ON THE PERMUTATION MODULES FOR ORTHOGONAL GROUPS $O_m^\pm(3)$ ACTING ON NONSINGULAR POINTS OF THEIR STANDARD MODULES

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Abstract. We describe the structure, including composition factors and submodule lattices, of cross-characteristic permutation modules for the natural actions of the orthogonal groups $O_m^\pm(3)$ with $m \geq 6$ on nonsingular points of their standard modules. These actions together with those studied in [2] are all examples of primitive rank 3 actions of finite classical groups on nonsingular points.

1. Introduction

Given a group $G$ acting on a set $\Omega$ and a field $\mathbb{F}$, the problem of determining the structure of the permutation $\mathbb{F}G$-module $\mathbb{F}\Omega$ has been studied extensively for many years. In particular, permutation modules as well as permutation representations for finite classical groups have received significant attention. We are interested in the action of a finite classical group $G$ on points (i.e. 1-dimensional subspaces) of the standard module associated with $G$.

The permutation module for the natural action of $G$ on singular points has been studied in great depth (for instance, see [8, 9, 10, 11]). However, not much has been known about the action of $G$ on nonsingular points. We note that in the linear and symplectic groups, all points are singular.

Problem 1.1. Let $G$ be a finite orthogonal or unitary group and $\mathbb{F}$ an algebraically closed field of cross characteristic. Describe the submodule structure of the permutation $\mathbb{F}G$-module for $G$ acting naturally on the set of nonsingular points of its standard module.

Let $P^0$ and $P$ be the sets of singular and nonsingular points, respectively, of the standard module associated with $G$. It is well known that the action of $G$ on $P^0$ is always transitive and rank 3. On the other hand, the transitivity of the action of $G$ on $P$ and the ranks of that action on orbits depend closely on the underlying field, which we will denote by $\mathbb{F}q$, of $G$. We do not have an exact formula for the ranks...
but they are “more or less” an increasing function of $q$. In particular, the structure of $\mathbb{F}P$ becomes more complicated when $q$ is large.

In [2], the authors studied the problem for orthogonal groups over a field of two elements and unitary groups over a field of four elements. This is the case (and only case!) when the action of $G$ on $P$ is transitive and rank 3.

In this article, we study the cross-characteristic permutation modules $\mathbb{F}P$ for the orthogonal groups $O_m^\pm(3)$ acting on $P$. It is not difficult to see that $O_m^\pm(3)$ has two orbits on $P$ and the action on each orbit is rank 3. These actions together with those studied in [2] are all examples of primitive rank 3 actions of finite classical groups on nonsingular points, as pointed out in an important paper by Kantor and Liebler (see [7]).

Drawing upon the methods introduced in [2], as well as in [9] and [11], we prove the following:

**Theorem 1.2.** Let $\mathbb{F}$ be an algebraically closed field of characteristic $\ell \neq 3$. Let $G$ be $O_m^\pm(3)$ ($m = 2n$ or $2n + 1$) with $m \geq 6$ and $P$ be the set of nonsingular points of the standard module associated with $G$. Then the permutation $\mathbb{F}G$-module $\mathbb{F}P$ of $G$ acting naturally on $P$ has the submodule structure as described in Tables 1, 2, and 3.

In these tables, $\delta_{i,j} = 1$ if $i \mid j$ and 0 otherwise.

| Conditions on $\ell$ and $n$ | Structure of $\mathbb{F}P$ |
|-------------------------------|-----------------------------|
| $\ell \neq 2, 3; \ell \nmid (3^n - 1)$ | $2\mathbb{F} \oplus X \oplus Y \oplus 2Z$ |
| $\ell \neq 2, 3; \ell \mid (3^n - 1)$ | $\mathbb{F} \oplus X \oplus Y \oplus Z \oplus Z$ |
| $\ell = 2; n$ even | $\mathbb{F} \oplus X \oplus \mathbb{F} \oplus Y$ |
| $\ell = 2; n$ odd | $2\mathbb{F} \oplus Y \oplus W \oplus X \oplus W$ |

where, $\dim X = \dim Y = \frac{(3^n - 1)(3^{n-1} - 1)}{8}, \dim Z = \frac{2^{2n} - 9}{8} - \delta_{\ell,3^n - 1},$ and $\dim W = \frac{(3^n - 1)(3^{n-1} + 3)}{8} - 1 - \delta_{2,n}$.

Let $V$ be a vector space of dimension $m \geq 6$ over the field of 3 elements $\mathbb{F}_3 = \{0, 1, -1\}$. Let $Q$ be a non-degenerate quadratic form on $V$, and let $(\cdot, \cdot)$ be the non-degenerate symmetric bilinear form on $V$ associated with $Q$ so that $Q(au + bv) = ...$
Table 2. Submodule structure of $\mathbb{F}O_{2n}(3)$-module $\mathbb{F}P$.

| Conditions on $\ell$ and $n$ | Structure of $\mathbb{F}P$ |
|------------------------------|-----------------------------|
| $\ell \neq 2, 3; \ell \nmid (3^n + 1)$ | $2\mathbb{F} \oplus X \oplus Y \oplus 2Z$ |
| $\ell \neq 2, 3; \ell \mid (3^n + 1)$ | $X \oplus Y \oplus Z \oplus Z$ |

For $\ell = 2; n$ even

$$
\begin{array}{ccc}
X & Y & F \\
\mathbb{F} & \mathbb{F} & \\
Y & W \oplus X & W \\
\mathbb{F} & \mathbb{F} & \\
X & Y & F \\
\end{array}
$$

For $\ell = 2; n$ odd

$$
\begin{array}{ccc}
\mathbb{F} & X & \mathbb{F} \\
\mathbb{F} & \mathbb{F} & \\
Y & W \oplus X & W \\
\mathbb{F} & \mathbb{F} & \\
\mathbb{F} & X & \mathbb{F} \\
\end{array}
$$

where, $\dim X = \dim Y = \frac{(3^n+1)(3^{n-1}+1)}{8} - \delta_{\ell,2}$, $\dim Z = \frac{3^{n-2}}{8} - \delta_{\ell,3^{n}+1}$, and $\dim W = \frac{(3^n+1)(3^{n-1}-3)}{8} - 1 + \delta_{2,n}$.

$a^2Q(u) + b^2Q(v) + ab(u,v)$ for any $a, b \in \mathbb{F}_3, u, v \in V$. Then $G = O^\kappa_m(3)$ is the full orthogonal group consisting of all linear transformations of $V$ preserving $Q$.

For $\kappa = \pm 1$, we denote

$$
P^\kappa := P^\kappa(Q) := \{ \langle v \rangle \in P \mid Q(v) = \kappa \}.
$$

$P^{+1}$ and $P^{-1}$ are often called the sets of plus points and minus points, respectively. We obtain the following isomorphism of $\mathbb{F}G$-modules:

$$
\mathbb{F}P \cong \mathbb{F}P^{+1} \oplus \mathbb{F}P^{-1}.
$$

Since $Q$ is a non-degenerate quadratic form on $V$, $-Q$ is also a non-degenerate quadratic form on $V$. The two isometry groups $O(V, Q)$ and $O(V, -Q)$ are canonically isomorphic, but the corresponding sets of nonsingular points are switched: $P^{-1}(Q) = P^{+1}(-Q)$ and $P^{+1}(Q) = P^{-1}(-Q)$. When $m$ is even the forms $Q$ and $-Q$ have the same discriminant but when $m$ is odd they do not. Therefore in Theorem 1.2 and its associated tables we see that for $m$ even there are two distinct isometry groups $G$, but for each the modules $\mathbb{F}P^{+1}$ and $\mathbb{F}P^{-1}$ are the same up to a diagonal automorphism of $G$, whereas for $m$ odd there is only one isometry group to consider, but the modules $\mathbb{F}P^{+1}$ and $\mathbb{F}P^{-1}$ are fundamentally different and indeed have different dimensions.
Table 3. Submodule structure of $\mathbb{F}O_{2n+1}(3)$-module $\mathbb{F}P$.

| Conditions on $\ell$ and $n$ | Structure of $\mathbb{F}P$ |
|-----------------------------|-----------------------------|
| $\ell \neq 2, 3; \ell \nmid (3^n - 1), \ell \mid (3^n + 1)$ | $2\mathbb{F} \oplus X \oplus Y \oplus 2Z$ |
| $\ell \neq 2, 3; \ell \mid (3^n - 1)$ | $\mathbb{F} \oplus X \oplus Y \oplus 2Z$ |
| $\ell \neq 2, 3; \ell \mid (3^n + 1)$ | $\mathbb{F} \oplus X \oplus Y \oplus 2Z$ |
| $\ell = 2; n$ even | $\mathbb{F} \oplus X_1 \oplus Y_1 \oplus Z_1$ |
| $\ell = 2; n$ odd | $\mathbb{F} \oplus X_1 \oplus Y_1 \oplus Z_1$ |

where, $\dim X = \frac{(3^n+1)(3^n-3)}{4} - \delta_{\ell,3^n-1}$, $\dim Y = \frac{(3^n-1)(3^n+3)}{4} - \delta_{\ell,3^n+1}$, $\dim Z = \frac{2^{2n-1}}{4}$, $\dim X_1 = \frac{(3^n-1)(3^n-3)}{8}$, $\dim Y_1 = \frac{(3^n+1)(3^n+3)}{8} - 1$, and $\dim Z_1 = \frac{(3^{2n}-9)}{8} - \delta_{2,n}$.

The paper is organized as follows. In the next section, we will outline the proof of the main theorem. Sections 3 and 4 are some preparations for the following sections. Each family of groups $O_{2n}^+(3)$, $O_{2n}^-(3)$, and $O_{2n+1}(3)$ is treated separately in sections 5, 6, and 7 respectively.

