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ISOTROPY REPRESENTATIONS ATTACHED TO THE ASSOCIATED CYCLES OF HARISH-CHANDRA MODULES (Theory of Prehomogeneous Vector Spaces)

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ISOTROPY REPRESENTATIONS
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1. Introduction

Let \( g \) be a complex semisimple Lie algebra with a nontrivial involutive automorphism \( \theta \) of \( g \). We write \( g = \mathfrak{k} \oplus \mathfrak{p} \) for the symmetric decomposition of \( g \) given by \( \theta \), where \( \mathfrak{k} \) and \( \mathfrak{p} \) denote the +1 and −1 eigenspaces for \( \theta \), respectively. Let \( K_C \) be a connected complex algebraic group with Lie algebra \( \mathfrak{k} \). We assume that the natural inclusion \( \mathfrak{k} \hookrightarrow g \) gives rise to a group homomorphism from \( K_C \) to \( G_C^{ad} \) through the exponential map. Here \( G_C^{ad} \) denotes the adjoint group of \( g \). Then, this homomorphism naturally induces the adjoint representation \( \text{Ad} \) of \( K_C \) on \( g \).

We say that a finitely generated \( g \)-module \( X \) is a \((g, K_C)\)-module, or a Harish-Chandra module, if the action on \( X \) of the Lie subalgebra \( \mathfrak{k} \) is locally finite and if it lifts up to a representation of \( K_C \) on \( X \) through the exponential map. It is a fundamental result of Harish-Chandra that the study of irreducible admissible representations of a real semisimple Lie group essentially reduces to that of irreducible \((g, K_C)\)-modules.

Let \( X \) be an irreducible \((g, K_C)\)-module. A \( K_C \)-stable good filtration of \( X \) naturally gives rise to a graded, compatible \((S(g), K_C)\)-module \( \text{gr} \ X \) annihilated by \( \mathfrak{k} \), where \( S(g) \) denotes the symmetric algebra of \( g \). By Borho-Brylinski [1] and Vogan [17], [18], the associated cycle \( \mathcal{C}(X) \) of \( X \) is defined to be the support \( \mathcal{V}(X) \) of \( \text{gr} \ X \) combined with the multiplicity at each irreducible component of \( \mathcal{V}(X) \). The support \( \mathcal{V}(X) \) is called the associated variety of \( X \). It is a \( K_C \)-stable affine algebraic cone contained in the set of nilpotent elements in \( \mathfrak{p} \), and each irreducible component of \( \mathcal{V}(X) \) is the closure \( \overline{O} \) of a nilpotent \( K_C \)-orbit \( O \) in \( \mathfrak{p} \). As we have shown in [5] and [20], the variety \( \mathcal{V}(X) \) controls some fundamental properties for \( X \).

The algebraic cycle \( \mathcal{C}(X) \) describes a sort of asymptotic behavior of \( X \) (cf. [16]). Moreover, it is shown by Vogan [17, Theorem 2.13] that the multiplicity of \( X \) at an irreducible component \( \overline{O} \) of \( \mathcal{V}(X) \) can be interpreted as the dimension of a certain finite-dimensional representation \((\varpi_O, \mathcal{V})\) of the isotropy subgroup \( K_C(X) \) of \( K_C \) at an \( X \in \mathcal{O} \). We call \( \varpi_O \) an isotropy representation attached to \( X \). In terms of \( \varpi_O \), the associated cycle \( \mathcal{C}(X) \) of \( X \) is expressed as

\[
\mathcal{C}(X) = \sum_O \dim \varpi_O \cdot [\overline{O}].
\]

In this paper, we continue our study in [24] (also in [23]) concerning the associated cycle \( \mathcal{C}(X) \) and the isotropy representation \( \varpi_O \) attached to a \((g, K_C)\)-module \( X \) with irreducible associated variety \( \mathcal{V}(X) = \overline{O} \).

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To be more precise, we first look at in Section 2 a relationship between the \((S(g), K_C)\)-module \(\text{gr} \, X\) and the induced representation \(\Gamma(\mathcal{W}) = \text{Ind}_{K_C(X)}^{K_C} (\varpi_{\mathcal{O}}, \mathcal{W})\) of \(K_C\) equipped with a natural \(S(g)\)-action. A reciprocity law of Frobenius type for such an induced module (Proposition 2.4) plays an important role. In fact, it is effectively used to prove an irreducibility criterion for \(\varpi_{\mathcal{O}}\) (Theorem 2.9). Section 2 does not contain new results, but it gives a survey of some part of [17, Sections 2-4] and [18, Lectures 6 and 7] in a slightly modified and simplified form (but for limited \(X\)'s). Some remarks and examples in connection with our recent works ([23], [24]) are also included.

In order to identify the isotropy representation \(\varpi_{\mathcal{O}}\), it is sometimes helpful to consider not only \(\text{gr} \, X\) but also its \(K_C\)-finite dual space consisting of certain (vector valued) polynomial functions on \(p\). We present this technique in Section 3. A sufficient condition is given in Proposition 3.2 for \(\text{gr} \, X\) being annihilated by the whole prime ideal \(I\) of \(S(g)\) defining \(\overline{\mathcal{O}}\). In such a case, the isotropy representation \(\varpi_{\mathcal{O}}\) can be described by means of the principal symbol of a differential operator on \(p\) of gradient-type (see [24]).

In Section 4, we focus our attention on the irreducible Harish-Chandra modules \(X\) of discrete series. As is well known, such an \(X\) has irreducible associated variety (cf. [21], [22]). The multiplicities in the associated cycles for discrete series have been intensively studied by Chang [2], [3], by using the theory of \(D\)-modules on the flag variety for \(g\). He succeeds to describe \(\mathcal{C}(X)\) explicitly for the real rank one case. Taniguchi applies in [14] and [15] the results of Chang in order to specify Whittaker functions associated with discrete series for some noncompact unitary or orthogonal Lie groups. Here in this paper, we would like to propose another approach to identify \(\mathcal{C}(X)\), by using a realization of \(X\) as the kernel of an invariant differential operator of gradient-type on the Riemannian symmetric space (cf. [7], [13]; [19], [25]). Through this approach, we can construct a certain \(K_C(X)\)-submodule \(U_{\lambda}(Q_c)\) of the representation \((\varpi_{\mathcal{O}}^*, \mathcal{W}^*)\) contragredient to \(\varpi_{\mathcal{O}}\), by improving our arguments in [22]. Moreover some evidences are given for this subrepresentation being large enough in the whole \(\varpi_{\mathcal{O}}^*\), by means of our technique given in Section 3. The main results are given as Theorem 4.4 and Corollary 4.6.

An enlarged version of this article will appear elsewhere.

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2. Graded module \(\text{gr} \, X\) and induced representation \(\Gamma(\mathcal{W})\)

As in Section 1, let \(X\) be an irreducible \((g, K_C)\)-module with irreducible associated variety \(\mathcal{V}(X) = \overline{\mathcal{O}}\), where \(\mathcal{O}\) is a nilpotent \(K_C\)-orbit in \(p\). This section introduces some elementary aspects of Vogan’s theory on the associated cycle and the isotropy representation attached to \(X\). The results in this section may be read off from [17] and [18] with a little bit of effort.

