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Dual Pairs and Kostant–Sekiguchi Correspondence. II. Classification of nilpotent elements

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Abstract: We classify the homogeneous nilpotent orbits in certain Lie color algebras and specialize the results to the setting of a real reductive dual pair.
For any member of a dual pair, we prove the bijectivity of the two Kostant–Sekiguchi maps by straightforward argument. For a dual pair we determine the correspondence of the real orbits, the correspondence of the complex orbits and explain how these two relations behave under the Kostant–Sekiguchi maps. In particular we prove that for a dual pair in the stable range there is a Kostant–Sekiguchi map such that the conjecture formulated in [6] holds. We also show that the conjecture cannot be true in general.

Keywords: Dual pairs, nilpotent orbits, Lie color algebras, Kostant-Sekiguchi correspondence
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1 Introduction

Let G be a real reductive group with a maximal compact subgroup K and corresponding Cartan decomposition $\mathfrak{g} = \mathfrak{k} \oplus \mathfrak{p}$ of the Lie algebra $\mathfrak{g}$ of G. As is well known, see [21], understanding the structure of the nilpotent G-orbits in $\mathfrak{g}$ is essential in the search for a complete description of the unitary dual of G. Due to a theorem of Kostant and

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Sekiguchi, [19], these (real) orbits are in one to one correspondence with the (complex) nilpotent $K_{\mathbb{C}}$-orbits in $\mathfrak{p}_{\mathbb{C}}$, which are amenable to the tools of the complex algebraic geometry. Furthermore, by the works of Barbasch-Vogan, Howe and Rossmann, Schmid and Vilonen, culminating in [20], the wave front of an irreducible admissible representation of G coincides with the associate variety of the corresponding Harish-Chandra module, by the Kostant-Sekiguchi correspondence of the orbits.

Let G_0 and G_1 be an irreducible real reductive dual pair acting on a symplectic vector space W (see [10, 11]). For readers convenience we recall that these are pairs (G_0, G_1) of type I

$$\begin{aligned}
&(Sp_{2n}(\mathbb{R}), O(p,q)), \quad (O(p,q), Sp_{2n}(\mathbb{R})),\\
&(Sp_{2n}(\mathbb{C}), O(p)), \quad (O(p), Sp_{2n}(\mathbb{C})),\\
&(U_{p,q}, U_{r,s}),\\
&(Sp_{p,q}, O^*_{2n}), \quad (O^*_{2n}, Sp_{p,q}),
\end{aligned}$$

and pairs of type II

$$(GL_m(\mathbb{D}), GL_n(\mathbb{D})), \ (\mathbb{D} = \mathbb{R}, \mathbb{C}, \text{ or } \mathbb{H}).$$

Let $K_0 \subseteq G_0$, $K_1 \subseteq G_1$ be maximal compact subgroups with the complexifications $K_{0,\mathbb{C}}$, $K_{1,\mathbb{C}}$. The groups K_0, K_1 centralize a positive definite, compatible complex structure J on W. Let $W^+_{\mathbb{C}}$ denote an i-eigenspace of J in $W_{\mathbb{C}}$, the complexification of W. Let $\mathfrak{g}_0$, $\mathfrak{g}_1$ denote the Lie algebras of G_0 and G_1, with the Cartan decompositions $\mathfrak{g}_0 = \mathfrak{k}_0 \oplus \mathfrak{p}_0$, $\mathfrak{g}_1 = \mathfrak{k}_1 \oplus \mathfrak{p}_1$. Let $\nu_0 : W \to \mathfrak{g}_0$, $\nu_1 : W \to \mathfrak{g}_1$ be the moment maps, as defined in [11] (see also [6] and [7]), and let $\mu_0 : W_{\mathbb{C}} \to \mathfrak{g}_{0,\mathbb{C}}$, $\mu_1 : W_{\mathbb{C}} \to \mathfrak{g}_{1,\mathbb{C}}$ be the analogous moment maps of the complexifications. Then $\mu_0(W^+_{\mathbb{C}}) \subseteq \mathfrak{p}_{0,\mathbb{C}}$, $\mu_1(W^+_{\mathbb{C}}) \subseteq \mathfrak{p}_{1,\mathbb{C}}$, and we have the following pair of diagrams

$$\begin{array}{ccccc}
\mathfrak{g}_0 & \xleftarrow{\nu_0} & W & \xrightarrow{\nu_1} & \mathfrak{g}_1 \\
\mathfrak{p}_{0,\mathbb{C}} & \xleftarrow{\mu_0} & W^+_{\mathbb{C}} & \xrightarrow{\mu_1} & \mathfrak{p}_{1,\mathbb{C}}
\end{array} \tag{1}$$

We call an element $w \in W$ nilpotent if $\nu_0(w)$ is nilpotent in $\mathfrak{g}_0$ (equivalently if $\nu_1(w)$ is nilpotent in $\mathfrak{g}_1$). Similarly we define nilpotent elements in $W_{\mathbb{C}}$ as elements mapped by either of μ_0, μ_1 onto nilpotent elements of the complexified Lie algebras.

Howe's correspondence provides a convenient tool for a construction of irreducible representations of classical groups with small wave front set. In fact the wave front set of a representation of the larger group may be estimated, and in some cases computed, in terms of the wave front set of the corresponding representation of the smaller one via the moment maps (1), (see [17]). Also, in some cases the associate varieties of the corresponding Harish-Chandra modules have been computed in [13]. Furthermore, as explained in [17], a pair of representations in Howe's correspondence, is determined by a temperate distribution, which lives on W. This distribution has its own wave front set, a union of nilpotent orbits, under the action of both members of the dual pair. We attempt to look for an analog of the Kostant-Sekiguchi Theorem for the (real) orbits in W and the (complex) orbits in $W^+_{\mathbb{C}}$. As the reader will see below, there is no direct analog, but there is some hope of finding a geometric link of the Kostant-Sekiguchi correspondences for the two groups, through W and $W^+_{\mathbb{C}}$.

In this paper we provide a description of the set of the nilpotent $G_0 \times G_1$-orbits in W and the set of the nilpotent $K_{0,\mathbb{C}} \times K_{1,\mathbb{C}}$-orbits in $W^+_{\mathbb{C}}$.

Both classification problems, as well as similar problems such as the problem of classifying nilpotent orbits in $\mathfrak{g}_0$,$\mathfrak{g}_1$ and in $\mathfrak{p}_{0,\mathbb{C}}$,$\mathfrak{p}_{1,\mathbb{C}}$ arise as special instances of a more general problem of classifying homogeneous nilpotent orbits in certain Lie color algebras. We solve this problem in Section 3 using the methods of Burgoyne and Cushman by checking that the ideas of [2] carry over to the situation we consider. In the context of Lie algebras of reductive groups the standard approach to the classification of nilpotent orbits uses the Jacobson-Morozov theorem and the representation theory of $\mathfrak{sl}_2$. We are not aware, however, of any analogue of the Jacobson-Morozov theorem for the Lie algebras studied in this paper. A reader interested in the history of the problem of classification of nilpotent orbits in classical Lie algebras may consult the introduction to [2] and the book [4]. In particular in [4], one can find a traditional, diagrammatic presentation of classification results, used also by Ohta in [15], [16] in his study of nilpotent orbits for classical symmetric pairs. We use a different approach, which seems more natural for our purposes.

In Section 4 we show how one can apply the general results of Section 3 to the classification problems described above in the case of a dual pair of type II, and in Section 5 we do the same for pairs of type I.

There are two bijections, $\mathcal{S}$ and $\bar{\mathcal{S}}$ (sometimes $\mathcal{S} \neq \bar{\mathcal{S}}$, see Proposition 6.6), referred to as Kostant-Sekiguchi correspondences, from the set of nilpotent G_0-orbits in $\mathfrak{g}_0$ onto the set of nilpotent $K_{0,\mathbb{C}}$-orbits in $\mathfrak{p}_{0,\mathbb{C}}$, and similarly for G_1 ([19]). In Section 6 we compute both maps, $\mathcal{S}$ and $\bar{\mathcal{S}}$, in terms of our parametrization of orbits in $\mathfrak{g}$ and in $\mathfrak{p}_{\mathbb{C}}$ for dual pairs of type I. As a main tool we use the description of the Cayley transform of a Cayley triple in $\mathfrak{g}$ by the conjugation by a special element of the complex group.

In [6], the following conjecture was stated.

Conjecture 1.1. Let $\mathcal{O} \subseteq \mathfrak{g}_1$ be a nilpotent orbit. Then

$$\mathcal{S}(\nu_0\nu_1^{-1}(\overline{\mathcal{O}})) = \mu_0\mu_1^{-1}(\overline{\mathcal{S}(\mathcal{O})}). \tag{2}$$

We provide a counterexample in Section 7 which proves that this conjecture is false, as stated. In some cases however, for instance for pairs in the stable range (see Section 8) the conjecture holds for an appropriate choice of the Kostant-Sekiguchi map. The determination of all orbits $\mathcal{O}$ for which the equality (2) holds might be of interest, but is beyond the scope of this paper.

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2 Sesqui-linear Forms

Let $\mathbb{D} = \mathbb{R}, \mathbb{C}$ or $\mathbb{H}$ (the quaternions), and let ι be a possibly trivial anti-involution on $\mathbb{D}$. (Notice that for a commutative field, an anti-involution is the same as an involution.) Let V be a left vector space over $\mathbb{D}$.

A sesqui-linear form on V is a map $\tau : V \times V \to \mathbb{D}$ such that for all $u, v, u', v' \in V$ and for all $a \in \mathbb{D}$,

$$\begin{aligned}&\tau(au, v) = a\tau(u, v), \quad \tau(u, av) = \tau(u, v)\iota(a)\\ &\tau(u + u', v) = \tau(u, v) + \tau(u', v), \quad \tau(u, v + v') = \tau(u, v) + \tau(u, v').\end{aligned}$$

For $\sigma = \pm 1$, we will say that the form τ is σ-hermitian if

$$\tau(u, v) = \sigma\iota(\tau(v, u))$$

for all $u, v \in V$.

We shall say that two subspaces $V', V'' \subseteq V$ are orthogonal (with respect to τ) if $\tau(v', v'') = 0$ for all $v' \in V'$ and all $v'' \in V''$. In this case we shall write $V' \perp V''$.

We shall say that the space V, or more precisely, the pair (V, τ) is decomposable if there are two non-zero subspaces $V', V'' \subseteq V$ such that $V = V' \oplus V''$ and $V' \perp V''$. Otherwise the space V, or the pair (V, τ) is called indecomposable. The form τ is called non-degenerate if the following two implications hold:

$$\begin{gathered}\text{if } \tau(u, v) = 0 \text{ for all } v \in V, \text{ then } u = 0, \text{ and}\\ \text{if } \tau(u, v) = 0 \text{ for all } u \in V, \text{ then } v = 0.\end{gathered}$$

Every σ-hermitian non-degenerate formed space (V, τ) is a direct sum of mutually orthogonal indecomposable spaces. Classification of indecomposable σ-hermitian forms is well known. We collect them in Table 1.

If $\mathbb{D} = \mathbb{R}$ or ι is nontrivial we define the signature of a form as follows. If the form τ is degenerate, then by the signature of τ, $\mathrm{sgn}(\tau)$, we mean the signature of the quotient form of τ on $V/\mathrm{Rad}(\tau)$. Suppose τ is nondegenerate. The signature of τ, $\mathrm{sgn}(\tau)$, is a pair of two nonnegative integers $\mathrm{sgn}(\tau) = (n_+, n_-)$ defined as follows. If the form is hermitian then n_+ (resp. n_-) is the dimension of any maximal subspace of V on which the restriction of τ is positive (resp. negative) definite. If $\mathbb{D} = \mathbb{C}$ and τ is skew-hermitian, then the form $-i\tau$ is hermitian and by definition $\mathrm{sgn}(\tau) = \mathrm{sgn}(-i\tau)$. If $\mathbb{D} = \mathbb{R}$ or $\mathbb{H}$ and τ is skew-hermitian, then $n_+ = n_- = \frac{1}{2}\dim_{\mathbb{D}}(V)$.

Fix a positive integer n and let

$$V = V_0 \oplus V_1 \oplus .. \oplus V_{n-1} \tag{3}$$

be a direct sum of left $\mathbb{D}$-vector spaces V_0, V_1, ..., V_{n-1}. We view V as a $\mathbb{Z}/n\mathbb{Z}$-graded vector space, via the above decomposition, where $\mathbb{Z}/n\mathbb{Z}$ is realized as the set $\{0, 1, 2, ..., n-$

$(\mathbb{D},\iota)$	$\sigma=1$	$\sigma=-1$
$(\mathbb{R},\ id)$	$(\mathbb{R},+)\ (x,y)\mapsto xy$ $(\mathbb{R},-)\ (x,y)\mapsto -xy$	$(\mathbb{R}^2,\ sk)\ (x,y)\mapsto x\begin{bmatrix}0&1\\-1&0\end{bmatrix}y^t$
$(\mathbb{C},\ id)$	$(\mathbb{C},\ sym)\ (x,y)\mapsto xy$	$(\mathbb{C}^2,\ sk)\ (x,y)\mapsto x\begin{bmatrix}0&1\\-1&0\end{bmatrix}y^t$
$(\mathbb{C},\bar{\cdot})$	$(\mathbb{C},+)\ (x,y)\mapsto x\bar{y}$ $(\mathbb{C},-)\ (x,y)\mapsto -x\bar{y}$	$(\mathbb{C},\ +i)\ (x,y)\mapsto xi\bar{y}$ $(\mathbb{C},\ -i)\ (x,y)\mapsto -xi\bar{y}$
$(\mathbb{H},\bar{\cdot})$	$(\mathbb{H},+)\ (x,y)\mapsto x\bar{y}$ $(\mathbb{H},-)\ (x,y)\mapsto -x\bar{y}$	$(\mathbb{H},\ sk)\ (x,y)\mapsto xj\bar{y}$

Table 1 The list of indecomposable σ-hermitian forms.

$1\}$ with addition modulo n. The subspace $V_a \subseteq V$ is called the subspace of degree a $(=0,1,2,...,n-1)$. The dimension vector of V is the sequence

$$\underline{\dim}(V)=(dim_{\mathbb{D}}(V_0),dim_{\mathbb{D}}(V_1),\ldots,dim_{\mathbb{D}}(V_{n-1})).$$

We shall say that the space V, or more precisely, the pair (V,τ) is decomposable if there are two non-zero graded subspaces $V',V''\subseteq V$ such that $V=V'\oplus V''$ and $V'\perp V''$. Otherwise the space V, or the pair (V,τ) is called indecomposable.

In this paper, we will consider sesquilinear forms τ on V for which there exists an involution $*$ of $\mathbb{Z}/n\mathbb{Z}$ and a function $\mathbb{Z}/n\mathbb{Z}\ni b\mapsto\sigma_b\in\{\pm1\}$ such that $\sigma_b=\sigma_{b^*}$ for every $b\in\mathbb{Z}/n\mathbb{Z}$ and the following conditions are satisfied.
(1) $V_b\perp V_c$ unless $c=b^*$.
(2) For every $b=0,1,2,...,n-1$, the form τ provides a non-degenerate pairing between V_b and V_{b^*},
(3) The form τ restricted to V_b if $b=b^*$, or to $V_b\oplus V_{b^*}$ if $b\neq b^*$, is σ_b-hermitian.

Two graded formed spaces (V,τ) and (V',τ') are called isometric if there is a $\mathbb{D}$-linear bijection $g:V\to V'$ such that

$$\tau(V_a)\subseteq V'_a \qquad (a=0,1,2,...,n-1),$$
$$\tau(u,v)=\tau'(gu,gv) \qquad (u,v\in V).$$

In that case we shall write $(V,\tau)\approx(V',\tau')$ and say that the map g is a graded isometry.

Lemma 2.1. Every graded formed space (V,τ) satisfying (1)-(3) above is isometric to an orthogonal direct sum of indecomposable graded formed spaces. Every indecomposable graded formed space either is concentrated in one degree b with $b=b^*$and coincides with one of the spaces listed in Table 1, or is equal to the sum $V_b\oplus V_{b^*}$ with $b\neq b^*$ where $\dim_{\mathbb{D}}(V_b)=\dim_{\mathbb{D}}(V_{b^*})=1$ and in a suitable basis the form τ is given by the matrix $\begin{bmatrix}0&1\\\sigma_b&0\end{bmatrix}$.

The following lemma is an easy consequence of the classification of (non-graded) σ-hermitian forms.

Lemma 2.2. Let $*$ be an involution of $\mathbb{Z}/n\mathbb{Z}$ and let (V, τ) and (V', τ') be two $\mathbb{Z}/n\mathbb{Z}$-graded formed spaces satisfying conditions (1)-(3) above. Then $(V, \tau) \approx (V', \tau')$ if and only if the following two conditions hold.
(1) $\underline{\dim}(V) = \underline{\dim}(V')$.
(2) $\operatorname{sgn}(\tau|_{V_b}) = \operatorname{sgn}(\tau'|_{V'_b})$ for every b such that $b = b^*$.

3 Classification of homogeneous nilpotent elements in certain Lie color algebras

Let n be an even positive integer and let

$$V = V_0 \oplus V_1 \oplus \cdots \oplus V_{n-1}$$

be a $\mathbb{Z}/n\mathbb{Z}$-graded left vector space over $\mathbb{D}$. For $a \in \mathbb{Z}/n\mathbb{Z}$ let

$$\operatorname{End}(V)_a = \{X \in \operatorname{End}(V);\ X(V_b) \subseteq V_{a+b} \text{ for } b \in \mathbb{Z}/n\mathbb{Z}\ \}.$$

Define a bilinear bracket

$$[-,-] : \operatorname{End}(V) \times \operatorname{End}(V) \to \operatorname{End}(V)$$

by the formula

$$[X, Y] = XY - (-1)^{ab} YX, \text{ for } X \in \operatorname{End}(V)_a,\ Y \in \operatorname{End}(V)_b. \tag{4}$$

Then $\operatorname{End}(V)$ becomes a Lie color algebra with respect to the symmetric bicharacter $\beta(a, b) = (-1)^{ab}$ on the group $\mathbb{Z}/n\mathbb{Z}$ (see [1]).

Fix $a \in \mathbb{Z}/n\mathbb{Z}$ and let $N \in \operatorname{End}(V)_a$ be nilpotent. Recall that the height of N, or the height of (N, V), is the integer $m \geq 0$ such that $N^m \neq 0$ and $N^{m+1} = 0$. We shall write $m = ht(N) = ht(N, V)$. The pair (N, V) of height m is called uniform if $Ker(N^m) = NV$.

Lemma 3.1. Suppose the pair (N, V) is uniform of height m. Then for any graded subspace $E \subseteq V$ complementary to $Ker(N^m)$,

$$V = E \oplus NE \oplus N^2E \oplus ... \oplus N^mE.$$

Moreover, $dim(E) = dim(NE) = ... = dim(N^mE)$.

Proof. By the choice of E, we have $V = E \oplus NV$. Hence, $NV \subseteq NE + N^2V$. Thus $V \subseteq E + NE + N^2V$. But $N^2V \subseteq N^2E + N^3V$. Hence, inductively,

$$V \subseteq E + NE + N^2E + ... + N^mE.$$

If for some $i_0 < i_1 < \ldots < i_k$ the intersection $N^{i_0}E \cap (N^{i_1}E + \ldots + N^{i_k}E)$ were nonzero, then $N^{i_0}e_0 = N^{i_1}e_1 + \ldots + N^{i_k}e_k$ for some $e_j \in E$, with $N^{i_0}e_0 \neq 0$, but then

$N^m e_0 = N^m(e_0 - N^{i_1-i_0}e_1 - \ldots - N^{i_k-i_1}e_k) = 0$, hence $e_0 = 0$ by the injectivity of N^m on E. Thus

$$V = E \oplus NE \oplus N^2E \oplus ... \oplus N^mE.$$

It remains to show the equality of dimensions. Suppose $v \in E$, $0 \leq i \leq m-1$ and $NN^iv = 0$. Then $N^mv = 0$. Hence $v = 0$, and therefore $N^iv = 0$. Thus the linear map

$$N^iE \ni u \mapsto Nu \in N^{i+1}E$$

is injective. Since this map is obviously surjective, we are done. □

It is clear that if E is a graded subspace satisfying the conditions of Lemma 3.1 then we can reconstruct the dimension vector of V from the dimension vector of E, since $\underline{\dim}(NE)$ is obtained from $\underline{\dim}(E)$ by a shift in grading by a. More precisely, we can identify dimension vectors with functions on $\mathbb{Z}/n\mathbb{Z}$ and let η be the left regular representation of $\mathbb{Z}/n\mathbb{Z}$ i.e.

$$(\eta_b f)(c) = f(c-b) \quad (b, c \in \mathbb{Z}/n\mathbb{Z}). \tag{5}$$

Then

$$\underline{\dim}(V) = (1 + \eta_a + \eta_a^2 + \ldots + \eta_a^m)\underline{\dim}(E). \tag{6}$$

3.1 A general linear Lie color algebra

The group $GL(V)_0 = GL(V) \cap \mathrm{End}(V)_0$ acts by conjugation on nilpotent elements in $\mathrm{End}(V)_a$ for every $a \in \mathbb{Z}/n\mathbb{Z}$. In this subsection we will classify the nilpotent orbits of this action. The result can also be found in [12]. We include the proof for completeness and to introduce some notation used in the following sections.

