K-TYPES OF MINIMAL REPRESENTATIONS
(p-ADIC CASE)

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Abstract. Let F be a p-adic field. Let G be a split simple simply connected group over F of type D_n, $(n \geq 4)$, or E_n, $(n = 6, 7, 8)$. Let K be a hyperspecial maximal compact subgroup of G. In this article we describe K-types of the minimal representation of G.

1. Minimal representation

It will be convinient for us to think of G as the group of F-points of a Chevalley group $\mathbf{G}$. Let $\mathcal{R}$ be the ring of integers of F. Then K is simply the group of $\mathcal{R}$-points of $\mathbf{G}$. Let ϖ be a uniformizing element of $\mathcal{R}$ and $\mathcal{R}/\varpi\mathcal{R} \cong \mathbb{F}_q$ the residue field of F.

Let K_1 be the first principal congruence subgroup. Then $K/K_1 \cong \mathbb{G}$ is the finite group of $\mathbb{F}_q$-points of $\mathbf{G}$. Let I, $K_1 \subset I \subset K$ be an Iwahori subgroup of G. Then $I/K_1 \cong \mathbb{B}$, a Borel subgroup of $\mathbb{G}$. Let H be the Hecke algebra of I-biinvariant compactly supported functions on G. The space of I-fixed vectors of a smooth representaton of G is naturally an H-module. It is a well known result of Borel [1] that this correspondence defines an equivalence between the category of representations of G generated by its I-fixed vectors and the category of representations of H.

The algebra H can be described as follows. Let $\Delta = \{\alpha_1, \dots \alpha_n\}$ be a set of simple roots. Let $-\alpha_0$ be the maximal root and let $\bar{\Delta} = \Delta \cup \{\alpha_0\}$. Let $<,>$ be a Killing form normalized so that $< \alpha_i, \alpha_i >= 2$ for all i. Then H is generated by T_i, $i = 0, \dots n$ satisfying the following relations:

$$T_iT_j = T_jT_i \qquad \text{if} \qquad < \alpha_i, \alpha_j >= 0;$$
$$T_iT_jT_i = T_jT_iT_j \qquad \text{if} \qquad < \alpha_i, \alpha_j >= -1;$$
$$\text{and} \qquad (T_i - q)(T_i + 1) = 0.$$

Define an irreducible H-module E by (see [7])

$$E = \oplus_{i=0}^{n} \mathbb{C}e_i$$

with the action of H given by

$$T_ie_j = \begin{cases} -e_j & \text{if } \alpha_i = \alpha_j; \\ qe_j + q^{\frac{1}{2}}e_i & \text{if } < \alpha_i, \alpha_j >= -1; \\ qe_j & \text{if } < \alpha_i, \alpha_j >= 0. \end{cases}$$

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Definition 1.1. *The minimal representation is the unique irreducible representation $V_{\min}$ such that the space of I-fixed vectors in $V_{\min}$ is isomorphic to E, as an H-module.*

Repeating previous constructions with Δ (instead of $\bar{\Delta}$) gives $\mathbb{H}$, the Hecke algebra of $\mathbb{B}$-biinvariant functions on $\mathbb{G}$ and an $\mathbb{H}$-module $\mathbb{E}$ which corresponds to $\mathbb{V}_{\min}$, the representation of $\mathbb{G}$ with the minimal dimension (see [3]). It is interesting to note that by setting $q = 1$, $\mathbb{H}$ becomes the group algebra of the Weyl group of G and $\mathbb{E}$ its reflection representation.

Let $h_1, \dots, h_n$ and x_α, $\alpha \in \Phi$ (Φ is the root system) be a Chevalley basis of $\mathfrak{g}$ as in [6]. Let $\mathfrak{g}_{\mathbb{Z}}$ be $\mathbb{Z}$-span of the Chevalley basis of $\mathfrak{g}$. Let

$$\mathfrak{g}_i = \mathfrak{g}_{\mathbb{Z}} \otimes_{\mathbb{Z}} \varpi^i \mathcal{R}.$$

Let v_F be an evaluation on F normalized so that $\mathrm{v}_F(\varpi) = 1$. If $\mathrm{v}_F(p) < p - 1$ then the exponential map is well defined on $\mathfrak{g}_1$, and it preserves Haar measures. The groups $K_i = \exp(\mathfrak{g}_i)$, $i = 1, 2 \dots$ are the principal congruence subgroups. If $\mathrm{v}_F(p) < 1/3(p-1)$ then the multiplication in K_1 can be defined using the Campbell-Hausdorff formula [9], LG 5.19.

