

# The Gelfand–Graev representation of classical groups in terms of Hecke algebras.\*

Petar Bakić, Gordan Savin

## Abstract

Let  $G$  be a  $p$ -adic classical group. The representations in a given Bernstein component can be viewed as modules for the corresponding Hecke algebra—the endomorphism algebra of a pro-generator of the given component. Using Heiermann’s construction of these algebras, we describe the Bernstein components of the Gelfand–Graev representation for  $G = \mathrm{SO}(2n+1)$  and  $\mathrm{Sp}(2n)$ .

## 1 Introduction

Let  $F$  be a non-Archimedean local field of residue characteristic  $q$ . Let  $G$  be the group of  $F$ -points of a connected, split reductive algebraic group defined over  $F$ ; in particular, the group  $G$  contains a Borel subgroup. Let  $U$  be the unipotent radical of the Borel subgroup and fix a non-degenerate (Whittaker) character  $\psi : U \rightarrow \mathbb{C}^\times$ . The Gelfand–Graev representation of  $G$  is  $\mathrm{c-ind}_U^G(\psi)$  where  $\mathrm{c-ind}$  stands for induction with compact support. The goal of this paper is to give an explicit description of the Bernstein components of the Gelfand–Graev representation.

Let us briefly describe what is known. Let  $K$  be a special maximal compact subgroup of  $G$  and  $I$  an Iwahori subgroup contained in  $K$ . Let  $\mathcal{H}$  be the Iwahori–Hecke algebra of  $I$ -biinvariant functions on  $G$ , and  $\mathcal{H}_K$  the subalgebra consisting of functions supported on  $K$ . Then  $\mathcal{H}_K$  is isomorphic to the group algebra of the Weyl group  $W$  of  $G$  and thus it has a one-dimensional representation  $\epsilon$  (the sign character). As an  $\mathcal{H}$ -module,  $(\mathrm{c-ind}_U^G \psi)^I$  is isomorphic to the projective  $\mathcal{H}$ -module [10]

$$\mathcal{H} \otimes_{\mathcal{H}_K} \epsilon.$$

If  $G = \mathrm{GL}_n$  then a similar statement holds for all Bernstein components with appropriate Hecke algebras arising from Bushnell–Kutzko types [11]. We build on methods of that paper. We finish this paragraph by mentioning a recent article of Mishra and Pattanayak [18] that considers Bernstein components of  $\mathrm{c-ind}_U^G(\psi)$  corresponding to representations induced from the Borel subgroup. Their result is formulated in terms of Hecke algebras arising from types constructed by Roche.

---

\*MSC2020: 11F70, 22E50, 20C08

Keywords: Hecke algebras, Gelfand–Graev representation

For a general  $G$  one does not have a complete theory of types and corresponding Hecke algebras, but there is a replacement: endomorphism algebras of pro-generators of Bernstein components.

It turns out that these algebras are more suited for the problem at hand. In more detail, let  $P = MN$  be a parabolic subgroup of  $G$ , and let  $\sigma$  be an irreducible cuspidal representation of  $M$ . Let  $M^\circ$  be the subgroup of  $M$  consisting of all  $m \in M$  such that  $|\chi(m)| = 1$  for all smooth characters  $\chi : M \rightarrow \mathbb{C}^\times$ . Let  $\sigma_0$  be an irreducible summand of  $\sigma$  restricted to  $M^\circ$ . Then  $i_P^G(\text{c-ind}_{M^\circ}^M(\sigma_0))$  is a projective  $G$ -module generating a single Bernstein component. Here  $i_P^G$  denotes normalized parabolic induction. Let

$$\mathcal{H} = \text{End}_G(i_P^G(\text{c-ind}_{M^\circ}^M(\sigma_0))).$$

Observe that we have a natural inclusion

$$\mathcal{A} = \text{End}_M(\text{c-ind}_{M^\circ}^M(\sigma_0)) \subseteq \mathcal{H}.$$

For every  $G$ -module  $\pi$ ,

$$\mathfrak{F}(\pi) = \text{Hom}_G(i_P^G(\text{c-ind}_{M^\circ}^M(\sigma_0)), \pi)$$

is naturally a right  $\mathcal{H}$  module. The functor  $\mathfrak{F}$  is an equivalence between the Bernstein component generated by  $i_P^G(\text{c-ind}_{M^\circ}^M(\sigma_0))$  and the category of right  $\mathcal{H}$ -modules.

Now assume  $\sigma$  is  $\psi$ -generic. Let

$$\Pi = \mathfrak{F}(\text{c-ind}_U^G(\psi)).$$

It is not difficult to see, using Bernstein's second adjointness, that  $\Pi \cong \mathcal{A}$ , as  $\mathcal{A}$ -modules. Thus understanding  $\Pi$  reduces to understanding  $\mathcal{H}$  modules isomorphic to  $\mathcal{A}$ . This was done for  $\text{GL}_n$  in [11]. We extend this computation to  $\mathcal{H}$  for  $G = \text{SO}(2n+1, F)$  and  $\text{Sp}(2n, F)$ . For classical groups the algebra  $\mathcal{H}$  has been computed by Heierman [16]; more recently, Solleveld [23] has studied the same algebra in a more general setting. If  $G = \text{SO}(2n+1, F)$  or  $\text{Sp}(2n, F)$ , it turns out that the algebra  $\mathcal{H}$  is a tensor product of Hecke algebras each of which is isomorphic to the Iwahori-Hecke algebra  $\text{GL}_n$  or to an algebra of the type  $\tilde{C}_n$ , with unequal parameters. Assume that  $\mathcal{H}$  corresponds to  $\tilde{C}_n$ . Its diagram has two special vertices, denoted by  $0$  and  $n$ . Corresponding to them, we have two finite subalgebras  $\mathcal{H}_0$  and  $\mathcal{H}_n$  of  $\mathcal{H}$ . We prove that any  $\mathcal{H}$ -module isomorphic to  $\mathcal{A}$  is necessarily

$$\mathcal{H} \otimes_{\mathcal{H}_0} \epsilon_0 \text{ or } \mathcal{H} \otimes_{\mathcal{H}_n} \epsilon_n$$

for a one-dimensional representation  $\epsilon_0$  or  $\epsilon_n$ . Here we moved to more familiar language of left  $\mathcal{H}$ -modules. This is harmless indeed, since  $\mathcal{H}$  is isomorphic to its opposite algebra; this follows from the Iwahori-Matsumoto relations. Finally, we determine precisely the isomorphism class of  $\Pi$ .

We expect a similar description to be available when  $G = \text{O}(2n)$ , but we do not treat it here. The case  $G = \text{SO}(2n)$  is significantly more involved due to the complicated structure of the  $R$ -group [14].

We finish this paper with an application to the Gan-Gross-Prasad restriction problem, and with an appendix where we show that  $\mathcal{H}$  is isomorphic with the Hecke algebra arising from the type constructed by Stevens.

We would like to thank K.-Y. Chan, Y. Sakellaridis, M. Solleveld and S. Stevens for useful communications. G. Savin is partially supported by a grant from the National Science Foundation, DMS-1901745.

## 2 Preliminaries

### 2.1 Notation

Throughout the paper,  $F$  will denote a non-Archimedean local field of residue characteristic  $q$  and uniformizer  $\varpi$ , equipped with the absolute value  $|\cdot|$  normalized in the usual way.

We let  $G$  denote the group of  $F$ -points of a connected, split reductive algebraic group defined over  $F$ . From §2.4 on, we specialize to the case where  $G$  is the special odd orthogonal group, or the symplectic group. If we want to emphasize the rank, we use  $G_n$  to denote  $\mathrm{SO}(2n+1, F)$  or  $\mathrm{Sp}(2n, F)$ . By  $\mathrm{Rep}(G)$  we denote the category of smooth complex representations of  $G$ .

For an arbitrary group  $H$ , we let  $X(H)$  denote the group of complex characters of  $H$ .

### 2.2 Unramified characters

If  $M$  is a Levi subgroup of  $G$ , we let  $M^\circ = \bigcap_\chi \ker |\chi|$ , the intersection taken over the set of all rational characters  $\chi : M \rightarrow F^\times$ . We say that a (complex) character  $\chi$  of  $M$  is unramified if it is trivial on  $M^\circ$ ; we let  $X^{\mathrm{nr}}(M)$  denote the group of all unramified characters on  $M$ . Then  $M/M^\circ$  is a free  $\mathbb{Z}$ -module of finite rank, and the group  $X^{\mathrm{nr}}(M) = X(M/M^\circ)$  has a natural structure of a complex affine variety. For any element  $m \in M$ , we denote by  $b_m$  the evaluation  $\chi \mapsto \chi(m)$ .

Now let  $\sigma$  be an irreducible cuspidal representation of  $M$ , and set  $M^\sigma = \{m \in M : {}^m\sigma \cong \sigma\}$ . Then  $M/M^\sigma$  is a finite Abelian group, and we let  $\mathcal{A}$  denote the ring of regular functions on the quotient variety  $X(M/M^\sigma)/X(M/M^\circ)$ . Since  $M^\sigma/M^\circ$  is once again a free  $\mathbb{Z}$ -module (of the same rank as  $M/M^\circ$ ), we have  $\mathcal{A} \cong \mathbb{C}[M^\sigma/M^\circ]$ . Furthermore, letting  $\sigma_0$  denote an arbitrary irreducible constituent of  $\sigma|_{M^\circ}$ , we have a canonical isomorphism  $\mathcal{A} \cong \mathrm{End}_M(\mathrm{c-ind}_{M^\circ}^M \sigma_0)$ . Indeed, this follows from a simple application of Mackey theory. We refer the reader to [16, §1.17, §4] for additional details.

### 2.3 The Hecke algebra of a Bernstein component

If  $\pi$  is an irreducible representation of  $G$ , there is a Levi subgroup  $M$  of  $G$  and an irreducible cuspidal representation  $\sigma$  of  $M$  such that  $\pi$  is (isomorphic to) a subquotient of  $i_P^G(\sigma)$ . Here  $P$  is a parabolic subgroup of  $G$  with Levi component  $M$ . The pair  $(M, \sigma)$  is determined by  $\pi$  up to conjugacy; we call  $(M, \sigma)$  the cuspidal support of  $\pi$ .

We say that the two pairs  $(M_1, \sigma_1)$  and  $(M_2, \sigma_2)$  as above are inertially equivalent if there exists an element  $g \in G$  and an unramified character  $\chi$  of  $M_2$  such that

$${}^g\sigma_1 = \sigma_2 \otimes \chi.$$

This is an equivalence relation on the set of all pairs  $(M, \sigma)$ . Given an equivalence class  $[(M, \sigma)]$ , we denote by  $\mathrm{Rep}_{(M, \sigma)}(G)$  the full subcategory of  $\mathrm{Rep}(G)$  defined by the requirement that all irreducible subquotients of every object in  $\mathrm{Rep}_{(M, \sigma)}(G)$  be supported within the inertial class  $[(M, \sigma)]$ . A classic result of Bernstein then shows that the category  $\mathrm{Rep}(G)$  decomposes as a direct product

$$\mathrm{Rep}(G) = \prod_{[(M, \sigma)]} \mathrm{Rep}_{(M, \sigma)}(G)$$

taken over the set of all inertial equivalence classes. We refer to  $\text{Rep}_{(M,\sigma)}(G)$  as the Bernstein component attached to the pair  $(M,\sigma)$ . For a detailed discussion of the above results, see [4] or [3].

For each Bernstein component  $\text{Rep}_{(M,\sigma)}(G)$  one can construct a projective generator  $\Gamma_{(M,\sigma)}$  by setting

$$\Gamma_{(M,\sigma)} = i_P^G(\text{c-ind}_{M^\circ}^M(\sigma_0)).$$

Here  $\sigma_0$  is any irreducible component of the (semisimple) restriction  $\sigma|_{M^\circ}$ . We now obtain a functor from the category  $\text{Rep}_{(M,\sigma)}(G)$  to the category of right  $\text{End}_G(\Gamma_{(M,\sigma)})$ -modules given by

$$\pi \mapsto \text{Hom}(\Gamma_{(M,\sigma)}, \pi).$$

The fact that  $\Gamma_{(M,\sigma)}$  is a projective generator implies that this is an equivalence of categories. This is [3], Lemma 22; a detailed proof of this fact is also given in [20], Theorem 1.5.3.1.

Given a Bernstein component  $\mathfrak{s} = (M,\sigma)$ , we use  $\mathcal{H}_{\mathfrak{s}}$  to denote  $\text{End}_G(\Gamma_{\mathfrak{s}})$  and refer to it as the Hecke algebra attached to the component  $\mathfrak{s}$ . Furthermore, for any  $\pi \in \text{Rep}(G)$  we let  $\pi_{\mathfrak{s}}$  denote the corresponding  $\mathcal{H}_{\mathfrak{s}}$ -module  $\text{Hom}(\Gamma_{\mathfrak{s}}, \pi)$ .