2.1. Associated cycle and isotropy representation. To start with, let us introduce our key notion precisely. Take an irreducible \(K_C\)-submodule \((\tau, V_\tau)\) of \(X\), which yields a \(K_C\)-stable good filtration of \(X\) in the following way:

\[
X_0 \subset X_1 \subset \cdots \subset X_n \subset \cdots, \quad X_n := U_n(g)V_\tau \quad (n = 0, 1, 2, \ldots).
\]

Here \(U(g)\) denotes the universal enveloping algebra of \(g\), and we write \(U_n(g) \quad (n = 0, 1, \ldots)\) for the natural increasing filtration of \(U(g)\). This filtration gives rise to a graded
$(S(\mathfrak{g}, K_{\mathbb{C}}))$-module $M = \text{gr } X$, annihilated by $S(\mathfrak{t})$, as follows:

\begin{equation}
M = \text{gr } X = \bigoplus_{n=0}^{\infty} M_n \quad \text{with} \quad M_n := X_n/X_{n-1} \quad (X_{-1} := \{0\}).
\end{equation}

We note that

\begin{equation}
M_n = S^n(\mathfrak{g})V_{\tau} \simeq S^n(\mathfrak{p})V_{\tau} \quad \text{with} \quad M_0 = V_{\tau},
\end{equation}

where $S^n(\mathfrak{v})$ is the homogeneous component of the symmetric algebra $S(\mathfrak{v})$ of degree $n$. By definition, the associated variety $\mathcal{V}(X)$ of $X$ is identified with the affine algebraic variety of $\mathfrak{g}$ given by the annihilator ideal $\text{Ann}_{S(\mathfrak{g})}M$ in $S(\mathfrak{g})$ of $M$:

\begin{equation}
\mathcal{V}(X) = \{ Z \in \mathfrak{g} \mid f(Z) = 0 \text{ for all } f \in \text{Ann}_{S(\mathfrak{g})}M \} \subset \mathfrak{p},
\end{equation}

where $S(\mathfrak{g})$ is viewed as the ring of polynomial functions on $\mathfrak{g}$ by identifying $\mathfrak{g}$ with its dual space through the Killing form $B$ of $\mathfrak{g}$.

The Hilbert Nullstellsensatz tells us that the radical of $\text{Ann}_{S(\mathfrak{g})}M$ coincides with the prime ideal $I = I(\mathcal{V}(X))$ defining the irreducible variety $\mathcal{V}(X)$: $I = \sqrt{\text{Ann}_{S(\mathfrak{g})}M}$. So we see $I^nM = \{0\}$ for some positive integer $n$, and we write $n_0$ for the smallest $n$ of this nature. Then, one gets a strictly decreasing filtration of the $(S(\mathfrak{g}), K_{\mathbb{C}})$-module $M$ as

\begin{equation}
M = I^0M \supsetneq I^1M \supsetneq \cdots \supsetneq I^{n_0}M = \{0\}.
\end{equation}

By the multiplicity $\text{mult}_I(X)$ of $X$ at $I$ is meant the length as an $S(\mathfrak{g})_I$-module of the localization $M_I$ of $M = \text{gr } X$ at the prime ideal $I$. Then, the associated cycle $C(X)$ of $X$ turns to be

\begin{equation}
C(X) = \text{mult}_I(X) \cdot [\overline{O}] \quad \text{with} \quad \mathcal{V}(X) = \overline{O}.
\end{equation}

Note that this cycle does not depend on the choice of a good filtration (2.1) of $X$.

Now, let us explain how the multiplicity $\text{mult}_I(X)$ can be interpreted as the dimension of an isotropy representation. For this, we take an element $X$ in the open $K_{\mathbb{C}}$-orbit $\mathcal{O} \subset \mathcal{V}(X)$. Set $K_{\mathbb{C}}(X) := \{ k \in K_{\mathbb{C}} \mid \text{Ad}(k)X = X \}$, the isotropy subgroup of $K_{\mathbb{C}}$ at $X$. We write $m(X)$ for the maximal ideal of $S(\mathfrak{g})$ which defines the one point variety $\{X\}$ in $\mathfrak{g}$:

\begin{equation}m(X) := \sum_{Y \in \mathfrak{g}}(Y - B(Y, X))S(\mathfrak{g}) \quad \text{for } X \in \mathcal{O}.
\end{equation}

For each $j = 0, \ldots, n_0 - 1$, we introduce a finite-dimensional $(S(\mathfrak{g}), K_{\mathbb{C}}(X))$-representation $\varpi_{\mathcal{O}}(j)$ acting on

\begin{equation}\mathcal{W}(j) := I^jM/m(X)I^jM,
\end{equation}

in the canonical way, and we set

\begin{equation}(\varpi_{\mathcal{O}}, \mathcal{W}) := \bigoplus_{j=0}^{n_0-1} (\varpi_{\mathcal{O}}(j), \mathcal{W}(j)).
\end{equation}

We call $\varpi_{\mathcal{O}}$ the isotropy representation attached to the data $(X, V_{\tau}, \mathcal{O})$, where $V_{\tau}$ yields the filtration (2.1) of $X$. The following lemma is essential for our succeeding discussion.

**Lemma 2.1** (cf. [17, Corollary 2.7] and [24, Remark 2.2]). *Let $N$ be a finitely generated $(S(\mathfrak{g}), K_{\mathbb{C}})$-module such that $IN = \{0\}$. Then, the length of $S(\mathfrak{g})_I$-module $N_I$ is equal to the dimension of the vector space $N/m(X)N$ for every $X \in \mathcal{O}$.***
This lemma tells us that the length of the $S(\mathfrak{g})_I$-module $(I^jM/I^{j+1}M)_I$ equals $\dim \omega_\mathcal{O}(j)$ by noting that the ideal $I$ annihilates the subquotient $I^jM/I^{j+1}M$ of $M$. Together with the exactness of localization, we immediately get the following

**Proposition 2.2.** One has $\text{mult}_I(X) = \dim \omega_\mathcal{O}$. Moreover, the equality

\[(2.10) \quad \text{mult}_I(X) = \dim \omega_\mathcal{O}(0) = \dim M/m(X)M\]

holds if and only if the support of the $S(\mathfrak{g})$-module $IM$ is contained in the boundary $\partial \mathcal{O} = \overline{\mathcal{O}} \setminus \mathcal{O}$.

**Remark 2.3.** The representation $\omega_\mathcal{O}(0)$ in (2.10) never vanishes because the annihilator ideal $\text{Ann}_{S(\mathfrak{g})} M/IM$ is equal to $I$ (cf. [23, Lemma 3.4]). Moreover, the equality (2.10) holds for a number of unitarizable $(\mathfrak{g}, K_C)$-modules $X$ with unique extreme $K_C$-types $\tilde{V}_\tau$. See Example 2.7 and Theorem 4.4 (1).

### 2.2. Induced module $\Gamma(\mathcal{Z})$

Let $(\omega, \mathcal{Z})$ be a finite-dimensional $(S(\mathfrak{g}), K_C(X))$-module with $X \in \mathcal{O}$. We write $\Gamma(\mathcal{Z})$ for the space of all left $K_C$-finite, holomorphic functions $f : K_C \to \mathcal{Z}$ satisfying

\[f(yh) = \omega(h)^{-1}f(y) \quad (y \in K_C, h \in K_C(X)).\]

Namely, $\Gamma(\mathcal{Z})$ consists of all $K_C$-finite, holomorphic cross sections of the $K_C$-homogeneous vector bundle $K_C \times_{K_C(X)} \mathcal{Z}$ on $K_C/K_C(X) \simeq \mathcal{O}$. Then, $\Gamma(\mathcal{Z})$ has a structure of $(S(\mathfrak{g}), K_C)$-module by the following actions:

\[(D \cdot f)(y) := \omega(\text{Ad}(y)^{-1}D)f(y), \quad (k \cdot f)(y) := f(k^{-1}y),\]

for $D \in S(\mathfrak{g})$, $k \in K_C$ and $f \in \Gamma(\mathcal{Z})$. We call $\Gamma(\mathcal{Z})$ the $(S(\mathfrak{g}), K_C)$-module induced from $\omega$. We note that, if $\mathcal{Z}$ is annihilated by the maximal ideal $m(X)$, the $S(\mathfrak{g})$-action on $\Gamma(\mathcal{Z})$ turns to be the multiplication of functions on the orbit $\mathcal{O}$:

\[(2.11) \quad (D \cdot f)(y) = D(\text{Ad}(y)X)f(y).\]

In this case, the annihilator in $S(\mathfrak{g})$ of any nonzero function $f \in \Gamma(\mathcal{Z})$ coincides with the prime ideal $I$ defining $\mathcal{O}$.