2. Notation and outline of the proof

2.1. Preliminaries. If the action of $G$ on a set $\Omega$ is rank 3 then the $\mathbb{F}G$-module $\mathbb{F}\Omega$ has two special submodules, the so-called graph submodules. The following description of these graph submodules is due to Liebeck (see [9]).

Let $G_\alpha$ be the stabilizer of $\alpha \in \Omega$. Then $G_\alpha$ acts on $\Omega$ with 3 orbits: one of them is $\{\alpha\}$ and the other two are denoted by $\Delta(\alpha)$ and $\Phi(\alpha)$. Define the parameters: $a = |\Delta(\alpha)|$, $b = |\Phi(\alpha)|$, $r = |\Delta(\alpha) \cap \Delta(\beta)|$, and $s = |\Delta(\alpha) \cap \Delta(\gamma)|$ for $\beta \in \Delta(\alpha)$ and $\gamma \in \Phi(\alpha)$. For any subset $\Delta$ of $\Omega$, we denote by $|\Delta|$ the element $\Sigma_{\delta \in \Delta} \delta$ of $\mathbb{F}\Omega$. For $c \in \mathbb{F}$, let $U_c$ be the $\mathbb{F}G$-submodule of $\mathbb{F}\Omega$ generated by all elements $v_{c,\alpha} = c\alpha + [\Delta(\alpha)]$, $\alpha \in \Omega$ and $U'_c$ be the $\mathbb{F}G$-submodule of $U_c$ generated by all elements
where $v_{c,\alpha} - v_{c,\beta} = c(\alpha - \beta) + [\Delta(\alpha)] - [\Delta(\beta)], \alpha, \beta \in \Omega$. The graph submodules of the permutation $\mathbb{F}G$-module $\mathbb{F}\Omega$ are defined to be $U'_{c_1}$ and $U'_{c_2}$ where $c_1$ and $c_2$ are the roots of the quadratic equation:

\begin{equation}
(x^2 + (r - s)x + s - a = 0.
\end{equation}

Setting $S(\mathbb{F}\Omega) = \{\sum_{\omega \in \Omega} a_{\omega} \mid a_{\omega} \in \mathbb{F}, \sum a_{\omega} = 0\}$ and $T(\mathbb{F}\Omega) = \{c[\Omega] \mid c \in \mathbb{F}\}$. $S(\mathbb{F}\Omega)$ and $T(\mathbb{F}\Omega)$ are $\mathbb{F}G$-submodules of $\mathbb{F}\Omega$ of dimensions $|\Omega| - 1, 1$, respectively. Moreover, $T(\mathbb{F}\Omega)$ is isomorphic to the one-dimensional trivial module.

Suppose that two graph submodules are different, i.e., $c_1 \neq c_2$. Since $v_{c_1,\alpha} - v_{c_2,\alpha} = (c_1 - c_2)\alpha$ for any $\alpha \in \Omega$, we have

\begin{equation}
U'_{c_1} \oplus U'_{c_2} = S(\mathbb{F}\Omega).
\end{equation}

The modules $U'_{c_1}$ and $U'_{c_2}$ are the eigenspaces of the linear transformation $T : \mathbb{F}\Omega \rightarrow \mathbb{F}\Omega$ defined by $T(\alpha) = [\Delta(\alpha)], \alpha \in \Omega$ corresponding to eigenvalues $-c_2$ and $-c_1$, respectively (see [2]). As $T$ has trace 0 with $T(\mathbb{F}\Omega)$ an eigenspace for the eigenvalue $a$, we can compute the dimensions of graph submodules from the following equations:

\begin{equation}
\dim U'_{c_1} + \dim U'_{c_2} = |\Omega| - 1, \\
c_2 \dim U'_{c_1} + c_1 \dim U'_{c_2} = a.
\end{equation}

We note that $\mathbb{F}\Omega$ has a nonsingular and $G$-invariant inner product defined by $\langle \sum_{\omega \in \Omega} a_{\omega} \omega, \sum_{\omega \in \Omega} b_{\omega} \omega \rangle = \sum_{\omega \in \Omega} a_{\omega} b_{\omega}$. If $U$ is a submodule of $\mathbb{F}\Omega$, we denote by $U^\perp$ the submodule of $\mathbb{F}\Omega$ consisting of all elements orthogonal to $U$. We need the following result, which is due to Liebeck and is stated as Lemma 2.1 in [2].

**Lemma 2.1 ([2]).** If $c$ is not a root of equation (2.1) then $U'_c = S(\mathbb{F}\Omega)$. Moreover, if $c_1$ and $c_2$ are roots of this equation then $\langle v_{c_1,\alpha}, v_{c_2,\beta} \rangle = s$ for any $\alpha, \beta \in \Omega$. Consequently, $\langle U'_{c_1}, U'_{c_2} \rangle = \langle U'_{c_2}, U'_{c_1} \rangle = 0$.

2.2. **Outline of the proof.** We first compute the roots of equation (2.1) and then determine the graph submodules of $\mathbb{F}P^+$ and $\mathbb{F}P^-$ by analyzing the geometry of $P$. As in the study of rank 3 permutation modules in cross-characteristic for finite classical group acting on singular points in [9, 10], the graph submodules are “minimal” in an appropriate sense (see Proposition 3.1).

The problem now is divided in two cases. In the easy case when the graph submodules are different, we have seen from (2.2) that their direct sum is $S(\mathbb{F}P^\kappa)$ ($\kappa = \pm 1$), a submodule of $\mathbb{F}P^\kappa$ of codimension 1. Therefore the full structure of $\mathbb{F}P = \mathbb{F}P^+ \oplus \mathbb{F}P^-$ can be determined without significant effort.

The difficult case is when the graph submodules are the same (i.e. $c_1 = c_2$). We will see later that the graph submodules of $\mathbb{F}P^+$ are equal if and only if those of $\mathbb{F}P^-$ as well as $\mathbb{F}P^0$ are equal and this happens when $\ell = \text{char}(\mathbb{F}) = 2$. We handle this case by constructing some relations between $\mathbb{F}P^0, \mathbb{F}P^+, \mathbb{F}P^-$ in [4].

"
2.3. Further notation. Given a finite group $G$, $\text{Irr}(G)$ and $\text{IBr}(G)$ will be the sets of irreducible complex characters and irreducible $\ell$-Brauer characters, respectively, of $G$. For $\chi \in \text{Irr}(G)$, by $\overline{\chi}$ we always mean its reduction modulo 2. Following [11], we denote by $\beta(M)$ the Brauer character of $G$ afforded by an $\mathbb{F}G$-module $M$. Furthermore, if $\beta(M) \in \text{IBr}(G)$ is a constituent of an $\ell$-Brauer character $\varphi$, we say that $M$ is a constituent of $\varphi$. Finally, if $H$ is a subgroup of $G$, we denote by $M|_H$ the restriction of $M$ to $H$.

3. Minimality of the graph submodules of $\mathbb{F}P^{+1}$ and $\mathbb{F}P^{-1}$

First we fix a basis $\mathcal{B}$ of $V$. If $Q$ is a quadratic form of type $+$ on $V$ with dimension $2n$, we consider $\mathcal{B} = \{e_1, ..., e_n, f_1, ..., f_n\}$ so that $(e_i, f_j) = \delta_{ij}$ and $(e_i, e_j) = (f_i, f_j) = 0$ for $i, j = 1, ..., n$. If $Q$ is of type $-$ on $V$ with dimension $2n$, then $\mathcal{B} = \{e_1, ..., e_n, f_1, ..., f_n\}$ where $(e_i, f_j) = \delta_{ij}$ and $(e_i, e_j) = (f_i, f_j) = 0$ for $i, j = 1, ..., n - 1$, $(e_i, f_n) = 0$, and $(e_n, e_n) = (f_n, f_n) = 1$. Finally, if $\dim V = 2n + 1$, then $\mathcal{B} = \{e_1, ..., e_n, f_1, ..., f_n, g\}$ where $(e_i, f_j) = \delta_{ij}$, $(e_i, e_j) = (f_i, f_j) = (e_i, g) = (f_i, g) = 0$, and $(g, g) = 1$ for $i, j = 1, ..., n$.

Going back to the action of $G$ on $P^\kappa$, $\kappa = \pm 1$, we assume from now on that $\Delta(\alpha) \subset P^\kappa \setminus \alpha$ consists of points orthogonal to $\alpha$ and $\Phi(\alpha) \subset P^\kappa \setminus \alpha$ consists of points not orthogonal to $\alpha$. Also, we use the notation $U^\kappa_c$ and $U^{\kappa'}_c$ for $U_c$ and $U'_c$, respectively. The graph submodules of $\mathbb{F}P^\kappa$ now are $U^\kappa_c$ and $U^{\kappa'}_c$ where $c_1$ and $c_2$ are roots of the equation $[2.1]$. At this point we understand that $c_1$ and $c_2$ depend on $\kappa$ but actually they do not, as we will see later on.

As in the study of rank 3 permutation modules in cross-characteristic for finite classical group acting on singular points in [9, 10], the graph submodules are “minimal” in the following sense:

**Proposition 3.1.** Suppose that $\text{char}(\mathbb{F}) \neq 3$. Then every nonzero $\mathbb{F}G$-submodule of $\mathbb{F}P^\kappa(\kappa = \pm 1)$ either is $T(\mathbb{F}P^\kappa)$ or contains a graph submodule.

**Proof.** We only give here the proof for the case $G = O^+_2(3)$ and $\kappa = +1$. Other cases are similar. We partly follow some ideas and notation from [2, 9, 10].