Though we do not use it here, we point out that there is another highly useful approach to analyzing Bernstein components, based on the theory of types developed by Bushnell and Kutzko [8]. One can show that the Hecke algebra used by Bushnell and Kutzko is in fact isomorphic to the algebra  $\mathcal{H}_{\mathfrak{s}}$  introduced above; we prove this fact in Appendix A. Therefore—for the purposes of this paper—the two approaches are equivalent.

## 2.4 Cuspidal representations

Here we briefly recall some facts and introduce notation related to cuspidal representations. For the sake of concreteness we now specialize to the case when  $G$  is a special odd orthogonal group or a symplectic group. We use  $G_n$  to denote  $\text{SO}(2n+1, F)$  or  $\text{Sp}(2n, F)$ .

Let  $\rho$  and  $\sigma$  be irreducible unitarizable cuspidal representations of  $\text{GL}_k(F)$  and  $G_{n_0}$  respectively. We consider the representation  $\nu^\alpha \rho \rtimes \sigma$ , where  $\alpha \in \mathbb{R}$ . Here and throughout the paper, we use  $\nu$  to denote the unramified character  $|\det|$  of the general linear group. If  $\rho$  is not self-dual, the above representation never reduces. If  $\rho$  is self-dual, then there exists a unique  $\alpha \geq 0$  such that  $\nu^\alpha \rho \rtimes \sigma$  is reducible; we denote it by  $\alpha_\rho$ .

The number  $\alpha_\rho$  has a natural description in terms of Langlands parameters. Let  $\phi$  be the L-parameter of  $\sigma$ . Set  $a_\rho = \max\{a : \rho \otimes S_a \text{ appears in } \phi\}$ , where  $S_a$  denotes the (unique) irreducible algebraic  $a$ -dimensional representation of  $\text{SL}_2(\mathbb{C})$ . If the set is empty, we let

$$a_\rho = \begin{cases} -1, & \text{if } \rho \text{ is of the same type as } \phi; \\ 0, & \text{otherwise.} \end{cases}$$

Then  $\alpha_\rho = \frac{a_\rho + 1}{2}$ .

## 2.5 The structure of the Hecke algebra

We now fix the setting for the rest of the paper. We retain the notation  $\rho, \sigma$  from the previous subsection, and consider the cuspidal component  $\mathfrak{s}$  attached to the representation

$$\underbrace{\rho \otimes \cdots \otimes \rho}_{n \text{ times}} \otimes \sigma$$

of the Levi subgroup  $M = \mathrm{GL}_k(F) \times \cdots \times \mathrm{GL}_k(F) \times G_{n_0}$  in  $G_N$ , where  $N = nk + n_0$ . In the rest of the paper, we restrict our attention to cuspidal components of the above form. This does not present a significant loss of generality, since the Hecke algebra of a general cuspidal component is the product of algebras corresponding to components described above. To simplify notation, we set  $\mathcal{H} = \mathcal{H}_{\mathfrak{s}}$ .

The structure of the Hecke algebra  $\mathcal{H}$  has been completely described by Heiermann [15, 16]. In his work, Heiermann shows that  $\mathcal{H}$  is a Hecke algebra with parameters (the type of the algebra and the parameters depending on the specifics of the given case). When the component in question is of the form described above, we have three distinct cases, which we now summarize. For basic definitions and results on Hecke algebras with parameters, we refer to the work of Lusztig [17].

In what follows, we let  $t$  denote the order of the (finite) group  $\{\chi \in X^{\mathrm{nr}}(M) : \rho \otimes \chi \cong \rho\}$ . In all three cases, the commutative algebra  $\mathcal{A}$  (see §2.2) is a subalgebra of  $\mathcal{H}$ . In the present setting, the rank of the free module  $M^\sigma/M^\circ$  is equal to  $n$ . We can thus identify  $\mathcal{A} = \mathbb{C}[M^\sigma/M^\circ]$  with the algebra of Laurent polynomials  $\mathbb{C}[X_1^\pm, \dots, X_n^\pm]$ . We fix this isomorphism explicitly: For  $i = 1, \dots, n$ , let  $h_i$  be the element of  $M$  which is equal to  $\mathrm{diag}(\varpi, 1, \dots, 1)$  on the  $i$ -th  $\mathrm{GL}$  factor, and equal to the identity elsewhere. Then  $X_i = b_{h_i}^t$ . The three cases are

- (i) No representation of the form  $\rho \otimes \chi$  with  $\chi \in X^{\mathrm{nr}}(M)$  is self-dual.

In this case, the algebra  $\mathcal{H}$  is described by an affine Coxeter diagram of type  $\tilde{A}_{n-1}$  with equal parameters  $t$ . In other words, it is isomorphic to the algebra  $\mathcal{H}_n$  described in [11]: there are elements  $T_1, \dots, T_{n-1}$  which satisfy the quadratic relation

$$(T_i + 1)(T_i - q^t) = 0, \quad i = 1, \dots, n-1$$

and commutation relations

$$T_i f - f^{s_i} T_i = (q^t - 1) \frac{f - f^{s_i}}{1 - X_{i+1}/X_i}, \quad i = 1, \dots, n-1,$$

where  $f^{s_i}$  is obtained from  $f \in \mathcal{A}$  by swapping  $X_i$  and  $X_{i+1}$ .

In the two remaining cases there is an unramified character  $\chi$  of  $M$  such that  $\rho \otimes \chi$  is self-dual. Without loss of generality, we may assume that  $\rho$  is self-dual. Then, up to isomorphism, there is a unique representation of the form  $\rho \otimes \chi$  which is also self-dual; we denote it by  $\rho^-$ . We set  $\alpha = \alpha_\rho$ ,  $\beta = \alpha_{\rho^-}$  (see §2.4 for notation). Since the situation is symmetric, we may (and will) assume that  $\alpha \geq \beta$ . We then have the following two cases:

- (ii)  $\alpha = \beta = 0$ .

In this case,  $\mathcal{H}$  is described by an affine Coxeter diagram of type  $\tilde{C}_n$ :

$$\begin{array}{ccccccccccccccc} & & & & & & & & & & & & & & & & & \\ \circ & \xrightarrow{4} & \circ & \xrightarrow{0} & \circ & \xrightarrow{t} & \circ & \xrightarrow{t} & \circ & \xrightarrow{t} & \cdots & \xrightarrow{t} & \circ & \xrightarrow{t} & \circ & \xrightarrow{4} & \circ \\ & & & & & & & & & & & & & & & & & \end{array}$$

The nodes correspond to operators  $T_0, \dots, T_n$  which satisfy the quadratic relations

$$T_0^2 = 1, \quad T_n^2 = 1, \quad (T_i + 1)(T_i - q^t) = 0 \quad \text{for } i = 1, \dots, n-1,$$

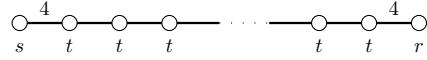
and the braid relations as prescribed by the diagram. The commutation relations for  $T_i, i = 1, \dots, n-1$  are the same as in case (i), whereas  $T_n$  satisfies

$$fT_n - T_n f^\vee = 0$$

with  $f^\vee(X_1, \dots, X_{n-1}, X_n) = f(X_1, \dots, X_{n-1}, 1/X_n)$ .

(iii)  $\alpha > 0$ .

In this case,  $\mathcal{H}$  is described by an affine Coxeter diagram of type  $\tilde{C}_n$ :



Here  $s = t(\alpha - \beta)$  and  $r = t(\alpha + \beta)$ . Again, the nodes correspond to operators  $T_0, \dots, T_n$  which satisfy quadratic relations analogous to those in (ii), along with the braid relations. The commutation relations for  $T_i, i = 1, \dots, n-1$  are the same as in case (i), whereas  $T_n$  satisfies

$$fT_n - T_n f^\vee = \left( (q^r - 1) + \frac{1}{X_n} (\sqrt{q}^{r+s} - \sqrt{q}^{r-s}) \right) \frac{f - f^\vee}{1 - 1/X_n^2}.$$

Cases (i)–(iii) correspond to the cases (I)–(III) listed in [15], Section 3.1. The above results are collected in Section 3.4 of [15]. A detailed construction of the operators  $T_i$  (starting from standard intertwining operators) is the subject matter of [16]; we do not need the details here, except in a special case discussed in the final part of Section 3.2. To facilitate the comparison of the above summary to the works of Heiermann [15, 16], we point out the way in which our summary deviates from them:

**Remark 2.1.** a) The explicit isomorphism  $\mathbb{C}[M^\sigma/M^\circ] \cong \mathbb{C}[X_1^\pm, \dots, X_n^\pm]$  we use is different than the one used in [15]; there, Heiermann sets  $X_i = b_{h_i h_{i+1}^{-1}}^t$  for  $i = 1, \dots, n-1$  (and, in case (ii),  $X_n = b_{h_{n-1} h_n}^t$ ).

b) The operator  $T_0$  which appears in cases (ii) and (iii) above is not needed to describe  $\mathcal{H}$ , and is therefore not used in [15] and [16]. To be precise, the Hecke algebra is generated over  $\mathcal{A}$  by the operators  $T_1, \dots, T_n$  and determined by the quadratic and braid relations they satisfy, along with the commutation relations listed above. Each of the operators  $T_1, \dots, T_n$  corresponds to a simple reflection in the Weyl group, whereas the operator  $T_0$  corresponds to the reflection given by the (in this case, unique) minimal element of the root system—see [17, §1.4]. In fact, we define  $T_0$  by setting

$$T_0 = \sqrt{q}^{s+2t(n-1)+r} X_1 T_w^{-1},$$

where  $T_w = T_1 \cdots T_{n-1} T_n T_{n-1} \cdots T_1$ —see [17, §2.8,3.3]. We use  $T_0$  out of convenience, as it allows a more symmetric description of certain  $\mathcal{H}$ -modules.

c) The description of  $\mathcal{H}$  in Case (ii) differs from the one given in [15], which views  $T_n$  as the non-trivial element of the  $R$ -group. However, one can verify that the description we use is equivalent. With our description, (ii) can be viewed as a special case of (iii) (with  $r = s = 0$ ); however, since our results in (ii) require additional analysis, we still state the two cases separately.

## 2.6 Generic representations

We recall only the most basic facts here; a general reference is e.g. [22].

Let  $B = TU$  denote the standard Borel subgroup of  $G_N$ , i.e. the group consisting of all upper-triangular matrices in  $G_N$ . Here  $T$  denotes the maximal torus (diagonal matrices), and  $U$  is the group of all unipotent upper-triangular matrices. We fix a non-degenerate character  $\psi$  of  $U$ . We say that a representation  $(\pi, V)$  of  $G_N$  is  $\psi$ -generic if there exists a so-called Whittaker functional—that is, a linear functional  $L : V \rightarrow \mathbb{C}$  such that

$$L(\pi(u)v) = \psi(u)L(v), \quad \forall u \in U, v \in V.$$

The key fact we use throughout is that the space of Whittaker functionals is at most one-dimensional. If  $\pi$  is an irreducible representation with a Whittaker functional  $L$ , one can consider the space  $\mathcal{V}$  of all functions  $f_v : G \rightarrow \mathbb{C}$ , where  $f_v(g) = L(\pi(g)v)$ ; we let  $G$  act on this space by right translations. Then  $v \mapsto f_v$  is a  $G$ -isomorphism; we say that  $\mathcal{V}$  is the Whittaker model for  $\pi$ .

Now let  $P = MN$  be a parabolic subgroup of  $G$ . If  $\sigma$  is an irreducible generic representation of  $M$ , then one can construct a Whittaker functional on  $i_P^G \sigma$  (see [22, Proposition 3.1] and equation (11) below); in other words, the induced representation is  $\psi$ -generic as well. We use this fact later, in Section 3.2.

## 3 The Gelfand–Graev representation

Let  $U$  be the group consisting of all unipotent upper-triangular matrices in  $G_N$ . We fix a non-degenerate character  $\psi : U \rightarrow \mathbb{C}^\times$  and consider the compactly induced representation  $\text{c-ind}_U^G(\psi)$ . This is the so-called Gelfand–Graev representation. It is the “universal”  $\psi$ -generic representation: every  $\psi$ -generic representation of  $G$  appears as a quotient (with multiplicity one) of  $\text{c-ind}_U^G(\psi)$ .

From this point on, we assume that the cuspidal representation  $\sigma$ —used to define the Bernstein component  $\mathfrak{s}$  in Section 2.5—is generic. We let  $\Pi$  denote  $(\text{c-ind}_U^G(\psi))$  viewed as an  $\mathcal{H}$ -module. Our goal is to determine the structure of  $\Pi$ .

We begin by investigating the structure of  $\Pi$  as an  $\mathcal{A}$ -module. We point out that the proof of the following proposition applies, without modification, to any split reductive  $p$ -adic group.

