|) \leq \begin{cases} 
q_{b-a}(|z|) & \text{if } a \geq 1 \\
\frac{q_{b-a}}{2}(|z|) & \text{if } a < 1.
\end{cases}
\]

The inequality for $a \geq 1$ follows from
\[
\frac{|z| + a + j}{a + j} = 1 + \frac{|z|}{a + j} \leq 1 + \frac{|z|}{1 + j}
\]
for each $j \geq 0$, and the other one is then a consequence of
\[
\Gamma_{a,b}(|z|) = \frac{(|z| + a) b}{(|z| + b) a} \Gamma_{a+1,b+1}(|z|).
\]

We also note that
\[
|\Gamma_{a,b}(z)| \geq 1 \quad \text{(Re}(z) \geq 0).
\]

Next we define positive half integers. In case $m_{2\alpha} = 0$ we set
\[
a_\tau := \rho\left(\frac{\alpha}{2}\right) = \frac{m_\alpha}{2} \quad \text{and} \quad b_\tau := \rho\left(\frac{\alpha}{2}\right) + s,
\]
and note that $b_\tau - a_\tau = s \in \mathbb{N}_0$.

For $m_{2\alpha} > 0$ we first note that $\rho\left(\frac{\alpha}{2}\right) = \frac{m_{2\alpha}}{2} + m_{2\alpha} =: d \in \mathbb{N}$ is a positive integer greater or equal to 2, as $m_\alpha$ is even when $m_{2\alpha} > 0$. Further we define positive half integers by
\[
a_\tau^1 := \rho\left(\frac{\alpha}{4}\right) = \frac{d}{2} \quad \text{and} \quad b_\tau^1 := \frac{1}{2}(s + r + d)
\]
and
\[
a_\tau^2 := \frac{1}{2}(d + 1 - m_{2\alpha}) \quad \text{and} \quad b_\tau^2 := \frac{1}{2}(s - r + d + 1 - m_{2\alpha}).
\]
Then both $b_\tau^1 - a_\tau^1 = \frac{1}{2}(s + r)$ and $b_\tau^2 - a_\tau^2 = \frac{1}{2}(s - r)$ are non-negative integers.

Having defined these constants, we rephrase [11, Ch. III, Cor. 11.3] as follows:

**Lemma 9.3.** Let $G$ be a group of real rank one and $\tau \in \hat{K}_M$. Then the following assertions hold:

1. If $m_{2\alpha} = 0$, then $a_\tau \geq \frac{1}{2}$ and
\[
\tilde{Q}_\tau(\lambda) = \Gamma_{a_\tau,b_\tau}(i\lambda\left(\frac{\alpha}{2}\right)).
\]
(2) If \( m_{2\alpha} > 0 \), then \( a_1^\tau \geq a_2^\tau \geq 1 \) and

\[
\tilde{Q}_\tau(\lambda) = \Gamma_{a_1^\tau, b_1^\tau}(i\lambda(\frac{\alpha_1^\tau}{2})) \Gamma_{a_2^\tau, b_2^\tau}(i\lambda(\frac{\alpha_2^\tau}{2})).
\]

9.1. **Proof of Theorem 9.1 in case of** \( m_{2\alpha} = 0 \). We identify \( a_2^z \) with \( \mathbb{C} \) via

\[
\mathbb{C} \leftrightarrow a_2^z, \quad z \mapsto z \alpha,
\]

i.e. \( \lambda = z\alpha \in a_2^z \) identifies with \( z \in \mathbb{C} \). In these coordinates we then have

\[
\tilde{Q}_\tau(z) = \Gamma_{m_0^\tau, m_0^\tau}, (iz),
\]

and it follows from (9.2) that \( |\tilde{Q}_\tau(z)| \leq (1 + 2s)q_s(|z|) \).

We recall that \( s \leq m[\tau] \) for every \( \tau \in \hat{K}_M \), and that \( m \in \mathbb{N} \). We write \( [\tau] \in \mathbb{N} \) for the smallest integer greater or equal than \(|\tau|\). We thus obtain the bound

\[
|\tilde{Q}_\tau(z)| \leq (1 + 2m[\tau])q_m[\tau](|z|). \tag{9.4}
\]

We recall the functions \( f_{n,R} \), depending on \( R > 0 \), as defined in (8.1). Let \( z_0 \in \mathbb{C} \) be so that \( \lambda_0 = z_0\alpha \). We assume that \( Rz_0 \) is not a non-zero integer integer Then \( f_{n,R}(z_0) \neq 0 \) for all \( n \in \mathbb{N}_0 \). For \( \tau \in \hat{K}_M \) we define the \( W \)-symmetric entire function

\[
\phi_\tau : \mathbb{C} \to \mathbb{C}; \quad z \mapsto \frac{f_{m[\tau], R}(z)}{f_{m[\tau], R}(z_0)}.
\]

Now given \( \lambda_0 = z_0\alpha \in a_2^z \) satisfying (4.3), we follow Ansatz 1 in Section 7.1 and define

\[
\tilde{F}_\tau(z) = \phi_\tau(z)\tilde{Q}_\tau(z)\tilde{Q}_\tau(z_0)^{-1} \in \text{End}_K(V_\tau \otimes V_\tau^M) \simeq \mathbb{C} \quad (z \in \mathbb{C}).
\]

Let \( F_\tau : a_2^z \to \text{End}_K(V_\tau \otimes V_\tau^M) \) be given by

\[
F_\tau(\zeta)(z) = \tilde{F}_\tau(z) \quad (z \in \mathbb{C}).
\]

It is immediate that \( F_\tau \) satisfies the conditions (i) and (ii) in Proposition 7.2 with \( \mathcal{H}_\tau = V_\tau \otimes V_\tau^M \).