Let $M$ be any $(S(\mathfrak{g}), K_C)$-module. If $\rho$ is an $(S(\mathfrak{g}), K_C(X))$-homomorphism from $M$ to $\mathcal{Z}$, we define a function $T_m : K_C \to \mathcal{Z}$ for each $m \in M$ by putting

\[(2.12) \quad T_m(y) := \rho(y^{-1} \cdot m) \quad (y \in K_C).\]

Then it is standard to verify that $T_m$ lies in $\Gamma(\mathcal{Z})$ and that the map $T : m \mapsto T_m$ ($m \in M$) gives an $(S(\mathfrak{g}), K_C)$-homomorphism from $M$ to $\Gamma(\mathcal{Z})$. More precisely, one readily obtains the following reciprocity law of Frobenius type.

**Proposition 2.4.** Under the above notation, the assignment $\rho \mapsto T$ sets up a linear isomorphism

\[(2.13) \quad \text{Hom}_{S(\mathfrak{g}), K_C(X)}(M, \mathcal{Z}) \simeq \text{Hom}_{S(\mathfrak{g}), K_C}(M, \Gamma(\mathcal{Z})).\]

Here, for $\Omega$-modules $A$ and $B$, we denote by $\text{Hom}_\Omega(A, B)$ the space of $\Omega$-homomorphisms from $A$ to $B$. 
2.3. Homomorphism $T = \Theta_j \tilde{T}(j)$. We now return to our setting in Section 2.1, where $M = \text{gr} X$ for an irreducible $(\mathfrak{g}, K_C)$-module $X$ with $\mathcal{V}(X) = \emptyset$. Take an integer $j$ such that $0 \leq j \leq n_0 - 1$. Let $\rho(j)$ denote the natural quotient map from $I^j M$ to $W(j) = I^j M/m(X)I^j M$. Correspondingly, we get an $(S(\mathfrak{g}), K_C)$-homomorphism $T(j) : I^j M \rightarrow \Gamma(W(j))$ by Proposition 2.4. It follows that

\[(2.14) \quad \text{Ker} T(j) = \bigcap_{Y \in \mathcal{O}} m(Y)I^j M \supset I^{j+1} M,\]

by the definition of $T(j)$ together with $m(Y) \supset I (Y \in \mathcal{O})$.

**Proposition 2.5.** The kernel $\text{Ker} T(j)$ of $T(j)$ is the largest $(S(\mathfrak{g}), K_C)$-submodule of $I^j M$ among those $N$ having the following two properties: (i) $N \supset I^{j+1} M$, and, (ii) the support of $N/I^{j+1} M$ is contained in $\partial \mathcal{O}$.

**Proof.** First, we show that $\text{Ker} T(j)$ have two properties (i) and (ii). The inclusion (2.14) assures (i). As for (ii), we consider a short exact sequence of $(S(\mathfrak{g}), K_C)$-modules:

\[(2.15) \quad 0 \rightarrow \text{Ker} T(j)/I^{j+1} M \rightarrow I^j M/I^{j+1} M \rightarrow I^j M/\text{Ker} T(j) \rightarrow 0.\]

Each module is annihilated by $I$. In view of Lemma 2.1, we find that the multiplicity of $I^j M/\text{Ker} T(j)$ at $I$ is equal to the dimension of vector space

\[(I^j M/\text{Ker} T(j))/m(X)(I^j M/\text{Ker} T(j)) \simeq I^j M/(m(X)I^j M + \text{Ker} T(j)) = W(j).\]

Here, the last equality follows from $\text{Ker} T(j) \subset m(X)I^j M$ (see (2.14)). This shows that the length of $S(\mathfrak{g})_I$-module $I^j M/I^{j+1} M$ and that of $I^j M/\text{Ker} T(j)$ coincide with one another. Hence $(\text{Ker} T(j)/I^{j+1} M)_I$ vanishes by (2.15). This means that the support of $\text{Ker} T(j)/I^{j+1} M$ is contained in $\partial \mathcal{O}$.

Second, let $N$ be any $(S(\mathfrak{g}), K_C)$-submodule of $I^j M$ with two properties (i) and (ii) in question. (2.14) tells us that $T(j)$ naturally induces an $(S(\mathfrak{g}), K_C)$-module map from $I^j M/I^{j+1} M$ to $\Gamma(W(j))$ which we denote by $\tilde{T}(j)$. Then, $\tilde{T}(j)(N/I^{j+1} M)$ must vanish by virtue of (2.11) together with the property (ii) for $N$. This proves $N \subset \text{Ker} T(j)$. \(\square\)

As for the injectivity of $T(j)$, one gets the following consequence of Proposition 2.5.

**Corollary 2.6.** The homomorphism $T(j) : I^j M \rightarrow \Gamma(W(j))$ is injective if and only if $\text{Ann}_{S(\mathfrak{g})} m = I$ for all $m \in I^j M \setminus \{0\}$. In this case, one has $I^{j+1} M = \{0\}$, i.e., $j = n_0 - 1$.

**Example 2.7.** We encounter the situation in the above corollary with $j = 0$, for example, if $X$ is a unitarizable highest weight module of a simple hermitian Lie algebra $\mathfrak{g}$, and $V_\tau$ in (2.1) is the extreme $K_C$-type of $X$. Note that the associated variety of such an $X$ is the closure of a “holomorphic” nilpotent $K_C$-orbit in $\mathfrak{p}$. See [23, Section 3.2] for details.

Summing up $\tilde{T}(j)$'s on $I^j M/I^{j+1} M$ $(j = 0, \ldots, n_0 - 1)$, we obtain an $(S(\mathfrak{g}), K_C)$-homomorphism $T := \Theta_j \tilde{T}(j)$:

\[(2.16) \quad \tilde{M}(I) := \bigoplus_j I^j M/I^{j+1} M \xrightarrow{T} \bigoplus_j \Gamma(W(j)) \simeq \Gamma(W),\]

where the support of the kernel $\text{Ker} T$ is contained in $\partial \mathcal{O}$. 


Remark 2.8. By using the "microlocalization technique", Vogan constructed a new $K_C$-stable $\mathbb{Z}$-gradation on $X$ such that the corresponding graded module embeds into $\Gamma(W)$ as a representation of $K_C$ (see [17, Theorem 4.2]). Thanks to this result, one always has $X \hookrightarrow \Gamma(W)$ as $K_C$-modules. Noting that $M(I) \simeq X$ as $K_C$-modules, we find that the above $T : M(I) \to \Gamma(W)$ must be an isomorphism if $T$ is surjective.

2.4. Irreducibility of $\varpi_\mathcal{O}$. The results in Sections 2.1–2.3 lead us to prove the following natural criterion for the irreducibility of isotropy representation $(\varpi_\mathcal{O}, W)$ of $K_C(X)$.

Theorem 2.9 (cf. [18, Proposition 7.6]; see also [24, Section 5]). The following two conditions on $X$ are equivalent to each other.

(a) $(\varpi_\mathcal{O}, W)$ is irreducible as a $K_C(X)$-module.

(b) If $N$ is any $(S(g), K_C)$-submodule of $M = \text{gr } X$, either the support of $N$ or that of the quotient $M/N$ is contained in $\partial \mathcal{O}$.

In this case, we have $\varpi_\mathcal{O} = \varpi_\mathcal{O}(0)$, or equivalently, the support of $IM$ is contained in $\partial \mathcal{O}$ by Proposition 2.2.

Proof. The implication (a) $\Rightarrow$ (b) is an easy consequence of the exactness of localization. In what follows let us prove (b) $\Rightarrow$ (a). First, we note that the condition (b) together with Remark 2.3 implies that the support of $IM$ is contained in $\partial \mathcal{O}$. Thus one gets $\varpi_\mathcal{O} = \varpi_\mathcal{O}(0)$, or,

$$W = W(0) = M/m(X)M.$$

Now, suppose by contraries that $W$ is not irreducible. Then, there exists a $K_C(X)$-stable subspace $C$ of $M$ such that $M \supsetneq C \supsetneq m(X)M$ and that $Z := M/C$ is irreducible as a $K_C(X)$-module. The condition $C \supset m(X)M$ assures that $C$ is $S(g)$-stable. Thus $Z$ becomes an $(S(g), K_C(X))$-module annihilated by $m(X)$.