Lemma 3.2. Let $N, N' \in \mathrm{End}(V)_a$ be nilpotent. Assume that the pairs (N,V), (N',V) are uniform of height m. Then the elements N, N' are in the same $GL(V)_0$-orbit if and only if $\underline{\dim}(V/Ker(N^m)) = \underline{\dim}(V/Ker(N'^m))$.

Proof. There is only one non-trivial implication which requires proof. Suppose $dim(V/Ker(N^m))_a = dim(V/Ker(N'^m))_a$ for all $a = 0, 1, 2, ..., n-1$. According to Lemma 3.1 we have decompositions

$$V = E \oplus NE \oplus N^2E \oplus ... \oplus N^mE,$$
$$V = E' \oplus N'E' \oplus N'^2E' \oplus ... \oplus N'^mE'.$$

Since by our assumption $dim(E_a) = dim(E'_a)$ for all a, there is a graded linear isomorphism $g : E \to E'$. We extend g to a graded linear isomorphism $g : V \to V$ by

$$gN^iv = N'^igv \qquad (v \in E;\ i = 0, 1, 2..., m).$$

Clearly $gNg^{-1} = N'$. □

Lemma 3.3. If the pair (N, V) is uniform of height m, then there exist graded N-invariant subspaces $V^j \subseteq V$ such that

$$V = V^1 \oplus V^2 \oplus ...,$$

where each pair (N, V^j) is uniform, and $dim(V^j/Ker(N|_{V^j})^m) = 1$ for each j.

Proof. This is clear from Lemma 3.1 via a decomposition of E into one dimensional subspaces. $\square$

Lemma 3.4. Let (N, V) be a pair of height m. Let $U \subseteq V$ be a graded subspace such that
(a) U is N-invariant,
(b) (N, U) is uniform of height m.
Then there is a graded N-invariant subspace $U' \subseteq V$ such that
(c) $V = U \oplus U'$.

Proof. We proceed by induction on m. If $m = 0$ then $N = 0$ and (c) is obvious. Suppose that $m \geq 1$. We know from Lemma 3.1 that there is a graded subspace E such that

$$U = E \oplus NE \oplus N^2E \oplus ... \oplus N^mE.$$

Hence, $U \cap Ker(N^m) = NE \oplus N^2E \oplus ... \oplus N^mE = NU$. This space is N-invariant. The pair $(N, U \cap Ker(N^m))$ is uniform of height $m - 1$. Moreover,

$$\begin{aligned} &U \cap Ker(N^m) \cap Ker(N|_{Ker(N^m)})^{m-1} = U \cap Ker(N^m) \cap Ker(N^{m-1}) \\ &= U \cap Ker(N^{m-1}) = N^2E \oplus N^3E \oplus ... \oplus N^mE \neq U \cap Ker(N^m). \end{aligned}$$

Hence, $U \cap Ker(N^m) \nsubseteq Ker(N|_{Ker(N^m)})^{m-1}$. Thus the pair of spaces $U \cap Ker(N^m) \subseteq Ker(N^m)$ satisfy conditions (a) and (b), but the height of $(N, Ker(N^m))$ is $m - 1$. Therefore, by induction, there exists a graded N-invariant subspace $U' \subseteq Ker(N^m)$ such that

$$Ker(N^m) = U \cap Ker(N^m) \oplus U'.$$

Hence,

$$U + Ker(N^m) = U \oplus U'. \tag{7}$$

If $V = U + Ker(N^m)$, we are done. Otherwise, choose a graded subspace $F \subseteq V$ such that $V = F \oplus (U + Ker(N^m))$. Let

$$W = F + NF + N^2F + ... + N^mF.$$

Then W is N-invariant and $ht(N, W) = m$. We claim that

$$U \cap W = 0. \tag{8}$$

Indeed, if this is not the case then there exist $e \in E \setminus \{0\}$ and $u \in N^{i+1}U$ for some i, $0 \leq i \leq m$, such that $N^ie + u \in W$. Hence $N^me \in W$. Since $NN^me = 0$, there exists $f \in F$

such that $N^m e = N^m f$. Hence, $f \in U + Ker(N^m)$ and therefore $f \in F \cap (U + Ker(N^m))$. But this last space is zero. Thus $0 = f = N^m f = N^m e = e$, a contradiction. Therefore (8) holds. If $V = U \oplus W$, we are done. Otherwise, notice that $V = (U \oplus W) + Ker(N^m)$. Moreover, the pair of spaces $U \oplus W \subset V$ satisfy conditions (a) and (b). Hence, by (7), $V = U \oplus (W \oplus U')$. □

Lemma 3.5. If the pair (N, V) is indecomposable, then it is uniform.

Proof. In order to avoid trivialities we assume $N \neq 0$ and $V \neq 0$. Let E be a graded subspace of V such that $V = E \oplus Ker(N^m)$, where $m = ht(N, V)$. Let $U = E \oplus NE \oplus N^2E \oplus ... \oplus N^m E$. It is easy to see that the subspace $U \subseteq V$ satisfies conditions (a) and (b) of Lemma 3.4. Hence, there is an N-invariant graded subspace $U' \subseteq V$ such that $V = U \oplus U'$. Since (N, V) is indecomposable, $U' = 0$. Thus $(N, V) = (N, U)$ is uniform. □

Corollary 3.6. If $V \neq 0$ and if the pair (N, V) is indecomposable, then it is uniform and $dim(V/Ker(N^m)) = 1$, where $m = ht(N, V)$.

Theorem 3.7. Let $N \in \mathrm{End}(V)_a$ be nilpotent. Then there exist graded N-invariant subspaces $V^j \subseteq V$ such that
(a) $V = V^1 \oplus V^2 \oplus \cdots \oplus V^s$,
(b) each (N, V^j) is indecomposable,
(c) $ht(N, V^1) \geq ht(N, V^2) \geq ....$
The decomposition (a) having the properties (b) and (c) is unique up to the action of $GL(V)_0^N$, the centralizer of N in $GL(V)_0$. Thus the above decomposition determines the $GL(V)_0$-orbit of N in $\mathrm{End}(V)_a$.

Proof. Let $E \subseteq V$ be a graded subspace complementary to the kernel of N^m, where m is the height of (N, V). Set $U = E \oplus NE \oplus N^2E \oplus ... \oplus N^m E$. Then the pair (N, U) is uniform. If $V = U$, the theorem follows from Lemmas 3.2 and 3.3. Otherwise, notice that the spaces $U \subseteq V$ satisfy the conditions (a), (b) of Lemma 3.4. Moreover, $V = U \oplus Ker(N^m)$. Hence, as in (7), there exists a graded N-invariant subspace $U' \subseteq Ker(N^m)$ such that $V = U \oplus U'$. In particular $ht(N, U') < ht(N, V)$. So we may proceed inductively. □

For $b \in \mathbb{Z}/n\mathbb{Z}$, let $\mathbb{D}[b]$ denote $\mathbb{Z}/n\mathbb{Z}$-graded space which is concentrated in homogeneous degree b and isomorphic to $\mathbb{D}$ as a non-graded space. If (N, V) is indecomposable with N of degree a and height m then

$$\begin{aligned} V &= \mathbb{D}[b] \oplus N\mathbb{D}[b] \oplus \cdots \oplus N^m\mathbb{D}[b] \\ &= \mathbb{D}[b] \oplus \mathbb{D}[b+a] \oplus \cdots \oplus \mathbb{D}[b+ma] \end{aligned}$$

for some $b \in \mathbb{Z}/n\mathbb{Z}$.

Corollary 3.8. Nilpotent orbits of the group $GL(V)_0$ in $\mathrm{End}(V)_a$ are parametrized by

sequences of pairs $(b_1, m_1), \ldots, (b_s, m_s)$ such that
(1) $m_1 \geq m_2 \geq \cdots \geq m_s \geq 0, \quad m_j \in \mathbb{N}, \quad b_j \in \{0, 1, \ldots, n-1\}$;
(2) $\underline{\dim}(V) = \sum_{j=1}^{s}(1 + \eta_a + \eta_a^2 + \cdots + \eta_a^{m_j})\underline{\dim}(\mathbb{D}[b_j])$;
(3) if $m_j = m_{j+1}$ then $b_j \leq b_{j+1}$.

3.2 The Lie color algebra of a formed space

Here we consider hermitian analogues of the orthosymplectic Lie color algebras of [1]. For the remainder of this section fix $\sigma = \pm 1$.

Define a map $S \in \mathrm{End}(V)_0$ by

$$S(v) = (-1)^a v \qquad (v \in V_a;\ a \in \mathbb{Z}/n\mathbb{Z}), \tag{9}$$

and let τ be a non-degenerate sesqui-linear form on V such that

$$\tau(u, v) = \sigma\iota(\tau(v, Su)) \qquad (u, v \in V). \tag{10}$$

We assume that the form τ provides a non-degenerate pairing between V_b and V_{-b} for each $b \in \mathbb{Z}/n\mathbb{Z}$, and that $V_b \perp V_c$ if $b + c \neq 0$, so that the involution * of Section 2 is given by $b^* = -b$. Let

$$\mathfrak{g}(V, \tau)_a = \{X \in \mathrm{End}(V)_a;\ \tau(Xu, v) + \tau(S^a u, Xv) = 0,\ u, v \in V\}$$

and let

$$\mathfrak{g}(V, \tau) = \bigoplus_{a \in \mathbb{Z}/n\mathbb{Z}} \mathfrak{g}(V, \tau)_a.$$

Then $\mathfrak{g}(V, \tau)$ is closed under the bracket defined in (4) and it is a Lie color subalgebra of $\mathrm{End}(V)$.

Let $G(V, \tau)_0$ denote the isometry group

$$G(V, \tau)_0 = \{g \in \mathrm{End}(V)_0;\ \tau(gu, gv) = \tau(u, v),\ u, v \in V\}. \tag{11}$$

The goal of this subsection is to classify the orbits of the group $G(V, \tau)_0$ in the set of nilpotent elements in each homogeneous component $\mathfrak{g}(V, \tau)_a$ of the algebra $\mathfrak{g}(V, \tau)$.

The following lemma states several easy to check properties of homogeneous elements of $\mathfrak{g}(V, \tau)$.

Lemma 3.9. Let $X \in \mathfrak{g}(V, \tau)_a$. Then

$$\begin{aligned} SX &= (-1)^a XS, \\ \tau(u, Sv) &= \tau(Su, v), \\ \tau(Xu, v) &= -\tau(u, S^a Xv), \\ \tau(u, Xv) &= -\tau(XS^a u, v). \end{aligned} \tag{12}$$

Define

$$\delta(k) = (-1)^{k(k-1)/2}.$$

Then for $k, l \geq 0$

$$\begin{aligned}(SX)^k &= \delta(k)^a S^k X^k,\\ S^l X^k &= (-1)^{akl} X^k S^l,\\ \tau(X^k u, v) &= (-1)^k \delta(k)^a \tau(u, S^{ak} X^k v),\\ \tau(u, X^k v) &= (-1)^k \delta(k+1)^a \tau(S^{ak} X^k u, v).\end{aligned} \tag{13}$$

Suppose henceforth that $N \in \mathfrak{g}(V, \tau)_a$ be nilpotent.

Lemma 3.10. Let $m = ht(N, V)$. Then the formula

$$\tilde{\tau}(\tilde{u}, \tilde{v}) = \tau(u, N^m v) \quad (\tilde{u} = u + Ker(N^m),\ \tilde{v} = v + Ker(N^m);\ u, v \in V)$$

defines a non-degenerate sesqui-linear form on the $\mathbb{Z}/n\mathbb{Z}$-graded space $\tilde{V} = V/Ker(N^m)$ and

$$\tilde{\tau}(\tilde{u}, \tilde{v}) = (-1)^m \delta(m+1)^a \sigma\iota\tilde{\tau}(S^{ma+1}\tilde{v}, \tilde{u}), \tag{14}$$

$$\tilde{\tau}(S\tilde{u}, \tilde{v}) = (-1)^{ma} \tilde{\tau}(\tilde{u}, S\tilde{v}), \tag{15}$$

$$\tilde{V}_b \text{ and } \tilde{V}_c \text{ are } \tilde{\tau}\text{-orthogonal, unless } b + c + ma = 0. \tag{16}$$

Proof. The fact that the form is well defined and the statements (14), (15) and (16) follow easily from (10) and (13). We will show that the form $\tilde{\tau}$ is non-degenerate. Due to (15), it is enough to show that for every non-zero $\tilde{v} \in \tilde{V}$ there exists $\tilde{u} \in \tilde{V}$ such that $\tilde{\tau}(\tilde{u}, \tilde{v}) \neq 0$. Let $\tilde{v} = v + Ker(N^m)$. Then $N^m v \neq 0$ and there exists $u \in V$ such that $\tau(u, N^m v) \neq 0$ and for $\tilde{u} = u + Ker(N^m)$ we have $\tilde{\tau}(\tilde{u}, \tilde{v}) \neq 0$. □

Theorem 3.11. Let (N, V) be uniform of height m. Then there is a graded subspace $F \subseteq V$, complementary to $Ker(N^m)$, such that

$$V = F \oplus NF \oplus N^2 F \oplus \ldots \oplus N^m F \tag{a}$$

and

$$N^k F \perp N^l F \quad \text{for } k + l \neq m. \tag{b}$$

Remark 3.12. It is clear from (13) that (b) is equivalent to

$$F \perp N^k F \quad \text{for } 0 < k \leq m - 1. \tag{b$'$}$$

Proof of Theorem 3.11. We will define inductively a sequence

$$F^{(0)}, F^{(1)}, \ldots, F^{(m-1)}$$

of subspaces of V such that for all $k = 0, 1, \dots, m-1$ the following conditions hold:
(i) $F^{(k)}$ is graded and $V = F^{(k)} \oplus NF^{(k)} \oplus N^2F^{(k)} \oplus ... \oplus N^mF^{(k)}$,
(ii) $F^{(k)} \perp N^{m-k}F^{(k)} + N^{m-k+1}F^{(k)} + \dots + N^{m-1}F^{(k)}$.
Then $F = F^{(m-1)}$ satisfies the conditions of the theorem.

It follows from Lemma 3.1 that for $F^{(0)}$ we can take any graded subspace complementary to $Ker(N^m)$. Assume that $k > 0$ and that the space $F^{(k-1)}$ has already been constructed. Set $E = F^{(k-1)}$ and let $E^* = \mathrm{Hom}_{\mathbb{D}}(E, \mathbb{D})$. Define two maps

$$\hat{\tau}_0,\, \hat{\tau} : E \to E^*,$$
$$\hat{\tau}_0(v)(u) = \tau(u, N^m v), \qquad \hat{\tau}(v)(u) = \tau(u, N^{m-k}v), \qquad (u, v \in E).$$

We know from Lemma 3.10 that $\hat{\tau}_0$ is a bijection.

Notice that
$$\tau(u, N^m \hat{\tau}_0^{-1}\hat{\tau}(v)) = \tau(u, N^{m-k}v) \qquad (u, v \in E). \tag{17}$$
Indeed, the left hand side of (17) is equal to

$$\tau(u, N^m \tau_0^{-1}\hat{\tau}(v)) = \hat{\tau}_0\hat{\tau}_0^{-1}\hat{\tau}(v)(u) = \hat{\tau}(v)(u) = \tau(u, N^{m-k}v).$$

Let
$$\rho = \rho_k = \frac{1}{2}\hat{\tau}_0^{-1}\hat{\tau} \tag{18}$$
and define the space $F^{(k)}$ as $F^{(k)} = (1 - N^k\rho)F^{(k-1)}$.

First we will show that the space $F^{(k)}$ is graded. We see from (17) that for any $v \in E$, $N^k\hat{\tau}_0^{-1}\hat{\tau}(v)$ coincides with the unique element $x \in N^kE$ such that for all $u \in E$, $\tau(u, N^{m-k}(x - v)) = 0$. Hence, if $v \in E_b := E \cap V_b$, then $\tau(u, N^{m-k}x) = 0$ for all $u \in \sum_{c \neq -c_0} E_c$, where $c_0 = (m-k)a + b$. Thus,

$$\begin{aligned} N^{m-k}x \in (N^mE) \cap \left(\sum_{c \neq -c_0} E_c\right)^{\perp} &= (N^mE) \cap \bigcap_{c \neq -c_0} E_c^{\perp} \\ = \bigcap_{c \neq -c_0} (N^mE) \cap E_c^{\perp} &= \bigcap_{c \neq -c_0} (N^mE) \cap V_c^{\perp} = (N^mE) \cap V_{(m-k)a+b}. \end{aligned}$$

Let us write $x = x_b + x'$, where $x_b \in V_b \cap N^kE$ and $x' \in \sum_{c \neq b} V_c \cap N^kE$. Since $N^{m-k}x \in V_{(m-k)a+b}$, we have $N^{m-k}x = N^{m-k}x_b$. Therefore, by the uniqueness of x, $x' = 0$. Hence, $x \in V_b \cap N^kE$. Thus $N^k\rho(E_b) \subseteq V_b \cap N^kE$ for all $b \in \mathbb{Z}/n\mathbb{Z}$ and the space $F^{(k)} = (1 - N^k\rho)E$ is graded.

It follows from the construction that $dim(F^{(k)}) \leq dim(E)$ and $E \subset F^{(k)} + N^kE$. Since $N^{m+1}F^{(k)} = 0$, we have

$$V = E \oplus NE \oplus N^2E \oplus ... \oplus N^mE \subset F^{(k)} + NF^{(k)} + N^2F^{(k)} + \cdots + N^mF^{(k)},$$

so the sum on the right hand side is also a direct sum.

It remains to prove that $F^{(k)}$ satisfies the orthogonality property (ii). For $u, v \in E$

$$\tau((1 - N^k\rho)u, N^{m-k}(1 - N^k\rho)v) = \tau(u, N^{m-k}v) - \tau(u, N^m\rho v) - \tau(N^k\rho u, N^{m-k}v), \tag{19}$$

because $N^k N^m = 0$. Furthermore, by (17),

$$\tau(u, N^m \rho v) = \frac{1}{2}\tau(u, N^{m-k} v),$$

and by (10), (13) and (17)

$$\begin{aligned}
\tau(N^k \rho u, N^{m-k} v) &= \sigma\iota\, \tau(N^{m-k} v, SN^k \rho u)\\
&= (-1)^{m-k}\delta(m-k)^a \sigma\iota\, \tau(v, S^{(m-k)a} N^{m-k} SN^k \rho u)\\
&= (-1)^{(m-k)(a+1)}\delta(m-k)^a \sigma\iota\tau(S^{(m-k)a+1} v, N^m \rho u)\\
&= \tfrac{1}{2}(-1)^{(m-k)(a+1)}\delta(m-k)^a \sigma\iota\tau(S^{(m-k)a+1} v, N^{m-k} u)\\
&= \tfrac{1}{2}(-1)^{(m-k)(a+1)}\delta(m-k)^a \tau(N^{m-k} u, S^{(m-k)a} v)\\
&= \tfrac{1}{2}(-1)^{(m-k)a}\tau(u, S^{(m-k)a} N^{m-k} S^{(m-k)a} v)\\
&= \tfrac{1}{2}\tau(u, N^{m-k} v).
\end{aligned}$$

Hence (19) is equal to zero and $F^{(k)}$ is orthogonal to $N^{m-k}F^{(k)}$. Notice also that for $i > 0$

$$\begin{aligned}
&\tau((1-N^k\rho)u, N^{m-k+i}(1-N^k\rho)v)\\
&= \tau(u, N^{m-k+i} v) - \tau(u, N^{m+i}\rho v) - \tau(N^k \rho u, N^{m-k+i} v) = \tau(u, N^{m-k+i} v).
\end{aligned}$$

Hence $F^{(k)}$ is also orthogonal to $N^l F^{(k)}$, $(l = m-k+1, \ldots, m-1)$, due to condition (ii) for $F^{(k-1)}$. □

Corollary 3.13. Let the pairs (N, V), (N', V) be uniform of height m with N, N' homogeneous of the same degree. Then the elements N, N' are in the same $G(V,\tau)_0$-orbit if and only if the spaces $(V/Ker(N^m), \tilde{\tau})$, $(V/Ker(N'^m), \tilde{\tau})$ are isometric.

Proof. It is easy to check that if N, N' are conjugate by an element of $G(V,\tau)_0$ then the above two graded spaces are isometric.

Conversely, suppose these two spaces are isometric. Let $N, N' \in \mathfrak{g}(V,\tau)_a$ and let $F, F' \subseteq V$ be as in Theorem 3.11 for N, N' respectively. By assumption, we have a graded bijection $g : F \to F'$ such that

$$\tau(gu, N'^m gv) = \tau(u, N^m v) \qquad (u, v \in F).$$

Set

$$g(N^k v) = N'^k g(v) \qquad (v \in F;\ k = 0, 1, 2, ..., m-1).$$

Then $g \in \mathrm{End}(V)$ is bijective and intertwines N and N'. Furthermore, for $u, v \in F$ and for $k = 0, 1, 2, ..., m-1$ we have

$$\begin{aligned}\tau(gN^k u, gN^{m-k}v) &= \tau(N'^k gu, N'^{m-k}gv)\\ &= (-1)^k\delta(k)^a\tau(gu, S^{ak}N'^m gv)\\ &= (-1)^{k+akm}\delta(k)^a\tau(gu, N'^m gS^{ak}v)\\ &= (-1)^{k+akm}\delta(k)^a\tau(u, N^m S^{ak}v)\\ &= (-1)^{k+ak}\delta(k)^a\tau(u, N^k S^{ak}N^{m-k}v)\\ &= (-1)^{ak}\delta(k)^a\delta(k+1)^a\tau(S^{ak}N^k u, S^{ak}N^{m-k}v)\\ &= \tau(N^k u, N^{m-k}v).\end{aligned}$$

Hence, $g \in G(V, \tau)_0$. □

Definition 3.14. The pair (N, V) is called indecomposable if V does not have any non-trivial orthogonal N-invariant direct sum decomposition into graded subspaces. Otherwise the pair (N, V) is called decomposable.

