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Discrete series representations with non-tempered embedding

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Abstract

We give an example of a semisimple symmetric space $G/H$ and an irreducible representation of $G$ which has multiplicity 1 in $L^2(G/H)$ and multiplicity 2 in $C^\infty(G/H)$.

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1. Introduction

Let $G$ be a real reductive group and $X = G/H$ an attached symmetric space. Let further $V$ be a Harish-Chandra module and $V^\infty$ its smooth Fréchet completion of moderate growth. We write $V^{-\infty} = (V^\infty)'$ for the strong dual of $V^\infty$. We recall that $V$ is called $H$-spherical provided

$$\text{Hom}_G(V^\infty, C^\infty(X)) \neq 0.$$ 

By Frobenius reciprocity $\text{Hom}_G(V^\infty, C^\infty(X))$ is isomorphic to the space $(V^{-\infty})^H$ of $H$-invariants in $V^{-\infty}$. It follows from [2, Corollary 3.10] that the space $(V^{-\infty})^H$ is finite dimensional.

Inside $(V^{-\infty})^H$ there are several subspaces of interest. In particular we mention

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• \((V^{-\infty})_{\text{disc}}^H\), the subspace of functionals whose generalized matrix coefficients lie in the Harish-Chandra Schwartz space \(\mathcal{C}(X) \subset L^2(X) \cap C^\infty(X)\),
• \((V^{-\infty})_{\text{temp}}^H\), the subspace of functionals whose generalized matrix coefficients are tempered, i.e., belong to \(L^{2+\epsilon}(X)\) for all \(\epsilon > 0\).

These subspaces satisfy
\[
(V^{-\infty})_{\text{disc}}^H \subset (V^{-\infty})_{\text{temp}}^H \subset (V^{-\infty})^H.
\] (1.1)

It follows from the tempered embedding theorem [6, Théorème 2] and the construction of wave packets [3, Théorème 1] that the subspaces \((V^{-\infty})_{\text{temp}}^H\) serve as the multiplicity spaces in the Plancherel decomposition of \(L^2(X)\). The Plancherel decomposition of \(L^2(X)\) is in general a mixture of discrete and continuous parts. The most continuous part of \(L^2(X)\) is the closed invariant subspace of \(L^2(X)\) that decomposes into a direct integral over the largest continuous families of representations. For these representations the space \((V^{-\infty})^H\) has been explicitly determined for almost every representation \(V\) in the families. See [4]. In this case \((V^{-\infty})_{\text{disc}}^H = \{0\}\) if \(X\) is not compact and \((V^{-\infty})_{\text{temp}}^H = (V^{-\infty})^H\). The same phenomenon occurs more generally for real spherical spaces as is described in [11, Theorem C].

In general there is no a priori reason for any of the inclusions (1.1) to be an equality, even if \((V^{-\infty})_{\text{disc}}^H \neq \{0\}\). However, no example appears to be recorded in the literature.

The objective of this paper is to provide an example where
\[
0 \neq (V^{-\infty})_{\text{disc}}^H = (V^{-\infty})_{\text{temp}}^H \subsetneq (V^{-\infty})^H.
\]

To be more specific this happens for \(X\) the \(n\)-dimensional one-sheeted hyperboloid which is homogeneous for the connected Lorentzian group \(G = \text{SO}_0(n, 1)\).

Let us briefly introduce the standard notions.

1.1. Notation

Let \(n \geq 3\) and let \(G = \text{SO}_0(n, 1)\) be the identity component of the special Lorentz group \(\text{SO}(n, 1)\). We denote by \(H\) the stabilizer of
\[
x_0 := (1, 0, \ldots, 0) \in \mathbb{R}^{n+1}
\]
in \(G\). The entry in the lower right corner of any matrix in \(\text{SO}(n, 1)\) is non-zero, and \(\text{SO}_0(n, 1)\) consists of those matrices for which this entry is positive. From this fact we see that \(H\) is the connected subgroup
\[
H = \begin{pmatrix} 1 & 0 \\ 0 & \text{SO}_0(n-1, 1) \end{pmatrix} \subset G.
\]

The group \(G\) acts transitively on the hyperboloid
\[
X := \{x \in \mathbb{R}^{n+1} \mid x_1^2 + \cdots + x_n^2 - x_{n+1}^2 = 1\},
\]
and the homogeneous space
\[
X = G/H = \text{SO}_0(n, 1)/\text{SO}_0(n-1, 1)
\]
is a symmetric space. The corresponding involution \(\sigma\) of \(G\) is given by conjugation with the diagonal matrix \(\text{diag}(-1, 1, \ldots, 1)\). The subgroup \(G^\sigma\) of \(G\) of \(\sigma\)-fixed elements is the stabilizer of \(\mathbb{R} x_0\). This subgroup has two components, one of which is \(H\). For our purpose it is important to use \(H\) rather than \(G^\sigma\). The pairs \((G, H)\) and \((G, G^\sigma)\) differ by the fact that \((G, G^\sigma)\) is a
Gelfand pair, whereas \((G, H)\) is not. In fact it has been shown by van Dijk [7] that \(X\) is the only symmetric space of rank one, which is not obtained as the homogeneous space of a Gelfand pair.

