FINITE GROUPS CONTAINING AN INTRINSIC 2-COMPONENT OF CHEVALLEY TYPE OVER A FIELD OF ODD ORDER

BY

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ABSTRACT. This paper extends the celebrated theorem of Aschbacher that classifies all finite simple groups $G$ containing a subgroup $L \cong \text{SL}(2, q)$, $q$ odd, such that $L$ is subnormal in the centralizer in $G$ of its unique involution. Under the same embedding assumptions, the main result of this work allows $L$ to be almost any Chevalley group over a field of odd order and determines the resulting simple groups $G$. The results of this paper are an essential ingredient in the current classification of all finite simple groups. Major sections are devoted to deriving various properties of Chevalley groups that are required in the proofs of the three theorems of this paper. These sections are of some independent interest.

1. Introduction. Let $L$ be a finite group. If $L = L'$ and $L/Z(L)$ is simple, then $L$ is said to be quasisimple. If $\pi$ is a set of prime integers, then $O^\pi(L)$ is the subgroup of $L$ generated by all $\pi$-elements of $L$ and $O_\pi(L)$ is the maximal normal $\pi$-subgroup of $L$. Clearly $O^\pi(L)$ is the intersection of all normal subgroups $M$ of $L$ such that $|L/M|_\pi = 1$. Also $O(L) = O_2(L)$ is the maximal normal subgroup of $L$ of odd order. If $L = L'$ and $L/O(L)$ is quasisimple, then $L$ is said to be 2-quasisimple.

Let $G$ denote a finite group. A subnormal quasisimple subgroup of $G$ is said to be a component of $G$ and a subnormal 2-quasisimple subgroup of $G$ is said to be a 2-component of $G$. Clearly every component of $G$ is a 2-component of $G$. Also $E(G)$ denotes the subgroup of $G$ generated by all components of $G$, $L_2(G)$ denotes the subgroup of $G$ generated by all 2-components of $G$, $F^*(G) = F(G)E(G)$ where $F(G)$ is the Fitting subgroup of $G$, $S(G)$ denotes the maximal normal solvable subgroup of $G$, $\mathfrak{S}(G)$ denotes the Schur multiplier of $G$ and $Z^*(G)$ denotes the full inverse image in $G$ of $Z(G/0(G))$. A subnormal subgroup $L$ of $G$ such that $O(L) = O(G)$ and $L/O(L)$ is isomorphic to $\text{PSL}(2, 3)$ or to $\text{SL}(2, 3)$ is called a solvable 2-component of $G$. As in [1] for simplicity of terminology, when it is not necessary to distinguish between 2-components and solvable 2-components, we will refer to both as 2-components. Also, when advantageous, we will refer to a 2-component which definitely is 2-quasisimple as a perfect 2-component. If $z$ is an involution of $G$ and if $J$ is a 2-component of $C_G(z)$ such that $z \in J$, then $J$ is said to be intrinsic in $C_G(z)$. 

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Finite simple Chevalley groups over finite fields of odd characteristic are listed in [16, §17.1] and specifically exclude $^2G_2(3)' \cong PSL(2, 8)$. We shall usually adhere to the notation of [16, §17.1]. Note that in the notation for the "twisted" groups, the field order parameter is always the order of the smaller field involved in the definition.

For any odd prime integer $p$, a finite group $G$ is said to be a Chevalley group over a finite field of characteristic $p$ if

1. $G$ is quasisimple and $G/Z(G)$ is a simple Chevalley group over a finite field of characteristic $p$; or
2. $p = 3$ and $G \cong SL(2, 3)$ or $G \cong PSL(2, 3)$.

Unless mentioned to the contrary, all groups in this article are finite. As is standard in the theory of finite groups, a simple finite group is nonabelian.

In order to state efficiently the main results of this paper, we introduce

**Definition 1.** Let $p$ denote an odd prime integer. A finite group $H$ will be said to be of $\mathfrak{M}(p)$-type if it satisfies the following three conditions.