The Killing form $<,>$, normalized by $< h_i, h_i >= 2$ for all i, is unimodular on $\mathfrak{g}_0$ if p is prime to the determinant of the Cartan matrix (which is 4, 3, 2 and 1 for D_n, E_6, E_7 and E_8 respectively). Note that $\mathrm{v}_F(p) < 1/3(p-1)$ implies that $p \neq 2, 3$, hence we can assume that the Killing form is unimodular on $\mathfrak{g}_0$.

Let f_i be the characteristic function of $\mathfrak{g}_i$. Let ψ be a non-trivial additive character of F with conductor $\mathcal{R}$. Let f be a locally constant compactly supported function on $\mathfrak{g}$. Define the Fourier transform $\hat{f}$ of f by

$$\hat{f}(x) = \int_{\mathfrak{g}} f(y)\psi(< x, y >)dy$$

where the Haar measure dy is normalized so that

$$\hat{f}_i = |\varpi|^{i \dim \mathfrak{g}} f_{-i}.$$

Let (π, V) be an irreducible representation of G. It defines a distribution Θ_π as follows. Let f be a locally constant function supported in $\mathfrak{g}_1$. Then

$$\Theta_\pi(f) = tr \int_{\mathfrak{g}} \pi(\exp x) f(x) dx.$$

A result of Howe and Harish-Chandra [4] says that there is a positive integer n_V and numbers $c_{\mathcal{O}}$ such that

$$\Theta_\pi(f) = \sum_{\mathcal{O}} c_{\mathcal{O}} \int \hat{f} \mu_{\mathcal{O}}$$

for every locally constant function f supported in $\mathfrak{g}_{n_V}$. Here the sum is taken over nilpotent orbits and $\mu_{\mathcal{O}}$ is a G-invariant measure on $\mathcal{O}$ constructed as follows. Let $x \in \mathcal{O}$ and let

$$B_x(y, z) =< x, [y, z] >$$

be a bilinear form on $\mathfrak{g}$. It induces a non-degenerate symplectic form on $T_{\mathcal{O},x}$, the tangent space of $\mathcal{O}$ at x. Then $\mu_{\mathcal{O}}(x) = |\wedge^d B_x|$ (we shall see on the example of the minimal orbit how this works).

Remark 1.2. *One expects that $n_V = 1$ for representations generated by its I-fixed vectors. Indeed, Waldspurger has shown this to be true for classical groups* [11].

Let $D = \max_{c_{\mathcal{O}} \neq 0} \frac{1}{2} \dim \mathcal{O}$. It follows from the character expansion (see [8]) that the dimension of the space of K_i-fixed vectors in V grows as q^{Di}.

The minimal non-trivial nilpotent orbit $\mathcal{O}_{\min}$ is the orbit of $x_{-\alpha_0}$. Let $\Theta_{\min}$ be the character of $V_{\min}$. Theorem 2.1 in [8] says that

$$\Theta_{\min}(f) = \int \hat{f}\mu_{\mathcal{O}_{\min}} + c \int \hat{f}\mu_0.$$

Hence the growth of $\dim V_{\min}^{K_i}$ is the slowest possible, justifying the name "minimal".

2. K-types

The main result is the following.

Proposition 2.1. *Assume that* $\mathrm{v}_F(p) < 1/3(p-1)$ *and* $n_{V_{\min}} = 1$. *Then*

$$V_{\min}|_K = \oplus_{i=0}^{\infty} V_i$$

where V_i are irreducible representations of K such that $V_{\min}^{K_{i-1}} \oplus V_i = V_{\min}^{K_i}$. Here $K_0 = K$, K_i, $i \geq 1$, are principal congruence subgroups and $V_{\min}^{K_i}$ is the space of K_i-fixed vectors. Furthermore $V_0 = \mathbb{C}$ (the trivial representation of K) and $V_1 = \mathbb{V}_{\min}$, the minimal representation of $\mathbb{G}$, pulled back to K. We also describe V_i for $i > 1$ explicitely.