The regular representation of \(G\) on \(C^\infty(X)\) decomposes as the direct sum
\[
C^\infty(X) = C^\infty_{\text{even}}(X) \oplus C^\infty_{\text{odd}}(X)
\]
of the invariant subspaces of functions that are even or odd with respect to the \(G\)-equivariant symmetry \(x \mapsto -x\). The restriction of the regular representation to \(C^\infty_{\text{even}}(X)\) is isomorphic to the regular representation on \(C^\infty(G/G^\sigma)\), and the non-Gelfandness of \((G, H)\) is therefore caused by the presence of the odd functions.

1.2. Main results

The Lorentzian manifold \(X\) carries the \(G\)-invariant Laplace–Beltrami operator \(\Delta\), which is obtained as the radial part of
\[
\square := -\frac{\partial^2}{\partial x_1^2} - \cdots - \frac{\partial^2}{\partial x_n^2} + \frac{\partial^2}{\partial x_{n+1}^2}
\]
on \(\mathbb{R}^{n+1}\). That is, for \(f \in C^\infty(X)\) we define \(\Delta f \in C^\infty(X)\) as \((\square \tilde{f})|_X\) where \(\tilde{f}\) is any extension of \(f\) to a function, homogeneous of degree 0, on some open neighborhood of \(X\) in \(\mathbb{R}^{n+1}\).

Let
\[
\rho := \frac{1}{2}(n - 1)
\]
and for each \(\lambda \in \mathbb{C}\) let \(E_\lambda(X)\) be the eigenspace
\[
E_\lambda(X) = \{ f \in C^\infty(X) \mid \Delta f = (\lambda^2 - \rho^2)f \}.
\]
The Laplace–Beltrami operator is a scalar multiple of the Casimir element associated to the Lie group \(G\), and hence every irreducible subspace \(V\) of \(C^\infty(X)\) is contained in \(E_\lambda(X)\) for some \(\lambda \in \mathbb{C}\). Apart from the sign, the scalar \(\lambda\) is uniquely determined by the infinitesimal character of \(V\). Conversely, since \(X = G/H\) is rank one, \(\pm \lambda\) determines the infinitesimal character.

Let
\[
E^\text{even}_\lambda(X) = E_\lambda(X) \cap C^\infty_{\text{even}}(X), \quad E^\text{odd}_\lambda(X) = E_\lambda(X) \cap C^\infty_{\text{odd}}(X).
\]
We can now state our main result.

The manifold \(X\) carries a \(G\)-invariant measure, which is unique up to scalar multiplication. We denote by \(L^2(X)\) the associated \(G\)-invariant space of square integrable functions.

The following theorem can be seen from the general theory of hyperbolic spaces over \(\mathbb{R}, \mathbb{C}\) and \(\mathbb{H}\) in [8]. See [15, Thm 6.1] and [16, Thm 6.4]. For the current simple situation it will be established along with Theorem 1.2.

**Theorem 1.1.** Let \(\lambda \in \mathbb{C}\) with \(\text{Re} \lambda > 0\). The intersections \(E^\text{even}_\lambda(X) \cap L^2(X)\) and \(E^\text{odd}_\lambda(X) \cap L^2(X)\) are either zero or irreducible. Moreover,
\[
E^\text{even}_\lambda(X) \cap L^2(X) \neq 0 \iff \lambda \in \rho + 1 + 2\mathbb{Z}
\]
\[
E^\text{odd}_\lambda(X) \cap L^2(X) \neq 0 \iff \lambda \in \rho + 2\mathbb{Z}.
\]

**Theorem 1.2.** For every \(0 < \lambda < \rho\) with \(\lambda \in \rho - \mathbb{N}\) the \(G\)-representations \(E^\text{even}_\lambda(X)\) and \(E^\text{odd}_\lambda(X)\) are irreducible and infinitesimally equivalent. Moreover in this case,
(1) if $\lambda - \rho$ is even then $\mathcal{E}^\text{odd}_\lambda(X)$ is contained in $L^2(X)$ and $\mathcal{E}^\text{even}_\lambda(X)$ is not contained in $C^\infty_{\text{temp}}(X)$,
(2) if $\lambda - \rho$ is odd then $\mathcal{E}^\text{even}_\lambda(X)$ is contained in $L^2(X)$ and $\mathcal{E}^\text{odd}_\lambda(X)$ is not contained in $C^\infty_{\text{temp}}(X)$.