Let $\phi_1 := \langle e_2 + f_2 \rangle$, $\phi_2 := \langle e_1 + e_2 + f_2 \rangle$, and $\phi_3 := \langle -e_1 + e_2 + f_2 \rangle$. Let $\Delta_1 := \{\langle \sum_{i=1}^n (a_i e_i + b_i f_i) \rangle \in P^{+1} \mid b_1 = 1, a_2 + b_2 = 0\}$, $\Delta_2 := \{\langle \sum_{i=1}^n (a_i e_i + b_i f_i) \rangle \in P^{+1} \mid b_1 = 1, a_2 + b_2 = -1\}$, $\Delta_3 := \{\langle \sum_{i=1}^n (a_i e_i + b_i f_i) \rangle \in P^{+1} \mid b_1 = a_2 + b_2 = 1\}$, $\Delta := \Delta_1 \cup \Delta_2 \cup \Delta_3$, and $\Phi := P^{+1} \setminus \Delta$. It is clear that, for $i, j = 1, 2, 3$,

$$[\Delta(\phi_i)] - [\Delta(\phi_j)] = [\Delta_i] - [\Delta_j].$$

Consider a subgroup $H < G$ consisting of orthogonal transformations sending elements of the basis $\{e_1, f_1, e_2, f_2, ..., e_n, f_n\}$ to those of basis $\{e_1, f_1 + \sum_{i=1}^n a_i e_i + \sum_{i=2}^n b_i f_i, e_2 - b_2 e_1, f_2 - a_2 e_1, ..., e_n - b_n e_1, f_n - a_n e_1\}$ respectively, where $a_i, b_i \in \mathbb{F}_3$ and $-a_1 = \sum_{i=2}^n a_i b_i$. In other words, $H$ is subgroup of isometries fixing $\langle e_1 \rangle$ and acting trivially on each factor of the series $0 \leq \langle e_1 \rangle \leq \langle e_1 \rangle^+ \leq V$. Let $K$ be the subgroup
of $H$ consisting of transformations fixing $\phi_1$. Let $P_1^{+1}$ be the set of plus points in $V_1 = \langle e_2, f_2, \ldots, e_n, f_n \rangle$. For each $\langle w \rangle \in P_1^{+1}$, define $B_{\langle w \rangle} = \{ \langle w \rangle, \langle e_1 + w \rangle, \langle -e_1 + w \rangle \}$. As in Propositions 2.1 and 2.2 of [9] and Lemmas 3.2 and 3.3 of [2], we have

(i) $|H| = 3^{2n-2}$, $|K| = 3^{2n-3}$, $|\Delta| = |\Delta_1| = |\Delta_2| = |\Delta_3| = 3^{2n-3}$;
(ii) $H$ acts regularly on $\Delta$ and $K$ has 3 orbits $\Delta_1, \Delta_2, \Delta_3$ on $\Delta$;
(iii) $\Phi = \bigcup_{\langle w \rangle \in P_1^{+1}} B_{\langle w \rangle}$;
(iv) $K$ fixes $B_{\phi_1}$ point-wise and is transitive on $B_w$ for every $\phi_1 \neq \langle w \rangle \in P_1^{+1}$;
(v) $H$ acts transitively on $B_w$ for every $\langle w \rangle \in P_1^{+1}$.

Suppose that $U$ is a nonzero submodule of $\mathbb{F}P^+$. Assume $U \neq T(\mathbb{F}P^+)$, so that $U$ contains an element of the form

$$u = a(x) + b(y) + \sum_{\delta \in P_1^{+1} \setminus \{(x), (y)\}} a_\delta \delta,$$

where $a, b, a_\delta \in \mathbb{F}$ and $a \neq b$. If $(x, y) = 0$, we choose an element $\langle z \rangle \in P_1^{+1}$ so that $(x, z)$ and $(y, z)$ are nonzero. Since $a \neq b$, the coefficient of $\langle z \rangle$ in $u$ is different from either $a$ or $b$. Therefore, with no loss, we may assume $(x, y) \neq 0$. Since $(e_2 + f_2, e_1 + e_2 + f_2) \neq 0$, there exists $g' \in G$ such that $\langle x \rangle g' = \phi_1$ and $\langle y \rangle g' = \phi_2$. Therefore, we can assume that $u = a\phi_1 + b\phi_2 + \sum_{\delta \in P_1^{+1} \setminus \{(\phi_1, \phi_2)\}} a_\delta \delta$.

Let $g \in G$ such that $e_1 g = e_1$ and $(e_2 + f_2) g = -(e_1 + e_2 + f_2)$. Then $\phi_1 g = \phi_2$, $\phi_2 g = \phi_1$, $\phi_3 g = \phi_3$, and therefore

$$u - ug = (a - b)(\phi_1 - \phi_2) + \sum_{\delta \in P_1^{+1} \setminus \{(\phi_1, \phi_2)\}} b_{\delta} \delta \in U \cap S(\mathbb{F}P^+),$$

where $b_\delta \in \mathbb{F}$. Note that $u - ug \in S(\mathbb{F}P^+)$. Therefore, if $c_\delta = b_\delta/(a - b)$, we get

$$u_1 := (u - ug)/(a - b) = \phi_1 - \phi_2 + \sum_{\delta \in P_1^{+1} \setminus \{(\phi_1, \phi_2, \phi_3)\}} c_\delta \delta \in U \cap S(\mathbb{F}P^+).$$

Hence we have $u_2 := \sum_{k \in K} u_1 k \in U \cap S(\mathbb{F}P^+)$. Moreover,

$$u_2 = 3^{2n-3}(\phi_1 - \phi_2) + \sum_{\delta \in \Delta} d_\delta \delta + \sum_{\langle w \rangle \in P_1^{+1}, \langle w \rangle \neq \phi_1} d_{\langle w \rangle} [B_{\langle w \rangle}],$$

where $d_\delta, d_{\langle w \rangle} \in \mathbb{F}$. Therefore $u_3 := \sum_{h \in H} u_2 h \in U \cap S(\mathbb{F}P^+)$ with

$$u_3 = \left( \sum_{\delta \in \Delta} d_\delta \right) [\Delta] + 3^{2n-2} \sum_{\langle w \rangle \in P_1^{+1}, \langle w \rangle \neq \phi_1} d_{\langle w \rangle} [B_{\langle w \rangle}].$$

It follows that

$$u_4 := 3^{2n-2}u_2 - u_3 = 3^{2n-5}(\phi_1 - \phi_2) + \sum_{\delta \in \Delta} f_\delta \delta \in U \cap S(\mathbb{F}P^+),$$

where $f_\delta \in \mathbb{F}$. Therefore $u_5 := \sum_{k \in K} u_4 k \in U \cap S(\mathbb{F}P^+)$. Moreover,
where \( f_3 = 3^{2n-2}d_3 - \sum_{\delta \in \Delta} d_\delta \). Hence
\[
u_5 := \sum_{k \in K} u_k k = 3^{6n-8}(\phi - \phi_2) + f[\Delta_1] + f'[\Delta_2] + f''[\Delta_3] \in U \cap S(\mathbb{F}P^1),
\]
where \( f, f', f'' \in \mathbb{F} \). In particular, \( f + f' + f'' = 0 \).

**Case 1:** \( f + f' = -f'' = 0 \). Then \( u_5 = 3^{6n-8}(\phi - \phi_2) + f[\Delta_1] + f'[\Delta_2] = 3^{6n-8}(\phi - \phi_2) + f([\Delta_1] - [\Delta_2]) = 3^{6n-8}(\phi - \phi_2) + f([\Delta(\phi_1)] - [\Delta(\phi_2)]) \in U \) by (3.4).

Assume that \( f = 0 \). Then \( u_5 = 3^{6n-8}(\phi_1 - \phi_2) \in U \). It follows that \( \phi_1 - \phi_2 \in U \). Hence \( \alpha - \beta \in U \) for every \( \alpha, \beta \in P^{+1} \) and therefore \( U \supseteq S(\mathbb{F}P^1) \), which implies that \( U \) contains a graph submodule.

It remains to consider \( f \neq 0 \). Then we have \( (3^{6n-8}/f)(\phi - \phi_2) + [\Delta(\phi_1)] - [\Delta(\phi_2)] \in U \). It follows that \( (3^{6n-8}/f)(\alpha - \beta) + [\Delta(\alpha)] - [\Delta(\beta)] \in U \) for every \( \alpha, \beta \in P^{+1} \) and hence \( U \supseteq U'_{3^{6n-8}/f} \), which implies that \( U \) contains a graph submodule by Lemma 2.1.

**Case 2:** \( f + f' \neq 0 \). Define an element \( g \in G \) which sends elements of the basis \( \{e_1, f_1, e_2, f_2, \ldots, e_n, f_n\} \) to those of basis \( \{e_1, f_1 - f_2, -e_1, -f_2, e_3, f_3, \ldots, e_n, f_n\} \) respectively. It is easy to check that \( \phi_1 g = \phi_2, \phi_2 g = \phi_1 \), and \( \phi_3 g = \phi_3 \). Also, \( \Delta_1 g = \Delta_2, \Delta_2 g = \Delta_1 \), and \( \Delta_3 g = \Delta_3 \). So we have
\[
u_6 := u_5 - u_5 g = 2 \cdot 3^{6n-8}(\phi - \phi_2) + (f + f')(\Delta[\Delta_1] - \Delta_2) \in U.
\]

As above, we obtain \( U \supseteq U'_{2 \cdot 3^{6n-8}/(f + f')} \), which again implies that \( U \) contains a graph submodule, as desired.

We will see later for \( \ell = 2 \) that \( c_1 = c_2 \) and hence \( \mathbb{F}P^\kappa \) has a unique graph submodule. In this case we set \( \mathcal{U}_1 := \mathcal{U}_{1,\kappa} \) and \( \mathcal{U}'_1 := \mathcal{U}'_{1,\kappa} \). The following lemma is an important property of the graph submodule and is useful in determining the modulo 2 structure of the permutation module.

**Lemma 3.2.** For \( \ell = 2 \) and \( \kappa = \pm 1 \),

(i) \( \mathcal{U}^\kappa = T(\mathbb{F}P^\kappa) \oplus \mathcal{U}^\kappa \). In particular, by Proposition 3.1, \( \mathcal{U}'_1 \) is simple and \( \mathcal{U}^\kappa \) is the socle of \( \mathbb{F}P^\kappa \).