1. $H$ is 2-quasisimple and $H/Z(H)$ is isomorphic to a simple Chevalley group over a finite field of characteristic $p$;
2. $|Z(H)|$ is even; and
3. if $H/Z(H)$ is isomorphic to $PSL(2n, p^r)$ or to $PSU(2n, p^r)$ for positive integers $n$ and $r$, then $|Z(H)|_2 = |\mathfrak{M}(H/Z(H))|_2$.

Also a finite group $H$ such that $H/O(H) \cong SL(2, 3)$ will be said to be of $\mathfrak{M}(3)$-type.

Note that any finite 2-quasisimple group that satisfies conditions (a) and (b) and that does not satisfy the hypotheses of condition (c) is of $\mathfrak{M}(p)$-type.

We now state the three main results of this paper. The first result can be viewed as an extension of [3, Corollary III].

**Theorem 1.** Let $G$ be a finite group such that $O^2(G)$ is 2-quasisimple. Suppose that $z$ is an involution of $G$ such that $C_G(z)$ contains an intrinsic solvable or perfect 2-component $L$ such that $L$ is of $\mathfrak{M}(p)$-type for some odd prime integer $p$. Then $O^2(G)/O(O^2(G))$ is isomorphic to a Chevalley group over a finite field of characteristic $p$ or $G/O(G)$ is isomorphic to $M_{11}$.

**Theorem 2.** Let $W$ be a 4-subgroup of the finite group $G$ and let $W^2 = \{z_1, z_2, z_3\}$. Suppose that $C_G(W)$ contains solvable or perfect 2-components $L_1$ and $L_2$ such that $z_i \in L_i$ and $L_i$ is of $\mathfrak{M}(p_i)$-type with $p_i$ an odd prime integer, for $i = 1$ and 2. Then $O(G)O^2(L_i)$ is subnormal in $G$ or $O^2(L_i)$ is contained in a unique perfect 2-component $K_i$ of $G$ such that $K_i/O(K_i)$ is isomorphic to $M_{11}$ or to a Chevalley group over a finite field of characteristic $p_i$, for $i = 1$ and 2.

**Theorem 3.** Let $G$ be a finite group such that $F^*(G)$ is simple. Suppose that $G$ contains a 4-subgroup $W$ such that $C_G(W)$ contains a perfect 2-component $L$ such that $L \cap W \neq 1$ and $L$ is of $\mathfrak{M}(p)$-type for some odd prime integer $p$. Let $w \in (L \cap W)^\mathfrak{F}$. Then $\langle L^{x(C_G(w))} \rangle$ is a single 2-component of $C_G(w)$ or $F^*(G)$ is a simple Chevalley group over a finite field of characteristic $p$. 

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At this point, it is appropriate to discuss the significance of the hypotheses, the methods of proof and the importance of these results.

Suppose that $K$ is a 2-quasisimple group such that $K/Z^*(K)$ is a simple Chevalley group over a finite field of odd prime characteristic $p$ and assume also that there does not exist an involution $t$ in $K$ such that $C_K(t)$ contains a perfect intrinsic 2-component of $\mathfrak{M}(p)$-type. Then, by Lemma 5.3, $K/O(K)$ is isomorphic to

(i) $\text{PSL}(2, q^n)$ for some positive integer $n$,

(ii) $2G_2(3^{2n}+1)$ for some positive integer $n$, or

(iii) a Chevalley group over a field of 3 elements and of Lie rank at most 4.

(In the cases of (iii) there is however an involution $t$ in $K$ such that $C_K(t)$ contains an intrinsic solvable 2-component by Lemma 5.2.) Consequently perfect intrinsic 2-components of $\mathfrak{M}(p)$-type of centralizers of involutions are, with these exceptions, available for such groups $K$. This observation and the results of this paper will be used in an inductive setting in [26] to show that a proof of the Unbalanced Group Conjecture and the $B(G)$-Conjecture and the classification of all finite groups $G$ with $F^*(G)$ simple that contain an involution $t$ such that $C_G(t)$ possesses a perfect 2-component $K$ such that $K/Z^*(K)$ is isomorphic to any simple Chevalley group over any finite field of odd characteristic depends on the solution of a few specific “standard component problems” related to the exceptions (iii) above.

This paper and [26] include an alternate approach to the results of J. H. Walter in [38] and [39].

