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On the character degrees of Sylow $p$-subgroups of Chevalley groups $G(p^f)$ of type $E$

Tung Le and Kay Magaard

Communicated by Karl Strambach

Abstract. Let $\mathbb{F}_q$ be a field of characteristic $p$ with $q$ elements. It is known that the degrees of the irreducible characters of the Sylow $p$-subgroup of $\text{GL}(\mathbb{F}_q)$ are powers of $q$. On the other hand Sangroniz (2003) showed that this is true for a Sylow $p$-subgroup of a classical group defined over $\mathbb{F}_q$ if and only if $p$ is odd. For the classical groups of Lie type $B$, $C$ and $D$ the only bad prime is 2. For the exceptional groups there are others. In this paper we construct irreducible characters for the Sylow $p$-subgroups of the Chevalley groups $D_4(q)$ with $q = 2^f$ of degree $q^3/2$. Then we use an analogous construction for $E_6(q)$ with $q = 3^f$ to obtain characters of degree $q^7/3$, and for $E_8(q)$ with $q = 5^f$ to obtain characters of degree $q^{16}/5$. This helps to explain why the primes 2, 3 and 5 are bad for the Chevalley groups of type $E$ in terms of the representation theory of the Sylow $p$-subgroup.

Keywords. Irreducible characters, root system, Lie type.

2010 Mathematics Subject Classification. 20C33, 20C15.

1 Introduction

Let $G$ be a Chevalley group defined over a field $\mathbb{F}_q$ of order $q$ and characteristic $p > 0$. By $\alpha_0$ we denote the highest root of the root system $\Sigma$ of $G$. It is well known that $\alpha_0$ is a positive integral linear combination of the fundamental roots of $\Sigma$. So without loss of generality, $\alpha_0 = \sum_{i=1}^{r} a_i \alpha_i$ where the $\alpha_i$ are fundamental roots of $\Sigma$. Recall that $p$ is a bad prime for $G$ if $p$ is a divisor of some $a_i$.

It is well known that if $G$ classical, then the only possible bad prime for $G$ is 2. On the other hand if $G$ is exceptional of type $E$, then the primes 3 and 5 are also bad. The “badness” of the prime evidences itself in the classification of the unipotent conjugacy classes of $G$. Here we aim to explain why the primes 3 and 5 are bad for groups of type $E$ in terms to the representation theory of the Sylow $p$-subgroup of $G = E_6(q)$ with prime 3 and $G = E_8(q)$ with prime 5. Let $UE_k(q)$ denote the unipotent radical of the standard Borel subgroup of $E_k(q)$ for $k = 6$ and 8.
i.e. the subgroup generated by all the positive root groups of $G$. By $U_k$ we denote the quotient $UE_k(q)/K_{k-1}$, where $K_{k-1}$ is the normal subgroup of $UE_k(q)$ generated by all root groups $X_\alpha$ such that $\alpha$ has height $k - 1$ or more. Clearly any character of $U_k$ inflates to a character of $UE_k(q)$. Abusing terminology slightly we call the image under the natural projection of a root group of $UE_k(q)$, a root group of $U_k$. We observe that $Z(U_k)$ is generated by the root groups of height $k - 2$ and hence $|Z(U_k)| = q^{k-1}$. We define the family

$$\mathcal{F}_k := \{\chi \in \text{Irr}(U_k) : X_\alpha \not\subseteq \ker(\chi) \text{ for all } X_\alpha \subset Z(U_k)\}.$$ 

**Theorem 1.1.** The following statements are true.

(a) If $q = 3^f$, then for all $\chi \in \mathcal{F}_6$ we have $\chi(1) \in \{q^7, q^{7/3}\}$. Moreover $\mathcal{F}_6$ contains exactly $(q - 1)^5(q^2 - (q - 1)/2)$ characters of degree $q^7$ and exactly $3^2(q - 1)^6/2$ characters of degree $q^{7/3}$.

(b) If $q = 5^f$, then for all $\chi \in \mathcal{F}_8$ we have $\chi(1) \in \{q^{16}, q^{16/5}\}$. Moreover $\mathcal{F}_8$ contains exactly $(q - 1)^8(q^3 + q^2 + q + 3/4)$ characters of degree $q^{16}$ and exactly $25(q - 1)^8/4$ characters of degree $q^{16/5}$.

We remark that $9(q - 1)^6/2, (q - 1)^5(q^2 - (q - 1)/2), (q - 1)^8(q^3 + q^2 + q + 3/4)$ and $25(q - 1)^8/4$ are not in $\mathbb{Z}[q]$. On the other hand we remark also that $|\mathcal{F}_6| = (q - 1)^5q^2 \in \mathbb{Z}[q]$ and every character in $\mathcal{F}_6$ has degree $q^7$ whenever $p \neq 3$, and that $|\mathcal{F}_8| = (q - 1)^7q^4 \in \mathbb{Z}[q]$ and every character in $\mathcal{F}_8$ has degree $q^{16}$ whenever $p \neq 5$. Taken together these remarks provide evidence for a generalization of Higman’s conjecture for groups of type $UE_i(q), i = 6, 7, 8$, see for example [2], namely that $|\text{Irr}(UE_i(q))| \not\in \mathbb{Z}[q]$ if and only if $p$ is a bad prime for $E_i(q)$.

To prove our main theorem we begin by analyzing our construction of the irreducible characters of the Sylow $2$-subgroup of $D_4(2^f)$ from [3]. Our starting point is the quotient of $UD_4(q)/K_4$ where $UD_4(q)$ is the unipotent radical of the standard Borel subgroup of the universal Chevalley group $D_4(q)$ and $K_4$ is the normal subgroup of $UD_4(q)$ generated by the root groups of roots of height 4 and 5. We showed that when $p = 2$, there exists a $UD_4(q)$ family of characters of degree $q^3/2$ of size $4(q - 1)^4$. As $UD_4(q)$ is a quotient of $UE_i(q)$ for $i = 6, 7, 8$, we also see families of irreducible characters of degree $q^3/2$ for groups of type $UE_i(q)$, where $i = 6, 7, 8$ and $q$ is even.

Our construction is fairly elementary. Starting with large elementary abelian normal subgroups, we construct our characters via induction, using Clifford theory. To compute the necessary stabilizers we critically use Proposition 1.3 and Lemma 1.5. Throughout this paper we fix a nontrivial homomorphism

$$\phi : (\mathbb{F}_q, +) \to \mathbb{C}^\times.$$
For each $a \in \mathbb{F}_q$, we define $\phi_a(x) := \phi(ax)$ for all $x \in \mathbb{F}_q$, and denote
\[
\mathbb{F}_q^\times := \mathbb{F}_q - \{0\}.
\]
Hence, $\{\phi_a : a \in \mathbb{F}_q^\times\}$ are all non-principal irreducible characters of $\mathbb{F}_q$.

**Definition 1.2.** For $a \in \mathbb{F}_q$, we define $T_a := \{t^p - a^{p^i - 1}t : t \in \mathbb{F}_q\}$.

We note that $T_0 = \mathbb{F}_q$.

**Proposition 1.3.** The following statements are true.

(a) $t^p - a^{p^i - 1}t = \prod_{c \in \mathbb{F}_p}(t - ca)$.

(b) If $a \in \mathbb{F}_q^\times$, then $T_a$ is an additive subgroup of $\mathbb{F}_q$ of index $p$.

(c) For each $a \in \mathbb{F}_q^\times$, there exists $b \in \mathbb{F}_q^\times$ such that $bT_a = \ker(\phi)$. Furthermore, $cbT_a = \ker(\phi)$ iff $c \in \mathbb{F}_p^\times$.

(d) $\{T_a : a \in \mathbb{F}_q^\times\} = \{\ker(\phi_a) : a \in \mathbb{F}_q^\times\}$ are all subgroups of index $p$ in $\mathbb{F}_q$.

**Proof.** See Section 5.1.

**Definition 1.4.** For each $a \in \mathbb{F}_q^\times$, we pick $a_\phi$ such that $a_\phi T_a = \ker(\phi)$.

By Proposition 1.3(c), $a_\phi$ exists and but is only determined up to a scalar in the prime field. In the definition above we make an arbitrary choice which is fixed throughout the paper.

Throughout we fix notation as follows. Let $G$ be a group. Set $G^\times := G - \{1\}$, denote by $\text{Irr}(G)$ the set of all complex irreducible characters of $G$, and $\text{Irr}(G)^\times := \text{Irr}(G) - \{1_G\}$. For $H, K \leq G$, and $\xi \in \text{Irr}(H)$, define
\[
\text{Irr}(G/K) := \{\chi \in \text{Irr}(G) : K \subset \ker(\chi)\},
\]
\[
\text{Irr}(G, \xi) := \{\chi \in \text{Irr}(G) : (\chi, \xi^G) \neq 0\},
\]
\[
\text{Irr}(G/K, \xi) := \text{Irr}(G/K) \cap \text{Irr}(G, \xi).
\]
Furthermore, for a character $\chi$ of $G$, we denote its restriction to $H$ by $\chi|_H$.

**Lemma 1.5.** Let $N \leq G$ and $1 \in X$ be a transversal of $N$ in $G$. Suppose $N$ is of the form $N = ZYM$ where $Y \leq N$, $Z \subset Z(N)$, $M \leq N$ and $X \subset N_G(ZY)$. If there is $\lambda \in \text{Irr}(ZY)$ such that $Y \subset \ker(\lambda)$, and $u\lambda \neq v\lambda$ for all $u \neq v \in X$, then the following are true.

(a) For all $\chi \in \text{Irr}(N/Y, \lambda)$, $\chi^G \in \text{Irr}(G)$. Moreover, if $\chi_1 \neq \chi_2 \in \text{Irr}(N/Y, \lambda)$, then $\chi_1^G \neq \chi_2^G$.

(b) The induction map from $\text{Irr}(N/Y, \lambda)$ to $\text{Irr}(G, \lambda)$ is bijective.

**Proof.** See Section 5.2.
We recall that a \( p \)-group \( P \) is monomial, i.e. for each \( \chi \in \text{Irr}(P) \), there exist a subgroup \( H \) of \( P \) and a linear character \( \lambda \) of \( H \) such that \( \chi = \lambda^P \). To construct irreducible characters whose degrees are not powers of \( q = p^f \), \( f > 1 \), we construct subgroups \( H \leq P \) and \( T \leq P \) such that \( T \) is a transversal of \( H \). Then we find a linear character \( \lambda \) of \( H \) such that the order of the stabilizer \( \text{Stab}_T(\lambda) \) of \( T \) is not a power of \( q \). Moreover we insure that \( \lambda \) is extendable to the inertial group \( I_P(\lambda) = H\text{Stab}_T(\lambda) \). Let \( \lambda_I \) denote some extension of \( \lambda \) to \( I_P(\lambda) \). By Clifford theory the induction of \( \lambda_I \) to \( P \) is irreducible and of degree not a power of \( q \). The existence of a suitable pair \( (H, \lambda) \) is based on Proposition 1.3. The reason being that a polynomial of the form \( x^p + a^{p-1}x \), with \( a \neq 0 \), appears in the formulae of the action of elements of \( T \) on the characters of \( H \).

We will now highlight the main steps of the constructions of our characters. We have deferred all of our proofs to Section 5.

2 Sylow 2-subgroups of the Chevalley groups \( D_4(2^f) \)

Let \( \mathbb{F}_q \) be a field of order \( q \) and characteristic 2. Let \( \Sigma := \langle \alpha_1, \alpha_2, \alpha_3, \alpha_4 \rangle \) be the root system of type \( D_4 \), see Carter [1, Chapter 3]. The Dynkin diagram of \( \Sigma \) is

\[
\begin{array}{cccc}
\alpha_1 & \alpha_2 & \alpha_3 & \alpha_4 \\
\end{array}
\]

The positive roots are those roots which can be written as positive integral linear combinations of the simple roots \( \alpha_1, \alpha_2, \alpha_3, \alpha_4 \). We write \( \Sigma^+ \) for the set of positive roots. We use the notation

\[
\begin{array}{c}
1 \\
1 & 2 & 1
\end{array}
\]

for the root \( \alpha_1 + \alpha_2 + 2\alpha_3 + \alpha_4 \) and we use a similar notation for the remaining positive roots. The 12 positive roots of \( \Sigma \) are given in Table 1.

For \( \alpha \in \Sigma \) we denote the corresponding root subgroup of the Chevalley group \( G \) by \( X_\alpha \) whose elements we label by \( x_\alpha(t) \) where \( t \in \mathbb{F}_q \). Note that \( X_\alpha \cong (\mathbb{F}_q, +) \).

We recall the commutator formula

\[
[x_\alpha(r), x_\beta(s)] = \begin{cases}
x_{\alpha+\beta}(-C_{\alpha,\beta}rs), & \text{if } \alpha + \beta \in \Sigma, \\
1, & \text{otherwise,}
\end{cases}
\]

see Carter [1, Theorem 5.2.2]. In \( \mathbb{F}_q \) it is the case that \( 1 = -1 \), since \( p = 2 \), and thus all non-zero coefficients \( C_{\alpha,\beta} \) are equal to 1. For positive roots, we use the ab-
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<table>
<thead>
<tr>
<th>Height</th>
<th>Roots</th>
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</thead>
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</tr>
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<td></td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>$\alpha_{11} := 1$</td>
</tr>
<tr>
<td>3</td>
<td>$\alpha_8 := 1$</td>
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<tr>
<td></td>
<td>1</td>
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<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>$\alpha_5 := 1$</td>
</tr>
<tr>
<td></td>
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</tr>
<tr>
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<td>1</td>
</tr>
<tr>
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<td>0</td>
</tr>
<tr>
<td>1</td>
<td>$\alpha_1$</td>
</tr>
<tr>
<td></td>
<td>$\alpha_2$</td>
</tr>
<tr>
<td></td>
<td>$\alpha_3$</td>
</tr>
<tr>
<td></td>
<td>$\alpha_4$</td>
</tr>
</tbody>
</table>

Table 1. Positive roots of the root system $\Sigma$ of type $D_4$.

The group $UD_4$ generated by all $X_\alpha$ for $\alpha \in \Sigma^+$ is a Sylow 2-subgroup of the Chevalley group $D_4(q)$. Each element $u \in UD_4$ can be written uniquely as

$$ u = x_1(t_1)x_2(t_2)x_3(t_3)x_4(t_4)x_5(t_5)x_6(t_6)x_7(t_7) \cdots x_{12}(t_{12}) $$

where $x_i(t_i) \in X_i$.

So we write $\prod_{i=1}^{12} x_i(t_i)$ as this order. We note that our ordering of the roots is slightly non-standard as the positions of $x_3$ and $x_4$ are reversed.

We define

$$ F_4 := \{ \chi \in \text{Irr}(UD_4(q)) : \chi|_{X_i} = \chi(1)\phi_{a_i} \text{ for each } a_8, a_9, a_{10} \in F_q^\times \}. $$
If $\Psi$ is a representation affording $\chi \in \mathcal{F}_4$, then
\[
\Psi([x_8(t_8), x_4(t_4)]) = [\Psi(x_8(t_8)), \Psi(x_4(t_4))]
\]
\[
= [\phi_{a_8}(t_8)\Psi(1), \Psi(x_4(t_4))] = \Psi(1) \quad \text{for all } t_4, t_8 \in \mathbb{F}_q.
\]
Therefore, $X_{11} = [X_8, X_4] \subset \ker(\chi)$, and similarly $X_{12} = [X_8, X_7] \subset \ker(\chi)$. Thus only the factor group $U = UD_4/X_{12}X_{11}$ acts on a module affording $\chi$. Therefore, we may work with $U$ which has order $q^{10}$, and $Z(U) = X_8X_9X_{10}$.

Let $H := [U, U] = X_5X_6X_7X_8X_9X_{10}$, and $T := X_1X_2X_4$. It is clear that $H$, $HX_3$ and $T$ are elementary abelian. The group $U$ can be visualized as in the figure above. The roots in boxes are in $T$, $\alpha_3$ which is neither in $T$ nor in $H$ is in a circle, whereas all other roots are in $H$. The broken lines indicate where the hooks, as defined in [3], centered at central roots are; for example $\alpha_2 + \alpha_5 = \alpha_6 + \alpha_1 = \alpha_8$. The hooks centered at $\alpha_8$, $\alpha_9$ and $\alpha_{10}$ intersect pairwise in sets of size two so as to form a triangle.

To study the characters $\chi \in \mathcal{F}_4$ we start with a linear character $\lambda$ of $H$ such that $\lambda|_{X_i} \neq 1_{X_i}$ for $i = 8, 9, 10$.

**Definition 2.1.** For $a_8, a_9, a_{10} \in \mathbb{F}_q^\times$ and $b_5, b_6, b_7 \in \mathbb{F}_q$, we define

(a) $\lambda_{a_8, a_9, a_{10}}^{b_5, b_6, b_7} = (\prod_{i=5}^{10} x_i(t_i)) := \phi(\sum_{i=5}^{7} b_it_i + \sum_{j=8}^{10} a_jt_j)$.

(b) $S_{567} := \{x_{567}(t) := x_5(a_{10}t)x_6(a_9t)x_7(a_8t) : t \in \mathbb{F}_q\}$.

(c) $S_{124} := \{x_{124}(t) := x_1(a_{10}t)x_2(a_9t)x_4(a_8t) : t \in \mathbb{F}_q\}$.

(d) $A := a_8a_9a_{10}$ and $t_0 := \frac{1}{A}(b_5a_{10} + b_6a_9 + b_7a_8)$.

(e) $F_{124} := \{1, x_{124}(t_0)\}$.

(f) $F_3 := \{1\}$ if $t_0 = 0$, and $F_3 := \{1, x_3(\frac{t_0}{A})\}$ otherwise.

It is easy to check that $S_{567}$, $S_{124}$, $F_{124}$, $F_3$ are subgroups of $U$. If $t_0 = 0$, then $F_{124} = F_3 = \{1\}$, otherwise $F_{124} \cong F_3 \cong (\mathbb{F}_2, +)$. Since $S_{124}, S_{567} \cong (\mathbb{F}_q, +)$, their linear characters are of the form

$\phi_{b_i}(x_i(t)) = \phi(b_it) \quad \text{where } i \in \{124, 567\} \text{ for all } b_i, t \in \mathbb{F}_q$.
For each $\xi \in \operatorname{Irr}(F_{124})$, $\xi = \phi_{b_{124}}|_{F_{124}}$ for some $\phi_{b_{124}} \in \operatorname{Irr}(S_{124})$, $b_{124} \in \mathbb{F}_q$. If $F_{124}$ is nontrivial, we choose $b_{124} \in \{0, a_{124}\} \cong (\mathbb{F}_2, +)$ where $\phi(a_{124}t_0) = -1$. The same for $F_3 \leq X_3$, for each $\xi \in \operatorname{Irr}(F_3)$, $\xi = \phi_{b_3}|_{F_3}$ for some $\phi_{b_3} \in \operatorname{Irr}(X_3)$ and $b_3 \in \{0, a_3\} \cong (\mathbb{F}_2, +)$ such that

$$\phi\left(a_3\frac{(t_0)\phi}{A}\right) = -1$$

if $(t_0)\phi$ exists.

For each $a_8, a_9, a_{10} \in \mathbb{F}_q^\times$, there are $q^3$ linear characters $\lambda_{a_8,a_9,a_{10}}^a$ of $H$. By definition of $t_0$, there are $q^2$ of them such that $t_0 = 0$ and $q^2(q-1)$ such that $t_0 \neq 0$. Therefore, there are $q^2$ cases where $F_{124}$, $F_3$ are trivial and $q^2(q-1)$ cases where $F_{124}$, $F_3$ are of order 2.

For all $x_1(t_1), x_2(t_2)x_4(t_4) \in T$, we have

$$x_1(t_1)x_2(t_2)x_4(t_4) = \lambda_{b_5}^{a_8,a_9,a_{10}}$$

Hence, $T$ acts on the set of linear characters $\{\lambda_{a_8,a_9,a_{10}}^a\}$. It is easy to check that $t_0$ is invariant under this action. The following lemma establishes some facts concerning $\lambda_{b_5}^{a_8,a_9,a_{10}}$.

**Lemma 2.2.** Set $\lambda := \lambda_{b_5}^{a_8,a_9,a_{10}}$. The following statements are true.

(a) $S_{124} = \operatorname{Stab}_T(\lambda)$ and $S_{567} = \{x \in X_5X_6X_7 : |\lambda^U(x)| = \lambda^U(1)\}$. Moreover, $\lambda^U|_{S_{567}} = \lambda^U(1)\phi_{A_{10}}$.

(b) $\lambda$ extends to $HX_3F_{124}$ and $HF_3S_{124}$. Let $\lambda_1$ and $\lambda_2$ be extensions of $\lambda$ to $HX_3F_{124}$. The inertia groups $I_U(\lambda_1) = HX_3F_{124}$.

(c) $\lambda_1^U = \lambda_2^U \in \operatorname{Irr}(U)$ iff $\lambda_1|_{F_3} = \lambda_2|_{F_3}$ and $\lambda_1|_{F_{124}} = \lambda_2|_{F_{124}}$.

**Proof.** See Section 5.3.1. $\square$

**Remark.** When $q$ is odd, both sets $\{x \in X_5X_6X_7 : |\lambda^U(x)| = \lambda^U(1) = q^4\}$ and $\operatorname{Stab}_T(\lambda)$ are trivial. Thus, $\lambda$ extends to $HX_3$ and each extension induces irreducibly to $U$ of degree $q^3$.

When $t_0 \neq 0$, the statement in Lemma 2.2 (c) makes sense since the dihedral subgroup $\langle F_{124}, F_3 \rangle \subset I_U(\lambda_1)$. By Lemma 2.2 (b), $X_3, S_{124} \subset I_U(\lambda)$ but $\lambda$ does not extend to $HX_3S_{124}$ as $[X_3, S_{124}] \not\subseteq \ker(\lambda)$.

By Lemma 2.2 (a), the action of $T$ acts on the set of $q^3$ linear $\lambda_{a_8,a_9,a_{10}}^a$ has $q$ orbits, each of size $q^2$. By Lemma 2.2 (b), all $q^3$ linear $\lambda_{a_8,a_9,a_{10}}^a$ extend to $HX_3$ and thus we obtain $q^4$ linear extensions. For $q^3$ of these $t_0 = 0$ and whereas $t_0 \neq 0$ for the other $q^3(q-1)$ characters.
If $t_0 = 0$, $F_{124}$ is trivial. By Lemma 2.2 (b), $\lambda$ extends to $I_U(\lambda) = HX_3 \leq U$, as $\eta$. The group $T$ is a transversal of $HX_3$ in $U$ and acts regularly on these $q^3$ linear, as $a_8, a_9, a_{10}$, so we denote it by $\chi^{a_8,a_9,a_{10}}_{8,9,10,q^3} \in \text{Irr}(U)$. This character is the unique $\chi \in \mathcal{F}_4$ of degree $q^3$ such that $\chi|_{X_i} = \chi(1)\phi_{a_i}$ where $i = 8, 9, 10$. Furthermore, by Lemma 2.2 (a), this is the unique constituent $\chi$ of $(\chi|_{X_8X_9X_{10}})^U$ such that $S_{567} \subset \ker(\chi)$.

If $t_0 \neq 0$, then $F_{124}$ and $F_3$ are isomorphic to $\mathbb{F}_2$. By Lemma 2.2 (b), $\lambda$ extends to $HX_3F_{124}$ as $\lambda_1$, and $\lambda_1^U \in \text{Irr}(U)$ of degree $\frac{q^3}{2}$. For each $t_0 \neq 0$, by Lemma 2.2 (c), all constituents $\lambda_1^U$ of $\lambda^U$ only depend on the restrictions of $\lambda_1$ to $F_{124}$ and $F_3$. Therefore, we denote these constituents of $\lambda^U$ by

$$\chi^{b_{124},b_3,t_0,a_8,a_9,a_{10}}_{8,9,10,q^3}$$

where $b_{124}, b_3 \in \mathbb{F}_2, t_0, a_8, a_9, a_{10} \in \mathbb{F}_q^\times$.

For each $a_8, a_9, a_{10} \in \mathbb{F}_q^\times$, there are $4(q - 1)$ characters $\chi \in \mathcal{F}_4$ of degree $\frac{q^3}{2}$ such that $\chi|_{X_i} = \chi(1)\phi_{a_i}$ where $i = 8, 9, 10$.