**Proposition 3.1.** *As  $\mathcal{A}$ -modules, we have  $\Pi \cong \mathcal{A}$ .*

*Proof.* The  $\mathcal{H}$ -module  $\Pi$  is given by  $\text{Hom}_G(\Gamma_{\mathfrak{s}}, \text{c-ind}_U^G(\psi))$ , where  $\Gamma_{\mathfrak{s}} = i_P^G(\text{c-ind}_{M^\circ}^M(\sigma_0))$ . Recall that  $\sigma_0$  was taken to be an arbitrary irreducible constituent of  $\sigma|_{M^\circ}$ . However, having now fixed the Whittaker datum for  $M$  (and thus for  $M^\circ$ ), there exists a unique irreducible summand of  $\sigma|_{M^\circ}$  which is  $\psi$ -generic. Thus, from now on, we assume  $\sigma_0$  is this unique  $\psi$ -generic constituent of  $\sigma|_{M^\circ}$ .

To view  $\Pi$  as an  $\mathcal{A} = \text{End}_M(\text{c-ind}_{M^\circ}^M(\sigma_0))$ -module, we use the Bernstein version of Frobenius reciprocity:

$$\Pi = \text{Hom}_G(i_P^G(\text{c-ind}_{M^\circ}^M(\sigma_0)), \text{c-ind}_U^G(\psi)) = \text{Hom}_M(\text{c-ind}_{M^\circ}^M(\sigma_0), r_{\overline{N}}(\text{c-ind}_U^G(\psi)));$$

here  $r_{\overline{N}}$  denotes the Jacquet functor with respect to  $\overline{P} = M\overline{N}$ , the parabolic opposite to  $P$ .

We now use the fact that  $r_{\overline{N}}(\text{c-ind}_U^G(\psi))$  is isomorphic to the Gelfand–Graev representation of  $M$ ,  $\text{c-ind}_{U \cap M}^M(\psi)$  (see [6, §2.2]). Furthermore, with the above choice of  $\sigma_0$ , the representation  $\text{c-ind}_{M^\circ}^M(\sigma_0)$  is precisely the sum of all maximal  $({}^m\sigma_0)$ -isotypic components of  $\text{c-ind}_{U \cap M}^M(\psi)$ , where  ${}^m\sigma_0$  ranges over the set of all  $M$ -conjugates of  $\sigma_0$ . Indeed,  $\text{c-ind}_{U \cap M}^M(\psi)$  is itself induced from the Gelfand–Graev representation of  $M^\circ$ ,  $\text{c-ind}_{U \cap M}^{M^\circ}(\psi)$ . Since  $\sigma_0$  appears with multiplicity one, and no other  $m$ -conjugate of  $\sigma_0$  is generic, we have  $\text{c-ind}_{U \cap M}^{M^\circ}(\psi) \cong \sigma_0 \oplus \sigma_0^\perp$ , where  $\sigma_0^\perp$  is a representation which contains no  $M$ -conjugate of  $\sigma_0$ . Inducing to  $M$  we get  $\text{c-ind}_{U \cap M}^M(\psi) = \text{c-ind}_{M^\circ}^M(\sigma_0) \oplus \text{c-ind}_{M^\circ}^M(\sigma_0^\perp)$ , which proves the above claim about isotypic components. Thus, viewed as an  $\mathcal{A}$ -module,  $\Pi$  is isomorphic to

$$\begin{aligned} \text{Hom}_M(\text{c-ind}_{M^\circ}^M(\sigma_0), r_{\overline{N}}(\text{c-ind}_U^G(\psi))) &= \text{Hom}_M(\text{c-ind}_{M^\circ}^M(\sigma_0), \text{c-ind}_{U \cap M}^M(\psi)) \\ &= \text{Hom}_M(\text{c-ind}_{M^\circ}^M(\sigma_0), \text{c-ind}_{M^\circ}^M(\sigma_0)) = \mathcal{A}. \end{aligned}$$

□

**Remark 3.2.** We point out that the above differs from the proof of the analogous statement in [11]. It is shown there that any  $\mathcal{H}$ -module  $\Pi$  which is

- (i) projective;
- (ii) finitely generated; and which satisfies
- (iii)  $\dim \text{Hom}_{\mathcal{H}}(\Pi, \pi) \leq 1$  for any principal series representation  $\pi$

is isomorphic to  $\mathcal{A}$  when viewed as an  $\mathcal{A}$ -module (see [11], Lemma 2.2, 2.3). The Gelfand–Graev representation can be shown to satisfy properties (i)–(iii): Property (i) is provided by Corollary 8.6 of [11]; (ii) is proved in [6], and (iii) follows from the multiplicity one property of generic representations. In Section 4 we present another useful application of the above approach to proving that an  $\mathcal{H}$ -module is isomorphic to  $\mathcal{A}$ .

Proposition 3.1 suggests the following approach to determining the  $\mathcal{H}$ -module structure of  $\Pi$ : First, we find all possible  $\mathcal{H}$ -module structures on  $\mathcal{A}$ . After that, we need only determine which one of those structures describes  $\Pi$ . In the following subsection, we compute the possible  $\mathcal{H}$ -structures on  $\mathcal{A}$ .

### 3.1 $\mathcal{H}$ -module structures on $\mathcal{A}$

In order to treat the case of general Bernstein components—and not just those described in §2.5—we work in a slightly more general setting in this section. We thus investigate the possible  $\mathcal{H}$ -module structures on  $\mathcal{A}$  (where  $\mathcal{H}$  is generated by  $T_0, \dots, T_n$  over  $\mathcal{A}$ ), but we assume that  $\mathcal{A} = \mathcal{A}'[X_1^\pm, \dots, X_n^\pm]$ , where  $\mathcal{A}'$  is an integral domain containing  $\mathbb{C}$  as a subring. For Bernstein components described in §2.5 we have  $\mathcal{A}' = \mathbb{C}$ ; in general,  $\mathcal{A}'$  itself is a (Laurent) polynomial ring over  $\mathbb{C}$ .

First, assume that we are in Case (i) (see §2.5). Then the situation is precisely the one treated in [11], and the possible  $\mathcal{H}$ -module structures on  $\mathcal{A}$  are determined in Section 2.2 there. We have the following:

**Proposition 3.3** (Case (i)). *Let  $\Pi$  be a  $\mathcal{H}$ -module which is isomorphic to  $\mathcal{A}$  as an  $\mathcal{A}$ -module. Then  $\Pi \cong \mathcal{H} \otimes_{\mathcal{H}_{S_n}} \epsilon$ , where  $\epsilon$  is a 1-dimensional representation of  $\mathcal{H}_{S_n}$ .*

Here  $\mathcal{H}_{S_n}$  denotes the finite-dimensional algebra generated by  $T_1, \dots, T_{n-1}$ ; we have  $\mathcal{H} = \mathcal{A} \otimes_{\mathbb{C}} \mathcal{H}_{S_n}$ . Furthermore,  $\mathcal{H}_{S_n}$  has precisely two one-dimensional representations:

$$\begin{aligned}\epsilon_{-1} : T_i &\mapsto -1 \quad \text{for } i = 1, \dots, n-1; \quad \text{and} \\ \epsilon_{q^t} : T_i &\mapsto q^t \quad \text{for } i = 1, \dots, n-1.\end{aligned}$$

We now treat Cases (ii) and (iii), simultaneously. Recall that in these cases the algebra  $\mathcal{H}$  is described by an affine Coxeter diagram of type  $\tilde{C}_n$ . We let  $\mathcal{H}_0$  and  $\mathcal{H}_n$  denote the algebra obtained by removing the vertices which correspond to  $T_0$  and  $T_n$ , respectively. In other words,  $\mathcal{H}_0$  is generated by  $T_1, \dots, T_n$  as an  $\mathcal{A}$ -algebra, whereas  $\mathcal{H}_n$  is generated by  $T_0, \dots, T_{n-1}$ . Note that we have  $\mathcal{H} = \mathcal{A} \otimes_{\mathbb{C}} \mathcal{H}_n = \mathcal{A} \otimes_{\mathbb{C}} \mathcal{H}_0$ . We now prove the following result.

**Proposition 3.4** (Cases (ii) and (iii)). *Let  $\Pi$  be a  $\mathcal{H}$ -module which is isomorphic to  $\mathcal{A}$  as an  $\mathcal{A}$ -module. Then*

$$\Pi \cong \mathcal{H} \otimes_{\mathcal{H}_0} \epsilon_0 \quad \text{or} \quad \Pi \cong \mathcal{H} \otimes_{\mathcal{H}_n} \epsilon_n.$$

Here  $\epsilon_0$  (resp.  $\epsilon_n$ ) is a 1-dimensional representation of  $\mathcal{H}_0$  (resp.  $\mathcal{H}_n$ ).

*Proof of Proposition 3.4.* We first restrict our attention to the subalgebra generated by  $T_1, \dots, T_{n-1}$ , which is contained in both  $\mathcal{H}_0$  and  $\mathcal{H}_n$ . This is precisely the algebra  $\mathcal{H}_{S_n}$  discussed in [11]. The possible  $\mathcal{H}_{S_n}$ -structures on  $\mathcal{A}$  are determined in §2.2 there. To summarize the relevant results, there exists an invertible element  $g_0 \in \mathcal{A}$  on which the operators  $T_1, \dots, T_n$  act by the same scalar, either  $q^t$  or  $-1$ .

We now determine how  $T_0$  and  $T_n$  act on  $g_0$ . Since  $g_0$  is invertible, we have  $T_n g_0 = f g_0$  for some  $f \in \mathcal{A}$ . Recall that  $T_n$  satisfies the quadratic relation

$$T_n^2 = (q^r - 1)T_n + q^r$$

as well as the commutation relation

$$T_n f - f^\vee T_n = \left( (q^r - 1) + \frac{1}{X_n} (\sqrt{q^{r+s}} - \sqrt{q^{r-s}}) \right) \frac{f - f^\vee}{1 - 1/X_n^2}.$$

Here, and throughout the proof, we let  $r = s = 0$  if we are considering Case (ii). Recall that  $f^\vee$  denotes the function  $f^\vee(X_1, \dots, X_n) = f(X_1, \dots, X_{n-1}, \frac{1}{X_n})$ . Using the above and comparing the two sides of  $T_n^2 g_0 = (q^r - 1)T_n g_0 + q^r g_0$ , we get

$$f f^\vee = (q^r - 1) \frac{X_n f^\vee - \frac{1}{X_n} f}{X_n - \frac{1}{X_n}} - (\sqrt{q^{r+s}} - \sqrt{q^{r-s}}) \frac{f - f^\vee}{X_n - \frac{1}{X_n}} + q^r.$$

To simplify notation, we now set  $b = q^r - 1$ ,  $c = (\sqrt{q^{r+s}} - \sqrt{q^{r-s}})$ . We also temporarily drop the index  $n$ , writing  $X$  instead of  $X_n$ . Clearing out the denominators, we rearrange the above equation into

$$(*) \quad (X^2 - 1) f f^\vee = b(X^2 f^\vee - f) - c(X f - X f^\vee) + q^r (X^2 - 1).$$

Our first goal is to find the possible solutions  $f \in \mathcal{A}$  of this equation.

**Lemma 3.5.** *The above equation has the following solutions:*

- (i)  $f = b + cX^{-1} + bX^{-2} + \dots + cX^{1-2d} + q^t X^{-2d}$ ,  $d \in \mathbb{Z}_{>0}$
- (ii)  $f = b + cX^{-1} + bX^{-2} + \dots + cX^{1-2d} - X^{-2d}$ ,  $d \in \mathbb{Z}_{>0}$
- (iii)  $f = b + cX^{-1} + bX^{-2} + \dots + bX^{-2d} \pm \sqrt{q}^{r\pm s} X^{-2d-1}$ ,  $d \in \mathbb{Z}_{\geq 0}$
- (iv)  $f = \mp \sqrt{q}^{r\pm s} X^{2d+1} - bX^{2d} - cX^{2d-1} - \dots - cX$ ,  $d \in \mathbb{Z}_{\geq 0}$
- (v)  $f = -q^r X^{2d} - cX^{2d-1} - \dots - bX^2 - cX$ ,  $d \in \mathbb{Z}_{>0}$
- (vi)  $f = X^{2d} - cX^{2d-1} - \dots - bX^2 - cX$ ,  $d \in \mathbb{Z}_{>0}$ .

along with the constant solutions  $f = q^t$  and  $f = -1$ .