(ii) \( \mathcal{U}^\kappa \) and \( \mathcal{U}'_1 \) are self-dual. Furthermore, \( \mathcal{U}^\kappa \) appears at least twice as a composition factor of \( \mathbb{F}P^\kappa \).

**Proof.** (i) If \( G = O_{2\kappa}(3) \) and \( \kappa = -1 \), let \( S \subset P^\kappa \) be the set of points of the form \( \langle e_n + v \rangle \) where \( v \in \langle e_1, \ldots, e_{n-1} \rangle \). In all other cases, let \( S \subset P^\kappa \) be the set of points of the form \( \langle e_n + \kappa f_n + v \rangle \) where \( v \in \langle e_1, \ldots, e_{n-1} \rangle \). We then have
\[
\sum_{\alpha \in S} v_{1,\alpha} = \sum_{\alpha \in S} (\alpha + [\Delta(\alpha)]) = \sum_{\alpha \in S} \alpha + 3^{\beta} \sum_{\beta \in \pi(P \cap S)} \beta = [P^\kappa],
\]
where \( i(\beta) = n - 2 \) or \( n - 1 \). Hence \( [P^\kappa] \in \mathcal{U}^\kappa \) or equivalently \( T(\mathbb{F}P^\kappa) \subset \mathcal{U}^\kappa \). As \( |S| = 3^{n-1} - 1 \neq 0 \) in \( \mathbb{F} \), \( T(\mathbb{F}P^\kappa) \not\subset \mathcal{U}^\kappa \). Since \( \mathcal{U}'_1 \) is a submodule of \( \mathcal{U}^\kappa \) of codimension at most 1, \( \mathcal{U}^\kappa = T(\mathbb{F}P^\kappa) \oplus \mathcal{U}'_1 \). This and Proposition 3.1 show that \( \mathcal{U}'_1 \) is simple and \( \mathcal{U}^\kappa \) is the socle of \( \mathbb{F}P^\kappa \).
Lemma 4.2. Also, \( P^\kappa \) is self-dual. It then follows that \( U^\kappa \) is also self-dual by (i). Therefore \( \mathbb{F}P^\kappa / U^\kappa \cong \text{Hom}_F(U^\kappa, \mathbb{F}) \cong U^\kappa \). Combining this with the inclusion \( U^\kappa \subseteq U^\kappa \) (by Lemma 2.1), we have that \( U^\kappa \) appears at least twice as a composition factor of \( \mathbb{F}P^\kappa \). \( \square \)

4. Relations between \( \mathbb{F}P^0, \mathbb{F}P^1 \) and \( \mathbb{F}P^{-1} \)

In this section, we establish some relations between the structures of \( \mathbb{F}P^0, \mathbb{F}P^1 \) and \( \mathbb{F}P^{-1} \). This helps us to understand \( \mathbb{F}P^1 \) and \( \mathbb{F}P^{-1} \) from the known results of \( \mathbb{F}P^0 \) in \([10, 11]\).

For \( i, j \in \{0, +1, -1\} \), define

\[
Q_{i,j} : \mathbb{F}P^i \to \mathbb{F}P^j, \quad \alpha \mapsto \{\beta \in P^j \mid \beta \perp \alpha\}.
\]

It is obvious that \( Q_{i,j} \) is an \( \mathbb{F}G \)-homomorphism. Also, \( Q_{i,j}(S(\mathbb{F}P^i)) \subseteq S(\mathbb{F}P^j) \). The following lemma is easy to check.

**Lemma 4.1.** \( \text{Im}(Q_{i,j}) \) and \( \text{Im}(Q_{i,j}|_{S(\mathbb{F}P^i)}) \) are nonzero and different from \( T(\mathbb{F}P^j) \). Also, \( \mathbb{F}P^i / \text{Ker}(Q_{i,j}) \cong \text{Im}(Q_{i,j}) \) and \( S(\mathbb{F}P^i)/\text{Ker}(Q_{i,j}|_{S(\mathbb{F}P^i)}) \cong \text{Im}(Q_{i,j}|_{S(\mathbb{F}P^i)}) \). \( \square \)

Let \( \rho^0, \rho^1, \) and \( \rho^{-1} \) be the complex permutation characters of \( G \) afforded by permutation modules \( \mathbb{C}P^0, \mathbb{C}P^1, \) and \( \mathbb{C}P^{-1} \), respectively. Recall that \( G \) acts with rank 3 on each \( P^i \) with \( i = 0, +1, -1 \). Hence \( \rho^i \) has 3 constituents, all of multiplicity 1 and exactly one of them is the trivial character.

**Lemma 4.2.** For \( i, j \in \{0, +1, -1\} \), \( \rho^i \) and \( \rho^j \) have a common nontrivial constituent.

**Proof.** This is an immediate consequence of Lemma 4.1. \( \square \)

5. The orthogonal groups \( O^+_m(3) \)

In this section, we always assume \( G = O^+_m(3) \). For \( \kappa = \pm 1 \), we have \( P^\kappa = \left\{ (\sum_{i=1}^{n}(a_i e_i + b_i f_i)) \mid a_i, b_i \in \mathbb{F}_3, \sum_{i=1}^{n} a_i b_i = \kappa \right\} \) and \( |P^\kappa| = 3^{n-1}(3^n - 1)/2 \). The parameters of the action of \( G \) on \( P^\kappa \) are:

\[
a = \frac{3^{n-1}(3^{n-1} - 1)}{2}, \quad b = 3^{2n-2} - 1, \quad r = \frac{3^{n-2}(3^{n-1} + 1)}{2}, \quad s = \frac{3^{n-1}(3^{n-2} - 1)}{2}.
\]

The equation (2.1) now has two roots \( 3^{n-2} \) and \( -3^{n-1} \). Therefore, \( \mathbb{F}P^\kappa \) has graph submodules \( U^\kappa_{3n-2} \) and \( U^\kappa_{3n-1} \).

We note that if \( \ell = \text{char}(\mathbb{F}) \neq 2, 3 \) then \( 3^{n-2} \neq -3^{n-1} \) and therefore two graph submodules are different.
Lemma 5.1. If $\ell = \text{char}(\mathbb{F}) \neq 2, 3$, then
\[
\dim U_{3n-2}^\kappa = \frac{(3^n - 1)(3^{n-1} - 1)}{8}, \quad \dim U_{3n-1}^\kappa = \frac{3^{2n} - 9}{8} \quad \text{and} \quad U_{3n-1}^\kappa \cong U_{-3n-1}^-.
\]

Proof. The dimensions of $U_{3n-2}^\kappa$ and $U_{3n-1}^\kappa$ follow from (2.3). Using results about the permutation module for $G$ acting on $P^0$ in [10], we see that $FP^0$ has two graph submodules of dimensions $(3^n - 1)(3^{n-1} + 3)/8$ and $(3^{2n} - 9)/8$, which we temporarily denote by $U_c'$ and $U_d'$, respectively. By Theorem 2.1 of [10], $U_c'$ and $U_d'$ are minimal in the same sense as in Proposition 3.1. Applying Lemma 4.1 and Proposition 3.1, we deduce that $U_{3n-1}^\kappa \cong U_d'$ and $U_{3n-1}^- \cong U_d'$ and the lemma follows. □

Proposition 5.2. Theorem 1.3 holds when $G = O^+_{2n}(3), n \geq 3$ and $\ell \neq 2, 3$.

Proof. First, consider $\ell \nmid (3^n - 1)$. Then $[P^\kappa] \not\in S(FP^\kappa)$ and we have
\[
FP \cong FP^1 \oplus FP^{-1} = T(FP^1) \oplus S(FP^1) \oplus T(FP^{-1}) \oplus S(FP^{-1}) \cong T(FP^1) \oplus U_{3n-2}^\kappa \oplus U_{3n-1}^\kappa \oplus T(FP^{-1}) \oplus U_{3n-2}^\kappa \oplus U_{3n-1}^-,
\]
where $X := U_{3n-2}^\kappa$, $Y := U_{3n-2}^\kappa$, and $Z := U_{3n-1}^- \cong U_{3n-1}^\kappa$ (Lemma 5.1). The modules $X, Y,$ and $Z$ are simple by Proposition 3.1.

Next we consider $\ell \mid (3^n - 1)$. It is easy to see that $T(FP^\kappa)$ is contained in $U_{3n-1}^\kappa$ but not in $U_{3n-2}^\kappa$. We then have $FP^\kappa = U_{3n-2}^\kappa \oplus U_{3n-1}^\kappa$, where $U_{3n-2}^\kappa$ is simple and $U_{3n-1}^\kappa$ is uniserial (by Proposition 3.1) with composition series
\[
0 \subset T(FP^\kappa) \subset U_{3n-1}^\kappa \subset U_{3n-1}^\kappa.
\]
Putting $X := U_{3n-2}^\kappa$, $Y := U_{3n-2}^\kappa$, and $Z := U_{3n-1}^\kappa / T(FP^\kappa)$, we get
\[
FP \cong X \oplus Y \oplus 2(F - Z - \mathbb{F}),
\]
as described in Table[1] □

For the rest of this section, we consider the case $\ell = \text{char}(\mathbb{F}) = 2$, where the two graph submodules are the same. We write $U^\kappa := U_1^\kappa = U_{3n-2}^\kappa = U_{3n-1}^\kappa$ and $U_1^\kappa := U_{3n-2}^\kappa = U_{3n-1}^\kappa$.

Proposition 5.3. Theorem 1.3 holds when $G = O^+_{2n}(3), n \geq 3$ and $\ell = 2$.