The next theorem lists the generic character values of all $\chi \in \text{Irr}(U)$ such that $\chi|_{X_i} = \chi(1)\phi_{a_i}$ where $i = 8, 9, 10$.

**Theorem 2.3.** For $a_8, a_9, a_{10} \in \mathbb{F}_q^\times$, suppose $\chi \in \text{Irr}(U)$ such that $\chi|_{X_i} = \chi(1)\phi_{a_i}$ where $i = 8, 9, 10$. Set $Z = F_{124}S_{567}X_8X_9X_{10}$ and the Kronecker

$$\delta_{i,j} = \begin{cases} 1, & \text{if } i = j, \\ 0, & \text{otherwise}. \end{cases}$$

The following statements are true.

(a) If $\chi(1) = q^3$, then

$$\chi = \chi^{a_8,a_9,a_{10}}_{8,9,10,q^3}$$

and

$$\chi\left(\prod_{i=1}^{10} x_i(t_i)\right) = \delta_{0,\tau_1} \delta_{0,\tau_2} \delta_{0,\tau_4} \delta_{0,\tau_3} \delta_{a_{8}\tau_5,\tau_7} \delta_{a_{8}\tau_6,a_9\tau_7} q^3 \phi\left(\sum_{i=8}^{10} a_i \tau_i\right).$$

(b) If $\chi(1) = \frac{q^3}{2}$, then

$$\chi = \chi^{b_{124},b_3,t_0,a_8,a_9,a_{10}}_{8,9,10,q^3}$$

for some $b_{124}, b_3 \in \mathbb{F}_2, t_0 \in \mathbb{F}_q^\times$

and

$$\chi\left(\prod_{i=1}^{10} x_i(t_i)\right) = \frac{q^3}{2} \phi\left(\frac{b_{124} t_1}{a_{10}} + A t_0 \frac{t_7}{a_8} + \sum_{i=8}^{10} a_i \tau_i\right).$$
On the character degrees of Sylow $p$-subgroups of $E(p^f)$

If $\prod_{i=1}^{10} x_i(t_i) \in Z$, and

$$\chi \left( \prod_{i=1}^{10} x_i(t_i) \right) = \delta_{a_{10}t_1} \delta_{a_{10}t_4} \delta_{a_{9}t_3} t_0^{\phi} \frac{q^2}{2}$$

$$\times \phi \left( b_{124} \frac{t_1}{a_{10}} + b_{3}t_3 + At_0 \frac{t_7}{a_8} + (\ast) + \sum_{i=8}^{10} a_it_i \right),$$

otherwise, where $t_0^\phi = \frac{(t_0)^\phi}{\Delta}$ and $(\ast) = \frac{A^2}{(t_0)^\phi} \left( \frac{t_5}{a_{10}} + \frac{t_7}{a_8} \right) \left( \frac{t_6}{a_9} + \frac{t_7}{a_8} \right)$.

**Proof.** See Section 5.3.2. \hfill \Box

### 3 Sylow 3-subgroups of the Chevalley groups $E_6(3^f)$

Let $F_q$ be a field of order $q$ and characteristic 3. We study $E_6(q)$ from the point of view of its Lie root system. Let $\Sigma := \langle \alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5, \alpha_6 \rangle$ be the root system of $E_6$, see Carter [1, Chapter 3]. The Dynkin diagram of $\Sigma$ is

```
   α1    α2
      \   /  \\   /вечером
     \ /   /  \\ /
      \  /   /  \\ /
       \ /   \  /
          \ /    /
             \ /
               α6
```

The positive roots are those roots which can be written as nonnegative integral linear combinations of the simple roots $\alpha_1, \alpha_2, \ldots, \alpha_6$. We write $\Sigma^+$ for the set of positive roots. Here, $|\Sigma^+| = 36$. We use the notation

$$2 \quad 1 \quad 2 \quad 3 \quad 2 \quad 1$$

for the root $\alpha_1 + 2\alpha_2 + 2\alpha_3 + 3\alpha_4 + 2\alpha_5 + \alpha_6$ and we use a similar notation for the remaining positive roots. Let $X_\alpha := \langle x_\alpha(t) : t \in F_q \rangle$ be the root subgroup corresponding to $\alpha \in \Sigma$. The group generated by all $X_\alpha$ for $\alpha \in \Sigma^+$ is a Sylow 3-subgroup of the Chevalley group $E_6(q)$, which we call $UE_6$.

In this section, we will construct irreducible characters of degree $\frac{q^2}{3}$ which are members of the following family of irreducible characters of $UE_6$ which is defined as follows:

$$\mathcal{F}_6 := \{ \chi \in \text{Irr}(UE_6) : \chi|_{X_\alpha} = \chi(1)^{\phi_\alpha}, \text{ht}(\alpha) = 4, \alpha \in F_q^\times \}. $$

Let $\psi$ be a representation affording some $\chi \in \mathcal{F}_6$. As in Section 2 we see that $X_\alpha \subset \ker(\chi)$ for all positive roots $\alpha$ with height greater than 4. Let $K_5$ be the normal subgroup of $UE_6$ generated by all root subgroups of height greater than 4.
Thus only the factor group $U := UE_6 / K_5$ acts on a module affording $\chi$. If $\alpha$ is a root of height at most 4, then the restriction of the canonical projection from $UE_6$ to $U$ is an injective and thus we may identify the root group $X_\alpha$ with its image in $U$. There are 21 roots $\alpha \in \Sigma^+$ with $ht(\alpha) \leq 4$. These 21 positive roots are given in Table 3. Therefore, the group $U$ has order $q^{21}$ and $Z(U) = X_1X_2X_3X_4X_5X_6X_7X_8X_9X_{10}X_{11}X_{12}X_{13}X_{14}X_{15}X_{16}X_{17}X_{18}X_{19}X_{20}X_{21}$.

For positive roots, we use the abbreviation $x_i(t) = x_{\alpha_i}(t), i = 1, 2, \ldots, 21$. Each element $u \in U$ can be written uniquely as

$$u = x_2(t_2)x_1(t_1)x_3(t_3)x_4(t_4)x_5(t_5)x_6(t_6)x_7(t_7)x_8(t_8)x_9(t_9)x_{10}(t_{10}) \cdots x_{21}(t_{21})$$

where $x_i(t_i) \in X_i$.

So we write $\prod_{i=1}^{21} x_i(t_i)$ in the order as above. We note that in our order the term $x_2$ precedes $x_1$.

<table>
<thead>
<tr>
<th>Height</th>
<th>Roots</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>$\alpha_{20} := \begin{array}{cccc} 1 \ 0 \ 0 \ 1 \ 1 \ 1 \end{array}$ $\alpha_{21} := \begin{array}{cccc} 0 \ 1 \ 1 \ 1 \ 1 \ 1 \end{array}$</td>
</tr>
<tr>
<td></td>
<td>$\alpha_{17} := \begin{array}{cccc} 1 \ 1 \ 1 \ 0 \ 0 \ 0 \end{array}$ $\alpha_{18} := \begin{array}{cccc} 0 \ 1 \ 1 \ 1 \ 1 \ 0 \end{array}$ $\alpha_{19} := \begin{array}{cccc} 1 \ 0 \ 1 \ 1 \ 1 \ 0 \end{array}$</td>
</tr>
<tr>
<td>3</td>
<td>$\alpha_{15} := \begin{array}{cccc} 0 \ 1 \ 1 \ 1 \ 0 \ 0 \end{array}$ $\alpha_{16} := \begin{array}{cccc} 0 \ 0 \ 0 \ 1 \ 1 \ 1 \end{array}$</td>
</tr>
<tr>
<td></td>
<td>$\alpha_{12} := \begin{array}{cccc} 0 \ 1 \ 1 \ 1 \ 0 \ 0 \end{array}$ $\alpha_{13} := \begin{array}{cccc} 1 \ 0 \ 1 \ 1 \ 0 \ 0 \end{array}$ $\alpha_{14} := \begin{array}{cccc} 1 \ 0 \ 0 \ 1 \ 1 \ 0 \end{array}$</td>
</tr>
<tr>
<td>2</td>
<td>$\alpha_{10} := \begin{array}{cccc} 0 \ 0 \ 1 \ 1 \ 0 \ 0 \end{array}$ $\alpha_{11} := \begin{array}{cccc} 0 \ 0 \ 0 \ 0 \ 1 \ 1 \end{array}$</td>
</tr>
<tr>
<td></td>
<td>$\alpha_{7} := \begin{array}{cccc} 0 \ 1 \ 1 \ 0 \ 0 \ 0 \end{array}$ $\alpha_{8} := \begin{array}{cccc} 1 \ 0 \ 1 \ 0 \ 0 \ 0 \end{array}$ $\alpha_{9} := \begin{array}{cccc} 0 \ 1 \ 1 \ 0 \ 0 \ 0 \end{array}$</td>
</tr>
<tr>
<td>1</td>
<td>$\alpha_2$ $\alpha_1$ $\alpha_3$ $\alpha_4$ $\alpha_5$ $\alpha_6$</td>
</tr>
</tbody>
</table>

Table 3. Positive roots of the root system $\Sigma$ of type $E_6$.

For all $\alpha, \beta \in \Sigma$ the length of an $\alpha$-chain through $\beta$ is at most 1. Thus the Chevalley commutator formula, see Cater [1, Theorem 5.2.2], yields

$$[x_\alpha(r), x_\beta(s)] = \begin{cases} x_{\alpha + \beta}(-C_{\alpha, \beta}rs), & \text{if } \alpha + \beta \in \Sigma, \\ 1, & \text{otherwise}. \end{cases}$$
For each extraspecial pair \((\alpha, \beta)\), we choose the coefficient \(C_{\alpha, \beta} := -1\). By computing directly or using MAGMA [5] with the following codes, all nontrivial commutators are given in Table 4.

\[
\begin{align*}
W := & \text{RootDatum("E6");} \\
R := & \text{PositiveRoots(W); A := R[1..21];} \\
& \text{for i in [7..21] do} \\
& \quad \text{for j in [1..(i-1)] do} \\
& \quad \quad \text{if (R[i]-R[j]) in A then} \\
& \quad \quad \quad \text{k := RootPosition(W,R[i]-R[j]);} \\
& \quad \quad \quad \text{if k le j then print k,"+",j,"="i,"(".LieConstant_C(W,1,1,k,j),")"; end if;} \\
& \quad \quad \text{end if;} \\
& \quad \text{end for;} \\
& \text{end for;}
\end{align*}
\]

\[
\begin{align*}
[x_1(t), x_3(u)] &= x_7(tu), & [x_2(t), x_4(u)] &= x_8(tu), \\
[x_3(t), x_4(u)] &= x_9(tu), & [x_4(t), x_5(u)] &= x_{10}(tu), \\
[x_5(t), x_6(u)] &= x_{11}(tu), & [x_1(t), x_9(u)] &= x_{12}(tu), \\
[x_4(t), x_7(u)] &= x_{12}(-tu), & [x_2(t), x_9(u)] &= x_{13}(tu), \\
[x_3(t), x_8(u)] &= x_{13}(tu), & [x_2(t), x_{10}(u)] &= x_{14}(tu), \\
[x_5(t), x_8(u)] &= x_{14}(-tu), & [x_3(t), x_{10}(u)] &= x_{15}(tu), \\
[x_5(t), x_9(u)] &= x_{15}(-tu), & [x_4(t), x_{11}(u)] &= x_{16}(tu), \\
[x_6(t), x_{10}(u)] &= x_{16}(-tu), & [x_1(t), x_{13}(u)] &= x_{17}(tu), \\
[x_7(t), x_8(u)] &= x_{17}(tu), & [x_2(t), x_{12}(u)] &= x_{17}(tu), \\
[x_1(t), x_{15}(u)] &= x_{18}(tu), & [x_7(t), x_{10}(u)] &= x_{18}(tu), \\
[x_5(t), x_{12}(u)] &= x_{18}(-tu), & [x_2(t), x_{15}(u)] &= x_{19}(tu), \\
[x_3(t), x_{14}(u)] &= x_{19}(tu), & [x_5(t), x_{13}(u)] &= x_{19}(-tu), \\
[x_2(t), x_{16}(u)] &= x_{20}(tu), & [x_8(t), x_{11}(u)] &= x_{20}(tu), \\
[x_6(t), x_{14}(u)] &= x_{20}(-tu), & [x_3(t), x_{16}(u)] &= x_{21}(tu), \\
[x_9(t), x_{11}(u)] &= x_{21}(tu), & [x_6(t), x_{15}(u)] &= x_{21}(-tu).
\end{align*}
\]

<table>
<thead>
<tr>
<th>Table 4. Commutator relations for type (E_6).</th>
</tr>
</thead>
</table>

Let \(H := (X_\alpha : \alpha_4 \neq \alpha \in \Sigma^+, (\alpha, \alpha_4) > 0) = H_4 H_3 H_2\) where

\[
H_4 := Z(U), \quad H_3 := \prod_{i=12}^{16} X_i, \quad H_2 := \prod_{i=8}^{10} X_i.
\]
and
\[ T := (X_2, X_1, X_3, X_5, X_6) = X_2X_1X_3X_7X_5X_6X_{11}. \]

It is clear that \(|H| = q^{13}|, |T| = q^7|, H_k \) is generated by all root groups of root height \( k \) in \( H \), and \( T \) is a transversal of \( HX_4 \) in \( U \). Both \( H \) and \( HX_4 \) are elementary abelian and normal in \( U \), and \( T \) is isomorphic to \( UA_2(q) \times UA_2(q) \times UA_1(q) \), where \( UA_k(q) \) is the unipotent subgroup of the standard Borel subgroup of the general linear group \( GL_{k+1}(q) \). We can visualize the group \( U \) in the following figure. The roots in boxes are in \( T \), the others outside are in \( H \), and \( \alpha_4 \) not in both \( H \) and \( T \) is in a circle. The dotted lines demonstrate the relations between roots to give a sum root in center, e.g. \( \alpha_7 + \alpha_{10} = \alpha_{18}, \alpha_7 + \alpha_8 = \alpha_{17} \) \( \ldots \). In addition, we have two triangles, as same as in Section 2 of \( UD_4(q) \), namely \( (\alpha_{17}, \alpha_{18}, \alpha_{19}) \) and \( (\alpha_{19}, \alpha_{20}, \alpha_{21}) \). These two triangles share a common pair of roots \( (\alpha_2, \alpha_{15}) \) where \( \alpha_2 + \alpha_{15} = \alpha_{19} \).

We consider \( \lambda \in \text{Irr}(H) \) such that \( \lambda |_{X_i} = \phi_{a_i} \neq 1_{X_i} \) for \( 17 \leq i \leq 21 \). Since the maximal split torus of \( E_6(q) \) acts transitively on \( \bigoplus_{i=17}^{21} \text{Irr}(X_i)^{X_i} \), we may assume that \( \lambda |_{X_i} = \phi \) for \( 17 \leq i \leq 21 \). So we set
\[ \lambda = \lambda_{b_{12}, b_{13}, b_{14}, b_{15}, b_{16}}^{b_8, b_9, b_{10}} \in \text{Irr}(H) \]
such that \( \lambda |_{X_i} = \phi_{b_i} \) where \( b_i \in F_q \) for all \( 8 \leq i \leq 16, i \neq 11 \).

**Definition 3.1.** For \( b_8, b_9, b_{10}, b_{12}, b_{13}, b_{14}, b_{15}, b_{16} \in F_q \), we define
(a) \( S_1 := \{ s_1(t, r, s) := x_2(t)x_1(t)x_3(-t)x_5(t)x_6(-t)x_7(r)x_{11}(s) : t, r, s \in F_q \} \).
(b) \( S_2 := \{ s_2(t) := s_1(t, 2t^2, 2t^2) : t \in F_q \} \).
Lemma 3.2. The following statements are true.

(a) \( R_3 = \{ x \in H_3 : |\lambda^U(x)| = \lambda^U(1) \} \) and \( S_1 = \text{Stab}_T(\lambda|_{H_4H_3}) \). Moreover, we have \( \lambda^U|_{R_3} = \lambda^U(1)\phi_{B_3} \).

(b) If \( B_3 \neq 0 \), then \( \text{Stab}_T(\lambda) = \{ 1 \} \). Hence, if \( \eta \) is an extension of \( \lambda \) to \( HX_4 \), then \( I_U(\eta) = HX_4 \).

We note that \( R_k \leq H_k \) for \( k = 2, 3 \), \( F_2 \leq S_2 \leq S_1 \leq T \), and \( F_4 \leq X_4 \). Since \( R_k \cong \mathbb{F}_q \), for each \( a \in \mathbb{F}_q \) we define \( \phi_a(r_k(t)) = \phi_a(t) \) for all \( r_k(t) \in R_k \). Hence, \( \text{Irr}(R_k) = \{ \phi_a : a \in \mathbb{F}_q \} \). Since \( S_2 \cong \mathbb{F}_q \), we can define \( \phi_a(s_2(t)) = \phi_a(t) \) for all \( s_2(t) \in S_2 \). When \( B_2 = c^2 \in \mathbb{F}_q^\times \), for each linear character \( \xi \in \text{Irr}(F_2) \) there is \( b_2 \in \{ 0, \pm a_2 \} \cong (\mathbb{F}_3, +) \) such that

\[ \xi = \phi_{b_2}|_{F_2} \quad \text{where} \quad \phi_{b_2} \in \text{Irr}(S_2) \quad \text{and} \quad \phi(a_2c) \neq 1. \]

Using the same argument for \( F_4 \), we find that for each character \( \xi \in \text{Irr}(F_4) \) there is \( b_4 \in \{ 0, \pm a_4 \} \cong (\mathbb{F}_3, +) \) such that

\[ \xi = \phi_{b_4}|_{F_4} \quad \text{where} \quad \phi_{b_4} \in \text{Irr}(X_4) \quad \text{and} \quad \phi(a_4c) \neq 1. \]

We first outline the induction process of \( \lambda \) up to \( U \), thereby explaining some of the notation in Definition 3.1. Later we give the detailed conditions that are necessary for each step of our construction.

\[
\begin{align*}
H : \lambda & \quad B_3 = 0 \quad HX_4S_1 \quad B_2 = c^2 \in \mathbb{F}_q^\times \quad HX_5S_2 \\
B_3 & \neq 0 \quad B_2 & \neq c^2 \quad b_2, b_4 \in \mathbb{F}_3 \\
U : \chi_{q^7}^{b_3, B_3} & \quad \chi_{q^7}^{B_2} & \quad \chi_{q^7}^{b_3, b_4, B_2} \\
\text{No:} \quad (q - 1)q & \quad (q + 1)/2 & \quad 9(q - 1)/2
\end{align*}
\]

Figure \( UE_6(q) \). Summary on the branching rules of \( \lambda \).

Let \( \overline{H_3} \) be the normal closure of \( H_3 \) in \( HX_4S_1 \). Since \( HX_4 \) is abelian, it follows that \( X_4 \subseteq \text{Stab}_U(\lambda) \). The main properties of \( \lambda = \lambda_{b_12, b_13, b_14, b_15, b_16} \) are as follows.

Lemma 3.2. The following statements are true.

(a) \( R_3 = \{ x \in H_3 : |\lambda^U(x)| = \lambda^U(1) \} \) and \( S_1 = \text{Stab}_T(\lambda|_{H_4H_3}) \). Moreover, we have \( \lambda^U|_{R_3} = \lambda^U(1)\phi_{B_3} \).

(b) If \( B_3 \neq 0 \), then \( \text{Stab}_T(\lambda) = \{ 1 \} \). Hence, if \( \eta \) is an extension of \( \lambda \) to \( HX_4 \), then \( I_U(\eta) = HX_4 \).
(c) If $B_3 = 0$, then there exists $x \in T$ such that
\[ x^\lambda = \lambda_{b_8',b_9,b'_{10}}^{0,0,0,0} \]
for some $b_8', b_9, b'_{10} \in \mathbb{F}_q$. Furthermore, $H_3 \subseteq \ker(x^\lambda)^{HX_4S_1}$ and the induction map from $\Irr(HX_4S_1, x^\lambda)$ to $\Irr(U, \lambda)$ is bijective.

Proof. See Section 5.4.1.

Remark. If $\gcd(q, 3) = 1$, then $\{x \in H_3 : |\lambda^U(x)| = \lambda^U(1)\}$ and $\Stab_T(\lambda)$ are trivial. Thus $\lambda$ extends to $HX_4$ and hence induces up to $U$ irreducibly.

By Lemma 3.2 (a), it is easy to see that $B_3 = B_3(\lambda)$ is $T$ invariant, i.e., we have $B_3(\lambda) = B_3(x^\lambda)$ for all $x \in T$. As above we fix the actions of $\lambda|X_i = \phi, 17 \leq i \leq 21$. Now $H$ has $q^8$ linear characters. On $q^7$ of these $B_3 = 0$, whereas $B_3 \neq 0$ on the $q^7(q - 1)$ remaining characters.

Case $B_3 \neq 0$: By Lemma 3.2 (b), each of the $q^7(q - 1)$ linear characters of $H$ with $B_3 \neq 0$ extends to $HX_4$ in $q$ different ways, yielding $q^8(q - 1)$ linear characters. Each of these induces irreducibly thereby partitioning the $q^8(q - 1)$ characters into families of size $[U : HX_4] = q^7$. Therefore when $B_3 \neq 0$, there are $\frac{q^8(q - 1)}{q} = q(q - 1)$ irreducible characters of $U$ lying over $\lambda$. They are parameterized by $(b_4, B_3)$, and we denote them by $\lambda_{q_7}^{b_4,B_3}$, where $b_4 \in \mathbb{F}_q$ and $B_3 \in \mathbb{F}_q^\times$.

Case $B_3 = 0$: As $H \leq U$, we have $\lambda, x^\lambda \in \Irr(H)$ and $\Irr(U, \lambda) = \Irr(U, x^\lambda)$ for all $x \in T$. Hence, by Lemma 3.2 (c), we may assume that $\lambda := \lambda_{b_8, b_9, b_{10}}^{0,0,0,0}$. Since $[U : HX_4S_1] = q^4$ and character induction map from $HX_4S_1$ to $U$ preserves irreducibility, those $q^7$ linear characters of $H$ with $B_3 = 0$ are partitioned into $q^3$ sets each of size $q^4$. Each of these sets contains a unique $HX_4S_1$-character of the form $\lambda_{b_8, b_9, b_{10}}^{0,0,0,0}$.

Lemma 3.3. The following statements are true.

(a) $R_2 = \{x \in H_2 : |\lambda^{HX_4S_1}(x)| = \lambda^{HX_4S_1}(1)\}$ and $S_2 = \Stab_{S_1}(\lambda)$. Moreover, $\lambda^{HX_4S_1}|_{R_2} = \lambda^{HX_4S_1}(1)\phi_{B_2}$.

(b) If $B_2 \notin \{c^2 : c \in \mathbb{F}_q^\times\}$ and let $\eta$ be an extension of $\lambda$ to $HX_4$, then we have $I_{HX_4S_1}(\eta) = HX_4$. Therefore, $S_2$ acts transitively and faithfully on all extensions of $\lambda$ to $HX_4$.

(c) If $B_2 = c^2 \in \mathbb{F}_q^\times$, then $\lambda$ extends to $HX_4F_2$ and $HF_4S_2$. Let $\lambda_1, \lambda_2$ be extensions of $\lambda$ to $HX_4F_2$. Then $I_{HX_4S_1}(\lambda_1) = HX_4F_2$. Moreover,
\[ \lambda_1^{HX_4S_1} = \lambda_2^{HX_4S_1} \iff \lambda_1|_{F_2} = \lambda_2|_{F_2} \text{ and } \lambda_1|_{F_4} = \lambda_2|_{F_4}. \]

Proof. See Section 5.4.2.
Remark. When $B_2 = c^2 \neq 0$, we see that 

$$HX_4F_3 \trianglelefteq U \quad \text{and} \quad HF_4S_2 \not\trianglelefteq U,$$

and both have index $\frac{q^3}{3}$ in $U$. By Lemma 3.2(c) and Lemma 3.3(c) all constituents of $\lambda^U$ have degree $\frac{q^3}{3}$. Hence, if $\eta$ is an extension of $\lambda$ to $HF_4S_2$, then $\eta^U \in \text{Irr}(U, \lambda)$. We have $X_4, S_2 \subset \text{I}_U(\lambda)$ and $\lambda$ extends to $HX_4F_3$ and $HF_4S_2$, but $\lambda$ does not extend to $HX_4S_2$.