*Proof.* Each  $f \in \mathcal{A}$  can be written as

$$(\dagger) \quad f = a_k X^k + a_{k-1} X^{k-1} + \dots + a_0 + a_{-1} X^{-1} + \dots + a_{-l} X^{-l}$$

for some functions  $a_{-l}, \dots, a_k \in \mathcal{A}'[X_1^\pm, \dots, X_{n-1}^\pm]$ , with  $a_k, a_{-l} \neq 0$ . We write  $\text{maxdeg}(f)$  for  $k$  and  $\text{mindeg}(f)$  for  $-l$ . Now let  $f$  be a solution of (\*). We begin our analysis of (\*) by solving some special cases. We claim the following:

- (1) If  $f = a_0$ , then  $a_0 = q^r$  or  $a_0 = -1$ .
- If  $f = a_1 X$ , then  $a_1 = \mp \sqrt{q}^{r\pm s}$ .
- If  $f = a_0 + a_{-1} X^{-1}$  and  $a_{-1} \neq 0$ , then  $a_0 = b$  and  $a_{-1} = \pm \sqrt{q}^{r\pm s}$ .

To verify this, we first look at solutions  $f = a_0$ . In this case the equation (\*) reduces to  $a_0^2 = ba_0 + q^r$ . This equation has two constant solutions,  $a_0 = -1$  and  $a_0 = q^r$ . These are also the only solutions, since  $\mathcal{A}$  has no zero divisors. When  $f(X) = a_1 X$ , the equation becomes  $a_1^2 + a_1 c - q^r = 0$ . Again, the only two solutions of this equation are the constant ones:  $a_1 = \mp \sqrt{q}^{r\pm s}$ . Finally, when  $f = a_0 + a_{-1} X^{-1}$ , the equation reduces to the following system:

$$a_1 b = a_1 a_0 \quad \text{and} \quad a_0^2 + a_{-1}^2 = a_0 b + a_{-1} c + q^r.$$

Since we are assuming that  $a_1 \neq 0$ , the first equation gives us  $a_0 = b$ , and then the second becomes  $a_{-1}^2 - ca_{-1} - q^r$ . Again, we have two solutions:  $a_{-1} = \pm \sqrt{q}^{r\pm s}$ .

Next, when  $f$  is a solution of (\*) given by  $(\dagger)$ , we observe:

$$(2) \quad k \text{ and } l \text{ cannot both be positive.}$$

Indeed, let LHS and RHS denote the left-hand side and the right-hand side of (\*), respectively. We then have  $\text{maxdeg}(\text{LHS}) = k+l+2$ , whereas  $\text{maxdeg}(\text{RHS}) \leq \max\{l+2, k+1, 2\}$ . Therefore equality of degrees cannot be achieved unless  $k \leq 0$  or  $l \leq 0$ . In fact, the same argument gives us a slightly stronger statement in one case:

$$(3) \quad \text{If } k \not\geq 0 \text{ then } a_0 = 0.$$

Finally, we make use of the following fact, which is readily verified by direct computation:

- (4) For any positive integer  $d$ ,  $f$  is a solution of (\*) if and only if  $X^{2d} f - R_d$  is also a solution.

Here  $R_d = \frac{bX^2 + cX}{X^2 - 1}(X^{2d} - 1) = bX^{2d} + cX^{2d-1} + \dots + bX^2 + cX$ .

We are now ready to find all the solutions. By (2), any solution of  $f$  either contains only positive powers of  $X$ , or only non-positive. We therefore consider two separate cases:

**Case A:**  $f$  has only non-positive powers, i.e.  $f = a_0 + a_{-1}X^{-1} + \dots + a_{-l}X^{-l}$ .

Let  $d = \lfloor l/2 \rfloor$ . We use (4) and look at another solution,  $g = X^{2d}f - R_d$ .

We first assume  $l = 2d$  is even. In this case  $g$  only has non-negative powers of  $X$ , but it has a non-zero constant term,  $a_{-l}$ . Therefore (3) shows that the coefficients next to the positive powers must be zero:  $a_0 - b = a_{-1} - c = \dots = a_{-l+1} - c = 0$ . Now (1) shows that there are only two possibilities for the constant term:  $a_{-l} = q^t$  or  $a_{-l} = -1$ . We thus get two solutions:

$$f = b + cX^{-1} + bX^{-2} + \dots + cX^{1-2d} + q^t X^{-2d} \quad \text{and} \quad f = b + cX^{-1} + bX^{-2} + \dots + cX^{1-2d} - X^{-2d}.$$

Next, assume that  $l = 2d + 1$  is odd. Now  $g$  has a non-zero coefficient (i.e.  $a_{-l}$ ) next to  $X^{-1}$ , so by (2) the coefficients next to positive powers must be equal to 0. This gives us  $a_0 = b, a_{-1} = c, \dots, a_{-l} = c$ . Furthermore,  $g$  is thus of the form  $a_{1-l} + a_{-l}X^{-1}$ , so we can read off the coefficients  $a_{1-l}$  and  $a_{-l}$  from (1). We thus arrive at two more solutions:

$$f = b + cX^{-1} + bX^{-2} + \dots + bX^{-2d} \pm \sqrt{q}^{r \pm s} X^{-2d-1}.$$

**Case B:**  $f$  only has positive powers, i.e.  $f = a_kX^k + \dots + a_1X$ .

This time, we set  $d = \lfloor k/2 \rfloor$  and use (4) to obtain the solution  $g = \frac{1}{X^{2d}}(f + R_d)$ .

First, assume that  $k = 2d + 1$  is odd. Then  $g$  has a non-zero coefficient (i.e.  $a_k$ ) next to  $X$ , so (2) and (3) imply that all the lower coefficients are zero. This immediately gives us  $a_1 = -c, a_2 = -b, \dots, a_{2d} = -b$ . Furthermore, we have  $g = a_kX$ , so (1) shows that we have two possibilities for  $a_k$ . We therefore get two solutions:

$$f = \mp \sqrt{q}^{r \pm s} X^{2d+1} - bX^{2d} - cX^{2d-1} - \dots - cX.$$

Finally, assume that  $k = 2d$  is even. First, if  $k > 2$ , consider another solution  $g' = X^{2-2d}(f + R_{2d-2})$ . Now  $g'$  has a non-zero coefficient (i.e.  $a_k$ ) next to  $X^2$ , so the coefficient next to non-positive powers of  $X$  have to be 0 by (2), (3). This gives us  $a_1 = -c, a_2 = -b, \dots, a_{2d-2} = -b$ . In particular, this shows that  $g = (a_k + b) + (a_{k-1} + c)X^{-1}$ . Since  $a_k + b \neq b$  (i.e.  $a_k \neq 0$ ), (1) shows that we have only two possibilities:

$$a_{k-1} + c = 0, \quad a_k + b \in \{q^r, -1\}.$$

In other words,  $a_{k-1} = -c$  and  $a_k \in \{-q^r, 1\}$ . We thus get the remaining solutions,

$$f = -q^r X^{2d} - cX^{2d-1} - \dots - bX^2 - cX \quad \text{and} \quad f = X^{2d} - cX^{2d-1} - \dots - bX^2 - cX.$$

□

We continue the proof of Proposition 3.4. We have just proved that  $T_n g_0 = f g_0$  where  $f \in \mathcal{A}$  is one of the elements listed in Lemma 3.5. First, assume that  $f$  is one of the constant solutions, i.e.  $f = -1$  or  $f = q^r$ . Then  $g_0$  is an invertible element of  $\mathcal{A}$  on which  $T_1, \dots, T_{n-1}, T_n$  all act as scalars. In other words, we have a one-dimensional representation  $\epsilon_0$  of the algebra  $\mathcal{H}_0$ . Since  $\mathcal{H} = \mathcal{A} \otimes_{\mathbb{C}} \mathcal{H}_0$ , it follows that the corresponding  $\mathcal{H}$ -module structure on  $\mathcal{A}$  is isomorphic to

$$\mathcal{H} \otimes_{\mathcal{H}_0} \epsilon_0.$$

Now, if  $f$  is of type (i) or (ii) listed in the statement of Lemma 3.5, set

$$g_1 = (X_1 X_2 \cdots \cdots X_n)^{-d} g_0.$$

Since  $(X_1 X_2 \cdots \cdots X_n)^{-d}$  commutes with  $T_1, \dots, T_{n-1}$ ,  $g_1$  is still an eigenvector for each of these operators. We claim that  $g_1$  is an eigenvector for  $T_n$  as well. Indeed, using the appropriate commutation relation and the fact that  $T_n$  commutes with  $X_1, \dots, X_{n-1}$ , we get

$$\begin{aligned} T_n g_1 &= (X_1 X_2 \cdots \cdots X_{n-1})^{-d} \cdot T_n X_n^{-d} g_0 \\ &= (X_1 X_2 \cdots \cdots X_{n-1})^{-d} \left( X_n^d T_n + \frac{b X_n + c}{X_n^2 - 1} (X_n^{-d} - X_n^d) \right) g_0 \\ &= (X_1 X_2 \cdots \cdots X_{n-1})^{-d} \left( X_n^d f + \frac{b X_n + c}{X_n^2 - 1} (X_n^{-d} - X_n^d) \right) g_0 \\ &= (X_1 X_2 \cdots \cdots X_{n-1})^{-d} \left( X_n^{2d} f - \frac{b X_n + c}{X_n^2 - 1} (X_n^{2d} - 1) \right) g_1. \end{aligned}$$

Simplifying the expression in the parentheses, we obtain  $\lambda X_n^{-d}$ , so that  $T_n g_1 = \lambda g_1$ , where  $\lambda = q^t$ , resp.  $-1$  when  $f$  is of type (i), resp. (ii). We have thus once more found a common eigenvector for  $T_1, \dots, T_{n-1}, T_n$ . Again, we deduce that the corresponding  $\mathcal{H}$ -module structure is isomorphic to  $\mathcal{H} \otimes_{\mathcal{H}_0} \epsilon_0$ , where  $\epsilon_0$  is a one-dimensional representation of  $\mathcal{H}_0$ .

When  $f$  is of type (v) or (vi), we use the same argument and arrive at the same conclusion. The only difference in this case is that we have to set  $g_1 = (X_1 X_2 \cdots \cdots X_n)^d g_0$  in order to obtain a common eigenvector for  $T_1, \dots, T_{n-1}, T_n$ .

In the remaining cases—that is, when  $f$  is of type (iii) or (iv)—we cannot find such an eigenvector, but we claim that we can find an invertible  $g_1 \in \mathcal{A}$  which is a common eigenvector for  $T_0, T_1, \dots, T_{n-1}$ . Just like in the previous cases, this will imply that the  $\mathcal{H}$ -structure on  $\mathcal{A}$  is isomorphic to  $\mathcal{H} \otimes_{\mathcal{H}_n} \epsilon_n$  for some one-dimensional representation  $\epsilon_n$  of  $\mathcal{H}_n$ .

If  $T_n g_0 = f g_0$  with  $f$  of type (iii), we set  $g_1 = (X_1 X_2 \cdots \cdots X_n)^{-d} g_0$ . If  $f$  is of type (iv), let  $g_1 = (X_1 X_2 \cdots \cdots X_n)^{d+1} g_0$ . In both cases,  $g_1$  is an eigenvector for  $T_1, \dots, T_{n-1}$  and a computation analogous to the one we carried out in for cases (i) and (ii) shows that we have

$$T_n g_1 = (b \pm \sqrt{q^{r \pm s}} X_n^{-1}) g_1.$$

The following lemma then shows that  $g_1$  is also an eigenvector for  $T_0$  and thus concludes the proof of Proposition 3.4.