Proposition 3.15. If the pair (N, V) is indecomposable then it is uniform.

Proof. Let $m = ht(N, V)$ and let $E \subseteq V$ be a graded subspace complementary to $Ker(N^m)$. Set $U = E + NE + N^2E + ... + N^mE$. Then U is a graded subspace of V preserved by N and it is easy to see that U is uniform. We will show that the restriction of the form τ to U is non-degenerate. Since, $U^\perp$ is N-invariant (by (12)) this will complete the proof.

Let $0 \leq k \leq i \leq m$ and let $u_i \in E$. Suppose

$$N^k u_k + N^{k+1}u_{k+1} + ... + N^m u_m \perp U.$$

Then $N^k u_k \perp N^{m-k}E$. Hence, by (13), $u_k \perp N^mE$. But $N^mE = N^mV$. Thus $u_k \perp N^mV$. Therefore $N^m u_k \perp V$. Hence, $u_k \in Ker(N^m) \cap E = \{0\}$. Similarly, $u_{k+1} = u_{k+2} = ... = u_m = 0$. □

Proposition 3.16. Let the pair (N, V) be uniform of height m. Then (N, V) is indecomposable if and only if the formed space $(V/Ker(N^m), \tilde{\tau})$ is indecomposable.

Proof. Clearly if (N, V) is decomposable then so is $(V/Ker(N^m), \tilde{\tau})$.

Conversely, suppose $(V/Ker(N^m), \tilde{\tau})$ is decomposable. Choose a subspace $F \subseteq V$ as in Theorem 3.11 and let

$$\tau_m(u, v) = \tau(u, N^m v) \quad (u, v \in F).$$

Then (F, τ_m) is isometric to $(V/Ker(N^m), \tilde{\tau})$, and hence is decomposable. Thus there exist two non-zero graded τ_m-orthogonal subspaces $F', F'' \subseteq F$ such that $F = F' \oplus F''$. Let $V' = F' + NF' + N^2F' + ... + N^mF'$ and let $V'' = F'' + NF'' + N^2F'' + ... + N^mF''$. Since the spaces F', F'' are τ_m-orthogonal, we have $F' \perp N^mF'$ and $F'' \perp N^mF''$, with respect to τ. Hence it is easy to see that $V = V' \oplus V''$ and $V' \perp V''$. □

It follows from Corollary 3.13 and Proposition 3.16 that in order to classify indecomposable nilpotent elements of height m in $\mathfrak{g}(V,\tau)_a$ up to the action of $G(V,\tau)_0$, we have to classify (up to grading-preserving isometry) indecomposable $\mathbb{Z}/n\mathbb{Z}$-graded formed spaces $(\tilde{V},\tilde{\tau})$.

Proposition 3.17. Let $(\tilde{V},\tilde{\tau})$ be an indecomposable $\mathbb{Z}/n\mathbb{Z}$-graded formed space. Let $a \in \mathbb{Z}/n\mathbb{Z}$ and let $m \in \mathbb{N}$. If $(\tilde{V},\tilde{\tau})$ satisfies (14), (15) and (16) then $dim(\tilde{V}) = 1$ or 2. Moreover one of the following two conditions holds.

(1) $\tilde{V} = \tilde{V}_b$ for some $b \in \mathbb{Z}/n\mathbb{Z}$ with $2b + ma = 0$ (which implies that ma is even) and $(\tilde{V}_b,\tilde{\tau})$ is nondegenerate indecomposable as a (nongraded) formed space.

(2) $\tilde{V} = \tilde{V}_b \oplus \tilde{V}_{-b-ma}$ for some $b \in \mathbb{Z}/n\mathbb{Z}$ with $2b+ma \neq 0$. In this case both summands are $\tilde{\tau}$-isotropic of dimension one and $\tilde{\tau}$ provides a pairing between them.

In both cases the form $\tilde{\tau}$ is $\tilde{\sigma}$-hermitian, where

$$\tilde{\sigma} = \tilde{\sigma}(a,b,m) = (-1)^m(-1)^{(ma+1)b}\delta(m+1)^a\sigma. \tag{20}$$

Any formed space as above will be called (a,m)-admissible.

Proof. Let

$$\tilde{V}_{even} = \tilde{V}_0 \oplus \tilde{V}_2 \oplus \ldots \oplus \tilde{V}_{n-2},$$
$$\tilde{V}_{odd} = \tilde{V}_1 \oplus \tilde{V}_3 \oplus \ldots \oplus \tilde{V}_{n-1}.$$

Assume first that $2|ma$. Then (15) is equivalent to the condition that $\tilde{V}_{even}$ and $\tilde{V}_{odd}$ are $\tilde{\tau}$-orthogonal. Indecomposability of $(\tilde{V},\tilde{\tau})$ forces $\tilde{V}_{even} = 0$ or $\tilde{V}_{odd} = 0$. Then condition (14) says that $\tilde{\tau}$ is $\tilde{\sigma}$-hermitian and once again from the indecomposability we see that we are in the case (1) or (2) of the proposition.

If $2 \nmid ma$ then (15) is equivalent to the condition that $\tilde{V}_{even}$ and $\tilde{V}_{odd}$ are $\tilde{\tau}$-isotropic. Indecomposability and conditions (14) and (16) guarantee that we are in case (2). □

Theorem 3.18. Let $N \in \mathfrak{g}(V,\tau)_a$ be a nilpotent. Then there exist a sequence

$$(F^{(1)}, F^{(2)}, \ldots, F^{(s)})$$

of graded subspaces of V and a sequence

$$m_1 \geq m_2 \geq \ldots \geq m_s \geq 0$$

of nonnegative integers such that

(1) for every $i = 1, 2, \ldots, s$, the space $F^{(i)}$ with the form $\tilde{\tau}_{(i)}$ given by the formula

$$\tilde{\tau}_{(i)}(u,v) = \tau(u, N^{m_i}v), \quad (u,v \in F^{(i)})$$

is an (a,m_i)-admissible space (as defined in Proposition 3.17);

(2) $V = \bigoplus_{i=1}^{s} F^{(i)} \oplus NF^{(i)} \oplus \cdots \oplus N^{m_i}F^{(i)}$.

Let $N' \in \mathfrak{g}(V,\tau)_a$ be another nilpotent element and let $(F'^{(1)}, F'^{(2)}, \dots, F'^{(s')})$ and $m'_1 \geq m'_2 \geq \dots \geq m'_{s'}$ be the sequences corresponding to N'. Then N and N' are $G(V,\tau)_0$-conjugate if and only if $s = s'$, $m_i = m'_i$ for every $i = 1, 2, \dots, s$ and, up to a permutation of indices i preserving the sequence $(m_i)_{i=1}^s$, the graded formed spaces $(F^{(i)}, \tilde{\tau}_{(i)})$ and $(F'^{(i)}, \tilde{\tau}'_{(i)})$ are isometric.

Proof. Let $E \subseteq V$ be a graded subspace complementary to $Ker(N^m)$, where $m = ht(N,V)$. Set $U = E + NE + N^2E + ... + N^mE$. As in the proof of Proposition 3.15 we verify that the restriction of τ to U is non-degenerate. Notice that

$$U^{\perp} \subseteq (N^mE)^{\perp} = (N^mV)^{\perp} = Ker(N^m).$$

Hence, $ht(N, U^{\perp}) < ht(N,V)$. After a finite number of steps we obtain

$$V = U^{(1)} \oplus U^{(2)} \oplus ... \oplus U^{(r)},$$

where the spaces $U^{(j)}$ are graded, N-invariant, mutually orthogonal, each pair $(N, U^{(j)})$ is uniform and

$$ht(N, U^{(1)}) > ht(N, U^{(2)}) > ... > ht(N, U^{(r)}).$$

Now we split each $(N, U^{(j)})$ into indecomposables and obtain

$$V = V^{(1)} \oplus V^{(2)} \oplus ... \oplus V^{(s)}.$$

Let $m_i = ht(N, V^{(i)})$ and let $F^{(i)}$ be a graded subspace of $V^{(i)}$ satisfying conditions of Theorem 3.11 for the restriction of N to $V^{(i)}$. Then the sequences $(F^{(1)}, F^{(2)}, \dots, F^{(s)})$ and $(m_1, m_2, \dots, m_s)$ satisfy conditions (1) and (2) of the theorem.

Consider a nilpotent element N' in the $G(V,\tau)_0$-orbit of N and assume that the sequences $(F'^{(1)}, F'^{(2)}, \dots, F'^{(s')})$ and $m'_1 \geq m'_2 \geq \dots \geq m'_{s'} \geq 0$ satisfy conditions (1) and (2). Then $m_1 = ht(V,N) = ht(V,N') = m'_1$. Denote this number by m and let

$$\ell = \max\{i : \ m_i = m\},$$
$$\ell' = \max\{i : \ m'_i = m\}.$$

Then the spaces

$$V/N^mV \approx F^{(1)} \oplus F^{(2)} \oplus \dots \oplus F^{(\ell)},$$
$$V/N'^mV \approx F'^{(1)} \oplus F'^{(2)} \oplus \dots \oplus F'^{(\ell')}$$

are isomorphic and the isomorphism becomes an isometry when we equip the spaces with the forms $\tilde{\tau}_{(1)} \oplus \tilde{\tau}_{(2)} \oplus \dots \oplus \tilde{\tau}_{(\ell)}$ and $\tilde{\tau}'_{(1)} \oplus \tilde{\tau}'_{(2)} \oplus \dots \oplus \tilde{\tau}'_{(\ell')}$, respectively. Hence $\ell = \ell'$ and, up to permutation of indices i, the formed spaces $(F^{(i)}, \tilde{\tau}_{(i)})$ and $(F'^{(i)}, \tilde{\tau}'_{(i)})$ are isometric for $i = 1, 2, \dots, \ell$. Now, the necessity of the condition follows by induction on the dimension of V.

It is clear from Corollary 3.13 that the above argument may be reversed. Hence the proof is complete. □

Corollary 3.19. Nilpotent orbits of the group $G(V,\tau)_0$ in $\mathfrak{g}(V,\tau)_a$ are parameterized by sequences

$$(F^{(i)}, \tilde{\tau}_{(i)}, m_i), \quad i = 1, \dots, s,$$

such that
(1) the space $(F^{(i)}, \tilde{\tau}_{(i)})$ is (a, m_i)-admissible for every $i = 1, 2, \dots, s$;
(2) $\underline{\dim}(V) = \sum_{i=1}^{s}(1 + \eta_a + \eta_a^2 + \cdots + \eta_a^{m_i})\underline{\dim}(F^{(i)})$;
(3) for $b = 0$ and for $b = n/2$,

$$\operatorname{sgn}(\tau|_{V_b}) = \sum_{i=1}^{s}\left(\sum_{\substack{k=0 \\ (m_i-2k)a\neq 0}}^{m_i} \dim F^{(i)}_{b-ka}\cdot(1,1) + \sum_{\substack{k=0 \\ (m_i-2k)a=0}}^{m_i} \operatorname{sgn}((-1)^{k+ka(b+1)}\tilde{\tau}_{(i)}|_{F^{(i)}_{b-ka}}) \right).$$

Two such sequences $(F^{(i)}, \tilde{\tau}_{(i)}, m_i)$, $i = 1, \dots, s$, and $(F'^{(i)}, \tilde{\tau}'_{(i)}, m'_i)$, $i = 1, \dots, s'$, determine the same orbit if and only if $s = s'$ and there exists a permutation π of the set $\{1, 2, \dots, s\}$ such that for $i = 1, 2, \dots, s$ the graded spaces $(F^{(i)}, \tilde{\tau}_{(i)})$ and $(F'^{(\pi i)}, \tilde{\tau}_{(\pi i)})$ are isometric and $m_i = m'_{\pi i}$.

Wherever convenient, we shall identify the orbit with the sequence (or with the formal direct sum) of triples $(F^{(i)}, \tilde{\tau}_{(i)}, m_i)$.

Proof. By Theorem 3.18, it remains to show that for every pair of sequences $(F^{(i)}, \tilde{\tau}_{(i)}, m_i)$, $i = 1, \dots, s$, satisfying conditions *1.–3.* of the corollary, there exists a corresponding nilpotent element $N \in \mathfrak{g}(V,\tau)_a$.

For an $a \in \mathbb{Z}/n\mathbb{Z}$ and a $\mathbb{Z}/n\mathbb{Z}$-graded vector space W, let $\eta_a W$ be a copy of W shifted in grading by a. For $i = 1, 2, \dots, s$, let

$$V'^{(i)} = F^{(i)} \oplus \eta_a F^{(i)} \oplus \eta_a^2 F^{(i)} \oplus \cdots \oplus \eta_a^{m_j} F^{(i)}$$

and

$$V' = V'^{(1)} \oplus V'^{(2)} \oplus \cdots \oplus V'^{(s)}.$$

We equip V' with a sesquilinear form τ' such that the spaces $V'^{(i)}$ are mutually orthogonal and for $u \in F^{(i)}$, $v \in F^{(i)}_b$

$$\tau'(\eta_a^k u, \eta_a^l v) = \begin{cases} (-1)^k(-1)^{ak(m_i+b)}\delta(k)^a\tilde{\tau}_{(i)}(u,v), & \text{if } k + l = m_i, \\ 0, & \text{otherwise.} \end{cases} \tag{21}$$

Then it follows from (13) that the formed spaces (V,τ) and (V',τ') are isometric. Defining a nilpotent endomorphism N' of V' by

$$N'(\eta_a^k u) = \begin{cases} \eta_a^{k+1}(u), & \text{for } k < m_i, \\ 0, & \text{for } k = m_i, \end{cases} \quad (u \in F^{(i)}), \tag{22}$$

we obtain the orbit corresponding to the sequence $(F^{(i)}, \tilde{\tau}_{(i)}, m_i)$, $i = 1, \dots, s$. □

4 Dual pairs of type II

Let $V = V_0 \oplus V_1$ be a $\mathbb{Z}/2\mathbb{Z}$-graded vector space over $\mathbb{D}$. The group $GL(V)_0 = GL(V) \cap \mathrm{End}(V)_0$ of degree zero linear automorphisms of V is isomorphic to the direct product $GL(V_0) \times GL(V_1)$. The results of section 3.1 give the classification of nilpotent orbits of $GL(V)_0$ in $\mathrm{End}(V)_0 = \mathrm{End}(V_0) \times \mathrm{End}(V_1)$, which reduces to the well known classification of nilpotent orbits of $GL(V_j)$ in $\mathrm{End}(V_j)$ via the Jordan normal form, and the classification of nilpotent orbits of $GL(V)_0$ in $\mathrm{End}(V)_1 = \mathrm{Hom}(V_0, V_1) \oplus \mathrm{Hom}(V_1, V_0)$, which is also well known (see [6], Section 2).

The formula

$$\begin{gathered} \langle (A,B),(A',B')\rangle = \mathrm{tr}_{\mathbb{D}/\mathbb{R}}(AB') - \mathrm{tr}_{\mathbb{D}/\mathbb{R}}(BA') \\ (A, A' \in \mathrm{Hom}(V_0,V_1), B, B' \in \mathrm{Hom}(V_1,V_0)) \end{gathered} \tag{23}$$

defines a non-degenerate symplectic form on the real vector space $W = \mathrm{Hom}(V_0, V_1) \oplus \mathrm{Hom}(V_1, V_0)$. The action of the group $GL(V_0) \times GL(V_1)$ on W preserves this form, hence the groups $GL(V_0)$, $GL(V_1)$ form a dual pair of type II in the symplectic group $Sp(W)$.

The maps

$$\mathrm{End}(V)_1 \ni N \to N^2|_{V_0} \in \mathrm{End}(V_0), \tag{24}$$
$$\mathrm{End}(V)_1 \ni N \to N^2|_{V_1} \in \mathrm{End}(V_1) \tag{25}$$

coincide with the moment maps

$$\nu_k : W \longrightarrow \mathrm{End}(V_k), \tag{26}$$
$$\mathrm{Hom}(V_0,V_1) \oplus \mathrm{Hom}(V_1,V_0) \ni (A,B) \to BA \in \mathrm{End}(V_0), \tag{27}$$
$$\mathrm{Hom}(V_0,V_1) \oplus \mathrm{Hom}(V_1,V_0) \ni (A,B) \to AB \in \mathrm{End}(V_1). \tag{28}$$

4.1 Nilpotent orbits in $\mathfrak{gl}_n(\mathbb{D})$

Theorem 3.7 and Corollary 3.8 give the following classification of nilpotent orbits of $GL(V)_0$ in $\mathrm{End}(V)_0 = \mathrm{End}(V_0) \times \mathrm{End}(V_1)$ in terms of the sizes of the blocks of the Jordan normal form of the restriction of a nilpotent endomorphism of V to V_k:

Corollary 4.1. The nilpotent orbits of the group $GL(V)_0$ in $\mathrm{End}(V)_0 = \mathrm{End}(V_0) \times \mathrm{End}(V_1)$ are parametrized by sequences of pairs $(b_1, m_1), \ldots, (b_s, m_s)$ such that
(1) $m_1 \geq m_2 \geq \cdots \geq m_s \geq 0,\ m_j \in \mathbb{N},\ b_j = 0, 1;$
(2) $\dim(V_k) = \sum_{b_j = k}(m_j + 1);$
(3) if $m_j = m_{j+1}$ then $b_j \leq b_{j+1};$
where for each $j = 1, \ldots, s$, $m_j + 1$ is the size of the appropriate block in V_{a_j}.

In particular, the nilpotent orbits of $GL(V_k)$ in $\mathrm{End}(V_k)$ are parametrized by sequences $m_1 \geq m_2 \geq \cdots \geq m_s > 0$ satisfying $\sum_j (m_j + 1) = \dim(V_k)$.

4.2 Nilpotent orbits in W

Theorem 3.7 and Corollary 3.8 give the classification of nilpotent orbits of the group $GL(V)_0 = GL(V_0) \times GL(V_1)$ in $W = \mathrm{End}(V)_1$ in terms of the parameters of the Jordan normal form. For an alternate description of the parametrization of orbits the reader may consult [6], Section 2. Let

$$d_k(b,m) = \left[\frac{m+1+\delta_{k,b}}{2}\right], \quad k = 0,1, \tag{29}$$

where $\delta_{k,b}$ is the Kronecker delta and $[x]$ is the largest integer less than or equal to x.

Corollary 4.2. The nilpotent orbits of the group $GL(V)_0$ in $W = \mathrm{End}(V)_1$ are parametrized by sequences of pairs $(b_1, m_1), \ldots, (b_s, m_s)$ such that
(1) $m_1 \geq m_2 \geq \cdots \geq m_s \geq 0,\ m_j \in \mathbb{N},\ b_j = 0,1;$
(2) $\dim(V_k) = \sum_j d_k(b_j, m_j);$
(3) if $m_j = m_{j+1}$ then $b_j \leq b_{j+1}$.

Now we describe the action of the moment maps (26) on nilpotent orbits in terms of the parameters introduced above.

Corollary 4.3. Let $\mathcal{O} \subseteq W$ be the nilpotent orbit which corresponds to the sequence $(b_1, m_1), \ldots, (b_s, m_s)$, then the image $\nu_k(\mathcal{O})$ is equal to the nilpotent orbit in $\mathrm{End}(V_k)$ corresponding to the sequence $(d_k(b_1, m_1), \ldots, d_k(b_s, m_s))$.

We end this section by giving an explicit description of all non-zero nilpotent indecomposable elements (N, V), $N \in \mathrm{End}(V)_1$.

Proposition 4.4. The following is a complete list of all non-zero nilpotent indecomposable elements (N, V), $N \in \mathrm{End}(V)_1$.

$$\begin{gathered} V = \bigoplus_{k=0}^{m} \mathbb{D}v_k,\ v_{even} \in V_0,\ v_{odd} \in V_1, \\ v_k = N^k v_0 \neq 0, 0 \leq k \leq m, Nv_m = 0. \end{gathered} \tag{a}$$

$$\begin{gathered} V = \bigoplus_{k=1}^{m+1} \mathbb{D}v_k,\ v_{even} \in V_0,\ v_{odd} \in V_1, \\ v_{k+1} = N^k v_1 \neq 0, 0 \leq k \leq m, Nv_{m+1} = 0. \end{gathered} \tag{b}$$

4.3 Nilpotent orbits in $\mathfrak{p}_{\mathbb{C}}$

Let $\mathfrak{gl}_n(\mathbb{D}) = \mathfrak{k} \oplus \mathfrak{p}$ be a Cartan decomposition of the general Lie algebra. The complexification $K_{\mathbb{C}}$ of the maximal compact subgroup $K \subseteq GL_n(\mathbb{D})$ acts on the complexification

$\mathfrak{p}_{\mathbb{C}}$ of $\mathfrak{p}$. For $\mathbb{D} = \mathbb{C}$ the action of $K_{\mathbb{C}}$ on $\mathfrak{p}_{\mathbb{C}}$ may be identified with the conjugation action of $GL_n(\mathbb{C})$ on $\mathfrak{gl}_n(\mathbb{C})$, so in this case the description of nilpotent orbits is as in Section 4.1. For $\mathbb{D} = \mathbb{R}, \mathbb{H}$ the classification of the nilpotent orbits is well known ([18]). Both in the case $\mathbb{D} = \mathbb{R}$ and in the case $\mathbb{D} = \mathbb{H}$ a nilpotent $K_{\mathbb{C}}$-orbit in $\mathfrak{p}_{\mathbb{C}}$ is uniquely determined by the Jordan canonical form of any of its element, hence by the corresponding partition of n if $\mathbb{D} = \mathbb{R}$ and of $2n$ if $\mathbb{D} = \mathbb{H}$. In the first case all partitions arise, in the second case a partition arises if and only if each of its parts occurs with an even multiplicity.