Next, we consider two induced $(S(g), K_C)$-modules $\Gamma(W)$ and $\Gamma(Z)$. The quotient map $W = M/m(X)M \longrightarrow Z = M/C$ gives rise to an $(S(g), K_C)$-homomorphism, say $\gamma$, from $\Gamma(W)$ to $\Gamma(Z)$ in the canonical way. Set $T' := \gamma \circ T(0)$, where $T(0) : M \to \Gamma(W)$ is the $(S(g), K_C)$-homomorphism defined in Section 2.3. Then, as shown in the proof of [18, Proposition 7.9], the image $T'(M)$ of $T'$ is a finitely generated $(S(g), K_C)$-submodule of $\Gamma(Z)$ whose isotropy representation is isomorphic to $Z$. This combined with $T'(M) \simeq M/\text{Ker } T'$ tells us that the multiplicity of $\text{Ker } T'$ at the prime ideal $I$ is equal to $\dim W - \dim Z > 0$. By the assumption (b), we find that the support of $M/\text{Ker } T' \simeq T'(M)$ is contained in $\partial \mathcal{O}$. This necessarily implies $\text{Ker } T' = M$, i.e., $T' = 0$, because the $S(g)$-module $T'(M) (\subset \Gamma(Z))$ admits no embedded associated primes by (2.11). Finally, the resulting equality $T' = 0$ means that

$$y^{-1} \cdot m + m(X)M = T(0)_m(y) \in C/m(X)M \quad \text{for all } y \in K_C \text{ and } m \in M.$$

This contradicts $C \neq M$.

Example 2.10. Let $X$ be an irreducible unitarizable highest weight $(g, K_C)$-module of a simple hermitian Lie algebra $g$, with extreme $K_C$-type $\nu_\tau$. In [23, Section 5], we have described the isotropy representation $\varpi_\mathcal{O} = \varpi_\mathcal{O}(0)$ explicitly, when $X$ is the theta lift of an irreducible representation of the compact groups $G' = O(k), U(k)$ and $Sp(k)$ with respect to the reductive dual pairs $(G, G') = (Sp(2n, \mathbb{R}), O(k)), (SU(p, q), U(k))$ and $(SO^*(2n), Sp(k))$, respectively. In particular, one finds that the representation $\varpi_\mathcal{O}$ is
irreducible if the dual pair \((G, G')\) is in the stable range with smaller member \(G'\). In this case, \(X \leftrightarrow \omega_\mathcal{O}\) essentially gives the Howe duality correspondence. See also [11].

It should be an important problem to specify the isotropy representations \(\omega_\mathcal{O}\) attached to (singular) unitary highest weight modules \(X\), for the remaining simple hermitian Lie algebras \(\mathfrak{g}\) with real forms \(\mathfrak{o}(p, 2)\), EIII and EVII. Toward this problem, an interesting investigation has been made by Kato and Ochiai [9, Section 5.2] for EVII case.

3. Utility of the dual \((S(\mathfrak{g}), K_\mathbb{C})\)-module

In this section, we do not assume that the associated variety \(\mathcal{V}(X)\) of \(X\) is irreducible. Let \(M = \text{gr} X\) be the graded \((S(\mathfrak{g}), K_\mathbb{C})\)-module attached to an irreducible \((\mathfrak{g}, K_\mathbb{C})\)-module \(X\) by (2.1) and (2.2). For any nilpotent element \(X \in \mathfrak{p}\), we can define \(m(X)\), \(\mathcal{W}(0) = M/m(X)M\) and \((S(\mathfrak{g}), K_\mathbb{C})\)-homomorphism \(T(0) : M \to \Gamma(\mathcal{W}(0))\), just as in Section 2. We are going to make a simple observation on the \(K_\mathbb{C}\)-finite dual \(M^*\) of \(M\) realized as a space of \(V^*_\mathcal{V}\)-valued polynomial functions on \(\mathfrak{p}\). This will be helpful to describe in Section 4 the isotropy representation \(\omega_\mathcal{O}\) for discrete series \(X\).

First, the tensor product \(S(\mathfrak{p}) \otimes V_\tau\) admits a natural structure of \((S(\mathfrak{g}), K_\mathbb{C})\)-module so that \(\mathfrak{f}\) annihilates the whole \(S(\mathfrak{p}) \otimes V_\tau\). Since \(M = S(\mathfrak{p})V_\tau\) with \(V_\tau = M_0\), there exists a unique surjective \((S(\mathfrak{g}), K_\mathbb{C})\)-homomorphism, say \(\pi\), from \(S(\mathfrak{p}) \otimes V_\tau\) to \(M\) such that \(\pi(1 \otimes v) = v\) for \(v \in V_\tau\). We write \(N\) for the kernel of \(\pi\). This is a graded \((S(\mathfrak{g}), K_\mathbb{C})\)-submodule of \(S(\mathfrak{p}) \otimes V_\tau\). On the other hand, we identify \((S(\mathfrak{p}) \otimes V_\tau^*)^*\) with the space of polynomial functions on \(\mathfrak{p}\) with values in \(V_\tau^* = \text{Hom}_\mathbb{C}(V_\tau, \mathbb{C})\). This space also becomes an \((S(\mathfrak{g}), K_\mathbb{C})\)-module on which \(\mathfrak{g}\) acts by directional differentiation through the quotient map \(\mathfrak{g} \to \mathfrak{g}/\mathfrak{f} \simeq \mathfrak{p}\). Note that the action of \(S(\mathfrak{g})\) on \((S(\mathfrak{p}) \otimes V_\tau^*)^*\) is locally finite.

Then, it is standard to verify that

\[
(S(\mathfrak{p}) \otimes V_\tau) \times (S(\mathfrak{p})^* \otimes V_\tau^*) \ni (D \otimes v, f) \mapsto (D \otimes v, f) \in \mathbb{C},
\]

\[
(D \otimes v, f) := ((T D \cdot f)(0), v)_{V_\tau^* \times V_\tau},
\]

(3.1)

gives a nondegenerate \((S(\mathfrak{g}), K_\mathbb{C})\)-invariant pairing, where \(T\) denotes the principal automorphism of \(S(\mathfrak{p})\) such that \(T Y = -Y\) for \(Y \in \mathfrak{p}\), and \((\cdot, \cdot)_{V_\tau^* \times V_\tau}\) is the dual pairing on \(V_\tau^* \times V_\tau\). Now, let \(M^*\) denote the \(K_\mathbb{C}\)-finite dual space of \(M\), viewed as an \((S(\mathfrak{g}), K_\mathbb{C})\)-module through the contragredient representation. We write \(N^\perp\) for the orthogonal of \(N\) in \((S(\mathfrak{p})^* \otimes V_\tau^*)^*\) with respect to \((\cdot, \cdot)\). Then, (3.1) yields a nondegenerate invariant pairing

\[
(\cdot, \cdot)_1 : M \times N^\perp \to \mathbb{C},
\]

(3.2)

which gives an isomorphism of \((S(\mathfrak{g}), K_\mathbb{C})\)-modules as

\[
M^* \simeq N^\perp \subset S(\mathfrak{p})^* \otimes V_\tau^*.
\]

(3.3)

For an integer \(n \geq 0\), we denote by \((N^\perp)_n\) the homogeneous component of \(N^\perp\) of degree \(n\): \((N^\perp)_n := N^\perp \cap (S^n(\mathfrak{p})^* \otimes V_\tau^*)\).