We continue by investigating condition (iii). For that we need to control the normalizing factors \( \tilde{Q}_\tau(z_0) \) and \( f_{m[\tau], R}(z_0) \). By (4.3) the real part of \( iz_0 \) is non-negative, and hence it follows from (9.4) that

\[
|\tilde{Q}_\tau(z_0)| \geq 1 \quad (\tau \in \hat{K}_M).
\]

Likewise, Lemma 8.5 gives a positive lower bound for \(|f_{m[\tau], R}(z_0)|\), uniformly in \( \tau \).

Let \( c, R_0 > 0 \) be as in Proposition 8.1 and assume that \( R > R_0 \) and \( \frac{(\log R)^2}{R^2} < cr \).

By perturbing \( R \) to a slightly smaller value we can ensure \( Rz_0 \) is not an integer, as assumed before. Let \( r' < r \) be such that \( \frac{(\log R)^2}{R^2} < cr' \). From Proposition 8.1 and (9.4) it follows that there exists a constant \( C > 0 \) so that

\[
|F_\tau(\lambda)| \leq C(1 + |\tau|) e^{c\tau|\alpha|} \|i\alpha^\tau\| \|\text{Im}\lambda\| \quad (\lambda \in a_2^z, \tau \in \hat{K}_M).
\]

By Proposition 7.2 this implies \( V_{\alpha_0}^\infty(n\tau) \subset C_{AR+\epsilon}^{\infty}(G/K) * v_{K, \lambda_0} \), where \( A = \pi \|\frac{1}{2}i\alpha^\tau\| \).

By Remark 8.6 the continuous embedding in the theorem follows. Finally, as \( v_{K, \lambda_0} \) is \( \mathcal{U}(g) \)-cyclic by Lemma 4.4 we have \( C_{AR}^{\infty}(G) * v_{K, \lambda_0} = (V_{\lambda_0})_R^{\min} \).
9.2. Proof of Theorem 9.1 in case of \( m_2 > 0 \). We now identify \( \mathfrak{a}_C^* \) with \( \mathbb{C} \) via 
\[ \mathbb{C} \ni z \mapsto 2z\alpha. \]
From Lemma 9.3 we then have 
\[ \widetilde{Q}_\tau(z) = \Gamma_{a^*_1}(iz) \Gamma_{a^*_2}(iz). \]
As before we apply (9.2). The result is now 
\[ \widetilde{Q}_\tau(-i|z|) \leq \left[ q^{m_2}(|z|) \right]^2. \]
Next we define the \( W \)-symmetric entire function 
\[ \phi_\tau(z) := \left[ f^{m_2}(z) \right]^2 \left[ f^{m_2}(z_0) \right]^2 \]
and argue along the same lines as before. This concludes the proof of Theorem 9.1.

10. The general higher rank case

The goal of this section is to prove the following

**Theorem 10.1.** Let \( V_{\lambda_0} \) be a representation of the \( K \)-spherical principal series with \( \lambda_0 \) satisfying (4.3). Then there exist positive constants \( c, R_0 \) independent of \( \lambda_0 \), such that for all \( R, r > 0 \) with \( R > R_0 \) and \( \frac{\log R^2}{R^2} < cr \) we have a continuous embedding
\[ V_{\lambda_0}(r) \subset C^\infty(G)^* v_{K,\lambda_0} = (V_{\lambda_0})^\min_R. \]

**Remark 10.2.** By the arguments in Remark 9.2 we obtain Theorem 1.2 of the introduction from Theorem 10.1 together with the reduction in Section 4.

To prepare for the proof of Theorem 10.1 we determine some estimates of the intertwining operators \( J_{w,\lambda} \). We start by recalling the standard procedure by which the study of \( J_{w,\lambda} \) is reduced to rank one.

10.1. Factorization of intertwining operators. Let \( w \in W \) and write
\[ w = s_1 s_2 \cdots s_n \]
as a reduced expression with simple reflections \( s_i \) associated to simple roots \( \alpha_i \in \Pi \). Set 
\[ w_j := s_{j+1} \cdots s_n \in W \quad (1 \leq j \leq n). \]
Then the reduced expression of \( w \) satisfies the condition
\[ w_j^{-1} \alpha_j \in \Sigma^+ \quad (1 \leq j \leq n) \]
and
\[ w_j^{-1} \alpha_j \neq w_k^{-1} \alpha_k \quad (1 \leq j < k \leq n). \]
See [3 VI.1.6 Corollaire 2]. Essential for our reasoning is the factorization
\[ J_{w,\lambda} = J_{s_1, w_1 \lambda} \circ J_{s_2, w_2 \lambda} \circ \cdots J_{s_{n-1}, w_{n-1} \lambda} \circ J_{s_n, \lambda}, \]
with each
\[ J_{s_j, w_j \lambda} : V^\infty_{w_j \lambda} \to V^\infty_{w_{j-1} \lambda} \]
a rank one intertwiner.
10.2. Rank one intertwining operators. Let \( s_\alpha \in W \) be the reflection in a simple root \( \alpha \in \Sigma^+ \). When restricted to a specific \( K \)-type \( \tau \in \hat{K}_M \), each \( J_{s_\alpha,\lambda}[\tau] \) is an element of \( \text{End}(V^M) \) depending rationally on \( \lambda \). We will describe the entries of a diagonal matrix for it.

Let \( \mathfrak{g}_\alpha \) be the semisimple rank one subalgebra of \( \mathfrak{g} \) generated by \( \alpha \). Then

\[
\mathfrak{g}_\alpha = \mathfrak{g}^{2\alpha} \oplus \mathfrak{g}^\alpha \oplus \mathfrak{g} = \mathfrak{a}_\alpha \oplus \mathfrak{m}_\alpha \oplus \mathfrak{g}^{-\alpha} \oplus \mathfrak{g}^{-2\alpha}
\]

with \( \mathfrak{a}_\alpha = \mathbb{R}\alpha^\vee \) and \( \mathfrak{m}_\alpha \subset \mathfrak{m} \) an ideal. In particular, the Cartan decomposition \( \mathfrak{g} = \mathfrak{t} \oplus \mathfrak{s} \) descends to \( \mathfrak{g}_\alpha \), and we obtain with \( \mathfrak{t}_\alpha := \mathfrak{g}_\alpha \cap \mathfrak{t} \) a maximal compact subalgebra of \( \mathfrak{g}_\alpha \).