Proof. Recall that, for $i = 0, \pm 1$, $\rho^i$ is the permutation character of $G$ afforded by $\mathbb{C}P^i$. Since $G$ acts with rank $3$ on each $P^i$, we have $\rho^i = 1 + \varphi^i + \psi^i$, where $\varphi^i, \psi^i \in \text{Irr}(G)$ and the $\psi^i$s have the same degree $(3^{2n} - 9)/3$ by Lemma 5.1. Recall that $\varphi = \psi^{-1} = (3^n - 1)(3^{n-1} - 1)/8$ from Lemma 5.1. Since the smallest degree of a nonlinear irreducible 2-Brauer characters of $G$ is $(3^n - 1)(3^{n-1} - 1)/8$ (see Theorem 1 of [4]), $\varphi^i$ and $\varphi^{-1}$ must be irreducible.
First we give the proof for \( n \) odd. From the study of \( \overline{\rho}^\kappa \) in Corollary 6.5 of \([\text{III}]\), we have \( \overline{\psi} = \beta(W) + \beta(X) + \beta(Y) \), where \( W, X, \) and \( Y \) are simple \( G \)-modules of dimensions \((3^n-1)(3^{n-1}+3)/8-2, (3^n-1)(3^{n-1}-1)/8, \) and \((3^n-1)(3^{n-1}-1)/8\), respectively. Furthermore, \( X \) and \( Y \) are not isomorphic. Now using Proposition 3.2(ii) together with the conclusion of the previous paragraph, we deduce that \( U'\kappa \) is isomorphic to either \( X \) or \( Y \) and \( \overline{\varphi}^\kappa = \beta(U'^\kappa) \).

Let \( U' + 1 \cong X \). We wish to show that \( U'-1 \cong Y \). Assuming the contrary, we then have \( U' + 1 \cong U' - 1 \cong X \) and therefore \( \overline{\varphi}^{+1} = \overline{\varphi}^{-1} \). Now we temporarily add subscript \( n \) to the standard notations. Then \( \overline{\varphi}^{+1} = \overline{\varphi}^{-1} \) and hence \( \overline{\rho}^{+1}_n = \overline{\rho}^{-1}_n \). Since \( \mathbb{F}P^\kappa_n \cong 5\mathbb{F}P^\kappa_{n-1} \oplus 2\mathbb{F}P^\kappa_{n-1} \oplus 2\mathbb{F}P^\kappa_{n-1} \oplus 2\mathbb{F} \) as \( \mathbb{F}G_{n-1} \)-modules, it follows that \( \overline{\rho}^{+1}_n = \overline{\rho}^{-1}_n \).

By downward induction, we get \( \overline{\varphi}^{1} = \overline{\varphi}^{-1} \), which is a contradiction by checking the complex and 2-Brauer character tables of \( O_n^+ \)(3) (see \([\text{III}]\)).

We have shown that \( U' + 1 \cong X \) and \( U' - 1 \cong Y \). Notice that, for \( \kappa = \pm 1 \), \( |P^\kappa| \neq 0 \) (in \( \mathbb{F} \)) and hence \( \mathbb{F}P^\kappa = T(\mathbb{F}P^\kappa) \oplus S(\mathbb{F}P^\kappa) \) and the composition factors of \( S(\mathbb{F}P^\kappa) \) are \( X \) (twice), \( Y \), and \( W \). By Proposition 3.4 and the self-duality of \( S(\mathbb{F}P^\kappa) \), the socle series of \( S(\mathbb{F}P^+1) \) and \( S(\mathbb{F}P^-1) \) are \( X - (Y \oplus W) - X \) and \( Y - (X \oplus W) - Y \), respectively, as described in Table 1.

Now we consider \( n \) even. In this case, \( \overline{\psi} = 1 + \beta(W) + \beta(X) + \beta(Y) \), where \( W, X, \) and \( Y \) are simple \( G \)-modules of dimensions \((3^n-1)(3^{n-1}+3)/8-2, (3^n-1)(3^{n-1}-1)/8, \) and \((3^n-1)(3^{n-1}-1)/8\), respectively. Repeating the above arguments, we see that \( U' + 1 \cong X \) and \( U' - 1 \cong Y \).

Notice that \( T(\mathbb{F}P^\kappa) \subset S(\mathbb{F}P^\kappa), T(\mathbb{F}P^\kappa) = S(\mathbb{F}P^{+1}), \) and \( S(\mathbb{F}P^\kappa)/T(\mathbb{F}P^{+1}) \) is self-dual and has composition factors: \( X \) (twice), \( Y \), and \( W \). Again, Proposition 3.4 gives the socle series of \( S(\mathbb{F}P^{+1})/T(\mathbb{F}P^{+1}) \): \( X - (W \oplus Y) - X \). The submodule structure of \( \mathbb{F}P^{+1} \) will be completely determined if we know that of \( U'^{+1}/U' \). Note that \( U'^{+1}/U' \) has composition factors: \( \mathbb{F} \) (twice), \( W \), and \( Y \). Using Lemma 4.1 and inspecting the structure of \( \mathbb{F}P^0 \), we see that \( Y \) must be a submodule of \( U'^{+1}/U' \) but \( W \) is not. Therefore, the structure of \( U'^{+1}/U' \) is \( Y \oplus (\mathbb{F} - W - \mathbb{F}) \).

Similarly, the structure of \( S(\mathbb{F}P^-1)/T(\mathbb{F}P^-1) \) is \( Y - (W \oplus X) - Y \) and that of \( U'^{-1}/U' \) is \( X \oplus (\mathbb{F} - W - \mathbb{F}) \). Now \( \mathbb{F}P \) is determined completely as described in Table 1.

Propositions 5.2 and 5.3 complete the proof of Theorem 1.2 for the type “+” orthogonal groups in even dimension.

6. The orthogonal groups \( O_{2n}^- (3) \)

In this section, we always assume \( G = O_{2n}^- (3) \). For \( \kappa = \pm 1 \), we have \( \overline{\rho}^\kappa = \{ (\sum_{i=1}^n (a_i e_i + b_i f_i)) \mid \sum_{i=1}^{n-1} a_i b_i - a_n^2 - b_n^2 = \kappa, a_i, b_i \in \mathbb{F}_3 \} \) and \( |P^\kappa| = 3^{n-1}(3^n + 1)/2 \).
The parameters of the action of $G$ on $P^\kappa$ are:

$$a = \frac{3^{n-1}(3^{n-1} + 1)}{2}, b = 3^{2n-2} - 1, r = \frac{3^{n-2}(3^{n-1} - 1)}{2}, s = \frac{3^{n-1}(3^{n-2} + 1)}{2}.$$ 

The equation (2.1) now has two roots $-3^{n-2}$ and $3^{n-1}$. Therefore, $\mathbb{F}P^\kappa$ has graph submodules $U_{3^{n-2}}^\kappa$ and $U_{3^{n-1}}^\kappa$.

**Lemma 6.1.** If $\ell = \text{char}(\mathbb{F}) \neq 2, 3$, then

$$\dim U_{3^{n-2}}^\kappa = \frac{(3^n + 1)(3^{n-1} + 1)}{8}, \dim U_{3^{n-1}}^\kappa = \frac{3^{2n} - 9}{8} \text{ and } U_{3^{n-1}}^\kappa \cong U_{3^{n-1}}^{-1}.$$ 

**Proof.** As in the proof of Lemma 5.1 \qed

**Proposition 6.2.** Theorem 1.2 holds when $G = O_{2n}^-(3), n \geq 3$ and $\ell \neq 2, 3$.

**Proof.** First we consider $\ell \nmid (3^n + 1)$. As in §3, $\mathbb{F}P \cong 2\mathbb{F} \oplus X \oplus Y \oplus 2Z$, where $X := U_{3^{n-2}}^{1+}, Y := U_{3^{n-2}}^{-1}, Z := U_{3^{n-1}}^{1+} \cong U_{3^{n-1}}^{-1}$ and $X, Y, Z$ are simple by Proposition 3.1.

Second we consider $\ell \mid (3^n + 1)$. We have $\mathbb{F}P^\kappa = U_{3^{n-2}}^{\kappa+} \oplus U_{3^{n-1}}^\kappa$, where $U_{3^{n-2}}^\kappa$ is simple and $U_{3^{n-1}}^\kappa$ is uniserial with composition series $0 \subset T(\mathbb{F}P^\kappa) \subset U_{3^{n-1}}^\kappa \subset U_{3^{n-1}}^\kappa$. Putting $X := U_{3^{n-2}}^{1+}, Y := U_{3^{n-2}}^{-1}$, and $Z := U_{3^{n-1}}^\kappa / T(\mathbb{F}P^\kappa)$, we obtain $\mathbb{F}P \cong X \oplus Y \oplus 2(\mathbb{F} - Z - \mathbb{F})$, as stated. \qed

For the rest of this section, we consider the case $\ell = 2$. As in §5 we have $\rho^i = 1 + \varphi^i + \psi$ for $i = 0, \pm 1, \varphi^i, \psi \in \text{Irr}(G)$, $\psi(1) = (3^{2n} - 9)/3$, and $\varphi^1(1) = \varphi^{-1}(1) = (3^{n+1}(3^{n-1} + 1)/8$. From Corollary 8.10 of [11], $\overline{\psi} = 1 + \beta(W) + \beta(X) + \beta(Y)$ when $n$ is even and $\overline{\psi} = 1 + 1 + \beta(W) + \beta(X) + \beta(Y)$ when $n$ is odd. Here, $X, Y, \text{ and } W$ are simple $\mathbb{F}G$-modules of dimensions $(3^n + 1)(3^{n-1} + 1)/8 - 1$, $(3^n + 1)(3^{n-1} + 1)/8 - 1$, and $(3^n + 1)(3^{n-1} - 3)/8 + 1 + \delta_{2,n}$, respectively. Moreover, $X \not\cong Y$ and $W$ has smallest dimension among simple $\mathbb{F}G$-modules of dimensions greater than 1.

**Lemma 6.3.** With the above notation,

(i) For $\kappa = \pm 1$, $U^\kappa$ is isomorphic to either $X$ or $Y$ and $\overline{\varphi^\kappa} = 1 + \beta(U^\kappa)$.