For $n \geq 4$ we have $\rho > 1$ and it follows that there exists at least one discrete series representation for $X = G/H$ which has multiplicity 1 in $C^\infty_{\text{temp}}(X)$, but for which the underlying Harish-Chandra module has multiplicity 2 in $C^\infty(X)$. It is observed in [7] that the tempered multiplicity of the unitary principal series of $X$ is two, but the phenomenon described here of representations for which the tempered multiplicity differs from the smooth multiplicity, is new.

The complete Plancherel decomposition for $SO_0(n, 1)/SO_0(n - 1, 1)$ is given in [12]. However, this is not needed for the proof of the above theorems.

We assume $n \geq 3$ throughout, since $n = 2$ would require a separate treatment. Moreover, Theorem 1.2 is empty for $n = 2$, just as it is for $n = 3$.

2. Proof of the main results

The proof of the two main theorems is divided into several parts. We begin with the analysis on $K$-types.

2.1. $K$-Types

Let $K \subset G$ be the stabilizer of $e_{n+1} = (0, \ldots, 0, 1) \in \mathbb{R}^{n+1}$, then $K \simeq SO(n)$ is a maximal compact subgroup of $G$.

We are going to use the diffeomorphism $S^{n-1} \times \mathbb{R} \sim \to X$ given by

$$(y, t) \mapsto (y_1 \cosh t, \ldots, y_n \cosh t, \sinh t) \in X$$

where $y = (y_1, \ldots, y_n) \in S^{n-1}$ and $t \in \mathbb{R}$. With the natural action of $SO(n)$ on $S^{n-1}$ the parameter dependence on $y$ is $K$-equivariant.

For each $j \in \mathbb{N}_0$ we denote by $\mathcal{H}_j \subset C^\infty(S^{n-1})$ the space of spherical harmonics of degree $j$. We recall that by definition $\mathcal{H}_j$ consists of the restrictions to $S^{n-1}$ of all harmonic polynomials on $\mathbb{R}^n$, homogeneous of degree $j$. Equivalently, $\mathcal{H}_j$ can be defined as the eigenspace

$$\mathcal{H}_j := \{h \in C^\infty(S^{n-1}) \mid \Delta_K h = -j(j + n - 2)h\},$$

where $\Delta_K$ is the angular part of the $n$-dimensional Laplacian

$$\frac{\partial^2}{\partial y_1^2} + \cdots + \frac{\partial^2}{\partial y_n^2}. $$

Each $\mathcal{H}_j$ is an irreducible $SO(n)$-invariant finite dimensional subspace of $C^\infty(S^{n-1})$, and the sum $\bigoplus_{j=0}^\infty \mathcal{H}_j$ of these subspaces is dense in $C^\infty(S^{n-1})$.

It follows that the space $C^\infty_K(X)$ of $K$-finite functions $f \in C^\infty(X)$ is spanned by all functions given in the coordinates $(y, t)$ by

$$f(y, t) = h(y)\varphi(t),$$

where $h \in C^\infty(S^{n-1})$ is a spherical harmonic, and $\varphi \in C^\infty(\mathbb{R})$. Thus

$$C^\infty_K(X) \simeq \bigoplus_{j=0}^\infty (\mathcal{H}_j \otimes C^\infty(\mathbb{R})).$$
Being homogeneous of degree \( j \), the spherical harmonics \( h \in \mathcal{H}_j \) satisfy \( h(-y) = (-1)^j h(y) \) for \( y \in S^{n-1} \). Therefore
\[
C_K^\infty(X)_{\text{even}} \cong \bigoplus_{\lambda=0}^\infty \big( \mathcal{H}_j \otimes C_{\text{parity}(j)}^\infty(\mathbb{R}) \big)
\]
where \( \text{parity}(j) \) denotes the parity even or odd of \( j \). Likewise
\[
C_K^\infty(X)_{\text{odd}} \cong \bigoplus_{\lambda=0}^\infty \big( \mathcal{H}_j \otimes C_{\text{parity}(j+1)}^\infty(\mathbb{R}) \big).
\]