The group $HX_4$ has $q^4$ linear characters $\lambda$ such that 

$$\lambda|_H = \lambda_{b_0,0,0,b_0,b_{10}}.$$ 

Since $F_4^\infty$ is even and cyclic, we see that for $\frac{q^3(q+1)}{2}$ of these $B_2 \notin \{c^2 : c \in F_4^\infty\}$, and for $\frac{q^3(q-1)}{2}$ of them $B_2 \in \{c^2 : c \in F_4^\infty\}$.

Case $B_2 \notin \{c^2 : c \in F_4^\infty\}$: By Lemma 3.3(b), there are $\frac{q^3(q+1)}{2|S_1|}$ irreducibles of degree $|S_1| = q^3$ which are parameterized by $B_2 \notin \{c^2 : c \in F_4^\infty\}$. By Lemma 3.2(c), we obtain $\frac{q^3(q+1)}{2}$ irreducibles of degree $q^3[U : HX_4S_1] = q^7$, which are denoted by $\chi_{B_2}^*$. By Lemma 3.2(c) and Lemma 3.3(c) all constituents of $\lambda^U$ have degree $\frac{q^3}{3}$.

Therefore, together with characters $\lambda_{q^7,4,3}$ as computed above, $\mathcal{F}_6$ has exactly $(q - 1)q + \frac{q+1}{2}$ irreducible characters $\chi$ of degree $q^7$ such that $\chi|X_i = \chi(1)\phi$ for all $X_i \subset Z(U)$.

Case $B_2 \in \{c^2 : c \in F_4^\infty\}$: By Lemma 3.3(c), let $\lambda_1$ be an extension of $\lambda$ to $HX_4F_2$, then $\lambda_1^{HX_4S_1}$ is irreducible of degree $[HX_4S_1 : HX_4F_2] = \frac{q^3}{3}$. These $\lambda_1^{HX_4S_1}$ only depend on $B_2$ and their restrictions to $F_2$ and $F_4$. Hence, by Lemma 3.2(c), $\lambda_1^U \in \text{Irr}(U)$ of degree $\frac{q^7}{3}$ is denoted by $\chi_{b_2,4,B_3}^*$ where $b_2, b_4 \in F_3$ and $B_2 \in \{c^2 : c \in F_4^\infty\}$.

Therefore, $\mathcal{F}_6$ has exactly $\frac{9(q-1)}{2}$ irreducibles of degree $\frac{q^7}{3}$ such that $\chi|X_i = \chi(1)\phi$ for all $X_i \subset Z(U)$.

By the transitivity of the conjugate action of the maximal split torus $T_0$ of the Chevalley group $E_6(q)$ on $\bigoplus_{i=17}^{21} \text{Irr}(X_i)^\infty$, there are $(q - 1)^5(q^2 - q + \frac{q+1}{2})$ characters $\chi \in \mathcal{F}_6$ of degree $q^7$, and $\frac{9(q-1)}{2}$ characters $\chi \in \mathcal{F}_6$ of degree $\frac{q^7}{3}$ such that $\chi|X_i = \chi(1)\phi_{a_i}$, where $a_i \in F_4^\infty$, $17 \leq i \leq 21$. This gives the proof for the next theorem.

**Theorem 3.4.** Let $\chi \in \mathcal{F}_6$. The following statements are true.

(a) If $\chi(1) = q^7$, then there exists $t \in T_0$ such that $^t\chi$ is either $\chi_{q^7,4,3}$ or $\chi_{q^7,3}$, for some $b_4 \in F_4$, $B_3 \in F_4^\infty$, and $B_2 \in F_4 - \{c^2 : c \in F_4^\infty\}$.

(b) If $\chi(1) = \frac{q^7}{3}$, then there exists $t \in T_0$ such that $^t\chi = \chi_{q^7,4,3}$, for some $b_4 \in F_3$ and $B_2 \in \{c^2 : c \in F_4^\infty\}$. 
4 Sylow 5-subgroups of the Chevalley groups $E_8(5^f)$

Let $\mathbb{F}_q$ be a field of order $q$ and characteristic 5. We study $E_8(q)$ from the point of view of its root system. Let $\Sigma := \langle \alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5, \alpha_6, \alpha_7, \alpha_8 \rangle$ be the root system of $E_8$, see Carter [1, Chapter 3]. The Dynkin diagram of $\Sigma$ is

![Dynkin diagram of $\Sigma$]

The positive roots are certain non-negative integral combinations of the simple roots $\alpha_1, \alpha_2, \ldots, \alpha_8$. We write $\Sigma^+$ for the set of positive roots and note that $|\Sigma^+| = 120$. We use the notation

$$3 \ 2 \ 4 \ 6 \ 5 \ 4 \ 3 \ 2$$

for the root $2\alpha_1 + 3\alpha_2 + 4\alpha_3 + 6\alpha_4 + 5\alpha_5 + 4\alpha_6 + 3\alpha_7 + 2\alpha_8$ and similar notation for the remaining positive roots. Let $X_\alpha := \langle x_\alpha(t) : t \in \mathbb{F}_q \rangle$ be the root subgroup corresponding to $\alpha \in \Sigma$. The group generated by all $X_\alpha$ for $\alpha \in \Sigma^+$ is a Sylow 5-subgroup of the Chevalley group $E_8(q)$, which we call $UE_8$.

In this section, we are going to construct irreducible characters $\chi$ of degree $q^{16}/5$ by considering the following family of irreducible characters of $UE_8$:

$$\mathcal{F}_8 := \{ \chi \in \text{Irr}(UE_8) : \chi|_{X_\alpha} = \chi(1)\phi_a, \text{ ht}(\alpha) = 6, \ a \in \mathbb{F}_q^\times \}.$$

Let $\psi$ be a representation affording some $\chi \in \mathcal{F}_8$. Using the same argument as in Section 2 we see that $X_\alpha \subset \ker(\psi)$ for all positive roots $\alpha$ with height greater than 6. Let $K_7$ be the normal subgroup of $UE_8$ generated by all root subgroups of root heights greater than 6. Clearly the representation $\psi$ is a module for the factor group $U := UE_8/K_7$. The restriction of the canonical projection from $UE_8$ to $U$ to $X_\alpha$ is injective whenever $\alpha$ has height 6 or less. Thus, in this case, we may identify $X_\alpha$ with its image in $U$. To remind the reader that $U$ is a factor group of $UE_8$ we denoted it by $E_8$ in the tables below. Recall that $|\Sigma^+|$ has exactly 43 positive roots of height less than or equal to 6, which are listed in Table 5.

For positive roots, we use the abbreviation $x_i(t) = x_{\alpha_i}(t), i = 1, 2, \ldots, 43$. Hence, $Z(U) = X_37X_{38}X_{39}X_{40}X_{41}X_{42}X_{43} = \langle X_\beta : \text{ht}(\beta) = 6 \rangle$. Each element $u \in U$ can be written uniquely as

$$u = x_2(t_2)x_1(t_1)x_3(t_3)x_4(t_4)x_5(t_5) \cdots x_{43}(t_{43}) \quad \text{where } x_i(t_i) \in X_i.$$

So we write $\prod_{i=1}^{43} x_i(t_i)$ in the order as above. We note that in our order the term $x_2$ precedes $x_1$. 
<table>
<thead>
<tr>
<th>Height</th>
<th>Roots</th>
</tr>
</thead>
</table>
| 6      | \( \alpha_{43} \) :=  \\
|        | \[
\begin{array}{ccccccc}
0 & 1 & 1 & 1 & 1 & 1 & 1 \\
\end{array}
\]  \\
\( \alpha_{40} \) := \( \alpha_{41} \) := \( \alpha_{42} \) :=  \\
|        | \[
\begin{array}{ccccccc}
1 & 1 & 1 & 1 & 1 & 1 & 1 \\
0 & 1 & 2 & 1 & 1 & 0 & 0 \\
0 & 1 & 1 & 1 & 1 & 1 & 0 \\
0 & 0 & 1 & 1 & 1 & 1 & 1 \\
\end{array}
\]  \\
\( \alpha_{37} \) := \( \alpha_{38} \) := \( \alpha_{39} \) :=  \\
|        | \[
\begin{array}{ccccccc}
1 & 1 & 2 & 1 & 0 & 0 & 0 \\
1 & 1 & 1 & 1 & 1 & 0 & 0 \\
1 & 1 & 1 & 1 & 1 & 0 & 0 \\
\end{array}
\]  \\
5      | \( \alpha_{36} \) :=  \\
|        | \[
\begin{array}{ccccccc}
0 & 0 & 1 & 1 & 1 & 1 & 1 \\
\end{array}
\]  \\
\( \alpha_{33} \) := \( \alpha_{34} \) := \( \alpha_{35} \) :=  \\
|        | \[
\begin{array}{ccccccc}
1 & 1 & 1 & 1 & 1 & 0 & 0 \\
0 & 0 & 1 & 1 & 1 & 1 & 0 \\
0 & 0 & 1 & 1 & 1 & 1 & 0 \\
0 & 1 & 1 & 1 & 1 & 1 & 0 \\
\end{array}
\]  \\
\( \alpha_{30} \) := \( \alpha_{31} \) := \( \alpha_{32} \) :=  \\
|        | \[
\begin{array}{ccccccc}
1 & 1 & 1 & 1 & 0 & 0 & 0 \\
1 & 1 & 1 & 1 & 1 & 0 & 0 \\
1 & 1 & 1 & 1 & 1 & 0 & 0 \\
1 & 1 & 1 & 1 & 1 & 0 & 0 \\
\end{array}
\]  \\
4      | \( \alpha_{29} \) :=  \\
|        | \[
\begin{array}{ccccccc}
0 & 0 & 0 & 1 & 1 & 1 & 1 \\
\end{array}
\]  \\
\( \alpha_{26} \) := \( \alpha_{27} \) := \( \alpha_{28} \) :=  \\
|        | \[
\begin{array}{ccccccc}
1 & 0 & 0 & 0 & 1 & 1 & 1 & 0 \\
0 & 1 & 1 & 1 & 1 & 0 & 0 \\
0 & 0 & 1 & 1 & 1 & 1 & 0 \\
0 & 0 & 1 & 1 & 1 & 1 & 0 \\
\end{array}
\]  \\
\( \alpha_{23} \) := \( \alpha_{24} \) := \( \alpha_{25} \) :=  \\
|        | \[
\begin{array}{ccccccc}
1 & 0 & 1 & 1 & 1 & 0 & 0 \\
1 & 1 & 1 & 1 & 0 & 0 & 0 \\
1 & 1 & 1 & 1 & 0 & 0 & 0 \\
\end{array}
\]  \\

To be continued
Table 5. Positive roots of the root system $\Sigma$ of type $\widetilde{E}_8$.

For all $\alpha, \beta \in \Sigma$ the length of an $\alpha$-chain through $\beta$ is at most 1. Thus the Chevalley commutator formula, see Carter [1, Theorem 5.2.2], yields

$$[x_\alpha(r), x_\beta(s)] = \begin{cases} x_{\alpha + \beta}(-C_{\alpha,\beta}rs), & \text{if } \alpha + \beta \in \Sigma, \\ 1, & \text{otherwise.} \end{cases}$$

For each extraspecial pair $(\alpha, \beta)$, we choose the coefficient $C_{\alpha,\beta} := -1$. By direct computation or using MAGMA [5], we record the nontrivial commutators are in Table 6 below.
\[ [x_1(t), x_3(u)] = x_9(tu), \quad [x_2(t), x_4(u)] = x_{10}(tu), \]
\[ [x_3(t), x_4(u)] = x_{11}(tu), \quad [x_4(t), x_5(u)] = x_{12}(tu), \]
\[ [x_5(t), x_6(u)] = x_{13}(tu), \quad [x_6(t), x_7(u)] = x_{14}(tu), \]
\[ [x_7(t), x_8(u)] = x_{15}(tu), \quad [x_1(t), x_{11}(u)] = x_{16}(tu), \]
\[ [x_4(t), x_9(u)] = x_{16}(-tu), \quad [x_2(t), x_{11}(u)] = x_{17}(tu), \]
\[ [x_3(t), x_{10}(u)] = x_{17}(tu), \quad [x_2(t), x_{12}(u)] = x_{18}(tu), \]
\[ [x_5(t), x_{10}(u)] = x_{18}(-tu), \quad [x_3(t), x_{12}(u)] = x_{19}(tu), \]
\[ [x_5(t), x_{11}(u)] = x_{19}(-tu), \quad [x_3(t), x_{13}(u)] = x_{20}(tu), \]
\[ [x_6(t), x_{11}(u)] = x_{20}(-tu), \quad [x_5(t), x_{14}(u)] = x_{21}(tu), \]
\[ [x_7(t), x_{13}(u)] = x_{21}(-tu), \quad [x_6(t), x_{15}(u)] = x_{22}(tu), \]
\[ [x_8(t), x_{14}(u)] = x_{22}(-tu), \quad [x_1(t), x_{17}(u)] = x_{23}(tu), \]
\[ [x_2(t), x_{16}(u)] = x_{23}(tu), \quad [x_9(t), x_{10}(u)] = x_{23}(tu), \]
\[ [x_1(t), x_{19}(u)] = x_{24}(tu), \quad [x_5(t), x_{16}(u)] = x_{24}(-tu), \]
\[ [x_9(t), x_{12}(u)] = x_{24}(tu), \quad [x_2(t), x_{19}(u)] = x_{25}(tu), \]
\[ [x_3(t), x_{18}(u)] = x_{25}(tu), \quad [x_5(t), x_{17}(u)] = x_{25}(-tu), \]
\[ [x_2(t), x_{20}(u)] = x_{26}(tu), \quad [x_6(t), x_{18}(u)] = x_{26}(-tu), \]
\[ [x_{10}(t), x_{13}(u)] = x_{26}(tu), \quad [x_3(t), x_{20}(u)] = x_{27}(tu), \]
\[ [x_6(t), x_{19}(u)] = x_{27}(-tu), \quad [x_{11}(t), x_{13}(u)] = x_{27}(tu), \]
\[ [x_4(t), x_{21}(u)] = x_{28}(tu), \quad [x_7(t), x_{20}(u)] = x_{28}(-tu), \]
\[ [x_{12}(t), x_{14}(u)] = x_{28}(tu), \quad [x_5(t), x_{22}(u)] = x_{29}(tu), \]
\[ [x_8(t), x_{21}(u)] = x_{29}(-tu), \quad [x_{13}(t), x_{15}(u)] = x_{29}(tu), \]
\[ [x_1(t), x_{25}(u)] = x_{30}(tu), \quad [x_2(t), x_{24}(u)] = x_{30}(tu), \]
\[ [x_5(t), x_{23}(u)] = x_{30}(-tu), \quad [x_9(t), x_{18}(u)] = x_{30}(tu), \]
\[ [x_1(t), x_{27}(u)] = x_{31}(tu), \quad [x_6(t), x_{24}(u)] = x_{31}(-tu), \]
\[ [x_9(t), x_{20}(u)] = x_{31}(tu), \quad [x_{13}(t), x_{16}(u)] = x_{31}(-tu), \]
\[ [x_4(t), x_{25}(u)] = x_{32}(tu), \quad [x_{10}(t), x_{19}(u)] = x_{32}(-tu), \]
\[ [x_{11}(t), x_{18}(u)] = x_{32}(-tu), \quad [x_{12}(t), x_{17}(u)] = x_{32}(tu), \]
\[ [x_2(t), x_{27}(u)] = x_{33}(tu), \quad [x_3(t), x_{26}(u)] = x_{33}(tu), \]
\[ [x_6(t), x_{25}(u)] = x_{33}(-tu), \quad [x_{13}(t), x_{17}(u)] = x_{33}(tu), \]
\[ [x_2(t), x_{28}(u)] = x_{34}(tu), \quad [x_7(t), x_{26}(u)] = x_{34}(-tu), \]

To be continued
\[ [x_{10}(t), x_{21}(u)] = x_{34}(tu), \quad [x_{14}(t), x_{18}(u)] = x_{34}(-tu), \]
\[ [x_{3}(t), x_{28}(u)] = x_{35}(tu), \quad [x_{7}(t), x_{27}(u)] = x_{35}(-tu), \]
\[ [x_{11}(t), x_{21}(u)] = x_{35}(tu), \quad [x_{14}(t), x_{19}(u)] = x_{35}(-tu), \]
\[ [x_{4}(t), x_{29}(u)] = x_{36}(tu), \quad [x_{8}(t), x_{28}(u)] = x_{36}(-tu), \]
\[ [x_{12}(t), x_{22}(u)] = x_{36}(tu), \quad [x_{15}(t), x_{20}(u)] = x_{36}(-tu), \]
\[ [x_{1}(t), x_{32}(u)] = x_{37}(tu), \quad [x_{4}(t), x_{30}(u)] = x_{37}(tu), \]
\[ [x_{10}(t), x_{24}(u)] = x_{37}(-tu), \quad [x_{12}(t), x_{23}(u)] = x_{37}(-tu), \]
\[ [x_{16}(t), x_{18}(u)] = x_{37}(-tu), \quad [x_{1}(t), x_{33}(u)] = x_{38}(tu), \]
\[ [x_{2}(t), x_{31}(u)] = x_{38}(tu), \quad [x_{6}(t), x_{30}(u)] = x_{38}(-tu), \]
\[ [x_{9}(t), x_{26}(u)] = x_{38}(tu), \quad [x_{13}(t), x_{23}(u)] = x_{38}(-tu), \]
\[ [x_{1}(t), x_{35}(u)] = x_{39}(tu), \quad [x_{7}(t), x_{31}(u)] = x_{39}(-tu), \]
\[ [x_{9}(t), x_{28}(u)] = x_{39}(tu), \quad [x_{14}(t), x_{24}(u)] = x_{39}(-tu), \]
\[ [x_{16}(t), x_{21}(u)] = x_{39}(tu), \quad [x_{4}(t), x_{33}(u)] = x_{40}(tu), \]
\[ [x_{6}(t), x_{32}(u)] = x_{40}(-tu), \quad [x_{10}(t), x_{27}(u)] = x_{40}(tu), \]
\[ [x_{11}(t), x_{26}(u)] = x_{40}(-tu), \quad [x_{17}(t), x_{20}(u)] = x_{40}(tu), \]
\[ [x_{2}(t), x_{35}(u)] = x_{41}(tu), \quad [x_{3}(t), x_{34}(u)] = x_{41}(tu), \]
\[ [x_{7}(t), x_{33}(u)] = x_{41}(-tu), \quad [x_{14}(t), x_{25}(u)] = x_{41}(-tu), \]
\[ [x_{17}(t), x_{21}(u)] = x_{41}(tu), \quad [x_{2}(t), x_{36}(u)] = x_{42}(tu), \]
\[ [x_{8}(t), x_{34}(u)] = x_{42}(-tu), \quad [x_{10}(t), x_{29}(u)] = x_{42}(tu), \]
\[ [x_{15}(t), x_{26}(u)] = x_{42}(-tu), \quad [x_{18}(t), x_{22}(u)] = x_{42}(tu), \]
\[ [x_{3}(t), x_{36}(u)] = x_{43}(tu), \quad [x_{8}(t), x_{35}(u)] = x_{43}(-tu), \]
\[ [x_{11}(t), x_{29}(u)] = x_{43}(tu), \quad [x_{15}(t), x_{27}(u)] = x_{43}(-tu), \]
\[ [x_{19}(t), x_{22}(u)] = x_{43}(tu). \]

Table 6. Commutator relations for type $\tilde{E}_8$.

Let $H := \langle X_\alpha : \alpha \neq \alpha_4, (\alpha, \alpha_4) > 0 \rangle = H_6 H_5 H_4 H_3 H_2$ where $(-,-)$ denotes the definite bilinear form of $\mathbb{R}^8$ with respect to which the roots of $\Sigma$ have length 1,

\[
H_6 := Z(U), \quad H_5 := \prod_{i=30}^{36} X_i, \quad H_4 := \prod_{i=24}^{29} X_i, \quad H_3 := \prod_{i=18}^{21} X_i, \quad H_2 := X_{12} X_{13}.
\]
Let $T := \langle X_1, X_3, X_4, X_2, X_6, X_7, X_8 \rangle = T_4T_3T_2T_1$ where

\[
T_4 := X_{23}, \quad T_3 := X_{16}X_{17}X_{22}, \\
T_2 := X_9X_{10}X_{11}X_{14}X_{15}, \quad T_1 := X_1X_3X_4X_2X_6X_7X_8.
\]

It is clear that $|H| = q^{26}$, $|T| = q^{16}$, $H_k$ is generated by all root groups in $H$ of root height $k$, just as for $T_k$ generated by all root subgroups in $T$ of height $k$, and $T$ is a transversal of $HX_5$ in $U$. Both $H$ and $HX_5$ are elementary abelian and normal in $U$. The group $T$ is isomorphic to $\text{UA}_4(q) \times \text{UA}_3(q)$, where $\text{UA}_k(q)$ is the unipotent subgroup of the standard Borel subgroup of the general linear group $\text{GL}_{k+1}(q)$. We note that if $\{\beta_1, \beta_2, \beta_3, \beta_4\}$ are the simple roots of type $A_4$, then the map from $(X_1, X_3, X_4, X_2)$ to $\text{UA}_4(q)$ that sends $x_1(t)$ to $x_{\beta_1}(t)$, $x_3(t)$ to $x_{\beta_2}(t)$, $x_4(t)$ to $x_{\beta_3}(t)$, and $x_2(t)$ to $x_{\beta_4}(-t)$ for all $t \in \mathbb{F}_q$ induces an isomorphism.

We consider linear characters $\lambda \in \text{Irr}(H)$ such that $\lambda|_{X_i} = \phi_{a_i}$ for $37 \leq i \leq 43$ and $\lambda|_{X_j} = \phi_{b_j}$ for all appropriate $j \leq 36$ where $a_i \in \mathbb{F}_q^\times$ and $b_j \in \mathbb{F}_q$. Since the maximal split torus of the Chevalley group $E_8(q)$ acts transitively on the product $\bigotimes_{i=37}^{43} \text{Irr}(X_i)^\times$, it suffices to suppose that $\lambda|_{X_i} = \phi$ for all $37 \leq i \leq 43$.

**Definition 4.1.** For $b_i \in \mathbb{F}_q$ where $i \in [12..13, 18..21, 24..36]$ we define

(a) $B_5 := b_{30} + b_{31} - b_{32} - b_{33} - 2b_{34} + 2b_{35} + 2b_{36}$.

(b) $B_4 := 2b_{24} - 2b_{25} + b_{26} - b_{27} - b_{28} + b_{29}$.

(c) $B_3 := b_{18} - b_{19} - b_{20} + b_{21}$.

(d) $B_2 := b_{12} - b_{13}$.

(e) $R_5 := \{r_5(v) := x_{30}(v)x_{31}(v)x_{32}(-v)x_{33}(-v)x_{34}(-2v)x_{35}(2v)x_{36}(2v) : v \in \mathbb{F}_q\}$.

(f) $R_4 := \{r_4(v) := x_{24}(2v)x_{25}(-2v)x_{26}(v)x_{27}(-v)x_{28}(v)x_{29}(v) : v \in \mathbb{F}_q\}$.

(g) $R_3 := \{r_3(v) := x_{18}(v)x_{19}(-v)x_{20}(v)x_{21}(v) : v \in \mathbb{F}_q\}$.

(h) $R_2 := \{r_2(v) := x_{12}(v)x_{13}(-v) : v \in \mathbb{F}_q\}$.

(i) $L_1 := \{l_1(u) := x_2(2u)x_1(u)x_3(-2u)x_4(u)x_6(u)x_7(2u)x_8(-2u) : u \in \mathbb{F}_q\}$, $S_1 := L_1T_2T_3T_4$.

(j) $L_2 := \{l_2(u) := l_1(u)x_9(u^2)x_{10}(-u^2)x_{11}(u^2)x_{14}(-u^2)x_{15}(2u^2) : t \in \mathbb{F}_q\}$, $S_2 := L_2T_3T_4$.

(k) $L_3 := \{l_3(u) := l_2(u)x_{16}(4u^3)x_{17}(2u^3)x_{22}(3u^3) : u \in \mathbb{F}_q\}$, $S_3 := L_3T_4$.

(l) $S_4 := \{s_4(u) := l_3(u)x_{23}(3u^4) : u \in \mathbb{F}_q\}$.