(ii) If we let $U^{1+} \cong X$, then $U^{-1} \cong Y$.

**Proof.** (i) We only give here the proof for $n$ even and $\kappa = 1$. Other cases are similar.

Assume the contrary: $U^{1+}$ is not isomorphic to both $X$ and $Y$. Lemma 3.2 then implies that $U^{1+} \cong W$ and $\beta(W)$ is a constituent of $\overline{\varphi^{1+}}$. Hence all other constituents of $\overline{\varphi^{1+}}$ have degrees at most $\varphi^{1+}(1) - \dim W = (3^n + 1)/2$, which imply that they are linear since $(3^n + 1)(3^{n-1} - 3)/8 - 1 + \delta_{2,n}$ is the smallest dimension of nonlinear irreducible 2-Brauer characters of $G$.

Let $P_{1}^0, P_{1}^{1+}, \text{ and } P_{1}^{-1}$ be the sets of singular points, plus points, and minus points, respectively, in $V_1 := \langle e_1, f_1, \ldots, e_{n-1}, f_{n-1} \rangle$. Note that $V_1$ equipped with $Q$ is an
orthogonal space of type +. Let \( G_1 := O_{2n-2}(3) \leq G \). Then we obtain an \( \mathbb{F}G_1 \)-isomorphism:

\[
FP^+ \cong 2\mathbb{F} \oplus FP^+ \oplus 4FP^{-1} \oplus 4FP^0.
\]

Inspecting the structures of \( FP^0 \) in Figure 5 of \[11\] and of \( FP^+ \) as well as \( FP^- \) in Table \[1\] we see that \( FP^+ \), when considered as \( \mathbb{F}G_1 \)-module, has 15 composition factors (counting multiplicities) of dimension 1 (actually all of them are isomorphic to \( \mathbb{F} \)). This contradicts the conclusion of the previous paragraph.

We have shown that \( U^+ \) is isomorphic to either \( X \) or \( Y \). Notice from Lemma 3.2 that \( U^+ \) appears at least twice as a composition factor of \( FP^+ \). The second statement of (i) now follows by comparing the degrees and using (6.6).

(ii) Assuming the contrary that \( U^- \not\cong Y \), then \( U^+ \cong U^- \cong X \). It follows that \( \varphi^+ = \varphi^- \) and hence \( \rho^+ = \rho^- \). Therefore, the isomorphism (6.6) together with \( FP^- \cong 2\mathbb{F} \oplus FP^+ \oplus 4FP^+ \oplus 4FP^0 \) imply that the modulo 2 permutation characters afforded by \( FP^+ \) and \( FP^- \) are the same. This is a contradiction as seen in the proof of Proposition 5.3.

Since we will use an induction argument to determine the structure of \( FP \), we temporarily add the subscript \( n \) to our standard notations. Notice that \( G_2 = O_4(3) \) acts with rank 3 on both \( P^{+1}_2 \) and \( P^{-1}_2 \). Everything we have proved for \( n \geq 3 \) works exactly the same in the case \( n = 2 \) except that \( W_2 = 0 \).

**Lemma 6.4.** The structures of \( FP^+_2 \) and \( FP^-_2 \) are given as follows:

\[
\begin{align*}
FP^+_2 : & \quad X_2 \\
| & \quad F \\
F & \oplus Y_2 \\
| & \quad F \\
| & \quad X_2 \\
F & \oplus Y_2
\end{align*}
\]

\[
\begin{align*}
FP^-_2 : & \quad Y_2 \\
| & \quad F \\
F & \oplus X_2 \\
| & \quad F \\
| & \quad Y_2
\end{align*}
\]

**Proof.** By Lemma 3.2 the module \( U^\kappa \) is simple and self-dual. The module \( FP^\kappa_2 \) has dimension 15 = 3^{2-1}(3^2 + 1)/2, and by Lemma 6.3 its submodule \( U^\kappa \) has dimension 4 = (3^2 + 1)(3^{2-1} + 1)/8 - 1. Therefore by Lemmas 3.2 and 4.1 the module \( U^\kappa \) appears twice as a composition factor of \( FP^\kappa_2 \) and once as a composition factor of \( FP^-_2 \).

As 15 is odd, \( FP^\kappa_2 = T(FP^\kappa_2) \oplus S(FP^\kappa_2) \). Here \( U^\kappa \) is the unique minimal submodule of the dimension 14 module \( S(FP^\kappa_2) \), and \( M = (U^\kappa)^\perp \cap S(FP^\kappa_2) \) its unique maximal submodule. The submodule \( M \) has dimension 10 and quotient \( S(FP^\kappa_2)/M \) isomorphic to \( U^\kappa \). The quotient \( Q = M/U^\kappa \) is thus self-dual of dimension 6, possessing two trivial composition factors in addition to the factor \( U^{-\kappa} \). There are only three
possibilities:

\[ Q = \mathbb{F} - U'' - \mathbb{F} \quad \text{or} \quad Q = \mathbb{F} \oplus U'' - \mathbb{F} \oplus \mathbb{F} \quad \text{or} \quad Q = (\mathbb{F} - \mathbb{F}) \oplus U'' - \mathbb{F}. \]

The first gives the lemma, so we must eliminate the second and third.

The usual dot product on the natural \( \mathbb{F}_3 \)-permutation module for \( \text{Sym}(6) \) is an invariant bilinear form with radical spanned by the vector of 1’s. The action of \( \text{Sym}(6) \) on the unique nontrivial composition factor thus gives an injection of \( \text{Sym}(6) \) into \( O^-_4(3) \). More specifically, \( O^-_4(3) \cong 2 \times \text{Sym}(6) \). With this in mind, we can choose notation so that the module \( \mathbb{F}P^\kappa_2 \) is the usual permutation module \( M^{(4,2)} \) for \( \text{Sym}(6) \) acting on the 15 unordered pairs from a set of size six.

As the representation theory of symmetric groups is highly developed (see, for instance, the elegant treatment in James’s book [5]), the lemma is presumably well known. Indeed the needed calculations can be done easily, following Example 5.2 of [5]. We give a short proof, using only some of the elementary theory.

By an easy calculation and [5, Cor. 8.5] the Specht submodule \( S = S^{(4,2)} \) of \( \mathbb{F}P^\kappa_2 = M^{(4,2)} \) has dimension 9, so it must have codimension 1 in \( M \) with \( S/U'' \) of dimension 5 in \( Q \). Assume (for a contradiction) that \( Q = \mathbb{F} \oplus U'' - \mathbb{F} \oplus \mathbb{F} \) or \( Q = (\mathbb{F} - \mathbb{F}) \oplus U'' - \mathbb{F} \). Then \( S/U'' \) must have shape \( \mathbb{F} \oplus U'' - \mathbb{F} \). In particular, the Specht module \( S \) has two maximal submodules, one of codimension 1 and the other of codimension 4. But by [5, Theorem 4.9], Specht modules have unique maximal submodules. This contradiction proves the lemma.

Lemma 6.5. For any \( n \geq 2 \), \( \mathbb{F}P_n^{+1} \) does not have any submodule of structure \( X_n - Y_n \). Similarly, \( \mathbb{F}P_n^{-1} \) does not have any submodule of structure \( Y_n - X_n \).

Proof. Case \( n = 2 \) is clear from Lemma 6.4. So we assume that \( n \geq 3 \). Let \( Q \) be the parabolic subgroup of \( G_n \) fixing \( \langle e_1 \rangle \). Then \( Q = O.L \) where \( O = O_3(Q) \), the maximal normal 3-subgroup of \( Q \) and \( L \cong G_{n-1} \times \mathbb{Z}_2 \), a Levi subgroup of \( G_n \). Set \( V_1 := \langle e_2, \ldots, e_n, f_2, \ldots, f_n \rangle \). Let \( P_1 \) be the set of plus points in \( V \) of the form \( \langle xe_1 + u \rangle \) and \( P_2 \) the set of plus points in \( V \) of the form \( \langle f_1 + xe_1 + u \rangle \) with \( x \in \mathbb{F}_3 \) and \( u \in V_1 \). Then \( P_n^{+1} \) is the disjoint union of \( P_1 \) and \( P_2 \).

It is clear that \( |P_2| = |O| = 3^{2n-2} \) and the stabilizer of \( \langle f_1 + e_1 \rangle \) in \( O \) is trivial. Therefore \( O \) acts transitively on \( P_2 \). This \( O \)-orbit is fixed under the action of \( G_{n-1} \) on the set of \( O \)-orbits on \( P^{+1} \). For any plus point \( \langle u \rangle \) in \( V_1 \), the \( O \)-orbit of \( \langle u \rangle \) consists of three points: \( \langle u \rangle \), \( \langle u + e_1 \rangle \), and \( \langle u - e_1 \rangle \). Hence the action of \( G_{n-1} \) on the set of \( O \)-orbits in \( P_1 \) is equivalent to that on the set of plus points in \( V_1 \). We have proved the following \( \mathbb{C}G_{n-1} \)-isomorphism:

\[
(6.7) \quad C_{\mathbb{C}P^{+1}_n}(O) \cong \mathbb{C}P^{+1}_{n-1} \oplus \mathbb{C},
\]

where \( C_{\mathbb{C}P^{+1}_n}(O) \) is the centralizer of \( O \) in \( \mathbb{C}P^{+1}_n \). If \( \chi \) is the character of \( G_n \) afforded by a module \( M \), we denote by \( C_\chi(O) \) the character of \( G_{n-1} \) afforded by \( C_M(O) \). The
isomorphism (6.7) then implies
\[(6.8) \quad C_{\phi_n^{+1}}(O) + C_{\psi_n}(O) = \varphi_{n-1}^{+1} + \psi_{n-1} + 1_{G_{n-1}}.\]
From Frobenius reciprocity,
\[\langle \psi_n|Q, 1_Q \rangle_Q = \langle \psi_n, 1_Q^{G_n} \rangle_{G_n} = \langle \psi_n, \rho_n^0 \rangle_{G_n} > 0.\]
Hence, $1_Q$ is a constituent of $\psi_n|Q$. It follows that $1_{G_{n-1}}$ is a constituent of $C_{\psi_n}(O)$.
Now we will show that $\psi_{n-1}$ is also a constituent of $C_{\psi_n}(O)$. Assume not. Then $\psi_{n-1}$ would be a constituent of $C_{\varphi_n^{+1}}(O)$ by (6.8). It follows that $\psi_{n-1}$ is contained in $C_{\varphi_n^{+1}}(O)$. As $\varphi_n^{+1}$ is always contained in $\psi_n$, we find that $2\psi_{n-1}$ is contained in $C_{\varphi_n^{+1}}(O) + C_{\psi_n}(O)$. The formula (6.8) then implies that $\psi_{n-1}$ is contained in $\varphi_n^{+1} + 1$, a contradiction.