Theorem 2 is a consequence of Theorem 1 and Theorem 3 is a consequence of Theorems 1 and 2. The proof of Theorem 1 is basically a combination of the fundamental results of M. Aschbacher in [3], of the ideas of M. Aschbacher, J. G. Thompson and J. H. Walter contained in [37] and of the insights of the author that accrued from the research for [24].

In order to illustrate the significance of condition (c) in the definition of groups of $\mathfrak{M}(p)$-type and with [3, Corollary III] in mind, consider a finite simple group $G$ with an involution $t$ such that $C_G(t)$ possesses a perfect intrinsic 2-component $K$ with $K/Z^*(K)$ isomorphic to a simple Chevalley group over a finite field of order $q = p^n$ with $p$ an odd prime and $n$ a positive integer that is not $\text{PSL}(2, q)$. By a fundamental property of such a group $A$ (cf. Lemma 5.4), there is an involution $z$ in $K$ such that $z \neq t$ and $C_K(z)$ contains both an intrinsic 2-component $J_1$ with $J_1/O(J_1) \cong \text{SL}(2, q)$ and at least one other 2-component $J_2$ of $\mathfrak{M}(p)$-type. Set $H = C_G(z)$. By [3, Corollary III], we may assume that $O(H)J_1$ is not subnormal in $H$. Also assume for simplicity of the present discussion that $O(H) = 1$ and $q \neq 3$; in which case both $J_1$ and $J_2$ are perfect.

Suppose that $K$ is of $\mathfrak{M}(p)$-type. Then the critical condition (c) in the definition of groups of $\mathfrak{M}(p)$-type (cf. Lemma 5.4) enables one to choose $J_2$ such that $t$ or $tz$ lies in $Z(J_2)$. Straightforward arguments using L-Balance [18, Theorem 3.1] and properties of 2-components imply that $J_1$ and $J_2$ both lie in the same intrinsic component $X$ of $E(H) = L_2(H)$ with $Z(X) \cap \langle t, z \rangle = \{z\}$. Set $\bar{X} = X/Z(X)$. Then $\bar{J}_2$ is an intrinsic 2-component of $C\bar{X}(t)$ of $\mathfrak{M}(p)$-type and we conclude, by induction, that $\bar{X}$ is a simple Chevalley group over a finite field of characteristic $p$. 
Since $\bar{J}_1 \cong \text{PSL}(2, q)$ and $\bar{J}_1$ is a component of $C_\mathbb{F}(\bar{J})$, it follows from the known possibilities for $\bar{X}$ that $\bar{X} \cong P\Omega(m, q_1)$ with $m \geq 7$ and $q_1$ a power of $p$. By repeating this argument, if necessary, we reduce to the case in which $K/O(K) \cong \text{Spin}(7, q)$.

Suppose on the other hand, that $\bar{X}$ is not of $\mathfrak{g}H(\mathfrak{p})$-type. In this case, if $\langle J_1, J_2 \rangle$ is contained in a single component $X$ of $E(H)$ (which is not even necessarily the case), then $\bar{J}_2$ is neither of $\mathfrak{g}H(\mathfrak{p})$-type in $\bar{X} = X/Z(X)$ nor intrinsic in $C_\mathbb{F}(\bar{J})$ since $J_2 \cap \langle t, z \rangle = \langle z \rangle$ and $|Z^*(\bar{J}_2)|_2 < |Z^*(J_2)|_2$. Consequently a wider inductive setting seems required in order to identify $X$ under these conditions and so the treatment of this particular problem is postponed to [26].

Finally we remark that the bulk of the proof of Theorem 1 is devoted to treating the cases in which $L/Z^*(L)$ is a simple Chevalley group over a field of 3 elements and in which $L/O(L) \cong \text{Spin}(7, q)$ for an odd prime power $q$.

In §2, we present various results that are required in our proofs of Theorems 1–3. Some of these lemmas are of independent interest. In §3, we utilize [12] to survey the conjugacy classes of involutions and semi-involutions and their centralizers in the classical linear groups over finite fields of odd order. These results are required at various points in our proofs in this paper, in [26] and are also of independent interest. In §4, we apply the theory of linear algebraic groups to survey the conjugacy classes of involutions and their centralizers in various Chevalley groups and their automorphism groups over finite fields of odd order. In some of these lemmas, since the machinery is available and for the sake of completeness, we derive more information than is actually required in this paper. However all of these results are required in [26] and are also of independent interest. In §5, we utilize our previous work to derive additional results that are required in our proofs of Theorems 1–3. Finally §§6–8 are devoted to proving Theorems 1–3, respectively.