We denote by \( G_\alpha := (\exp(\mathfrak{g}_\alpha)) \) the analytic subgroup of \( G \) associated to \( \mathfrak{g}_\alpha \), by \( K_\alpha := \exp(\mathfrak{t}_\alpha) \) the maximal compact subgroup of \( G_\alpha \) with Lie algebra \( \mathfrak{t}_\alpha \), and by \( M_\alpha \) the group \( M \cap K_\alpha \). Note that \( M \) normalizes \( G_\alpha \). Hence if we branch \( V^M \) with respect to \( K_\alpha \), then

\[
V^M = \bigoplus_{\delta \in K_\alpha \backslash M_\alpha} m(\delta) V^{M_\alpha}_{\delta},
\]

where \( m(\delta) \) denotes the multiplicity of \( \delta \) in \( \tau^\vee|_{K_\alpha} \). As \( K_\alpha/M_\alpha \) is symmetric, each \( V^{M_\alpha}_{\delta} \) is one-dimensional. We choose an orthonormal basis (depending on \( j \)) of \( V^{M_\alpha}_{\delta} \) of vectors from these one-dimensional subspaces.

For elements \( \frac{1}{2} \leq a \leq b \) with \( a, b \in \frac{1}{2}\mathbb{N} \) and \( b - a \in \mathbb{N}_0 \), we recall the polynomials \( \Gamma_{a,b}(z) \) from \( \text{[4.1]} \). With respect to the chosen basis the operator \( J_{s_\alpha,\lambda}[\tau] \) is of diagonal form, say

\[
D_\tau(\lambda) = \text{diag}(d_1^\tau(\lambda), \ldots, d_l^\tau(\lambda)),
\]

and each diagonal entry is of the form (see \( \text{[15.6]}, \text{Lemma 9.3} \))

\[
d_k^\tau(\lambda) = \frac{\Gamma_{a,b}(i\lambda(\frac{\gamma}{\gamma_0}))\Gamma_{a',b'}(-i\lambda(\frac{\gamma}{\gamma_0}))}{\Gamma_{a,b}(i\lambda(\frac{\gamma}{\gamma_0}))\Gamma_{a',b'}(i\lambda(\frac{\gamma}{\gamma_0}))} \quad (1 \leq k \leq l(\tau)), \quad (10.4)
\]

where \( \gamma_\alpha = 2 \) and \( a' = b'_k \) if \( m_\alpha = 0 \), and otherwise \( \gamma_\alpha = 4 \). The parameters \( a \) and \( a' \) depend only on \( \alpha \), and for all \( \tau \in \hat{K} \) the parameters \( b_k \) and \( b'_k \) satisfy

\[
b_k - a \leq b_k - a \leq m|\tau| \quad (1 \leq k \leq l(\tau))
\]

for some \( m \in \mathbb{N} \) independent of \( \tau \) and \( \alpha \). Therefore we may and shall assume that \( b_k, b'_k \leq m|\tau| \) for all non-trivial \( \tau \).

10.3. Cancellation of poles and estimate. Let \( \alpha \in \Sigma^+ \) be a simple root and let \( \tau \in \hat{K}_M \). In the following lemma we determine a polynomial on \( \mathfrak{a}_C^\vee \) which cancels the poles of \( J_{s_\alpha,\lambda}[\tau] \). Moreover, we give an estimate of the product of \( J_{s_\alpha,\lambda}[\tau] \) with this polynomial.

As in Section \( \text{[4]} \) we write \( [\tau] = |\tau| \). We define the following polynomial on \( \mathbb{C} \),

\[
e_\tau(z) := \Gamma_{1,m|\tau|+1}(z)^2 \Gamma_{\frac{1}{2},m|\tau|+\frac{1}{2}}(z)^2, \quad (10.5)
\]

and recall the polynomials \( q_{m}(z) \) from \( \text{[8.2]} \). In particular, we see from \( \text{[4.2]} \) that we can estimate the polynomial \( e_\tau(z) \) by

\[
|e_\tau(z)| \leq (1 + 2|\tau|)^2 q_{m|\tau|}(|z|)^4 \quad (10.6)
\]

for all \( z \in \mathbb{C} \) and all \( \tau \in \hat{K} \).

**Lemma 10.3.** Let \( \alpha \in \Sigma^+ \) be simple.
Lemma 10.4. There exist \( R > R \) for every \( \tau \) such that

\[
\lambda \mapsto e_\tau(i\lambda(\frac{a^\vee}{\gamma_0})) J_{s_n,\lambda}[\tau]
\]

is polynomial for every \( \tau \) in \( \bar{K} \).

(ii) There exists a constant \( C > 0 \) such that

\[
\| e_\tau(i\lambda(\frac{a^\vee}{\gamma_0})) J_{s_n,\lambda}[\tau] \|_{op} \leq C(1 + |\tau|)^4 q_{m[\tau]}(\|\lambda(\frac{a^\vee}{\gamma_0})\|)^8
\]

for every \( \tau \in \bar{K} \) and \( \lambda \in a^c_\vee \).