**Lemma 3.6.** *Let  $g$  be an invertible element of  $\mathcal{A}$  which is an eigenvector for  $T_1, \dots, T_{n-1}$  and such that  $T_n g = (b \pm \sqrt{q^{r \pm s}} X_n^{-1}) g$ . Then  $g$  is also an eigenvector for  $T_0$ .*

*Proof.* Recall that  $T_0 = \sqrt{q}^{s+2(n-1)t+r} X_1 T_w^{-1}$ , with  $T_w = T_1 \cdots T_{n-1} T_n T_{n-1} \cdots T_1$ . In both cases, all the operators  $T_1, \dots, T_{n-1}$  act by the same scalar  $\lambda \in \{-1, q^t\}$ . We therefore have

$$T_0 g = \sqrt{q}^{s+2(n-1)t+r} \lambda^{-(n-1)} X_1 T_1^{-1} \cdots T_{n-1}^{-1} T_n^{-1} g.$$

We now recall that  $T_n^{-1} = \frac{1}{q^r}(T_n - b)$ ; this follows from the quadratic relation for  $T_n$ . Therefore, by the assumption in the statement of the lemma,  $T_n^{-1} g = \pm \sqrt{q}^{\pm s-r} X_n^{-1} g$ . Thus

$$(5) \quad T_0 g = \mu \cdot \lambda^{-(n-1)} \cdot \sqrt{q}^{2(n-1)t} X_1 T_1^{-1} \cdots T_{n-1}^{-1} X_n^{-1} g,$$

with  $\mu \in \{-1, q^s\}$ . Finally, it remains to notice that for every  $i = 1, \dots, n-1$  we have

$$(6) \quad T_i^{-1} X_{i+1}^{-1} = \frac{1}{q^t} X_i^{-1} T_i.$$

Indeed, from the quadratic relation we have  $T_i^{-1} = \frac{1}{q^t}(T_i - (q^t - 1))$ . Combining this with the commutation relation for  $T_i$ , we get (6). Successively applying (6) to (5) (and taking into account that each  $T_i$  acts on  $g$  by  $\lambda$ ), we get

$$T_0 g = \mu g,$$

which we needed to prove. Notice that the possible eigenvalues are precisely the zeros of  $(x - q^s)(x + 1) = 0$ , the quadratic equation satisfied by  $T_0$ .  $\square$

The above lemma shows that in cases (iii) and (iv) we have an invertible element  $g_1 \in \mathcal{A}$  which is a common eigenvector for  $T_0, T_1, \dots, T_n$ . Consequently, the  $\mathcal{H}$ -module structure on  $\mathcal{A}$  is given by  $\mathcal{H} \otimes_{\mathcal{H}_n} \epsilon_n$  for some one-dimensional representation  $\epsilon_n$  of  $\mathcal{H}_n$ . This concludes the proof of Proposition 3.4.  $\square$

In view of Proposition 3.4, there are eight candidates for the  $\mathcal{H}$ -structure (four, if  $n = 1$ ): First, we may take the tensor product over  $\mathcal{H}_0$  or  $\mathcal{H}_n$ ; after that, there are four 1-dimensional representations of  $\mathcal{H}_0$  (resp.  $\mathcal{H}_n$ ) to choose from. To verify this, note that the braid relations imply that—in any 1-dimensional representation—the operators  $T_1, \dots, T_{n-1}$  act by the same scalar, which has to be a zero of the quadratic relation satisfied by  $T_i$ :  $(x - q^t)(x + 1) = 0$ . We therefore have two possibilities for the action of the operators  $T_i$ , and two additional possibilities (again, the zeroes of the quadratic relation) for  $T_n$  (resp.  $T_0$ ). For example, the 1-dimensional representations of  $\mathcal{H}_0$  are given by

$$\begin{array}{ll} \epsilon_{-1,-1} : \{T_n \mapsto -1, T_i \mapsto -1\} & \epsilon_{q^r,-1} : \{T_n \mapsto q^r, T_i \mapsto -1\} \\ \epsilon_{-1,q^t} : \{T_n \mapsto -1, T_i \mapsto q^t\} & \epsilon_{q^r,q^t} : \{T_n \mapsto q^r, T_i \mapsto q^t\}. \end{array}$$

**Corollary 3.7. General case.** *Let  $\Pi$  be an  $\mathcal{H}$ -module which is isomorphic to  $\mathcal{A}$  as an  $\mathcal{A}$ -module. Then there exists a finite subalgebra  $\mathcal{H}_W \cong \mathbb{C}[W]$ , where  $W$  is a finite group, such that  $\mathcal{H} \cong \mathcal{A} \otimes \mathcal{H}_W$ , and*

$$\Pi \cong \mathcal{H} \otimes_{\mathcal{H}_W} \epsilon,$$

where  $\epsilon$  is a 1-dimensional representation of  $\mathcal{H}_W$ .

*Proof.* Recall that  $\mathcal{H}$  is a tensor product of Hecke algebras each of which is isomorphic to the Iwahori Hecke algebra of  $\mathrm{GL}_n$  or an algebra of type  $\tilde{C}_n$  with unequal parameters. Propositions 3.3 and 3.4 deal with these two cases, with additional flexibility that allows  $\mathcal{A} = \mathcal{A}'[X_1^\pm, \dots, X_n^\pm]$ , where  $\mathcal{A}' = \mathbb{C}[Y_1^\pm, \dots, Y_m^\pm]$ . Thus the corollary follows by repeated application of these two propositions.  $\square$

### 3.2 The Gelfand–Graev module

To complete the analysis of the Gelfand–Graev representation, we need to determine which of the  $\mathcal{H}$ -module structures from the previous section is isomorphic to  $\Pi = (\text{c-ind}_U^G(\psi))_{\mathfrak{s}}$ . We consider the cases (i)–(iii) separately.

**Case (i).** Let  $\delta$  be the unique irreducible subrepresentation of  $\rho\nu^{\frac{n-1}{2}} \times \rho\nu^{\frac{n-3}{2}} \times \cdots \times \rho\nu^{\frac{1-n}{2}}$ . Then  $\pi = \delta \rtimes \sigma$  is an irreducible generic representation. The corresponding  $\mathcal{H}$ -module is 1-dimensional: by the Bernstein version of Frobenius reciprocity, we have

$$(7) \quad \begin{aligned} \text{Hom}_G(\Gamma_{\mathfrak{s}}, \pi) &= \text{Hom}_M(\text{c-ind}_{M^{\circ}}^M(\rho \otimes \cdots \otimes \rho \otimes \sigma), \nu^{\frac{1-n}{2}} \rho \otimes \cdots \otimes \nu^{\frac{n-1}{2}} \rho \otimes \sigma \\ &\quad \oplus \nu^{\frac{1-n}{2}} \rho^{\vee} \otimes \cdots \otimes \nu^{\frac{n-1}{2}} \rho^{\vee} \otimes \sigma) \end{aligned}$$

Since  $\rho^{\vee}$  is not an unramified twist of  $\rho$  in this case, the above Hom-space is only 1-dimensional. By Proposition 3.3,  $\text{Hom}_G(\Gamma_{\mathfrak{s}}, \Pi)$  is isomorphic to either  $\Pi \cong \mathcal{H} \otimes_{\mathcal{H}_{S_n}} \epsilon_{-1}$  or  $\Pi \cong \mathcal{H} \otimes_{\mathcal{H}_{S_n}} \epsilon_{q^t}$ . To determine which, we need only look at the action of  $\mathcal{H}$  on the 1-dimensional module  $\pi$ . We now need to examine the definition of the operators  $T_i, i = 1, \dots, n-1$ . In [16],  $T_i$  is defined in §5.2 by the formula

$$(8) \quad T_i = R_i + (q^t - 1) \frac{X_i/X_{i+1}}{X_i/X_{i+1} - 1}.$$

The intertwining operator  $R_i$  has a pole at 0, and a zero at the point of reducibility—see [16, §1.8]. Since  $\nu^{\frac{3-n}{2}-i} \rho \times \nu^{\frac{3-n}{2}-i+1} \rho$  reduces, the operator  $R_i$  acts by 0 in this case. It therefore remains to determine the action of  $X_i/X_{i+1}$ . Equation (7) shows that it suffices to determine the action of  $X_i/X_{i+1}$  on

$$\text{Hom}_M(\text{c-ind}_{M^{\circ}}^M(\rho \otimes \cdots \otimes \rho \otimes \sigma), \nu^{\frac{1-n}{2}} \rho \otimes \cdots \otimes \nu^{\frac{n-1}{2}} \rho \otimes \sigma).$$

Recalling the definition of  $X_i$  (§2.5), we immediately see that  $X_i/X_{i+1}$  acts by

$$\frac{(|\varpi|^{\frac{3-n}{2}-i})^t}{(|\varpi|^{\frac{3-n}{2}-i+1})^t} = \frac{q^{t(\frac{n-3}{2}+i)}}{q^{t(\frac{n-3}{2}+i-1)}} = q^t.$$

This implies that  $T_i$  also acts by  $(q^t - 1) \frac{q^t}{q^t - 1} = q^t$ . Since  $\pi$  is a quotient of  $\Pi$ , we conclude that we must have  $\Pi \cong \mathcal{H} \otimes_{\mathcal{H}_{S_n}} \epsilon_{q^t}$ .

**Case (iii).** In this situation, the  $\mathfrak{s}$ -component of the Gelfand–Graev representation has two irreducible generic representations whose  $\mathcal{H}$ -module is one-dimensional. These are the two (generalized) Steinberg representations:  $\pi$  and  $\pi'$ , which are the unique irreducible subrepresentations of

$$\nu^{\alpha+n-1} \times \cdots \times \nu^{\alpha} \rtimes \sigma \quad \text{and} \quad \nu^{\beta+n-1} \rho^- \times \cdots \times \nu^{\beta} \rho^- \rtimes \sigma$$

respectively. Recall that  $\alpha$  (resp.  $\beta$ ) is the unique positive real number such that  $\nu^{\alpha} \rho \rtimes \sigma$  (resp.  $\nu^{\beta} \rho^- \rtimes \sigma$ ) reduces (see §2.5). We now compare the action of the operators  $T_0, \dots, T_n$  on these two representations—that is, on  $\text{Hom}_G(\Gamma_{\mathfrak{s}}, \pi)$  and  $\text{Hom}_G(\Gamma_{\mathfrak{s}}, \pi^-)$ , where  $\Gamma_{\mathfrak{s}}$  is the projective generator defined in §2.3.

We start by analyzing the action on  $\pi$ . We first focus on  $T_i, i = 1, \dots, n-1$ . Again,  $T_i$  is defined by (8), and once more the operator  $R_i$  acts by 0. By the Bernstein version of Frobenius reciprocity, we have

$$\mathrm{Hom}_G(\Gamma_{\mathfrak{s}}, \pi) = \mathrm{Hom}_M(\mathrm{c-ind}_{M^{\circ}}^M(\rho \otimes \dots \otimes \rho \otimes \sigma), \nu^{-\alpha-n+1}\rho \otimes \dots \otimes \nu^{-\alpha}\rho \otimes \sigma).$$

We immediately see that  $X_i/X_{i+1}$  acts by

$$\frac{(|\varpi|^{-\alpha-n+i})^t}{(|\varpi|^{-\alpha-n+i+1})^t} = \frac{q^{t(\alpha+n-i)}}{q^{t(\alpha+n-i-1)}} = q^t.$$

Again, this shows that  $T_i$  acts by  $(q^t - 1) \frac{q^t}{q^t - 1} = q^t$ . For  $T_n$  we have a similar formula:

$$(9) \quad T_n = R_n + (q^r - 1) \frac{X_n \left( X_n - \frac{q^{t\beta} - q^{t\alpha}}{q^r - 1} \right)}{X_n^2 - 1}.$$

Once more,  $R_n$  acts by 0, and  $X_n$  acts by  $(|\varpi|^{-\alpha})^t = q^{t\alpha}$ . Recalling that  $r = t(\alpha + \beta)$ , we see that  $T_n$  acts by  $q^r$ . Finally, since

$$T_0 = \sqrt{q^{r+2t(n-1)+s}} X_1 T_1^{-1} \dots T_{n-1}^{-1} T_n^{-1} T_{n-1}^{-1} \dots T_1^{-1},$$

and since  $X_1$  acts by  $q^{(\alpha+n-1)t}$ , we see that  $T_0$  acts by  $\frac{\sqrt{q^{r+2t(n-1)+s}}}{q^{2t(n-1)} \cdot q^r} q^{(\alpha+n-1)t} = q^s$ .

We do the same with  $\pi^-$ . Again,  $X_i/X_{i+1}$  acts by  $q^t$  which shows that  $T_i$  acts by  $q^t$  as well. This time  $X_n$  acts by  $-q^{t\beta}$ : recall that  $\rho^- = \chi_0 \otimes \rho$  with  $X_n(\chi_0) = -1$ , so  $X_n(\chi_0 \nu^{-\beta}) = -q^{t\beta}$ . Repeating the above calculations we now see that  $T_n$  acts by  $q^r$ , whereas  $T_0$  acts by  $-1$ .

The above analysis allows us to single out the  $\mathcal{H}$ -module structure on  $\Pi$ . Since  $T_0$  does not act by the same scalar on  $\pi$  and  $\pi^-$ , we deduce that  $\Pi = \mathcal{H} \otimes_{\mathcal{H}_0} \epsilon$  for some 1-dimensional representation  $\epsilon$  of  $\mathcal{H}_0$ . Now, since every  $T_i$  ( $i = 1, \dots, n-1$ ) acts by  $q^t$  and  $T_n$  acts by  $q^r$ , we deduce that  $\Pi = \mathcal{H} \otimes_{\mathcal{H}_0} \epsilon_{q^r, q^t}$  (see the end of §3.1 for notation).