(m) If $B_2 = c^4 \in \mathbb{F}_q^\times$, $F_4 := \{s_4(uc) : u \in \mathbb{F}_s\}$ and $F_5 := \{x_5(u\alpha \phi) : \alpha \in \mathbb{F}_s\}$.
It is easy to check that for \( k \in [2..5] \), \( R_k \leq H_k \) of order \( q \), \( S_k \leq S_{k-1} \leq T \) with \( S_5 = \{1\} \), and \( F_4 \leq S_4 \), \( F_5 \leq X_5 \) of order 5. It is noted that all \( B_i \) are defined for each \( \lambda \) as above, hence \( B_i = B_i(\lambda) \). Since \( R_k \cong \mathbb{F}_q \), for each \( a \in \mathbb{F}_q \) we define \( \phi_a(r_k(t)) = \phi_a(t) \) for all \( r_k(t) \in R_k \). Hence, \( \text{Irr}(R_k) = \{ \phi_a : a \in \mathbb{F}_q \} \). Since \( S_4 \cong \mathbb{F}_q \), we can define \( \phi_a(s_4(t)) = \phi_a(t) \) for all \( s_4(t) \in S_4 \). When \( B_2 = c^4 \in \mathbb{F}_q \), for each linear character \( \xi \in \text{Irr}(F_4) \) there is \( b_4 \in \{ ta_4 : t \in \mathbb{F}_5 \} \cong (\mathbb{F}_5, +) \) such that \( \xi = \phi_{b_4}|_{F_4} \) where \( \phi_{b_4} \in \text{Irr}(S_4) \) and \( \phi(a_4c) \neq 1 \). Use the same argument for \( F_5 \leq X_5 \), for each \( \xi \in \text{Irr}(F_5) \) there is \( b_5 \in \{ ta_5 : t \in \mathbb{F}_5 \} \cong (\mathbb{F}_5, +) \) such that \( \xi = \phi_{b_5}|_{F_5} \) where \( \phi_{b_5} \in \text{Irr}(X_5) \) and \( \phi(a_5c_5) \neq 1 \).

We first outline the induction process of \( \lambda \) up to \( U \), thereby explaining some of the notation in Definition 4.1. Later we give the detailed conditions that are necessary for each step of our construction.

\[
\begin{array}{cccc}
H : \lambda & B_5 = 0 & HX_5S_1 & B_4 = 0 & HX_5S_2 & B_3 = 0 & HX_5S_3 \\
U : \chi_{q_16}^{b_5,B_2,B_3} & B_5 \neq 0 & \chi_{q_16}^{b_5,B_2,B_4} & B_4 \neq 0 & \chi_{q_16}^{B_5,B_3} & B_3 \neq 0 & \chi_{q_16}^{B_2} & B_2 \neq c^4 & \chi_{q_16}^{b_4,b_5,B_2} & B_2 = c^4 \in \mathbb{F}_q^\times \\
No: (q-1)q^3 & (q-1)q^2 & (q-1)q & 3(q-1)/4 & 25(q-1)/4
\end{array}
\]

Figure \( UE_3(q) \). Summary on the branching rules of \( \lambda \).

Let \( \overline{H_5} \) be the normal closure of \( H_5 \) in \( HX_5S_1 \). Clearly \( X_5 \subset \text{Stab}_U(\lambda) \). The important properties of the \( \lambda \)'s are the following.

**Lemma 4.2.** The following statements are true.

(a) \( R_5 = \{ x \in H_5 : |\lambda^U(x)| = \lambda^U(1) \} \) and \( S_1 = \text{Stab}_U(\lambda|_{H_6H_5}) \). Moreover, we have \( \lambda^U|_{R_5} = \lambda^U(1)\phi_{B_5} \).

(b) If \( B_5 \neq 0 \), then \( \text{Stab}_T(\lambda) = \{ 1 \} \). Hence, if \( \eta \) is an extension of \( \lambda \) to \( HX_5 \), then \( I_U(\eta) = HX_5 \). Furthermore, if \( \eta, \eta' \) are two extensions of \( \lambda|_{H_6H_5H_4} \) to \( HX_5 \), then \( \eta^U = \eta'^U \) iff \( B_i(\eta) = B_i(\eta') \) for \( i = 2,3 \) and \( \eta|x_5 = \eta'|x_5 \).

(c) If \( B_5 = 0 \), then there exists \( x \in T \) such that \( x\lambda|x_1 = 1_{X_1} \) for all \( X_1 \subset H_5 \). Furthermore, we have the inclusion \( \overline{H_5} \subset \ker(x\lambda)^{HX_5S_1} \) and the induction map from \( \text{Irr}(HX_5S_1, x\lambda) \) to \( \text{Irr}(U, \lambda) \) is bijective.

**Proof.** See Section 5.5.1. \( \square \)

**Remark.** When \( (q, 5) = 1 \), both \( R_5 \) and \( \text{Stab}_T(\lambda) \) are trivial. Hence, \( \lambda \) extends to \( HX_5 \) and each extension induces irreducibly to \( U \), yielding a family of characters of degree \( [U : HX_5] = q^{16} \).
Lemma 4.2 (a) can be deduced from the following figure.

![Diagram](image)

Figure $UE_8(q)$. Relations of between root heights 5 in $H$ and 1 in $T$.

We have $q^{19}$ linear characters $\lambda$ of $H$ such that $\lambda|_{X_i} = \phi$ for all $X_i \subset Z(U)$. In these, there are $q^{18}$ linear characters of $H$ which are partitioned into $q^{12}$ families each of size $q^6$. Each family contains a unique member $\lambda \in \text{Irr}(H)$ such that $\lambda|_{X_i} = \phi$ for all $X_i \subset H_6$, $\lambda|_{X_i} = 1_{X_i}$ for all $X_i \subset H_5$, and $\lambda|_{X_i} = \phi_{b_i}$ for all $X_i \subset H_4H_3H_2$ where $b_i \in \mathbb{F}_q$. Let $\lambda \in \text{Irr}(H)$ be one of these $q^{12}$ representatives. Now we describe how $\lambda$ induces up to $HX_5S_1$. Let $\overline{H_5H_4}$ be the normal closure of $H_5H_4$ in $HX_5S_2$.

**Lemma 4.3.** The following statements are true.

(a) $R_4 = \{x \in H_4 : |\lambda^{HX_5S_1}(x)| = \lambda^{HX_5S_1}(1)\}$ and $S_2 = \text{Stab}_{S_1}(\lambda|_{H_6H_5H_4})$. Moreover, $\lambda^{HX_5S_1}|_{R_4} = \lambda^{HX_5S_1}(1)\phi_{B_4}$.

(b) If $B_4 \neq 0$, then $\text{Stab}_{S_1}(\lambda) = \{1\}$. Hence, if $\eta$ is an extension of $\lambda$ to $HX_5$, then $I_{HX_5S_1}(\eta) = HX_5$. Furthermore, if $\eta, \eta'$ are two extensions of $\lambda|_{H_6H_5H_4H_3}$ to $HX_5$, then $\eta^{HX_5S_1} = \eta'^{HX_5S_1}$ iff $B_2(\eta) = B_2(\eta')$ and $\eta|_{X_5} = \eta'|_{X_5}$.
(c) If $B_4 = 0$, then there exists $x \in S_1$ such that $x\lambda|X_i = 1_{X_i}$ for all $X_i \subset H_5 H_4$. Furthermore, we have the inclusion $H_5 H_4 \subset \ker(x\lambda) ^{H X_5 S_2}$ and the induction map from $\text{Irr}(H X_5 S_2, x\lambda)$ to $\text{Irr}(H X_5 S_1, \lambda)$ is bijective.

**Proof.** See Section 5.5.2. \hfill $\square$

The main idea of Lemma 4.3 (a) can be visualized in the following figure.

![Figure UE8(q). Relations of between root heights 4 in H and 2 in T.](image)

Recall that we have $q^{12}$ linear characters $\lambda$ of $H$ such that $\lambda|X_i = \phi$ for all $X_i \subset Z(U)$ and $\lambda|X_i = 1_{X_i}$ for all $X_i \subset H_5$. For $q^{11}$ of these we have $B_4 = 0$ whereas $B_4 \neq 0$ for the remaining $q^{11}(q - 1)$.

Case $B_4 \neq 0$: Lemma 4.3 (a) implies that $B_4 = B_4(\lambda)$ is invariant under the action of $S_1$. Therefore, by Lemma 4.3 (b), these $q^{11}(q - 1)$ linear characters with $B_4 \neq 0$ extend to $H X_5$ and each extension induces irreducibly to $H X_5 S_1$. Thus, we obtain $q^{12}(q - 1) = q^2(q - 1)$ irreducible characters of $H X_5 S_1$ of degree $|S_1| = q^{10}$ which are parameterized by $(b_5, B_2, B_4)$ where $b_5, B_2 \in \mathbb{F}_q$ and $B_4 \in \mathbb{F}_q^\times$. Now Lemma 4.2 (c) implies that we obtain $q^2(q - 1)$ characters of $U$ of degree $q^{16}$. We denote these by $\lambda_{q^{16}, b_5, B_2, B_4}$.

Case $B_4 = 0$: By Lemma 4.3 (c) the induction map from $H X_5 S_2$ to $H X_5 S_1$ is bijective. Thus our $q^{11}$ linear characters of $H$ with $B_4 = 0$ can be partitioned into $q^6$ families each of which has a unique representative $\lambda$ such that $\lambda|X_i = \phi$ for all $X_i \subset H_6$, $\lambda|X_i = 1_{X_i}$ for all $X_i \subset H_5 H_4$, and $\lambda|X_i = \phi b_i$ for all $X_i \subset H_3 H_2$ where $b_i \in \mathbb{F}_q$. Let $\lambda \in \text{Irr}(H)$ be one of above $q^6$ linear characters of $H$. Thus it suffices to describe how $\lambda$ induces up to $H X_5 S_2$. Let $H_5 H_4 H_3$ be the normal closure of $H_5 H_4 H_3$ in $H X_5 S_3$.

**Lemma 4.4.** The following statements are true.

(a) $R_3 = \{x \in H_3 : |\lambda|^{H X_5 S_2} (x)| = \lambda|^{H X_5 S_2} (1)\}$, $S_3 = \text{Stab}_{S_2}(\lambda|_{H_6 H_5 H_4 H_3})$. Moreover, $\lambda|^{H X_5 S_2} |_{R_3} = \lambda|^{H X_5 S_2} (1) \phi_{B_3}$.
(b) If $B_3 \neq 0$, then $\text{Stab}_{S_2}(\lambda) = \{1\}$. Hence, if $\eta$ is an extension of $\lambda$ to $HX_5$, then $I_{HX_5S_2}(\eta) = HX_5$. Furthermore, if $\eta$ and $\eta'$ are two extensions of $\lambda$ to $HX_5$, then $\eta^{HX_5S_2} = \eta'^{HX_5S_2}$ if $\eta|_{X_5} = \eta'|_{X_5}$.

(c) If $B_3 = 0$, then there exists $x \in S_2$ such that

\[
^x\lambda|_{X_i} = 1_{X_i} \quad \text{for all } X_i \subset H_5H_4H_3.
\]

Furthermore, we have the inclusion $H_5H_4H_3 \subset \ker(^x\lambda)^{HX_5S_3}$ and the induction map from $\text{Irr}(HX_5S_3, ^x\lambda)$ to $\text{Irr}(HX_5S_2, \lambda)$ is bijective.

**Proof.** See Section 5.5.3. □

The main idea of Lemma 4.4 (a) can be described as follows.

![Figure UE8(q). Relations of between root heights 3 in H and 3 in T.](image)

Recall that we have $q^6$ linear characters $\lambda$ of $H$ such that $\lambda|_{X_3} = \emptyset$ for all $X_i \subset Z(U)$ and $\lambda|_{X_i} = 1_{X_i}$ for all $X_i \subset H_5H_4$. Of these, there are $q^5$ with $B_3 = 0$ and $q^5(q - 1)$ with $B_3 \neq 0$.

Case $B_3 \neq 0$: Lemma 4.4 (a) implies that $B_3 = B_3(\lambda)$ is invariant under the action of $S_2$. Therefore, by Lemma 4.4 (b), these $q^5(q - 1)$ linear characters with $B_3 \neq 0$ extend to $HX_5$ and each extension induces irreducibly to $HX_5S_2$. Thus, we obtain $\frac{q^6(q-1)}{|S_2|} = q^5$ irreducible characters of $HX_4S_2$ of degree $|S_2| = q^5$ which are parameterized by $(b_5, B_3)$ where $b_5 \in \mathbb{F}_q$ and $B_3 \in \mathbb{F}_q^\times$. Thus using Lemma 4.3 (c) and Lemma 4.2 (c), we obtain $q(q - 1)$ characters of $U$ of degree $q^{16}$. We denote these by $\chi_{q_16}^{b_5, B_3}$.

Case $B_3 = 0$: Lemma 4.4 (c) implies that $q^5$ linear characters of $H$ with $B_3 = 0$ can be partitioned in $q^2$ families of characters each of which is represented by a $\lambda$ of $H$ such that $\lambda|_{X_i} = \emptyset$ for all $X_i \subset H_6$, $\lambda|_{X_i} = 1_{X_i}$ for all $X_i \subset H_5H_4H_3$, and $\lambda|_{X_i} = \phi_{b_i}$ for all $X_i \subset H_2$ where $b_i \in \mathbb{F}_q$. Let $\lambda \in \text{Irr}(H)$ be one of above $q^2$ linear of $H$. It suffices to consider how $\lambda$ induces up to $HX_5S_3$.

**Lemma 4.5.** The following statements are true.

(a) $R_2 = \{x \in H_2 : |\lambda^{HX_5S_3}(x)| = |\lambda^{HX_5S_3}(1)| \} \quad \text{and} \quad S_4 = \text{Stab}_{S_3}(\lambda)$. Moreover, $\lambda^{HX_5S_3}|_{R_2} = |\lambda^{HX_5S_3}(1)\phi_{B_2}|$.
(b) If $B_2 \not\in \{c^4 : c \in \mathbb{F}_q^\times\}$ and let $\eta$ be an extension of $\lambda$ to $HX_5$, then we have $I_{HX_5S_3}(\eta) = HX_5$. Therefore, $S_3$ acts transitively and faithfully on all extensions of $\lambda$ to $HX_5$.

(c) If $B_2 = c^4 \in \mathbb{F}_q^\times$, then $\lambda$ extends to $HX_5F_4$ and $HF_5S_4$. Let $\lambda_1, \lambda_2$ be two extensions of $\lambda$ to $HX_5F_4$. Then $I_{HX_5S_3}(\lambda_1) = HX_5F_4$. Moreover,

$$\lambda_1^{HX_5S_3} = \lambda_2^{HX_5S_3} \iff \lambda_1|_{F_4} = \lambda_2|_{F_4} \text{ and } \lambda_1|_{F_5} = \lambda_2|_{F_5}.$$ 

Proof. See Section 5.5.4.

It is noted that $\text{Stab}_{S_3}(\lambda) = \text{Stab}_T(\lambda)$. The main idea of Lemma 4.5 (a) can be visualized in the following figure.

![Figure UE8(q)](image-url)

Recall that we have $q^2$ linear characters $\lambda$ of $H$ such that $\lambda|_{X_i} = \phi$ for all $X_i \subset Z(U)$ and $\lambda|_{X_i} = 1_{X_i}$ for all $X_i \subset H_5H_4H_3$. Lemma 4.5 (a) implies that $B_2 = B_2(\lambda)$ is invariant under the action of $S_3$. Since $\mathbb{F}_q^\times$ is cyclic, we have

$$|\{c^4 : c \in \mathbb{F}_q^\times\}| = \frac{q-1}{4}.$$ 

Therefore, there are $\frac{q(q-1)}{4}$ linear characters of $B_2 \not\in \{c^4 : c \in \mathbb{F}_q^\times\}$, and there are $\frac{3q(q-1)}{4}$ linear characters of $B_2 \not\in \{c^4 : c \in \mathbb{F}_q^\times\}$.

Case $B_2 \not\in \{c^4 : c \in \mathbb{F}_q^\times\}$: These linear characters of $B_2 \not\in \{c^4 : c \in \mathbb{F}_q^\times\}$ extend to $HX_5$ and each extension induces irreducibly to $HX_5S_3$ of degree $|S_3| = q^2$. By Lemma 4.4 (c), Lemma 4.3 (c) and Lemma 4.2 (c), we obtain $\frac{3(q-1)}{4}$ characters of $U$ of degree $q^{16}$ which we denote by $\chi_{B_2}^{q^{16}}$.

The irreducibles of degree $q^{16}$ lie in the families

$$\chi_{q^{16}}^{B_5, B_2, B_4}, \chi_{q^{16}}^{B_5, B_2, B_3}, \chi_{q^{16}}^{B_5, B_3}, \text{ and } \chi_{q^{16}}^{B_2}.$$ 

Therefore, $\mathcal{F}_8$ contains exactly $q^3(q-1) + q^2(q-1) + q(q-1) + \frac{3(q-1)}{5}$ characters of $U$ of degree $q^{16}$ such that $\chi|_{X_i} = \chi(1)\phi$ for all $X_i \subset Z(U)$.

Case $B_2 \in \{c^4 : c \in \mathbb{F}_q^\times\}$: By Lemma 4.5 (c), if $\lambda_1$ is an extension of the character $\lambda$ to $HX_5F_4$, then $\lambda_1^{HX_5S_3}$ is irreducible of degree $[HX_5S_3 : HX_5F_4] = q^2_5$. These $\lambda_1^{HX_5S_3}$ only depend on $B_2$ and their restrictions to $F_4, F_5$. Hence, Lemma 4.4 (c), Lemma 4.3 (c) and Lemma 4.2 (c) imply that $\lambda_1^U \in \text{Irr}(U)$ is of de-
On the character degrees of Sylow $p$-subgroups of $E(p^f)$

We denote the characters so obtained by $\chi_{q^{16}/5}$ where $b_4, b_5 \in \mathbb{F}_5$ and $B_2 \in \{c^4 : c \in \mathbb{F}_q^\times\}$.

Therefore, $\mathcal{F}_8$ has exactly $\frac{25(q-1)}{4}$ irreducibles of degree $\frac{q^{16}}{5}$ such that $\chi|_{X_i} = \chi(1)\phi$ for all $X_i \subset Z(U)$.

The maximal split torus $T_0$ of the Chevalley group $E_8(q)$ acts transitively via conjugation on $\bigoplus_{i=37}^{43} \text{Irr}(X_i)^\times$, and thus there are $(q-1)^8(q^3 + q^2 + q + \frac{3}{4})$ characters $\chi \in \mathcal{F}_8$ of degree $q^{16}$, and $\frac{25(q-1)^8}{4}$ characters $\chi \in \mathcal{F}_8$ of degree $\frac{q^{16}}{5}$ such that $\chi|_{X_i} = \chi(1)\phi a_i$, where $a_i \in \mathbb{F}_q^\times$, $37 \leq i \leq 43$. This proves our next theorem.

**Theorem 4.6.** Let $\chi \in \mathcal{F}_8$. The following statements are true.

(a) If $\chi(1) = q^{16}$, then there exists $t \in T_0$ such that $t\chi$ is an element of

$$\left\{\chi_{q^{16}/5}^{b_4, b_5, B_2}, \chi_{q^{16}/5}^{b_5, B_2, B_3}, \chi_{q^{16}/5}^{b_4, B_3, B_2}, \chi_{q^{16}/5}^{b_5, B_2, B_3}\right\}.$$

(b) If $\chi(1) = q^{16}/5$, then there exists $t \in T_0$ such that $t\chi = \chi_{q^{16}/5}^{b_4, b_5, B_2}$.

## 5 All proofs

In all proofs, we use the following technique:

(a) For all the decomposition of the commutator formula into product, we apply the formula $[a, bc] = [a, c][a, b]^c$.

(b) For $H \leq G$ and $L \leq G$, for each $\lambda \in \text{Irr}(L)$, $\text{Stab}_G(\lambda) := \{x \in G : x\lambda = \lambda\}$, and $\text{Stab}_G(\lambda) \subset \text{Stab}_G(\lambda|_H) =: K$, hence, $\text{Stab}_G(\lambda) = \text{Stab}_K(\lambda)$.

(c) For $K \leq G$ and $H \leq G$, to extend a linear character $\lambda$ of $H$ to $HK$, we check if $[HK, HK] \subset \ker(\lambda)$.

### 5.1 Proof of Proposition 1.3

Let $a \in \mathbb{F}_q^\times$. Part (a) is clear since the degree of the polynomial $t^p - a^{p-1}t$ is $p$ and the $\mathbb{F}_p$-multiples of $a$ are clearly zeros. As $\mathbb{F}_q$ is of characteristic $p$, the map $\rho_a : \mathbb{F}_q \rightarrow \mathbb{F}_q$ defined by $\rho_a(t) = t^p - a^{p-1}t$ is $\mathbb{F}_p$-linear. By part (a) the kernel of the map is 1-dimensional and thus (b) follows. Evidently (d) follows from (c).

Now we are going to prove (c).
To prove (c) we note that the set $\mathbb{T}_a$ defined before Proposition 1.3 is the image of the above $\mathbb{F}_p$-homomorphism $\rho_a$. The kernel of $\rho_a$ is $a\mathbb{F}_p$, and $\mathbb{T}_a$ is an $\mathbb{F}_p$-hyperplane of $\mathbb{F}_q$. Since $\gcd(q-1, p) = 1$, for $b \in \mathbb{F}_q^\times$ there exists $s \in \mathbb{F}_q^\times$ such that $b = s^p$. We have

$$b(t^p - a^{p-1}t) = s^p(t^p - a^{p-1}t) = (st)^p - (sa)^{p-1}s \in \mathbb{T}_sa = \text{im}(\rho_{sa}).$$

Hence, $\mathbb{F}_q^\times$ acts on $\{\mathbb{T}_a : a \in \mathbb{F}_q^\times\}$. The first claim follows as left multiplication of $\mathbb{F}_q^\times$ on itself is transitive on $\mathbb{F}_q^\times$, hence on $\mathbb{F}_p$-one spaces, and thus by duality also on $\mathbb{F}_p$-hyperplanes. The second claim follows as the stabilizer of each $\mathbb{F}_p$-hyperplane in this action of $\mathbb{F}_q^\times$ is $\mathbb{F}_p$. \hfill $\Box$

### 5.2 Proof of Proposition 1.5

(a) Suppose $\chi \in \text{Irr}(N/Y, \lambda)$, we are going to show that $\chi^G \in \text{Irr}(G)$ by showing that the inertia group $I_G(\chi) = N$.

Since $Y \subset \text{ker}(\chi)$ and $Z \subset Z(N)$, we have $\chi|_Z = \chi(1)\lambda$. As $X \subset N_G(ZY)$, for each $x \in X$, $x^\lambda \in \text{Irr}(ZY)$. Hence, for any $u \neq v \in X$ we have

$$u^x\chi|_Z = \chi(1)^u\lambda \neq \chi(1)^v\lambda = v^x\chi|_Z,$$

i.e. $u^x \neq v^x$. Therefore, $x \in X$ such that $x^x = \chi$ iff $x = 1$. Since $X$ is a transversal of $N$ in $G$, this shows that the inertia group $I_G(\chi) = N$.

The above argument also proves that for $\chi_1, \chi_2 \in \text{Irr}(N/Y, \lambda)$ and $u \neq v \in X$ we have $u^x\chi_1 \neq v^x\chi_2$. So by Mackey’s formula for the double coset $N \setminus G/N = G/N$ represented by $X$, we have

$$(\chi_1^G, \chi_2^G) = (\chi_1^G|_N, \chi_2) = \sum_{x \in X} (x^\chi_1, \chi_2) = (\chi_1, \chi_2) = \begin{cases} 1, & \text{if } \chi_1 = \chi_2, \\ 0, & \text{otherwise.} \end{cases}$$

(b) It is enough to show that the induction map is surjective, i.e. for each character $\xi \in \text{Irr}(G, \lambda)$ there exists $\chi \in \text{Irr}(N/Y, \lambda)$ such that $\xi = \chi^G$.

Suppose $\xi|_N = \sum_{i \in S} a_i \chi_i$ where $a_i \in \mathbb{N}^\times$ and $S \subset \text{Irr}(H)$. By Frobenius reciprocity,

$$0 \neq (\xi, \lambda^G) = (\xi|_Z, \lambda),$$

there exists at least a constituent $\chi_0$ of $\xi|_N$ such that $(\chi_0|_Z, \lambda) \neq 0$, i.e. we have $\chi_0 \in \text{Irr}(N, \lambda)$.