Our notation is fairly standard and tends to follow the notation of [16]. In particular, if $X$ is a group and $Y \subseteq X$, then $\mathfrak{g}(Y)$ denotes the set of involutions of $Y$. Also if $X$ is a group such that $|X/X'| = |\mathfrak{g}(X)| = 1$, then $X$ has a universal covering group and it is denoted by Cov$(X)$ (cf. [21]).

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2. Preliminary results. In this section, we present several lemmas that are required at various points in our proofs of Theorems 1–3. Some of these results are of independent interest.

The first lemma is well known and is presented without a (trivial) proof.

**Lemma 2.1.** Let $\pi$ be a set of prime integers. Let $G$ be a group and let $N$ be a subnormal subgroup of $G$ such that $|G : N|_\pi = 1$. Then $O^\pi(G) = O^\pi(N)$ and $O^\sigma(\pi)(G) = O^\pi(\sigma)(G) = O^\sigma(\pi)(N)$.

**Lemma 2.2.** Let $X$ and $M$ be subgroups of the group $G$ with $M \subseteq G$. Let $\pi$ be a set of prime integers and set $\bar{G} = G/M$. Then the following two conditions hold.

(a) $O^\pi(\bar{X}) \leq O^\pi(\bar{X})$; and
(b) $O^\pi(\bar{X}) = O^\pi(\bar{X})$. 

Proof. Clearly $MO_n(X) \subseteq MX$ and $\left( MO_n(X) \right) / M \cong O_n(X) / (M \cap O_n(X))$ is a $\pi$-group; thus (a) holds. Also $MO_n(X) \subseteq MX$ and $\left( MX \right) / (MO_n(X)) \cong X / (O_n(X)(M \cap X))$ which is an epimorphic image of $X / O_n(X)$. On the other hand, if $x$ is a $\pi'$-element of $X$, then $\bar{x}$ is a $\pi'$-element of $\bar{X}$ and hence $O_n(\bar{X}) \subseteq O_n(\bar{X})$. Thus (b) also holds and we are done.

Lemma 2.3. Let $H$ and $K$ be subgroups of a group $G$ and set $M = \langle H, K \rangle$. Note that $[H, K] \leq M$ (cf. [16, Theorem 2.2.1(iii)]) and set $\overline{M} = M / [H, K]$. Then the following two conditions hold.

(a) $\overline{M} = \overline{H} \cdot \overline{K}$; and
(b) $\langle K^H \rangle = [K, H] K \leq M$ and $\langle H^K \rangle = [K, H] H \leq M$.

Proof. Since $\overline{M} = \langle \overline{H}, \overline{K} \rangle$ and $[\overline{H}, \overline{K}] = [H, K]$, (a) holds. For (b), note that $[K, H] \leq \langle K^H \rangle$ and $\langle K^K \rangle = \langle \overline{K}^H \rangle = \langle \overline{K} \rangle$. Thus (b) also holds.

Lemma 2.4. Let $G$ be a not necessarily finite group such that $G = H \times K$ for subgroups $H$ and $K$. Let $\alpha$ be an endomorphism of $G$ such that $\alpha^2$ leaves $H$ invariant and $H^\alpha = K$. Then $\alpha^2$ leaves $K$ invariant, $K^\alpha \leq H$ and $C_G(\alpha) = \{ hk \mid h \in C_H(\alpha^2) \}$ and $k = h^\alpha \in K \Rightarrow H = \alpha^2$.

Proof. Clearly $K^\alpha = H^\alpha = K$, so that $\alpha^2$ leaves $K$ invariant and $K^\alpha \leq H^\alpha = H$. Let $h \in H$ and $k \in K$ and suppose that $(hk)^\alpha = hk$. Then $h^\alpha = k$, $k^\alpha = h$, $h^\alpha^2 = k^\alpha = h$ and the lemma follows.