**Case (ii)** The first part of our analysis remains the same as in Case (iii). The representation

$$\nu^{n-1}\rho \times \nu^{n-2}\rho \times \dots \times \rho \rtimes \sigma$$

has two irreducible subrepresentations (both of which are in discrete series when  $n > 1$ , and tempered when  $n = 1$ ), only one of which is generic. Denote the generic subrepresentation by  $\pi$ . Let  $\pi^-$  denote the generic representation resulting from an analogous construction, when  $\rho$  is replaced by  $\rho^-$ . Again, the  $\mathcal{H}$ -modules corresponding to  $\pi$  and  $\pi^-$  are 1-dimensional, and the same calculations we used in Case (iii) show that the operators  $T_i, i = 1, \dots, n-1$  act by  $q^t$ . This leaves us four possible  $\mathcal{H}$  structures to consider

$$(10) \quad \begin{aligned} \mathcal{H} \otimes_{\mathcal{H}_0} \epsilon_0, & \quad \text{with} \quad \epsilon_0(T_n) = \pm 1 \quad (\text{and } \epsilon_0(T_i) = q^t, i = 1, \dots, n-1); \quad \text{and} \\ \mathcal{H} \otimes_{\mathcal{H}_n} \epsilon_n, & \quad \text{with} \quad \epsilon_n(T_0) = \pm 1 \quad (\text{and } \epsilon_n(T_i) = q^t, i = 1, \dots, n-1). \end{aligned}$$

So far, we have been able to view Case (ii) as a special instance of Case (iii) which occurs when  $r = s = 0$ . However, to obtain an explicit description of the Gelfand–Graev module, we need more information than we used above in Case (iii). The reason is that the standard intertwining operator  $\chi\rho \rtimes \sigma \rightarrow \chi^{-1}\rho^\vee \rtimes \sigma$  no longer has a pole when  $X_n(\chi) = \pm 1$ . In Case (iii), the operator  $R_n$  (see formula (9))—which is constructed from the standard intertwining operator—vanishes at the point of reducibility, and the action of  $T_n$  is determined by the action of the function

$$(q^r - 1) \frac{X_n \left( X_n - \frac{q^{t\beta} - q^{t\alpha}}{q^r - 1} \right)}{X_n^2 - 1}$$

used to remove the poles of  $R_n$ . In this case however,  $R_n$  no longer vanishes and is regular at the point of reducibility; consequently, the above function does not appear in the construction and we have  $T_n = R_n$ . We know that this operator acts by 1 or  $-1$  on the  $\mathcal{H}$ -modules  $\pi$  and  $\pi^-$ , but we still have a certain amount of freedom in our choices. Indeed, as one verifies easily, the operator  $T'_n = (-1)^e X_n^f T_n$  (where  $e \in \{0, 1\}$ ,  $f \in \mathbb{Z}$ ) satisfies the same relations as  $T_n$ . Therefore, we obtain the same Hecke algebra if we replace  $T_n$  by  $T'_n$ , but the action of  $T'_n$  on  $\pi$  obviously differs from the action of  $T_n$ .

In fact, we know that  $X_n$  acts on  $\pi$  by 1, and on  $\pi^-$  by  $-1$ . Therefore  $X_n^2$  acts by 1 on both, so replacing  $T_n$  by  $X_n^2 T_n$  does not affect our description of the Gelfand–Graev module. We thus have 4 choices that affect the description ( $e = 0$  or  $1$ ;  $f$  even or odd), and as we vary the four choices, the description of the Gelfand–Graev module varies through all four possibilities described in (10) above.

This discussion shows that—to determine the action explicitly—we need to specify the choices appearing in the construction of the operator  $R_n$ . We now explain one possible normalization using Whittaker models. To be concrete, we now focus on  $G = \mathrm{SO}(2N+1)$ ; the same approach is possible when  $G$  is the symplectic group. We also specialize our discussion to the case  $n = 1$  to simplify notation (thus, the cuspidal representation which defines the component is  $\rho \otimes \sigma$ ); the general case is analogous and follows from this one. We thus drop the subscripts and write  $T, X$  instead of  $T_n, X_n$ .

We fix a non-degenerate character  $\psi$  of the unipotent radical  $U$  of  $G = \mathrm{SO}(2N+1)$ . Let  $V_\rho$  denote the space of the representation  $\rho$ , and let  $\lambda$  be a  $\psi$ -Whittaker functional on  $V_\rho$ :  $\lambda(\rho(u)v) = \psi(u)\lambda(v)$ , for  $v \in V_\rho$ . Notice that  $\lambda$  is then also a  $\psi$ -Whittaker functional for  $\rho \otimes \chi$  for any unramified character  $\chi \in \mathrm{GL}_k(F)$ : we have

$$\lambda((\chi \otimes \rho)(u)v) = \chi(u)\psi(u)\lambda(v) = \psi(u)\lambda(v),$$

since  $\det u = 1$  and thus  $u \in \ker \chi$ . Abusing notation, we also let  $\lambda$  denote the  $\psi$ -Whittaker functional of  $\rho \otimes \sigma$  (or  $\chi\rho \otimes \sigma$  for any unramified  $\chi$ , as we have just shown). Following Proposition 3.1 of [22], we now form a  $\psi$ -Whittaker functional  $\Lambda_\chi$  on the space of  $i_P^G(\chi\rho \otimes \sigma)$  by setting

$$(11) \quad \Lambda_\chi(f) = \int_N \lambda(f(wn)) \psi(n)^{-1} dn,$$

where  $w$  is a representative of the non-trivial element of the Weyl group; in our case, we

take  $w$  to be the block anti-diagonal matrix

$$\begin{pmatrix} & & I_k \\ & I_{2(N-k)+1} & \\ I_k & & \end{pmatrix}.$$

Since  $\pi$  and  $\pi^-$  are generic, it suffices to determine the action of  $T$  on their respective Whittaker functionals if we want to determine how  $T$  acts on the  $\mathcal{H}$ -modules  $\text{Hom}_G(\Gamma_{\mathfrak{s}}, \pi)$  and  $\text{Hom}_G(\Gamma_{\mathfrak{s}}, \pi^-)$ .

For any unramified character  $\chi$ , we have the specialization map  $\text{sp}_{\chi} : \Gamma_{\mathfrak{s}} \mapsto i_P^G(\chi\rho \otimes \sigma)$  (cf. [16, §3.1]). The unique (up to scalar multiple) element of  $\text{Hom}_G(\Gamma_{\mathfrak{s}}, \pi)$  factors through  $\text{sp}_1 : \Gamma_{\mathfrak{s}} \rightarrow i_P^G(\rho \otimes \sigma)$ ; similarly, any element of  $\text{Hom}_G(\Gamma_{\mathfrak{s}}, \pi^-)$  factors through  $\text{sp}_{\chi_0}$  (recall that  $\rho^- = \chi_0 \otimes \rho$ ). Notice that  $\Lambda_1$  and  $\Lambda_{\chi_0}$  are the Whittaker models of  $\pi$  and  $\pi^-$ , respectively.

To determine the action of  $T$  on  $\Lambda_{\chi}$  (for any  $\chi$ ), we must compare  $\Lambda_{\chi} \text{sp}_{\chi}$  and  $\Lambda_{\chi} \circ \text{sp}_{\chi} \circ T$ . The operator  $T$  is defined by the following property:

$$\text{sp}_{\chi} T = \varphi \circ J(\chi^{-1}) \circ \text{sp}_{\chi^{-1}}$$

(cf. [16, §3.1, 3.2]). Here  $J(\chi^{-1})$  denotes the standard intertwining operator  $i_P^G(\chi^{-1}\rho \otimes \sigma) \rightarrow i_P^G(\chi\rho^{\vee} \otimes \sigma)$ . To explain  $\varphi$ , recall that  $\rho$  is assumed to be self-dual. Therefore, we can fix an isomorphism  $\varphi : \rho^{\vee} \mapsto \rho$  and induce to an isomorphism  $i_P^G(\chi\rho^{\vee} \otimes \sigma) \rightarrow i_P^G(\chi\rho \otimes \sigma)$  for any unramified  $\chi$ , which we again denote by  $\varphi$  by abuse of notation.

Let  $\Lambda_{\chi}^{\vee}$  denote the Whittaker functional on  $i_P^G(\chi\rho^{\vee} \otimes \sigma)$  obtained using (11) from a fixed Whittaker functional  $\lambda^{\vee}$  for  $\rho^{\vee}$ . By the uniqueness of Whittaker functionals,  $\Lambda_{\chi} \circ \varphi = c \cdot \Lambda_{\chi}^{\vee}$  for some constant  $c$ . Furthermore, since  $\varphi$  is induced from an isomorphism  $\varphi : \rho^{\vee} \mapsto \rho$ , it follows immediately that  $c$  does not depend on  $\chi$ . Therefore, we have

$$\Lambda_{\chi} \circ \text{sp}_{\chi} \circ T = c \cdot \Lambda_{\chi}^{\vee} \circ J(\chi^{-1}) \circ \text{sp}_{\chi^{-1}}.$$

Note that there is a natural way to normalize  $\varphi$  in such a way that  $c = 1$ . We denote by  $g^{\tau}$  the transpose of an element  $g \in GL_k(F)$  with respect to the anti-diagonal (and with  $g^{-\tau}$  its inverse). One can then define a new representation  $\rho_1$  by  $\rho_1(g) = \rho(g^{-\tau})$ . This representation is isomorphic to the contragredient of  $\rho$ ; the advantage is that it acts on  $V_{\rho}$ , the space of  $\rho$ . Furthermore, for any diagonal matrix (i.e. an element of the maximal torus)  $t \in GL_k(F)$ , we may conjugate  $\rho_1$  to get  $\rho_2(g) = {}^t\rho_1(g) = \rho_1(t^{-1}gt)$ . Then  $\rho_2 \cong \rho_1$ , and with a suitable choice of  $t$ ,  $\rho_2$  becomes  $\psi$ -generic with the same Whittaker functional  $\lambda$ . For example, assume  $\psi$  is given by

$$\psi(u) = \psi_0(u_{1,2} + \cdots + u_{k-1,k})$$

where  $\psi_0$  is a non-trivial additive character of  $F$ , and  $u$  is an upper-triangular unipotent matrix with entries  $u_{1,2}, \dots, u_{k-1,k}$  above the main diagonal. Then one checks immediately that  $t = \text{diag}(1, -1, \dots, (-1)^{k-1})$  gives

$$\lambda(\rho_2(u)v) = \psi(u)\lambda(v)$$

for any  $v \in V_{\rho}$ . In short, we may assume  $\Lambda_{\chi} \circ \text{sp}_{\chi} \circ T = \Lambda_{\chi}^{\vee} \circ J(\chi^{-1}) \circ \text{sp}_{\chi^{-1}}$ .

This leads to the second choice we have to make in the construction of  $T$ : that of the normalization of the intertwining operator  $J$ . Here we choose the standard normalization introduced by Shahidi; cf. Theorem 3.1, [22]. Under this assumption, we have

$$\Lambda_\chi^\vee \circ J(\chi^{-1}) = \Lambda_{\chi^{-1}}$$

for every unramified character  $\chi$ . Thus

$$\Lambda_\chi \circ \text{sp}_\chi \circ T = \Lambda_{\chi^{-1}} \circ \text{sp}_{\chi^{-1}}.$$

With this, we are ready to compare the action of  $T$  on  $\pi$  and  $\pi^-$ . For  $\pi$  we specialize at  $\chi = 1$ ; this gives us

$$\Lambda_1 \circ \text{sp}_1 \circ T = \Lambda_1 \circ \text{sp}_1,$$

i.e.  $T$  acts trivially.

For  $\pi^-$  we specialize at  $\chi_0$ . We notice that  $\chi_0^{-1} = \chi_0 \eta$  for some character  $\eta$  such that  $\eta \circ \rho \cong \rho$ . This shows that  $\text{sp}_{\chi^{-1}} = \phi_\eta \circ \text{sp}_{\chi_0}$ , where  $\phi_\eta$  is the isomorphism  $\rho \mapsto \eta \otimes \rho$  defined in [16, §1.17] (again, we induce to  $\phi_\eta : i_P^G(\rho \otimes \sigma) \rightarrow i_P^G(\eta \rho \otimes \sigma)$  and abuse the notation). Finally, using the uniqueness of Whittaker functionals again, we see that  $\Lambda_{\chi \eta} \circ \phi_\eta = d \cdot \Lambda_\chi$  for some constant  $d$  which does not depend on  $\chi$ . We can normalize  $\phi_\eta$  so that  $d = 1$ ; then we have

$$\Lambda_{\chi_0} \circ \text{sp}_{\chi_0} \circ T = \Lambda_{\chi_0^{-1}} \circ \text{sp}_{\chi_0^{-1}} = \Lambda_{\chi_0 \eta} \circ \phi_\eta \circ \text{sp}_{\chi_0} = \Lambda_{\chi_0} \circ \text{sp}_{\chi_0}.$$

Therefore,  $T$  acts trivially on  $\pi^-$  as well.

To summarize, if we use Shahidi's normalization of the standard intertwining operator, and normalize  $\varphi$  as we did above, it follows that  $T$  acts trivially on both  $\pi$  and  $\pi^-$ . This implies that the Gelfand–Graev module is isomorphic to

$$\mathcal{H} \otimes_{\mathcal{H}_0} \epsilon_0$$

(see (10)), where  $\epsilon_0(T_n) = 1$ . Note that this is analogous to our results in Case (iii), because  $T_n$  again acts by  $q^r$ , only this time  $r = 0$ .