4.4 Nilpotent orbits in $W_{\mathbb{C}}^{+}$

The complete classification of the nilpotent orbits in $W_{\mathbb{C}}^{+}$ was given in [6] (in fact, as noted in [6], in the context of symmetric spaces it was described earlier by Ohta). It turns out that it can also be obtained as a special case of the classification of Section 3.

Consider first the case $\mathbb{D} = \mathbb{R}$. Let $U = U_0 \oplus U_1 \oplus U_2 \oplus U_3$ be the $\mathbb{Z}/4\mathbb{Z}$-graded complex vector space defined by $U_0 = V_0 \otimes \mathbb{C}$, $U_2 = V_1 \otimes \mathbb{C}$, $U_1 = U_3 = 0$, endowed with a nondegenerate symmetric form φ with U_0 orthogonal to U_2. Then the group $G(U,\varphi)_0$ of homogeneous isometries of U, equal to $O(U_0) \times O(U_2)$, is isomorphic to $K_{\mathbb{C}} \times K'_{\mathbb{C}}$, and its conjugation action on $\mathfrak{g}(U,\varphi)_2$ can be identified with the action of $K_{\mathbb{C}} \times K'_{\mathbb{C}}$ on $W_{\mathbb{C}}^{+}$ (see Section 3 of [6]). It is easy to see that Theorem 3.18 and Corollary 3.19 describe a classification of nilpotent orbits in $W_{\mathbb{C}}^{+}$ equivalent to Theorem 3.6 in [6].

The case $\mathbb{D} = \mathbb{H}$ is similar. Let $U = U_0 \oplus U_1 \oplus U_2 \oplus U_3$ be the $\mathbb{Z}/4\mathbb{Z}$-graded complex vector space, defined by $U_0 = U_2 = 0$, $U_1 = V_0|_{\mathbb{C}}$, $U_3 = V_1|_{\mathbb{C}}$, with the complex structures being the restriction of the structures of vector spaces over $\mathbb{H}$. Let φ be a nondegenerate skew-symmetric form on U with U_1 orthogonal to U_3. Then $\mathfrak{g}(U,\varphi)_2$ can be identified with $W_{\mathbb{C}}^{+}$. The group $G(U,\varphi)_0$ of homogeneous isometries of U is equal to $Sp(U_1) \times Sp(U_3)$, and it is isomorphic to $K_{\mathbb{C}} \times K'_{\mathbb{C}}$. Its conjugation action on $\mathfrak{g}(U,\varphi)_2$ can be identified with the action of $K_{\mathbb{C}} \times K'_{\mathbb{C}}$ on $W_{\mathbb{C}}^{+}$ (see Section 4 of [6]). Theorem 3.18 and Corollary 3.19 give a classification of nilpotent orbits in $W_{\mathbb{C}}^{+}$ equivalent to Theorem 4.5 in [6].

5 Dual Pairs of type I

Now we consider the case of the Lie color algebra of a $\mathbb{Z}/2\mathbb{Z}$-graded formed space $V = V_0 \oplus V_1$. Let τ be the form considered in (10) with $\sigma = 1$. Then $\tau = \tau_0 \oplus \tau_1$, where τ_0 is a non-degenerate hermitian form on V_0 and τ_1 is a non-degenerate skew-hermitian form on V_1.

The group $G(V,\tau)_0$, defined in (11), is isomorphic to the direct product $G(V_0,\tau_0) \times G(V_1,\tau_1)$, by restriction. Similarly, the component of degree 0 of $\mathfrak{g}(V,\tau)$ is a Lie algebra isomorphic to the direct sum of the corresponding Lie algebras

$$\mathfrak{g}(V,\tau)_0 = \mathfrak{g}(V_0,\tau_0) \oplus \mathfrak{g}(V_1,\tau_1).$$

Hence the classification of $G(V,\tau)_0$ orbits in $\mathfrak{g}(V,\tau)_0$ is equivalent to the classification of $G(V_0,\tau_0)$ orbits in $\mathfrak{g}(V_0,\tau_0)$ and $G(V_1,\tau_1)$ orbits in $\mathfrak{g}(V_1,\tau_1)$. We consider this case in

Section 5.1.

in Section 5.2 we explain how the action of $G(V,\tau)_0$ on $\mathfrak{g}(V,\tau)_1$ may be viewed in terms of dual pairs of type I.

5.1 Nilpotent orbits in the Lie algebra of an isometry group

In order to describe $G(V,\tau)_0$ orbits in $\mathfrak{g}(V,\tau)_0$ we begin with a classification of $(0,m)$-admissible spaces. It follows from Proposition 3.17 that if the space $(\tilde{V},\tilde{\tau})$ is $(0,m)$-admissible, then $\tilde{V}=\tilde{V}_b$ for some $b=0,1$ and $\tilde{\tau}$ is σ'-hermitian nondegenerate indecomposable form with $\sigma'=(-1)^{b+m}$. Such forms are well known and are tabulated in Table 1. A complete classification of the orbits is given by Theorem 3.18 (with $a=0$).

The closure relations between nilpotent orbits in the Lie algebras of isometry groups of formed spaces have been described by Djokovic. If $X,Y\in\mathfrak{g}(V_b,\tau_b)$, $b=0,1$, are nilpotent, then by Theorem 6 in [8],

$$\mathcal{O}_Y\subset\overline{\mathcal{O}_X}\text{ if and only if }\operatorname{sgn}\tau_b(\_,Y^k\_)\leq\operatorname{sgn}\tau_b(\_,X^k\_),\quad k=1,2,\ldots,\tag{30}$$

where "$(m,n)\leq(m',n')$" means "$m\leq m'$ and $n\leq n'$". If a nilpotent orbit $\mathcal{O}\in\mathcal{NO}\mathfrak{g}(V_b,\tau_b)$ is identified with the sequence $(F^{(i)},\tilde{\tau}_{(i)},m_i)$, $i=1,2,\ldots,s$, as above, then for $X\in\mathcal{O}$ and $k=0,1,\ldots$

$$\begin{aligned}\operatorname{sgn}\tau_b(-,X^k-)=&\sum_{\substack{k\leq m_i\\ 2\mid m_i-k}}\Big[\frac{1}{2}(m_i-k)(f_i,f_i)+\operatorname{sgn}(-1)^{\frac{m_i-k}{2}}\tilde{\tau}_{(i)}\Big]\\&+\sum_{\substack{k\leq m_i\\ 2\nmid m_i-k}}\frac{1}{2}(m_i-k+1)(f_i,f_i)\end{aligned}\tag{31}$$

where $f_i=\dim_{\mathbb{D}}F^{(i)}$.

5.2 Nilpotent orbits in W

Let W be the real vector space $W=\operatorname{Hom}_{\mathbb{D}}(V_0,V_1)$. The groups $G(V_0,\tau_0)$, $G(V_1,\tau_1)$ act on the space W by the formula:

$$\begin{gathered}g_0(w)=wg_0^{-1},\quad g_1(w)=g_1w\\(g_0\in G(V_0,\tau_0),\ g_1\in G(V_1,\tau_1),\ w\in W).\end{gathered}\tag{32}$$

Define a map $\operatorname{Hom}(V_0,V_1)\ni w\to w^*\in\operatorname{Hom}(V_1,V_0)$ by

$$\tau_1(wv_0,v_1)=\tau_0(v_0,w^*v_1)\qquad(v_0\in V_0,v_1\in V_1).\tag{33}$$

Then the formula

$$\langle w,w'\rangle=-\operatorname{tr}_{\mathbb{D}/\mathbb{R}}(w'^*w)\qquad(w,w'\in\operatorname{Hom}(V_0,V_1))\tag{34}$$

defines a non-degenerate symplectic form on the real vector space $\mathrm{Hom}(V_0, V_1)$. It is easy to see that the action (32) preserves the form (34). Hence the groups $G(V_0, \tau_0)$, $G(V_1, \tau_1)$ form a dual pair of type I in the symplectic group defined by the form (34). Furthermore, the maps

$$\begin{aligned} \nu_0 : \mathfrak{g}(V, \tau)_1 \ni N \mapsto N^2|_{V_0} \in \mathfrak{g}(V_0, \tau_0), \\ \nu_1 : \mathfrak{g}(V, \tau)_1 \ni N \mapsto N^2|_{V_1} \in \mathfrak{g}(V_1, \tau_1) \end{aligned} \tag{35}$$

coincide with the moment maps

$$\begin{aligned} \mathrm{Hom}(V_0, V_1) \ni w \mapsto -w^*w \in \mathfrak{g}(V_0, \tau_0), \\ \mathrm{Hom}(V_0, V_1) \ni w \mapsto -ww^* \in \mathfrak{g}(V_1, \tau_1). \end{aligned} \tag{36}$$

Lemma 5.1. The map $\mathfrak{g}(V, \tau)_1 \ni N \mapsto N|_{V_0} \in \mathrm{Hom}(V_0, V_1)$ is an $\mathbb{R}$-linear bijection which intertwines the adjoint action of $G(V, \tau)_0$ on $\mathfrak{g}(V, \tau)_1$ with the action of $G(V_0, \tau_0) \times G(V_1, \tau_1)$ on $\mathrm{Hom}(V_0, V_1)$ given by (32).

Proof. Let $N \in \mathfrak{g}(V, \tau)_1$. Then for $v_0 \in V_0$ and $v_1 \in V_1$

$$\tau_1(Nv_0, v_1) = \tau(Nv_0, v_1) = \tau(v_0, SNv_1) = -\tau_0(v_0, Nv_1).$$

Hence, $N|_{V_1} = -(N|_{V_0})^*$. Thus the $\mathbb{R}$-linear map $N \to N|_{V_0}$ is bijective.

For $g \in G(V, \tau)_0$, let $g_0 = g|_{V_0}$ and let $g_1 = g|_{V_1}$. Then

$$(gNg^{-1})|_{V_0} = g_1(N|_{V_0})g_0^{-1}.$$

□

Notice that in terms of Lemma 5.1, the symplectic form (34) coincides with the graded trace

$$\langle N, N' \rangle = \frac{1}{4}\, tr_{\mathbb{D}/\mathbb{R}}([SN, N']), \quad (N, N' \in \mathfrak{g}(V, \tau)_1), \tag{37}$$

where $[-, -]$ is the bracket defined in (4) i.e.

$$[SN, N'] = SNN' + N'SN \in \mathfrak{g}(V, \tau)_0. \tag{38}$$

We will say that an element $w \in \mathrm{Hom}(V_0, V_1)$ is nilpotent if the element $w + w^*$ is a nilpotent endomorphism of $V_0 \oplus V_1$. Observe that $w \in \mathrm{Hom}(V_0, V_1)$ is nilpotent if and only if its image by the moment map ν_0 (equivalently ν_1) is nilpotent. We see from Lemma 5.1 that the problem of classifying the nilpotent orbits in the symplectic space $\mathrm{Hom}(V_0, V_1)$ under the action of the dual pair $G(V_0, \tau_0)$, $G(V_1, \tau_1)$ is equivalent to the problem of classifying the nilpotent $G(V, \tau)_0$-orbits in $\mathfrak{g}(V, \tau)_1$, considered in section 2.2. In order to obtain a classification of the orbits we need the list of all $(1, m)$-admissible spaces. This list is provided in Table 2. The following proposition gives an explicit description of indecomposable graded nilpotent morphisms. The proposition follows directly from Theorem 3.18 and Table 2.

Case 1. m even

$(\mathbb{D},\iota)$	$m\equiv 0 \pmod 4$	$m\equiv 2 \pmod 4$
$(\mathbb{R},\ id)$	$(\mathbb{R}[0],\ +)$ $(\mathbb{R}[0],\ -)$ $(\mathbb{R}^2[1],\ sk)$	$(\mathbb{R}^2[0],\ sk)$ $(\mathbb{R}[1],\ +)$ $(\mathbb{R}[1],\ -)$
$(\mathbb{C},\ id)$	$(\mathbb{C}[0],\ sym)$ $(\mathbb{C}^2[1],\ sk)$	$(\mathbb{C}^2[0],\ sk)$ $(\mathbb{C}[1],\ sym)$
$(\mathbb{C},\bar{\cdot})$	$(\mathbb{C}[0],\ +)$ $(\mathbb{C}[0],\ -)$ $(\mathbb{C}[1],\ i)$ $(\mathbb{C}[1],\ -i)$	$(\mathbb{C}[0],\ i)$ $(\mathbb{C}[0],\ -i)$ $(\mathbb{C}[1],\ +)$ $(\mathbb{C}[1],\ -)$
$(\mathbb{H},\bar{\cdot})$	$(\mathbb{H}[0],\ +)$ $(\mathbb{H}[0],\ -)$ $(\mathbb{H}[1],\ sk)$	$(\mathbb{H}[0],\ sk)$ $(\mathbb{H}[1],\ +)$ $(\mathbb{H}[1],\ -)$

Case 2. m odd

$m\equiv 1 \pmod 4$	$m\equiv 3 \pmod 4$
$\tilde{V}=\mathbb{D}[0]\oplus\mathbb{D}[1]$	$\tilde{V}=\mathbb{D}[0]\oplus\mathbb{D}[1]$
$\tilde{\tau}(x,y)=x\cdot J_2'\cdot\iota(y)^t$	$\tilde{\tau}(x,y)=x\cdot J_2\cdot\iota(y)^t$
where $J_2'=\left[\begin{smallmatrix}0&1\\1&0\end{smallmatrix}\right]$	where $J_2=\left[\begin{smallmatrix}0&1\\-1&0\end{smallmatrix}\right]$

Table 2 The list of $\mathbb{Z}/2\mathbb{Z}$-graded $(1,m)$-admissible spaces.

Proposition 5.2. For a 1-hermitian form α with $\operatorname{sgn}\alpha=(n_+,n_-)$ let $sign(\alpha)=n_+-n_-$. The following is a complete list of all non-zero nilpotent indecomposable elements (N,V), $N\in\mathfrak{g}(V,\tau)_1$.

(a)
$m\in 4\mathbb{Z}$;

$V=\sum_{k=0}^{m}\mathbb{D}v_k,\ v_{even}\in V_0,\ v_{odd}\in V_1$;

$v_k=N^kv_0\neq 0, 0\leq k\leq m, Nv_m=0$;

$\tau(v_k,v_l)=0$

if $l\neq m-k, \tau(v_k,v_{m-k})=(-1)^k\delta(k)\delta(\frac{m}{2})sgn(\tau_0)$,

where $s=1$ if $\mathbb{D}=\mathbb{C}$ and $\iota=1,$ and $s=sign(\tau_0)$ otherwise;

$$\text{(b)}\quad \begin{array}{l} m \in 4\mathbb{Z}, \mathbb{D} \neq \mathbb{R}, \iota \neq 1; \\ V = \sum_{k=1}^{m+1} \mathbb{D}v_k,\ v_{even} \in V_0,\ v_{odd} \in V_1; \\ v_{k+1} = N^k v_1 \neq 0, 0 \leq k \leq m, Nv_{m+1} = 0; \\ \tau(v_k, v_l) = 0 \\ \text{if } l \neq m+2-k, \tau(v_k, v_{m+2-k}) = \delta(k-1)\tau(v_1, v_{m+1}), \\ \tau(v_1, v_{m+1}) = i\, sign(-i\tau_1)\delta(1+\frac{m}{2}) \text{ if } \mathbb{D} = \mathbb{C}; \\ \tau(v_1, v_{m+1}) = j \text{ if } \mathbb{D} = \mathbb{H}; \end{array}$$

$$\text{(c)}\quad \begin{array}{l} m \in 4\mathbb{Z}, \mathbb{D} \neq \mathbb{H}, \iota = 1; \\ V = \sum_{k=1}^{m+1} (\mathbb{D}v_k \oplus \mathbb{D}v'_k),\ v_{even}, v'_{even} \in V_0,\ v_{odd}, v'_{odd} \in V_1; \\ v_{k+1} = N^k v_1 \neq 0, v'_{k+1} = N^k v'_1 \neq 0, 0 \leq k \leq m, Nv_{m+1} = 0, \\ Nv'_{m+1} = 0; \\ \tau(v_k, v_l) = \tau(v'_k, v'_l) = 0,\ 1 \leq k, l \leq m+1, \\ \tau(v_k, v'_l) = \tau(v'_k, v_l) = 0,\ l \neq m+2-k, \\ \tau(v_k, v'_{m+2-k}) = -\tau(v'_k, v_{m+2-k}) = \delta(k-1),\ 1 \leq k \leq m+1; \end{array}$$

$$\text{(d)}\quad \begin{array}{l} m \in 2\mathbb{Z} \setminus 4\mathbb{Z}, \mathbb{D} \neq \mathbb{R}, \iota \neq 1; \\ V = \sum_{k=0}^{m} \mathbb{D}v_k,\ v_{even} \in V_0,\ v_{odd} \in V_1; \\ v_k = N^k v_0 \neq 0, 0 \leq k \leq m, Nv_m = 0; \\ \tau(v_k, v_l) = 0 \text{ if } l \neq m-k, \tau(v_k, v_{m-k}) = \delta(k-1) i\, sign(-i\tau_1), \\ (\text{here } -i\tau_1 \text{ is hermitian}); \end{array}$$

$$\text{(e)}\quad \begin{array}{l} m \in 2\mathbb{Z} \setminus 4\mathbb{Z}; \\ V = \sum_{k=1}^{m+1} \mathbb{D}v_k,\ v_{even} \in V_0,\ v_{odd} \in V_1; \\ v_{k+1} = N^k v_1 \neq 0, 0 \leq k \leq m, Nv_{m+1} = 0; \\ \tau(v_k, v_l) = 0 \\ \text{if } l \neq m+2-k, \tau(v_k, v_{m+2-k}) = \delta(k)\tau(v_1, v_{m+1}), \\ \tau(v_1, v_{m+1}) = -\delta(1+\frac{m}{2}) sign(\tau_0); \end{array}$$

$m \in 2\mathbb{Z} \setminus 4\mathbb{Z}, \mathbb{D} \neq \mathbb{H}, \iota = 1;$

$V = \sum_{k=0}^{m} (\mathbb{D}v_k \oplus \mathbb{D}v'_k),\ v_{even}, v'_{even} \in V_0,\ v_{odd}, v'_{odd} \in V_1;$

$v_k = N^k v_0 \neq 0, v'_k = N^k v'_0 \neq 0, 0 \leq k \leq m, Nv_m = 0,$

(f) $Nv'_m = 0;$

$\tau(v_k, v_l) = \tau(v'_k, v'_l) = 0,\ 0 \leq k, l \leq m,$

$\tau(v_k, v'_l) = \tau(v'_k, v_l) = 0,\ l \neq m-k,$

$\tau(v_k, v'_{m-k}) = -\tau(v'_k, v_{m-k}) = \delta(k-1),\ 0 \leq k \leq m;$

$m \in 2\mathbb{Z}+1;$

$V = \sum_{k=0}^{m} (\mathbb{D}v_k \oplus \mathbb{D}v'_{k+1}),\ v_{even}, v'_{even} \in V_0,\ v_{odd}, v'_{odd} \in V_1;$

$v_k = N^k v_0 \neq 0, v'_{k+1} = N^k v'_1 \neq 0, 0 \leq k \leq m, Nv_m = 0,$

$Nv'_{m+1} = 0;$

(g)

$\tau(v_k, v_l) = \tau(v'_{k+1}, v'_{l+1}) = 0,\ 0 \leq k, l \leq m,$

$\tau(v_k, v'_{l+1}) = \tau(v'_{k+1}, v_l) = 0,\ l \neq m-k,$

$\tau(v_k, v'_{m+1-k}) = \delta(k)\delta(m), \tau(v'_{k+1}, v_{m-k}) = \delta(k-1),$

$0 \leq k \leq m.$

Now we will describe the action of moment maps ν_0 and ν_1, defined by (35), on the nilpotent orbits in W. Since moment maps respect decomposition and group action, it is enough to treat the case of indecomposable elements in W. Let (V, τ) be a $\mathbb{Z}_2$-graded formed space and let $N \in \mathfrak{g}(V, \tau)_1$ be indecomposable of height m. Then the orbit of N is uniquely determined by the isometry class of the space $(V/NV, \tilde{\tau})$ defined in Lemma 3.10. Recall (Proposition 3.17) that $\tilde{\tau}$ is σ-hermitian for some $\sigma = \pm 1$. For $k = 0, 1$, the image $\nu_k(N) = N^2|_{V_k}$ of N under the moment map ν_k is a nilpotent uniform element of $\mathfrak{g}(V_k, \tau_k)$. Let m_k be its height. In order to identify the orbit of $\nu_k(N)$, we have to consider a formed space $(V_k/N^2V_k, \hat{\tau}_k)$, where

$$\hat{\tau}_k(\hat{u}, \hat{v}) = \tau(u, N^{2m_k} v), \quad (u, v \in V_k) \tag{39}$$

and, for $u \in V$, $\hat{u}$ denotes the coset of u in V/N^2V.