Since $\lambda|_Y = \lambda(1)1_Y$ and $(\chi_0|_Y, \lambda|_Y) \geq (\chi_0|_Z, \lambda) > 0$, we have that $\chi_0$ is a constituent of $1_Y^N$. Since $Y \trianglelefteq N$, all constituents of $1_Y^N$ are $\text{Irr}(N/Y)$. Therefore, $\chi_0 \in \text{Irr}(N/Y, \lambda)$. By (a), $\chi_0^G \in \text{Irr}(G)$, hence it forces $\xi = \chi_0^G$. \hfill $\Box$
5.3 Proofs of Section “Sylow 2-subgroups of $D_4(2^f)$”

5.3.1 Proof of Lemma 2.2

Set $\lambda = \lambda_{b_3,b_5,b_6,b_7}^{a_8,a_9,a_{10}}$ for the whole proof.

(a) First we show that $\text{Stab}_T(\lambda) = S_{124}$. Since $^y\lambda(x) = \lambda(x)$ iff $\lambda(x^{-1}x^y) = \lambda([x, y]) = 1$ and $X_8X_9X_{10} \subset Z(U)$, it suffices to check for $[X_5X_6X_7, T]$. For all $t, s \in \mathbb{F}_q$, we have

$$[x_5(t) x_6(t) x_7(t), x_1(s) x_2(s) x_4(s)] = x_8(t_6s_1 + t_5s_2) x_9(t_7s_1 + t_5s_4) x_{10}(t_7s_2 + t_6s_4).$$

Therefore, $x_1(s) x_2(s) x_4(s) \in \text{Stab}_T(\lambda)$ iff for all $t_5, t_6, t_7 \in \mathbb{F}_q$,

$$1 = \phi(a_8(t_6s_1 + t_5s_2) + a_9(t_7s_1 + t_5s_4) + a_{10}(t_7s_2 + t_6s_4))$$

$$= \phi(t_5(a_8s_2 + a_9s_4) + t_6(a_8s_1 + a_{10}s_4) + t_7(a_9s_1 + a_{10}s_2))$$

iff $a_8s_2 + a_9s_4 = a_8s_1 + a_{10}s_4 = a_9s_1 + a_{10}s_2 = 0$, i.e. $\frac{s_1}{a_{10}} = \frac{s_2}{a_9} = \frac{s_4}{a_8}$. So $\text{Stab}_T(\lambda) = S_{124}$.

We first find all elements of $X_5X_6X_7$ which act scalarly on a module affording $\lambda^U$. As $X_3T$ is a transversal of $H$ in $U$ and $[X_3, X_5X_6X_7] = \{1\}$, it is enough to find the ones of $X_5X_6X_7$ which commute with $T$, i.e. find $x_5x_6x_7 \in X_5X_6X_7$ such that $\lambda([x_5x_6x_7, x_1x_2x_4]) = 1$ for all $x_1x_2x_4 \in T$. This shows that for all $s_i \in \mathbb{F}_q$, we need

$$1 = \phi(a_8(t_6s_1 + t_5s_2) + a_9(t_7s_1 + t_5s_4) + a_{10}(t_7s_2 + t_6s_4))$$

$$= \phi(s_1(a_8t_6 + a_9t_7) + s_2(a_8t_5 + a_{10}t_7) + s_4(a_9t_5 + a_{10}t_6))$$

iff $a_8t_6 + a_9t_7 = a_8t_5 + a_{10}t_7 = a_9t_5 + a_{10}t_6 = 0$, i.e. $\frac{t_5}{a_{10}} = \frac{t_6}{a_9} = \frac{t_7}{a_8}$. Hence, $\prod_{i=5}^{7} x_i(t) = x_5^{a_7}(\frac{t_7}{a_8}) \in S_{567}$. So

$$S_{567} = \{x \in X_5X_6X_7 : |\lambda^U(x)| = \lambda^U(1)\}.$$

Now, to prove that $\lambda^U|_{S_{567}} = q^4\phi_{A_{10}}$, it suffices to check that $\lambda(x_{567}(t)) = \phi_{A_{10}}(t)$. For each $x_{567}(t) = x_5(a_{10}t)x_6(a_9t)x_7(a_8t) \in S_{567}$, we have

$$\lambda(x_{567}(t)) = \phi(t(b_5a_{10} + b_6a_9 + b_7a_8)) = \phi(tA_{10}) = \phi_{A_{10}}(t).$$

(b) We study $\text{Irr}(U, \lambda)$ in two ways. Let

$$K_1 := HX_3F_{124} \quad \text{and} \quad K_2 := HS_{124}F_3.$$
Since $H = [U, U]$, it is clear that $H_1, K_1 \leq U$.

\[
\begin{array}{c}
H \\
\downarrow \\
HX_3 \\
\downarrow \\
K_1 = HX_3F_{124} \\
\downarrow \\
U \\
\end{array}
\]

\[
\begin{array}{c}
HS_{124} \\
\downarrow \\
K_2 = HS_{124}F_3
\end{array}
\]

Since $HX_3$ is abelian, $\lambda$ extends to $HX_3$ as $\eta_1$. By (a), $S_{124} = \text{Stab}_T(\lambda)$, for all $x \in H, x_{124} \in S_{124}$, $\lambda([x, x_{124}]) = 1$, hence $\lambda$ extends to $HS_{124}$ as $\eta_2$. To show that $\lambda$ extends to $K_1$ and $K_2$, we prove that $[K_1, K_1] \subset \ker(\eta_1), [K_2, K_2] \subset \ker(\eta_2)$. We have

\[
[x_3(t_3), x_1(s_1)x_2(s_2)x_4(s_4)] = x_5(s_1t_3)x_6(s_2t_3)x_7(s_4t_3)x_8(s_1s_2t_3)x_9(s_1s_4t_3)x_{10}(s_2s_4t_3),
\]

and

\[
\lambda(x_5(s_1t_3)x_6(s_2t_3)x_7(s_4t_3)x_8(s_1s_2t_3)x_9(s_1s_4t_3)x_{10}(s_2s_4t_3)) = \phi(t_3(b_5s_1 + b_6s_2 + b_7s_4 + a_8s_1s_2 + a_9s_1s_4 + a_1s_2s_4)) = (*)
\]

Plug $s_1 = a_1t, s_2 = a_2t, s_4 = a_8t$ into $(*), we have

\[
(*) = \phi(t_3(t(b_5a_1 + b_6a_9 + b_7a_8) + t^2a_8a_9a_10)) = \phi(t_3At(t_0 + t)).
\]

Now we distinguish two cases, $t_0 = 0$ and $t_0 \neq 0$. First, if $t_0 = 0, \phi(t_3At^2) = 1$ for all $t_3$ iff $t = 0$, hence, $\text{Stab}_T(\eta_1) = \{1\} = F_{124}, i.e.$

\[
I_U(\eta_1) = HX_3.
\]

And $\phi(t_3At^2) = 0$ for all $t$ iff $t_3 = 0$, hence, $\text{Stab}_{X_3}(\eta_2) = \{1\} = F_3, i.e.$

\[
I_U(\eta_2) = HS_{124}.
\]

If $t_0 \neq 0$, then $\phi(t_3At(t_0 + t)) = 1$ for all $t_3$ iff $t \in \{0, t_0\}. Therefore, we have $[K_1, K_1] \subset \ker(\lambda). For each $\eta \in \text{Irr}(HX_3, \lambda), \text{Stab}_T(\eta) = \{1, x_{124}(t_0)\} = F_{124}$.

We have $\phi(t_3At(t_0 + t)) = 1$ for all $t$ iff $t_3 \in \{0, \frac{(t_0)\phi}{A}\}$, by Proposition 1.3. Hence, $[K_2, K_2] \subset \ker(\lambda). For each $\gamma \in \text{Irr}(HS_{124}, \lambda), \text{Stab}_{X_3}(\gamma) = \{1, x_3\left(\frac{(t_0)\phi}{A}\right)\} = F_3$.

So $\lambda$ extends to $K_1$ and $K_2$. Now for each $\lambda_i \in \text{Irr}(K_i, \lambda), I_U(\lambda_i) = K_i, i = 1, 2.$
(c) Let \( \lambda_1, \lambda_2 \) be extensions of \( \lambda \) to \( K_1 \). Let \( \eta \) be an extension of \( \lambda \) to \( K_2 \). By (b), we have \( \lambda_1^U, \lambda_2^U, \eta^U \in \text{Irr}(U, \lambda) \).

We choose \( 1 \in S \subset T \) as a representative set of the double coset \( K_1 \setminus U / K_2 \). By Mackey’s formula, since \( K_1 \cap K_2 = HF_3F_{124} \) and \( K_1 \subseteq U \), we have

\[
(\lambda_1^U, \eta^U) = \sum_{s \in S} (s \lambda_1|_{K_1 \cap K_2}, \eta|_{sK_1 \cap K_2})
\]

\[
= \sum_{s \in S} (s \lambda_1|_{HF_3F_{124}}, \eta|_{HF_3F_{124}}).
\]

For each \( s \in S \), if \( s \lambda_1|_{HF_3F_{124}} = \eta|_{HF_3F_{124}} \), then \( s \lambda_1|_H = \eta|_H \). Since both are extensions of \( \lambda \) from \( H \), we have \( s \lambda = \lambda \), i.e. \( s \in \text{Stab}_T(\lambda) = S_{124} \). There is a unique \( s = 1 \in S \cap S_{124} \) since \( S \) is a representative set of \( K_1 \setminus U / K_2 \). Therefore,

\[
(\lambda_1^U, \eta^U) = (\lambda_1|_{HF_3F_{124}}, \eta|_{HF_3F_{124}}) = 1 \iff \lambda_1|_{F_i} = \eta|_{F_i}, i \in \{124, 3\}.
\]

So \( \lambda_1^U = \eta^U = \lambda_2^U \in \text{Irr}(U, \lambda) \) iff \( \lambda_1|_{F_i} = \lambda_2|_{F_i}, i \in \{124, 3\} \).

We remark that since \( K_1, K_2 \subseteq U \), the double coset \( K_1 \setminus U / K_2 \) equals

\[
U / K_1 K_2 = U / H X_3 S_{124}.
\]

Hence we see that \( S = X_1 X_2 \) is a transversal of \( U / K_1 K_2 \).

5.3.2 Proof of Theorem 2.3

Fix \( a_8, a_9, a_{10} \in F_q^\times \) and set \( \lambda = \lambda_{b_5, b_6, b_7}^{a_8, a_9, a_{10}} \) for some \( b_5, b_6, b_7 \in F_q \) throughout the whole proof. By Lemma 2.2 and using the same notation, we mostly find the generic character values: in (a)

\[
\chi_{8,9,10,q^3}^{a_8,a_9,a_{10}} = \eta_1^U \quad \text{where } t_0 = 0,
\]

and in (b)

\[
\chi_{8,9,10,q^3}^{b_{124},b_3,t_0,a_8,a_9,a_{10}} = \eta_1^U \quad \text{where } b_{124}, b_3 \in F_2, t_0 \in F_q^\times.
\]

(a) Suppose \( t_0 = 0 \) and \( F_{124} = \{1\} \). Call \( \eta \) an extension of \( \lambda \) to \( H X_3 \). By Lemma 2.2 (b), \( I_U(\eta) = H X_3 \). Therefore, we have \( \eta^U \in \text{Irr}(U) \) and \( \eta^U(1) = q^3 \). By Lemma 2.2 (a), \( S_{567}X_8X_9X_{10} \subset Z(\eta^U) \), hence

\[
|\eta^U(x)| = q^3 \quad \text{for all } x \in S_{567}X_8X_9X_{10}.
\]

We have \( |S_{567}X_8X_9X_{10}|q^{10} = |U| \). As the scalar product \( (\eta^U, \eta^U) = 1 \), we see that \( \eta^U(x) = 0 \) if \( x \notin S_{567}X_8X_9X_{10} \). So we have derived the stated formula.
(b) Suppose \( t_0 \neq 0 \), and \( |F_3| = |F_{124}| = 2 \). By Lemma 2.2 (b), let \( \eta_1, \eta_2 \) be extensions of \( \lambda \) to \( K_1 := HX_3F_{124} \) and \( K_2 := HS_{124}F_3 \) respectively such that \( \eta_1|_{F_i} = \eta_2|_{F_i} = \phi_{b_i} \), where \( b_i \in \mathbb{F}_2, i \in \{124, 3\} \). The proof of Lemma 2.2 (c) implies that \( \eta_1 U = \eta_2 U \).

We choose \( V \subset T \) as a transversal of \( K_1 \) in \( U \), and \( 1 \in S \subset X_3 \) such that \( SX_1X_2 \) is a transversal of \( K_2 \) in \( U \), so \( |S| = q/2 \). Since \( K_1 \cong U \), we have

\[
\eta_1 U \left( \prod_{i=1}^{10} x_i \right) = \sum_{x \in V} x \eta_1 \left( \prod_{i=1}^{10} x_i \right) = 0 \text{ if } x_1x_2x_4 \notin K_1.
\]

Since \( T \) is abelian, it follows that \( [x, y] = 1 \) for all \( x \in V \) and \( y \in F_{124} \). Therefore, \( F_{124} \subset Z(\eta_1 U) \) and hence

\[
\eta_1 U \left( \prod_{i=1}^{10} x_i(t_i) \right) = \delta_{a_{10}t_1,a_{10}t_4} \delta_{a_{124}t_1,a_{124}t_4} \phi \left( b_{124} \frac{t_1}{a_{10}} \right) \eta_1 U \left( x_3(t_3) \prod_{i=1}^{10} x_i(t_i) \right)
\]

Since \( K_2 \subset U \), we have

\[
\eta_2 U \left( \prod_{i=5}^{10} x_i \right) = \sum_{x \in SX_1X_2} x \eta_2 \left( \prod_{i=5}^{10} x_i \right) = 0 \text{ if } x \notin F_3.
\]

Since \( X_8X_9X_{10} \subset Z(U) \), we need to compute the two following cases:

\[ \eta_2 U \left( \prod_{i=5}^{7} x_i \right) \text{ and } \eta_2 U \left( x_3 \prod_{i=5}^{7} x_i \right) \text{ with } x_3 \in F_3^X. \]

Since \( [X_3, X_5X_6X_7] = \{1\} \), we have

\[
\eta_2 U (x_5x_6x_7) = \sum_{x \in SX_1X_2} x \eta_2 (x_5x_6x_7) = \frac{q}{2} \sum_{x_1x_2 \in X_1X_2} x \eta_2 (x_5x_6x_7).
\]

Now \( (x_5x_6x_7)^x \in X_3 \) where \( x \in X_1 \), so substituting with \( x_5(t_5)x_6(t_6)x_7(t_7) \) and \( x_1(s_1)x_2(s_2) \), yields

\[
\eta_2 U \left( \prod_{i=5}^{7} x_i(t_i) \right)
\]

\[
= \frac{q}{2} \sum_{s_1,s_2} \eta_2 (x_5(t_5)x_6(t_6)x_7(t_7)x_8(t_5s_2 + t_6s_1)x_9(t_7s_1)x_{10}(t_7s_2))
\]

\[
= \frac{q}{2} \eta_2 (x_5(t_5)x_6(t_6)x_7(t_7)) \sum_{s_1,s_2} \phi (a_8(t_5s_2 + t_6s_1) + a_9t_7s_1 + a_{10}t_7s_2)
\]

\[
= \frac{q}{2} \eta_2 (x_5(t_5)x_6(t_6)x_7(t_7)) \sum_{s_1,s_2} \phi (s_1(a_8t_6 + a_9t_7) + s_2(a_8t_5 + a_{10}t_7)).
\]
Since \( \sum_{t \in \mathbb{F}_q} \phi(t) = 0 \), we obtain non-zero values only if \( a_8 t_6 + a_9 t_7 = 0 \) and \( a_7 t_5 + a_{10} t_7 = 0 \). Hence, \( \frac{t_5}{a_1} = \frac{t_6}{a_9} = \frac{t_7}{a_8} \), and \( \prod_{i=5}^{7} x_i(t_i) = x_{567}(\frac{t_7}{a_8}) \in S_{567} \).

By Lemma 2.2 (a), we have

\[
\eta_2 U \left( \prod_{i=5}^{7} x_i(t_i) \right) = \delta_{a_8 t_5, a_{10} t_7} \delta_{a_8 t_6, a_9 t_7} \frac{q^3}{2} \eta_2 \left( x_{567} \left( \frac{t_7}{a_8} \right) \right)
\]

\[
= \delta_{a_8 t_5, a_{10} t_7} \delta_{a_8 t_6, a_9 t_7} \frac{q^3}{2} \phi \left( A_0 \frac{t_7}{a_8} \right).
\]

Therefore, we have \( \eta_2 U \left( \prod_{i=1}^{10} x_i(t_i) \right) = \frac{q^3}{2} \phi \left( b_{124} \frac{t_5}{a_1} + A_0 \frac{t_7}{a_8} + \sum_{i=8}^{10} a_i t_i \right) \) if \( \prod_{i=1}^{10} x_i(t_i) \in F_{124} S_{567} X_8 X_9 X_{10} = Z \), as stated in the theorem.

Now we compute \( \eta_2 U (x_3 \prod_{i=5}^{7} x_i) \) with \( x_3 \in F_3^X = \{ x_3(t_0^\phi) \}, t_0^\phi = \left( \frac{t_0 A}{A} \right) \). As \( I_U(\eta_2) = K_2 \trianglelefteq U \) and \( SX_1 X_2 \) is a representative set of \( U/K_2 \),

\[
(\chi \eta_2)^U = \eta_2 U \in \text{Irr}(U) \quad \text{for all} \ x \in SX_1 X_2.
\]

For each \( x_2(s) \in X_2 \), we have

\[
x_2(s) \eta_2(x_5(t)) = \eta_2(x_5(t) x_8(t s)) = \phi(b_5 t + a_8 t s) = \phi(t(b_5 + a_8 s)).
\]

So instead of choosing \( s = \frac{b_5}{a_8} \), we suppose that \( \eta_2 \) has \( b_5 = 0 \), i.e. \( \eta_2(x_5) = 1 \) for all \( x_5 \in X_5 \). It is easy to check that \( t_0, \eta_2|_{F_{124}} = \phi b_{124} \) and \( \eta_2|_{F_3} = \phi b_3 \) are invariant under conjugation.

We have

\[
[x_3(t_3) x_5(t_5) x_6(t_6) x_7(t_7), x_1(s_1) x_2(s_2)]
\]

\[
= x_3(t_3) x_5(t_5 + t_3 s_1) x_6(t_6 + t_3 s_2) x_7(t_7)
\]

\[
\times x_8(t_3 s_1 s_2 + t_5 s_2 + t_6 s_1) x_9(t_7 s_1) x_{10}(t_7 s_2).
\]

Therefore,

\[
\eta_2 U (x_3(t_3) x_5(t_5) x_6(t_6) x_7(t_7))
\]

\[
= \sum_{x \in SX_1 X_2} x \eta_2(x_3(t_3) x_5(t_5) x_6(t_6) x_7(t_7))
\]

\[
= \frac{q}{2} \sum_{x \in X_1 X_2} x \eta_2(x_3(t_3) x_5(t_5) x_6(t_6) x_7(t_7))
\]

\[
= \frac{q}{2} \sum_{s_1, s_2} \eta_2(x_3(t_3) x_5(t_5 + t_3 s_1) x_6(t_6 + t_3 s_2) x_7(t_7)
\]

\[
\times x_8(t_3 s_1 s_2 + t_5 s_2 + t_6 s_1) x_9(t_7 s_1) x_{10}(t_7 s_2))
\]
\[
\begin{align*}
= & \frac{q}{2} \eta_2 \left( x_3(t_3) \prod_{i=5}^{7} x_i(t_i) \right) \\
& \times \sum_{s_1, s_2} \phi(b_6 t_3 s_2 + a_8 (t_3 s_1 s_2 + t_5 s_2 + t_6 s_1) + a_9 t_7 s_1 + a_{10} t_7 s_2) \\
= & \frac{q}{2} \eta_2 (x_3(t_3) x_6(t_6) x_7(t_7)) \\
& \times \sum_{s_1, s_2} \phi(s_1(a_8 t_3 s_2 + a_8 t_6 + a_9 t_7) + s_2(b_6 t_3 + a_{10} t_7 + a_8 t_5)).
\end{align*}
\]

Set \( C(t_5, t_6, t_7) = \sum_{s_1, s_2} \phi(s_1(a_8 t_3 s_2 + a_8 t_6 + a_9 t_7) + s_2(b_6 t_3 + a_{10} t_7 + a_8 t_5)). \)

We have

\[
\begin{align*}
C(t_5, t_6, 0) &= \sum_{s_1, s_2} \phi(s_1(t_3 s_2 + t_6) a_8 + s_2(b_6 t_3 + a_8 t_5)) \\
&= q \sum_{s_2 = t_6 \overrightarrow{t_3}} \phi \left( \frac{t_6}{t_3} (b_6 t_3 + a_8 t_5) \right) \\
&= q \phi \left( b_6 t_6 + \frac{a_8 t_5 t_6}{t_3} \right).
\end{align*}
\]

Therefore, we get

\[
\eta_2^{U_x} (x_3(t_3) x_5(t_5) x_6(t_6)) = \frac{q^2}{2} \eta_2 (x_3(t_3) x_6(t_6)) \phi \left( \frac{a_8 t_5 t_6}{t_3} \right) \\
= \frac{q^2}{2} \eta_2 (x_3(t_3)) \phi \left( \frac{a_8 t_5 t_6}{t_3} \right).
\]

Since

\[
x_5(t_5) x_6(t_6) x_7(t_7) = x_5 \left( t_5 + \frac{a_{10} t_7}{a_8} \right) x_6 \left( t_6 + \frac{a_9 t_7}{a_8} \right) x_7 \left( \frac{t_7}{a_{10}} \right),
\]

where

\[
x_{567} \left( \frac{t_7}{a_8} \right) = x_5 \left( \frac{a_{10} t_7}{a_8} \right) x_6 \left( \frac{a_9 t_7}{a_8} \right) x_7 \left( \frac{t_7}{a_{10}} \right) \in S_{124} \subset Z(\eta_2^{U_x})
\]

and

\[
\eta_2 \left( x_{567} \left( \frac{t_7}{a_8} \right) \right) = \phi_{A_{10}} \left( \frac{t_7}{a_8} \right),
\]

where

\[
A_{10} = \left( \begin{array}{cc}
a_{10} & t_7 \\
a_8 & \end{array} \right),
\]
we have
\[
\eta_2^U (x_3(t_3)x_5(t_5)x_6(t_6)x_7(t_7)) = \phi_{At_0} \left( \frac{t_7}{a_8} \right) \eta_2^U \left( x_3(t_3)x_5\left( t_5 + \frac{a_{10}t_7}{a_8} \right)x_6\left( t_6 + \frac{a_{9}t_7}{a_8} \right) \right)
\]
\[
= \phi \left( At_0 \frac{t_7}{a_8} \right) \frac{q^2}{2} \eta_2(x_3(t_3)) \phi \left( \frac{a_8}{t_3} \left( t_5 + \frac{a_{10}t_7}{a_8} \right) \left( t_6 + \frac{a_{9}t_7}{a_8} \right) \right)
\]
\[
= \frac{q^2}{2} \phi \left( b_3t_3 + At_0 \frac{t_7}{a_8} + \frac{a_8^2a_{9}a_{10}}{(t_0)_{\phi}} \left( t_5 + \frac{a_{10}t_7}{a_8} \right) \left( t_6 + \frac{a_{9}t_7}{a_8} \right) \right)
\]
\[
= \frac{q^2}{2} \phi \left( b_3t_0^\phi + At_0 \frac{t_7}{a_8} + \frac{A^2}{(t_0)_{\phi}} \left( t_5 + \frac{t_7}{a_8} \right) \left( t_6 + \frac{t_7}{a_8} \right) \right). \quad \Box
\]

5.4 Proof of Section “Sylow 3-subgroups of $E_6(3^f)$”

5.4.1 Proof of Lemma 3.2

Set $\lambda = \lambda_{b_{12},b_{13},b_{14},b_{15},b_{16}}$ throughout the whole proof.

(a) Recall $H_3 = \prod_{i=12}^{16} X_i \leq H$ is elementary abelian and $H_4H_3 \leq U$. First, we show that $R_3 = \{ x \in H_3 : |\lambda^U(x)| = \lambda^U(1) \}$ and $\lambda^U(r_3(t)) = q^8 \phi_{b_3}(t)$ for all $r_3(t) \in R_3$.