This completes our analysis of the structure of  $\mathcal{H}$ . We conclude the section by providing an alternative proof for the following result of [6]:

**Corollary 3.8.** *We have*

$$\text{End}_{\mathcal{H}}(\Pi) \cong Z(\mathcal{H}),$$

*the center of  $\mathcal{H}$ .*

*Proof.* Obviously,  $Z(\mathcal{H})$  is contained in  $\text{End}_{\mathcal{H}}(\Pi)$ , so we need to prove that any element of  $\text{End}_{\mathcal{H}}(\Pi)$  is given by a multiplication with an element  $f \in Z(\mathcal{H})$ . We prove the corollary in case (iii); the proof in cases (i) and (ii) is analogous.

We start by recalling that  $Z(\mathcal{H}) = \mathcal{A}^W$ , the Weyl group invariants of  $\mathcal{A}$ . Now let  $f \in \text{End}_{\mathcal{H}}(\Pi)$ . We have  $\text{End}_{\mathcal{H}}(\Pi) \subseteq \text{End}_{\mathcal{A}}(\Pi)$ , but we know that  $\Pi = \mathcal{A}$  as an  $\mathcal{A}$ -module. Therefore,  $f \in \text{End}_{\mathcal{A}}(\mathcal{A}) = \mathcal{A}$ . Thus, it remains to prove that  $f$  is invariant under the action of the Weyl group.

It suffices to prove that  $f$  is invariant under the set of simple reflections which generate the Weyl group. In other words, we need to prove that

$$f^\vee = f \quad \text{and} \quad f^{s_i} = f, \quad i = 1, \dots, n-1,$$

using the notation of §2.5. This follows immediately from what we now know about the structure of  $\Pi$  as an  $\mathcal{H}$ -module:  $\Pi = \mathcal{H} \otimes_{\mathcal{H}_0} \epsilon$ . In other words, we have shown that there exists an element  $g \in \mathcal{A} \cong \Pi$  (constructed in §3.1) on which the elements  $T_1, \dots, T_{n-1}$  and  $T_n$  act by scalar multiplication with  $q^t$ , and  $q^r$ , respectively.

We now look at the commutation relation

$$T_n f - f^\vee T_n = \left( (q^r - 1) + \frac{1}{X_n} (\sqrt{q}^{r+s} - \sqrt{q}^{r-s}) \right) \frac{f - f^\vee}{1 - 1/X_n^2}$$

satisfied by  $T_n$  and  $f$ . Applying this to  $g$  (recall that  $T_n g = q^r g$ ), and using the fact that  $f$  is in  $\text{Hom}_{\mathcal{H}}(\Pi)$  (so that  $T_n f g = f T_n g$ ), we get

$$(f - f^\vee) q^r \cdot g = \left( (q^r - 1) + \frac{1}{X_n} (\sqrt{q}^{r+s} - \sqrt{q}^{r-s}) \right) \frac{f - f^\vee}{1 - 1/X_n^2} \cdot g.$$

This is an equality in  $\mathcal{A}$ . Since  $q^r \neq \left( (q^r - 1) + \frac{1}{X_n} (\sqrt{q}^{r+s} - \sqrt{q}^{r-s}) \right) \frac{1}{1 - 1/X_n^2}$  and  $g \neq 0$ , it follows that  $f - f^\vee$  must be 0. Therefore  $f = f^\vee$ . We get  $f = f^{s_i}$  in the same way, using the commutation relations satisfied by the operators  $T_i$ . This proves the corollary.  $\square$

## 4 An application to the GGP restriction problem

The theory of Bernstein-Zelevinsky derivatives implies that the restriction of an irreducible supercuspidal representation of  $\text{GL}(n+1)$  to  $\text{GL}(n)$  is isomorphic to the Gelfand-Graev representation of  $\text{GL}(n)$ . The goal of this short section is to show that, in the language of Hecke algebra modules, a similar statement holds for representations of orthogonal groups. More precisely, let  $\text{SO}(2n+2)$  be an orthogonal group containing split  $\text{SO}(2n+1)$ . We have:

**Lemma 4.1.** *Let  $\sigma$  be an irreducible representation of  $\text{SO}(2n+2)$ . For any inertial data  $\mathfrak{s}$  of  $\text{SO}(2n+1)$ , let  $\sigma[\mathfrak{s}]$  be the corresponding Bernstein summand of  $\sigma$ . We have:*

- *If  $\sigma$  is supercuspidal then it is projective  $\text{SO}(2n+1)$ -module.*
- *$\dim \text{Hom}_{\text{SO}(2n+1)}(\sigma, \pi) \leq 1$  for any irreducible representation  $\pi$  of  $\text{SO}(2n+1)$ .*
- *$\sigma[\mathfrak{s}]$  is finitely generated  $\text{SO}(2n+1)$ -module.*

*Proof.* The first statement is a known observation:  $\sigma$  is a direct summand of  $C_c(\text{SO}(2n+2))$  (the space of locally constant and compactly supported functions on  $\text{SO}(2n+2)$ ) and this module stays projective after restriction to  $\text{SO}(2n+1)$ . The second is the multiplicity one theorem [2]. For the third, observe that we have a surjection

$$C_c(\text{SO}(2n+2)) \rightarrow \sigma^\vee \boxtimes \sigma.$$

By Theorem A in [1] or Remark 5.1.7 in [21], the Bernstein components of  $C_c(\text{SO}(2n+2))$ , considered an  $\text{SO}(2n+2) \times \text{SO}(2n+1)$ -module, are finitely generated. The third bullet now follows at once.  $\square$

**Proposition 4.2.** *Let  $\sigma$  be an irreducible supercuspidal representation of  $\mathrm{SO}(2n+2)$ . Let  $\mathfrak{s}$  be inertial data for  $\mathrm{SO}(2n+1)$  such that  $\sigma[\mathfrak{s}] \neq 0$ . Let  $\mathcal{Z}$  be the center of the Bernstein component corresponding  $\mathfrak{s}$ . Then for every maximal ideal  $\mathcal{J}$  in  $\mathcal{Z}$  there exists unique irreducible representation  $\pi$  of  $\mathrm{SO}(2n+1)$  annihilated by  $\mathcal{J}$  such that  $\mathrm{Hom}_{\mathrm{SO}(2n+1)}(\sigma, \pi) \cong \mathbb{C}$ .*

*Proof.* Let  $\Gamma_{\mathfrak{s}}$  be the projective generator associated to the inertial data  $\mathfrak{s}$ , and  $\mathcal{H}$  the algebra of endomorphisms of  $\Gamma_{\mathfrak{s}}$ . Since  $\sigma[\mathfrak{s}] \neq 0$ , combining the above lemma and the Remark 3.2 one concludes that

$$\mathrm{Hom}_{\mathrm{SO}(2n+1)}(\Gamma_{\mathfrak{s}}, \sigma) \cong \mathcal{A}$$

as  $\mathcal{A}$ -modules, and then by Corollary 3.7

$$\mathrm{Hom}_{\mathrm{SO}(2n+1)}(\Gamma_{\mathfrak{s}}, \sigma) \cong \mathcal{H} \otimes_{\mathcal{H}_W} \epsilon$$

for some finite subalgebra  $\mathcal{H}_W \cong \mathbb{C}[W]$ , where  $W$  is a finite group, such that  $\mathcal{H} \cong \mathcal{A} \otimes \mathcal{H}_W$  and  $\mathcal{A}^W$  is the center  $\mathcal{Z}$  of  $\mathcal{H}$ , that is, the center of the Bernstein component corresponding to  $\mathfrak{s}$ .

Now recall that all irreducible representations annihilated by  $\mathcal{J}$  are subquotients of a single principal series representation

$$\mathcal{H} \otimes_{\mathcal{A}} \chi \cong \mathcal{H}_W$$

where  $\chi$  is a character of  $\mathcal{A}$ . Observe that the principal series is isomorphic to  $\mathcal{H}_W \cong \mathbb{C}[W]$  as an  $\mathcal{H}_W$ -module. Since the one-dimensional type  $\epsilon$  appears with multiplicity one in  $\mathcal{H}_W$ , there exists unique irreducible representation annihilated by  $\mathcal{J}$  containing the type  $\epsilon$ . But precisely these representations are irreducible quotients of  $\mathcal{H} \otimes_{\mathcal{H}_W} \epsilon$ , by the Frobenius reciprocity.  $\square$

Note that the above result is compatible with Gan–Gross–Prasad conjectures [13], and it sheds some light on them: two irreducible representations of  $\mathrm{SO}(2n+1)$  belonging to the same  $L$ -packet (and the same Bernstein component) cannot both be quotients of  $\sigma$ . Of course, the above proposition holds for any  $\sigma$  that is projective as an  $\mathrm{SO}(2n+1)$ -module. It would be interesting to classify irreducible  $\sigma$  that are projective when restricted to  $\mathrm{SO}(2n+1)$ . Projectivity of restriction from  $\mathrm{GL}(n+1)$  to  $\mathrm{GL}(n)$  was studied in [12] and a complete classification of irreducible representations of  $\mathrm{GL}(n+1)$  that are projective as  $\mathrm{GL}(n)$ -modules was obtained in [9].

## Appendix A An isomorphism of projective generators

Let  $G$  be a reductive group and  $\mathfrak{s}$  be an inertial class of cuspidal data  $(M, \sigma)$ , where  $M$  is a Levi subgroup of  $G$ . By Bushnell and Kutzko [8], for any such  $\mathfrak{s}$  there should be a type  $(J, \lambda)$ , where  $J$  is a compact subgroup of  $G$ , and  $\lambda$  is an irreducible representation of  $J$  such that  $\mathrm{c-ind}_J^G \lambda$  is a projective generator for  $\mathrm{Rep}_{\mathfrak{s}}(G)$ . One is interested in the structure of the Hecke algebra  $\mathcal{H}(G, \lambda) = \mathrm{End}_G(\mathrm{c-ind}_J^G \lambda)$ . In this section we show that under certain conditions (when  $(J, \lambda)$  exists) that the Hecke algebra  $\mathcal{H}(G, \lambda) = \mathrm{End}_G(\mathrm{c-ind}_J^G \lambda)$  is isomorphic to the algebra  $\mathcal{H}_{\mathfrak{s}} = \mathrm{End}_G(\Gamma_{\mathfrak{s}})$  constructed in Section 2.3. More precisely, we have the following:

**Theorem A.1.** *Assume that  $G$  is a classical group and that the residue characteristic of  $F$  is different from 2. Let  $\mathfrak{s} = [(M, \sigma)]$  be an inertial equivalence class in  $G$ . There exists an  $\mathfrak{s}$ -type  $(J, \lambda)$  such that the generators  $\Gamma_{\mathfrak{s}}$  and  $\text{c-ind}_J^G \lambda$  are isomorphic.*

*Proof.* We use the theory of covers developed by Bushnell and Kutzko. Any inertial equivalence class  $\mathfrak{s} = [(M, \sigma)]$  in  $G$  also determines a (cuspidal) inertial equivalence class  $\mathfrak{s}_M = [(M, \sigma)]$  in  $M$ . Let  $(J, \lambda)$  be a type for  $\mathfrak{s}$  and  $(J_M, \lambda_M)$  a type for  $\mathfrak{s}_M$ . We say that the  $(J, \lambda)$  is a cover of the type  $(J_M, \lambda_M)$  if  $J$  decomposes with respect to  $M$  (in particular,  $J_M = J \cap M$  and  $\lambda_M = \lambda|_M$ ) and the equivalence of categories  $\text{Rep}_{\mathfrak{s}}(G) \rightarrow \mathcal{H}(G, \lambda)\text{-Mod}$  commutes with parabolic induction and the Jacquet functor in the appropriate sense (see Definition 8.1 and paragraph 5 of Introduction in [8]). We then have the following.

**Lemma A.2** (Theorem 7.9 (iii) of [8]). *Let  $P$  be any parabolic subgroup with Levi factor  $M$ . For any smooth representation  $V \in \text{Rep}(G)$ , the Jacquet functor with respect to  $P$  induces an isomorphism*

$$V^\lambda = (V_N)^{\lambda_M}.$$

Here  $V^\lambda$  denotes the  $\lambda$ -isotype of  $V$ , i.e. the sum of all  $G$ -invariant subspaces of  $V$  isomorphic to  $\lambda$ .

We use this to reduce the proof of Theorem A.1 to the case of cuspidal components.