Proof. We may assume \( |\tau| \neq 0 \) since \( J_{s_n,\lambda}[\tau] = 1 \) for the trivial \( K \)-type. We fix a simple root \( \alpha \in \Sigma^+ \) and define polynomials \( d^k_+ \) and \( d^k_- \) to be the numerator and denominator in (10.4), respectively. Then

\[
d^k_\tau(\lambda) = \frac{d^k_+ (\lambda)}{d^k_- (\lambda)}.
\]

Next we make the following observation: \( \Gamma_{a,b}(z) \) divides \( \Gamma_{a,b+n}(z) \) for all \( n \in \mathbb{N} \), and \( \Gamma_{a,b}(z) \) divides \( \Gamma_{a-n,b}(z) \) for all \( n \in \mathbb{N} \) such that \( a - n \geq \frac{1}{2} \). It follows that

\[
d^k_\tau(\lambda) | e_\tau(i\lambda(\frac{a^\vee}{\gamma_0})))
\]

for all \( k \), and this implies (i). Moreover, together with (9.3) it implies

\[
\left| e_\tau(i\lambda(\frac{a^\vee}{\gamma_0})) \right| \leq \frac{e_\tau(|\lambda(\frac{a^\vee}{\gamma_0})|)}{d^k_- (|\lambda|)} \leq e_\tau(|\lambda(\frac{a^\vee}{\gamma_0})|)
\]

for all \( \lambda \in a^c_\vee \). For the numerator \( d^k_+(\lambda) \) we find

\[
|d^k_+(\lambda)| \leq e_\tau(|\lambda(\frac{a^\vee}{\gamma_0})|)
\]

also for all \( \lambda \in a^c_\vee \). Hence

\[
\left| e_\tau(i\lambda(\frac{a^\vee}{\gamma_0})) d^k_\tau(\lambda) \right| \leq e_\tau(|\lambda(\frac{a^\vee}{\gamma_0})|)^2
\]

for all indices \( k \). By (10.6) this implies (ii). \( \square \)

10.4. Application of Proposition 8.1. The following lemma contains the main estimate for the proof of Theorem 10.1. Recall from (8.1) the functions \( f_{n,R} \). We will determine an estimate for a product of these functions with \( J_{w,\lambda} \). For this we use Lemma 10.3, Proposition 8.1 and the factorization (10.3).

Let

\[
h := 8\pi \max_{\alpha \in \Sigma^+} \| \frac{a^\vee}{\gamma_0} \|.
\]

Lemma 10.4. There exist \( c, R_0 > 0 \) and for every \( r > 0 \) a constant \( C_r > 0 \) so that for every \( R > R_0 \) with

\[
\frac{(\log R)^2}{R^a} < cr
\]

one has

\[
\left\| \left( \prod_{\alpha \in \Sigma^+} f_{m[\tau],R}(\lambda(\frac{a^\vee}{\gamma_0}))^8 e_\tau(i\lambda(\frac{a^\vee}{\gamma_0})) \right) J_{w,\lambda}[\tau] \right\|_{op} \leq C_r \left[ (1 + |\tau|)^4 e^{8mr|\tau|} e^{HR\|\Im \lambda\|} \right]^{|\Sigma^+|}
\]
for all $\tau \in \hat{K}$, $\lambda \in \mathfrak{a}_C^\circ$ and $w \in W$.

Proof. Let $c$, $R_0$ be as in Proposition 8.1 and let $r > 0$. We first show that there exists a constant $C_r > 0$ such that if $R > R_0$ satisfies (10.7) then

$$
\|f_{m[\tau],R}(\lambda \frac{w^\tau}{\gamma_0})^8 e_\tau(i\lambda \frac{w^\tau}{\gamma_0}) J_{s_\tau,\lambda}[\tau]\|_{op} \leq C_r(1 + |\tau|^4 e^{8mr|\tau|} e^{hR|Im \lambda|}) \quad (10.8)
$$

for all $\tau \in \hat{K}$, $\lambda \in \mathfrak{a}_C^\circ$ and all simple roots $\alpha \in \Sigma^+$.

We apply Proposition 8.1 with $n = m[\tau]$ and

$$P(z) = (1 + |\tau|)^{-4} e_\tau(iz) J_{s_\tau,\lambda}[\tau],$$

where

$$\mu = \lambda \frac{w^\tau}{\gamma_0}^{-1} \lambda \in \mathfrak{a}_C^\circ.$$

The estimate in Lemma 10.3 ensures the proposition is applicable. Hence

$$\|f_{m[\tau],R}(z)^8 e_\tau(iz) J_{s_\tau,\lambda}[\tau]\|_{op} \leq (1 + |\tau|^4 [C_r e^{rm[\tau]} e^{\pi R|Im z||}]^8.$$

By inserting $z = \lambda \frac{w^\tau}{\gamma_0}$ and $|\tau| \leq |\tau| + 1$ we obtain (10.8) for some $C_r > 0$.

Let $w \in W$ and consider the factorization (10.3) of $J_{w,\lambda}$. By submultiplicativity of the operator norm we obtain from (10.8) that

$$\left\| \left( \prod_{j=1}^n f_{m[\tau],R}(\lambda \frac{w_j^{-1} \gamma_j}{\gamma_0})^8 e_\tau(i\lambda \frac{w_j^{-1} \gamma_j}{\gamma_0}) \right) J_{w,\lambda}[\tau] \right\|_{op} \leq [C_r(1 + |\tau|^4 e^{8mr|\tau|} e^{hR|Im \lambda|})^n.$$

The $w_j^{-1} \gamma_j$ are all distinct and positive by (10.2) and (10.1), respectively. Hence each factor of the above product over $j$ occurs exactly once in

$$\prod_{\alpha \in \Sigma^+} [f_{m[\tau],R}(\lambda \frac{w^\tau}{\gamma_0})^8 e_\tau(i\lambda \frac{w^\tau}{\gamma_0})].$$

On the other hand, since by (10.6) the scalar valued polynomial $e_\tau$ satisfies the estimate

$$|e_\tau(z)| \leq (1 + 2|\tau|)^4 q_{m[\tau]}(|z|)^4 \leq (1 + 2|\tau|)^4 q_{a[\tau]}(|z|)^8,$$

we obtain in analogy with (10.8) that

$$|f_{m[\tau],R}(\lambda \frac{w^\tau}{\gamma_0})^8 e_\tau(\lambda \frac{w^\tau}{\gamma_0})| \leq C_r(1 + |\tau|^4 e^{8mr|\tau|} e^{hR|Im \lambda|})$$

for every $\alpha \in \Sigma^+$. We apply this estimate to the roots $\alpha \in \Sigma^+$ which are not of the form $w_j^{-1} \gamma_j$ for any $j$ and obtain the estimate as stated in the lemma.