Noting that \(M = V_\tau + m(X)M\), we have a natural \(K_\mathbb{C}(X)\)-homomorphism

\[
V_\tau \to \mathcal{W}(0) = M/m(X)M \to 0.
\]

This induces an embedding \(\mathcal{W}(0)^* \hookrightarrow V_\tau^*\) by passing to the dual. In this way, we regard \(\mathcal{W}(0)^*\) as a \(K_\mathbb{C}(X)\)-submodule of \(V_\tau^*\).
For each integer \( n \geq 0 \), let \( \Psi_n \) be the \( K_C \)-submodule of \( S^n(p^*) \otimes V_r^* \) generated by the vectors \( X^n \otimes v^* \) (\( v^* \in W(0)^* \)):

\[
\Psi_n := \langle X^n \otimes v^* \mid v^* \in W(0)^* \rangle_{K_C}.
\]

Here the polynomial function \( X^n \otimes v^* \in S^n(p^*) \otimes V_r^* \) is defined by

\[
X^n \otimes v^* : p \ni Z \mapsto B(X,Z)^n v^* \in \mathbb{C}
\]

through the Killing form \( B \) of \( g \). We set

\[
\Psi := \bigoplus_{n=0}^{\infty} \Psi_n \subset S(p^*) \otimes V_r^*.
\]

Then, it is standard to verify the following

**Lemma 3.1.** (1) \( \Psi \) is an \((S(g), K_C)\)-submodule of \( S(p^*) \otimes V_r^* \) contained in \( N^\perp \).

(2) We write \( \perp \Psi \) for the orthogonal of \( \Psi \) in \( M \) with respect to the pairing \( \langle \cdot, \cdot \rangle_1 \) on \( M \times N^\perp \). Let \( T(0) : M \rightarrow \Gamma(W(0)) \) be the \((S(g), K_C)\)-homomorphism defined in Section 2.3. Then, one gets

\[
\ker T(0) \cap M_n = \perp \Psi \cap M_n \quad \text{for every integer } n \geq 0.
\]

In particular, \( \perp \Psi = \oplus_n \perp \Psi \cap M_n \) is contained in \( \ker T(0) \).

**Proof.** (1) It is easy to see that \( \Psi \) is \((S(g), K_C)\)-stable by noting that

\[
Y \cdot ((\text{Ad}(y)X)^n \otimes y \cdot v^*) = nB(\text{Ad}(y)X,Y)(\text{Ad}(y)X)^{n-1} \otimes y \cdot v^* \in \Psi_{n-1},
\]

for \( Y \in g, v^* \in W(0)^* \) and \( y \in K_C \). To prove \( \Psi \subset N^\perp \), let \( \varphi_{v^*} \) denote the linear form on \( S(p) \otimes V_r \), which is the pull back of \( v^* \in W(0)^* \) through the quotient map

\[
S(p) \otimes V_r \xrightarrow{\pi} M \rightarrow W(0) = M/m(X)M.
\]

Then \( \varphi_{v^*} \) is zero on the subspace \( m(X) \otimes V_r + N \subset S(p) \otimes V_r \).

If \( \tilde{m} = \sum_j Y_j^n \otimes v_j \) (\( Y_j \in p, v_j \in V_r \)) is a homogeneous element of \( N \) of degree \( n \), it follows that

\[
\langle \tilde{m}, X^n \otimes v^* \rangle = \sum_j n!B(X,Y_j)^n(v_j, v^*)_{V_r \times V_r} = n!\varphi_{v^*}(\tilde{m}) = 0,
\]

by noting that \( Y_j^n - B(X,Y_j)^n \in m(X) \). Hence one gets \( (\text{Ad}(y)X)^n \otimes y \cdot v^* \in y \cdot N^\perp = N^\perp \) for all \( v^* \in W(0)^* \), \( y \in K_C \) and \( n \geq 0 \). Thus we obtain (1).

(2) Let \( m = \sum_j Y_j^n \cdot v_j \) be an element of \( M_n \) with \( Y_j \in p \) and \( v_j \in V_r \). Just in the proof of (1), we see that \( m \in \perp \Psi \) if and only if

\[
0 = \langle m, (\text{Ad}(y)X)^n \otimes y \cdot v^* \rangle = \sum_j n!B(Y_j, \text{Ad}(y)X)^n(y^{-1} \cdot v_j, v^*)_{V_r \times V_r} = n!\langle T(0)m(y), v^* \rangle_{W(0)^*}
\]

for all \( v^* \in W(0)^* \) and \( y \in K_C \). This means \( m \in \ker T(0) \). \( \square \)

Now, let \( \mathcal{O} = \text{Ad}(K_C)X \) be the nilpotent \( K_C \)-orbit through \( X \). We write \( I \) for the ideal defining the Zariski closure \( \overline{\mathcal{O}} \) of \( O \), and let \( \{ D_i \mid i = 1, \ldots, r \} \) be a finite set of homogeneous elements of \( S(p) \) which generates the ideal \( I \). We set \( n(i) := \deg D_i \).

**Proposition 3.2.** Assume that \( \Psi_{n(i)} = (N^\perp)^{n(i)} \) for \( i = 1, \ldots, r \). Then we get \( I \subset \text{Ann}_{S(g)}M \). In this case, the multiplicity of \( M \) at \( I \) equals \( \dim W(0) \) by Lemma 2.1.
\textbf{Proof.} We see for every $v \in V_\tau$ that
\[ T(0)D_i v(y) = (D_i \cdot T(0)v)(y) = D_i(\text{Ad}(y)X)T(0)v(y) = 0 \quad (y \in K_\mathbb{C}), \]
since $D_i \in I$ and $\text{Ad}(y)X \in \mathcal{O}$. It then follows that $D_i v = 0$ by Lemma 3.1 (2) together with the assumption $\Psi_{n(i)} = (N^\perp)^{n(i)}$, which is equivalent to $\psi \cap M_{n(i)} = \{0\}$. Hence, $D_i$ annihilates $V_\tau$ and so the whole $M = S(p)V_\tau$. This shows the assertion. \hfill \Box

In particular, if the associated variety $\mathcal{V}(X)$ is irreducible, i.e., $\mathcal{V}(X) = \overline{\mathcal{O}}$, as in previous sections, the conclusion of the above proposition turns to be
\begin{equation}
I = \text{Ann}_{S(\mathfrak{g})} M, \quad \text{and} \quad \mathcal{W} = \mathcal{W}(0).
\end{equation}
In this case, the dual $K_\mathbb{C}(X)$-module $\mathcal{W}^* = \mathcal{W}(0)^*$ can be specified by means of the principal symbol of a differential operator on $\mathfrak{p}$ of gradient-type (see [24, Theorem 4.1]). Moreover, the $(S(\mathfrak{g}), K_\mathbb{C})$-module $\Psi$ is almost equal to $N^\perp \simeq M^*$, because the support of $\psi \subset \text{Ker} T(0)$ is contained in $\partial \mathcal{O}$ by Proposition 2.5.

\section*{4. ISOTROPY REPRESENTATION ATTACHED TO DISCRETE SERIES}

In this section, we assume that $\mathfrak{g} = \mathfrak{k} \oplus \mathfrak{p}$ is an equi-rank algebra (cf. [12]), i.e., $\text{rank} \mathfrak{g} = \text{rank} \mathfrak{k}$, and we study the isotropy representations attached to irreducible $(\mathfrak{g}, K_\mathbb{C})$-modules of discrete series, by refining our discussion in [22].

\subsection*{4.1. Discrete series}

We begin with a quick review on the discrete series representations, and let us fix our notation. As is well known, the complex Lie algebra $\mathfrak{g}$ has a $\theta$-stable real form $\mathfrak{g}_0$ such that
\[ \mathfrak{g}_0 = \mathfrak{k}_0 \oplus \mathfrak{p}_0 \quad \text{with} \quad \mathfrak{k}_0 := \mathfrak{k} \cap \mathfrak{g}_0, \quad \mathfrak{p}_0 := \mathfrak{p} \cap \mathfrak{g}_0, \]
gives a Cartan decomposition of $\mathfrak{g}_0$. Such a real form $\mathfrak{g}_0$ is unique up to $K_\mathbb{C}$-conjugacy. Take a maximal abelian subalgebra $\mathfrak{t}_0$ of $\mathfrak{k}_0$, and we write $\mathfrak{t}$ for the complexification of $\mathfrak{t}_0$ in $\mathfrak{k}$. Since $\mathfrak{g}$ is an equi-rank algebra, $\mathfrak{t}$ turns to be a Cartan subalgebra of $\mathfrak{g}$. We write $\Delta$ for the root system of $(\mathfrak{g}, \mathfrak{t})$. The subset of compact (resp. noncompact) roots will be denoted by $\Delta_c$ (resp. $\Delta_n$).