2.2. Eigenspaces

With respect to the coordinates (2.1) on \( X \) we have (see [14, p. 455])
\[
\Delta = \frac{\partial^2}{\partial t^2} + 2\rho \tanh t \frac{\partial}{\partial t} - \frac{1}{\cosh^2 t} \Delta_K.
\]
The \( K \)-finite eigenfunctions for \( \Delta \) belong to \( C^\infty(X) \), and they can be determined as follows. Let
\[
\mathcal{E}_{\lambda,K}(X) := \mathcal{E}_{\lambda}(X) \cap C_K^\infty(X),
\]
be the Harish-Chandra module of \( \mathcal{E}_{\lambda}(X) \), and for each \( j \in \mathbb{N}_0 \) let
\[
\mathcal{E}_{\lambda,j}(X) := \mathcal{E}_{\lambda}(X) \cap \big( \mathcal{H}_j \otimes C^\infty(\mathbb{R}) \big).
\]
By separating the variables \( y \) and \( t \) we see that \( \mathcal{E}_{\lambda,j} \) is spanned by the functions \( f(y,t) = h(y)\varphi(t) \) for which \( h \in \mathcal{H}_j \) and
\[
\left( \frac{d^2}{dt^2} + 2\rho \tanh t \frac{d}{dt} + \frac{j(j+n-2)}{\cosh^2 t} \right) \varphi = (\lambda^2 - \rho^2) \varphi.
\]
(2.2)
This differential equation is invariant under sign change of \( t \). The solution with \( \varphi(0) = 1 \) and \( \varphi'(0) = 0 \) is even, and the solution with \( \varphi(0) = 0 \) and \( \varphi'(0) = 1 \) is odd. Thus the solution space decomposes as the direct sum of the one-dimensional subspaces of even and odd solutions, and we have
\[
\mathcal{E}_{\lambda,j}^{\text{even}}(X) = \bigoplus_{j=0}^\infty \mathcal{E}_{\lambda,j}^{\text{even}}(X),
\]
\[
\mathcal{E}_{\lambda,j}^{\text{odd}}(X) = \bigoplus_{j=0}^\infty \mathcal{E}_{\lambda,j}^{\text{odd}}(X)
\]
where \( \mathcal{E}_{\lambda,j}^{\text{even}}(X) \cong \mathcal{E}_{\lambda,j}^{\text{odd}}(X) \cong \mathcal{H}_j \) are equivalent irreducible \( K \)-types for each \( j \).

2.3. Hypergeometric functions

In fact (2.2) can be transformed into a standard equation of special function theory. We first prepare for the anticipated asymptotic behavior of \( \varphi \) by substituting \( \Phi(t) = (\cosh t)^{\lambda+\rho} \varphi(t) \). This leads to the following equation for \( \Phi(t) \)
\[
\Phi''(t) - 2\lambda \tanh t \Phi'(t) - ab(1 - \tanh^2 t) \Phi(t) = 0,
\]
(2.3)
where \( a = \lambda + \rho + j \) and \( b = \lambda - \rho + 1 - j \).

Next we change variables. With
\[
x = \frac{1}{2}(1 - \tanh t) = (1 + e^{2t})^{-1} \in (0, 1)
\]
we replace the limits \( t = \infty \) and \( t = -\infty \) by \( x = 0 \) and \( x = 1 \), respectively. We write \( \Phi(t) = F(x) \), so that
\[
\varphi(t) = (\cosh t)^{\lambda-\rho} F((1 + e^{2t})^{-1}).
\]
Since \( \tanh t = 1 - 2x \) and \( 1 - \tanh^2t = 4x(1 - x) \) this gives
\[
(x')^2 F''(x) + x'' F'(x) - 2\lambda(1 - 2x) F'(x)x' - ab 4x(1 - x)F(x) = 0,
\]
and since
\[
x' = -2x(1 - x), \quad x'' = 4x(1 - x)(1 - 2x),
\]
we arrive at the following equation for the function \( F(x) \)
\[
x(1 - x)F''(x) + (\lambda + 1)(1 - 2x)F'(x) - abF(x) = 0. \tag{2.4}
\]

Recall the hypergeometric function \( F(a, b; c; x) = \sum_{m=0}^{\infty} \frac{(a)_m (b)_m}{(c)_m} x^m \)
which with the notation \( (a)_m := \prod_{k=0}^{m-1} (a + k) \) is defined by the Gauss series
\[
F(a, b; c; x) = \sum_{m=0}^{\infty} \frac{(a)_m (b)_m}{(c)_m} x^m.
\]
for \( x \in \mathbb{C} \) with \(|x| < 1\), for all \( a, b, c \in \mathbb{C} \) except \( c \in -\mathbb{N}_0 \). It solves Euler’s hypergeometric differential equation
\[
(x(1-x))'' + (c - (a + b + 1)x) w' - ab w = 0. \tag{2.5}
\]
The function \( F(a, b; c; x) \) is analytic at \( x = 0 \) with the value 1, and unless \( c \) is an integer it is the unique solution with this property.