10.5. Conclusion of proof. We can now give the proof of Theorem 10.1 following Ansatz 2 from Section 7.2. Recall that $\lambda_0$ satisfies (1.3), that is,

$$Re(i\lambda_0(\alpha^\vee)) \geq 0$$

for all $\alpha \in \Sigma^+$. We define the following functions on $\mathfrak{a}_C^\circ$.

1. We choose a polynomial $p_{\lambda_0} : \mathfrak{a}_C^\circ \to \mathbb{C}$ such that

$$\begin{cases}
    p_{\lambda_0}(\lambda_0) = \frac{1}{|W_{\lambda_0}|}, \\
    p_{\lambda_0}(w\lambda_0) = 0 \quad (w \in W \setminus W_{\lambda_0}),
\end{cases}$$

where $W_{\lambda_0} \subset W$ is the stabilizer of $\lambda_0$. 


II. For each \( \tau \in \hat{K}_M \) we define a polynomial
\[
p_{\tau}(\lambda) := \prod_{\alpha \in \Sigma^+} e_{\tau}(i\lambda(\frac{\alpha}{\gamma_0})) \prod_{\alpha \in \Sigma^+} e_{\tau}(i\lambda_0(\frac{\alpha}{\gamma_0})).
\]
It follows from (10.5) and (9.3) that
\[
|e_{\tau}(i\lambda_0(\frac{\alpha}{\gamma_0}))| \geq 1 \quad (10.9)
\]
for all \( \alpha \in \Sigma^+ \).

III. For every \( R > 0 \) for which
\[
\forall \alpha \in \Sigma^+ : \quad R\lambda_0(\frac{\alpha}{\gamma_0}) \notin \mathbb{Z} \setminus \{0\}, \quad (10.10)
\]
we define for each \( n \in \mathbb{N}_0 \) an entire function on \( a_C^* \) by
\[
\psi_{n,R}(\lambda) := \prod_{\alpha \in \Sigma^+} f_{n,R}(\lambda(\frac{\alpha}{\gamma_0})) \prod_{\alpha \in \Sigma^+} f_{n,R}(\lambda_0(\frac{\alpha}{\gamma_0})).
\]
By (10.10) and Lemma 8.5 there exists a constant \( c_{R} > 0 \) so that
\[
|f_{n,R}(\lambda_0(\frac{\alpha}{\gamma_0}))| \geq c_{R} \quad (10.11)
\]
for all \( n \in \mathbb{N}_0 \) and \( \alpha \in \Sigma^+ \).

After these definitions we let
\[
\phi_{\tau}(\lambda) := p_{\tau}(\lambda)[\psi_{m[\tau],R}(\lambda)]
\]
for \( \tau \in \hat{K}_M \), and we define \( F_{\tau} : a_C^* \rightarrow \text{End}(V_{\tau}) \) by
\[
F_{\tau}(\lambda) = \sum_{w \in W} \phi_{\tau}(w^{-1}\lambda)p_{\lambda_0}(w^{-1}\lambda)J_{w,w^{-1}\lambda}[\tau] \quad (\lambda \in a_C^*).
\]
We are going to apply Proposition 7.2 to \( F_{\tau} \), and for that we need to verify its conditions (i)-(iii). As explained in Section 7.2, condition (i) follows from the fact that \( v_{K,\lambda_0} \) is cyclic for \( V_{\lambda_0} \) (see (7.1)), and (ii) is an automatic consequence of the cocycle condition
\[
J_{w_2,w_1\lambda} \circ J_{w_1,\lambda} = J_{w_2w_1,\lambda}
\]
for the intertwining operators.

Let \( c, R_0 \) be as in Lemma 10.4, and let \( r > 0 \) and \( R > R_0 \) satisfy (10.7). Let \( r' < r \) be such that
\[
\frac{(\log R)^2}{R^2} < cr'.
\]
By perturbing \( R \) to a slightly smaller value we may assume that (10.10) is valid. It follows from Lemma 10.4 together with the denominator estimates (10.9)-(10.11) that there exists a constant \( C > 0 \) so that for every \( \lambda \in a_C^* \) and \( \tau \in \hat{K}_M \)
\[
\|F_{\tau}(\lambda)\|_{op} \leq C(1 + |\tau|)^{4|\Sigma^+|} e^{ar'|\tau|} (1 + \|\lambda\|)^{\deg p_{\lambda_0} e^{AR}\|\text{Im}\lambda\|},
\]
where \( a = 8m|\Sigma^+| \) and \( A = h|\Sigma^+| \). This gives the remaining condition (iii) of Proposition 7.2, and with that can conclude that there is a continuous embedding
\[
V_{\lambda_0}(ar) \subset C_{AR+c}^\infty(G) * v_{K,\lambda_0}.
\]
By Remark 8.6 this implies the continuous embedding in Theorem 10.1. Finally, as \( v_{K,\lambda_0} \) is \( \mathcal{U}(g) \)-cyclic by Lemma 4.4 we have \( C_{R}^\infty(G) * v_{K,\lambda_0} = (V_{\lambda_0})_{\text{min}}^R \).
Appendix A. The domains \( \mathfrak{k}(R) \)

We recall the open Ad\((K)\)-invariant domains \( \mathfrak{k}(R) \), with \( R > 0 \), from (3.3). In this appendix we describe these in two interesting examples.