Let $G$ be a connected Lie group with Lie algebra of $\mathfrak{g}_0$ such that $K_\mathbb{C}$ is the complexification of a maximal compact subgroup $K$ of $G$. An irreducible unitary representation $\sigma$ of $G$ is called a member of discrete series if the matrix coefficients of $\sigma$ are square-integrable on $G$. We are concerned with the irreducible $(\mathfrak{g}, K_\mathbb{C})$-modules $X$ of discrete series, consisting of $K$-finite vectors for such $\sigma$'s. For example, we refer to [7], [13], and also [19, I, Section 1] for the parametrization and realization of discrete series representations.

Now, let $X = X_\Lambda$ be the $(\mathfrak{g}, K_\mathbb{C})$-module of discrete series with Harish-Chandra parameter $\Lambda \in \mathfrak{t}^*$. Since the parameter $\Lambda$ is regular and real on $\sqrt{-1}\mathfrak{t}_0$, there exists a unique positive system $\Delta^+$ of $\Delta$ for which $\Lambda$ is dominant:
\begin{equation}
\Delta^+ := \{ \alpha \in \Delta \mid (\Lambda, \alpha) > 0 \}. \tag{4.1}
\end{equation}
We denote by $(\tau, V_\tau)$ the unique lowest $K_\mathbb{C}$-type of $X$ which occurs in $X$ with multiplicity one. Set $\Delta^+_c := \Delta^+ \cap \Delta_c$ (resp. $\Delta^+_n := \Delta^+ \cap \Delta_n$). The $\Delta^+_c$-dominant highest weight $\lambda$ (say) for $\tau$ is called the Blattner parameter of $X$. Then, $\lambda$ is expressed as $\lambda = \Lambda - \rho_c + \rho_n$ with $\rho_c := (1/2) \cdot \sum_{\alpha \in \Delta^+_c} \alpha$ and $\rho_n := (1/2) \cdot \sum_{\beta \in \Delta^+_n} \beta$. 

4.2. Results of Hotta-Parthasarathy. In what follows, we assume that the Blattner parameter $\lambda$ of $X$ is far from the walls (defined by compact roots) in the sense of [19, I, Definition 1.7]. Let $M = \text{gr } X = \bigoplus_{n \geq 0} M_n$ be the graded $(S(\mathfrak{g}), K_C)$-module defined through the lowest $K_C$-type $V_\tau$. As in Section 3, we have a natural quotient map $\pi : S(p) \otimes V_\tau \to N = \text{Ker } \pi$. This subsection explains the structure of graded modules $M$, $N$, and $M^* \simeq N^\perp$ by interpreting the results of Hotta-Parthasarathy [7].

For this, we first decompose the tensor product $p \otimes V_\tau$ as

$$p \otimes V_\tau = V_\tau^+ \oplus V_\tau^- \quad \text{as } K_C\text{-modules},$$

where $V_\tau^\pm$ denotes the sum of irreducible $K_C$-submodules of $p \otimes V_\tau$ with highest weights $\lambda \pm \beta$ ($\beta \in \Delta_+^\ast$), respectively. The inclusion $V_\tau^- \hookrightarrow p \otimes V_\tau$ naturally induces a quotient map of $K_C$-modules:

$$(4.2) \quad P : p^* \otimes V_\tau^* = (p \otimes V_\tau)^* \to (V_\tau^-)^*.$$

Hereafter, we replace $p^*$ by $p$ through the identification $p = p^*$ by the Killing form $B_{p \times p}$.

Let $B_c$ be the Borel subgroup of $K_C$ with Lie algebra $b_c = t \oplus \sum_{\alpha \in \Delta^-} \mathfrak{g}_\alpha$, where $\mathfrak{g}_\alpha$ is the root subspace of $\mathfrak{g}$ corresponding to a root $\alpha$. We set

$$(4.3) \quad p_{\pm} := \bigoplus_{\beta \in \Delta_+^\pm} \mathfrak{g}_{\pm \beta}.$$

Then, we have $p = p_+ \oplus p_-$ as vector spaces, and $p_-$ is stable under the action of $B_c$.

If $U$ is a holomorphic $B_c$-module, the $i$-th cohomology space $H^i(K_C/B_c; U)$ of $K_C/B_c$ with coefficients in the sheaf of holomorphic sections of the vector bundle $K_C \times_{B_c} U$ has a structure of $K_C$-module.

The following theorem can be read off from the proof of [7, Theorem 1], by taking into account the Blattner multiplicity formula [8] for discrete series. (See also [13]; [22].)

**Theorem 4.1** (Hotta-Parthasarathy). (1) One has $N = S(p)V_\tau^-.$

(2) The orthogonal $N^\perp$ of $N$ in $S(p) \otimes V_\tau^*$ coincides with the kernel of the differential operator $D$ on $p$ of gradient-type defined as follows:

$$(4.4) \quad (Df)(Z) := P \left( \sum_{\ell} X_\ell \otimes (X_\ell \cdot f)(Z) \right) \quad (f \in S(p) \otimes V_\tau^*, \ Z \in p).$$

Here $\{X_\ell\}_\ell$ is an orthonormal basis of $p_0$ with respect to the Killing form.

(3) For every integer $n \geq 0$, the dual $M^*_n$ of $M_n$ is isomorphic to the cohomology space:

$$H^s(K_C/B_c; S^n(p_-) \otimes C_{-\lambda - 2\rho_c}) \quad \text{with } s := \dim K_C/B_c,$$

as a $K_C$-module. Here $C_{-\lambda - 2\rho_c}$ denotes the one dimensional $B_c$-module corresponding to $-\lambda - 2\rho_c \in \mathfrak{t}^\ast$.

**Remark 4.2.** The operator $D$ in the above theorem gives the “polynomialization” of an invariant differential operator of gradient-type (on the Riemannian symmetric space for $(\mathfrak{g}_0, \mathfrak{k}_0)$) whose kernel realizes the maximal globalization of dual $(\mathfrak{g}, K_C)$-module $X^*$ of discrete series.
4.3. Description of associated cycle. For a positive number $c$, we say that a linear form $\mu$ on $t$ satisfies the condition (FFW($c$)) if

$$(\mu, \alpha) \geq c \quad \text{for all} \quad \alpha \in \Delta^+_t.$$ 

Theorem 4.1 coupled with the Borel-Weil Bott theorem for the group $K_C$ leads us to the following proposition, which is crucial to describe the associated cycle of $X$.

**Proposition 4.3** (cf. [22, Section 6.1]). (1) Let $v^*_\lambda$ be a nonzero lowest weight vector of $V^*_\tau$ of weight $-\lambda$. Then, $N^\perp = \ker D$ contains the $K_C$-submodule $\langle S(p_-) \otimes v^*_\lambda \rangle_{K_C}$ generated by $S(p_-) \otimes v^*_\lambda$.

(2) For any integer $n \geq 0$, there exists a positive constant $c_n$ such that

$$N^\perp_n = \langle S^n(p_-) \otimes v^*_\lambda \rangle_{K_C}$$

holds if the Blattner parameter $\lambda$ satisfies the condition (FFW($c_n$)).

Now, let $O$ be the unique nilpotent $K_C$-orbit in $p$ which intersects $p_-$ densely. Then one sees that $\overline{O} = \text{Ad}(K_C)p_-$. As before, we write $I$ for the prime ideal of $S(t)$ defining $\overline{O}$. It follows from the the claim (1) in Proposition 4.3 that $\text{Ann}_{S(t)}M \subset I$, i.e., $\mathcal{V}(X) \supset \overline{O}$. Also, the same claim shows $p_- \otimes v^*_\lambda \in \ker P$, which can be easily verified by noting that $-\lambda - \beta (\beta \in \Delta^+_t)$ cannot be a weight of $(V^*_\tau)^*$. 

