COMPACT LIE GROUPS: EULER CONSTRUCTIONS
AND GENERALIZED DYSON CONJECTURE

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Abstract. A generalized Euler parameterization of a compact Lie group is a way for parameterizing the group starting from a maximal Lie subgroup, which allows a simple characterization of the range of parameters. In the present paper we consider the class of all compact connected Lie groups. We present a general method for realizing their generalized Euler parameterization starting from any symmetrically embedded Lie group. Our construction is based on a detailed analysis of the geometry of these groups. As a byproduct this gives rise to an interesting connection with certain Dyson integrals. In particular, we obtain a geometry based proof of a Macdonald conjecture regarding the Dyson integrals correspondent to the root systems associated to all irreducible symmetric spaces. As an application of our general method we explicitly parameterize all groups of the class of simple, simply connected compact Lie groups. We provide a table giving all necessary ingredients for all such Euler parameterizations.

1. Introduction

A simple procedure to parameterize compact simple Lie groups is provided by the generalized Euler parameterization [2, 8, 17, 18]. The role of Lie groups both in mathematics and in physics is very important and well known. In several situations their local properties are sufficient, but there are also numerous concrete applications that require explicit realizations of the group matrices including the correct range of the parameters. This is the case in lattice gauge theories or in separability criteria for entangled configurations in quantum mechanics, just to cite two relevant physical examples. For $SU(2)$ this problem has a natural solution in the Euler parameterization. Important progress was first achieved in [17] (followed by [18]), where the authors were able to define generalized Euler angles for $SU(N)$ groups. However, their construction was quite involved and does not allow an obvious generalization to other Lie groups. In [5, 7], studying the case of $G_2$, a more general strategy (later reviewed in [6]), which was expected to be applicable case by case to all compact simply connected simple Lie groups, was developed. Indeed, it was first applied to the $SU(N)$ case in [8], showing the drastic simplification with respect to [17, 18], and successively to the exceptional Lie groups $F_4$, $E_6$ and $E_7$ in [4, 3] and [2], respectively. It is only after these several years’ experience that we realized that the success of our method was due to the deep geometrical structure of the compact connected simple Lie groups and, in fact, of all compact
connected Lie groups. In the present paper we will analyze the geometry underlying our generalized Euler parameterization. This, beyond providing us with a final strategy valid for parameterizing all compact connected Lie groups, will also provide us with a direct connection between the geometry of compact Lie groups and certain integrals known as generalized Dyson integrals. As a consequence, we will obtain a geometrical proof of a class of particular cases of a conjecture stated in [14] by Macdonald, and already proved in general by Opdam in [15].

1.1. Geometry of the Euler parameterization. Let us consider the geometric structure underlying the generalized Euler parameterization of a simple Lie group. Let $\mathfrak{g} \equiv \text{Lie}(G)$ be the Lie algebra of a real compact Lie group $G$. More precisely, we will assume that $\mathfrak{g}$ is some matrix realization supporting a faithful representation of $G = \exp \mathfrak{g}$. Our strategy is to start from a maximal symmetrically embedded proper subgroup $H$ of $G$. Let $G'$ be any real form of $G$ different from the compact one. Then $G'$ contains a maximal compact subgroup $H$ which is invariant under the action of the Cartan involution, and $H$ can be embedded in $G$. For any real form this is our choice for $H$ (in other words $G/H$ is the compact dual of the noncompact symmetric space $G'/H$). In particular when $G'$ is the split form we will call $H$ the “the maximal compact subgroup of a split form $G'$ of $G$ (MCS)”. This has the property $\dim G = 2 \dim H + r = 2h + r$, where $r$ is the rank of $G$. For the split case, the generalized Euler parameterization of $G$ takes the form

$$
G[x_1, \ldots, x_h; y_1, \ldots, y_r; z_1, \ldots, z_h] = H[x_1, \ldots, x_h] \exp(y_1 c_1 + \ldots + y_r c_r) \cdot H[z_1, \ldots, z_h],
$$

(1.1)

where $H[x_1, \ldots, x_m]$ is a parameterization of the maximal subgroup and $c_1, \ldots, c_r$ is a basis for a Cartan subalgebra $\mathfrak{c}$ in the complement of Lie($H$) in $\mathfrak{g}$. Since the group is compact, one can choose $c_i$ so that the coordinates $y_i$ are periodic. A parameterization obtained in this way in general is redundant for two reasons.

The first one is due to the fact that $H$ contains a finite subgroup $\Gamma$ of the maximal torus $T^r = \exp \mathfrak{c}$ of $G$. Indeed, we will see that $\Gamma$ is isomorphic to $(\mathbb{Z}_2)^r$ if $G$ is simply connected, otherwise to one of its proper subgroups. Thus,

$$
H[x_1, \ldots, x_h] \exp(y_1 c_1 + \ldots + y_r c_r)H[z_1, \ldots, z_h] = H[x_1, \ldots, x_h] \gamma^{-1} \cdot \exp(y_1 c_1 + \ldots + y_r c_r) \gamma H[z_1, \ldots, z_h],
$$

for any $\gamma \in \Gamma$, so that we must reduce the range of the $\tilde{x}$ coordinates w.r.t. the action of $\Gamma$:

$$
H[x_1, \ldots, x_h] \gamma^{-1} = H[\tilde{x}_1, \ldots, \tilde{x}_h].
$$

This is easily accomplished by accordingly restricting the range.

The second problem is due to the fact that the Weyl group $W$ acts nontrivially on $t \in T^r$,

$$
t \mapsto w^{-1} tw \in T^r,
$$

for any $w \in W$, so also the range of the $\tilde{y}$ coordinates has to be reduced. We will show that this problem can be completely characterized in terms of the highest root of $G$: after a suitable linear change of variables $s_i = \sum_{j=1}^r A_{ij} y^j$ we will see that the right range of coordinates is expressed by the set of inequalities

$$
0 \leq n_1 s_1 + \ldots + n_r s_r \leq \pi, \quad 0 \leq s_i \leq \pi, \quad i = 1, \ldots, r,
$$

(1.2)

where $(n_1, \ldots, n_r)$ are the coefficients of the highest root $\alpha$ w.r.t. a basis of simple roots: $\alpha = n_1 \alpha_1 + \ldots + n_r \alpha_r$. The volume of the whole group $G$ can be expressed in
terms of the volume of the MCS subgroup \( H \) times an integral directly connected to the generalized Dyson integral. On the other hand, the volumes of the compact Lie groups can be computed employing the Macdonald formula \([13]\). Thus, incidentally, we see that our construction will turn out to be equivalent to proving certain particular cases of a conjecture due to Macdonald, generalizing the Dyson integrals \([14]\).

This construction is more involved, but it works as well for nonsimplyconnected compact Lie groups, as we will show in Section 2.2. Moreover, this parameterization applies to all compact connected Lie groups. Furthermore, we will extend all the results to the case in which a more general subgroup \( H \) symmetrically embedded in \( G \) is considered, in place of the MCS one. In this case the construction will turn out to be related to a version of Macdonald’s conjecture for certain integrals associated to nonreduced root lattices. In fact, the more interesting point is not the proof of this conjecture, which can be obtained in a more general form using different methods \((15); \text{ see also } 16\), but its relation to the geometry of compact symmetric spaces.

We remark that this parameterization is also useful for concrete applications in physics. Indeed, one often needs to work with an explicit realization of the parameterization of a Lie group, including the right range for the parameters.