A.1. The unit disc: \( G = SU(1, 1) \). While treating this example we use a notation so that the generalization to general Hermitian symmetric spaces becomes straightforward. First note that \( G = SL(2, \mathbb{C}) \) acts transitively on the projective space \( \mathbb{P}^1(\mathbb{C}) \). We identify \( \mathbb{P}^1(\mathbb{C}) \) with \( \mathbb{C} \cup \{\infty\} \) via the map

\[
\mathbb{P}^1(\mathbb{C}) \to \mathbb{C} \cup \{\infty\}, \quad \mathbb{C} \left( \begin{array}{c} z \\ 1 \end{array} \right) \mapsto z.
\]

We define the subgroups of \( G \)

\[
K = \left\{ k_\theta := \begin{pmatrix} e^{i\theta} & 0 \\ 0 & e^{-i\theta} \end{pmatrix} \mid \theta \in \mathbb{R} \right\} \quad \text{and} \quad A = \left\{ a_t = \begin{pmatrix} \cosh t & \sinh t \\ \sinh t & \cosh t \end{pmatrix} \mid t \in \mathbb{R} \right\}
\]

and note that \( K = \left\{ \begin{pmatrix} z & 0 \\ 0 & z^{-1} \end{pmatrix} \mid z \in \mathbb{C}^* \right\} \). Further we define unipotent abelian subgroups of \( G \) by

\[
P^+ := \left\{ \begin{pmatrix} 1 & z \\ 0 & 1 \end{pmatrix} \mid z \in \mathbb{C} \right\} \quad \text{and} \quad P^- := \left\{ \begin{pmatrix} 1 & 0 \\ z & 1 \end{pmatrix} \mid z \in \mathbb{C} \right\}.
\]

Note that \( P^+ \) and \( P^- \) are the stabilizers of \( \infty \) and \( 0 \), respectively. Then both \( K P^+ \) and \( K P^- \) are Borel subgroups of \( G \) with \( K P^+ \cap K P^- = K \). Hence, \( Z = G/K \) is realized as an open affine subvariety of the projective variety \( G/K P^+ \times G/K P^- \) via

\[
gK \mapsto (gK P^+, gK P^-).
\]

In more concrete terms, if we identify \( G/K P^+ \times G/K P^- \) with \( \mathbb{P}^1(\mathbb{C}) \times \mathbb{P}^1(\mathbb{C}) \) via

\[
(g_1 K P^+, g_2 K P^-) \mapsto (g_1 i(0), g_2(0)),
\]

then \( Z \) is given by

\[
Z = \mathbb{P}^1(\mathbb{C}) \times \mathbb{P}^1(\mathbb{C}) \setminus \{(z, w) : w \neq \phi(z)\}.
\]

where \( \phi \) is the automorphism of \( \mathbb{P}^1(\mathbb{C}) \) which is induced from the linear map \( \mathbb{C}^2 \ni (z_1, z_2) \mapsto (-z_1, z_2) \in \mathbb{C}^2 \).

Let us denote by \( \mathcal{D} = \{ z \in \mathbb{C} \mid |z| < 1 \} \) the open unit disk (i.e. the bounded realization of \( G/K \)) and note that

\[
Z = G/K = \{(z, \overline{z}) : z \in \mathcal{D} \} \subset Z.
\]

Now one has that the crown domain is given by

\[
\Xi = \mathcal{D} \times \mathcal{D} \subset Z.
\]

(A similar result holds for general Hermitian symmetric spaces, see [4, Sect. 3] or [13, Th. 7.7].) For \( R > 0 \) we note that

\[
A_R = \left\{ a_t \in A \mid |t| \leq R/\sqrt{8} \right\}.
\]
Now we calculate
\[ k_{i\theta} a_t \cdot z_0 = (e^{2\theta} \tanh t, e^{-2\theta} \tanh t) \in Z_C. \]
This is in \( \Xi = D \times D \) precisely if \( \theta \in (-r, r) \) for \( r > 0 \) defined by \( e^{2r} \tanh \frac{R}{\sqrt{8}} = 1 \).
Thus we have shown:

**Proposition A.1.** Let \( G = SU(1, 1), R > 0 \). Then
\[
\mathfrak{t}(R) = \{ Y \in \mathfrak{t} \mid \| Y \| < \beta_R/\sqrt{8}\},
\]
where \( \beta_R = \frac{1}{2} \log \left( \coth \left( \frac{R}{\sqrt{8}} \right) \right) \).

**A.2. The hyperboloids:** \( G = SO_o(1, n) \). Let \( G = SO_o(1, n) \) with \( K = SO(n, \mathbb{R}) \) being embedded into \( G \) as the lower right corner. (The group \( G \) does not satisfy the condition that it is the group of real points of a connected algebraic reductive group defined over \( \mathbb{R} \). Instead one could consider the group \( SO(1, n) \), which would satisfy this condition, but for convenience of notation we rather work with its connected component.) Consider the following quadratic form on \( \mathbb{C}^{n+1} \)
\[
\square(u) = u_0^2 - u_1^2 - \ldots - u_n^2
\]
and let \( u \cdot v \) be the bilinear pairing obtained by polarization. Then
\[
Z = G/K = \{ x \in \mathbb{R}^{n+1} \mid \square(x) = 1, x_0 > 0 \},
\]
\[
Z_C = G_C/K_C = \{ u \in \mathbb{C}^{n+1} \mid \square(u) = 1 \}
\]
and
\[
\Xi = \{ u = x + iy \in Z_C \mid \square(x) > 0, x_0 > 0 \},
\]
see [7, p.96]. The canonical base point in \( Z_C \) is given by \( z_0 = (1, 0 \ldots, 0)^T \in Z_C \).

Set \( l = \left\lfloor \frac{n}{2} \right\rfloor \) and note that \( l \) is the rank of \( K \). Our choice and parametrization of \( t \) are as follows:
\[
\mathbb{R}^l \ni \beta = (\beta_1, \ldots, \beta_l) \mapsto T_\beta := \text{diag}(0, \beta_1 U, \ldots, \beta_l U) \in \mathfrak{t}
\]
where
\[
U = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}
\]
and the first zero in the diagonal matrix means the zero \( 1 \times 1 \)-matrix in case \( n \) is even and the zero \( 2 \times 2 \)-matrix if \( n \) is odd.