Since $\lambda$ is linear and $\lambda(x) \in \mathbb{C}$ for all $x \in H$, the induction formula gives that $|\lambda^U(x)| = \lambda^U(1)$ iff $\lambda(y) = \lambda(x)$ for all $y \in TX_4$, where $TX_4$ is a transversal of $H$ in $U$. Since $\lambda(y) = \lambda(x)$ iff $\lambda([x,y]) = 1$, we are going to find all $x \in H_3$ such that $\lambda([x,y]) = 1$ for all $y \in TX_4$. It is clear that

\[
[X_i, X_4] = \{ 1 \} = [X_i, X_7X_{11}] \quad \text{for all } 12 \leq i \leq 16.
\]

Here, we write $\prod_{j=1}^{6} x_j(u_j) \in T$ with $u_4 = 0$. It suffices to check that statement for all $y = \prod_{j=1}^{6} x_j(u_j) \in T$. For $t_i, u_j \in \mathbb{F}_q$, we have

\[
\left[ \prod_{i=12}^{16} x_i(t_i), \prod_{j=1}^{6} x_j(u_j) \right] = [x_{12}(t_{12}), x_{2}(u_2)][x_{15}(t_{15}), x_{2}(u_2)][x_{16}(t_{16}), x_{2}(u_2)][x_{13}(t_{13}), x_{1}(u_1)]
\times [x_{15}(t_{15}), x_{1}(u_1)][x_{14}(t_{14}), x_{3}(u_3)][x_{16}(t_{16}), x_{3}(u_3)][x_{12}(t_{12}), x_{5}(u_5)]
\times [x_{13}(t_{13}), x_{5}(u_5)][x_{14}(t_{14}), x_{6}(u_6)][x_{15}(t_{15}), x_{6}(u_6)]
= x_{17}(-t_{12}u_2)x_{19}(-t_{15}u_2)x_{20}(-t_{16}u_2)x_{17}(-t_{13}u_1)x_{18}(-t_{15}u_1)x_{19}(-t_{14}u_3)
\times x_{21}(-t_{16}u_3)x_{18}(t_{12}u_5)x_{19}(t_{13}u_5)x_{20}(t_{14}u_6)x_{21}(t_{15}u_6).
\]
Since \( \lambda(x_i(t)) = \phi(t) \), \( 17 \leq i \leq 21 \), for all \( u_j \in \mathbb{F}_q \), we force
\[
(-t_{12} - t_{15} - t_{16})u_2 + (-t_{13} - t_{15})u_1 + (-t_{14} - t_{16})u_3
\]
\[
+ (t_{12} + t_{13})u_5 + (t_{14} + t_{15})u_6 = 0.
\]
So we have a system with variables \( t_i \):
\[
\begin{align*}
-t_{12} - t_{15} - t_{16} &= 0, \\
-t_{13} - t_{15} &= 0, \\
-t_{14} - t_{16} &= 0, \\
t_{12} + t_{13} &= 0, \\
t_{14} + t_{15} &= 0.
\end{align*}
\]
Since \( \gcd(q, 3) = 3 \), we have 
\[
t_{12} = t_{16} = t_{15}, t_{13} = t_{14} = -t_{15} \quad \text{for all } t_{15} = t \in \mathbb{F}_q.
\]
So \( x \in H_3 \) satisfies \( |\lambda^U(x)| = \lambda^U(1) \) iff
\[
x = x_{12}(t)x_{13}(-t)x_{14}(-t)x_{15}(t)x_{16}(t) = r_3(t) \in R_3 \quad \text{for } t \in \mathbb{F}_q,
\]
i.e. \( R_3 = \{ x \in H_3 : |\lambda^U(x)| = \lambda^U(1) \} \).

The computation that shows that \( \lambda^U|_{R_3} = \lambda^U(1)\phi_{B_3} \) also shows that it is sufficient to check that \( \lambda(r_3(t)) = \phi_{B_3}(t) \). For each \( r_3(t) \in R_3 \), we have
\[
\lambda(r_3(t)) = \phi(t(b_{12} - b_{13} - b_{14} + b_{15} + b_{16})) = \phi_{B_3}(t).
\]
Now we show that \( S_1 = \text{Stab}_T(\lambda|_{H_4H_3}) \). Since \([H_4,T] = [H_3, X_7X_11] = \{1\} \), it suffices to find \( y \in X_2X_1X_3X_5X_6 \) such that \( \lambda([x, y]) = 1 \) for all \( x \in H_3 \). Using the computation of \( \prod_{i=16}^{12} x_i(t_i), \prod_{j=1}^{6} x_j(u_j) \) above, we see that
\[
(-u_2 + u_5)t_{12} + (-u_1 + u_5)t_{13} + (-u_3 + u_6)t_{14}
\]
\[
+ (u_1 + u_2 - u_6)t_{15} + (-u_2 - u_3)t_{16} = 0
\]
for all \( t_j \in \mathbb{F}_q \). So we have a system with variables \( u_j \):
\[
\begin{align*}
-u_2 + u_5 &= 0, \\
-u_1 + u_5 &= 0, \\
-u_3 + u_6 &= 0, \\
-u_1 - u_2 + u_6 &= 0, \\
-u_2 - u_3 &= 0.
\end{align*}
\]
As \( \gcd(q, 3) = 3 \), we have \( u_1 = u_5 = u_2, u_3 = u_6 = -u_2 \) for all \( u_2 = t \in \mathbb{F}_q \). So \( \prod_{j=1}^{6} x_j(u_j) = x_2(t)x_1(t)x_3(-t)x_5(t)x_6(-t) = s_1(t) \in S_1 \).
(b) Since \( H = Z(U)H_3X_8X_9X_{10} \), to find \( \text{Stab}_T(\lambda) \subset \text{Stab}_T(\lambda|_{H_4H_3}) = S_1 \), by (a), it is enough to find \( s_1 \in S_1 \) such that \( s_1\lambda(x_i) = \lambda(x_i) \) for \( i = 8, 9, 10 \). Again, for each \( x_i(t_i) \in X_i \), \( i = 8, 9, 10 \), and \( s_1 = s_1(t, r, s) \in S_1 \), we compute \([x_i, s_1]::

\[
[x_8(t_8), s_1] = x_20(t_8)x_17(\tau_8r)x_14(\tau_8t)x_20(\tau_8t^2)x_13(\tau_8t)x_19(\tau_8t^2),
\]

\[
[x_9(t_9), s_1] = x_21(t_9)x_15(\tau_9t)x_21(\tau_9t^2)x_12(\tau_9t)x_18(\tau_9t^2)x_13(\tau_9t)
\times x_19(\tau_9t^2)x_17(\tau_9t^2),
\]

\[
[x_{10}(t_{10}), s_1] = x_18(-t_{10}r)x_16(-t_{10}t)x_15(t_{10}t)x_21(-t_{10}t^2)x_14(-t_{10}t)
\times x_20(t_{10}t^2)x_19(-t_{10}t^2).
\]

Since \( \lambda(x_i(t)) = \phi(b_it) \), \( 12 \leq i \leq 16 \), and \( \lambda(x_i(t)) = \phi(t) \), \( 17 \leq i \leq 21 \), from \( \lambda([x_9(t_9), s_1]) = \lambda([x_{10}(t_{10}), s_1]) = 1 \) for all \( t_9, t_{10} \in \mathbb{F}_q \), we have

\[
s = 2t^2 + b_{12}t + b_{13}t - b_{15}t \quad \text{and} \quad r = 2t^2 - b_{14}t + b_{15}t - b_{16}t.
\]

From \( \lambda([x_8(t_8), s_1]) = 1 \) for all \( t_8 \in \mathbb{F}_q \), we have \( s - r + b_{14}t + b_{13}t = 0 \). Therefore, \( s_1 \in \text{Stab}_T(\lambda) \) iff \( r, s \) are as above and

\[
s - r + b_{14}t + b_{13}t = 2t^2 + b_{12}t + b_{13}t - b_{15}t - (2t^2 - b_{14}t + b_{15}t - b_{16}t)
\]

\[
+ b_{14}t + b_{13}t
\]

\[
= t(b_{12} - b_{13} - b_{14} + b_{15} + b_{16})
\]

\[
= tB_3 = 0.
\]

Therefore, if \( B_3 \neq 0 \), then \( \text{Stab}_T(\lambda) = \{1\} \).

(c) By (a), \( T/S_1 \) acts faithfully on the set of all extensions of \( \lambda|_{H_4} \) to \( H_4H_3 \) with the same \( B_3 \). Since \( |T/S_1| = q^4 = |H_3/R_3| \), it follows that this action is transitive. Therefore, with \( B_3 = 0 \), there exists \( x \in T \) such that \( x\lambda = \lambda_{b_8', b_9', b_{10}'} \)

for some \( b_8', b_9', b_{10}' \in \mathbb{F}_q \).

Now set \( \lambda = \lambda_{b_8, b_9, b_{10}} \) and \( \overline{H}_3 \) is the normal closure of \( H_3 \) in \( HX_4S_1 \). To show that

\[
\overline{H}_3 \subset \ker(\lambda^{HX_4S_1}) \preceq HX_4S_1,
\]

it suffices to show that \( H_3 \subset \ker(\lambda^{HX_4S_1}) \). By (a), \( \text{Stab}_{TX_4}(\lambda|_{H_4H_3}) = S_1X_4 \) which is a transversal of \( H \) in \( HX_4S_1 \), the claim holds by the induction formula and \( H_3 \subset \ker(\lambda) \).

By Lemma 1.5 above for \( G = U \) with \( N = M = HX_4S_1 \), \( X = X_1X_3X_5X_6 \), \( Y = \overline{H}_3 \) and \( Z = H_4 \), the induction map from \( \text{Irr}(HX_4S_1/\overline{H}_3, \lambda) \) to \( \text{Irr}(U, \lambda) \) is bijective. Since \( \overline{H}_3 \subset \lambda^{HX_4S_1} \), \( \text{Irr}(HX_4S_1/\overline{H}_3, \lambda) = \text{Irr}(HX_4S_1, \lambda) \).
5.4.2 Proof of Lemma 3.3

Recall that $R_2 = \{ r_2(t) := x_8(-t)x_9(t)x_{10}(t) : t \in \mathbb{F}_q \} \leq H_2 = X_8X_9X_{10}$ and 

$$\lambda = \lambda_{b_8,b_9,b_{10}}.$$ 

By Lemma 3.2 (c), it suffices to work with the quotient group $HX_4S_1/\overline{H_3}$.

(a) The fact that $S_2 = \text{Stab}_{S_1}(\lambda)$ is a direct consequence of Lemma 3.2 (b) with $B_3 = 0$. Recall that $X_4S_1$ is a transversal of $H$ in $HX_4S_1$ and $[H_2, X_4] = \{1\}$. So to show that $R_2 = \{ x \in H_2 : |\lambda^{HX_4S_1}(x)| = |\lambda^{HX_4S_1}(1)| \}$ we find all $x \in H_2$ such that $\lambda([x, y]) = 1$ for all $y \in S_1$. Since $H \leq HX_4S_1$ is abelian, using the computation in Lemma 3.2 (b), for $s_1(t, r, s) \in S_1$ and $x_8(t_8)x_9(t_9)x_{10}(t_{10}) \in H_2$ we have

$$[x_8(t_8)x_9(t_9)x_{10}(t_{10}), s_1(t, r, s)] = [x_8(t_8), s_1(t, r, s)][x_9(t_9), s_1(t, r, s)][x_{10}(t_{10}), s_1(t, r, s)] = x_{20}(t_8s)x_{17}(-t_8r)x_{20}(-t_8t^2)x_{19}(t_8t^2)x_{21}(t_9s)x_{21}(-t_9t^2)$$

$$\times x_{18}(-t_9t^2)x_{19}(-t_9t^2)x_{17}(t_9t^2)x_{18}(-t_{10}r)x_{21}(-t_{10}t^2)$$

$$\times x_{20}(t_{10}t^2)x_{19}(-t_{10}t^2).$$

Therefore, with $\lambda|_{X_i} = \phi$ for all $17 \leq i \leq 21$, for all $t, r, s \in \mathbb{F}_q$ we need

$$(t_8 + t_9)s - (t_8 + t_{10})r + (t_9 - t_{10})t^2 = 0$$

So $t_9 = t_{10} = u$ and $t_8 = -u$ for all $u \in \mathbb{F}_q$, i.e. $x = r_2(u) \in R_2$.

To show that $\lambda^{HX_4S_1}|_{R_2} = \lambda^{HX_4S_1}(1)\phi_{b_2}$, it is enough to check that

$$\lambda(r_2(t)) = \phi_{b_2}(t).$$

For each $r_2(t) \in R_2$ we have

$$\lambda(r_2(t)) = \phi(t(-b_8 + b_9 + b_{10})) = \phi_{b_2}(t).$$

(b) Suppose that $B_2 \not\in \{ c^2 : c \in \mathbb{F}_q^\times \}$. Let $\eta$ be an extension of $\lambda$ to $HX_4$. By (a), we have $S_2 = \text{Stab}_{S_1}(\lambda)$, hence $\text{Stab}_{S_1}(\eta|_{H}) = S_2$. Since $S_1$ is a transversal of $HX_4$ in $HX_4S_1$, to find $\text{Stab}_{S_1}(\eta)$, it is enough to find all $s_2(t) \in S_2$ such that $\eta([x_4, s_2(t)]) = 1$ for all $x_4 \in X_4$. For each $s_2(t) \in S_2$, we have

$$[x_4(t_4), s_2(t)] = x_{10}(t_4t)x_9(t_4t)x_{21}(2t_4t^3)x_{21}(-t_4t^3)x_8(-t_4t)$$

$$\times x_{20}(-2t_4t^3)x_{17}(2t_4t^3)x_{20}(t_4t^3)x_{19}(-t_4t^3).$$

Since $\eta(x_i(t)) = \phi(b_it)$, $8 \leq i \leq 10$, and $\eta(x_i(t)) = \phi(t)$, $17 \leq i \leq 21$, for all $t_4 \in \mathbb{F}_q$, $\eta([x_4(t_4), s_3(t)]) = 1$ forces

$$t_4(t^3 - B_2t) = t_4(t^3 - B_2t) \in \ker(\phi).$$
Since $t_4(t^3 - B_2 t) \in \ker(\phi)$ for all $t_4 \in \mathbb{F}_q$, we have $0 = t^3 - B_2 t = t(t^2 - B_2)$. Since $B_2 \notin \{c^2 : c \in \mathbb{F}_q^\times\}$, the equation $t(t^2 - B_2) = 0$ has only the trivial solution $t = 0$ in $\mathbb{F}_q$. Therefore, $s_2(t) = 1$, i.e. $\text{Stab}_{S_1}(\eta) = \{1\}$. Hence,

$$I_{HX_4S_1}(\eta) = HX_4.$$  

(c) Suppose $B_2 = c^2 \in \mathbb{F}_q^\times$ and let $\eta$ be an extension of $\lambda$ to $HX_4$. Using the computation in (b), we continue with the analysis for the solutions of $t$ to obtain $t_4(t^2 - B_2) \in \ker(\phi)$ for all $t_4 \in \mathbb{F}_q$. So it forces $t(t^2 - B_2) = 0$. This equation has three solutions $\{0, \pm c\}$. Hence, $\text{Stab}_{S_1}(\eta) = \{1, s_2(\pm c)\} = F_2$. So

$$I_{HX_4S_1}(\eta) = HX_4F_2.$$  

By the above argument,

$$[HX_4F_2, HX_4F_2] \subset \ker(\eta),$$

hence $\eta$ extends to $I_{HX_4S_1}(\eta)$.

To show that $\lambda$ extends to $HF_4S_2$, we check $[HF_4S_2, HF_4S_2] \subset \ker(\lambda)$. Using the same argument, it is enough to check that $[s_2(t), x_4(t_4)] \in \ker(\lambda)$. By the computation in (b), we need $t_4(t^3 - B_2 t) = t_4(t^3 - c^2 t) \in \ker(\phi)$ for all $t_4 \in \mathbb{F}_q$. By Proposition 1.3, since $t_4 \in \{0, \pm c\}$, the claim holds.

Let $\lambda_1, \lambda_2$ be two extensions of $\lambda$ to $HX_4F_2$, and $\gamma$ an extension of $\lambda$ to $HF_4S_2$. Since the degree of all the irreducible constituents of $\lambda^{HX_4S_1}$ is $q^3/3$, we have $\lambda_1^{HX_4S_1}, \lambda_2^{HX_4S_1}, \gamma^{HX_4S_1} \in \text{Irr}(HX_4S_1, \lambda)$.

Choose $1 \in S \subset S_1$ as a representative set of the double coset

$$HF_4S_2 \backslash HX_4S_1/HX_4F_2.$$  

As $HF_4S_2 \cap HX_4F_2 = HF_4F_2$ and $HX_4F_2 \leq HX_4S_1$, by Mackey’s formula,

$$(\lambda_1^{HX_4S_1}, \gamma^{HX_4S_1}) = \sum_{s \in S}(^s\lambda_1|_{s(HX_4F_2)\cap HF_4S_2}, \gamma|_{s(HX_4F_2)\cap HF_4S_2})$$

$$= \sum_{s \in S}(^s\lambda_1|_{HF_4F_2}, \gamma|_{HF_4F_2}).$$

For each $s \in S$, if $^s\lambda_1|_{HF_4F_2} = \gamma|_{HF_4F_2}$, then $^s\lambda_1|_H = \gamma|_H$. Since both are extensions of the character $\lambda$, we have $^s\lambda = \lambda$, i.e. $s \in \text{Stab}_{S_1}(\lambda) = S_2$. There is a unique $1 \in S \cap S_2$ since $S$ is a representative set of $HF_4S_2 \backslash HX_4S_1/HX_4F_2$. So

$$(\lambda_1^{HX_4S_1}, \gamma^{HX_4S_1}) = (\lambda_1|_{HF_4F_2}, \gamma|_{HF_4F_2}) = 1 \text{ iff } \lambda_1|_{F_i} = \gamma|_{F_i}, i \in \{2, 4\}.$$  

Therefore, $\lambda_1^{HX_4S_1} = \gamma^{HX_4S_1} = \lambda_2^{HX_4S_1}$ iff $\lambda_1|_{F_i} = \lambda_2|_{F_i}, i \in \{2, 4\}$. □
5.5 Proofs of Section “Sylow 5-subgroups of $E_8(5^f)$”

5.5.1 Proof of Lemma 4.2

(a) First we find all $x \in H_5$ such that $|\lambda^U(x)| = \lambda^U(1)$. Since $TX_5$ is a transversal of $H$ in $U$, we get $[H_5, X_5] = \{1\} = [H_5, T_k]$ for all $k \geq 2$, and $y\lambda(x) = \lambda(x)$ iff $\lambda([x, y]) = 1$, it suffices to find all $x \in H_5$ such that $\lambda([y, x]) = 1$ where $y \in T_1$. For each $y = \prod_{i=1}^8 x_i(u_i) \in T_1$ with $u_5 = 0$, and $x = \prod_{j=30}^{36} x_j(v_j) \in H_5$, to abbreviate our notation we write $x_i$ for $x_i(-)$ and plug in the parameters in $(-)$ as need be. We have

\[
\left[ \prod_{j=30}^{36} x_j(v_j), \prod_{i=1}^8 x_i(u_i) \right]
\]

\[
= [x_{30}, x_4][x_{30}, x_6][x_{31}, x_2][x_{31}, x_7][x_{32}, x_1][x_{32}, x_6][x_{33}, x_1] \\
\times [x_{33}, x_4][x_{33}, x_7][x_{34}, x_3][x_{34}, x_8][x_{35}, x_2][x_{35}, x_1][x_{35}, x_8] \\
\times [x_{36}, x_2][x_{36}, x_3]
\]

\[
= x_{37}(-v_{30}u_4)x_{38}(v_{30}u_6)x_{38}(-v_{31}u_2)x_{39}(v_{31}u_7)x_{37}(-v_{32}u_1) \\
\times x_{40}(v_{32}u_6)x_{38}(-v_{33}u_1)x_{40}(-v_{33}u_4)x_{41}(v_{33}u_7) \\
\times x_{41}(-v_{34}u_3)x_{42}(v_{34}u_8)x_{41}(-v_{35}u_2)x_{39}(-v_{35}u_1) \\
\times x_{43}(v_{35}u_8)x_{42}(-v_{36}u_2)x_{43}(-v_{36}u_3).
\]

Since $\lambda|x_i = \phi$ for all $i \in [37\.43]$, for all $s_j$ we need

\[
(-v_{31} - v_{35} - v_{36})u_2 + (-v_{32} - v_{33} - v_{35})u_1 + (-v_{34} - v_{36})u_3 \\
+ (-v_{30} - v_{33})u_4 + (v_{30} + v_{32})u_6 + (v_{31} + v_{33})u_7 \\
+ (v_{34} + v_{35})u_8 = 0.
\]

Therefore, we obtain a system with variables $v_i$ as follows:

\[
\begin{align*}
-v_{31} - v_{35} - v_{36} &= 0, \\
-v_{32} - v_{33} - v_{35} &= 0, \\
-v_{34} - v_{36} &= 0, \\
-v_{30} - v_{33} &= 0, \\
v_{30} + v_{32} &= 0, \\
v_{31} + v_{33} &= 0, \\
v_{34} + v_{35} &= 0.
\end{align*}
\]
Since \(\gcd(q, 5) = 5\), we have

\[
(v_{30}, v_{31}, v_{32}, v_{33}, v_{34}, v_{35}, v_{36}) = (v, v, -v, -v, -2v, 2v, 2v)
\]

for all \(v \in F_q\). Hence, \(x = r_5(v) \in R_5\), i.e. \(R_5 = \{x \in H_5 : |\lambda^U(x)| = \lambda^U(1)\}\).

To show that \(\lambda^U |_{R_5} = \lambda^U(1) \phi_{B_5}\), it suffices to check that \(\lambda(r_5(v)) = \phi_{B_5}(v)\).

For each \(r_5(v) \in R_5\), we have

\[
\lambda(r_5(v)) = \phi(v(b_{30} + b_{31} - b_{32} - b_{33} - 2b_{34} + 2b_{35} + 2b_{36})) = \phi_{B_5}(v).
\]

To show that \(S_1 = \text{Stab}_T(\lambda |_{H_6H_5})\), we find all \(y \in T\) such that \(\lambda([x, y]) = 1\) for all \(x \in H_6H_5\). Since \(H_6 = \text{Z}(U)\) and \([H_5, T_k] = \{1\}\) for all \(k \geq 2\), it is sufficient to find \(y \in T_1\) such that \(\lambda([x, y]) = 1\) for all \(x \in H_5\). Using the above computation of \([\prod_{j=30}^{36} x_j(v_j), \prod_{i=1}^{8} x_i(u_i)]\), we find \(u_i\) such that for all \(v_j\)

\[
(-u_4 + u_6)v_{30} + (-u_2 + u_7)v_{31} + (-u_1 + u_6)v_{32} + (-u_1 - u_4 + u_7)v_{33}
+ (-u_3 + u_8)v_{34} + (-u_2 - u_1 + u_8)v_{35} + (-u_2 - u_3)v_{36} = 0.
\]

Therefore, we obtain a system with variables \(u_i\) as follows:

\[
\begin{align*}
-u_4 + u_6 &= 0, \\
-u_2 + u_7 &= 0, \\
-u_1 + u_6 &= 0, \\
-u_1 - u_4 + u_7 &= 0, \\
-u_3 + u_8 &= 0, \\
-u_2 - u_1 + u_8 &= 0, \\
-u_2 - u_3 &= 0.
\end{align*}
\]

Since \(\gcd(q, 5) = 5\), we have

\[
(u_2, u_1, u_3, u_4, u_6, u_7, u_8) = (2u, u, -2u, u, u, 2u, -2u)
\]

for all \(u \in F_q\). So \(y = l_1(u) \in L_1\), i.e. \(S_1 = \text{Stab}_T(\lambda |_{H_6H_5})\).