Proof. We first describe K-types contained in $V_{\min}^{K_1}$. Let B be a Borel subgroup of G. Since $G = BK$ and $V_{\min} \subset \mathrm{ind}_B^G \chi$ for some unramified character χ, it follows that

$$V_{\min}^{K_1} \subset C(\mathbb{B} \backslash \mathbb{G})$$

and

$$V_{\min}^{I} \subset C(\mathbb{B} \backslash \mathbb{G} / \mathbb{B}).$$

Hence the K-types contained in $V_{\min}^{K_1}$ are obtained by restricting the H-module E to $\mathbb{H}$. Since $E|_{\mathbb{H}} = \mathbb{C} \oplus \mathbb{E}$ the claim follows.

To continue we need to describe $\mathcal{O}_{\min}$. Write $\alpha_0 = m_1\alpha_1 + \ldots + m_n\alpha_n$. Let $h_0 = m_1h_1 + \ldots + m_nh_n$. Then $(x_{\alpha_0}, h_0, x_{-\alpha_0})$ is an $sl(2)$-triple. Let

$$\mathfrak{g}(i) = \{x \in \mathfrak{g} \mid [h_0, x] = ix\}.$$

Then $\mathfrak{g} = \oplus_{-2 \leq i \leq 2} \mathfrak{g}(i)$. Assume that α_1 is the unique simple root such that $< \alpha_0, \alpha_1 > \neq 0$. Then $\mathfrak{p} = \oplus_{i \geq 0} \mathfrak{g}(i)$ is the maximal parabolic subalgebra corresponding to α_1 (see the diagrams on the end of this section). The unipotent radical of $\mathfrak{p}$ is $\mathfrak{g}(1) \oplus \mathfrak{g}(2)$. It is a Heisenberg Lie algebra with center $\mathfrak{g}(2)$, spanned by $x_{-\alpha_0}$. Let

$$\mathfrak{s} = [\mathfrak{g}(0), \mathfrak{g}(0)] \oplus \mathfrak{g}(1) \oplus \mathfrak{g}(2).$$

It is the centralizer of $x_{-\alpha_0}$. Let S be the centralizer of $x_{-\alpha_0}$ in G and let $\mathbb{S} \subset \mathbb{G}$ the corresponding finite group.

Lemma 2.2. *Let $g = \#\mathbb{G}/\mathbb{S}$ and $d = 1/2\dim\mathcal{O}_{\min}$ (d=2n-3,11,17 and 29, respectively). If $i > 2$ then*
$$\dim V_{\min}^{K_i} - \dim V_{\min}^{K_{i-1}} = gq^{d(i-2)}.$$

Proof. Let $\chi_i(x) = |\varpi|^{-i\dim\mathfrak{g}} f_0(\varpi^{-i}x)$. Then $P_i = \pi(\chi_i)$ is a projection on $V_{\min}^{K_i}$. Since $\dim V_{\min}^{K_i} = tr(P_i)$ and $\hat{\chi}_i(x) = f_{-i}(x)$, it follows that

$$\dim V_{\min}^{K_i} - \dim V_{\min}^{K_{i-1}} = \int (f_{-i} - f_{-i+1})\mu_{\mathcal{O}_{\min}}.$$

Write $\mathcal{O}_{\min} = x_{-\alpha_0}^G$. Since $G = KB$, it follows that $\mathcal{O}_{\min} = \cup \varpi^i x_{-\alpha_0}^K$. Hence

$$\mathcal{O}_{\min} \cap (\mathfrak{g}_{-i} \setminus \mathfrak{g}_{-i+1}) = \varpi^{-i} x_{-\alpha_0}^K.$$