Take an element $X \in O \cap p_-$. By virtue of our discussion in [24, Section 3], we find that the $K_C(X)$-module $W(0)^* = (M/m(X)M)^* \subset V^*_\tau$ consists exactly of all the vectors $v^* \in V^*_\tau$ satisfying $P(X \otimes v^*) = 0$. Let $N_{K_C}(X, p_-)$ be the totality of elements $k \in K_C$ such that $\text{Ad}(k)X \in p_-$ (cf. [3]). For any subset $R$ of $N_{K_C}(X, p_-)$, we denote by $\mathcal{U}_\lambda(R)$ the $K_C(X)$-submodule of $V^*_\tau$ generated by $R^{-1} \cdot v^*_\lambda$:

$$\mathcal{U}_\lambda(R) := \langle R^{-1} \cdot v^*_\lambda \rangle_{K_C(X)}.$$ 

Then, we readily find from $p_- \otimes v^*_\lambda \in \ker P$ that

$$\mathcal{U}_\lambda(R) \subset W(0)^*,$$

and so $\langle X^n \otimes \mathcal{U}_\lambda(R) \rangle_{K_C} \subset \Psi_n \subset (N^\perp)_n$, for every $n \geq 0$. Moreover one gets the equality

$$\langle X^n \otimes \mathcal{U}_\lambda(R) \rangle_{K_C} = \langle S^n(p_-) \otimes v^*_\lambda \rangle_{K_C},$$

if $\text{Ad}(R)X \subset p_-$ is Zariski dense in $p_-$. This is true when $R$ equals the whole $N_{K_C}(X, p_-)$, because $\text{Ad}(N_{K_C}(X, p_-))X = O \cap p_-$ is dense in $p_-$. 

As in Section 3, we take homogeneous generators $D_i (i = 1, \ldots, r)$ of the ideal $I$ such that $\text{deg} D_i = n(i)$. We set $c(I) := \max_i (c_{n(i)})$. By virtue of Proposition 3.2 together with (4.5), (4.6) and (4.7), we come to the following conclusion.

**Theorem 4.4.** Assume that the Blattner parameter $\lambda$ of discrete series $X$ is far from the walls and that it satisfies the condition (FFW($c(I)$)).

(1) One gets $I = \text{Ann}_{S(t)}M$ and so $\mathcal{V}(X) = \text{Ad}(K_C)p_- = \overline{O}$. Moreover, the $K_C(X)$-module $W^*$ contragredient to the isotropy representation $(\varpi_O, W)$ is described as

$$W^* = W(0)^* = \{v^* \in V^*_\tau \mid P(X \otimes v^*) = 0\},$$

where $X \in O \cap p_-$, and $P : p \otimes V^*_\tau \to (V^*_\tau)^*$ is the $K_C$-homomorphism in (4.2).
(2) Let $R$ be a subset of $N_{K_{C}}(X, p_{-})$ such that $\text{Ad}(R)X$ is Zariski dense in $p_{-}$. Then, the $K_{C}(X)$-submodule $\mathcal{U}_{\lambda}(R) = \langle R^{-1} \cdot v_{\lambda}^{*} \rangle_{K_{C}(X)} \subset \mathcal{W}^{*}$ is exhaustive in the following sense: for every integer $n \geq 0$, one has

\begin{equation}
\langle X^{n} \otimes \mathcal{W}^{*} \rangle_{K_{C}} = \langle X^{n} \otimes \mathcal{U}_{\lambda}(R) \rangle_{K_{C}}
\end{equation}

if $\lambda$ satisfies $\text{FFW}(c_{n})$.

Remark 4.5. (1) The assertions $I = \text{Ann}_{g}(\theta)M$ and $\mathcal{V}(X) = \text{Ad}(K_{C})p_{-} = \overline{\Theta}$ have been obtained in [22]. But, in that paper, we did not discuss the possibility of applying the results to describe the isotropy representation.

(2) One should get a result similar to Theorem 4.4, more generally for the derived functor modules $\mathcal{A}_{q}(\lambda)$.

(3) Compare Theorem 4.4 (1) with Chang’s result [3, Proposition 1.4] established by means of the localization theory of Harish-Chandra modules.

4.4. Submodule $\mathcal{U}_{\lambda}(Q_{c})$. In this subsection, we give a natural choice of $R \subset N_{K_{C}}(X, p_{-})$ for which we expect to have the property (4.9). Let $\Pi$ be the set of simple roots in $\Delta^{+}$. We write $S = \Pi \cap \Delta_{c}$ for the totality of compact simple roots. Then, there exists a unique element $H_{S} \in \mathfrak{t}$ such that

$$\alpha(H_{S}) = \begin{cases} 0 & \text{if } \alpha \in S, \\ 1 & \text{if } \alpha \in \Pi \setminus S. \end{cases}$$

The adjoint action of $H_{S}$ yields a gradation on the Lie algebra $\mathfrak{g}$ as

$$\mathfrak{g} = \bigoplus_{j} \mathfrak{g}(j) \quad \text{with} \quad \mathfrak{g}(j) := \{Z \in \mathfrak{g} | (\text{ad} H_{S})Z = jZ\}.$$  

Here $j$ runs through the integers such that $|j| \leq \delta(H_{S})$ with the highest root $\delta$. Note that

$$\mathfrak{k} = \bigoplus_{j \text{ even}} \mathfrak{g}(j), \quad \mathfrak{p} = \bigoplus_{j \text{ odd}} \mathfrak{g}(j) \quad \text{with} \quad \mathfrak{p}_{\pm} = \bigoplus_{j > 0, \pm \text{ even}} \mathfrak{g}(\pm j).$$

Now, we set

$$\mathfrak{q} := \bigoplus_{j \leq 0} \mathfrak{g}(j), \quad \mathfrak{l} := \mathfrak{g}(0) \subset \mathfrak{k} \quad \text{and} \quad \mathfrak{u} := \bigoplus_{j < 0} \mathfrak{g}(j).$$

Then, $\mathfrak{q} = \mathfrak{l} \oplus \mathfrak{u}$ gives the Levi decomposition of the standard parabolic subalgebra $\mathfrak{q}$ of $\mathfrak{g}$ associated with the subset $S$ of $\Pi$. We write $Q$ (resp. $Q_{c}$) for the parabolic subgroup of $G_{C} := G_{C}^{\text{ad}}$ (resp. of $K_{C}$) with Lie algebra $\mathfrak{q}$ (resp. $\mathfrak{q} \cap \mathfrak{k}$). The group $Q$ (resp. $Q_{c}$) admits the Levi decomposition $Q = LU$ (resp. $Q_{c} = L_{C}U_{c}$), where $L$ and $U$ (resp. $L_{C}$ and $U_{c}$) are the connected subgroups of $Q$ (resp. $Q_{c}$) with Lie algebras $\mathfrak{l}$ and $\mathfrak{u}$ (resp. $\mathfrak{l}$ and $\mathfrak{u} \cap \mathfrak{k}$) respectively. Note that $\text{Ad}(L_{C}) = L$. The parabolic subgroup $Q$ acts on its nilradical $\mathfrak{u}$, and so $Q_{c}$ acts on $\mathfrak{p}_{-} = \mathfrak{p} \cap \mathfrak{u}$ by the adjoint action. Thus, $Q_{c}$ is contained in $N_{K_{C}}(X, p_{-})$ for all $X \in p_{-}$, and the corresponding $K_{C}(X)$-submodule $\mathcal{U}_{\lambda}(Q_{c})$ of $\mathcal{V}^{*}$ turns to be

\begin{equation}
\mathcal{U}_{\lambda}(Q_{c}) = \langle (V_{\lambda}^{*})^{\ast} \rangle_{K_{C}(X)}.\end{equation}

Here, $(V_{\lambda}^{*})^{\ast} = U(\mathfrak{l})v_{\lambda}^{*}$ denotes the irreducible $L_{C}$-submodule of $V_{\tau}^{*}$ generated by the lowest weight vector $v_{\lambda}^{*}$.