Lemma 2.5. Let $G$ be a not necessarily finite group with a nontrivial subgroup $H$ of index 2 such that $H = K_1 \times K_2$ for subgroups $K_1$ and $K_2$. Assume that $K_1$ and $K_2$ are conjugate in $G$. Then the following two conditions hold.

(a) There is an involution $t \in G - H$ such that $K_1^t = K_2$ and $C_H(t) = \{ k_1k_1^t \mid k_1 \in K_1 \}$; and
(b) $\delta(G - H) = t^G = t^H$.

Proof. Let $x \in G - H$. Then $x^2 = k_1k_2$ where $k_i \in K_i$ for $i = 1, 2$ and $K_1^x = K_2$. Hence $k_1^x = k_2$, $k_2^x = k_1$, $(k_1^x)^2 = 1$ and (a) holds. Assume that $\gamma = u_1u_2t \in \delta(G - H)$ where $u_i \in K_i$ for $i = 1, 2$. Then $1 = \gamma^2 = u_1u_2u_1^t$; hence $u_1^t = u_1^{-1}$, $u_2t^u_2^{-1} = u_2u_1t = \gamma$ and (b) also holds.

Lemma 2.6. Let $\alpha$ be an endomorphism of the group $G$ such that $g^\alpha \in gZ(G)$ for all $g \in G$. Then the following two conditions hold.

(a) $\alpha$ is the identity on $G'$; and
(b) the function $\tilde{\alpha} : G \to Z(G)$ defined by $g^\tilde{\alpha} = g^{-1}g^\alpha$ is a group homomorphism.

Proof. If $g, h \in G$, then $[g, h]^\alpha = [g^\alpha, h^\alpha] = [g, h]$. Thus (a) holds. If $g, h \in G$, then $(gh)^{-1}(gh)^\alpha = h^{-1}g^{-1}g^\alpha h^\alpha = (g^{-1}g^\alpha)(h^{-1}h^\alpha)$. Thus (b) holds and we are done.

Lemma 2.7. Let $G$ be a group such that $(|G / G'|, \left| \mathfrak{N}(G) \right|) = 1$. Let $H$ be a subgroup of $G$ such that $H \leq G' \cap Z(G)$ and $(|G / G'|, \left| H \right|) = 1$, let $M = \text{Cov}(G)$ and set $\overline{G} = G / H$. Then $(|\overline{G} / \overline{G}'|, \left| \mathfrak{N}(\overline{G}) \right|) = 1$ and $M$ is a universal covering group of $\overline{G}$.
Proof. Let $\alpha: M \to G$ and $\pi: G \to \overline{G}$ denote the canonic epimorphisms. Let $\beta = \pi \circ \alpha$. Thus $\beta: M \to \overline{G}$ is an epimorphism, $\text{Ker}(\beta) = \alpha^{-1}(H)$ and $\text{Ker}(\alpha) = \mathfrak{m}(G)$. Note that $\alpha^{-1}(G') = M' \text{Ker}(\alpha) = M'$ since $\text{Ker}(\alpha) \leq M' \cap Z(M)$. Thus $\text{Ker}(\beta) \leq M'$ and $\overline{G}/\overline{G'} \cong G/G' \cong M/M'$. Also $\alpha([M, \text{Ker}(\beta)]) = [G, H] = 1$, so that $[M, \text{Ker}(\beta)] \leq \text{Ker}(\alpha) \leq M' \cap Z(M)$. Fix $k \in \text{Ker}(\beta)$ and define $\tau: M \to K \text{Ker}(\alpha)$ by $m \tau = [m, k]$ for $m \in M$. If $m_1, m_2 \in M$, then

$$(m_1, m_2) \tau = [m_1, m_2, k] = [m_1, k][m_1, m_2, k][m_2, k] = [m_1, k][m_2, k] = m_1^* m_2^*$$