With the standard choice of \( A \) and \( R' := \frac{R}{\sqrt{2(n-1)}} \) we have
\[
A_R = \left\{ \begin{pmatrix} \cosh t & 0 & \sinh t \\ 0 & 1 & 0 \\ \sinh t & 0 & \cosh t \end{pmatrix} \mid |t| \leq R' \right\}
\]
and an easy computation yields
\[
K A_R \cdot z_0 = \left\{ \begin{pmatrix} \cosh t \\ u \end{pmatrix} \mid u \in \mathbb{R}^n, t \in [-R', R'], \|u\|_2 = |\sinh t| \right\}.
\]
In the sequel we only treat the case of \( n = 2l \) being even; the odd case requires just a small modification.
With $k_\beta = \exp(iT_\beta)$ we obtain from (A.1) that

$$k_\beta \left( \begin{array}{c} \cosh t \\ u \end{array} \right) = \left( \begin{array}{c} \cosh t \\ u_1 \cosh \beta_1 - iu_2 \sinh \beta_1 \\ iu_1 \sinh \beta_1 + u_2 \cosh \beta_1 \\ \vdots \end{array} \right).$$

The right hand side is now in the crown domain if and only if

$$\Box \left( \Re k_\beta \left( \begin{array}{c} \cosh t \\ u \end{array} \right) \right) = \cosh^2 t - \cosh^2 \beta_1 (u_1^2 + u_2^2) - \cdots - \cosh^2 \beta_l (u_{n-1}^2 + u_n^2) > 0.$$

There is no loss of generality in restricting our attention to the closure $t^+$ of a chamber in $\mathfrak{t}$, i.e. we may assume that $\beta_1 \geq \beta_2 \geq \cdots \geq \beta_{l-1} \geq |\beta_l| \geq 0$. Then the condition from above for all $u$ with $\|u\|_2 = |\sinh t|$ means nothing else as

$$\cosh^2 t - (\cosh^2 \beta_1) \sinh^2 t > 0$$

for all $t \in [-R', R']$. A short calculation reformulates that in

$$|\sinh \beta_1| < \frac{1}{\sinh R'}.$$

We have thus shown:

**Proposition A.2.** For $G = \text{SO}_o(1, n)$, $R > 0$ and the notation introduced from above one has that

$$t(R)^+ = \left\{ T_\beta \in t^+ \mid |\sinh \beta_1| < \frac{1}{\sinh R'} \right\}$$

where $R' = R/\sqrt{2(n-1)}$.

**Appendix B. The Helgason conjecture**

In this appendix we briefly describe how (1.1) implies the Helgason conjecture. We are essentially following Schmid's approach from [20].

For $\lambda \in \mathfrak{a}_C^*$ we define

$$\mathcal{P}_\lambda : V_\lambda^\infty \to C^\infty(G/K), \quad v \mapsto \left( g \mapsto \int_K v(gk) \, dk \right).$$

This map admits a continuous extension to the space $V_\lambda^{-\omega} := (V_\lambda^\omega)'$. Let $\mathbb{D}(G/K)$ be the commutative algebra of $G$-invariant differential operators on $G/K$. As before, let $v_{K,\lambda}$ be the $K$-fixed vector in $V_\lambda$ with $v_{K,\lambda}(e) = 1$. Note that

$$\mathcal{P}_\lambda(v)(g) = \langle g^{-1} \cdot v, v_{K,-\lambda} \rangle \quad (v \in V_\lambda). \quad (B.1)$$

The algebra $\mathcal{U}(\mathfrak{g})^K/\mathcal{U}(\mathfrak{g})^K \cap \mathcal{U}(\mathfrak{g})\mathfrak{k}$ acts from the right on smooth functions on $G/K$. In fact $\mathbb{D}(G/K)$ is isomorphic to $\mathcal{U}(\mathfrak{g})^K/\mathcal{U}(\mathfrak{g})^K \cap \mathcal{U}(\mathfrak{g})\mathfrak{k}$. Note that $\mathcal{U}(\mathfrak{g})^K$ acts by scalars on $\mathbb{C}v_{K,-\lambda}$, and hence $\mathbb{D}(G/K)$ acts by a character $\chi_\lambda$ on the image of $\mathcal{P}_\lambda$. We write $C^\infty(G/K)_\lambda$ for the space of joint eigenfunctions of $\mathbb{D}(G/K)$ with eigencharacter $\chi_\lambda$.

The following theorem is the Helgason conjecture, which was first proven in [12].
**Theorem B.1.** Let $\lambda \in a_\mathbb{C}^*$ be so that the $K$-spherical vector $v_{K,-\lambda}$ in $V_{-\lambda}$ is $\mathcal{U}(\mathfrak{g})$-cyclic. Then $\mathcal{P}_{\lambda}$ defines a $G$-equivariant isomorphism

$$V_{\lambda}^- \rightarrow \mathcal{C}_\infty(G/K)_{\lambda} \quad (B.2)$$

of topological vector spaces.

**Remark B.2.** By Lemma 4.4 $v_{K,-\lambda}$ is $\mathcal{U}(\mathfrak{g})$-cyclic if $-\lambda$ satisfies (4.3).

We derive the theorem from (1.1). We recall Schmid’s maximal globalization of a Harish-Chandra module $V$,

$$V_{\text{max}} = \text{Hom}_{(\mathfrak{g},K)}(V^\vee, \mathcal{C}_\infty(G)),$$

where $V^\vee$ is the dual Harish-Chandra module of $V$, i.e. the space of $K$-finite vectors in the algebraic dual of $V$. Further, $\mathcal{C}_\infty(G)$ is considered as a $(\mathfrak{g},K)$-module, where $\mathfrak{g}$ and $K$ act via the right-regular representation.

By taking matrix coefficients one sees that any globalization of $V$ embeds continuously into $V_{\text{max}}$. Here by globalization we understand a completion of $V$ to a representation of $G$ on a complete Hausdorff topological vector space $E = \nabla$. Note that the assignment $V \mapsto V_{\text{max}}$ is functorial. We define $V^{-\omega}$ as the continuous dual of $(V^\vee)^\omega$ equipped with the strong topology.