(b) Suppose \(B_5 \neq 0\). To show that \(\text{Stab}_T(\lambda) = \{1\}\), we are going to show that

\[
\begin{align*}
\text{Stab}_{S_1}(\lambda |_{H_6H_5H_4}) &= T_3T_4, \\
\text{Stab}_{T_3T_4}(\lambda |_{H_6H_5H_4H_3}) &= T_4, \\
\text{Stab}_{T_4}(\lambda) &= \{1\}.
\end{align*}
\]

First, we show that \(\text{Stab}_{S_1}(\lambda |_{H_6H_5H_4}) = T_3T_4\). By considering root heights, it is clear that \([H_6H_5H_4, T_3T_4] = \{1\}\), hence, \(T_3T_4 \subset \text{Stab}_{S_1}(\lambda |_{H_6H_5H_4})\). It suffices to show that \(\text{Stab}_{L_1T_2}(\lambda |_{H_6H_5H_4}) = \{1\}\), i.e. there is no nontrivial \(y \in L_1T_2\)
such that $\lambda([h, y]) = 1$ for all $h \in H_5 H_4$. For each

$$y = \prod_{i=1}^{15} x_i(u_i) \in L_1 T_2$$

(with $u_5 = u_{12} = u_{13} = 0$ and $\prod_{i=1}^{8} x_i(u_i) = l_1(u)$), and

$$h = \prod_{j=24}^{36} x_j(v_j) \in H_5 H_4,$$

we have

$$\left[ \prod_{j=24}^{36} x_j(v_j), \prod_{i=1}^{15} x_i(u_i) \right] = [x_{24}, x_{10}][x_{24}, x_{14}][x_{25}, x_{14}][x_{26}, x_{15}][x_{26}, x_{9}][x_{26}, x_{11}][x_{27}, x_{15}]$$

$$\times [x_{27}, x_{10}][x_{29}, x_{11}][x_{24}, x_2][x_{24}, x_2], x_6][x_{24}, x_2], x_4]$$

$$\times [x_{24}, x_6][x_{24}, x_6], x_7][x_{25}, x_1][x_{25}, x_1], x_4][x_{25}, x_1], x_6]$$

$$\times [x_{25}, x_4][x_{25}, x_4], x_6][x_{25}, x_6][x_{25}, x_6], x_7][x_{26}, x_3]$$

$$\times [[x_{26}, x_3], x_4][x_{26}, x_3], x_7][x_{26}, x_7][x_{26}, x_7], x_8][x_{27}, x_2]$$

$$\times [[x_{27}, x_2], x_1][x_{27}, x_2], x_4][x_{27}, x_2], x_7][x_{27}, x_1]$$

$$\times [[x_{27}, x_1], x_7][x_{27}, x_7][x_{28}, x_8][x_{28}, x_2][x_{28}, x_2], x_3]$$

$$\times [[x_{28}, x_2], x_8][x_{28}, x_3][x_{28}, x_3], x_8][x_{28}, x_8][x_{29}, x_4]$$

$$= x_{37}(v_{24} u_{10}) x_{39}(v_{24} u_{14}) x_{41}(v_{25} u_{14}) x_{42}(v_{26} u_{15}) x_{38}(-v_{26} u_9)$$

$$\times x_{40}(v_{26} u_{11}) x_{43}(v_{27} u_{15}) x_{40}(v_{27} u_{10}) x_{39}(-v_{28} u_9)$$

$$\times x_{42}(-v_{29} u_{10}) x_{43}(-v_{29} u_{11}) x_{30}(-2v_{24} u) x_{38}(-2v_{24} u^2)$$

$$\times x_{37}(2v_{24} u^2) x_{31}(v_{24} u) x_{39}(v_{24} u^2) x_{30}(-v_{25} u) x_{37}(v_{25} u^2)$$

$$\times x_{38}(-v_{25} u^2) x_{32}(-v_{25} u) x_{40}(-v_{25} u^2) x_{33}(v_{25} u) x_{41}(2v_{25} u^2)$$

$$\times x_{33}(2v_{26} u) x_{40}(-2v_{26} u^2) x_{41}(4v_{26} u^2) x_{34}(2v_{26} u)$$

$$\times x_{42}(-v_{26} u^2) x_{33}(-v_{27} u) x_{38}(2v_{27} u^2) x_{40}(2v_{27} u^2)$$

$$\times x_{41}(-v_{27} u^2) x_{31}(-v_{27} u) x_{39}(-2v_{27} u^2) x_{35}(v_{27} u)$$

$$\times x_{43}(-v_{27} u^2) x_{34}(-2v_{28} u) x_{41}(-4v_{28} u^2) x_{42}(4v_{28} u^2)$$

$$\times x_{35}(2v_{28} u) x_{43}(-4v_{28} u^2) x_{36}(-v_{28} u) x_{36}(-v_{29} u).$$
Since \( \lambda|_{X_i} = \phi \) for all \( i \in [37..43] \) and \( \lambda|_{X_i} = \phi_{b_i} \) for the others, after evaluating the above at \( \lambda \) and setting this to 1, for all \( v_j \), we need

\[
v_{24}(u_{10} + u_{14} - 2b_{30}u + b_{31}u + 2u^2) \\
+ v_{25}(u_{14} - b_{30}u - b_{32}u + b_{33}u + u^2) \\
+ v_{26}(u_{15} - u_9 + u_{11} + 2b_{33}u - 2u^2 + 2b_{34}u) \\
+ v_{27}(u_{15} + u_{10} - 2b_{33}u - b_{31}u + 2b_{35}u - u^2) \\
+ v_{28}(-u_9 - 2b_{34}u + 2b_{35}u + u^2 - 2b_{36}u) \\
+ v_{29}(-u_{10} - u_{11} - b_{36}u) = 0.
\]

Hence, we have a system with variables \( u_i \) and \( u \):

\[
\begin{align*}
  u_{10} + u_{14} - 2b_{30}u + b_{31}u + 2u^2 &= 0, \\
  u_{14} - b_{30}u - b_{32}u + b_{33}u + u^2 &= 0, \\
  u_{15} - u_9 + u_{11} + 2b_{33}u - 2u^2 + 2b_{34}u &= 0, \\
  u_{15} + u_{10} - 2b_{33}u - b_{31}u + 2b_{35}u - u^2 &= 0, \\
  -u_9 - 2b_{34}u + 2b_{35}u + u^2 - 2b_{36}u &= 0, \\
  -u_{10} - u_{11} - b_{36}u &= 0,
\end{align*}
\]

which is equivalent to

\[
\begin{align*}
  u_9 &= u^2 + (3b_{34} + 2b_{35} + 3b_{36})u, \\
  u_{10} &= -u^2 + (b_{30} - b_{31} - b_{32} + b_{33})u, \\
  u_{11} &= u^2 + (-b_{30} + b_{31} + b_{32} - b_{33} - b_{36})u, \\
  u_{14} &= -u^2 + (b_{30} + b_{32} - b_{33})u, \\
  u_{15} &= 2u^2 + (-b_{30} + 2b_{31} + b_{32} + b_{33} + 3b_{35})u, \\
  (b_{30} + b_{31} - b_{32} - b_{33} - 2b_{34} + 2b_{35} + 2b_{36})u &= 0. \\
\end{align*}
\]

The last equation is actually \( B_5u = 0 \). Since \( B_5 \neq 0 \), we have

\[
u = 0 \quad \text{and} \quad u_9 = u_{10} = u_{11} = u_{14} = u_{15} = 0,
\]

i.e. \( \text{Stab}_{L_1T_2}(\lambda|_{H_6H_5H_4}) = \text{Stab}_{T_1T_2}(\lambda|_{H_6H_5H_4}) = \{1\} \).

Thus \( T_1T_2 \) acts faithfully on the set of all extensions of \( \lambda|_{H_6} \) to \( H_6H_5H_4 \) with the same \( B_5 \neq 0 \), which is invariant under the action of \( T \), i.e. \( B_5(\lambda) = B_5(\lambda_x) \) for all \( x \in T \). Since \( |H_5H_4/R_5| = q^{12} = |T_1T_2| \), this action is transitive. Therefore, we choose \( \lambda|_{X_i} = \phi \) for all \( i \in [37..43] \), \( \lambda|_{X_36} = \phi_{B_5/2} \), and \( \lambda|_{X_i} = 1_{X_i} \) for
the others $X_i \subset H_5 H_4$. By the root heights, we have

$$R_5 \prod_{i=37}^{43} X_i \subset Z(HX_5 T_4 T_3)$$

$$HX_5 T_4 T_3 \leq U$$

$$H_4 \prod_{i=30}^{35} X_i \subset HX_5 T_4 T_3.$$  

By Lemma 1.5 for $G = U$ with $N = M = HX_5 T_3 T_4$, $X = T_1 T_2$, $Z = H_6 R_5$ and $Y = H_4 \prod_{i=30}^{35} X_i$, the induction map from $\text{Irr}(HX_5 T_4 T_3 / Y, \lambda)$ to $\text{Irr}(U, \lambda)$ is bijective. As $X_5 T_4 T_3 = \text{Stab}_{X_5 T_3}(\lambda|_{H_6 H_5 H_4})$ is a transversal of $H$ in $HX_5 T_4 T_3$, we have $\lambda^{HX_5 T_4 T_3}|_Y = [HX_5 T_4 T_3 : H]|H_Y = |X_5 T_4 T_3|_Y$. Hence,

$$\text{Irr}(HX_5 T_4 T_3 / Y, \lambda) = \text{Irr}(HX_5 T_4 T_3, \lambda).$$

Next, we find $\text{Stab}_{T_4 T_3}(\lambda|_{H_6 H_5 H_4 H_3})$. Since $[H_6 H_5 H_4 H_3, T_4 T_4] = [H_3, T_3]$, we find $y \in T_3$ such that $\lambda([x, y]) = 1$ for all $x \in H_3$. For each

$$y = \prod_{j=16,17,22} x_j(u_j) \in T_3$$

and

$$x = \prod_{i=18}^{21} x_i(v_i) \in H_3$$

we have

$$[x, y] = [x_{18}, x_{16}] [x_{18}, x_{22}] [x_{19}, x_{22}] [x_{20}, x_{17}] [x_{21}, x_{17}]$$

$$= x_{37}(v_{18 u_{16}}) x_{42}(v_{18 u_{22}}) x_{43}(v_{19 u_{22}}) x_{40}(-v_{20 u_{17}})$$

$$\times x_{39}(-v_{21 u_{16}}) x_{41}(-v_{21 u_{17}}).$$

Since $\lambda|_{X_i} = \phi$ for all $i \in [37..43]$, for all $v_i$ we need

$$v_{18}(u_{16} + u_{22}) + v_{19} u_{22} - v_{20} u_{17} + v_{21}(-u_{17} - u_{16}) = 0.$$  

The only solution is $(u_{16}, u_{17}, u_{22}) = (0, 0, 0)$, i.e. $\text{Stab}_{T_4 T_3}(\lambda|_{H_6 H_5 H_4 H_3}) = T_4$. Next, we find $\text{Stab}_{T_4}(\lambda)$. Since $[H, T_4] = [H_2, T_4]$, we find $y \in T_4$ such that $\lambda([x, y]) = 1$ for all $x \in H_2$. For each

$$y = x_{23}(u_{23}) \in T_4$$

and

$$x = x_{12}(v_{12}) x_{13}(v_{13}) \in H_2$$

we have

$$[x_{12}(v_{12}) x_{13}(v_{13}), x_{23}(u_{23})] = [x_{12}, x_{23}] [x_{13}, x_{23}]$$

$$= x_{37}(-v_{12} u_{23}) x_{38}(-v_{13} u_{23}).$$

Evaluate with $\lambda$, for all $v_i$ we need $(-v_{12} - v_{13}) u_{23} = 0$. Therefore, the only solution is $u_{23} = 0$, i.e. $\text{Stab}_{T_4}(\lambda) = \{1\}$. So we finish the proof of $\text{Stab}_{T_4}(\lambda) = \{1\}$.
Let \( \eta, \eta' \) be two extensions of \( \lambda|_{H_0H_5H_4} \) to \( HX_5 \). By the bijection of the induction map from \( \text{Irr}(HX_5T_4T_3, \lambda) \) to \( \text{Irr}(U, \lambda) \), it suffices to show that \( \eta^{HX_5T_4T_3} = \eta'^{HX_5T_4T_3} \) iff \( \eta|_{R_j} = \eta'|_{R_j} \) for \( j = 2, 3 \) and \( \eta|_{X_5} = \eta'|_{X_5} \). By Mackey’s formula and the fact that the double coset \( HX_5 \backslash HX_5T_4T_3/HX_5 = HX_5T_4T_3/HX_5 \) is represented by \( T_4T_3 \) we have

\[
(\eta^{HX_5T_4T_3}, \eta'^{HX_5T_4T_3}) = \sum_{y \in T_4T_3} (\nu, \eta, \eta').
\]

Since \( [X_5, T_3T_4] \subset H_4 \prod_{i=30}^{35} X_i \subset \ker(\lambda) \), we have \( \nu|_{X_5} = \eta|_{X_5} \). Therefore, the restrictions to \( X_5 \) of both \( \eta, \eta' \) are clear for the proof. To show for the restrictions to \( R_k \) with \( k = 2, 3 \), we are going to prove that

\[
R_2R_3 = \{ x \in H_2H_3 : |\lambda^{HX_5T_4T_3}(x)| = \lambda^{HX_5T_4T_3}(1) \}
\]

and

\[
T_4T_3 = \text{Stab}_{T_4T_3}(\lambda|_{R_2R_3}).
\]

Then by \( \text{Stab}_{T_4T_3}(\lambda) = \{1\} \) and \( |T_4T_3| = q^4 = |H_3H_2/R_2R_3| \), the claim holds.

By the above computations of \( [H_3, T_3] \) and \( [H_2, T_4] \) we find all \( x \in H_2H_3 \) such that \( \lambda([x, y]) = 1 \) for all \( y \in T_4T_3 \). For

\[
y = x_{16}(u_{16})x_{17}(u_{17})x_{22}(u_{22})x_{23}(u_{23}) \in T_3T_4
\]

and

\[
x = x_{12}(v_{12})x_{13}(v_{13}) \prod_{i=18}^{21} x_i(v_i) \in H_2H_3,
\]

we solve for \( v_i \) in the following:

\[
u_{16}(v_{18} - v_{21}) + u_{17}(-v_{20} - v_{21}) + u_{22}(v_{18} + v_{19}) + u_{23}(-v_{12} - v_{13}) = 0.
\]

We obtain a system with variables \( v_i \):

\[
\begin{align*}
v_{18} - v_{21} &= 0, \\
-v_{20} - v_{21} &= 0, \\
v_{18} + v_{19} &= 0, \\
-v_{12} - v_{13} &= 0.
\end{align*}
\]

We obtain solutions

\[
(v_{18}, v_{19}, v_{20}, v_{21}) = (v, -v, -v, v) \quad \text{and} \quad (v_{12}, v_{13}) = (s, -s) \quad \text{for all} \quad v, s \in \mathbb{F}_q.
\]

Therefore, \( x \in R_2R_3 \). Hence, \( \nu \lambda|_{R_2R_3} = \lambda|_{R_2R_3} \) for all \( y \in T_4T_3 \).
(c) Suppose that \( B_5 = 0 \). By (a), \( T/S_1 \) acts faithfully on the set of all extensions of \( \lambda|_{H_6} \) to \( H_6H_5 \) with the same \( B_5 \). Since \( |H_5|/|R_5| = q^6 = |T/S_1| \), this action is transitive. Hence, there exists \( x \in T \) such that \( \lambda|_{X_i} = 1_{X_i} \) for all \( X_i \subset H_5 \). Let \( \lambda \) be this linear. So \( S_1 X_5 = \text{Stab}_{T/H_5}(\lambda|_{H_6H_5}) \), a transversal of \( H \) in \( HX_5S_1 \), and \( \lambda|_{HX_5S_1} = \lambda|_{H_5S_1} \) for all \( X_i \subset H_5 \) and \( H \subset \ker(\lambda|_{H_5S_1}) \) and so is its normal closure \( HX_5S_1 \).

By Lemma 1.5 with \( G = U \), \( N = M = HX_5S_1 \), \( X = \prod_{i=1}^4 X_iX_6X_7 \), \( Z = H_6 \) and \( Y = HX_5 \), the induction map from \( \text{Irr}(HX_5S_1/HX_5, \lambda) \) to \( \text{Irr}(U, \lambda) \) is bijective. Since \( HX_5 \subset \ker(\lambda|_{H_5S_1}) \), we have \( \text{Irr}(HX_5S_1/HX_5, \lambda) = \text{Irr}(HX_5S_1, \lambda) \). \( \square \)

5.5.2 Proof of Lemma 4.3

Recall that \( \lambda \) is a linear character of \( H \) such that \( \lambda|_{X_i} = \phi \) for all \( X_i \subset H_6 \), \( \lambda|_{X_i} = 1_{X_i} \) for all \( X_i \subset H_5 \), and \( \lambda|_{X_i} = \phi_{b_i} \) for the others \( X_i \subset H_4H_3H_2 \) where \( b_i \in \mathbb{F}_q \). By Lemma 4.2 (c), we work with the quotient group \( HX_5S_1/HX_5 \). Abusing the notation of root groups, we call them root groups in the quotient group.

(a) By computation (*) in Lemma 4.2 (b) with \( B_5 = 0 \),

\[
S_2 = \text{Stab}_{H_6H_5}(\lambda|_{H_6H_5H_4}).
\]

Now we show the identity \( R_4 = \{ x \in H_4 : [\lambda|_{HX_5S_1}(x)] = [\lambda|_{HX_5S_1}(1)] \} \). For each \( l_1y_2y_3y_4 \in L_1T_2T_3T_4 = S_1 \) and \( h_4 \in H_4 \), we have \( [h_4, l_1y_2y_3y_4] = [h_4, l_1y_2] \). Hence, we are going to find all elements \( h_4 \in H_4 \) such that \( \lambda([h_4, l_1y_2]) = 1 \) for all \( l_1y_2 \in L_1T_2 \). Using the computation of \( \prod_{j=24}^{36} x_j(v_j) \cdot \prod_{i=1}^{15} x_i(u_i) \) in Lemma 4.2 (b) with \( b_j = 0 \) for \( j \in [30..36] \), we solve for \( v_i \) in the following equation:

\[
u_9(-v_26 - v_28) + u_{10}(v_{24} + v_{27} - v_{29}) + u_{11}(v_{26} - v_{29}) + u_{14}(v_{24} + v_{25}) + u_{15}(v_{26} + v_{27}) + u^2(2v_{24} + v_{25} - 2v_{26} - v_{27} + v_{28}) = 0.
\]

So we obtain a system with variables \( v_i \):

\[
\begin{align*}
-v_{26} - v_{28} &= 0, \\
v_{24} + v_{27} - v_{29} &= 0, \\
v_{26} - v_{29} &= 0, \\
v_{24} + v_{25} &= 0, \\
v_{26} + v_{27} &= 0, \\
2v_{24} + v_{25} - 2v_{26} - v_{27} + v_{28} &= 0.
\end{align*}
\]

Thus, \( (v_{24}, v_{25}, v_{26}, v_{27}, v_{28}, v_{29}) = (2v, -2v, v, -v, -v, v) \) is a solution for all \( v \in \mathbb{F}_q \), i.e. \( \lambda([h_4, l_1y_2]) = 1 \) for all \( l_1y_2 \in L_1T_2 \) iff \( h_4 = r_4(v) \in R_4 \).
It is clear that $\lambda^{HX_5S_1}(r_4(v)) = \lambda^{HX_5S_1}(1)\phi_B(v)$ for all $r_4(v) \in R_4$ by checking directly that $\lambda(r_4(v)) = \phi_B(v)$.

(b) Suppose that $B_4 \neq 0$. Since $\text{Stab}_T(\lambda|_{H_6H_5H_4}) = S_2 = L_2T_3T_4$, we are going to show that $\text{Stab}_{S_2}(\lambda|_{H_6H_5H_4H_3}) = T_4$, and then $\text{Stab}_{T_4}(\lambda) = 1$ is done by using the same argument in Lemma 4.2 (b). This means that we find all $y \in S_2$ such that $\lambda([x, y]) = 1$ for all $x \in H_3$ since $\lambda([H_6H_5H_4, S_2]) = \{1\}$.

It is clear that $T_4 \subset \text{Stab}_{S_2}(\lambda|_{H_6H_5H_4H_3})$. So by (a) and $|H_3| = q^k = |L_2T_3|$, it suffices to show that $L_2T_3$ acts faithfully on the set of all extensions of $\lambda|_{H_6H_5H_4}$ to $H_6H_5H_4H_3$, i.e. $\text{Stab}_{L_2T_3}(\lambda|_{H_6H_5H_4H_3}) = \{1\}$. By the root heights and the fact that $H$ is abelian, $[H_3, L_2T_3] = [H_3, T_3][H_3, L_2]$, where $[H_3, T_3]$ is computed in Lemma 4.2 (b). Since we work with $HX_5S_1/\overline{H_5}$, for each

\[ x = \prod_{i=18}^{21} x_i(v_i) \in H_3 \quad \text{and} \quad y = \prod_{j=1}^{11} x_j(u_j) \prod_{j=14}^{17} x_j(u_j)x_{22}(u_{22}) \in L_2T_3, \]

we have

\[
[x, y] = [x, x_{16}x_{17}x_{22}]x_{18}x_3[[[x_{18}, x_3], x_4], x_6][[[x_{18}, x_3], x_6], x_7] \\
\times[[x_{18}, x_3], x_{14}]x_{18}x_6[[[x_{18}, x_6], x_7], x_8][[[x_{18}, x_6], x_{15}] \\
\times[[x_{18}, x_6], x_{11}] x_{18}x_7[x_{19}, x_2][[[x_{19}, x_2], x_1], x_4] \\
\times[[x_{19}, x_2], x_1], x_6][[[x_{19}, x_2], x_4], x_6][[[x_{19}, x_2], x_6], x_7] \\
\times[[x_{19}, x_2], x_{14}]x_{19}x_1[[[x_{19}, x_1], x_6], x_7][[[x_{19}, x_1], x_{10}] \\
\times[[x_{19}, x_1], x_{14}] x_{19}x_6[[[x_{19}, x_6], x_7], x_8][[[x_{19}, x_6], x_{10}] \\
\times[[x_{19}, x_6], x_{15}]x_{20}x_2[[[x_{20}, x_2], x_3], x_4][[[x_{20}, x_2], x_3], x_7] \\
\times[[x_{20}, x_2], x_7], x_8][[[x_{20}, x_2], x_{15}][[[x_{20}, x_2], x_{11}], x_{15}] \\
\times[x_{20}, x_3][[[x_{20}, x_3], x_7], x_8][[[x_{20}, x_3], x_{10}][[[x_{20}, x_3], x_{15}] \\
\times[x_{20}, x_7][[[x_{20}, x_7], x_9][[[x_{21}, x_4], x_9][[[x_{21}, x_8] \\
\times[[x_{21}, x_8], x_{10}][[[x_{21}, x_8], x_{11}] \\
\times x_{37}(v_{18}u_{16})x_{42}(v_{18}u_{22})x_{43}(v_{19}u_{22})x_{40}(-v_{20}u_{17})x_{39}(-v_{21}u_{16}) \\
\times x_{41}(-v_{21}u_{17})x_{25}(2v_{18}u)x_{40}(-2v_{18}u^3)x_{41}(4v_{18}u^3) \\
\times x_{41}(-2v_{18}u^3)x_{26}(v_{18}u)x_{42}(-4v_{18}u^3)x_{42}(2v_{18}u^3)x_{40}(v_{18}u^3) \\
\times x_{38}(-v_{18}u^3)x_{25}(-2v_{19}u)x_{37}(-2v_{19}u^3)x_{38}(2v_{19}u^3) \\
\times x_{40}(2v_{19}u^3)x_{41}(-4v_{19}u^3)x_{41}(2v_{19}u^3)x_{24}(-v_{19}u) \\
\times x_{39}(-2v_{19}u^3)x_{37}(v_{19}u^3)x_{39}(v_{19}u^3)x_{27}(v_{19}u)x_{43}(-4v_{19}u^3)
\[ x_{40}(-v_{19}u^3)x_{43}(2v_{19}u^3)x_{26}(-2v_{20}u)x_{40}(4v_{20}u^3) \\
\times x_{41}(-8v_{20}u^3)x_{42}(8v_{20}u^3)x_{42}(-4v_{20}u^3)x_{40}(-2v_{20}u^3) \\
\times x_{38}(2v_{20}u^3)x_{27}(2v_{20}u)x_{43}(-8v_{20}u^3)x_{40}(-2v_{20}u^3) \\
\times x_{43}(4v_{20}u^3)x_{28}(2v_{20}u)x_{39}(-2v_{20}u^3)x_{28}(-v_{21}u)x_{39}(v_{21}u^3) \\
\times x_{29}(-2v_{21}u)x_{42}(-2v_{21}u^3)x_{43}(2v_{21}u^3). \]

Evaluating at \( \lambda \) and setting the result equal to 1, we see that the following equation is true for all \( v_i \):

\[
v_{18}(u_{16} + u_{22} + 2b_{25}u + b_{26}u - 2u^3) \\
+ v_{19}(u_{22} - b_{24}u - 2b_{25}u + b_{27}u - 3u^3) \\
+ v_{20}(-u_{17} - 2b_{26}u + 2b_{27}u + 2b_{28}u - 3u^3) \\
+ v_{21}(-u_{16} - u_{17} - b_{28}u - 2b_{29}u + u^3) = 0.
\]

So we obtain a system with variables \( u_j \) and \( u \):

\[
\begin{align*}
    u_{16} + u_{22} + 2b_{25}u + b_{26}u - 2u^3 &= 0, \\
    u_{22} - b_{24}u - 2b_{25}u + b_{27}u - 3u^3 &= 0, \\
    -u_{17} - 2b_{26}u + 2b_{27}u + 2b_{28}u - 3u^3 &= 0, \\
    -u_{16} - u_{17} - b_{28}u - 2b_{29}u + u^3 &= 0,
\end{align*}
\]

which is equivalent to:

\[
\begin{align*}
    u_{22} &= 3u^3 + (b_{24} + 2b_{25} - b_{27})u, \\
    u_{17} &= 2u^3 + (3b_{26} + 2b_{27} + 2b_{28})u, \\
    u_{16} &= 4u^3 + (2b_{26} - 2b_{27} - 3b_{28})u, \\
    (2b_{24} - 2b_{25} + b_{26} - b_{27} - b_{28} + b_{29})u &= 0.
\end{align*}
\]

The last equation in the system is actually \( B_4u = 0 \). Since \( B_4 \neq 0 \), the only solution of this system is \( (u_{16}, u_{17}, u_{22}) = (0, 0, 0) \), i.e.

\[ \text{Stab}_{L_2T_3}(\lambda|H_6H_5H_4H_3) = \{1\}. \]

Hence, \( \text{Stab}_{S_2}(\lambda|H_6H_5H_4H_3) = T_4 \) and \( \text{Stab}_{S_1}(\lambda) = \{1\} \).