1.2. Macdonald’s conjecture. Macdonald’s conjecture \([14]\) may be considered as a generalization of a conjecture due to Dyson \([10]\). Let \( R \) be a reduced root system, \( e^\alpha \) denote the formal exponential corresponding to \( \alpha \in R \) and \( k \) be a nonnegative integer. Then Macdonald conjectured (cf. \([14]\), Conjecture 2.1) that the constant term in the polynomial

\[
\prod_{\alpha \in R} (1 - e^\alpha)^k
\]

should be equal to \( \prod_{i=1}^l \left( \frac{k d_i}{k} \right) \), where the \( d_i \) are the degrees of the fundamental invariants of the Weyl group of \( R \) and \( l \) the rank of \( R \). Macdonald wrote this relation in an equivalent form which will turn out to be useful later. Let \( G \) be a compact connected Lie group, \( T \) a maximal torus of \( G \), such that \( R \) is the root system of \((G,T)\) and define

\[
\Delta(t) = \prod_{\alpha \in R^+} (e^{\alpha/2}(t) - e^{-\alpha/2}(t)),
\]

where \( t \in T \), the exponentials are regarded as characters of \( T \) and \( R^+ \) is a choice of positive roots. Then \( |\Delta(t)|^2 = \prod_{\alpha \in R}(1 - e^\alpha(t)) \) is a positive real-valued continuous function on \( T \). This function enters in Weyl’s integration formula

\[
\int_G f(x)dx = \frac{1}{|W|} \int_T |\Delta(t)|^2 f(t)dt
\]

for any continuous class function \( f \) on \( G \). In \([15]\), \( dx \) and \( dt \) are the normalized Haar measure on \( G \) and \( T \) respectively (\( \int_G dx = \int_T dt = 1 \)). Thus, the conjecture can be rewritten as (cf. \([14]\), Conjecture 2.1’)

\[
\int_T |\Delta(t)|^{2k}dt = \prod_{i=1}^l \left( \frac{k d_i}{k} \right).
\]
The equivalence of the two formulations follows from the fact that the integration over \( T \) kills all but the trivial character, or in other words, selects the constant term in \(|\Delta(t)|^{2k} = \prod_{\alpha \in R} (1 - e^{\alpha}(t))^k\). An observation that generalizes further the conjecture is that \((1.6)\) makes sense if the integer \( k \) is replaced by a complex number, \( s \), with positive real part, \( \Re(s) > 0 \). In this case the right hand side is replaced by

\[
\prod_{i=1}^{l} \frac{\Gamma(sd_i + 1)}{\Gamma(s + 1)\Gamma(sd_i - s + 1)}.
\]

In the same paper Macdonald generalized the conjecture further (cf. [14], Conjecture 2.3). For this, let \( R \) be a root system, now not necessarily reduced, and for each \( \alpha \in R \) let \( k_{\alpha} \) be a nonnegative integer such that \( k_{\alpha} = k_\beta \) if \( |\alpha| = |\beta| \). Then the constant term in the Laurent polynomial

\[
\prod_{\alpha \in R} (1 - e^{\alpha})^{k_{\alpha}}
\]

should be equal to the product

\[
\prod_{\alpha \in R} \left( \frac{|\langle \rho_k, \tilde{\alpha} \rangle + k_{\alpha} + \frac{1}{2}k_{\alpha/2}|!}{|\langle \rho_k, \tilde{\alpha} \rangle + \frac{1}{2}k_{\alpha/2}|!} \right),
\]

where \( \rho_k = \frac{1}{2} \sum_{\alpha \in R^+} k_{\alpha} \alpha, \tilde{\alpha} = \frac{2\alpha}{|\alpha|^2} \) is the coroot corresponding to \( \alpha \), \( k_{\alpha/2} = 0 \) if \( \frac{1}{2} \alpha \notin R \) and \( \langle , \rangle \) is the usual scalar product induced by the Killing form. When the \( k_{\alpha} \) are all equal this reduces to the previous conjecture.

Macdonald’s conjecture was proved in a slightly more general form by Opdam [15] considering \( k_{\alpha} \) a complex valued Weyl invariant function with positive real part. This is the content of Theorem 4.1 of [15]:

**Theorem 1** (Macdonald-Opdam). Let \( R \) be a possibly nonreduced root system, and let \( k \in \mathbb{K} \) such that \( \Re(k_{\alpha}) \geq 0 \), \( \forall \alpha \in R \). Then

\[
\int_T \sigma(k,t)dt = \prod_{\alpha \in R^+} \frac{\Gamma(|\langle \rho(k), \tilde{\alpha} \rangle + k_{\alpha} + \frac{1}{2}k_{\alpha/2} + 1|)}{\Gamma(|\langle \rho(k), \tilde{\alpha} \rangle + \frac{1}{2}k_{\alpha/2} + 1|)}
\]

where \( \sigma(k,t) = \prod_{\alpha \in R^+} \left| t^{\frac{1}{2}k_{\alpha}} - t^{-\frac{1}{2}k_{\alpha}} \right|^{2\alpha} \) and \( T \) is the compact part in the “polar decomposition” of the maximal torus.

2. **The Split Case**

In this section we describe our general construction of the Euler parameterization for an arbitrary compact connected Lie group, \( G \), relative to a specific choice of the corresponding subgroups \( H \).

2.1. **The compact Lie groups.** Let \( G_0 \) be a real compact connected semisimple Lie group (cf. the definition in [11], page 131). This means that \( G_0 \simeq G_1 \times G_2 \times \cdots \times G_n \), where \( G_i, i = 1, \ldots, n \), are simple Lie groups uniquely determined (up to permutations). Let \( H \simeq H_1 \times H_2 \times \cdots \times H_n \) such that \( H_i \) is a maximal Lie subgroup symmetrically embedded in \( G_i \). Then \( H \) is connected (see [11], Chapter VI, Theorem 1.1). In general, \( H_i \) is not simple, nor semisimple, but it has the form

\[1\text{The vector space } \mathbb{K} \cong \mathbb{C}^n \text{ is the space of all complex valued Weyl invariant functions on } R, \text{ and equals the numbers of conjugacy classes of roots in } R, \text{ and elements of } \mathbb{K} \text{ are called multiplicity functions on } R. \text{ The notation } k_{\alpha} \text{ denotes the evaluation of } k \in \mathbb{K} \text{ on } \alpha \in R.\]
$H_i \simeq H_{0,i} \times T^{*i}/\Delta_i$, where $H_{0,i}$ is semisimple, $T^{*i}$ is an Abelian torus, and $\Delta_i$ a finite subgroup. Since our aim is to construct the Euler parameterization of $G_0$ relative to the subgroup $H$, and then applying the same procedure to $H$ inductively, we are forced to consider the more general case

\[(2.1)\quad G \simeq G_0 \times T^s/\Delta,\]

with $G_0$ as before, $T^s$ an Abelian torus, and $\Delta$ a finite subgroup.

Remark. The class of compact connected Lie groups of the form (2.1) coincides with the class of all compact connected Lie groups. We need only show that any compact connected Lie group $G$ has the form (2.1). Let $G_0 := G'$ be the derived group and let the torus $T^s = Z^0$ be the connected component of the identity of the center $Z$ of $G$. Then, the multiplication map $m : G' \times Z^0 \to G$ is surjective. Indeed, it is a homomorphism since $Z^0$ is central. Moreover, since $\text{Lie}(G^0) \oplus \text{Lie}(Z^0) = \text{Lie}(G)$, the differential of $m$ is surjective, so the image of $m$ is open. Since $G$ is connected, it follows that $m$ is surjective. The kernel of $m$ is obtained by embedding $G' \cap Z^0$ in $G' \times Z^0$ via $\gamma \to (\gamma, \gamma^{-1})$, $\gamma \in G' \cap Z^0$. The image of such a map is the kernel of $m$ and is a finite group.