We can now apply Theorem 4.4 to deduce
Corollary 4.6. Under the assumption in Theorem 4.4, the $K_C(X)$-submodule $U_X(Q_c)$ of $W^*$ is exhaustive in the sense of (4.9), if $p_-$ is a prehomogeneous vector space under the adjoint action of the group $Q_c$, and if $X \in \mathcal{O} \cap p_-$ lies in the open $Q_c$-orbit in $p_-$. 

4.5. Relation to the Richardson orbit. We end this article by looking at the condition for $p_-$ in Corollary 4.6, and also some related conditions, in relation to the Richardson $G_C$-orbit associated with the parabolic subalgebra $q$.

First, let us recall some basic facts on the Richardson orbit (cf. [6, Chapter 5]). The $G_C$-stable subset $G_C \cdot u \subset g$ forms an irreducible affine variety of $g$ whose dimension is equal to $2 \dim u$. Noting that $G_C \cdot u$ consists of nilpotent elements only, there exists a unique $G_C$-orbit $\bar{O}$ such that

$$\bar{O} = G_C \cdot u,$$

by the finiteness of the number of nilpotent $G_C$-orbits in $g$. $\bar{O}$ is called the Richardson $G_C$-orbit associated with $q$. The parabolic subgroup $Q$ acts on $u$ prehomogeneously, and $\bar{O} \cap u$ turns to be a single $Q$-orbit in $u$. Moreover, the centralizer in $g$ of any element $X \in \bar{O} \cap u$ is contained in $q$.

Now, we have two nilpotent $G_C$-orbits $G_C \cdot \mathcal{O}$ and $\bar{O}$ with the closure relation $G_C \cdot \mathcal{O} \subset \bar{O}$. By virtue of a result of Kostant-Rallis [10, Proposition 5], this relation implies that

$$\dim \mathcal{O} = \frac{1}{2} \dim G_C \cdot \mathcal{O} \leq \frac{1}{2} \dim \bar{O} = \dim u. \quad (4.11)$$

In particular, we find that the Gelfand-Kirillov dimension $\dim \mathcal{V}(X) = \dim \mathcal{O}$ of discrete series $X$ cannot exceed $\dim u$. The following proposition tells us when these two orbits turn to be equal.

Proposition 4.7. The following three conditions (a), (b) and (c) on the positive system $\Delta^+ = \{ \alpha | (\Lambda, \alpha) > 0 \}$ are equivalent with each other:

(a) $G_C \cdot \mathcal{O} = \bar{O}$, \hspace{1cm} (b) $\dim \mathcal{O} = \dim u$, \hspace{1cm} (c) $\bar{O} \cap p_- \neq \emptyset$.

In this case, $\mathcal{O} \cap p_-$ is a single open $Q_c$-orbit in $p_-$, and so one gets the conclusion of Corollary 4.6.

Proof. The equivalence (a) $\Leftrightarrow$ (b) is a direct consequence of (4.11). The condition (a) immediately implies (c), since $\mathcal{O} \subset G_C \cdot \mathcal{O} = \bar{O}$ contains an element of $p_-$. Conversely, if $\bar{O} \cap p_- \neq \emptyset$, this is a nonempty open subset of $p_-$, since $\bar{O} \cap p_- = (\bar{O} \cap u) \cap p_-$ with $\bar{O} \cap u$ open in $u$. Hence, $\bar{O} \cap p_-$ intersects $\mathcal{O}$. We thus get (c) $\Rightarrow$ (a). This proves the equivalence of three conditions in question.

Next, we assume the condition (b) $\Leftrightarrow$ (a) $\Leftrightarrow$ (c), and let $X$ be any element of $\mathcal{O} \cap p_-$. We write $\mathfrak{z}_g(X)$ for the centralizer of $X$ in a Lie subalgebra $s$ of $g$. By noting that $\mathfrak{z}_g(X) \subset q$, the dimension of the $Q_c$-orbit $\text{Ad}(Q_c)X$ is calculated as

$$\dim \text{Ad}(Q_c)X = \dim q \cap \mathfrak{t} - \dim \mathfrak{z}_{g \cap \mathfrak{t}}(X) = (\dim \mathfrak{t} - \dim u \cap \mathfrak{t}) - \dim \mathfrak{z}_s(X) \leq \dim \mathcal{O} - \dim u \cap \mathfrak{t} = \dim u - \dim u \cap \mathfrak{t} = \dim p_-,$$

where we used the condition (b) for the forth equality. This shows that the orbit $\text{Ad}(Q_c)X$ is open in $p_-$ for every $X \in \mathcal{O} \cap p_-$. We thus find that $\mathcal{O} \cap p_-$ forms a single $Q_c$-orbit, because of the uniqueness of the open $Q_c$-orbit in $p_-$. \hfill \square
Remark 4.8. Each of the conditions (a), (b) and (c) in Proposition 4.7 is equivalent to Assumption 2.5 in [2] concerning the generically finiteness of the moment map defined on the conormal bundle $T_{Z_1}(G_C/Q)$, where $Z_1$ is a closed $K_C$-orbit in $G_C/Q$ through the origin $eQ$.

Suggested by Corollary 4.6 and Proposition 4.7, let us consider the following three conditions on the positive system $\Delta^+$:

(C1) $\mathcal{O} \cap p_- \neq \emptyset$ ($\Leftrightarrow$ dim $\mathcal{O} =$ dim $u$ $\Leftrightarrow$ $G_C \cdot \mathcal{O} = \mathcal{O}$, by Proposition 4.7),

(C2) $\mathcal{O} \cap p_-$ is a single $Q_C$-orbit,

(C3) $p_-$ is a prehomogeneous vector space under the adjoint action of $Q_C$.

Proposition 4.7 says (C1) $\Rightarrow$ (C2), and the implication (C2) $\Rightarrow$ (C3) is obvious.

As for the conditions (C2) and (C3), we can show the following

Proposition 4.9. One gets (C3) if $\mathcal{O} \cap g(-1) \neq \emptyset$. Moreover, the equality $\text{Ad}(Q_c)(\mathcal{O} \cap g(-1)) = \mathcal{O} \cap p_-$ assures (C2).

Proof. Let $X \in \mathcal{O} \cap g(-1)$. Since $\mathcal{O} = \text{Ad}(K_C)X$ contains a nonempty open subset of $p_-$, we find that $[\mathfrak{t}, X] \supset p_-$. We set $\mathfrak{k}_+ := \oplus_{j>0}g(2j)$. Then $\mathfrak{t} = \mathfrak{k} \oplus \mathfrak{q} \oplus \mathfrak{k}_+$ is a direct sum of vector spaces. Then it follows from the assumption $X \in g(-1)$ that $[\mathfrak{k}_+, X] \subset p_+$ and $[\mathfrak{k} \cap q, X] \subset p_-$. We thus obtain

$$p_- = [\mathfrak{k}, X] \cap p_- = [\mathfrak{k} \cap q, X].$$

Hence $\text{Ad}(Q_c)X$ is open in $p_-$, and one gets (C3).

The above argument shows that any element $X \in \mathcal{O} \cap p_-$ lies in the unique open $Q_C$-orbit in $p_-$. This proves the latter claim, too.□

Following Gross-Wallach [4], we say that a discrete series $(g, K_C)$-module $X$ is small if $\delta(H_S) \leq 2$, or equivalently, $g(j) = \{0\}$ if $|j| \geq 3$. Here $\delta$ is the highest root of $\Delta^+$ as before. In this case, one has $p_- = g(-1)$, and so the above proposition implies

Corollary 4.10. The positive system $\Delta^+$ corresponding to a small discrete series admits the property (C2).

Remark 4.11. By case-by-case analysis, Chang [3] proved the property (C2) for any discrete series representations of simple Lie groups of $\mathbb{R}$-rank one.

We can give an explicit, combinatorial algorithm to find out whether or not a given $\Delta^+$ satisfies the condition (C1), for the case of arbitrary discrete series of $SU(p, q)$. We will discuss it elsewhere.

References


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