With \( a = \lambda + \rho + j \) and \( b = \lambda - \rho + 1 - j \) as above we have \( a + b + 1 = 2(\lambda + 1) \). By comparing (2.4) and (2.5) we conclude that for each \( \lambda \notin -\mathbb{N} \) the function
\[
\varphi_{\lambda, j}(t) := (\cosh t)^{-\lambda - \rho} F(\lambda + \rho + j, \lambda - \rho + 1 - j; 1 + \lambda; (1 + e^{2t})^{-1})
\]
solves (2.2).

### 2.4. \( L^2 \)-Behavior

In the coordinates \((y, t)\) an invariant measure on \( X \) is given by
\[
cosh^{n-1} t \, dt \, dy
\]
where \( dt \) and \( dy \) are invariant measures on \( \mathbb{R} \) and \( S^{n-1} \), respectively. Hence a function \( f(y, t) = h(y)\varphi(t) \) is square integrable if and only if
\[
\int_{\mathbb{R}} |\varphi(t)|^2 \cosh^{n-1} t \, dt < \infty.
\]

Let \( \tilde{\varphi}_{\lambda, j}(t) = \varphi_{\lambda, j}(-t) \). By symmetry this function also solves (2.2), and it belongs to \( L^2(\mathbb{R}, \cosh^{n-1} t \, dt) \) if and only if \( \varphi_{\lambda, j} \) does.

**Lemma 2.1.** Let \( \text{Re} \lambda > 0 \) and \( j \in \mathbb{N}_0 \).

1. If \( j \in \lambda - \rho + \mathbb{N} \) then \( \varphi_{\lambda, j} \in L^2(\mathbb{R}, \cosh^{n-1} t \, dt) \).
2. If \( j \notin \lambda - \rho + \mathbb{N} \) then \( \varphi_{\lambda, j} \) and \( \tilde{\varphi}_{\lambda, j} \) are linearly independent, and for a sufficiently small \( \epsilon > 0 \) no non-trivial linear combination belongs to \( L^{2+\epsilon}(\mathbb{R}, \cosh^{n-1} t \, dt) \).

**Proof.** It follows from the definition of \( \varphi_{\lambda, j}(t) \) that
\[
(\cosh t)^{\lambda + \rho} \varphi_{\lambda, j}(t) \to 1, \quad t \to \infty.
\]
Since $2\rho = n - 1$ this means $\varphi_{\lambda,j}$ has the desired $L^2$-behavior in the positive direction for all $Re \lambda > 0$. The only issue is with the negative direction, or equivalently, with $\tilde{\varphi}_{\lambda,j}(t)$ for $t \to \infty$.

We first consider (1). The assumption that $j \in \lambda - \rho + \mathbb{N}$ implies that $b = \lambda - \rho + 1 - j \in -\mathbb{N}_0$. The Gauss series for $F(a, b; c; x)$ terminates and defines a polynomial when $a$ or $b$ is a non-positive integer. In particular $F(a, b; c; x)$ is then a bounded function on $[0, 1]$. It then follows from the definition of $\varphi_{\lambda,j}$ that

$$(\cosh t)^{\lambda + \rho} \varphi_{\lambda,j}(t)$$

is bounded on $\mathbb{R}$, and hence $|\varphi_{\lambda,j}(t)|^2 (\cosh t)^{2\rho}$ is integrable. This proves (1).

Now consider (2). According to Gauss (see [1, Thm. 2.1.3]) we have

$$\lim_{x \to 1^-} (1 - x)^{a+b-c} F(a, b; c; x) = A := \frac{\Gamma(c) \Gamma(a + b - c)}{\Gamma(a) \Gamma(b)}$$

if $Re(a + b - c) > 0$. We apply this to $t \to \infty$ in

$$(\cosh t)^{\lambda + \rho} \tilde{\varphi}_{\lambda,j}(t) = F(\lambda + \rho + j, \lambda - \rho + 1 - j; 1 + \lambda; (1 + e^{-2t})^{-1}).$$

Here $a + b - c = \lambda$ and

$$A = \frac{\Gamma(1 + \lambda) \Gamma(\lambda)}{\Gamma(\lambda + \rho + j) \Gamma(\lambda - \rho + 1 - j)}.$$

Since $x = (1 + e^{-2t})^{-1}$ implies $1 - x = (1 + e^{2t})^{-1}$ it follows that

$$e^{-2\lambda t}(\cosh t)^{\lambda + \rho} \tilde{\varphi}_{\lambda,j}(t) \to A, \quad t \to \infty.$$

In particular we note that $A \neq 0$ if $j \notin \lambda - \rho + \mathbb{N}$. Under this condition we see that no non-trivial linear combination of $\varphi_{\lambda,j}$ and $\tilde{\varphi}_{\lambda,j}$ exhibits $L^{2+\epsilon}$-behavior in both directions $\pm \infty$.