The parameterization of $G$ from $G_0$ is quite elementary, and we can concentrate here on the parameterization of $G_0$ only. From now on we will assume that

\[(2.2)\quad G \equiv G_0.\]

Note that $H$ is symmetrically embedded in $G$, but is not maximal, unless $G$ is simple.

Let $\mathfrak{g}$ and $\mathfrak{h}$ be the Lie algebras associated to $G$ and $H$ respectively. In this section, we will assume that $H$ is MCS; with this, we mean that $H_i$ is an MCS subgroup of $G_i$. Since in this case $\text{rank}(G/H) = \text{rank}G$, we can choose a Cartan subalgebra $\mathfrak{c}$ of $\mathfrak{g}$ such that $\mathfrak{c} \cap \mathfrak{h} = 0$. Thus, the generalized Euler parameterization of the group $G$ w.r.t. $H$ takes the form

\[(2.3)\quad G = (H'/\Gamma)e^\mathfrak{c}H,\]

where $H'$ is a copy of $H$ and $\Gamma = H \cap e^\mathfrak{c}$ is a finite subgroup of the maximal torus that will be specified later. In Section 3 we will extend the parameterization to an arbitrary symmetrically embedded subgroup. Before entering the details of the construction, we need to specify some further technical facts.

2.2. Some technical facts and definitions. Any finite dimensional semisimple Lie algebra $\mathfrak{g}$ admits a unique compact form. There is a unique (up to isomorphisms) simply connected, compact Lie group $\tilde{G}$ having $\mathfrak{g}$ as the associated Lie algebra. However, more in general, there is more than one connected compact Lie group having the same Lie algebra. These are a finite number:

\[(2.4)\quad G^k = \tilde{G}/\Gamma^k, \quad k = 1, 2, \ldots, m,\]

where $\Gamma^k$ are finite subgroups of the center $Z$ of $\tilde{G}$. Notice that $\tilde{G}$ has finite center (cf. [9], Proposition 23.11, page 200). In particular, we set $G^1 \equiv \tilde{G}$ and $G^m \equiv G/Z =: G_Z$. Then each $G^k$ is a covering of $G_Z$ and is covered by $\tilde{G}$. It
is known that each of such groups admits a faithful linear representation (cf. \cite{9}, Theorem 4.2, page 26). Let $(R_k, V_k)$ be such a representation for $G^k$ (in particular $(Ad, g)$ is faithful for $G_Z$). It induces a faithful representation $(\rho_i, V_i)$ of $g$, so that the following diagram is commutative:

\[
\begin{array}{ccc}
G^k & \xrightarrow{\rho_k} & Aut(V_k) \\
\exp_{G^k} & & \Exp \\
g & \xrightarrow{\rho_k} & \End(V_k)
\end{array}
\]

Since $G^k$ is compact, $R_k$ is injective and continuous, and $Aut(V_k)$ is $T_2$, then $G^k$ and $R_k(G^k)$ are homeomorphic (see \cite{12}, Theorem 8.8), and, in particular, they have the same fundamental group. Thus, we parameterize the desired compact $G^k$ form by working with the right $G^k$-faithful representation of the algebra.

Let $H$ be a subgroup of $G$ as defined previously. If we are working with a $G$-faithful representation $(\rho, V)$ for $g$, then $\rho$ will decompose into a direct sum of representations of the Lie algebra $\mathfrak{h}$ of $H$, among which at least one is surely $H$-faithful (whereas the complementary ones will give rise to compact forms of the group covered by $H$). As a consequence, one can construct the corresponding parameterization of $H$ by worrying about the $H$-faithful representation only, which is automatically present in the decomposition.

2.3. Parameterization. The problem of parameterizing $H$ and $H'$ is then the same as for $G$ and can be obtained inductively. Thus, if we want to get an almost everywhere one to one parameterization of $G$, the only problem is to determine the right range for the parameterization of the toric part

\[(2.5)\quad e^{\gamma y_1, \ldots, y_r} = \exp(y_1 c_1 + \ldots + y_r c_r).\]

Now, we will see that the range for the $y$’s is independent from the starting $G$-faithful representation, depending on the adjoint representation only. This means that such determination is in a sense universal, and the details discriminating among the different compact forms of $G$ will depend only on the periodicities of the $U(1)$ factors entering the parameterizations and the action of the finite subgroups. Furthermore, employing the isomorphism $G \simeq G_1 \times G_2 \times \ldots \times G_n$, we can parameterize each factor independently. Thus without loss of generality, we focus on the case when $G$ is simple. In particular, then, $H$ is maximal in $G$.

Using the notation in Section 2.1 we write $g = \mathfrak{h} + \mathfrak{p} = \mathfrak{h} \oplus \mathfrak{c} \oplus \mathfrak{p}'$, with $\dim \mathfrak{h} = \dim \mathfrak{p}' = h$ and $\dim \mathfrak{c} = r$. Now consider the complexification $g_{\mathfrak{c}}$ of $g$. It also has the decomposition $g_{\mathfrak{c}} = W_- \oplus \mathfrak{c} \oplus W_+$, where $W_{\pm}$ is the direct sum of the root spaces $W_{\pm \alpha}$ such that $\alpha$ is a positive root. We can thus pick out the following two bases for $g_{\mathfrak{c}}$:

- $\{c_i\}_{i=1}^r \cup \{\lambda_{\alpha_a} \uplus \lambda_{-\alpha_a}\}_{a=1}^h$, where $\lambda_{\alpha}$ is the eigenvector corresponding to the root $\alpha$ and the $\alpha_a$ are the positive roots;

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\footnote{We are grateful to S. Pigola for explaining these points to us.}
\( \{ c_i \}_{i=1}^r \cup \{ t_a \}_{a=1}^h \cup \{ p_b \}_{b=1}^h \), where \( t_a \) and \( p_b \) generate \( \mathfrak{h} \) and \( \mathfrak{p}' \) respectively and are chosen so that \( \text{ad}_{t_a} \) and \( \text{ad}_{p_b} \) are diagonalizable, and the decomposition is Killing orthogonal.

Notice that only the second one is a basis for the compact algebra \( \mathfrak{g} \). It satisfies the following relations:

\[
\begin{align*}
[t_a, t_b] &\in \mathfrak{h}, \quad [t_a, c_i] \in \mathfrak{p}', \quad [t_a, p_b] \in \mathfrak{p}, \\
[c_i, c_j] &\in 0, \quad [c_i, p_b] \in \mathfrak{h}, \quad [p_a, p_b] \in \mathfrak{h}.
\end{align*}
\] (2.6)

Indeed, the maximal symmetrically embedded compact subalgebras are in biunivocal correspondence with the real forms or, equivalently, with the Cartan decompositions of the algebra. This means that there exists an involution \( \theta : \mathfrak{g} \to \mathfrak{g}, \theta^2 = \text{id} \), such that \( \mathfrak{h} \) and \( \mathfrak{p} \) are the corresponding eigenspaces, with eigenvalues 1 and \(-1\) respectively. Since \( \theta \) is a homomorphism, this implies

\[
\mathfrak{h}, \mathfrak{h} \subseteq \mathfrak{h}, \quad [\mathfrak{h}, \mathfrak{p}] \subseteq \mathfrak{p}, \quad [\mathfrak{p}, \mathfrak{p}] \subseteq \mathfrak{h},
\] (2.7)

and the Killing orthogonality between the two spaces. Moreover, \( \text{ad} \)-invariance of the Killing form \( \langle \cdot, \cdot \rangle \) implies

\[
\langle [t_a, c_i], c_j \rangle = \langle t_a, [c_i, c_j] \rangle = 0,
\] (2.8)

so that \( [t_a, c_i] \in \mathfrak{p}' \).