We have shown that both $1_{G_{n-1}}$ and $\psi_{n-1}$ are constituents of $C_{\psi_n}(O)$. Therefore $C_{\varphi_n^{+1}}(O) = \varphi_{n-1}^{+1}$. It follows by Lemma 6.3 that $C_{X_n}(O) \cong X_{n-1}$. Similarly, $C_{Y_n}(O) \cong Y_{n-1}$.

Now we prove the lemma by induction. Assuming that the lemma is true for $n-1$ and supposing the contrary that $\mathbb{F}P_n^{+1}$ has a submodule of structure $X_n - Y_n$. Proposition 3.1 and the previous paragraph then show that $C_{(X_n - Y_n)}(O) \cong X_{n-1} - Y_{n-1}$ is a submodule of $C_{\mathbb{F}P_n^{+1}}(O) \cong \mathbb{F}P_{n-1}^{+1} \oplus \mathbb{F}$. We deduce that $X_{n-1} - Y_{n-1}$ is a submodule of $\mathbb{F}P_{n-1}^{+1}$, contradicting the induction hypothesis. \hfill \Box

**Proposition 6.6.** Theorem 7.3 holds when $G = O_{2n}(3), n \geq 3$ and $\ell = 2$.

**Proof.** Using Proposition 3.1 and Lemma 3.2, we see that the structure of $\mathbb{F}P^{\kappa}$ will be determined if we know that of $U'^{\perp} / U'^{\perp}$. We study $U'^{+1} / U'^{+1}$ first.

Consider the case $n$ even. Then, for $\kappa = \pm 1$, $|P^{\kappa}| \neq 0$ and therefore $\mathbb{F}P^{\kappa} = T(\mathbb{F}P^{\kappa}) \oplus S(\mathbb{F}P^{\kappa})$.

From the constituents of $\varphi^{+1}$ and $\psi$, the composition factors of $U'^{+1} / U'^{+1}$ are: $\mathbb{F}$ (3 times), $Y$, and $W$. Since $\mathbb{F}P^{\kappa} = T(\mathbb{F}P^{\kappa}) \oplus S(\mathbb{F}P^{\kappa})$, we know that $U'^{+1} / U'^{+1}$ has a direct summand $\mathbb{F}$. Furthermore, $X \cong U'^{+1}$ is the socle of $S(\mathbb{F}P^{+1})$ by Proposition 3.1. Lemma 4.1 now implies that $\text{Im}(Q_{0,+1}|S(\mathbb{F}P^0)) \cong S(\mathbb{F}P^0) / \text{Ker}(Q_{0,+1}|S(\mathbb{F}P^0))$ also has socle $X$. Inspecting the structure of $\mathbb{F}P^0$ given in Figure 8 of [11], we see that the only quotient of $S(\mathbb{F}P^0)$ having $X$ as the socle is $X - W$. This means that $S(\mathbb{F}P^1)$ has submodule of structure $X - W$ and therefore $W$ is a submodule of $U'^{+1} / U'^{+1}$. By self-duality, $W$ must be a direct summand of $U'^{+1} / U'^{+1}$.

By Lemma 6.5, $Y$ is not a submodule of $U'^{+1} / U'^{+1}$. Combining this with the previous paragraph, we conclude that the structure of $U'^{+1} / U'^{+1}$ is $\mathbb{F} \oplus W \oplus (\mathbb{F} - Y - \mathbb{F})$.

Now we consider the case $n$ odd. By Lemma 4.1 $\text{Im}(Q_{0,+1})$ is nonzero and different from $T(\mathbb{F}P^{+1})$. Hence it has the socle either $X$ or $\mathbb{F} \oplus X$ by Proposition 3.1. Notice that $\text{Im}(Q_{0,+1}) \cong \mathbb{F}P^0 / \text{Ker}(Q_{0,+1})$. Inspecting the structure of $\mathbb{F}P^0$ again, we learn
that the structure of $\text{Im}(Q_{n+1})$ must be $X - F - W - F$. It follows that $U'_{+1}/U'_{+1}$ has a submodule of structure $F - W - F$. Recall that $U'_{+1}/U'_{+1}$ has composition factors: $F$ (4 times), $Y$, and $W$ and $Y$ is not its submodule by Lemma 6.5. By self-duality, the structure of $U'_{+1}/U'_{+1}$ is $(F - Y - F) \oplus (F - W - F)$.

Arguing similarly for $\kappa = -1$, the structure of $U'_{-1}/U'_{-1}$ is $F \oplus W \oplus (F - X - F)$ when $n$ even and $(F - X - F) \oplus (F - W - F)$ when $n$ odd.

Propositions 6.2 and 6.6 complete the proof of Theorem 1.2 for the type “−” orthogonal groups in even dimension.

7. The orthogonal groups $O_{2n+1}(3)$

In this section, we assume $G = O_{2n+1}(3)$. For $\kappa = \pm 1$, we have $P^\kappa = \{ (cg + \sum a_i e_i + b_i f_i) | a_i, b_i \in F, \sum a_i b_i - c^2 = \kappa \}$ and $|P^\kappa| = 3^n(3^n - \kappa)/2$. The parameters of the action of $G$ on $P^\kappa$ are:

\[
\begin{align*}
a &= \frac{3^{n-1}(3^n + \kappa)}{2}, \\
b &= (3^n + \kappa)(3^{n-1} - \kappa), \\
r &= s &= \frac{3^{n-1}(3^{n-1} + \kappa)}{2}.
\end{align*}
\]

Equation (2.1) now has two roots $-3^{n-1}$ and $3^{n-1}$. Therefore, for $\kappa = \pm 1$, $FP^\kappa$ has graph submodules $U'_{-3n-1}$ and $U'_{3n-1}$.

**Lemma 7.1.** If $\ell = \text{char}(F) \neq 2, 3$, then

\[
U'_{-3n-1} \cong U'_{3n-1}, \quad \dim U'_{-3n-1} = \dim U'_{3n-1} = \frac{3^{2n} - 1}{4},
\]

\[
\dim U'_{-3n-1} = \frac{(3^n - 1)(3^n + 3)}{4}, \quad \text{and} \quad \dim U'_{3n-1} = \frac{(3^n + 1)(3^n - 3)}{4}.
\]

**Proof.** This is similar to the proof of Lemma 5.1. We remark in this case that $U'_{-3n-1}$ and $U'_{3n-1}$ are isomorphic to graph submodules of $FP^\kappa$.

**Proposition 7.2.** Theorem 1.2 holds when $G = O_{2n+1}(3), n \geq 3$ and $\ell \neq 2, 3$.

**Proof.** Case 1: $\ell \nmid (3^n - 1), \ell \nmid (3^n + 1)$. In this case, $FP \cong 2F \oplus X \oplus Y \oplus 2Z$, where $X := U'_{3n-1}^1, Y := U'_{3n-1}^{-1}$, and $Z := U'_{3n-1}^1 \cong U'_{3n-1}^{-1}$. By Proposition 3.1, $X, Y$, and $Z$ are simple.

Case 2: $\ell | (3^n - 1)$. We have

\[
FP^{-1} = T(FP^{-1}) \oplus U'_{-3n-1} \oplus U'_{3n-1} \cong F \oplus Y \oplus Z,
\]

where $Y := U'_{-3n-1}^{-1}, Z := U'_{3n-1}^{-1} \cong U'_{3n-1}^1$ and

\[
FP^+ = U'_{3n-1}^1 \oplus U'_{-3n-1}^{-1} \cong U'_{3n-1}^1 \oplus Z,
\]

\[
\begin{align*}
\text{dim } U'_{-3n-1} &= (3^n - 1)(3^n + 3) \\
\text{dim } U'_{3n-1} &= (3^n + 1)(3^n - 3).
\end{align*}
\]
where $U_{3n-1}^+$ is uniserial with composition series $0 \subset T(\mathbb{F}P^1) \subset U_{3n-1}^{+1} \subset U_{3n-1}^+$.