This proves (2) and concludes the proof of the lemma. 

2.5. Parity of $\varphi_{\lambda,j}$

We have seen that $\varphi_{\lambda,j}$ and $\tilde{\varphi}_{\lambda,j}$ are independent solutions to (2.2) when $j \notin \lambda - \rho + \mathbb{N}$. For $j \in \lambda - \rho + \mathbb{N}$ they are proportional, as the following lemma shows. For $\alpha, \beta > -1$ and $l \in \mathbb{N}_0$ let

$$P_l^{(\alpha, \beta)}(z) := \frac{(\alpha + 1)_l}{l!} F(l + \alpha + \beta + 1, -l; \alpha + 1; \frac{1}{2}(1 - z))$$

be the corresponding Jacobi polynomial (see [5, page 115]).

**Lemma 2.2.** Assume $j = \lambda - \rho + 1 + l \in \mathbb{N}_0$ where $l \in \mathbb{N}_0$. Then

1. $$(\frac{(\lambda + 1)_l}{l!}) \varphi_{\lambda,j}(t) = (\cosh t)^{-\lambda - \rho} P_l^{(\lambda, \lambda)}(\tanh t),$$
2. $\varphi_{\lambda,j}(-t) = (-1)^j \varphi_{\lambda,j}(t),$

for all $t \in \mathbb{R}$.

Note that with the repeated indices $P_l^{(\lambda, \lambda)}$ is in fact a Gegenbauer polynomial.

**Proof.** By definition

$$\varphi_{\lambda,j}(t) = (\cosh t)^{-\lambda - \rho} F(2\lambda + 1 + l, -l; \lambda + 1; x)$$

where $x = (1 + e^{2t})^{-1} = \frac{1}{2}(1 - \tanh t)$. The List (1) follows immediately. Then (2) follows since a Gegenbauer polynomial is even or odd according to the parity of its degree.
2.6. \( K \)-Types in \( L^2 \)

For \( \lambda \in \mathbb{C} \) with \( \text{Re} \lambda \geq 0 \) we define
\[
D_{\lambda} := N_0 \cap (\lambda - \rho + \mathbb{N})
\]
if \( \lambda - \rho \in \mathbb{Z} \) and \( \lambda > 0 \), and by \( D_{\lambda} = \emptyset \) otherwise. Furthermore we let
\[
U_{\lambda} := \bigoplus_{j \in D_{\lambda}} (\mathcal{H}_j \otimes \varphi_{\lambda,j}).
\]

It follows from Lemma 2.2 and the fact that the parity of \( \mathcal{H}_j \) is \((-1)^j\) that \( U_{\lambda} \subset \mathcal{E}^\text{even}_{\lambda,K}(X) \) if \( \lambda - \rho \) is odd, and \( U_{\lambda} \subset \mathcal{E}^\text{odd}_{\lambda,K}(X) \) if \( \lambda - \rho \) is even.

**Lemma 2.3.** For all \( \lambda \in \mathbb{C} \) with \( \text{Re} \lambda > 0 \) we have
\[
U_{\lambda} = \mathcal{E}_{\lambda,K}(X) \cap L^2(X) = \mathcal{E}_{\lambda,K}(X) \cap C^\infty_{\text{temp}}(X).
\] (2.6)

**Proof.** Let \( \text{Re} \lambda > 0 \). When \( \lambda - \rho \notin \mathbb{Z} \) it follows immediately from Lemma 2.1(2) that \( \mathcal{E}_{\lambda,j}(X) \cap C^\infty_{\text{temp}}(X) = \{0\} \) for each \( j \in N_0 \). Since \( U_{\lambda} = \{0\} \) in this case (2.6) follows. Assume from now on that \( \lambda - \rho \in \mathbb{Z} \). It then follows from Lemma 2.1(1) that \( U_{\lambda} \subset L^2(X) \).

To complete the proof we will find for each \( j \in N_0 \) a second solution to (2.2), which is linearly independent from \( \varphi_{\lambda,j} \), and which is not tempered. There are two cases, depending on the parity of \( n \).