The rules \( [c_i, p_b] \in \mathfrak{h}, \) \( [t_a, c_i] \in \mathfrak{p}' \) allow us to provide a simple relation between the two bases defined above. Indeed, we can obtain from \( \mathfrak{g} \) a new real form of \( \mathfrak{g}_C \) by means of Weyl’s unitary trick, which consists of defining the new generators

\[
\tilde{t}_a = t_a, \quad \tilde{c}_j = ic_j, \quad \tilde{p}_b = ip_b.
\]

This is the noncompact form \( \mathfrak{g}_r \), with signature \( r \). In this case, the operators \( \text{ad}_{\tilde{h}_j} \) are represented by symmetric matrices since \( \text{ad} \)-invariance and symmetry of the Killing form give

\[
\langle [\tilde{c}_i, \tilde{p}_a], \tilde{t}_b \rangle = -\langle \tilde{p}_a, [\tilde{c}_i, \tilde{t}_b] \rangle,
\] (2.9)

and the form is positive definite over the \( \tilde{t}_b \) and negative over the complementary space. This means that such matrices can be diagonalized, with real eigenvalues, by means of real combinations of the vectors \( t_a, \tilde{p}_b \). Then, an eigenvector corresponding to a nonzero root \( \alpha \) will have the form \( \lambda_\alpha = t_\alpha + ip_\alpha \), with \( t_\alpha \in \mathfrak{h} \) and \( p_\alpha \in \mathfrak{p} \). Notice that both \( t_\alpha \) and \( p_\alpha \) are necessarily nonvanishing. Indeed, \( [c, \lambda_\alpha] = \alpha(c)\lambda_\alpha \) for all \( c \in \mathfrak{c} \) implies

\[
[c, t_\alpha] = i\alpha(c)p_\alpha, \quad [c, p_\alpha] = -i\alpha(c)t_\alpha,
\] (2.10)

and \( t_\alpha = 0 \) or \( p_\alpha = 0 \) would imply \( \alpha(c) = 0 \) for any \( c \in \mathfrak{c} \).

In conclusion, we can choose the basis \( t_a, p_b, c_i \) so that the relation between the two bases is

\[
\lambda_\alpha = t_\alpha + ip_\alpha, \quad \lambda_{-\alpha} = t_\alpha - ip_\alpha, \quad a = 1, \ldots, h.
\] (2.11)

Moreover, since \( (\lambda_\alpha, \lambda_\beta) \neq 0 \) if and only if \( \alpha + \beta = 0 \), we can normalize the basis so that it becomes an orthonormal basis.

Now, we show that these known facts have interesting consequences for the Euler parameterization. We can write

\[
G[x_1, \ldots, x_h, y_1, \ldots, y_r, z_1, \ldots, z_h] = e^{\sum_{a=1}^h x_at_a} e^{\sum_{i=1}^r y_i c_i} e^{\sum_{b=1}^h z_bp_b} = (H'/T)e^H.
\] (2.12)
The invariant measure expressed in terms of this parameterization is
\( d\mu_G[\vec{x}; \vec{y}; \vec{z}] = d\mu_H[\vec{z}]d\mu_B[\vec{x}; \vec{y}], \)
where \( d\mu_H[\vec{z}] \) is the invariant measure associated to \( H \) and
\( d\mu_B[\vec{x}; \vec{y}] = \det J(\vec{x}, \vec{y}) \prod_{a=1}^{h} dx_a \prod_{i=1}^{r} dy_i, \)
where \( J(\vec{x}, \vec{y}) \) is the Jacobian matrix with components
\( J_a^b := \langle e^{-\epsilon}H'^{-1} \frac{\partial H'}{\partial x_a} e^\epsilon, p_b \rangle. \)

Notice that \( H'^{-1}dH' =: J_H \) is the left invariant one form for the \( H \) subgroup in the \( H' \) parameterization, \( J_H = \sum_{a=1}^{h} J_a^a t_a. \)
Thus
\( d\mu_B[\vec{x}; \vec{y}] = d\mu_H[\vec{x}] \det M \prod_{i=1}^{r} dy_i, \quad M_a^b := \langle e^{-\epsilon}t_a e^\epsilon, p_b \rangle. \)

Now \( t_a = (\lambda_{a_+} + \lambda_{-a_+})/2 \) so that
\( e^{-\epsilon}t_a e^\epsilon = \cosh(\alpha_a(\mathbf{c}))t_a + i \sinh(\alpha_a(\mathbf{c}))p_a. \)

Since the roots are real on \( \hat{c}_i \), if we define \( \bar{\alpha}_a \equiv (\alpha_{a_1}^1, \ldots, \alpha_{a_r}^r) \) with \( \alpha_{a_i} = \alpha_a(\hat{c}_i) \), we get \( \alpha_a(\mathbf{c}) = -i \sum_{i=1}^{r} \alpha_{a_i}^i y_i \equiv -i\bar{\alpha}_a \cdot \vec{y}. \) Then
\( \det M = \prod_{a=1}^{h} \sin(\bar{\alpha}_a \cdot \vec{y}). \)

Thus, the invariant measure takes the form
\( d\mu_G[\vec{x}; \vec{y}; \vec{z}] = d\mu_H[\vec{z}]d\mu_H[\vec{x}] \prod_{a=1}^{h} \sin(\bar{\alpha}_a \cdot \vec{y}) \prod_{i=1}^{r} dy_i. \)

The range of the \( z \) coordinates is such as to cover the subgroup \( H \), whereas the range \( R_y \) for the \( y \) coordinates is defined by the conditions \( 0 \leq \bar{\alpha}_a \cdot \vec{y} \leq \pi, \) and the range for the \( x \) coordinates is such as to cover \( H'/\Gamma. \) In particular, as a consequence of equation (2.17), the range for the \( y_i \)'s depends on the adjoint representation and not on the particular \( G \)-faithful representation we are considering. Notice that equation (2.19) implies the interesting relation
\( \int_{R_y} \prod_{a=1}^{h} \sin(\bar{\alpha}_a \cdot \vec{y}) \prod_{i=1}^{r} dy_i = \frac{\text{Vol}(G)}{\text{Vol}(H)^2} |\Gamma|, \)
where the volumes can be computed by means of Macdonald’s formula [13] and \( |\Gamma| \) is the cardinality of \( \Gamma. \)

When \( G \) is simply connected, it is easy to see that \( \Gamma \simeq \mathbb{Z}^r_2. \) Indeed, the elements of \( \Gamma = H \cap e^\mathbf{c} \) are the elements of \( e^\mathbf{c} \) whose square is the identity (see [11], Section VII, Theorem 8.5). Since the basis \( c_1, \ldots, c_r \) of \( \mathbf{c} \) can be chosen so that \( e^{tc_i} \) has period \( T, \) \( \Gamma \) is generated by \( e^{Tc_i}, \) which proves our claim. In particular, \( |\Gamma| = 2^r. \)