Lemma 5.3. With the above notation, the form $\hat{\tau}_k$ is σ_k-hermitian for a suitable $\sigma_k = \pm 1$. Specifically, there are three possibilities.
(1) $2m_k = m$. Then $V_k/N^2V_k = V/NV$, $\hat{\tau}_k(\hat{u}, \hat{v}) = \tilde{\tau}(\tilde{u}, \tilde{v})$ and $\sigma_k = \sigma$.
(2) $2m_k = m-1$. Then $V_k/N^2V_k = V_k/(NV \cap V_k) \oplus NV_{k+1}/(N^2V \cap NV_{k+1})$ and if $u \in V_b$, $v \in V_{k+1}$ then $\hat{\tau}_k(\hat{u}, \widehat{Nv}) = \tilde{\tau}(\widetilde{u}, \widetilde{v})$, $\hat{\tau}_k(\widehat{Nv}, \hat{u}) = (-1)^b \tilde{\tau}(\widetilde{v}, \widetilde{u})$. In particular, $\sigma_k = (-1)^k \sigma$.

(3) $2m_k = m-2$. Then $V_k/N^2V_k = NV/N^2V = NV_{k+1}/N^2V_{k+1}$ and if $u = Nu'$, $v = Nv'$, where $u', v' \in V_{k+1}$, then $\hat{\tau}_k(\hat{u}, \hat{v}) = (-1)^m(-1)^k\tilde{\tau}(\widetilde{u'}, \widetilde{v'})$. In particular, $\sigma_k = \sigma$.

Using Lemma 5.3, one can easily describe how the moment maps act on indecomposable orbits in W. The detailed description is given in Table 3.

The first column contains the parameter $(V/NV, \tilde{\tau})$ describing an orbit in W and its height m, the second column contains the parameters of the image of that orbit under the projection ν_0 and the third, the image under the projection ν_1. For the details on the last column see (74).

5.3 Nilpotent orbits in $\mathfrak{p}_{\mathbb{C}}$

We assume that if $\mathbb{D} = \mathbb{C}$ then the involution ι is nontrivial.

Lemma 5.4. Up to conjugation by $G(V,\tau)_0$, there is a unique element $T \in G(V,\tau)_0$ such that $T^2 = S$ and such that the form $\tau(Tu, v)$ $(u, v \in V)$, is hermitian and positive definite. In particular $\theta = Ad(T)$ is a Cartan involution on $\mathfrak{g}(V,\tau)_0$.

Furthermore, the following diagram

$$\begin{array}{ccc} \mathfrak{g}(V,\tau)_1 \ni N & \longrightarrow & N|_{V_0} \in \mathrm{Hom}(V_0, V_1) \\ T\Big\downarrow & & J\Big\downarrow \\ \mathfrak{g}(V,\tau)_1 \ni TNT^{-1} & \longrightarrow & (TNT^{-1})|_{V_0} \in \mathrm{Hom}(V_0, V_1) \end{array}$$

defines a positive compatible complex structure J on the symplectic space $\mathrm{Hom}(V_0, V_1)$ (i.e. J preserves the symplectic form $\langle \_, \_ \rangle$ defined in (34), $J^2 = -1$ and the form $\langle J\_, \_ \rangle$ is symmetric and positive definite).

If we define a map $\mathfrak{g}(V,\tau)_1 \ni N \to N^\dagger \in \mathfrak{g}(V,\tau)_1$ by $\tau(TNu, v) = \tau(Tu, N^\dagger v)$, then $J(N) = SN^\dagger$.

Proof. We shall give an explicit construction of T. For integers $p \geq 0$, $q \geq 0$ $(p+q > 0)$ and for $n \geq 1$, let

$$I_{p,q} = \begin{bmatrix} I_p & 0 \\ 0 & -I_q \end{bmatrix}, \quad J_{2n} = \begin{bmatrix} 0 & I_n \\ -I_n & 0 \end{bmatrix}.$$

There are three cases to consider.

$$\text{(a)} \quad \begin{aligned} &\mathbb{D} = \mathbb{R},\ V_0 = \mathbb{R}^{p+q}, V_1 = \mathbb{R}^{2n}, \\ &\tau_0(u,v) = u^t I_{p,q} v \qquad (u, v \in V_0), \\ &\tau_1(u,v) = u^t J_{2n} v \qquad (u, v \in V_1), \\ &T|_{V_0} := I_{p,q}, \quad T|_{V_1} := J_{2n}; \end{aligned}$$

$(V/NV, \tilde{\tau})$	m	$(V_0/N^2V_0, \hat{\tau}_0)$	m_0	$(V_1/N^2V_1, \hat{\tau}_1)$	m_1	
$(\mathbb{D},\ \iota) = (\mathbb{R},\ id)$						
$(\mathbb{R}[0],\ +)$	$4s$	$(\mathbb{R},\ +)$	$2s$	$(\mathbb{R},\ -)$	$2s-1$	S
$(\mathbb{R}[0],\ -)$	$4s$	$(\mathbb{R},\ -)$	$2s$	$(\mathbb{R},\ +)$	$2s-1$	S
$(\mathbb{R}^2[1],\ sk)$	$4s$	$(\mathbb{R}^2,\ sk)$	$2s-1$	$(\mathbb{R}^2,\ sk)$	$2s$	$S, \bar{S}$
$(\mathbb{R}[1],\ +)$	$4s+2$	$(\mathbb{R},\ +)$	$2s$	$(\mathbb{R},\ +)$	$2s+1$	$\bar{S}$
$(\mathbb{R}[1],\ -)$	$4s+2$	$(\mathbb{R},\ -)$	$2s$	$(\mathbb{R},\ -)$	$2s+1$	$\bar{S}$
$(\mathbb{R}^2[0],\ sk)$	$4s+2$	$(\mathbb{R}^2,\ sk)$	$2s+1$	$(\mathbb{R}^2,\ sk)$	$2s$	$S, \bar{S}$
$(\mathbb{R}[0] \oplus \mathbb{R}[1],\ J_2')$	$4s+1$	$(\mathbb{R},\ +) \oplus (\mathbb{R},\ -)$	$2s$	$(\mathbb{R}^2,\ sk)$	$2s$	
$(\mathbb{R}[0] \oplus \mathbb{R}[1],\ J_2)$	$4s+3$	$(\mathbb{R}^2,\ sk)$	$2s+1$	$(\mathbb{R},\ +) \oplus (\mathbb{R},\ -)$	$2s+1$	
$(\mathbb{D},\ \iota) = (\mathbb{C},\ id)$						
$(\mathbb{C}[0],\ sym)$	$4s$	$(\mathbb{C},\ sym)$	$2s$	$(\mathbb{C},\ sym)$	$2s-1$	$S, \bar{S}$
$(\mathbb{C}^2[1],\ sk)$	$4s$	$(\mathbb{C}^2,\ sk)$	$2s-1$	$(\mathbb{C}^2,\ sk)$	$2s$	$S, \bar{S}$
$(\mathbb{C}^2[0], sk)$	$4s+2$	$(\mathbb{C}^2,\ sk)$	$2s+1$	$(\mathbb{C}^2,\ sk)$	$2s$	$S, \bar{S}$
$(\mathbb{C}[1],\ sym)$	$4s+2$	$(\mathbb{C},\ sym)$	$2s$	$(\mathbb{C},\ sym)$	$2s+1$	$S, \bar{S}$
$(\mathbb{C}[0] \oplus \mathbb{C}[1],\ J_2')$	$4s+1$	$(\mathbb{C},\ sym)^{\oplus 2}$	$2s$	$(\mathbb{C}^2,\ sk)$	$2s$	$S, \bar{S}$
$(\mathbb{C}[0] \oplus \mathbb{C}[1],\ J_2)$	$4s+3$	$(\mathbb{C}^2,\ sk)$	$2s+1$	$(\mathbb{C},\ sym)^{\oplus 2}$	$2s+1$	$S, \bar{S}$
$(\mathbb{D},\ \iota) = (\mathbb{C},\ \bar{\cdot})$						
$(\mathbb{C}[0],\ +)$	$4s$	$(\mathbb{C},\ +)$	$2s$	$(\mathbb{C},\ -)$	$2s-1$	S
$(\mathbb{C}[0],\ -)$	$4s$	$(\mathbb{C},\ -)$	$2s$	$(\mathbb{C},\ +)$	$2s-1$	S
$(\mathbb{C}[1],\ +i)$	$4s$	$(\mathbb{C},\ +i)$	$2s-1$	$(\mathbb{C},\ +i)$	$2s$	$\bar{S}$
$(\mathbb{C}[1],\ -i)$	$4s$	$(\mathbb{C},\ -i)$	$2s-1$	$(\mathbb{C},\ -i)$	$2s$	$\bar{S}$
$(\mathbb{C}[0],\ +i)$	$4s+2$	$(\mathbb{C},\ +i)$	$2s+1$	$(\mathbb{C},\ -i)$	$2s$	S
$(\mathbb{C}[0],\ -i)$	$4s+2$	$(\mathbb{C},\ -i)$	$2s+1$	$(\mathbb{C},\ +i)$	$2s$	S
$(\mathbb{C}[1],\ +)$	$4s+2$	$(\mathbb{C},\ +)$	$2s$	$(\mathbb{C},\ +)$	$2s+1$	$\bar{S}$
$(\mathbb{C}[1],\ -)$	$4s+2$	$(\mathbb{C},\ -)$	$2s$	$(\mathbb{C},\ -)$	$2s+1$	$\bar{S}$
$(\mathbb{C}[0] \oplus \mathbb{C}[1],\ J_2')$	$4s+1$	$(\mathbb{C},\ +) \oplus (\mathbb{C},\ -)$	$2s$	$(\mathbb{C},\ +i) \oplus (\mathbb{C},\ -i)$	$2s$	$S, \bar{S}$
$(\mathbb{C}[0] \oplus \mathbb{C}[1],\ J_2)$	$4s+3$	$(\mathbb{C},\ +i) \oplus (\mathbb{C},\ -i)$	$2s+1$	$(\mathbb{C},\ +) \oplus (\mathbb{C},\ -)$	$2s+1$	$S, \bar{S}$
$(\mathbb{D},\ \iota) = (\mathbb{H},\ \bar{\cdot})$						
$(\mathbb{H}[0],\ +)$	$4s$	$(\mathbb{H},\ +)$	$2s$	$(\mathbb{H},\ -)$	$2s-1$	S
$(\mathbb{H}[0],\ -)$	$4s$	$(\mathbb{H},\ -)$	$2s$	$(\mathbb{H},\ +)$	$2s-1$	S
$(\mathbb{H}[1],\ sk)$	$4s$	$(\mathbb{H},\ sk)$	$2s-1$	$(\mathbb{H},\ sk)$	$2s$	$S, \bar{S}$
$(\mathbb{H}[0],\ sk)$	$4s+2$	$(\mathbb{H},\ sk)$	$2s+1$	$(\mathbb{H},\ sk)$	$2s$	$S, \bar{S}$
$(\mathbb{H}[1],\ +)$	$4s+2$	$(\mathbb{H},\ +)$	$2s$	$(\mathbb{H},\ +)$	$2s+1$	$\bar{S}$
$(\mathbb{H}[1],\ -)$	$4s+2$	$(\mathbb{H},\ -)$	$2s$	$(\mathbb{H},\ -)$	$2s+1$	$\bar{S}$
$(\mathbb{H}[0] \oplus \mathbb{H}[1],\ J_2')$	$4s+1$	$(\mathbb{H},\ +) \oplus (\mathbb{H},\ -)$	$2s$	$(\mathbb{H},\ sk)^{\oplus 2}$	$2s$	$S, \bar{S}$
$(\mathbb{H}[0] \oplus \mathbb{H}[1],\ J_2)$	$4s+3$	$(\mathbb{H},\ sk)^{\oplus 2}$	$2s+1$	$(\mathbb{H},\ +) \oplus (\mathbb{H},\ -)$	$2s+1$	$S, \bar{S}$

Table 3 Moment maps on indecomposable orbits in W.

(b)
$$\begin{aligned}
&\mathbb{D}=\mathbb{C},\ V_0=\mathbb{C}^{p+q}, V_1=\mathbb{C}^{r+s},\\
&\tau_0(u,v)=u^t I_{p,q}\iota(v) \qquad (u,v\in V_0),\\
&\tau_1(u,v)=u^t i I_{r,s}\iota(v) \qquad (u,v\in V_1),\\
&T|_{V_0}:=I_{p,q},\ \ T|_{V_1}:=-iI_{r,s};
\end{aligned}$$

(c)
$$\begin{aligned}
&\mathbb{D}=\mathbb{H},\ V_0=\mathbb{H}^{p+q}, V_1=\mathbb{H}^{n},\\
&\tau_0(u,v)=u^t I_{p,q}\iota(v) \qquad (u,v\in V_0),\\
&\tau_1(u,v)=u^t j I_{n}\iota(v) \qquad (u,v\in V_1),\\
&T|_{V_0}:=I_{p,q},\ \ T|_{V_1}:=\text{right multiplication by } j^{-1},\\
&\text{where } j\in\mathbb{H} \text{ is such that } \mathbb{H}=\mathbb{C}\oplus j\mathbb{C},\ \iota(j)=-j=j^{-1}\\
&\text{and } jzj^{-1}=\iota(z) \text{ for } z\in\mathbb{C}.
\end{aligned}$$

For the last statement we notice that for $u, v \in V$ and for $N \in \mathfrak{g}(V,\tau)_1$ we have

$$\tau(TNu,v)=\tau(TNT^{-1}Tu,v)=\tau(Tu,STNT^{-1}v).$$

Hence, $N^\dagger = STNT^{-1}$, and therefore $J(N) = TNT^{-1} = SN^\dagger$, as claimed.

Via a case by case analysis we see that the condition $T^2 = S$ determines T up to a sign, and this sign is determined by the positivity of the form $\tau(Tu, v)$. Thus there is a one to one correspondence between the elements T and the maximal compact subgroups. Hence T is unique up to conjugation. □

Let $K = G(V,\tau)_0^T$ and let $\mathfrak{k} = \mathfrak{g}(V,\tau)_0^T$. Since the form $\tau(Tu, v)$ $(u, v \in V)$ is hermitian and positive definite, K is a maximal compact subgroup of $G(V,\tau)_0$ corresponding to the Cartan involution θ and $\mathfrak{k}$ is the Lie algebra of K. Let $\mathfrak{p}$ be the (-1)-eigenspace of θ on $\mathfrak{g}(V,\tau)_0$ so that

$$\mathfrak{g}(V,\tau)_0=\mathfrak{k}\oplus\mathfrak{p} \tag{40}$$

is the corresponding Cartan decomposition. Set $\mathfrak{p}_0 = \mathfrak{p}\cap\mathfrak{g}(V_0,\tau_0)$, $\mathfrak{k}_0 = \mathfrak{k}\cap\mathfrak{g}(V_0,\tau_0)$, and similarly for $\mathfrak{p}_1, \mathfrak{k}_1$. Then we have the Cartan decompositions

$$\mathfrak{g}(V_0,\tau_0)=\mathfrak{k}_0\oplus\mathfrak{p}_0, \tag{41}$$
$$\mathfrak{g}(V_1,\tau_1)=\mathfrak{k}_1\oplus\mathfrak{p}_1, \tag{42}$$

with maximal compact subgroups K_0, K_1.

In order to describe the complexifications $\mathfrak{p}_\mathbb{C}$ and $K_\mathbb{C}$ of $\mathfrak{p}$ and K let us define

$$U=V\otimes_{\mathbb{R}}\mathbb{C} \text{ if } \mathbb{D}=\mathbb{R},\ \text{ and } U=V|_\mathbb{C} \text{ if } \mathbb{D}=\mathbb{C} \text{ or } \mathbb{H}. \tag{43}$$

Then U is a vector space over $\mathbb{C}$ and the element T constructed in Lemma 5.4 acts on U. Since $T^4 = S^2 = 1$, T has at most four eigenvalues: $1, i, -1, -i$. Let

$$U_k = \{u \in U;\ Tu = i^k u\} \qquad (k = 0, 1, 2, 3). \tag{44}$$

Then

$$U = U_0 \oplus U_1 \oplus U_2 \oplus U_3 \tag{45}$$

and U is a $\mathbb{Z}/4\mathbb{Z}$-graded vector space over $\mathbb{C}$.

Let us first analyze the case of $\mathbb{D} = \mathbb{C}$. In this case $\mathfrak{p}_{\mathbb{C}} = \mathrm{End}(U)_2$ and $K_{\mathbb{C}} = GL(U_0) \times GL(U_1) \times GL(U_2) \times GL(U_3)$. Since

$$\mathrm{End}(U)_2 = \mathrm{Hom}(U_0, U_2) \oplus \mathrm{Hom}(U_2, U_0) \oplus \mathrm{Hom}(U_1, U_3) \oplus \mathrm{Hom}(U_3, U_1),$$

the problem of the classification of nilpotent $K_{\mathbb{C}}$-orbits in $\mathfrak{p}_{\mathbb{C}}$ is equivalent to the analogous problem for the nilpotent orbits of $K_{0,\mathbb{C}} = GL(U_0) \times GL(U_2)$ in $\mathfrak{p}_{0,\mathbb{C}} = \mathrm{Hom}(U_0, U_2) \oplus \mathrm{Hom}(U_2, U_0)$ and the nilpotent orbits of $K_{1,\mathbb{C}} = GL(U_1) \times GL(U_3)$ in $\mathfrak{p}_{1,\mathbb{C}} = \mathrm{Hom}(U_1, U_3) \oplus \mathrm{Hom}(U_3, U_1)$.

This is exactly the problem studied in Section 4.2. As an immediate application of Corollary 4.2 we get the description of the indecomposable nilpotents in $\mathfrak{p}_{\mathbb{C}}$ in this case.

Proposition 5.5. If $\mathbb{D} = \mathbb{C}$ and the anti-involution ι is nontrivial, then there are two orbits of indecomposable nilpotent elements $(N, U_0 \oplus U_2)$ in $\mathfrak{p}_{0,\mathbb{C}}$, determined by the condition $\tilde{U} = \mathbb{C}[b]$, $b = 0, 2$, and there are two orbits of indecomposable nilpotent elements $(N, U_1 \oplus U_3)$ in $\mathfrak{p}_{1,\mathbb{C}}$, determined by the condition $\tilde{U} = \mathbb{C}[b]$, $b = 1, 3$.

Until stated otherwise, suppose that $\mathbb{D} = \mathbb{R}$ or $\mathbb{H}$. We shall define a sesqui-linear form ϕ on the space U, as follows.

If $\mathbb{D} = \mathbb{R}$ we let ϕ be the unique complex linear extension of the form τ. Then $\phi|_{U_0+U_2}$ is symmetric, and $\phi|_{U_0}$, $\phi|_{U_2}$ are non-degenerate. Furthermore, $\phi|_{U_1+U_3}$ is skew-symmetric, and $\phi|_{U_1} = 0$, $\phi|_{U_3} = 0$.

If $\mathbb{D} = \mathbb{H}$ we define

$$\phi(u, v) = \left(\frac{1}{2i} \left(i\tau(u, v) + \tau(u, v)i \right) - \tau(u, v) \right) j \quad (u, v \in U). \tag{46}$$

Lemma 5.6. The form ϕ defined in *(46)* is a $\mathbb{C}$-valued, $\mathbb{C}$-bilinear non-degenerate form on U. The restricted form $\phi|_{U_0+U_2}$ is skew-symmetric, and $\phi|_{U_0}$, $\phi|_{U_2}$ are non-degenerate. Similarly, $\phi|_{U_1+U_3}$ is symmetric, and $\phi|_{U_1} = 0$, $\phi|_{U_3} = 0$. Moreover, for $x \in \mathrm{End}_{\mathbb{H}}(V)_0$ and for $u, v \in V$, we have $\tau(xu, v) = -\tau(u, xv)$ if and only if $\phi(xu, v) = -\phi(u, xv)$.

Proof. Notice that for any quaternion $q = a + bj$, where $a, b \in \mathbb{C}$, we have

$$\left(\frac{1}{2i} \left(iq + qi \right) - q \right) j = b.$$

Hence ϕ takes values in $\mathbb{C}$. Since $zj = j\overline{z}$, for $z \in \mathbb{C}$, it is easy to check that ϕ is bilinear over $\mathbb{C}$. Furthermore, $\iota(q) = \overline{a} - bj$, so

$$\left(\frac{1}{2i}\left(i\iota(q) + \iota(q)i\right) - \iota(q)\right) j = -b.$$

Thus, if a restriction of τ to a subspace $U' \subset U$ is hermitian then $\phi|_{U'}$ is skew-symmetric, and if $\tau|_{U'}$ is skew-hermitian then $\phi|_{U'}$ is symmetric.

Suppose $\phi(u, v) = 0$ for all $v \in W$. Then $\tau(u, v) \in \mathbb{C}$ for all $v \in W$. But then $\tau(u, jv) = -\tau(u, v)j \in \mathbb{C}j$. Hence $\tau(u, v) = 0$ for all $v \in U$. Thus $u = 0$, so ϕ is non-degenerate.

The last claim follows from equation (46) defining ϕ in terms of τ and from the following, easy to check, equation expressing τ in terms of ϕ:

$$\tau(u, v) = -\phi(u, jv) + \phi(u, v)j \qquad (u, v \in U).$$

□

In both cases the form ϕ is non-degenerate and bilinear over $\mathbb{C}$.