If \( n \) is even, then \( \rho \), and hence also \( \lambda \), is not an integer. In that case we already have a second solution at hand, namely \( \varphi_{-\lambda,j} \). Since
\[
(cosh t)^{-\lambda+j} \varphi_{-\lambda,j}(t) \to 1, \quad t \to \infty,
\]
this function \( \varphi_{-\lambda,j} \) does not belong to any \( L^p(\mathbb{R}, \cosh^{n-1} t \, dt) \) if \( \text{Re} \lambda > \rho \). When \( 0 < \text{Re} \lambda < \rho \) it belongs to \( L^{2+\epsilon} \) only for \( \epsilon > \frac{2 \text{Re} \lambda}{\rho - \text{Re} \lambda} \).

We now assume \( n \) is odd. Then \( \rho \) and \( \lambda \) are positive integers. We need to find a solution linearly independent from \( F(a,b;c;x) \) to the hypergeometric Eq. (2.5) with
\[
a = \lambda + \rho + j, \quad b = \lambda - \rho + 1 - j, \quad c = 1 + \lambda.
\]

By the method of Frobenius one finds (see [13, p. 5]) such a solution \( G(a,b,c;x) \). It has the form
\[
G(x) = x^{-\lambda} \sum_{v=0}^{\infty} a_v x^v + \log x \sum_{v=0}^{\infty} b_v x^v
\]
for some explicit power series with \( a_0 = 1 \) and \( b_0 \neq 0 \). The corresponding solution to (2.2) is
\[
(cosh t)^{-\lambda-\rho} G(a,b,c; (1 + e^{2t})^{-1}).
\]

It behaves like \( (cosh t)^{-\lambda-\rho}(1 + e^{2t})^\lambda \) as \( t \to \infty \) and as before it is not tempered with respect to the invariant measure. \( \square \)
2.7. Irreducibility

Let $\lambda \in \rho + \mathbb{Z}$ and assume $\lambda > 0$. It follows from Lemma 2.3 that $U_{\lambda}$ is $(g, K)$-invariant. We will prove that it is an irreducible $(g, K)$-module by using the infinitesimal element

$$T = E_{n+1,1} + E_{1,n+1} \in g = \mathfrak{so}(n, 1),$$

(2.7)
as a raising and lowering operator between the functions $\varphi_{\lambda,j}$ which generate $U_{\lambda}$ together with $K$. For this we need to find the derivative of $\varphi_{\lambda,j}$.

Lemma 2.4. Let $j = \lambda - \rho + 1 + l \in \mathbb{N}_0$ where $l \in \mathbb{N}_0$. There exist constants $A_l, B_l \in \mathbb{R}$ such that

$$\varphi'_{\lambda,j} = A_l \varphi_{\lambda,j+1} + B_l \varphi_{\lambda,j-1}.$$  

Both $A_l$ and $B_l$ are non-zero, except when $l = 0$ or $j = 0$, in which cases only $A_l$ is non-zero.

Proof. Recall from Lemma 2.2

$$\varphi_{\lambda,j}(t) = \frac{n}{(\rho+1)l} (\cosh t)^{-\lambda-\rho} P_l^{(\lambda,\lambda)}(\tanh t)$$

for $j = \lambda - \rho + 1 + l$. It follows that

$$\varphi'_{\lambda,j}(t) = \frac{n}{(\rho+1)l} (\cosh t)^{-\lambda-\rho} \left( - (\lambda + \rho)x P_l^{(\lambda,\lambda)}(x) + (1 - x^2)(P_l^{(\lambda,\lambda)})'(x) \right)$$

where $x = \tanh t$.

We obtain from [9, (4.7)] that

$$(1 - x^2)(P_l^{(\lambda,\lambda)})'(x) = (l + 2\lambda + 1)x P_l^{(\lambda,\lambda)}(x) - \frac{(l+1)(l+2\lambda+1)}{l+\lambda+1} P_{l+1}^{(\lambda,\lambda)}(x).$$

By [5, (5.5.5)] the polynomials $P_l^{(\lambda,\lambda)}$ satisfy a three term recurrence relation

$$n(l+\lambda+1)(2l+2\lambda+1)x P_l^{(\lambda,\lambda)}(x) = (l+\lambda)(l+\lambda+1) P_{l-1}^{(\lambda,\lambda)}(x) + (l+1)(l+2\lambda+1) P_{l+1}^{(\lambda,\lambda)}(x).$$

With this relation we can eliminate $x P_l^{(\lambda,\lambda)}(x)$ and obtain $\varphi'_{\lambda,j}$ as a linear combination of $\varphi_{\lambda,j+1}$ and $\varphi_{\lambda,j-1}$. The coefficients turn out to be

$$A_l = -\frac{(\lambda + \rho + l)(2\lambda + l + 1)}{2\lambda + 2l + 1}, \quad B_l = \frac{l(\lambda - \rho + l + 1)}{2\lambda + 2l + 1}.$$  

All these coefficients are non-zero, except $B_l$ when $l = 0$ or $\lambda - \rho + l + 1 = 0$.  