When \( G \) is not simply connected, this is not true in general and \( \Gamma \) is isomorphic to a proper subgroup of \( \mathbb{Z}^r_2. \) Indeed, if \( \Phi : \hat{G} \rightarrow G \) is the universal covering map, then \( \Gamma \simeq \Phi(\mathbb{Z}^r_2). \)
2.4. Connections with the generalized Dynson integrals. Let us now look closer at the integral (2.20). It is convenient to introduce the following change of variables. Let $\alpha_{a_1}, \ldots, \alpha_{a_r}$ be simple roots. Then, we define the new coordinates $s_i, i = 1, \ldots, r,$ by

\begin{equation}
    s_i := \bar{y} \cdot \bar{\alpha}_a.
\end{equation}

From this we get

\begin{equation}
    ds_1 \wedge \ldots \wedge ds_r = V_F \prod_{i=1}^r \frac{||\alpha_{a_i}||^2}{2} dy_1 \wedge \ldots \wedge dy_r,
\end{equation}

where $V_F$ is the volume of the fundamental region (parallelogram) defined by the simple coroots $\bar{\alpha}_a$. Then, the integral in (2.20) takes the form

\begin{equation}
    I = 2^r V_F \prod_{i=1}^r \frac{||\alpha_{a_i}||^2}{2} \int_{\bar{R}_s} \prod_{a=1}^h \sin(\bar{n}_a \cdot \bar{s}) \prod_{i=1}^r ds_i,
\end{equation}

where $\bar{n}_a$ are the coordinates of the positive roots expressed w.r.t. the simple roots and take values in $\mathbb{N}^r$ and $\bar{R}_s$ is the range for the $s$ coordinates. In particular, for the simple roots we have

\begin{equation}
    \prod_{i=1}^r \sin(\bar{n}_a \cdot \bar{s}) = \prod_{i=1}^r \sin(s_i),
\end{equation}

so that the range of coordinates is a subset of the cube $0 \leq s_i \leq \pi$. The remaining conditions are $0 \leq \bar{n}_a \cdot \bar{s} \leq \pi$ for all the other positive roots. The hyperplanes $\bar{n}_a \cdot \bar{s} = k\pi$, with $k$ an integer, cut the cube into a tiling whose sectors are all equivalent, being related to each other by the Weyl reflections. We know that for a simple group the highest root (relative to the simple root system) $\alpha_{\bar{a}} = \sum_{i=1}^r \bar{n}_i \alpha_a$, has the property $\bar{n}_i \geq n^i_a$ for all $a$ and $i$ (indeed, it is nothing but the highest weight of the adjoint representation). Thus, the inequalities $0 \leq \bar{n}_a \cdot \bar{s} \leq \pi$ defining the tiling reduce just to one. Indeed,

\begin{equation}
    0 \leq \bar{n} \cdot \bar{s} \leq \pi
\end{equation}

inside the cube implies all the remaining inequalities and then defines a fundamental region $\Delta$. The volume of this region is

\begin{equation}
    V = \int_{\Delta} \prod_{i=1}^r ds_i = \prod_{i=1}^r \bar{n}_i \int_{0 \leq y_1 + \ldots + y_r \leq \pi, 0 \leq y_i \leq \pi} \prod_{i=1}^r dy_i = \frac{\pi^r}{r! \prod_{i=1}^r \bar{n}_i},
\end{equation}

whereas the torus has volume $\pi^r$, so that the number $\nu$ of elementary cells in the cube is

\begin{equation}
    \nu = r! \prod_{i=1}^r \bar{n}_i.
\end{equation}

Thus, we can write

\begin{equation}
    I = \frac{2^r}{V_F \prod_{i=1}^r ||\alpha_{a_i}||^2} \frac{1}{r! \prod_{i=1}^r \bar{n}_i} \int_{\bar{Q}_s} \prod_{a=1}^h |\sin(\bar{n}_a \cdot \bar{s})| \prod_{i=1}^r ds_i,
\end{equation}
Q being the cube. By setting \(2s_i = \zeta_i\) this can also be written as

\[
I = \frac{(2\pi)^r}{2^h V_F \prod_{i=1}^r \|\alpha_i\|^2 \pi^r \prod_{i=1}^r n_i} J_\frac{1}{2}, \tag{2.29}
\]

\[
J_\frac{1}{2} = \frac{1}{(2\pi)^r} \int_0^{2\pi} d\zeta_1 \cdots \int_0^{2\pi} d\zeta_r \prod_{\alpha \in R} (1 - e^{i\alpha \cdot \zeta})^\frac{1}{2}. \tag{2.30}
\]

Here \(J_\frac{1}{2}\) is a generalized Dyson integral, as conjectured by Macdonald in \[14\], Conjecture 2.1”.

\section*{Conjecture 2.1”}
For all \(s \in \mathbb{C}\) with \(\text{Re}(s) > 0\),

\[
J_s = \frac{1}{(2\pi)^r} \int_0^{2\pi} d\zeta_1 \cdots \int_0^{2\pi} d\zeta_r \prod_{\alpha \in R} (1 - e^{i\alpha \cdot \zeta})^s = \prod_{i=1}^r \frac{\Gamma(sd_i + 1)}{\Gamma(s + 1)\Gamma(sd_i - s + 1)}. \tag{2.31}
\]

This formula is known as Macdonald’s conjecture; in fact it has been proven for all root systems \[15\]. From (2.20) and (2.29) we get

\[
J_\frac{1}{2} = \frac{2^h V_F r! \prod_{i=1}^r (n_i \|\alpha_i\|^2)}{\pi^r} \frac{\text{Vol}(G)}{\text{Vol}(H)^2} \frac{\|\Gamma\|}{2^r}. \tag{2.32}
\]

The last factor is 1 for \(G\) simply connected. This formula provides a proof of (2.31) for \(s = \frac{1}{2}\) and for all the reduced simple lattices.

\section*{3. Arbitrary Maximal Symmetric Embedded Subgroups}

As in the previous section we restrict our attention to the case of \(G\) simple. Here we extend previous results to the general case when \(H\) is not an MCS. In this case

\[
l := \text{Rank}(G/H) < \text{Rank}(G) = r,
\]

so that the largest possible intersection between the Cartan subalgebra \(c\) of \(g\) and the complement of \(h\) has dimension \(l\). We choose the Cartan subalgebra \(c\) just in this way, so that

\[
c = c_h \oplus c_p, \quad c_p := c \cap p, \quad \dim c_p = l, \quad c_h \subset h.
\]

Let us fix a basis \(k_1, \ldots, k_s\) for \(c_h\), \(h_1, \ldots, h_l\) for \(c_p\), \(s + l = r\). Let \(\mathfrak{k}\) be the largest Lie subalgebra of \(h\) such that \([\mathfrak{k}, c_p] = 0\). It is the Lie algebra of the normalizer \(K\) of \(c_p\) in \(H\). Thus, we can write \(h =: \mathfrak{k} \oplus \mathfrak{h}\) and \(p =: c_p \oplus \mathfrak{p}\), so that

\[
g = (\mathfrak{k} \oplus \mathfrak{h}) \oplus (c_p \oplus \mathfrak{p}). \tag{3.3}
\]

Since \(h\) is maximal, we have

\[
[h, h] \subseteq h, \quad [p, p] \subseteq h, \quad [h, p] \subseteq p. \tag{3.4}
\]

Moreover, \([\mathfrak{k}, c_p] = 0\) implies

\[
[h, c_p] \subseteq \mathfrak{h}, \quad [\mathfrak{p}, c_p] \subseteq \mathfrak{h}. \tag{3.5}
\]