Let $\mathcal{O}_i = \varpi^{-i} x_{-\alpha_0}^K$. Then $\mathcal{O}_i$ breaks into g K_1-orbits

$$\mathcal{O}_i = \cup_{j=1}^g \mathcal{O}_{i,j}.$$

Assume that $\mathcal{O}_{i,1}$ is the K_1-orbit of $x_{-\alpha_0}$. Hence

$$\dim V_{\min}^{K_i} - \dim V_{\min}^{K_{i-1}} = g\int_{\mathcal{O}_{i,1}} \mu_{\mathcal{O}_{\min}}.$$

To compute the volume of $\mathcal{O}_{i,1}$ we need to describe precisely the normalization of $\mu_{\mathcal{O}_{\min}}$ at $\varpi^{-i}x_{-\alpha_0}$. Let $\mathfrak{s}'$ be the span of h_0, $\mathfrak{g}(-2)$ and $\mathfrak{g}(-1)$. Then $\mathfrak{g} = \mathfrak{s} \oplus \mathfrak{s}'$ and the tanget space of $\mathcal{O}_{\min}$ at $x_{-\alpha_0}$ can naturally be identified with $\mathfrak{s}'$. Note that $\mathfrak{g}(-1) \oplus \mathfrak{g}(-2)$ is a Heisenberg Lie algebra with center $\mathfrak{g}(-2)$, spanned by x_{α_0}. Let $\{e_1, \dots e_{d-1}, f_1, \dots f_{d-1}\}$ be the part of the Chevalley basis contained in $\mathfrak{g}(-1)$ labeled so that $[e_j, f_k] = \delta_{j,k}x_{\alpha_0}$ ($\delta_{j,k} = 1$ if $j = k$ and 0 otherwise). We complete it to a basis of $\mathfrak{s}'$ by adding $e_d = x_{\alpha_0}$ and $f_d = \frac{1}{2}h_0$.

Let $\mathfrak{s}'_{\mathbb{Z}[1/2]}$ be $\mathbb{Z}[1/2]$-span of $\{e_1, \dots e_d, f_1, \dots f_d\}$. Let $\mathfrak{g}_{\mathbb{Z}[1/2]}$ and $\mathfrak{s}_{\mathbb{Z}[1/2]}$ be $\mathbb{Z}[1/2]$-span of the Chevalley basis and of its part contained in $\mathfrak{s}$ respectively. Since $m_1 = 2$, and 2 is invertible in $\mathbb{Z}[1/2]$,
$$\mathfrak{g}_{\mathbb{Z}[1/2]} = \mathfrak{s}_{\mathbb{Z}[1/2]} \oplus \mathfrak{s}'_{\mathbb{Z}[1/2]}.$$
Let
$$\mathfrak{s}'_i = \mathfrak{s}_{\mathbb{Z}[1/2]} \otimes_{\mathbb{Z}[1/2]} \varpi^i\mathcal{R}.$$
and let $S'_i = \exp\mathfrak{s}'_i$, $i = 1, 2 \dots$. Define analogously $\mathfrak{s}_i$ and S_i. Also, since p is odd

$$\mathfrak{g}_i = \mathfrak{g}_{\mathbb{Z}} \otimes_{\mathbb{Z}} \varpi^i\mathcal{R} = \mathfrak{g}_{\mathbb{Z}[1/2]} \otimes_{\mathbb{Z}[1/2]} \varpi^i\mathcal{R}.$$

Hence $\mathfrak{g}_i = \mathfrak{s}_i \oplus \mathfrak{s}'_i$, $K_i = S_iS'_i$, $i = 1, 2 \dots$ and we have a sequence of measure-preserving bijections:
$$\mathcal{O}_{1,j} \cong S'_1 \cong \mathfrak{s}'_1.$$

Since $\mathfrak{s}_1'$ is the $\mathcal{R}$-span of ϖe_j and ϖf_j $j = 1, \ldots d$, and

$$|B_{\varpi^{-i}x_{-\alpha_0}}(\varpi e_j, \varpi f_k)| = \delta_{j,k} q^{(i-2)}$$

it follows that the volume of $\mathcal{O}_{i,1}$ is $q^{d(i-2)}$. The lemma is proved.