Let $M = K \cap H$ be the stabilizer in $K$ of $x_0$, that is

$$M = \begin{pmatrix} 1 & 0 \\ 0 & \text{SO}(n-1) \end{pmatrix} \subset \text{SO}(n, 1) = G.$$  

Then $S^{n-1} \simeq K/M$. Let $h_j \in \mathcal{H}_j$ be the zonal spherical harmonic. This is the unique function in $\mathcal{H}_j$ which is $M$-invariant and has the value 1 at the origin $(1, 0, \ldots, 0)$ of $S^{n-1}$. Furthermore, let $f_{\lambda,j} \in \mathcal{E}_{\lambda}(X)$ be defined by

$$f_{\lambda,j}(y, t) = h_j(y) \varphi_{\lambda,j}(t).$$

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With the element $T$ from (2.7) the coordinates $(y, t)$ are determined from

$$\frac{K}{M} \times \mathbb{R} \ni (k M, t) \mapsto k \exp(tT)x_0 \in X,$$

and since $T$ is centralized by $M$ the left derivative $L_T f_{\lambda, j}$ by $T$ is again $M$-invariant. It follows that for each $j \in \mathbb{N}_0$, the function $L_T f_{\lambda, j} \in \mathcal{E}_{\lambda, K}(X)$ is a linear combination of the same family of functions $f_{\lambda, j}$ in $\mathcal{E}_{\lambda, K}(X)$. Since $h_j(x_0) = 1$ for all $j$, the coefficients can be determined from the restriction to

$$\{(\cosh t, 0, \ldots, 0, \sinh t) \mid t \in \mathbb{R}\} \subset X,$$

on which $L_T$ acts just by $\frac{d}{dt}$, and hence they are given by Lemma 2.4. It follows immediately that $U_\lambda$ has no non-trivial $(g, K)$-invariant subspaces.

### 2.8. Equivalence

Let $\lambda \in \rho + \mathbb{Z}$ and assume $0 < \lambda < \rho$.

#### Lemma 2.5.

The $(g, K)$-modules $\mathcal{E}_{\lambda, K}^{even}(X)$ and $\mathcal{E}_{\lambda, K}^{odd}(X)$ are irreducible and equivalent.

**Proof.** The assumption on $\lambda$ implies that $D_\lambda = \mathbb{N}_0$, and hence $U_\lambda$ is equal to one of the two modules $\mathcal{E}_{\lambda, K}^{even}(X)$ and $\mathcal{E}_{\lambda, K}^{odd}(X)$, depending on the parity of $\lambda - \rho$. For simplicity of exposition, let us assume a specific parity, say even, of $\lambda - \rho$. Then $\mathcal{E}_{\lambda, K}^{odd}(X) = U_\lambda$ is irreducible as seen in Section 2.7.

By Kostant’s theorem [10, Thm. 8] an irreducible $(g, K)$-module, which contains the trivial $K$-type, is uniquely determined up to equivalence by its infinitesimal character. Hence $\mathcal{E}_{\lambda, K}^{odd}(X)$ is equivalent to the irreducible subquotient of $\mathcal{E}_{\lambda, K}^{even}(X)$ containing $\mathcal{E}_{\lambda, 0}^{even}(X)$. Since $\mathcal{E}_{\lambda, K}^{even}(X)$ and $\mathcal{E}_{\lambda, K}^{even}(X)$ contain the same $K$-types, all with multiplicity one, we conclude that this subquotient is equal to $\mathcal{E}_{\lambda, K}^{even}(X)$. The lemma is proved. □

### 3. Conclusion

Assume $\text{Re} \lambda > 0$. Then $\mathcal{E}_{\lambda, K}(X) \cap L^2(X) = U_\lambda$ by Lemma 2.3. By definition $U_\lambda$ is non-zero if and only if $\lambda - \rho \in \mathbb{Z}$. In Section 2.6 we saw that it consists of even functions on $X$ when $\lambda - \rho$ is odd, and vice versa. Finally, irreducibility was seen in Section 2.7. Thus the proof of Theorem 1.1 is complete.

Assume $\lambda \in \rho + \mathbb{Z}$ and $0 < \lambda < \rho$. Then $\mathcal{E}_{\lambda, K}^{even}(X)$ and $\mathcal{E}_{\lambda, K}^{odd}(X)$ are irreducible and equivalent by Lemma 2.5. One of them equals $U_\lambda$ and belongs to $L^2(X)$, whereas we have seen in Lemma 2.3 that the other one is non-tempered. This proves Theorem 1.2.

### References