Notice that the roots of \(g\) can be divided as follows. Since \(c_h\) is the Cartan subalgebra of both \(\mathfrak{k}\) and \(h\), \(\text{Rank}(\mathfrak{k}) = \text{Rank}(h) = s\). We represent the roots as the simultaneous eigenvalues of the operators (\(\text{ad}_{k_1}, \ldots, \text{ad}_{k_s}; \text{ad}_{h_1}, \ldots, \text{ad}_{h_l}\)). The eigenvectors of the roots \(\alpha_{h,a}, a = 1, \ldots, k - s (k := \dim K)\), of \(\mathfrak{k}\) are in the complexification of \(\mathfrak{k}\) and thus in the kernel of \(\text{ad}_{h_i}, i = 1, \ldots, l\) the last \(l\) components are zero. Indeed, these are all the nonvanishing roots with this property; the remaining ones have necessarily nonvanishing elements out of the first \(s\) ones. We
will call the corresponding roots \( \alpha_{p,b}, b = 1, \ldots, 2q \), where \( q \) is the number of positive roots. This root system is not reduced so that each root \( \alpha_{p,b} \) has multiplicity \( m_b \), and \( \sum_{b=1}^{q} m_b = h - k \). Indeed, these correspond to the nonvanishing roots of the \( h_i \). As usual, we can divide all roots in positive and negative, \( R = R^+ \oplus R^- \). This will determine a corresponding decomposition of the restricted root system: \( R_p = R_p^+ \oplus R_p^- \). The main difference w.r.t. the case of an MCS subgroup is that now \( R_p \) is not a reduced root lattice system and generically each root \( \alpha \) is characterized by a multiplicity \( m_\alpha \geq 1 \). All such systems are classified in [11]; see also [11].

From now on, we can proceed exactly as in the previous section, by choosing an orthonormal basis of \( g \), \( B = B_K \cup \{ t_1, \ldots, t_{h-k} \} \cup \{ h_1, \ldots, h_l \} \cup \{ p_1, \ldots, p_{h-k} \} \), where \( B_K = \{ k_1, \ldots, k_m, g_1, \ldots, g_{h-k} \} \) is an orthonormal basis for \( t \), the \( t_a \) generate \( \hat{h} \), and the \( p_b \) generate \( \hat{b} \). The Euler parameterization for \( G \) is then

\[
G[\vec{x}; \vec{y}; \vec{z}] = e^{\sum_{a=1}^{h-k} x^a t_a} e^{\sum_{i=1}^{l} y^i h_i} H[z_1, \ldots, z_h],
\]

where \( H \) can be parameterized itself by means of the Euler parameterization, but it is not important here. The range of the \( z \) coordinates must be chosen in such a way as to cover the whole subgroup \( H \). The invariant measure can be computed exactly as in the previous section, giving

\[
d\mu_G[\vec{x}; \vec{y}; \vec{z}] = d\mu_H[\vec{y}] d\mu_{H/K}[\vec{x}] \prod_{i=1}^{l} \sin^{m_\alpha}(\vec{\alpha}_{p,a} \cdot \vec{y}) \prod_{i=1}^{q} dy_i,
\]

where \( \vec{\alpha}_{p,a} := (\alpha^1_{p,a}, \ldots, \alpha^l_{p,a}) \), \( a = 1, \ldots, q \), are the last \( l \) components of the positive \( \alpha_{p,a} \), corresponding to the eigenvalues of the \( \text{ad}_{h_i} \) only. As before, we can choose a basis of \( l \) simple roots \( \vec{\alpha}_1, \ldots, \vec{\alpha}_l \) in \( R_p^+ \) to prove that the range for the coordinates \( \vec{y} \) is given by

\[
0 \leq \sum_{i=1}^{l} n_i \vec{\alpha}_i \cdot \vec{y} \leq \pi,
\]

where \( \sum_{i=1}^{l} n_i \vec{\alpha}_i \) is the highest root of the quotient manifold.

### 3.1. Further connections with the generalized Dyson integrals

In [14] Macdonald proposed a generalization of the Dyson integrals extended to not necessarily reduced root lattices. This general conjecture has been proved by Opdam [15] in the form:

\[
\mathcal{J}_{\{k_\alpha\}} = \frac{1}{(2\pi)^r} \int_0^{2\pi} d\zeta_1 \ldots \int_0^{2\pi} d\zeta_r \prod_{\alpha \in R_p^+} (1 - e^{\vec{n}_\alpha \cdot \vec{\zeta}})^{k_\alpha}
= \prod_{\alpha \in R_p^+} \frac{\Gamma(\langle \rho(k), \vec{\alpha} \rangle + k_\alpha + \frac{1}{2} k_2^2 + 1) \Gamma(\langle \rho(k), \vec{\alpha} \rangle - k_\alpha - \frac{1}{2} k_2^2 + 1)}{\Gamma(\langle \rho(k), \vec{\alpha} \rangle + \frac{1}{2} k_2^2 + 1) \Gamma(\langle \rho(k), \vec{\alpha} \rangle - \frac{1}{2} k_2^2 + 1)},
\]

where \( R_p \) is a root system, \( R_p^+ \) is a choice of corresponding positive roots,

\[
\rho(k) = \frac{1}{2} \sum_{R_p^+} k_\alpha \alpha,
\]
and $k$ is a Weyl invariant function over $R_p$ whose values $k_\alpha$ have positive real part. For example, the multiplicities $m_\alpha$ select such a function. Finally, $\langle \rho(k), \alpha \rangle$ indicates the invariant product with the coroot $\check{\alpha}$.

Repeating the same procedure as in Section 2.4 we get the following formula:

$$J_{ppp}^p \left\{ \frac{m_\alpha}{2} \right\} = \frac{2^{h-k} |\alpha_1 \wedge \ldots \wedge \alpha_l|! \prod_{i=1}^l n_i}{\pi^l} \frac{\text{Vol}(G)\text{Vol}(K)\text{Vol}(H)^2}{\text{Vol}(H)}.$$  

(3.11)

Compared with Theorem 4.1 in [15], with the invariant functions $k_\alpha = m_\alpha/2$, this expression indeed provides the right value for the generalized Dyson integrals $J_{ppp}^p \left\{ \frac{m_\alpha}{2} \right\}$, thus a proof of Macdonald’s conjecture ([14], Conjecture 2.3) for $k_\alpha = m_\alpha/2$ and for the lattices associated to all the irreducible symmetric spaces. The ingredients necessary to compute (3.11) are given in Table 1. One then easily checks, case by case, that formula (3.11) provides the same result as (3.9).

4. Euler parameterizations of the simply connected simple Lie groups

As an application of our results, we summarize how to realize the generalized Euler parameterization of any simple, simply connected, compact Lie group $G$ w.r.t. a maximal symmetrically embedded Lie subgroup $H$. This is given by expression (3.6), which we repeat here for convenience:

$$G[\vec{x}; \vec{y}; \vec{z}] = e^{\sum_{a=1}^{h-k} x^a t_a e^{\sum_{i=1}^l y^i h_i} H[z_1, \ldots, z_h]}.$$  

(4.1)

The parameterization of $H[z_1, \ldots, z_h]$ can be done inductively in the same way. As we have seen, this is obtained by putting the subgroup $K$ in evidence so that $z_1, \ldots, z_h$ are chosen in such a way as to cover the whole $H$: the coordinates $x_1, \ldots, x_{h-k}$ have the same range as $z_1, \ldots, z_{h-k}$. Finally, the range for $y_1, \ldots, y_l$ is specified by (3.8). All possible Euler parameterizations of the simple, simply connected, compact Lie groups are listed in Table 1.

From the same table one can easily verify that formula (3.11) indeed agrees with (3.9), thus providing an alternative proof of the Macdonald-Dyson conjecture for all simple groups for the case $k_\alpha = m_\alpha/2$. The volumes of the groups can be computed as in [13].