A straightforward argument shows that $\mathfrak{g}(U, \phi)_0$ coincides with the complexification $\mathfrak{k}_{\mathbb{C}}$ of $\mathfrak{k} = \mathfrak{g}(V, \tau)_0^T$ (the centralizer of T in $\mathfrak{g}(V, \tau)_0$), and that $K = G(V, \tau)_0^T$ is a maximal compact subgroup of $G(V, \tau)_0$. Thus

$$\begin{aligned} K_{\mathbb{C}} = G(U, \phi)_0^T &= \{g \in G(U, \phi);\ gT = Tg\} \\ &= \{g \in G(U, \phi);\ g(U_k) = U_k \text{ for all } k\}, \\ \mathfrak{p}_{\mathbb{C}} = \mathfrak{g}(U, \phi)_2 &= \{x \in g(U, \phi);\ x(U_k) \subseteq U_{k+2} \text{ for all } k\}. \end{aligned} \tag{47}$$

As explained in Theorem 3.18, the orbits of $K_{\mathbb{C}}$ in $\mathfrak{p}_{\mathbb{C}}$ are determined by $(2, m)$-admissible spaces $(\tilde{U}, \tilde{\phi})$. According to Proposition 3.17, they are as follows.

Proposition 5.7. If $\mathbb{D} = \mathbb{R}$ then ϕ satisfies condition (10) with $\sigma = 1$ and $(2, m)$-admissible spaces $(\tilde{U}, \tilde{\phi})$ are of the form:
(1) $\tilde{U} = \mathbb{C}[b]$, where $b + m$ is even and $\tilde{\phi}$ is symmetric;
(2) $\tilde{U} = \mathbb{C}[b] \oplus \mathbb{C}[b + 2]$, where $b + m$ is odd and $\tilde{\phi}$ is skew-symmetric.
If $\mathbb{D} = \mathbb{H}$ then ϕ satisfies condition (10) with $\sigma = -1$ and $(2, m)$-admissible spaces $(\tilde{U}, \tilde{\phi})$ are of the form:
(1) $\tilde{U} = \mathbb{C}^2[b]$, where $b + m$ is even and $\tilde{\phi}$ is skew-symmetric;
(2) $\tilde{U} = \mathbb{C}[b] \oplus \mathbb{C}[b + 2]$, where $b + m$ is odd and $\tilde{\phi}$ is symmetric with maximal isotropic subspaces $\mathbb{C}[b]$ and $\mathbb{C}[b + 2]$.

5.4 Nilpotent orbits in $W_{\mathbb{C}}^+$

By definition, the space $W_{\mathbb{C}}^+$ is equal to the i-eigenspace of J acting on $W_{\mathbb{C}}$, the complexification of W. In the case of $\mathbb{D} = \mathbb{C}$ the space $W_{\mathbb{C}}$ can be identified with the the direct sum $\mathrm{Hom}(V_0, V_1) \oplus \mathrm{Hom}(V_1, V_0)$ with the complex structure $iX = X^*$ and we have

$W_{\mathbb{C}}^+ = \mathrm{End}(U)_1$. The problem of classification of $K_{\mathbb{C}}$-orbits in $W_{\mathbb{C}}^+$ is equivalent to the problem of classification of $GL(U)_0$-orbits in $\mathrm{End}(U)_1$.

As in Section 4.2 the classification follows from Corollary 3.8. We leave the details to the reader.

In the case of $\mathbb{D} = \mathbb{R}$ or $\mathbb{H}$ we have $W_{\mathbb{C}}^+ = \mathfrak{g}(U,\phi)_1$ and $K_{\mathbb{C}}$-orbits in $W_{\mathbb{C}}^+$ are $G(U,\phi)_0$-orbits in $\mathfrak{g}(U,\phi)_1$. In order to understand them in terms of Theorem 3.18, we need to list $(1,m)$-admissible spaces.

Proposition 5.8. With σ as in Proposition 5.7, all $(1,m)$-admissible spaces $(\tilde{U},\tilde{\phi})$ are as follows:
(1) if $4 \mid 2b+m$ then $\tilde{U} = \tilde{U}_b$ and $\tilde{\phi}$ is σ-symmetric;
(2) if $4 \nmid 2b+m$ then $\tilde{U} = \tilde{U}_b \oplus \tilde{U}_{-b-m}$, where $2b+m \neq 0$, and $\tilde{\phi}$ is σ'-symmetric with $\sigma' = (-1)^{(m+1)b}\delta(m)\sigma$.

Table 4 lists all the indecomposable orbits in $W_{\mathbb{C}}^+$ and the corresponding orbits obtained via the moment maps μ_0 and μ_1, in terms of the notation explained above.

6 The Cayley transform and the Kostant-Sekiguchi correspondence

We begin by recalling Kostant-Sekiguchi bijections $\mathcal{S}$ and $\bar{\mathcal{S}}$ [19].

Let G be a real reductive Lie group with the Lie algebra $\mathfrak{g}$ and let $\mathfrak{g}_{\mathbb{C}}$ be the complexification of $\mathfrak{g}$. Recall that a standard triple (e,f,h) in $\mathfrak{g}$ is a triple of elements $e,f,h \in \mathfrak{g}$ satisfying conditions

$$[e,f] = h,\ [h,e] = 2e,\ [h,f] = -2f.$$

Fix a Cartan involution θ of $\mathfrak{g}$, with Cartan decompositions $\mathfrak{g} = \mathfrak{k} \oplus \mathfrak{p}$, $\mathfrak{g}_{\mathbb{C}} = \mathfrak{k}_{\mathbb{C}} \oplus \mathfrak{p}_{\mathbb{C}}$. A standard triple (e,f,h) in $\mathfrak{g}$ is a *Cayley* triple, if

$$f = -\theta(e), h = -\theta(h).$$

(To the best of our knowledge, such triples appeared for the first time in published literature in [9, Section 14].)

By definition, the Cayley transform of a Cayley triple (e,f,h) is the standard triple (e',f',h') in $\mathfrak{g}_{\mathbb{C}}$ defined by

$$\begin{aligned} e' &= \frac{1}{2}(e+f-ih), \\ f' &= \frac{1}{2}(e+f+ih), \\ h' &= -i(e-f). \end{aligned} \tag{48}$$

The Kostant-Sekiguchi map $\mathcal{S}$ sends the G-orbit of e in $\mathfrak{g}$ into the $K_{\mathbb{C}}$-orbit of e' in $\mathfrak{p}_{\mathbb{C}}$, where $K_{\mathbb{C}}$ is the complexification of K. The Kostant-Sekiguchi map $\bar{\mathcal{S}}$, equal to the composition of $\mathcal{S}$ with the complex conjugation of $\mathfrak{g}_{\mathbb{C}}$ over the real form $\mathfrak{g} \subseteq \mathfrak{g}_{\mathbb{C}}$, maps

$\mathcal{O}$	$\mu_0(\mathcal{O})$	$\mu_1(\mathcal{O})$
	$\mathbb{D}=\mathbb{R}$	
$(\mathbb{C}[0],\, sym,\, 4k)$	$(\mathbb{C}[0],\, sym,\, 2k)$	$(\mathbb{C}[1],\, sym,\, 2k{-}1)$
$(\mathbb{C}[2],\, sym,\, 4k)$	$(\mathbb{C}[2],\, sym,\, 2k)$	$(\mathbb{C}[3],\, sym,\, 2k{-}1)$
$(\mathbb{C}[1],\, sym,\, 4k{+}2)$	$(\mathbb{C}[2],\, sym,\, 2k)$	$(\mathbb{C}[1],\, sym,\, 2k{+}1)$
$(\mathbb{C}[3],\, sym,\, 4k{+}2)$	$(\mathbb{C}[0],\, sym,\, 2k)$	$(\mathbb{C}[3],\, sym,\, 2k{+}1)$
$(\mathbb{C}[1]\oplus\mathbb{C}[3],\, sk,\, 4k)$	$(\mathbb{C}[0]\oplus\mathbb{C}[2],\, sk,\, 2k{-}1)$	$(\mathbb{C}[1]\oplus\mathbb{C}[3],\, sk,\, 2k)$
$(\mathbb{C}[0]\oplus\mathbb{C}[3],\, sym,\, 4k{+}1)$	$(\mathbb{C}[0],\, sym,\, 2k)^{\oplus 2}$	$(\mathbb{C}[1]\oplus\mathbb{C}[3],\, sk,\, 2k)$
$(\mathbb{C}[1]\oplus\mathbb{C}[2],\, sym,\, 4k{+}1)$	$(\mathbb{C}[2],\, sym,\, 2k)^{\oplus 2}$	$(\mathbb{C}[1]\oplus\mathbb{C}[3],\, sk,\, 2k)$
$(\mathbb{C}[0]\oplus\mathbb{C}[2],\, sk,\, 4k{+}2)$	$(\mathbb{C}[0]\oplus\mathbb{C}[2],\, sk,\, 2k{+}1)$	$(\mathbb{C}[1]\oplus\mathbb{C}[3],\, sk,\, 2k)$
$(\mathbb{C}[0]\oplus\mathbb{C}[1],\, sk,\, 4k{+}3)$	$(\mathbb{C}[0]\oplus\mathbb{C}[2],\, sk,\, 2k{+}1)$	$(\mathbb{C}[1],\, sym,\, 2k{+}1)^{\oplus 2}$
$(\mathbb{C}[2]\oplus\mathbb{C}[3],\, sk,\, 4k{+}3)$	$(\mathbb{C}[0]\oplus\mathbb{C}[2],\, sk,\, 2k{+}1)$	$(\mathbb{C}[3],\, sym,\, 2k{+}1)^{\oplus 2}$
	$\mathbb{D}=\mathbb{C}.$	
$(\mathbb{C}[0],\, m)$	$(\mathbb{C}[0],\, [\frac{m}{2}])$	$(\mathbb{C}[1],\, [\frac{m-1}{2}])$
$(\mathbb{C}[1],\, m)$	$(\mathbb{C}[2],\, [\frac{m-1}{2}])$	$(\mathbb{C}[1],\, [\frac{m}{2}])$
$(\mathbb{C}[2],\, m)$	$(\mathbb{C}[2],\, [\frac{m}{2}])$	$(\mathbb{C}[3],\, [\frac{m-1}{2}])$
$(\mathbb{C}[3],\, m)$	$(\mathbb{C}[0],\, [\frac{m-1}{2}])$	$(\mathbb{C}[3],\, [\frac{m}{2}])$
	$\mathbb{D}=\mathbb{H}.$	
$(\mathbb{C}^2[0],\, sk,\, 4k)$	$(\mathbb{C}^2[0],\, sk,\, 2k)$	$(\mathbb{C}^2[1],\, sk,\, 2k{-}1)$
$(\mathbb{C}^2[2],\, sk,\, 4k)$	$(\mathbb{C}^2[2],\, sk,\, 2k)$	$(\mathbb{C}^2[3],\, sk,\, 2k{-}1)$
$(\mathbb{C}^2[1],\, sk,\, 4k{+}2)$	$(\mathbb{C}^2[2],\, sk,\, 2k)$	$(\mathbb{C}^2[1],\, sk,\, 2k{+}1)$
$(\mathbb{C}^2[3],\, sk,\, 4k{+}2)$	$(\mathbb{C}^2[0],\, sk,\, 2k)$	$(\mathbb{C}^2[3],\, sk,\, 2k{+}1)$
$(\mathbb{C}[1]\oplus\mathbb{C}[3],\, sym,\, 4k)$	$(\mathbb{C}[0]\oplus\mathbb{C}[2],\, sym,\, 2k{-}1)$	$(\mathbb{C}[1]\oplus\mathbb{C}[3],\, sym,\, 2k)$
$(\mathbb{C}[0]\oplus\mathbb{C}[3],\, sk,\, 4k{+}1)$	$(\mathbb{C}^2[0],\, sk,\, 2k)$	$(\mathbb{C}[1]\oplus\mathbb{C}[3],\, sym,\, 2k)$
$(\mathbb{C}[1]\oplus\mathbb{C}[2],\, sk,\, 4k{+}1)$	$(\mathbb{C}^2[2],\, sk,\, 2k)$	$(\mathbb{C}[1]\oplus\mathbb{C}[3],\, sym,\, 2k)$
$(\mathbb{C}[0]\oplus\mathbb{C}[2],\, sym,\, 4k{+}2)$	$(\mathbb{C}[0]\oplus\mathbb{C}[2],\, sym,\, 2k{+}1)$	$(\mathbb{C}[1]\oplus\mathbb{C}[3],\, sym,\, 2k)$
$(\mathbb{C}[0]\oplus\mathbb{C}[1],\, sym,\, 4k{+}3)$	$(\mathbb{C}[0]\oplus\mathbb{C}[2],\, sym,\, 2k{+}1)$	$(\mathbb{C}^2[1],\, sk,\, 2k{+}1)$
$(\mathbb{C}[2]\oplus\mathbb{C}[3],\, sym,\, 4k{+}3)$	$(\mathbb{C}[0]\oplus\mathbb{C}[2],\, sym,\, 2k{+}1)$	$(\mathbb{C}^2[3],\, sk,\, 2k{+}1)$

Table 4 Moment maps on indecomposable orbits in $W^+_{\mathbb{C}}$.

the G-orbit of e into the $K_{\mathbb{C}}$-orbit of f'. We shall focus on the map $\mathcal{S}$. The computations for $\bar{\mathcal{S}}$ are parallel, with i replaced by $-i$.

Proposition 6.1. Let (e, f, h) be a standard triple in $\mathfrak{g}_{\mathbb{C}}$, and let

$$\mathcal{C} = \exp(i\frac{\pi}{4}ad(e+f)) \in \mathrm{Aut}(\mathfrak{g}_{\mathbb{C}}), \tag{49}$$

$$\bar{\mathcal{C}} = \exp(-i\frac{\pi}{4}ad(e+f)) \in \mathrm{Aut}(\mathfrak{g}_{\mathbb{C}}). \tag{50}$$

Then

$$\begin{aligned}
\mathcal{C}(e) &= \bar{\mathcal{C}}(f) = \frac{1}{2}(e+f-ih),\\
\mathcal{C}(f) &= \bar{\mathcal{C}}(e) = \frac{1}{2}(e+f+ih),\\
\mathcal{C}(h) &= -\bar{\mathcal{C}}(h) = -i(e-f).
\end{aligned} \tag{51}$$

In particular, if (e, f, h) is a Cayley triple in $\mathfrak{g}$, then the triple

$$(\mathcal{C}(e), \mathcal{C}(f), \mathcal{C}(h))$$

is equal to the Cayley transform of (e, f, h).

Proof. The following formulas are easy to check:

$$\begin{aligned}
&ad(e+f)^{2k}e = 2^{2k-1}(e-f) \qquad (k \geq 1),\\
&ad(e+f)^{2k+1}e = -2^{2k}h \qquad (k \geq 0),\\
&ad(e+f)^{2k}f = -2^{2k-1}(e-f) \qquad (k \geq 1),\\
&ad(e+f)^{2k+1}f = 2^{2k}h \qquad (k \geq 0),\\
&ad(e+f)^{2k}h = 2^{2k}h \qquad (k \geq 0),\\
&ad(e+f)^{2k+1}h = -2^{2k+1}(e-f) \qquad (k \geq 0).
\end{aligned}$$

Hence, for any $z \in \mathbb{C}$,

$$\begin{aligned}
&\exp(z\, ad(e+f))e = \cosh^2(z)e - \sinh^2(z)f - \cosh(z)\sinh(z)h,\\
&\exp(z\, ad(e+f))f = -\sinh^2(z)e + \cosh^2(z)f + \cosh(z)\sinh(z)h,\\
&\exp(z\, ad(e+f))h = \cosh(2z)h - \sinh(2z)(e-f).
\end{aligned}$$

Substitution of $z = \pm i\frac{\pi}{4}$ into this formulas completes the proof. □

If G is a complex group then there are identifications $\mathfrak{p}_{\mathbb{C}} = \mathfrak{g}$ and $K_{\mathbb{C}} = G$ such that the $K_{\mathbb{C}}$ orbits in $\mathfrak{p}_{\mathbb{C}}$ become the G orbits in $\mathfrak{g}$ and $S = \bar{S}$ is the identity.

Let V and τ be as in Section 5.1, with additional assumption that either $V = V_0$ or $V = V_1$. Let T be as in Section 5.3, let θ be the Cartan involution on $\mathfrak{g}(V, \tau)$ equal to the conjugation by T and assume that $e, f, h \in \mathfrak{g}(V, \tau)$ form a Cayley triple. Then $i(e+f)$ is in the complexification of $\mathfrak{g}(V, \tau)$ which coincides with $\mathfrak{g}(U, \phi)$ as in section 5.4. Set

$$c = \exp(i\frac{\pi}{4}(e+f)) \in G(U, \phi), \tag{52}$$

$$\bar{c} = \exp(-i\frac{\pi}{4}(e+f)) \in G(U, \phi). \tag{53}$$

Then a standard Lie theory argument shows that the automorphism $\mathcal{C} \in \mathrm{Aut}(\mathfrak{g}(V, \tau)_{\mathbb{C}}) = \mathrm{Aut}(\mathfrak{g}(U, \phi))$ defined by (49) is equal to conjugation by c. In particular Proposition 6.1 implies that the Kostant-Sekiguchi map $\mathcal{S}$ sends the orbit of e to the orbit of cec^{-1}. Similarly, the Kostant-Sekiguchi map $\bar{\mathcal{S}}$ sends the orbit of e to the orbit of $\bar{c}e\bar{c}^{-1}$.

6.1 The Kostant-Sekiguchi correspondence for indecomposable nilpotents

In this section we will compute the maps $e \longmapsto \mathcal{C}(e) = cec^{-1}$, $e \longmapsto \bar{\mathcal{C}}(e) = \bar{c}e\bar{c}^{-1}$ for indecomposable nilpotents $e \in \mathfrak{g}(V,\tau)$. We will do this by a case-by-case analysis, according to the classification of nilpotent orbits in $\mathfrak{g}(V,\tau)$ described in Section 5.1. In each case we will

- define the space V,
- describe the action of e on an explicit basis of V,
- define the form τ in this basis,
- define the map $T : V \longrightarrow V$ in this basis,
- compute the elements $c, \bar{c} \in G(U,\phi)$ in the basis of U induced by the chosen basis of V,
- compute the formed spaces $(\tilde{U},\tilde{\phi})$ corresponding to the nilpotent elements (cec^{-1}, U), $(\bar{c}e\bar{c}^{-1}, U)$ as in section 5.3.

We begin with a general construction, which will be used in all cases.

Let ξ be a non-degenerate symplectic form on $\mathbb{R}^2$, and let $\epsilon_1, \epsilon_2 \in \mathbb{R}^2$ be a basis such that

$$\xi(\epsilon_1,\epsilon_1) = \xi(\epsilon_2,\epsilon_2) = 0, \quad \xi(\epsilon_1,\epsilon_2) = 1. \tag{54}$$

We extend the form ξ to the tensor algebra of $\mathbb{R}^2$, and restrict to the subspace $S^m\mathbb{R}^2$ of symmetric homogeneous tensors of degree $m = 0, 1, 2, ...$ Then a straightforward calculation shows that

$$\xi(\epsilon_1^k\epsilon_2^{m-k}, \epsilon_1^l\epsilon_2^{m-l}) = \begin{cases} (-1)^{m-k}\dfrac{k!(m-k)!}{m!}, & \text{if } \ l = m-k, \\ 0, & \text{otherwise.} \end{cases} \tag{55}$$

Let $\mathbb{V} = S^m\mathbb{R}^2$. We set

$$\tau(u,v) = (-1)^m\xi(u,v) \qquad (u, v \in \mathbb{V}). \tag{56}$$

Let $v_k = \epsilon_1^k\epsilon_2^{m-k}$, $0 \le k \le m$. Then (55) may be rewritten as

$$\tau(v_k, v_l) = \begin{cases} (-1)^k\dfrac{k!(m-k)!}{m!}, & \text{if } \ l = m-k, \\ 0, & \text{otherwise.} \end{cases} \tag{57}$$

Let $\mathbb{T} : \mathbb{V} \to \mathbb{V}$ be a linear map defined by

$$\mathbb{T}v_k = (-1)^{m-k}v_{m-k} \qquad (0 \le k \le m). \tag{58}$$

Then (57) implies that $\mathbb{T} \in G(\mathbb{V},\tau)$ and that the form $\tau(\mathbb{T}_-,_-)$ is symmetric and positive definite. Let $E, F, H \in \mathfrak{g}(\mathbb{R}^2,\xi)$ (a Lie algebra isomorphic to $sl_2(\mathbb{R})$) be defined by

$$\begin{aligned} &E(\epsilon_1) = 0, \ \ F(\epsilon_1) = \epsilon_2, \ H(\epsilon_1) = \epsilon_1, \\ &E(\epsilon_2) = \epsilon_1, \ F(\epsilon_2) = 0, \ \ H(\epsilon_2) = -\epsilon_2. \end{aligned} \tag{59}$$

These elements act on $\mathbb{V}$ and it is easy to check that

$$E(v_k) = (m-k)v_{k+1},\ F(v_k) = kv_{k-1},\ H(v_k) = (-m+2k)v_k. \tag{60}$$

The formulas (58) and (60) imply that the elements E, F and H form a Cayley triple in $\mathfrak{g}(\mathbb{V},\tau)$ with respect to the Cartan involution $\theta = Ad(\mathbb{T})$.