Recall [5], Lemma 1.2, that irreducible representations of K_1/K_i are parametrized by K_1-orbits in $\mathfrak{g}_{-i}/\mathfrak{g}_{-1}$. To describe the corespondence, recall that the Fourier transform defines an isomorphism between the spaces of functions $C(\mathfrak{g}_1/\mathfrak{g}_i)$ and $C(\mathfrak{g}_{-i}/\mathfrak{g}_{-1})$. Let $\mathcal{O}$ be a K_1-orbit in $\mathfrak{g}_{-i}/\mathfrak{g}_{-1}$ and $E_{\mathcal{O}}$ the corresponding irreducible representation of K_1. Then

(1) the character of $E_{\mathcal{O}}$, pulled back to $\mathfrak{g}_1$ via log, is the Fourier transform of the characteristic function of $\mathcal{O}$ divided by $\#\mathcal{O}^{1/2}$.
(2) $\dim E_{\mathcal{O}} = \#\mathcal{O}^{1/2}$; this is a consequence of (1).

Let $\mathcal{O}_{i,j} \subset \mathcal{O}_i$, $(i \geq 2)$ be a K_1-orbit. Then $\mathcal{O}'_{i,j} = \mathcal{O}_{i,j} + \mathfrak{g}_{-1}$ is a K_1-orbit in $\mathfrak{g}_{-i}/\mathfrak{g}_{-1}$. Since $\mathcal{O}'_{i,j}$ are K-conjugated and $\#\mathcal{O}_{i,1} = \#K_1/S_1K_{i-1} = q^{2d(i-2)}$, it follows that

(1) $\dim E_{\mathcal{O}'_{i,j}} = q^{d(i-2)}$.
(2) $E_{\mathcal{O}_{i,j}}$ is a summand of $V_{\min}$.

From this and Lemma 2.2 we conclude that

$$V_{\min}^{K_i} = V_{\min}^{K_{i-1}} \ \oplus \ (\oplus_{j=1}^{g} E_{\mathcal{O}'_{i,j}}).$$

Let $S_0 = S \cap K$. Obviously, S_0 preserves $E_{\mathcal{O}'_{i,1}} \subset V_{\min}^{K_i}$. Let

$$V_i = \operatorname{ind}_{S_0K_1}^{K} E_{\mathcal{O}'_{i,1}}.$$

Since

$$V_i|_{K_1} = \oplus_{j=1}^{g} E_{\mathcal{O}'_{i,j}}$$

it follows from the Mackey's irreducibility criterion ([10] Prop. 23) that V_i is irreducible. Also, by the Frobenius reciprocity $V_i \subset V_{\min}$. The proposition is proved.

We proceed to write down V_i, the irreducible representations of K/K_i. Let ψ_i be a character of $\mathfrak{g}$ defined by $\psi_i(x) = \psi(< x, \varpi^{-i}x_{-\alpha_0} >)$. If $j \leq i \leq 2j$ then $K_j/K_i \cong \mathfrak{g}_j/\mathfrak{g}_i$ (this follows from the Campbell-Hausdorff formula). Hence ψ_i defines a character of K_j/K_i. We first describe $E_{\mathcal{O}'_{i,1}}$. We have two cases.

(1) i is even. Write $i = 2j$. Then ψ_i defines a character of K_j/K_i. Note that $\psi_i|_{S_j} = 1$. Therefore, since S_1 centralizes ψ_i, we can extend ψ_i to S_1K_j by $\psi_i|_{S_1} = 1$. Then

$$E_{\mathcal{O}'_{i,1}} = \operatorname{ind}_{S_1K_j}^{K_1} \psi_i.$$

(2) i is odd. Write $i = 2j+1$. Then ψ_i defines a character of K_{j+1}/K_i. As in the even case extend ψ_i to S_1K_{j+1}. Then $S_1K_j/\ker\psi_i$ is a Heisenberg group. Let ρ_i be the corresponding irreducible representation such that the center acts via the character ψ_i. Then

$$E_{\mathcal{O}'_{i,1}} = \operatorname{ind}_{S_1K_j}^{K_1} \rho_i.$$

We know apriori that $E_{\mathcal{O}'_{i,1}}$ extends to S_0. Since $[\mathbb{S},\mathbb{S}]=\mathbb{S}$ the extension is unique in view of the following lemma (take $A=S_0K_1$ and $B=K_1$).