We point out the fact that not all subgroups $H$ and $K$ are semisimple but can contain $U(1)$ factors which must be discussed separately. The measure is normalized so that the volume of a $U(1)$ factor is just the length of its period. It is interesting to notice that such periods can be related to the length of the roots. We will provide a proof of this fact together with a detailed construction of Table 1 which requires much more space, in a separate publication. Here we limit ourselves to specifying the length of the period for the $U(1)$ factors appearing in the table after normalizing the long roots of $G$ to $\sqrt{2}$. They are the following:

- in the $A_{III_a}$ case there is a phase factor in $H$ with period $T_H = 2\pi \sqrt{\frac{p+q}{pq}}$, whereas $K$ contains $p$ phase factors with periods $T_i = \frac{2\pi}{i} \sqrt{2i(i+1)}$, for $i = 1, \ldots, p-1$ and $T_p = 2\pi \sqrt{\frac{2p(p+q)}{q-p}}$;
- in the $A_{III_b}$ case there is a phase factor in $H$ with period $T_H = 2\pi \sqrt{\frac{q}{p}}$, and $p-1$ phase factors in $K$ with periods $T_i = \frac{2\pi}{i} \sqrt{2i(i+1)}$, for $i = 1, \ldots, p-1$;
in the AIV case there is a phase factor in $H$ with period $T_H = 2\pi \sqrt{\frac{n+1}{n}}$,
and a phase factor in $K$ with period $T_K = 2\pi \sqrt{\frac{n+1}{2(n-1)}}$;

- in the CI case the phase factor in $H$ has period $T_H = 2\pi \sqrt{2n}$;
- in the DI case the phase factor in $K$ has period $T_K = 4\pi$;
- in the DII case the subgroup $H$ is $U(2(n + 1)) \simeq SU(2(n + 1)) \times U(1)/\mathbb{Z}_{2n+1}$, and the period of the phase factor is $T_H = 4\pi \sqrt{2n + 1}$, whereas the phase factor in $K$ has period $T_K = 4\pi$;
- in the DI case the subgroup $H$ is $U(2n) \simeq SU(2n) \times U(1)/\mathbb{Z}_{2n}$, and the period of the phase factor is $T_H = 4\pi \sqrt{2n}$; and
- in the EII case the two phase factors in $K$ have periods $T_{K_1} = 4\pi$ and $T_{K_2} = 4\pi \sqrt{3}$;
- in the EIII case the periods of the phase factors in $H$ and in $K$ are $T_H = 4\pi \sqrt{3}$ and $T_K = 4\pi \sqrt{3}$;
- in the EVII case the period of the phase factor in $H$ is $T_H = 2\pi \sqrt{\frac{3}{2}}$.

Moreover, there are some particular cases that must be considered separately in the table, so that we list them apart:

- AI: for $n = 1$, $H = SO(2)$ with period $T = 4\pi$ and obviously $\alpha_h$ is not defined;
  for $n = 2$, $H = SO(3)$ which has only the short root, so that $|\alpha_G|/|\alpha_H| = 2$;
- BL$_a$: for $n = 2$, $H = SO(2) \times SO(3)$ whose phase factor has period $T = 4\pi$ and $|\alpha_G|/|\alpha_H| = \sqrt{2}$;
  for $n = 3$, $H = SO(3) \times SO(4)$ and the ratios of the root lengths are $|\alpha_G|/|\alpha_{SO(3)}| = \sqrt{2}$ and $|\alpha_G|/|\alpha_{SO(4)}| = 1$;
- BL$_b$: for $p = 2 > q > 0$, $H = SO(2) \times SO(q)$ whose phase factor has period $T = 4\pi$, and the ratio of the root lengths is $|\alpha_G|/|\alpha_{SO(q)}| = 1$;
  for $p = 3$ and $q > 5$, $H = SO(3) \times SO(q)$, and the ratios of the root lengths are $|\alpha_G|/|\alpha_{SO(3)}| = \sqrt{2}$ and $|\alpha_G|/|\alpha_{SO(q)}| = 1$;
- BI: for $n = 1$ is the same as AI for $n = 1$;
- DI$_b$: for $n = 2$, $H = SO(2) \times SO(2)$ whose phase factors have both period $T = 4\pi$;
- DI$_c$: for $n = 3$, $H = SO(2) \times SO(4)$ whose phase factor has period $T = 4\pi$;
- DI$_b$: for $p = 2$, $q > 3$, $H = SO(2) \times SO(q)$ whose phase factor has period $T = 4\pi$;
  for $p = 3$ and $q > 4$, $H = SO(3) \times SO(q)$, and the ratios of the root lengths are $|\alpha_G|/|\alpha_{SO(3)}| = \sqrt{2}$ and $|\alpha_G|/|\alpha_{SO(q)}| = 1$;
- DI: for $n = 2$, $H = SO(3)$, and the ratio of the root lengths is $|\alpha_G|/|\alpha_{SO(3)}| = \sqrt{2}$.

In this list the unspecified data can be read from Table 1. Note that in the table we are referring to the universal coverings, so that $SO(3) \simeq SU(2)$, $USp(4) \simeq SO(5)$, $USp(2) \simeq SU(2)$, $SO(6) \simeq SU(4)$, $SO(4) \simeq SU(2) \times SU(2)$, and $SO(n) \simeq Spin(n)$; in EVII $Ss(16) \simeq SO(16)/\mathbb{Z}_2$ is a semispin group. In the second column we indicate the compact form associated to the real form listed in the third column. $Z$ indicates the center of the compact form. In particular, $Z$ is $\mathbb{Z}_4$ if the dimension of the spin group is $4k + 2$ and $\mathbb{Z}_2 \times \mathbb{Z}_2$ if the dimension is $4k$. 