**Lemma A.3.** *Let  $(J, \lambda)$  be a type for  $\mathfrak{s} = [(M, \pi)]$  in  $G$ , and let  $(J_M, \lambda_M)$  be a type for  $\mathfrak{s}_M = [(M, \pi)]$  in  $M$ . Assume that  $(J, \lambda)$  is a cover of  $(J_M, \lambda_M)$ .*

*If the Bernstein generator  $\Gamma_{\mathfrak{s}_M}$  is isomorphic to the Bushnell–Kutzko generator  $\text{c-ind}_{J_M}^M \lambda_M$  for the cuspidal component  $\text{Rep}_{\mathfrak{s}_M}(M)$ , then we also have an isomorphism of generators for the component  $\text{Rep}_{\mathfrak{s}}(G)$ .*

*Proof.* Lemma A.2 shows that we have

$$\text{Res}_{J_M}^J((\text{Res}_J^G V)^\lambda) = (\text{Res}_{J_M}^M r_N(V))^{\lambda_M}$$

for any  $G$ -module  $V$ . Here  $\text{Res}_H^G$  denotes the restriction functor from  $G$  to  $H$ , and  $r_N$  the Jacquet functor with respect to  $P = MN$ . In other words, we get the following isomorphism of functors  $\text{Rep}(G) \rightarrow \text{Rep}(J_M)$ :

$$(*) \quad \text{Res}_{J_M}^J \circ (\lambda\text{-iso}) \circ \text{Res}_J^G = (\lambda_M\text{-iso}) \circ \text{Res}_{J_M}^M \circ r_N,$$

where we have used  $\lambda$ -iso (resp.  $\lambda_M$ -iso) to denote taking the  $\lambda$ - (resp.  $\lambda_M$ -) isotype.

All of the above functors have left adjoints:

- $\text{c-ind}_{J_M}^J$  and  $\text{c-ind}_{J_M}^M$  for  $\text{Res}_{J_M}^J$  and  $\text{Res}_{J_M}^M$ , respectively;
- $i_{\overline{P}}^G$  for  $r_N$  (this is the Bernstein form of Frobenius reciprocity; here  $\overline{P} = M\overline{N}$  is the parabolic subgroup opposite to  $P$ )
- $\lambda$ -iso and  $\lambda_M$ -iso are self-adjoint, because we are working with (necessarily semisimple) representations of compact groups  $J$  and  $J_M$ .

Since adjoints are unique (up to equivalence), taking the adjoint of  $(*)$  we get

$$\text{c-ind}_J^G \circ (\lambda\text{-iso}) \circ \text{c-ind}_{J_M}^J = i_{\bar{P}}^G \circ \text{c-ind}_{J_M}^M \circ (\lambda_M\text{-iso}).$$

We now apply both sides of the above equality to  $\lambda_M$ . On the right-hand side, we get  $i_{\bar{P}}^G(\text{c-ind}_{J_M}^M \lambda_M)$ . By the assumptions from the statement of the lemma, we have  $\text{c-ind}_{J_M}^M \lambda_M = \Gamma_{s_M}$ ; therefore,  $i_{\bar{P}}^G(\text{c-ind}_{J_M}^M \lambda_M)$  is exactly the Bernstein generator  $i_{\bar{P}}^G(\Gamma_{s_M}) = \Gamma_s$ . Here we used the fact that the construction of the Bernstein generator does not depend on the choice of parabolic  $P$  (we choose  $\bar{P}$ ) with fixed Levi  $M$  (cf. [3, Proposition 35]).

On the left-hand side, we get  $\text{c-ind}_J^G((\text{c-ind}_{J_M}^J \lambda_M)^\lambda)$ . However, Frobenius reciprocity gives us  $\dim \text{Hom}_J(\text{c-ind}_{J_M}^J \lambda_M, \lambda) = \dim \text{Hom}_{J_M}(\lambda_M, \lambda|_M) = 1$ , which follows from  $\lambda|_M = \lambda_M$ . Therefore  $(\text{c-ind}_{J_M}^J \lambda_M)^\lambda = \lambda$ , and the left-hand side becomes  $\text{c-ind}_J^G(\lambda)$ , i.e. the Bushnell–Kutzko generator. Thus

$$\text{c-ind}_J^G(\lambda) \cong \Gamma_s,$$

as claimed.  $\square$

The above lemma allows us to focus on cuspidal components of the form  $\mathfrak{s}_M = [(M, \sigma)]$  in  $M$ . If we want to prove the isomorphism of generators in general, it remains to prove that the generators of the cuspidal components are isomorphic. In other words, we would like to show that

$$\text{c-ind}_{M^\circ}^M \sigma_0 = \text{c-ind}_{J_M}^M \lambda_M,$$

where  $\sigma_0$  is an (any) irreducible constituent of  $\sigma|_{M^\circ}$ . We shall accomplish this under the following assumptions. Assume that

$$\sigma = \text{c-ind}_{\tilde{J}_M}^M \tilde{\lambda}_M$$

where (see (5.5) in [8])

- $\tilde{J}_M$  is compact modulo center subgroup of  $M$  such that  $J_M = \tilde{J}_M \cap M^\circ$ ,
- the restriction of  $\tilde{\lambda}_M$  to  $J_M$  is  $\lambda_M$ ,
- any  $x \in M$  which intertwines the representation  $\lambda_M$  belongs to  $\tilde{J}_M$ .

**Lemma A.4.** *Let  $\sigma = \text{c-ind}_{\tilde{J}_M}^M \tilde{\lambda}_M$  be a cuspidal representation of  $M$  where the pair  $(\tilde{J}_M, \tilde{\lambda}_M)$  satisfies the above three bullets. Then  $\sigma_0 = \text{c-ind}_{J_M}^{M^\circ} \lambda_M$  is an irreducible  $M^\circ$ -summand of  $\sigma$ , and we have a canonical isomorphism*

$$\text{c-ind}_{M^\circ}^M \sigma_0 \cong \text{c-ind}_{J_M}^M \lambda_M.$$

*Proof.* Using Frobenius reciprocity and Mackey theory (provided by [26, §5.5] in this setting), we get

$$\begin{aligned} \text{Hom}_{M^\circ}(\sigma_0, \sigma_0) &\cong \text{Hom}_{M^\circ}(\text{c-ind}_{J_M}^{M^\circ} \lambda_M, \text{c-ind}_{J_M}^{M^\circ} \lambda_M) \\ &\cong \text{Hom}_{J_M}(\lambda_M, \bigoplus_x \text{c-ind}_{J_M \cap J_M^x}^J \text{Res}_{J_M \cap J_M^x}^{J_M^x} \lambda_M^x) \end{aligned}$$

where the sum is taken over a set of double coset representatives in  $J_M \backslash M^\circ / J_M$ . Fixing one such  $x$ , we see that

$$\text{Hom}_{J_M}(\lambda_M, \text{c-ind}_{J_M \cap J_M^x}^J \text{Res}_{J_M \cap J_M^x}^{J_M^x} \lambda^x) \cong \text{Hom}_{J_M \cap J_M^x}(\lambda_M, \lambda_M^x)$$

(here we are using Frobenius reciprocity for a compact group, so that restriction is also a left adjoint for c-ind). Since only  $x \in \tilde{J}_M$  intertwine  $\lambda_M$ , and  $J_M = \tilde{J}_M \cap M^\circ$ , we have

$$\text{Hom}_{M^\circ}(\sigma_0, \sigma_0) \cong \text{Hom}_{J_M}(\lambda_M, \lambda_M) = \mathbb{C},$$

which we needed to prove.  $\square$

According to (5.5) in [8], if  $M$  is a general linear group over a division algebra, then the conditions of the above lemma are satisfied for every irreducible cuspidal representation  $\sigma$  of  $M$ . Clearly, if the conditions are satisfied for  $(M_1, \sigma_1)$  and  $(M_2, \sigma_2)$  then they are satisfied for  $M = M_1 \times M_2$  and  $\sigma = \sigma_1 \otimes \sigma_2$ . Recall that a Levi subgroup in a classical group is a product of general linear groups and a smaller classical group. By a result of Stevens [24] irreducible cuspidal representations of classical groups are induced from open compact subgroups if  $F$  has odd residue characteristic. Thus, in these cases, for every irreducible cuspidal representation  $\sigma$  of  $M$  there exists a type  $(\tilde{J}_M, \tilde{\lambda}_M)$  satisfying the three bullets above. Moreover, by [7] and [25] (for general linear groups) and [19] (for classical groups),  $G$  admits a type  $(J, \lambda)$  which is a cover of type  $(J_M, \lambda_M)$ .

This completes the proof of Theorem A.1.  $\square$

We remark that Theorem A.1 holds beyond classical groups, provided that the conditions of two lemmas are satisfied. For exceptional  $G_2$  examples, see [5].

## References

- [1] A. Aizenbud, N. Avni, and D. Gourevitch. Spherical pairs over close local fields. *Comment. Math. Helv.*, 87(4):929–962, 2012.
- [2] A. Aizenbud, D. Gourevitch, S. Rallis, and G. Schiffmann. Multiplicity one theorems. *Annals of Math.* (2), 172(2):1407–1434, 2010.
- [3] J. Bernstein. Representations of  $p$ -adic groups. Lectures given at Harvard University, Fall 1992. *Notes by K. Rumelhart*.
- [4] J. Bernstein. Le “centre” de Bernstein (rédigé par P. Deligne). In *Representations of reductive groups over a local field*, pages 1–32, 1984.
- [5] C. Blondel. Une méthode de construction de types induits et son application à  $G_2$ . *J. Algebra*, 213(1):231–271, 1999.
- [6] C. J. Bushnell and G. Henniart. Generalized Whittaker models and the Bernstein center. *American Journal of Mathematics*, 125(3):513–547, 2003.
- [7] C. J. Bushnell and P. C. Kutzko. *The admissible dual of  $GL(N)$  via compact open subgroups*, volume 129 of *Annals of Mathematics Studies*. Princeton University Press, 1993.

[8] C. J. Bushnell and P. C. Kutzko. Smooth representations of reductive p-adic groups: structure theory via types. *Proceedings of the London Mathematical Society*, 77(3):582–634, 1998.

[9] K. Y. Chan. Homological branching law for  $(\mathrm{GL}_{n+1}, \mathrm{GL}_n)$ : Projectivity and indecomposability. *Invent. Math.*, 255:299–345, 2021.

[10] K. Y. Chan and G. Savin. Iwahori component of the Gelfand–Graev representation. *Mathematische Zeitschrift*, 288(1–2):125–133, 2018.

[11] K. Y. Chan and G. Savin. Bernstein–Zelevinsky derivatives: a Hecke algebra approach. *International Mathematics Research Notices*, 2019(3):731–760, 2019.

[12] K. Y. Chan and G. Savin. A vanishing Ext-branching theorem for  $(\mathrm{GL}_{n+1}, \mathrm{GL}_n)$ . *Duke Math. J.*, 2021. doi:10.1215/00127094-2021-0028.

[13] W. T. Gan, B. H. Gross, and D. Prasad. In *Sur les conjectures de Gross et Prasad. I.*, volume 346 of *Astérisque*, pages 1–109. Société Mathématique de France, Paris, 2012.

[14] D. Goldberg. Reducibility of induced representations for  $\mathrm{Sp}(2n)$  and  $\mathrm{SO}(n)$ . *American Journal of Mathematics*, 116(5):1101–1151, 1994.

[15] V. Heiermann. Paramètres de Langlands et algèbres d’entrelacement. *International Mathematics Research Notices*, 2010(9):1607–1623, 2010.

[16] V. Heiermann. Opérateurs d’entrelacement et algèbres de Hecke avec paramètres d’un groupe réductif p-adique: le cas des groupes classiques. *Selecta Mathematica*, 17(3):713–756, 2011.

[17] G. Lusztig. Affine Hecke algebras and their graded version. *Journal of the American Mathematical Society*, 2(3):599–635, 1989.

[18] M. Mishra and B. Pattanayak. Principal series component of Gelfand–Graev representation, 2020. arXiv:2010.13341.

[19] M. Miyauchi and S. Stevens. Semisimple types for  $p$ -adic classical groups. *Mathematische Annalen*, 358(1–2):257–288, 2014.

[20] A. Roche. The Bernstein decomposition and the Bernstein centre. In C. Cunningham and M. Nevins, editors, *Ottawa Lectures on Admissible Representations of Reductive p-adic Groups*, Fields Institute Monographs 26, pages 3–52. American Mathematical Society, Providence, RI, 2009.

[21] Y. Sakellaridis and A. Venkatesh. *Periods and harmonic analysis on spherical varieties*, volume 396 of *Astérisque*. Société Mathématique de France, Paris, 2017.

[22] F. Shahidi. On certain L-functions. *American Journal of Mathematics*, 103:297–355, 1981.

[23] M. Solleveld. Endomorphism algebras and Hecke algebras for reductive p-adic groups. arXiv:2005.07899.

- [24] S. Stevens. The supercuspidal representations of  $p$ -adic classical groups. *Inventiones mathematicae*, 172(2):289–352, 2008.
- [25] S. Stevens and V. Séchère. Smooth representations of  $\mathrm{GL}_m(D)$  VI: semisimple types. *International Mathematics Research Notices*, 2012(13):2994–3039.
- [26] M. Vignéras. *Représentations  $l$ -modulaires d'un groupe réductif  $p$ -adique avec  $l \neq p$* , volume 137 of *Progress in Math*. Birkhäuser, 1996.