Setting $X := U_{3n-1}^{+1}/T(\mathbb{F}P^1)$, we get

$$\mathbb{F}P \cong \mathbb{F} \oplus (\mathbb{F} - X - \mathbb{F}) \oplus Y \oplus 2Z.$$

**Case 3:** $\ell | (3^n + 1)$. As in Case 2,

$$\mathbb{F}P \cong \mathbb{F} \oplus X \oplus (\mathbb{F} - Y - \mathbb{F}) \oplus 2Z,$$

where $X := U_{3n-1}^{+1}$, $Y := U_{3n-1}^{-1}/T(\mathbb{F}P^1)$, and $Z := U_{3n-1}^{-1} \cong U_{3n-1}^{-1}$. \(\square\)

Now we consider the case $\ell = 2$. Following Lemma 7.3, we assume that $\rho^\circ = 1 + \varphi^\circ + \psi$ for $\kappa = \pm 1$, where $\varphi^\circ, \psi \in \text{Irr}(G)$, $\varphi^\circ(1) = (3^n + \kappa)(3^n - \kappa)/4$, and $\psi(1) = (3^{2n} - 1)/4$. Then $\rho^0 = 1 + \varphi^0 + \psi$. From Corollary 7.5 of [11], we have

$$\varphi^0 = \chi + \beta(X_1) \text{ and } \varphi^+ = 1 + \chi + \beta(Y_1),$$

where $\chi$ is a 2-Brauer character of $G$ and $X_1, Y_1$ are simple $G$-modules of dimensions $3^n - 1, 3^n - 3, 3^n + 1, 3^n + 3)/8 - 1$, respectively. Furthermore, $\chi = \beta(Z_1)$ if $n$ is odd and $\chi = 1 + \beta(Z_1)$ if $n$ is even, where $Z_1$ is a simple module of dimension $(3^{2n} - 9)/8 - 2n$. The following lemma gives the decomposition of $\psi$ into irreducible 2-Brauer characters of $G$.

**Lemma 7.3.** With the above notation, $U^+ \cong X_1$ and $U^- \cong Y_1$. Consequently, $\psi = \beta(X_1) + \beta(Y_1)$.

**Proof.** By Proposition 3.1 and Lemma 4.1, the submodule $\text{Im}(Q_{0,+1})$ of $\mathbb{F}P^1$ has $U^+$ as a composition factor. It follows that $U^+ \in \{X_1, Y_1, Z_1\}$ since $\text{Im}(Q_{0,+1}) \cong \mathbb{F}P^0/\text{Ker}(Q_{0,+1})$ and the composition factors of $\mathbb{F}P^0$ are: $\mathbb{F}$ (twice or four times), $X_1$, $Y_1$, and $Z_1$ (twice) (see Figure 6 of [11]).

Set $G_1 := O_{2n}^+(3) \leq G$. Let $P_1^+$ and $P_1^-$ be the sets of plus points and minus points in $\langle e_1, \ldots, e_n, f_1, \ldots, f_n \rangle$. Since $P_1^+ = P_1^+ \cup \{v + g \mid \langle v \rangle \in P_1^-\} \cup \{v - g \mid \langle v \rangle \in P_1^-\}$, we have $\mathbb{F}P^1|_{G_1} \cong \mathbb{F}P_1^+ \oplus 2\mathbb{F}P_1^-$. Moreover, if $P_1^- + g := \{v + g \mid \langle v \rangle \in P_1^-\}$ and $P_1^- - g := \{v - g \mid \langle v \rangle \in P_1^-\}$ then we get an $\mathbb{F}G_1$-isomorphism:

$$U^+|_{G_1} \cong \langle v_{1,\alpha} \mid \alpha \in P_1^+ \rangle \oplus \langle v_{1,\alpha} \mid \alpha \in P_1^- + g \rangle \oplus \langle v_{1,\alpha} \mid \alpha \in P_1^- - g \rangle,$$

where all summands are clearly nonzero and nontrivial $\mathbb{F}G_1$-modules. These summands are submodules of $\mathbb{F}P_1^+ \oplus 2\mathbb{F}P_1^-$. It follows that, by Proposition 3.1, each of them contains a graph submodule of $\mathbb{F}P_1^+$ or $\mathbb{F}P_1^-$. Notice that the dimensions of the graph submodules of $\mathbb{F}P_1^+$ as well as $\mathbb{F}P_1^-$ are $(3^n - 1)(3^n - 1)/8$.

We have shown that $U^+|_{G_1}$ has 3 composition factors (counting multiplicities) of degree $(3^n - 1)(3^n - 1)/8$. If $U^+|_{G_1}$ has another nonlinear composition factor, $\dim U^+ + 1$ would be at least $4(3^n - 1)(3^n - 1)/8 + 1$ since the smallest degree of nonlinear irreducible 2-Brauer character of $G_1$ is $(3^n - 1)(3^n - 1)/8$ (see Table 1 of [4]). This contradicts the fact that $U^+ \in \{X_1, Y_1, Z_1\}$, whence $U^+|_{G_1}$ has exactly 3 nonlinear composition factors, all of degree $(3^n - 1)(3^n - 1)/8$. 

Recall that $U'^{+1}|_{G_1}$ is a submodule of $\mathbb{F}P^{+1} \oplus 2\mathbb{F}P^{-1}$. It follows that $U'^{+1}$ has at most 6 composition factors of dimension 1 (see Table 4). Combining this with the conclusion of the previous paragraph, we obtain $\dim U'^{+1} \leq 3(3^n - 1)(3^{n-1} - 1)/8 + 6$. This forces $\dim U'^{+1} = \dim X_1 + 1$ and therefore $U'^{+1} \cong X_1$ again by $U'^{+1} \in \{X_1, Y_1, Z_1\}$.

The arguments for $U'^{-1} \cong Y_1$ are similar. Since $U'^{\kappa}$ appears at least twice as a composition factor of $\mathbb{F}P^{\kappa}$ (see Lemma 3.2), both $U'^{+1}$ and $U'^{-1}$ are constituents of $\psi$. Therefore $\psi = \beta(X_1) + \beta(Y_1)$ by comparing degrees. \hfill \Box

**Proposition 7.4.** Theorem 1.2 holds when $G = O_{2n+1}(3), n \geq 3$ and $\ell = 2$.

**Proof.** Case 4: $n$ even. We know from Lemma 7.3 that $U'^{+1} \cong X_1$. The self duality of $U'^{+1}$ from Lemma 3.2 then implies that $U'^{+1}/U'^{+1}$ has composition factors: $\mathbb{F}$ (twice), $Z_1$, and $Y_1$. Using Lemma 4.1 and inspecting the structure of $\mathbb{F}P^0$ (see Figure 6 of [11]), we see that $Y_1$ must be a submodule of $U'^{+1}/U'^{+1}$ but $Z_1$ is not. Therefore, the structure of $U'^{+1}/U'^{+1}$ is $Y_1 \oplus (\mathbb{F} - Z_1 - \mathbb{F})$ and hence that of $\mathbb{F}P^0$ is determined.

Now we determine the structure of $\mathbb{F}P^{-1}$. Since $[P^{-1}] \notin S(\mathbb{F}P^{-1})$, $\mathbb{F}P^{-1} = T(\mathbb{F}P^{-1}) \oplus S(\mathbb{F}P^{-1})$. Also, $U'^{-1} \cong Y_1$ is the socle of $S(\mathbb{F}P^{-1})$. Since $S(\mathbb{F}P^{-1})$ is self-dual, its head is also (isomorphic to) $Y_1$. Hence $S(\mathbb{F}P^{-1})/\ker(Q_{-1,0}|_{S(\mathbb{F}P^{-1})}) \cong \text{Im}(Q_{-1,0}|_{S(\mathbb{F}P^{-1})})$ has $Y_1$ as head. From the submodule structure of $\mathbb{F}P^0$, we find that $\text{Im}(Q_{-1,0}|_{S(\mathbb{F}P^{-1})})$ is uniserial with socle series $\mathbb{F} - Z_1 - \mathbb{F} - Y_1$. So $S(\mathbb{F}P^{-1})$ has a quotient $\mathbb{F} - Z_1 - \mathbb{F} - Y_1$. Again by its self-duality, it has a submodule $Y_1 - \mathbb{F} - Z_1 - \mathbb{F}$, which implies that $U'^{-1}/U'^{-1}$ has a submodule $\mathbb{F} - Z_1 - \mathbb{F}$. Notice that $U'^{-1}/U'^{-1}$ is self-dual and has composition factors: $\mathbb{F}$ (twice), $X_1$, and $Z_1$. Its structure must be $\mathbb{F} \oplus X_1 \oplus (\mathbb{F} - Z_1 - \mathbb{F})$, as described in Table 3.

Case 5: $n$ odd. First we find the structure of $\mathbb{F}P^+$. Composition factors of $U'^{+1}/U'^{+1}$ are $\mathbb{F}$, $Y_1$, and $Z_1$. Therefore, the structure of $U'^{+1}/U'^{+1}$ is simply $\mathbb{F} \oplus Y_1 \oplus Z_1$ by its self-duality.

Now we turn to $\mathbb{F}P^{-1}$. By Proposition 3.1, the socle of $\text{Im}(Q_{0,-1})$ is either $Y_1$ ($\cong U'^{-1}$) or $\mathbb{F} \oplus Y_1$ ($\cong U^{-1}$). Notice that $\text{Im}(Q_{0,-1}) \cong \mathbb{F}P^0/\ker Q_{0,-1}$ and $\mathbb{F}P^0$ has only one quotient having such socle, which is $Y_1 - (\mathbb{F} \oplus Z_1)$ (see the structure of $\mathbb{F}P^0$ in Figure 6 of [11]). We deduce that $\mathbb{F}P^{-1}$ has a submodule of structure $Y_1 - (\mathbb{F} \oplus Z_1)$. We temporarily set $\mathbb{F}_1 := T(\mathbb{F}P^{-1})$ and $\mathbb{F}_2 := \mathbb{F}P^{-1}/S(\mathbb{F}P^{-1})$. Then the submodule of $\mathbb{F}P^{-1}$ of structure $Y_1 - (\mathbb{F} \oplus Z_1)$ must be $\mathbb{F}_1 - (\mathbb{F}_2 \oplus Z_1)$. It follows that $U'^{-1}/U'^{-1}$ has a submodule $\mathbb{F}_2 \oplus Z_1$. Recall that $U'^{-1}/U'^{-1}$ is self-dual and has composition factors: $\mathbb{F}_1, \mathbb{F}_2, Z_1,$ and $X_1$, we conclude that its structure is $\mathbb{F}_1 \oplus \mathbb{F}_2 \oplus Z_1 \oplus X_1$. \hfill \Box

Propositions 7.2 and 7.4 complete the proof of Theorem 1.2 for the orthogonal groups in odd dimension.

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