The point of this construction is to avoid direct calculation of the exponential in (52). Instead we proceed as follows. Let $\mathbb{U} = \mathbb{C}\otimes\mathbb{V} = S^m\mathbb{C}^2$ be the complexification of $\mathbb{V}$. The complexification of the group $G(\mathbb{R}^2,\xi)$ (isomorphic to $SL(2,\mathbb{C})$) acts on the space $\mathbb{U}$. Consider E, F as elements of $\mathbb{C}^2$. It is easy to check that for $z\in\mathbb{C}$,

$$\begin{aligned}\exp(z(E+F))(\epsilon_1) &= \cosh(z)\epsilon_1 + \sinh(z)\epsilon_2\\ \exp(z(E+F))(\epsilon_2) &= \sinh(z)\epsilon_1 + \cosh(z)\epsilon_2,\end{aligned}$$

and hence, as an endomorphism of $\mathbb{U}$,

$$\exp(z(E+F))(v_k) = \sum_{l=0}^{k}\sum_{j=0}^{m-k}\begin{pmatrix}k\\ l\end{pmatrix}\begin{pmatrix}m-k\\ j\end{pmatrix}\cosh(z)^{m-k+l-j}\sinh(z)^{k-l+j}v_{l+j}.$$

Therefore, by taking $z = i\frac{\pi}{4}$,

$$c(v_k) = 2^{-m/2}\sum_{l=0}^{k}\sum_{j=0}^{m-k}\begin{pmatrix}k\\ l\end{pmatrix}\begin{pmatrix}m-k\\ j\end{pmatrix} i^{k-l+j}v_{l+j}. \tag{61}$$

The formulas (58) and (61) imply that

$$\mathbb{T}(c(v_k)) = i^{m-2k}c(v_k) \qquad (0\le k\le m). \tag{62}$$

Similarly,

$$\mathbb{T}(\bar{c}(v_k)) = (-i)^{m-2k}\bar{c}(v_k) \qquad (0\le k\le m). \tag{63}$$

We are now ready for the computation of the Kostant-Sekiguchi maps for all indecomposable orbits. Consider first the case $\mathbb{D}=\mathbb{R}$. According to our analysis in Section 5.1 there are six possibilities for the formed space $(\tilde{V},\tilde{\tau})$ corresponding to an indecomposable nilpotent element $e\in\mathfrak{g}(V,\tau)$ of height m, namely $(\mathbb{R}[b],+), (\mathbb{R}[b],-)$ with $b+m$ even, $(\mathbb{R}^2[b],sk)$ with $b+m$ odd, $b=0,1$, where as usual $\mathbb{R}^k[b]$ denotes the graded vector space concentrated in degree b.

For an explicit realization of the first case, let $(V,\tau) = (\mathbb{V}[b],\tau)$, $T=\mathbb{T}$ and $e=E$. The space V has a decomposition

$$V = \mathbb{R}v_0\oplus\mathbb{R}v_1\oplus ...\oplus\mathbb{R}v_m, \tag{64}$$

with $e(\mathbb{R}v_k) = \mathbb{R}v_{k+1}$ and

$$\tau(v_0, e^m(v_0)) = m!, \tag{65}$$

which implies that the space $(\tilde{V}, \tilde{\tau})$ is of the form $(\mathbb{R}[b], +)$.

The complexification U of V (equal to $\mathbb{U}$ in this case) has a decomposition

$$U = \mathbb{C}c(v_0) \oplus \mathbb{C}c(v_1) \oplus ... \oplus \mathbb{C}c(v_m), \tag{66}$$

with $cec^{-1}(\mathbb{C}c(v_k)) = \mathbb{C}c(v_{k+1})$. Moreover, by (62),

$$T(c(v_0)) = i^m c(v_0).$$

This implies that the formed space $(\tilde{U}, \tilde{\phi})$ is of the form $(\mathbb{C}[\overline{m}], \tilde{\phi})$ with $\tilde{\phi}$ symmetric, $\overline{m} = m \mod 4$, so this is the formed space corresponding to the nilpotent element $(cec^{-1}, U) \in \mathfrak{g}(U, \phi)_2$. Similarly, by (63)

$$T(\bar{c}(v_0)) = i^{-m} c(v_0),$$

This implies that the formed space $(\tilde{U}, \tilde{\phi})$ is now of the form $(\mathbb{C}[\overline{-m}], \tilde{\phi})$ with $\tilde{\phi}$ symmetric, so this is the formed space corresponding to the nilpotent element $(\bar{c}e\bar{c}^{-1}, U) \in \mathfrak{g}(U, \phi)_2$.

In the same way, if we consider the space $(V, \tau') = (\mathbb{V}[b], -\tau)$ with $T = -\mathbb{T}$, the indecomposable formed space corresponding to (e, V) will be of type $(\mathbb{R}[b], -)$, the indecomposable formed space corresponding to (cec^{-1}, U) will be of type $(\mathbb{C}[\overline{m+2}], \tilde{\phi})$ with $\tilde{\phi}$ symmetric (the eigenvalue of T on $c(v_0)$ is equal to $-i^m = i^{m+2}$ in this case), and the indecomposable formed space corresponding to $(\bar{c}e\bar{c}^{-1}, U)$ will be of type $(\mathbb{C}[\overline{-m+2}], \tilde{\phi})$ with $\tilde{\phi}$ symmetric.

Finally we consider the space $V = \mathbb{V} \otimes \mathbb{R}^2$ with the form $\tau \otimes \xi$, where ξ is the skew-symmetric form on $\mathbb{R}^2$ defined in (54). Let R be the endomorphism of $\mathbb{R}^2$ defined by $R(\epsilon_1) = \epsilon_2$, $R(\epsilon_2) = -\epsilon_1$. Then the form $\xi(R\ ,\ )$ is symmetric and positive definite. Let $T = \mathbb{T} \otimes R : V \longrightarrow V$. The form $(\tau \otimes \xi)(T_-, _-)$ is symmetric and positive definite. Moreover, $T \in G(V \otimes \mathbb{R}^2, \tau \otimes \xi)$, and it is clear that the elements $e = E \otimes 1$, $f = F \otimes 1$, $h = H \otimes 1$ form a Cayley triple in $\mathfrak{g}(V \otimes \mathbb{R}^2, \tau \otimes \xi)$ with respect to the Cartan involution $Ad(T)$. Let $U = V \otimes \mathbb{C}$. We have

$$(\tau \otimes \xi)(v_0 \otimes \epsilon_\mu, e^m(v_0 \otimes \epsilon_\nu)) = \tau(v_0, E^m(v_0))\xi(\epsilon_\mu, \epsilon_\nu) = m!\xi(\epsilon_\mu, \epsilon_\nu),$$

$$c(v_k \otimes \epsilon_\nu) = 2^{-m/2} \sum_{l=0}^{k} \sum_{r=0}^{m-k} \begin{pmatrix} k \\ l \end{pmatrix} \begin{pmatrix} m-k \\ r \end{pmatrix} i^{k-l+r} v_{l+r} \otimes \epsilon_\nu,$$

$$T(c(v_k \otimes \epsilon_\nu)) = i^{m-2k} c(v_k \otimes R(\epsilon_\nu)).$$

Hence, in particular,

$$\begin{aligned} T(c(v_0 \otimes \epsilon_1) + ic(v_0 \otimes \epsilon_2)) &= -i^{m+1}(c(v_0 \otimes \epsilon_1) + ic(v_0 \otimes \epsilon_2)), \\ T(c(v_0 \otimes \epsilon_1) - ic(v_0 \otimes \epsilon_2)) &= \quad i^{m+1}(c(v_0 \otimes \epsilon_1) - ic(v_0 \otimes \epsilon_2)). \end{aligned} \tag{67}$$

It follows that T has two eigenvalues i^{m+1}, i^{m+3} on the space $\tilde{U}$, so the formed space $(\tilde{U}, \tilde{\phi})$ is of type $(\mathbb{C}[\overline{m+1}] \oplus \mathbb{C}[\overline{m+3}], \tilde{\phi})$. Similarly, we have

$$\begin{aligned} T(\bar{c}(v_0 \otimes \epsilon_1) + i\bar{c}(v_0 \otimes \epsilon_2)) &= -i^{-m+1}(\bar{c}(v_0 \otimes \epsilon_1) + i\bar{c}(v_0 \otimes \epsilon_2)), \\ T(\bar{c}(v_0 \otimes \epsilon_1) - i\bar{c}(v_0 \otimes \epsilon_2)) &= \quad i^{-m+1}(\bar{c}(v_0 \otimes \epsilon_1) - i\bar{c}(v_0 \otimes \epsilon_2)), \end{aligned} \tag{68}$$

hence the formed space $(\tilde{U}, \tilde{\phi})$ is of type $(\mathbb{C}[\overline{-m+1}] \oplus \mathbb{C}[\overline{-m+3}], \tilde{\phi})$ in this case.

We summarize our computations in the following proposition.

Proposition 6.2. The Kostant-Sekiguchi correspondences for the orbits of indecomposable nilpotent elements in Lie algebras of isometries of formed spaces over $\mathbb{R}$ map the orbit $\mathcal{O} \subseteq \mathfrak{g}(V, \tau)$ of a nilpotent element of height m corresponding to a formed space $(\tilde{V}, \tilde{\tau})$ into the orbits $\mathcal{S}(\mathcal{O}), \bar{\mathcal{S}}(\mathcal{O}) \subseteq \mathfrak{g}(U, \phi)$ corresponding to the formed spaces $(\tilde{U}, \tilde{\phi})$ as in the following table.

m	$\mathcal{O}$	$\mathcal{S}(\mathcal{O})$	$\bar{\mathcal{S}}(\mathcal{O})$
even	$(\mathbb{R}[0], +)$	$(\mathbb{C}[\overline{m}], sym)$	$(\mathbb{C}[\overline{m}], sym)$
even	$(\mathbb{R}[0], -)$	$(\mathbb{C}[\overline{m+2}], sym)$	$(\mathbb{C}[\overline{m+2}], sym)$
odd	$(\mathbb{R}^2[0], sk)$	$(\mathbb{C}[0] \oplus \mathbb{C}[2], sk)$	$(\mathbb{C}[0] \oplus \mathbb{C}[2], sk)$
odd	$(\mathbb{R}[1], +)$	$(\mathbb{C}[\overline{m}], sym)$	$(\mathbb{C}[\overline{m+2}], sym)$
odd	$(\mathbb{R}[1], -)$	$(\mathbb{C}[\overline{m+2}], sym)$	$(\mathbb{C}[\overline{m}], sym)$
even	$(\mathbb{R}^2[1], sk)$	$(\mathbb{C}[1] \oplus \mathbb{C}[3], sk)$	$(\mathbb{C}[1] \oplus \mathbb{C}[3], sk)$

Now assume that $\mathbb{D} = \mathbb{C}$ or $\mathbb{H}$. Let $\tau_{\mathbb{D}}$ be a hermitian form on $\mathbb{D}$ such that $\tau_{\mathbb{D}}(1,1) = 1$. Consider the left vector space $V = \mathbb{D} \otimes \mathbb{V}$ over $\mathbb{D}$, with the form $\tau_{\mathbb{D}} \otimes \tau$. Then the map $T = 1 \otimes \mathbb{T}$ belongs to $G(V, \tau_{\mathbb{D}} \otimes \tau)$ and the form $(\tau_{\mathbb{D}} \otimes \tau)(T_{-}, _{-})$ is hermitian and positive definite. Furthermore, it is clear that the elements $e = 1 \otimes E$, $f = 1 \otimes F$, $h = 1 \otimes H$ form a Cayley triple in $\mathfrak{g}(V, \tau_{\mathbb{D}} \otimes \tau)$ with respect to $Ad(T)$. The equality (65) implies that the indecomposable formed space $(\tilde{V}, \widetilde{\tau_{\mathbb{D}} \otimes \tau})$ is of the form $(\mathbb{D}[b], +)$.

Moreover, the map c defined in (52), can be written as

$$c(1 \otimes v_k) = 2^{-m/2} \sum_{l=0}^{k} \sum_{r=0}^{m-k} \begin{pmatrix} k \\ l \end{pmatrix} \begin{pmatrix} m-k \\ r \end{pmatrix} i^{k-l+r} \otimes v_{l+r},$$

and therefore

$$T(c(1 \otimes v_k)) = i^{m-2k} c(1 \otimes v_k) \qquad (0 \le k \le m). \tag{69}$$

Similarly,

$$T(\bar{c}(1 \otimes v_k)) = i^{-m-2k} \bar{c}(1 \otimes v_k) \qquad (0 \le k \le m). \tag{70}$$

Assume that $\mathbb{D}=\mathbb{C}$ with ι the complex conjugation. By the results of Section 5.1 there are two possibilities for the formed space corresponding to a indecomposable nilpotent element of height m, namely $(\mathbb{C},+)$ and $(\mathbb{C},-)$ for even m and $(\mathbb{C},+i)$ and $(\mathbb{C},-i)$ for odd m (we assume that $\mathbb{C}$ is in degree zero in all cases). Similarly, by Proposition 5.5 the formed space $\tilde{U}$ corresponding to an orbit of an indecomposable nilpotent element in $\mathfrak{p}_{\mathbb{C}}$ is of the form $\mathbb{C}[k]$, $k=0,2$. In the above construction the space $(\tilde{V},\widetilde{\tau_{\mathbb{C}}\otimes\tau})$ is of the form $(\mathbb{C},+)$, and the space $\tilde{U}$ is equal to $\mathbb{C}[\overline{m}]$. When we replace the form $\tau_{\mathbb{C}}$ by $i^k\tau_{\mathbb{C}}$ and the map T by $i^{-k}T$, we will get the remaining cases of the following proposition.

Proposition 6.3. The Kostant-Sekiguchi correspondences for the orbits of indecomposable nilpotent elements in Lie algebras of isometries of formed spaces over $\mathbb{C}$ map the orbit $\mathcal{O}\subseteq\mathfrak{g}(V,\tau)$ of a nilpotent element of height m corresponding to a formed space $(\tilde{V},\tilde{\tau})$ into the orbits $\mathcal{S}(\mathcal{O}),\bar{\mathcal{S}}(\mathcal{O})\subseteq\mathfrak{g}(U,\phi)$ corresponding to the space $\tilde{U}$ as in the following table.

$\mathcal{O}$	$\mathcal{S}(\mathcal{O})$	$\bar{\mathcal{S}}(\mathcal{O})$
$(\mathbb{C}[0],+,2s)$	$(\mathbb{C}[2s],2s)$	$(\mathbb{C}[2s],2s)$
$(\mathbb{C}[0],-,2s)$	$(\mathbb{C}[2s+2],2s)$	$(\mathbb{C}[2s+2],2s)$
$(\mathbb{C}[0],+i,2s+1)$	$(\mathbb{C}[2s],2s+1)$	$(\mathbb{C}[2s+2],2s+1)$
$(\mathbb{C}[0],-i,2s+1)$	$(\mathbb{C}[2s+2],2s+1)$	$(\mathbb{C}[2s],2s+1)$
$(\mathbb{C}[1],+,2s+1)$	$(\mathbb{C}[2s+1],2s+1)$	$(\mathbb{C}[2s+3],2s+1)$
$(\mathbb{C}[1],-,2s+1)$	$(\mathbb{C}[2s+3],2s+1)$	$(\mathbb{C}[2s+1],2s+1)$
$(\mathbb{C}[1],+i,2s)$	$(\mathbb{C}[2s+3],2s)$	$(\mathbb{C}[2s+3],2s)$
$(\mathbb{C}[1],-i,2s)$	$(\mathbb{C}[2s+1],2s)$	$(\mathbb{C}[2s+1],2s)$

Now assume that $\mathbb{D}=\mathbb{H}$, so our formed space is equal to $(V,\tau_{\mathbb{H}}\otimes\tau)$. It follows that

$$T(c(1\otimes v_0))=i^m c(1\otimes v_0),$$

and similarly

$$T(c(j\otimes v_0))=i^m c(j\otimes v_0),$$

where j is the element of the standard basis $\{1,i,j,k\}$ of $\mathbb{H}$, hence the formed space $(\tilde{U},\tilde{\phi})$ is of the form $(\mathbb{C}^2[\overline{m}],\tilde{\phi})$ with $\tilde{\phi}$ skew-symmetric.

If we replace the form τ by $-\tau$ and the map T by $-T$, we will obtain the nilpotent element (e,V) whose corresponding indecomposable formed space $(\tilde{V},\widetilde{\tau_{\mathbb{H}}\otimes\tau})$ is of the form $(\mathbb{D}[b],-)$, and the nilpotent element (cec^{-1},U) whose corresponding indecomposable formed space $(\tilde{U},\tilde{\phi})$ is of the form $(\mathbb{C}^2[\overline{m+2}],\tilde{\phi})$ with $\tilde{\phi}$ skew-symmetric.

The last case to consider is the case $(\tilde{V},\tilde{\tau})$ of type $(\mathbb{H}[b],sk)$ with $b+m$ odd. We proceed as follows.

For $x, y \in \mathbb{H}$ set $\tau'_{\mathbb{H}}(x,y) = xj\iota(y) \in \mathbb{H}$. Then $\tau'_{\mathbb{H}}$ is a skew-hermitian form on the left vector space $\mathbb{H}$. Consider the space $V = \mathbb{H} \otimes \mathbb{V}$ with the form $\tau'_{\mathbb{H}} \otimes \tau$. Let $e = 1 \otimes E$, as before. Since

$$(\tau'_{\mathbb{H}} \otimes \tau)(1 \otimes v_0, e^m(1 \otimes v_0)) = \tau'_{\mathbb{H}}(1,1)\tau(v_0, E^m(v_0)) = m!\, j,$$

the formed space $(\tilde{V}, \widetilde{\tau'_{\mathbb{H}} \otimes \tau})$ is of the form $(\mathbb{H}[b], sk)$.

Let $R_{j^{-1}}$ denote right multiplication by j^{-1} on $\mathbb{H}$. Then the map $T = R_{j^{-1}} \otimes \mathbb{T}$ belongs to $G(\mathbb{H} \otimes V, \tau'_{\mathbb{H}} \otimes \tau)$ and the form $(\tau'_{\mathbb{H}} \otimes \tau)(T_{-},_{-})$ is hermitian and positive definite. Furthermore the elements $e = 1 \otimes E$, $f = 1 \otimes F$, $h = 1 \otimes H$ form a Cayley triple in $\mathfrak{g}(\mathbb{H} \otimes V, \tau'_{\mathbb{H}} \otimes \tau)$ with respect to the Cartan involution $Ad(T)$. A straightforward calculation using (58) and (61) shows that

$$\begin{aligned} T(c(1 \otimes v_0)) &= -i^m c(j \otimes v_0), \\ T(c(j \otimes v_0)) &= \quad i^m c(1 \otimes v_0), \end{aligned} \tag{71}$$

hence

$$\begin{aligned} T(c(1 \otimes v_0) + ic(j \otimes v_0)) &= i^{m+1}(c(1 \otimes v_0) + ic(j \otimes v_0)), \\ T(c(1 \otimes v_0) - ic(j \otimes v_0)) &= i^{m+3}(c(1 \otimes v_0) - ic(j \otimes v_0)), \end{aligned} \tag{72}$$

so the restriction of T to the space $c(\mathbb{H} \otimes v_0)$ has two eigenvalues i^{m+1} and i^{m+3}. The eigenspaces are isotropic with respect to the form $\tilde{\phi}$ if ϕ is the form defined in (46) with τ in (46) replaced by $\tau'_{\mathbb{H}} \otimes \tau$. It follows that the indecomposable formed space $(\tilde{U}, \tilde{\phi})$ corresponding to cec^{-1} is of the form $(\mathbb{C}[\overline{m+1}] \oplus \mathbb{C}[\overline{m+3}], \tilde{\phi})$ with $\tilde{\phi}$ symmetric.

We summarize our computations in the following proposition.

Proposition 6.4. The Kostant-Sekiguchi correspondences for the orbits of indecomposable nilpotent elements in Lie algebras of isometries of formed spaces over $\mathbb{H}$ map the orbit $\mathcal{O} \subseteq \mathfrak{g}(V, \tau)$ of a nilpotent element of height m corresponding to a formed space $(\tilde{V}, \tilde{\tau})$ into the orbits $\mathcal{S}(\mathcal{O}), \bar{\mathcal{S}}(\mathcal{O}) \subseteq \mathfrak{g}(U, \phi)$ corresponding to the formed spaces $(\tilde{U}, \tilde{\phi})$ as in the following table.

m	$\mathcal{O}$	$\mathcal{S}(\mathcal{O})$	$\bar{\mathcal{S}}(\mathcal{O})$
even	$(\mathbb{H}[0], +)$	$(\mathbb{C}^2[\overline{m}], sk)$	$(\mathbb{C}^2[\overline{m}], sk)$
even	$(\mathbb{H}[0], -)$	$(\mathbb{C}^2[\overline{m+2}], sk)$	$(\mathbb{C}^2[\overline{m+2}], sk)$
odd	$(\mathbb{H}[0], sk)$	$(\mathbb{C}[0] \oplus \mathbb{C}[2], sym)$	$(\mathbb{C}[0] \oplus \mathbb{C}[2], sym)$
odd	$(\mathbb{H}[1], +)$	$(\mathbb{C}^2[\overline{m}], sk)$	$(\mathbb{C}^2[\overline{m+2}], sk)$
odd	$(\mathbb{H}[1], -)$	$(\mathbb{C}^2[\overline{m+2}], sk)$	$(\mathbb{C}^2[\overline{m}], sk)$
even	$(\mathbb{H}[1], sk)$	$(\mathbb{C}[1] \oplus \mathbb{C}[3], sym)$	$(\mathbb{C}[1] \oplus \mathbb{C}[3], sym)$

We will say that an orbit $\mathcal{O} \subseteq \mathfrak{g}(V,\tau)$ is indecomposable if for every (or equivalently some) element $N \in \mathcal{O}$ the element (N,V) is indecomposable. Similarly we define indecomposable orbits in $\mathfrak{g}(U,\phi)$.