| Label | $G$ | $G_s$ | $\text{dim}(G)$ | $\text{dim}(G_s)$ | $\text{dim}(\mathcal{H})$ | $\Delta_{\mathcal{H}/\mathcal{H}_s}$ | $\mathcal{H}_s/\mathcal{H}_{s_s}$ | $\mathcal{K}$ | $\mathcal{K}/\mathcal{K}_{s_s}$ | $\mathcal{K}_{s_s}$ | $\mathcal{K}_{s_s}$ |
|-------|-----|-----|-------------|-------------|----------------|----------------|------------------|-----|----------------|-----|-----|
| A1    | SU(n+1) | SU(n+1) | $n^2 + 2n$ | $Z_{n+1}$ | SU(n+1)/Z_{n+1} | $n(n+1)/2$ | $A_n$ ($n \geq 1$) | (1,1,1) | $\sqrt{2}$ | (1,0) | $Z_{n+1}$ | - | $V_{n+1}$ |
| AII   | $SU(2n)$ | $SU(2n)$ | $4n^2 - 1$ | $Z_{2n}$ | $SU(2n)/Z_{2n}$ | $2^n + n$ | $A_n$ ($n > 1$) | (1,1,1) | 1 | $4^n(0,0)$ | $\sqrt{2}$ | $SU(2n)$ | 1 | $V_{2n}$ |
| AIII  | $SU(p+q)$ | $SU(p+q)$ | $(p+q)^2 - 1$ | $Z_{p+q}$ | $SU(p+q)/Z_{p+q}$ | $2^{p+q} - 1$ | $B_1(1 < p < q)$ | (1,1,1) | 1 | $2^{p+q} - 1$ | (1,0,0) | $SU(p+q)$ | p | $V_{p+q}$ |
| AIV   | $SU(2p)$ | $SU(2p)$ | $4p^2 - 1$ | $Z_{2p}$ | $SU(2p)/Z_{2p}$ | $2^{2p} - 1$ | $C_p$ ($p > 1$) | (2,2,1) | 1 | (2,1,0,0) | 1 | $SU(2p)$ | 1 | $V_{2p}$ |
| B    | $SU(n+1)$ | $SU(n+1)$ | $n^2 + 2n$ | $Z_{n+1}$ | $SU(n+1)/Z_{n+1}$ | $n^2$ | $A_1$ | (2) | 1 | (2,2-1,1) | 1 | $SU(n+1)$ | 1 | $V_{n+1}$ |
| B1    | $SO(2n+1)$ | $SO(2n+1)$ | $2n^2 + n$ | $Z_{2n+1}$ | $SO(2n+1)/Z_{2n+1}$ | $n^2$ | $B_n$ ($n > 3$) | (2,2,1) | 1 | (1,1,0,0) | 1 | $Z_{2n+1}$ | - | $V_{2n+1}$ |
| B1L   | $SO(p+q)$ | $SO(2n+1)$ | $(p+q)^2 - 1$ | $Z_{p+q}$ | $SO(p+q)/Z_{p+q}$ | $2^{p+q} - 1$ | $B_1(1 < p < q)$ | (1,1,1) | 1 | (2,1,0,0) | 1 | $SO(p+q)$ | p+q | $V_{p+q}$ |
| B1H   | $SO(2n)$ | $SO(2n)$ | $2n^2 + n$ | $Z_{2n}$ | $SO(2n)/Z_{2n}$ | $2^{2n} - 1$ | $C_n$ | (2,2,1) | 1 | (3,1) | 0 | 1 | $SU(2n)$ | 1 | $V_{2n}$ |
| B2    | $Sp(2n)$ | $Sp(2n)$ | $n^2 + 2n$ | $Z_{2n}$ | $Sp(2n)/Z_{2n}$ | $4^{n+2} - 2n$ | $C_n$ | (2,2,1) | 1 | (3,1,0,0) | $\sqrt{2}$ | $SU(2n)$ | 1 | $V_{2n}$ |
| B1L   | $Sp(2p)$ | $Sp(2p)$ | $(p+q)^2 - 1$ | $Z_{p+q}$ | $Sp(2p)/Z_{p+q}$ | $2^{p+q} - 1$ | $B_1(1 < p < q)$ | (2,2,1) | 1 | (4,4,0,0) | 1 | $USp(2p)$ | 1 | $V_{2p}$ |
| C1    | $Spin(2n)$ | $Spin(2n)$ | $n^2 + 2n$ | $Z_{2n}$ | $Spin(2n)/Z_{2n}$ | $4^{n+2} - 2n$ | $C_n$ | (2,2,1) | 1 | (3,1) | 0 | 1 | $SU(2n)$ | 1 | $V_{2n}$ |
| C1L   | $Spin(2p)$ | $Spin(2p)$ | $(p+q)^2 - 1$ | $Z_{p+q}$ | $Spin(2p)/Z_{p+q}$ | $2^{p+q} - 1$ | $B_1(1 < p < q)$ | (2,2,1) | 1 | (4,4,0,0) | 1 | $USp(2p)$ | 1 | $V_{2p}$ |
| D    | $SO(2n)$ | $SO(2n)$ | $2n^2 + n$ | $Z_{2n}$ | $SO(2n)/Z_{2n}$ | $n^2$ | $B_n$ ($n > 3$) | (2,2,1) | 1 | (1,1,0,0) | 1 | $Z_{2n}$ | - | $V_{2n}$ |
| D1    | $SO(2n)$ | $SO(2n)$ | $2n^2 + n$ | $Z_{2n}$ | $SO(2n)/Z_{2n}$ | $n^2$ | $B_n$ ($n > 3$) | (2,2,1) | 1 | (1,1,0,0) | 1 | $Z_{2n}$ | - | $V_{2n}$ |
| D1L   | $SO(p+q)$ | $SO(2n)$ | $(p+q)^2 - 1$ | $Z_{p+q}$ | $SO(p+q)/Z_{p+q}$ | $2^{p+q} - 1$ | $B_1(1 < p < q)$ | (2,2,1) | 1 | (2,1,0,0) | 1 | $SO(p+q)$ | p+q | $V_{p+q}$ |
| DH1   | $SO(2n)$ | $SO(2n)$ | $2n^2 + n$ | $Z_{2n}$ | $SO(2n)/Z_{2n}$ | $n^2$ | $B_n$ ($n > 3$) | (2,2,1) | 1 | (1,1,0,0) | 1 | $SU(2n)$ | 1 | $V_{2n}$ |
| DII   | $SU(2n)$ | $SU(2n)$ | $2n^2 + n$ | $Z_{2n}$ | $SU(2n)/Z_{2n}$ | $n^2$ | $C_n$ | (2,2,1) | 1 | (1,1,0,0) | 1 | $SU(2n)$ | 1 | $V_{2n}$ |
| E    | $E_6(78)$ | $E_6(78)$ | 78 | $Z_{78}$ | $E_6(78)/Z_{78}$ | 36 | $E_6$ | (2,3,4) | 1 | (1,2,1,0,0) | 1 | $SU(27)$ | 1 | $V_{78}$ |
| E1    | $E_6(78)$ | $E_6(78)$ | 78 | $Z_{78}$ | $E_6(78)/Z_{78}$ | 36 | $E_6$ | (2,3,4) | 1 | (1,2,1,0,0) | 1 | $SU(27)$ | 1 | $V_{78}$ |
| E12   | $E_8(248)$ | $E_8(248)$ | 248 | $Z_{248}$ | $E_8(248)/Z_{248}$ | 120 | $E_8$ | (2,3,4,6,8) | 1 | (1,0,0) | 1 | $SU(248)$ | 1 | $V_{248}$ |
| E13   | $E_8(248)$ | $E_8(248)$ | 248 | $Z_{248}$ | $E_8(248)/Z_{248}$ | 120 | $E_8$ | (2,3,4,6,8) | 1 | (1,0,0) | 1 | $SU(248)$ | 1 | $V_{248}$ |
| F1    | $F_4(10)$ | $F_4(10)$ | 10 | $Z_{10}$ | $F_4(10)/Z_{10}$ | 5 | $F_4$ | (2,2) | 1 | (1,1,0) | 1 | $Z_5$ | - | $V_{10}$ |
| F11   | $F_4(10)$ | $F_4(10)$ | 10 | $Z_{10}$ | $F_4(10)/Z_{10}$ | 5 | $F_4$ | (2,2) | 1 | (1,1,0) | 1 | $Z_5$ | - | $V_{10}$ |
| G    | $G_2(14)$ | $G_2(14)$ | 14 | $Z_2$ | $G_2(14)/Z_2$ | 6 | $G_2$ | (2,1) | 1 | (1,1,0) | 1 | $Z_2$ | - | $V_{14}$ |
In the column $\Lambda_{G/H}$ we indicate the reduced form of the root system associated to the symmetric space $G/H$. However, these in general can also contain double roots. Notice that the rank of the reduced system gives the rank of the symmetric space. The quotients $|\alpha_G|/|\alpha_H|$, $|\alpha_G|/|\alpha_{G/H}|$ and $|\alpha_H|/|\alpha_K|$ indicate the ratio of the long roots (including eventual double roots) of the indicated root systems. $(n_1, \ldots, n_r)$ are the coefficients of the highest root of the root system for the symmetric manifold. $m_\lambda = (m_{\lambda l}, m_{\lambda s})$ and $m_{2\lambda} = (m_{2\lambda l}, m_{2\lambda s})$ indicate the multiplicities of the roots of the reduced lattice and of the double roots respectively, where $l$ and $s$ denote long and short respectively. In the last column $\rho$ denotes a choice for a $G$-faithful representation of the algebra; $V_\lambda$ means the fundamental representation associated to the $i$-th weight in the corresponding Dynkin diagram.

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