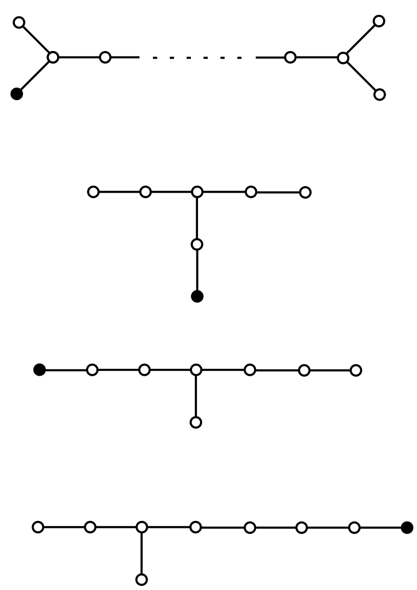
Lemma 2.3. *Let A be a group and B a normal subgroup. Let $C=A/B$. Assume that $[C,C]=C$. Let ρ be an irreducible finite-dimensional representation of B. If ρ extends to A then it extends uniquely.*

Proof. Let ρ_1 and ρ_2 be two extensions. By the Schur Lemma, for any $a\in A$ there exists a scalar $\chi(a)$ such that $\rho_1(a)=\chi(a)\rho_2(a)$. Obviously, χ is a character of C. Since $[C,C]=C$, it must be trivial. The lemma is proved.

We now give precise definitions of V_i, $i=2,3\ldots$. Again we have two cases.

(1) i is even. Write $i=2j$. Then ψ_i defines a character of K_j/K_i. Extend ψ_i to S_0K_j by $\psi_i|_{S_0}=1$. Then
$$V_i=\mathrm{ind}_{S_0K_j}^K\,\psi_i.$$
(2) i is odd. Write $i=2j+1$. Then ψ_i defines a character of K_{j+1}/K_i. Extend ψ_i to S_1K_{j+1} by $\psi_i|_{S_1}=1$. Then $S_1K_j/\ker\psi_i$ is a Heisenberg group. Let ρ_i be the corresponding irreducible representation such that the center acts via the character ψ_i. It extends to S_0 via the usual Weil representation argument. Then
$$V_i=\mathrm{ind}_{S_0K_j}^K\,\rho_i.$$

We conclude this paper by giving some explicit data. Recall that the extended Dynkin diagram for G is a graph obtained from the set of roots $\bar{\Delta}$ by connecting α_i and α_j if and only if $<\alpha_i,\alpha_j>=-1$:



The black vertex in each diagram corresponds to the root α_0.

Recall that α_1 is the unique simple root such that $< \alpha_0, \alpha_1 >= -1$. Since $\mathbb{S}$ is a semi-direct product of a Heisenberg group of order q^{2d-1}, and a semi-simple, simply connected group with the Dynkin diagram obtained by removing α_1 from the Dynkin diagram of $\mathbb{G}$, one can compute $g = \#\mathbb{G}/\mathbb{S}$ using formulas in [2], page 75. The answers are:

$$D_n \qquad \frac{(q^n-1)(q^{2n-4}-1)(q^{2n-2}-1)}{(q^2-1)(q^{n-2}-1)}$$

$$E_6 \qquad \frac{(q^8-1)(q^9-1)(q^{12}-1)}{(q^3-1)(q^4-1)}$$

$$E_7 \qquad \frac{(q^{12}-1)(q^{14}-1)(q^{18}-1)}{(q^4-1)(q^6-1)}$$

$$E_8 \qquad \frac{(q^{20}-1)(q^{24}-1)(q^{30}-1)}{(q^6-1)(q^{10}-1)}$$

Finally, we note that

$$\dim \mathbb{V}_{\min} = gq/(q^{d+1}-1)$$

$d = 1/2 \dim \mathcal{O}_{\min}$, and it is $2n-3$, 11, 17 and 29 respectively.

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