The above argument also proves that \( L_1T_2T_3 \) acts transitively on the set of all extensions of \( \lambda|H_6H_5H_4 \) to \( H_6H_5H_4H_3 \) with the same \( B_4 \neq 0 \). The number of
these extensions is \(|H_4H_3|/|R_4|\). Therefore, there exists an element \(x \in L_1T_2T_3\) such that \(\lambda|_{X_i} = \phi\) for all \(X_i \subset H_6\), \(\lambda|_{X_{29}} = \phi_{B_4}\), \(\lambda|_{X_i} = 1_{X_i}\) for the others \(X_i \subset H_5H_4H_3\). Let \(\lambda\) be this linear character. By Lemma 1.5 with \(G = HX_5S_1\), \(N = M = HX_5T_4\), \(X = L_1T_2T_3\), \(Z = H_6R_4\), \(Y = H_3\prod_{i=24}^{28} X_i\), the induction map from \(\text{Irr}(HX_5T_4/Y, \lambda)\) to \(\text{Irr}(HX_5S_1, \lambda)\) is bijective. Let \(\eta, \eta'\) be two extensions of \(\lambda\) to \(HX_5S_2\) to \(HX_5\). We have \(\eta^{HX_5S_2}, \eta^{HX_5S_2} \in \text{Irr}(HX_5S_2/Y, \lambda)\). Using the same argument in Lemma 4.2 (b), we obtain \((\eta^{HX_5S_2}, \eta^{HX_5S_2}) = 1\) iff \(\eta|_{R_2} = \eta'|_{R_2}\) and \(\eta|x_5 = \eta'|x_5\).

(c) Suppose that \(B_4 = 0\). By (a), \(S_1/S_2\) acts faithfully on the set of all extensions of \(\lambda|_{H_6H_5}\) to \(H_6H_5H_4\) with the same \(B_4\). Since \(|S_1/S_2| = q^5 = |H_4/R_4|\), it follows that this action is transitive. Hence, with \(B_4 = 0\), there exists an element \(x \in S_1\) such that \(\lambda|_{X_i} = 1_{X_i}\) for all \(X_i \subset H_5H_4\). Let \(\lambda\) be this linear character. Since \(S_2X_5 = \text{Stab}_{S_1x_5}(\lambda|_{H_6H_5H_4})\) is a transversal of \(H\) in \(HX_5S_2\), we have

\[
\lambda^{HX_5S_2}|_{H_4} = [HX_5S_2 : H]\lambda|_{H_4} = |X_5S_2|1_{H_4}.
\]

So \(H_4 \in \ker(\lambda^{HX_5S_2})\). By Lemma 1.5 for \(G = HX_5S_1\) with \(N = M = HX_5S_2\), \(X = T_2\), \(Y = H_4\) and \(Z = H_6\), the induction map from \(\text{Irr}(HX_5S_2/\overline{H_5H_4}, \lambda)\) to \(\text{Irr}(HX_5S_1, \lambda)\) is bijective where \(\overline{H_5H_4}\) is the normal closure of \(H_5H_4\) in \(HX_5S_2\). Since \(H_5H_4 \subset \ker(\lambda^{HX_5S_2})\), we have

\[
\text{Irr}(HX_5S_2/\overline{H_5H_4}, \lambda) = \text{Irr}(HX_5S_2, \lambda).
\]

### 5.5.3 Proof of Lemma 4.4

Recall that \(\lambda\) is a linear character of \(H\) such that \(\lambda|_{X_i} = \phi\) for all \(X_i \subset H_6\), \(\lambda|_{X_i} = 1_{X_i}\) for all \(X_i \subset H_5H_4\), and \(\lambda|_{X_i} = \phi_{b_i}\) for the others \(X_i \subset H_3H_2\) where \(b_i \in \mathbb{F}_q\). By Lemma 4.3 (c), we work with the quotient group \(HX_5S_2/\overline{H_5H_4}\). Abusing language slightly, we call the images of root groups in a quotient group root groups also.

(a) By the computation in Lemma 4.3 (b) with \(B_4 = 0\), it is clear that

\[
S_3 = \text{Stab}_{S_2}(\lambda|_{H_6H_5H_4H_3}).
\]

Now we show that \(R_3 = \{x \in H_3 : |\lambda^{HX_5S_2}(x)| = \lambda^{HX_5S_2}(1)\}\). Since \(X_5S_2\) is a transversal of \(H\) in \(HX_5S_2\), we are going to find \(x \in H_3\) such that \(\lambda([x, y]) = 1\) for all \(y \in S_2\). Since \([H_3, X_5] = \{1\} = [H_3, T_4]\), it is enough to work with \(x \in H_3\) and \(y \in S_2T_3\). For each

\[
x = \prod_{i=18}^{21} x_i(v_i) \in H_3 \quad \text{and} \quad y = \prod_{j=1}^{11} x_j(u_j) \prod_{j=14}^{17} x_j(u_j)x_{22}(u_{22}) \in S_2T_3,
\]

\[\text{Download Date} | 10/27/12 7:05 AM\]
by the computation in Lemma 4.3, we find \((v_i)_{i \in [18..21]}\) satisfying for all \(u_f\) and \(u\) in the following equation:

\[
u_{16}(v_{18} - v_{21}) + u_{17}(-v_{20} - v_{21}) + u_{22}(v_{18} + v_{19}) + u^3(-2v_{18} - 3v_{19} - 3v_{20} + v_{21}) = 0.
\]

We have a system with variables \(v_i\):

\[
\begin{align*}
v_{18} - v_{21} &= 0, \\
-v_{20} - v_{21} &= 0, \\
v_{18} + v_{19} &= 0, \\
-2v_{18} - 3v_{19} - 3v_{20} + v_{21} &= 0.
\end{align*}
\]

Its solutions are \((v_{18}, v_{19}, v_{20}, v_{21}) = (u, -u, -u, u)\) for all \(u \in \mathbb{F}_q\), i.e. we have \(x = r_3(u) \in R_3\). Now to show that \(\lambda^{H\times S_2}|_{R_3} = [H\times S_2 : H]\phi_{B_3}\), it is enough to check \(\lambda(t_3(t)) = \phi_{B_3}(t)\) which is clear.

(b) Suppose that \(B_3 \neq 0\). By (a) we have \(\text{Stab}_{S_2}(\lambda|_{H_6H_5H_4H_3}) = S_3 = L_3T_4\). To show that \(\text{Stab}_{S_2}(\lambda) = \{1\}\), since \(|L_3T_4| = q^2 = |H_2|\), we show that \(L_3T_4\) acts faithfully on the set of all extensions of \(\lambda|_{H_6H_5H_4H_3}\) to \(H\), i.e. proving that there is no nontrivial \(y \in L_3T_4\) such that \(\lambda((x, y)) = 1\) for all \(x \in H_2\).

By the root heights, \([H_2, L_3T_4] = [H_2, T_4][H_2, L_3]\), where \([H_2, T_4]\) is computed in Lemma 4.2 (b). For

\[
x = x_{12}(v_{12})x_{13}(v_{13}) \in H_2 \quad \text{and} \quad y = l_3(u)x_{23}(u_{23}) \in L_3T_4,
\]

we have

\[
[x, y] = [x, x_{23}][x, l_3]
\]

\[
= [x_{12}, x_{23}][x_{12}, x_2][[x_{12}, x_2, x_3], x_4], x_6][[x_{12}, x_2, x_3], x_6, x_7]
\times [x_{12}, x_6][[x_{12}, x_2], x_3, x_4][[x_{12}, x_2], x_6, x_9]
\times [x_{12}, x_6][[x_{12}, x_2], x_3, x_14][[x_{12}, x_2], x_6, x_9]
\times [[x_{12}, x_2], x_6, x_11][[x_{12}, x_2], x_6, x_15][[x_{12}, x_3], x_6, x_10]
\times [[x_{12}, x_3], x_6, x_15][[x_{12}, x_6], x_7, x_9][[x_{12}, x_2], x_22]
\times [[x_{12}, x_2], x_16][[x_{12}, x_3], x_22][[x_{12}, x_6, x_17]
\times [[x_{12}, x_9], x_{10}][[x_{12}, x_9], x_{14}][x_{13}, x_{23}][x_{13}, x_4][x_{13}, x_7]
\times [[x_{13}, x_4], x_7, x_9][[x_{12}, x_7], x_8, x_{10}][[x_{13}, x_7], x_8, x_{11}]
\times [[x_{13}, x_4], x_17][x_{13}, x_7, x_{16}][x_{13}, x_7, x_17][x_{13}, x_{10}, x_{15}]
\times [[x_{13}, x_{10}, x_11][x_{13}, x_{11}, x_{15}]
\]
\[
\begin{align*}
&= x_{37}(-v_{12}u_{23})x_{18}(-2v_{12}u)x_{40}(4v_{12}u^4)x_{41}(-8v_{12}u^4)x_{42}(8v_{12}u^4) \\
&\quad \times x_{19}(2v_{12}u)x_{43}(-8v_{12}u^4)x_{20}(v_{12}u)x_{41}(4v_{12}u^4)x_{38}(2v_{12}u^4) \\
&\quad \times x_{40}(-2v_{12}u^4)x_{42}(-4v_{12}u^4)x_{40}(-2v_{12}u^4)x_{43}(4v_{12}u^4) \\
&\quad \times x_{39}(-2v_{12}u^4)x_{42}(-6v_{12}u^4)x_{37}(-8v_{12}u^4)x_{43}(6v_{12}u^4) \\
&\quad \times x_{40}(-2v_{12}u^4)x_{37}(v_{12}u^4)x_{39}(v_{12}u^4)x_{38}(-v_{13}u_{23}) \\
&\quad \times x_{20}(-v_{13}u)x_{21}(2v_{13}u)x_{39}(2v_{13}u^4)x_{42}(-4v_{13}u^4) \\
&\quad \times x_{43}(4v_{13}u^4)x_{40}(2v_{13}u^4)x_{39}(-8v_{13}u^4)x_{41}(-4v_{13}u^4) \\
&\quad \times x_{42}(2v_{13}u^4)x_{40}(v_{13}u^4)x_{43}(-2v_{13}u^4).
\end{align*}
\]

Evaluating \(\lambda\) and setting the result equal to 1, we obtain in the following equation:

\[
v_{12}(-s_{23} - 2b_{18}u + b_{20}u + 2b_{19}u - 2u^4) \\
+ v_{13}(-u_{23} - b_{20}u + 2b_{21}u - 2u^4) = 0.
\]

We have a system with variables \(u_j\) and \(u\):

\[
\begin{cases}
-u_{23} - 2b_{18}u + b_{20}u + 2b_{19}u - 2u^4 = 0, \\
-u_{23} - 2b_{20}u + 2b_{21}u - 2u^4 = 0.
\end{cases}
\]

It is equivalent to

\[
\begin{cases}
u_{23} = 3u^4 + (-2b_{18} + b_{20} + 2b_{19})u, \\
(b_{18} - b_{20} - b_{19} + b_{21})u = 0.
\end{cases}
\]

The last equation is actually \(B_3u = 0\). Since \(B_3 \neq 0\), it follows that the only solution is \((u_{23}, u) = (0, 0)\), i.e. \(\text{Stab}_{L_3T_4}(\lambda) = \{1\}\) or \(L_3T_4\) acts faithfully on the set of all extensions of \(\lambda|_{H_6H_5H_4H_3}\) to \(H\). Hence, we also get \(\text{Stab}_{S_2}(\lambda) = \{1\}\).

Therefore, there is an element \(x \in L_3T_4\) such that \(^x\lambda|_{X_i} = \phi\) for all \(X_i \subset H_6\), \(^x\lambda|_{X_{21}} = \phi_{B_3}\), \(^x\lambda|_{X_i} = 1_{X_i}\) for the others \(X_i \subset H_5H_4H_3\). Let \(\lambda\) be this linear. By Lemma 1.5 with \(G = HX_5S_2\), \(N = M = HX_5\), \(X = S_2\), \(Y = \prod_{i=18}^{20} X_i\) and \(Z = H_6X_{21}\), the induction map from \(\text{Irr}(HX_5/Y, \lambda)\) to \(\text{Irr}(HX_5S_2, \lambda)\) is bijective. Using the same method as in Lemma 4.2 (c), we see that the rest of the statement holds.

(c) Suppose \(B_3 = 0\). By (a), \(S_2/S_3\) acts faithfully on the set of all extensions of \(\lambda|_{H_6H_5H_4}\) to \(H_6H_5H_4H_3\) with the same \(B_3\). Since \(|S_2/S_3| = q^3 = |H_3/R_3|\), this action is transitive. Hence, there exists \(x \in S_2\) such that \(^x\lambda|_{X_i} = 1_{X_i}\) for all
$X_i \subset H_5 H_4 H_3$. Let $\lambda$ be this linear. Since $X_5 S_3$ is a transversal of $H$ in $HX_5 S_3$ and $S_3 = \text{Stab}_{S_2}(\lambda|_{H_5 H_5 H_4 H_3})$, we have 
\[ \lambda HX_5 S_3|_{H_5 H_4 H_3} = \lambda HX_5 S_3(1) \lambda|_{H_5 H_4 H_3}. \]
Therefore, 
\[ H_5 H_4 H_3 \subset \ker(\lambda HX_5 S_3), \]
so is its normal closure $\bar{H_5 H_4 H_3}$ in $HX_5 S_3$.

By Lemma 1.5 with $G = HX_5 S_2$, $N = M = HX_5 S_3$, $X = T_3$, $Y = H_3$ and $Z = H_6$, the induction map from $\text{Irr}(HX_5 S_3/Y, \lambda)$ to $\text{Irr}(HX_5 S_2, \lambda)$. Since we have $Y \subset \ker(\lambda HX_5 S_3)$, it follows that $\text{Irr}(HX_5 S_3/Y, \lambda) = \text{Irr}(HX_5 S_3, \lambda)$. □

### 5.5.4 Proof of Lemma 4.5

Recall that $\lambda$ is a linear character of the group $H$ such that $\lambda|_{X_i} = \phi$ for all $X_i \subset H_6 = Z(U)$, $\lambda|_{X_i} = 1_{X_i}$ for all $X_i \subset H_5 H_4 H_3$, and $\lambda|_{X_i} = \phi_{b_i}$ for the others $X_i \subset H_2$ where $b_i \in \mathbb{F}_q$. By Lemma 4.3 (c), we work with the quotient group $HX_5 S_3/\bar{H_5 H_4 H_3}$. Abusing language slightly, we call the images of root groups in a quotient group root groups also.

(a) By the computation in Lemma 4.4 (b) with $B_3 = 0$, $S_4 = \text{Stab}_{S_3}(\lambda)$. Now we show that $R_2 = \{x \in H_2 : |\lambda HX_5 S_3(x)| = |\lambda HX_5 S_3(1)| \}$.

Since $X_5 S_3$ is a transversal of $H$ in $HX_5 S_3$, we are going to find $x \in H_2$ such that $\lambda([x, y]) = 1$ for all $y \in S_3$. As $[H_2, X_5] = \{1\}$, it is enough to work with $x \in H_2$ and $y \in S_4$. For each $x = \prod_{i=13}^{1} x_i(u_i) \in H_2$ and $y = l_3(u) x_{23}(u_{23}) \in S_3 T_4$, by the computation in Lemma 4.4 (b), we find $(v_{12}, v_{13})$ satisfying for all $u_{23}$ and $u$ in the following equation:

\[ u_{23}(-v_{12} - v_{13}) + 2u^4(-v_{12} - v_{13}) = 0. \]

So $(v_{12}, v_{13}) = (v, -v)$ for all $v \in \mathbb{F}_q$, i.e. $x = r_2(v)$. Since $\lambda(r_2(v)) = \phi_{B_2}(v)$ for all $r_2(v) \in R_2$, we have $\lambda^{HX_5 S_3}|_{H_2} = [HX_5 S_3 : H]\phi_{B_2}$.

(b) Suppose that $B_2 \in \mathbb{F}_q - \{e^4 : c \in \mathbb{F}_q^\times \}$. Let $\eta$ be an extension of $\lambda$ to $HX_5$. Since $S_4 = \text{Stab}_{S_3}(\lambda)$, to get $I_{HX_5 S_3}(\eta) = HX_5$, we show that $S_4$ acts transitively on the set of all extensions of $\lambda$ to $HX_5$. Hence, we find all $l_4 \in S_4$ such that $\lambda([h x_5, l_4]) = 1$ for all $h \in H$ and $x_5 \in X_5$. Since $S_4 = \text{Stab}_{S_3}(\lambda)$, we have $\lambda([h, l_4]) = 1$ for all $h \in H$, $l_4 \in S_4$. Thus we compute $[x_5, l_4]$. Since we work with $HX_5 S_3/\bar{H_5 H_4 H_3}$, for each $x_5(u_5) \in X_5$ and $l_4(u) \in S_4$, we have

\[ [x_5(u_5), l_4(u)] = [x_5, x_4] [[[x_5, x_4], x_9], x_{10}][[[x_5, x_4], x_9], x_{14}] \]
\[ \times [[[x_5, x_4], x_6], x_7], x_9][[[x_5, x_4], x_6], x_{17}][[[x_5, x_4], x_{23}] \]
\[ \times [x_5, x_6] [[[x_5, x_6], x_{10}], x_{11}][[[x_5, x_6], x_{10}], x_{15}] \]
Continue the computation in part (b), the equation
\[ H \xrightarrow{\phi} S \]
Hence, we have
\[ I_{H} = HX_{5} = X_{5} \]
i.e. Stab_{S}(\eta) = \{1\}, or \[ I_{H_{X_{5}}S_{3}}(\eta) = HX_{5} \]
\[ c \] Suppose \( B_{2} = c^{4} \in \mathbb{F}_{q}^{\times} \). Let \( \eta \) be an extension of the character \( \lambda \) to \( HX_{5} \).
Continue the computation in part (b), the equation \( u(u^{4} - B_{2}) = 0 \) has five solutions \( u \in \{ac : a \in \mathbb{F}_{5}\} \), i.e. \( l_{4}(u) \in F_{4} \). Hence, we have \( I_{H_{X_{5}}S_{3}}(\eta) = HX_{5}F_{4} \).
Since \([HX_{5}, F_{4}] \subset \ker(\eta), \eta \) extends to \( HX_{5}F_{4} \), i.e. \( \lambda \) extends to \( HX_{5}F_{4} \).
Since \( S_{4} = \text{Stab}_{S_{3}}(\lambda) \cong \mathbb{F}_{q} \), we have
\[ [H, S_{4}] \subset \ker(\lambda). \]
So \( \lambda \) extends to \( HS_{4} \subseteq HX_{5}S_{3} \). Let \( \lambda' \) be an extension of \( \lambda \) to \( HS_{4} \). We find \( I_{H_{X_{5}}S_{3}}(\lambda') \). Since \( \text{Stab}_{X_{5}S_{3}}(\lambda') \subset \text{Stab}_{X_{5}S_{3}}(\lambda'|H) = X_{5}S_{4} \), it is enough to find all \( x_{5} \in X_{5} \) such that \( \lambda'([x_{5}, hl_{4}]) = 1 \) for all \( hl_{4} \in HS_{4} \). Since \( HX_{5} \) is abelian, we have
\[ [x_{5}, hl_{4}] = [x_{5}, l_{4}]. \]
For each \( x_{5}(v_{5}) \in X_{5} \) and \( l_{4}(u) \in S_{4} \), by the computation in (b), we need
\[ v_{5}(u^{5} - B_{2}u) \in \ker(\phi) \quad \text{for all} \ u \in \mathbb{F}_{q}. \]
By Proposition 1.3, there are five solutions \( v_{5} \in \{ac_{\phi} : a \in \mathbb{F}_{5}\} \), i.e. \( x_{5}(v_{5}) \in F_{5} \). Hence, \( I_{H_{X_{5}}S_{3}}(\lambda') = HF_{5}S_{4} \). Since \([F_{5}, S_{4}] \subset \ker(\lambda'), \lambda' \) extends to \( HF_{5}S_{4} \), i.e. \( \lambda \) extends to \( HF_{5}S_{4} \).
Let \( \lambda_1, \lambda_2 \) be two extensions of \( \lambda \) to \( HX_5F_4 \), and let \( \gamma \) be an extension of \( \lambda \) to \( HF_5S_3 \). Since the degree of all irreducible constituents of \( \lambda HX_5S_3 \) is \( q^2 \), we have

\[
\lambda_1 HX_5S_3, \lambda_2 HX_5S_3, \gamma HX_5S_3 \in \text{Irr}(HX_5S_3, \lambda).
\]

Choose \( 1 \in S \subset S_3 \) as a representative set of the double coset

\[
HF_5S_4 \backslash HX_5S_3 / HX_5F_4.
\]

As \( HF_5S_4 \cap HX_5F_4 = HF_5F_4 \) and \( HX_5F_4 \leq HX_5S_3 \), by Mackey’s formula,

\[
(\lambda_1 HX_5S_3, \gamma HX_5S_3) = \sum_{s \in S} (\lambda_1 |_{HF_5F_4}, \gamma |_{HF_5F_4}) = \sum_{s \in S} (\lambda_1 |_{HF_5F_4}, \gamma |_{HF_5F_4}).
\]

For each \( s \in S \), if \( s \lambda_1 |_{HF_5F_4} = \gamma |_{HF_5F_4} \), then \( s \lambda = \lambda \), i.e. \( s \in \text{Stab}_3(\lambda) = S_4 \). There is a unique \( 1 \in S \cap S_4 \) since \( S \) is a representative set of \( HF_5S_4 \backslash HX_5S_3 / HX_5F_4 \). So

\[
(\lambda_1 HX_5S_3, \gamma HX_5S_3) = (\lambda_1 |_{HF_5F_4}, \gamma |_{HF_5F_4}) = 1 \text{ iff } \lambda_1 |_{F_i} = \gamma |_{F_i}, i \in \{4, 5\}.
\]

Therefore, \( \lambda_1 HX_5S_3 = \gamma HX_5S_3 = \lambda_2 HX_5S_3 \) iff \( \lambda_1 |_{F_i} = \lambda_2 |_{F_i}, i \in \{4, 5\} \). \( \square \)

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