Corollary 6.5. The image of an indecomposable nilpotent orbit in $\mathfrak{g}(V,\tau)$ under a Kostant-Sekiguchi correspondence is also indecomposable.

6.2 The Kostant-Sekiguchi correspondences for general nilpotent elements

Let $N \in \mathfrak{g}(V,\tau)$ be an arbitrary nilpotent element, and let

$$(V,\tau) = (V^{(1)},\tau^{(1)}) \oplus \ldots \oplus (V^{(s)},\tau^{(s)}) \tag{73}$$

be an orthogonal decomposition such that each of the spaces $V^{(k)}$ is N-invariant and each of the restrictions $N^{(k)} = N|_{V^{(k)}}$ is an idecomposable nilpotent element in $\mathfrak{g}(V^{(k)},\tau^{(k)})$. Let $U^{(k)} = V^{(k)}\otimes\mathbb{C}$ if $\mathbb{D} = \mathbb{R}$, and $U^{(k)} = V^{(k)}|_{\mathbb{C}}$ if $\mathbb{D} = \mathbb{C},\mathbb{H}$. By the results of the previous subsection for each k there exists $T^{(k)} \in G(V^{(k)},\tau^{(k)})$ such that the form $\tau^{(k)}(T^{(k)}\_,\_)$ is hermitian and positive definite, and that $e^{(k)} = N^{(k)},\ f^{(k)} = -T^{(k)}e^{(k)}(T^{(k)})^{-1}, h^{(k)} = [e^{(k)},f^{(k)}]$ is a Cayley triple in $\mathfrak{g}(V^{(k)},\tau^{(k)})$ with respect to the Cartan involution $\theta^{(k)} = Ad(T^{(k)})$.

Moreover, if $c^{(k)}$ denotes the element $c^{(k)} = \exp(i\frac{\pi}{4}(e^{(k)} + f^{(k)})) \in G(U^{(k)},\phi^{(k)})$ (with $\phi^{(k)}$ defined by $\tau^{(k)}$ as in (46)), then the $G(U^{(k)},\phi^{(k)})$-orbit through $c^{(k)}e^{(k)}(c^{(k)})^{-1}$ is the image of the $G(V^{(k)},\tau^{(k)})$-orbit through $e^{(k)}$ by the Kostant-Sekiguchi correspondence $\mathcal{S}$.

Define $T \in G(V,\tau)$ as $T = T^{(1)} \oplus \ldots \oplus T^{(s)}$, then the form $\tau(T\_,\_)$ is hermitian and positive definite, and the triple $e = N, f = -TeT^{-1}, h = [e,f]$ is a Cayley triple in $\mathfrak{g}(V,\tau)$ with respect to the Cartan involution $\theta = Ad(T) = \theta^{(1)} \oplus \ldots \oplus \theta^{(s)}$. The element $c \in G(U,\phi)$ defined in (52) is equal to the product of commuting elements $c = c^{(1)}\cdot\ldots\cdot c^{(s)}$ and the nilpotent element $(cec^{-1},U) \in \mathfrak{g}(U,\phi)_2$, whose orbit in $\mathfrak{g}(U,\phi)_2$ is equal to the image of the $G(V,\tau)$-orbit of e under the Kostant-Sekiguchi correspondence $\mathcal{S}$, is equal to the orthogonal sum

$$(cec^{-1},U) = (c^{(1)}e^{(1)}(c^{(1)})^{-1},U^{(1)}) \oplus \ldots \oplus (c^{(s)}e^{(s)}(c^{(s)})^{-1},U^{(s)}).$$

We can conclude that the Kostant-Sekiguchi correspondence $\mathcal{S}$ is compatible with orthogonal decompositions of nilpotent elements in $\mathfrak{g}(V,\tau)$. The same statement holds for $\bar{\mathcal{S}}$.

A simple analysis of Propositions 6.2, 6.3 and 6.4 verifies the following statement.

Proposition 6.6. The maps $\mathcal{S}$,$\bar{\mathcal{S}}$ are not equal if the corresponding group $G(V_b,\tau_b)$ is isomorphic to $Sp_{2n}(\mathbb{R})$, O^*_{2n}, or $U_{p,q}$ (with $p,q > 0$). For the remaining isometry groups and for the general linear groups $\mathcal{S} = \bar{\mathcal{S}}$.

7 A counterexample

For two nilpotent orbits $\mathcal{O}_0 \subset \mathfrak{g}_0$ and $\mathcal{O}_1 \subset \mathfrak{g}_1$ we shall write $\mathcal{O}_0 \sim_W \mathcal{O}_1$ if and only if there is an orbit $\mathcal{O} \subset W$ such that

$$\mathcal{O}_0 = \nu_0(\mathcal{O}) \text{ and } \mathcal{O}_1 = \nu_1(\mathcal{O}).$$

Similarly, $\mathcal{O}_0 \sim_{W_{\mathbb{C}}^+} \mathcal{O}_1$ if and only if there is an orbit $\mathcal{O} \subset W_{\mathbb{C}}^+$ such that

$$\mathcal{O}_0 = \mu_0(\mathcal{O}) \text{ and } \mathcal{O}_1 = \mu_1(\mathcal{O}).$$

The relation $\sim_W$ is determined by Table 3 and the relation $\sim_{W_{\mathbb{C}}^+}$ is determined by Table 4. For an indecomposable orbit $\mathcal{O} \subset W$, the last column of the corresponding row of Table 3 contains $\mathcal{S}$ if and only if

$$\mathcal{S}\mu_0(\mathcal{O}) \sim_{W_{\mathbb{C}}^+} \mathcal{S}\mu_1(\mathcal{O}) \tag{74}$$

and similarly for $\bar{\mathcal{S}}$. In particular we see that (except for complex groups) there is no choice of the Kostant–Sekiguchi map $\mathcal{S}$ or $\bar{\mathcal{S}}$ for which the two relations would be compatible.

Below we provide a simple example (beyond the stable range) where the conjecture 1.1 is not true no matter which of the two possible Kostant-Sekiguchi maps is chosen.

We consider the dual pair $(O_{3,1}(\mathbb{R}), Sp_4(\mathbb{R}))$. Let $\mathcal{O}$ be the nilpotent orbit in $\mathfrak{o}_{3,1}$ corresponding to $(\mathbb{R},+,2)\oplus(\mathbb{R},+,0)$. The closure $\bar{\mathcal{O}}$ is the union of two orbits: $\mathcal{O}$ and $(\mathbb{R},+,0)^{\oplus 3}\oplus(\mathbb{R},-,0)$ (the zero orbit). In these terms

$$\begin{aligned}\nu_1\nu_0^{-1}(\bar{\mathcal{O}}) = \{&(\mathbb{R},+,1)\oplus(\mathbb{R},-,1),\ (\mathbb{R},+,3),\ (\mathbb{R},+,1)^{\oplus 2},\\ &(\mathbb{R},+,1)\oplus(\mathbb{R}^2,sk,0),\ (\mathbb{R}^2,sk,0)^{\oplus 2}\}\,.\end{aligned}$$

Then by Proposition 6.2 we have

$$\begin{aligned}\mathcal{S}(\nu_1\nu_0^{-1}(\bar{\mathcal{O}})) = \{&(\mathbb{C}[3],\ sym,\ 1)\oplus(\mathbb{C}[1],\ sym,\ 1),\ (\mathbb{C}[3],\ sym,\ 3),\\ &(\mathbb{C}[1],\ sym,\ 1)^{\oplus 2}, (\mathbb{C}[1]\oplus\mathbb{C}[3],\ sk,\ 0)^{\oplus 2},\\ &(\mathbb{C}[1],\ sym,\ 1)\oplus(\mathbb{C}[1]\oplus\mathbb{C}[3],\ sk,\ 0)\}.\end{aligned} \tag{75}$$

On the other hand

$$\mathcal{S}(\bar{\mathcal{O}}) = \{(\mathbb{C}[2],\ sym,\ 2)\oplus(\mathbb{C}[0],\ sym,\ 0),\ (\mathbb{C}[0],\ sym,\ 0)\}$$

and, by Table 4,

$$\begin{aligned}\mu_1\mu_0^{-1}(\mathcal{S}(\bar{\mathcal{O}})) = \{&(\mathbb{C}[3],\ sym,\ 1)^{\oplus 2},\ (\mathbb{C}[1],\ sym,\ 3),\\ &(\mathbb{C}[1],\ sym,\ 1)\oplus(\mathbb{C}[3],\ sym,\ 1),\\ &(\mathbb{C}[1]\oplus\mathbb{C}[3],\ sk,\ 0)\oplus(\mathbb{C}[3],\ sym,\ 1),\\ &(\mathbb{C}[1]\oplus\mathbb{C}[3],\ sk,\ 0)\oplus(\mathbb{C}[1],\ sym,\ 1),\\ &(\mathbb{C}[1]\oplus\mathbb{C}[3],\ sk,\ 0)^{\oplus 2}\}.\end{aligned} \tag{76}$$

In particular

$$\mathcal{S}(\nu_1\nu_0^{-1}(\bar{\mathcal{O}})) \neq \mu_1\mu_0^{-1}(\mathcal{S}(\bar{\mathcal{O}})) = \mu_1\mu_0^{-1}(\overline{\mathcal{S}\mathcal{O}}),$$

the equality holds because $\mathcal{S}$ commutes with orbit closures ([3], [16, p. 177]).

Replacing the Kostant-Sekiguchi map $\mathcal{S}$ by $\bar{\mathcal{S}}$ results in exchanging degrees 1 and 3 in (75) and in (76) (see Proposition 6.2), and these sets remain different.

8 Dual pairs of type I in the stable range

Recall that a dual pair $G(V_0,\tau_0)$, $G(V_1,\tau_1)$ is in the stable range with $G(V_1,\tau_1)$ - the smaller member if the dimension of V_1 is less than or equal to the Witt index of the form τ_0. The goal of this section is to verify the following special case of Conjecture 1.1.

Theorem 8.1. Let $G(V_0,\tau_0)$, $G(V_1,\tau_1)$ be a dual pair in the stable range with $G(V_1,\tau_1)$ - the smaller member. Then for every orbit
$\mathcal{O}\in\mathcal{NO}\mathfrak{g}(V_1,\tau_1)$ there is a unique orbit $\mathcal{O}_{max}\in\mathcal{NO}\mathfrak{g}(V_0,\tau_0)$ such that

$$\nu_0\nu_1^{-1}(\overline{\mathcal{O}})=\overline{\mathcal{O}_{max}}. \tag{77}$$

Moreover,

$$\mu_0\mu_1^{-1}(\overline{\mathcal{S}(\mathcal{O})})=\overline{\mathcal{S}(\mathcal{O}_{max})}. \tag{78}$$

Furthermore

$$\mathcal{S}(\nu_0\nu_1^{-1}(\overline{\mathcal{O}}))=\mu_0\mu_1^{-1}(\overline{\mathcal{S}(\mathcal{O})}). \tag{79}$$

The same holds for τ_0 skew-hermitian, τ_1 hermitian and S replaced by $\bar{S}$.

Notice that, since Sekiguchi correspondence commutes with orbit closures, (77) and (78) imply (79):

$$S(\nu_0\nu_1^{-1}(\overline{\mathcal{O}}))=S(\overline{\mathcal{O}_{max}})=\overline{S(\mathcal{O}_{max})}=\mu_0\mu_1^{-1}(\overline{\mathcal{S}(\mathcal{O})})=\nu_0\nu_1^{-1}(S\overline{\mathcal{O}})).$$

For a nilpotent $\mathcal{O}\in\mathcal{N}O\mathfrak{g}(V_1,\tau_1)$ we define $\mathcal{O}_{max}\in\mathcal{N}O\mathfrak{g}(V_0,\tau_0)$ as follows. Let $(F^{(i)},\tilde{\tau}_i,m_i)$, $i=1,2,\dots s$, be the sequence corresponding to $\mathcal{O}$. Consider the sequence $(F^{(i)},-\tilde{\tau}_i,m_i+1)$, $i=1,2,\dots s$. This sequence defines an orbit $\mathcal{O}'\in\mathcal{N}O\mathfrak{g}(V_0',\tau_0')$, where

$$\begin{aligned}
\operatorname{sgn}(\tau_0') &= \sum_{i:2|m_i+1}\left[\frac{1}{2}(m_i+1)(f_i,f_i)+\operatorname{sgn}(-1)^{\frac{m_i-1}{2}}\tilde{\tau}_{(i)}\right]\\
&\quad+\sum_{i:2|m_i}\frac{1}{2}(m_i+2)(f_i,f_i)\\
&=\sum_i\frac{1}{2}(m_i+1)(f_i,f_i)+\sum_{i:2|m_i+1}\operatorname{sgn}(-1)^{\frac{m_i-1}{2}}\tilde{\tau}_{(i)}\\
&\quad+\sum_{i:2|m_i}\frac{1}{2}(f_i,f_i).
\end{aligned}$$

Notice that $\sum_i(m_i+1)f_i=dimV_1$ and, for m_i+1 even, $\operatorname{sgn}(\tau_i)$ equals $(1,0)$ or $(0,1)$. Moreover

$$2\#\{i:2|m_i+1\}+\sum_{i:2|m_i}f_i\le\dim(V_1).$$

Hence $\operatorname{sgn}\tau_0'\le(\dim(V_1),\dim(V_1))$. Therefore there exists a formed space (V_0'',τ_0'') such that $(V_0',\tau_0')\oplus(V_0'',\tau_0'')$ is isometric to (V_0,τ_0). Define $\mathcal{O}_{max}\in\mathcal{N}O\mathfrak{g}(V_0,\tau_0)$ as the orbit through the extension by zero on V_0'' of any $X'\in\mathcal{O}'$.

Let $X \in \mathcal{O}$ and $X_{max} \in \mathcal{O}_{max}$. Then

$$\operatorname{sgn} \tau_0(\_, X_{max}^k\_) = \operatorname{sgn}(-\tau_1)(\_, X^{k-1}\_), \quad k = 1, 2, \dots. \tag{80}$$

The following lemma is a simple consequence of (80).

Lemma 8.2. Suppose $\mathcal{O}, \mathcal{O}' \in \mathcal{N}O\mathfrak{g}(V_1, \tau_1)$ and $\mathcal{O}' \subset \overline{\mathcal{O}}$. Then $\mathcal{O}'_{max} \subset \overline{\mathcal{O}_{max}}$.

The next lemma (which holds even withe stable range assumption) may be verified by a computation based on Lemma 3.9.

Lemma 8.3. Let $\mathcal{O} \in \mathcal{N}O\mathfrak{g}(V_b, \tau_b)$ and $\mathcal{O}' \in \mathcal{N}O\mathfrak{g}(V_{b+1}, \tau_{b+1})$ with $\mathcal{O} \sim_W \mathcal{O}'$. If $X \in \mathcal{O}'$ and $Y \in \mathcal{O}$ then

$$\operatorname{sgn} \tau_b(\_, Y^k\_) \leq \operatorname{sgn}(-1)^b \tau_{b+1}(\_, X^{k-1}\_), \quad k = 1, 2, \dots. \tag{81}$$

Lemma 8.4. Suppose $\mathcal{O} \in \mathcal{N}O\mathfrak{g}(V_1, \tau_1)$ and $\mathcal{O}' \sim_W \mathcal{O}$. Then $\mathcal{O}' \subset \overline{\mathcal{O}_{max}}$.

Proof. Let $X \in \mathcal{O}$, $X_{max} \in \mathcal{O}_{max}$ and $X' \in \mathcal{O}'$. By (80) and Lemma 8.3

$$\operatorname{sgn} \tau_1(\_, X_{max}^k\_) \; = \; \operatorname{sgn}(-\tau_0)(\_, X^{k-1}\_) \; \geq \; \operatorname{sgn} \tau_1(\_, X'^k\_)$$

for $k = 1, 2, \dots$. □

The following lemma verifies (77).

Lemma 8.5. For any $\mathcal{O} \in \mathcal{N}O\mathfrak{g}(V_1 \tau_1)$

$$\nu_0 \nu_1^{-1}(\overline{\mathcal{O}}) = \overline{\mathcal{O}_{max}}.$$

Proof. Suppose that $\mathcal{O}' \subset \overline{\mathcal{O}}$ and $\mathcal{O}'' \sim_W \mathcal{O}'$. Then by Lemma 8.4, $\mathcal{O}'' \subset \overline{\mathcal{O}'_{max}}$ and, by Lemma 8.2, $\mathcal{O}'_{max} \subset \overline{\mathcal{O}_{max}}$. Hence $\mathcal{O}'' \subset \overline{\mathcal{O}_{max}}$. Thus

$$\nu_0 \nu_1^{-1}(\overline{\mathcal{O}}) \subset \overline{\mathcal{O}_{max}}.$$

For the reverse inclusion, we proceed as follows. Consider a nilpotent orbit $\mathcal{O}'' \subset \overline{\mathcal{O}_{max}}$. Let $(F^{(i)}, \tilde{\tau}_i, m_i)$, $i = 1, 2, \dots s$, be the sequence corresponding to $\mathcal{O}''$. Suppose $m_i > 0$ for $1 \leq i \leq t$ and $m_i = 0$ for $i > t$. The sequence $(F^{(i)}, -\tilde{\tau}_i, m_i - 1)$, $i = 1, 2, \dots t$, defines a nilpotent orbit $\mathcal{O}' \in \mathcal{N}O\mathfrak{g}(V'_1, \tau'_1)$ for the apropriate formed space (V'_1, τ'_1) which is skew-hermitian. Therefore there is a formed space (V''_1, τ''_1) such that the space $(V'_1 \oplus V''_1, \tau'_1 \oplus \tau''_1)$ is isometric to (V_1, τ_1). Let $\mathcal{O}''_{min} \in \mathcal{N}O\mathfrak{g}(V_1, \tau_1)$ be the orbit through the extension by zero on V''_1 of any element of $\mathcal{O}'$.

As in (80), for $Y \in \mathcal{O}''$ and $Y_{min} \in \mathcal{O}''_{min}$, we have

$$\operatorname{sgn} \tau_1(\_, Y_{min}^k\_) = \operatorname{sgn}(-\tau_0)(\_, Y^{k+1}\_), \quad k = 1, 2, \dots.$$

Let $X \in \mathcal{O}$ and $X_{max} \in \mathcal{O}_{max}$. Since $\mathcal{O}'' \subset \overline{\mathcal{O}_{max}}$. we have

$$\operatorname{sgn}(-\tau_0)(\_, Y^{k+1}\_) \leq \operatorname{sgn}(-\tau_1)(\_, X^{k+1}_{max}\_).$$

By (80),

$$\operatorname{sgn}(-\tau_1)(\_, X^{k+1}_{max}\_) = \operatorname{sgn}\tau_0(\_, X^k\_).$$

We obtain $\mathcal{O}'' \subset \nu_0\nu_1^{-1}(\overline{\mathcal{O}})$ which completes the proof. □

Now we consider $K_{\mathbb{C}}$-orbits in $\mathfrak{p}_{\mathbb{C}}$. In terms of (47) let

$$\mathfrak{p}_{0,\mathbb{C}} = \mathfrak{g}(U_0 \oplus U_2, \phi)_2$$

and

$$\mathfrak{p}_{1,\mathbb{C}} = \mathfrak{g}(U_1 \oplus U_3, \phi)_2.$$

Let $\mathcal{O} \subset \mathfrak{p}_{0,\mathbb{C}}$ be a nilpotent orbit corresponding to a sequence $(F^{(i)}, \tilde{\phi}_i, m_i)$, $i = 1, 2, \ldots, s$, as in Corollary 3.19. For a graded space F let $\eta_{-1}F$ be the same space with the grading shifted by -1. The sequence $(\eta_{-1}F^{(i)}, \tilde{\phi}_i, m_i + 1)$, $= 1, 2, \ldots, s$, defines a nilpotent orbit $\mathcal{O}' \subset \mathfrak{g}(U_1' \oplus U_3', \phi')_2$, where $(U_1' \oplus U_3', \phi')$ is of the same type as $(U_1 \oplus U_3, \phi)$ and there exists $(U_1'' \oplus U_3'', \phi'')$ such that $(U_1' \oplus U_3', \phi') \oplus (U_1'' \oplus U_3'', \phi')$ is isometric to $(U_1 \oplus U_3, \phi)$. Let $\mathcal{O}_{max} \subset \mathfrak{p}_{1,\mathbb{C}}$ be the orbit through the extension by zero on $U_1'' \oplus U_3''$ of any element of $\mathcal{O}'$.

By Lemmas 10 and 14 in [16], , (see also [14]),

$$\overline{\mathcal{O}_{max}} = \mu_0\mu_1^{-1}(\overline{\mathcal{O}}). \tag{82}$$

Our description of the Kostant-Sekiguchi correspondences in Section 6 and definitions of $\mathcal{O}_{max}$ in both cases imply

$$S(\mathcal{O}_{max}) = (S\mathcal{O})_{max}. \tag{83}$$

The last two equations prove (78).

The proof of the theorem for τ_0 skew-hermitian and τ_1 hermitian is completely analogous.

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