**Proposition B.4.** For every Harish-Chandra module $V$ we have

$$V_{\text{max}} = V^{-\omega}$$

as topological $G$-modules.

**Proposition B.5.** Let $\lambda \in a_\mathbb{C}^*$ be so that the $K$-spherical vector $v_{K,-\lambda}$ in $V_{-\lambda}$ is $\mathcal{U}(\mathfrak{g})$-cyclic. Then

$$(V_{\lambda})_{\text{max}} = \mathcal{C}_\infty(G/K)_{\lambda}$$

as topological $G$-modules.
For the proof of the proposition we need the following lemma.

**Lemma B.6.** Let \( \lambda \in a_C^+ \). If \( v_{K,-\lambda} \) is \( U(g) \)-cyclic in \( V_{-\lambda} \), then

\[
V_{-\lambda} = U(g) \otimes_{U(g) \oplus U(g)^K} C v_{K,-\lambda}
\]

as \((g,K)\)-modules.

**Proof.** By assumption the natural map \( U(g) \otimes_{U(g) \oplus U(g)^K} C v_{K,-\lambda} \rightarrow V_{-\lambda} \) of \((g,K)\)-modules is surjective. It remains to prove injectivity. Recall from (B.3) that \( U(g) = \mathcal{H}^*(s) \mathcal{I}^*(s) \oplus U(g)^K \). Since \( \mathcal{I}^*(s) = \mathcal{H}^*(s) \mathcal{I}^*(s) \cap U(g)^K \), we have as \( K \)-modules

\[
U(g) \otimes_{U(g) \oplus U(g)^K} C v_{K,-\lambda} = \mathcal{H}^*(s) \mathcal{I}^*(s) \oplus_{\mathcal{I}^*(s)} C v_{K,-\lambda} \simeq \mathcal{H}^*(s).
\]

By Kostant-Rallis [15] the right-hand side is \( K \)-isomorphic to \( \mathbb{C}[K/M] \). Since \( V_{-\lambda} \) is \( K \)-isomorphic to \( \mathbb{C}[K/M] \) as well, the assertion follows from the finite dimensionality of the \( K \)-isotypes. \( \square \)

**Proof of Proposition B.5.** By Lemma B.6 we have the following equalities of \( G \)-modules,

\[
(V_\lambda)_{\max} = \text{Hom}_{(g,K)}(V_{-\lambda}, C^\infty(G))
\]

\[
= \text{Hom}_{(g,K)}(U(g) \otimes_{U(g) \oplus U(g)^K} C v_{K,-\lambda}, C^\infty(G))
\]

\[
= \text{Hom}_{U(g) \oplus U(g)^K}(C v_{K,-\lambda}, C^\infty(G))
\]

\[
= \text{Hom}_{U(g) \oplus U(g)^K}(C v_{K,-\lambda}, C^\infty(G/K))
\]

The assertion now follows from the definition of \( C^\infty(G/K)_\lambda \). \( \square \)

**Proof of Theorem B.7.** In view of Proposition B.4 and Proposition B.5 both sides of (B.2) are isomorphic to \((V_\lambda)_{\max}\). Furthermore, as \( v_{K,-\lambda} \) is \( U(g) \)-cyclic, it follows from (B.1) that \( P_\lambda \) is injective, and hence bijective, on the space of \( K \)-finite vectors. The theorem now follows from the functoriality of the maximal globalizations. \( \square \)

**Appendix C. An application to eigenfunctions on \( Z = G/K \)**

We recall the crown domain \( \Xi \subset Z_C \), the natural \( G \)-extension of \( Z \) inside of \( Z_C \). Also we recall from the preceding appendix that \( V_{\lambda,\max} = C^\infty(Z)_\lambda \) for every spherical principal series \( V_\lambda \), \( \lambda \in a_C^+ \). We mentioned in the introduction that for every \( K \)-spherical Harish-Chandra module \( V \) with \( K \)-spherical vector \( v_K \) that the orbit map

\[
f_v : G/K \rightarrow V^\infty, \quad gK \mapsto g \cdot v_K
\]

extends holomorphically to \( \Xi \), see [13] Th. 1.1. Therefore, every \( \mathcal{D}(Z) \)-eigenfunction extends holomorphically to \( \Xi \), and thus we obtain that \( C^\infty(Z)_\lambda = \mathcal{O}(\Xi)_\lambda \), i.e.

\[
V_{\lambda,\max} = \mathcal{O}(\Xi)_\lambda
\]

by Prop. B.5. Now for every \( r > 0 \) we define \( K \)-invariant enlargements of \( \Xi \) inside of \( Z_C \) by

\[
Z_C(r) := K_C(r) \cdot \Xi = \exp(i\mathfrak{t}_r) \cdot \Xi \subset Z_C.
\]

It is not clear whether \( Z_C(r) \) is simply connected. Out of precaution we pass to the simply connected cover \( \tilde{Z}_C(r) \) of \( Z_C(r) \). Note that \( K \) acts naturally on the complex
manifold $\tilde{Z}_C(r)$. From the definition of $V_{\lambda,r}^\omega$ and $V_{\lambda}^\omega \subset V_{\lambda,\text{max}} = \mathcal{O}(\Xi)_\lambda$ we thus obtain

$$V_{\lambda,r}^\omega = \mathcal{O}(\tilde{Z}_C(r))_\lambda.$$  

Hence the fact that $V_{\lambda,r}^\omega \subset V_{\lambda,\min}(R)$ for $(\log R)^2 \leq cr$ (see Theorem 10.1) implies the following

**Theorem C.1.** Let $-\lambda \in \mathfrak{a}_C^*$ satisfying (1.3) and $r, R > 0$ such that $(\log R)^2 < cr$. Then any $f \in \mathcal{O}(\tilde{Z}_C(r))_\lambda$ can be factorized as

$$f = \psi * \phi_\lambda$$

where $\phi_\lambda$ is the Harish-Chandra spherical function in $C^\infty(G/K)_\lambda$ and $\psi \in C^\infty_R(G)$.

**References**