by [16, Lemma 2.2.4(i)] since $[m_1, k] \in Z(M)$. Thus $\tau$ is a homomorphism. Since $(|M/M'|, |\text{Ker}(\alpha)|) = (|G/G'|, |\mathfrak{m}(G)|) = 1$, we conclude that $\text{Im}(\tau) = 1$. Hence $k \in Z(M)$ and $\text{Ker}(\beta) \leq M' \cap Z(M)$. Now [21, Theorem 3(ii) and Corollary 1.2] imply that $M$ is a covering group of $\overline{G}$. Thus $\text{Ker}(\beta) = \mathfrak{m}(\overline{G})$ by [21, Lemma 1(i)]. Since $\text{Ker}(\alpha) \leq \text{Ker}(\beta)$ and $\alpha(\text{Ker}(\beta)) = H$, it follows that $\text{Ker}(\beta)/\text{Ker}(\alpha) = H$. Thus $|\mathfrak{m}(\overline{G})| = |\text{Ker}(\beta)| = |H| |\text{Ker}(\alpha)|$ and $|\mathfrak{m}(\overline{G})|$ is relatively prime to $|G/G'| = |\overline{G}/\overline{G'}|$. The result now follows from a celebrated result of I. Schur (cf. [21, Theorem 3]).

**Corollary 2.7.1.** If $G$ is a quasisimple group, then $G$ is a homomorphic image of $\text{Cov}(G/Z(G))$. If $G$ is a 2-quasisimple group, then $G/\text{O}(G)$ is a homomorphic image of $\text{Cov}(G/Z^*(G))$.

**Lemma 2.8.** $\text{SL}(2,3)$ is a universal covering group of $\text{SL}(2,3)$ and of $\text{PSL}(2,3)$.

**Proof.** By [28, V, Satz 25.5; 21, Theorem 3(i)], $\text{SL}(2,3)$ is a universal covering group of $\text{SL}(2,3)$. Then Lemma 2.7 implies that $\text{SL}(2,3)$ is a universal covering group of $\text{PSL}(2,3)$.

The next result is obvious.

**Lemma 2.9.** Suppose that $L$ is a solvable 2-component of the group $G$. Then $O(L) = O(G)$, $O^2(L) < O^3(L)$ and $O(L)O^2(L) < L = O(L)O^3(L) = O^2(L)$.

**Lemma 2.10.** Let $G$ be a group with $O(G) = 1$, let $H = O^2(G)$, let $N \leq Z(G)$ and set $\overline{G} = G/N$. Suppose that $\overline{G}$ is isomorphic to $\text{PSL}(2,3)$ or $\text{SL}(2,3)$. Then the following two conditions hold.

(a) $G = N \ast H$ and $H$ is isomorphic to $\text{PSL}(2,3)$ or to $\text{SL}(2,3)$; and

(b) if $G \cong \text{SL}(2,3)$, then $H \cong \text{SL}(2,3)$.

**Proof.** Clearly $Z(G) \leq O_2(G)$ and (b) follows from (a). Also $O^2(\overline{G}) = O^2(G) = H$ by Lemma 2.2. Thus $G = N \ast H$ and we may assume that $G = H = O^2(G)$. Set $Q = O_2(G)$ and observe that $|G| = 3|Q|$ and $G = Q \langle \rho \rangle$ for some element $\rho$ of order 3. By [16, Theorem 5.3.5 and Theorem 2.2.1], we have $Q = [Q, \langle \rho \rangle]C_Q(\rho)$ and $[Q, \langle \rho \rangle] \triangleleft G$. Set $\overline{G} = G/[Q, \langle \rho \rangle]$. Then $\overline{G} = C_Q(\rho) \ast \langle \rho \rangle = O^2(\overline{G})$ and hence $C_Q(\rho) \leq [Q, \langle \rho \rangle] = Q \cong G'$. Consider the natural epimorphism $\pi: G \to \overline{G} = G/N$. Since $\text{Ker}(\pi) = N \leq Z(G) \cap G'$, it follows from Lemma 2.8 and [21, Lemma 1(ii)] that $G$ is a homomorphic image of $\text{SL}(2,3)$. Thus (a) holds and we are done.
Lemma 2.11. Let $G$ be a group. Then the following six conditions hold.

(a) $E(G)$ is the irredundant central product of the distinct perfect components of $G$ and $J$ is a perfect component of $G$ if and only if $J$ is a minimal perfect normal subgroup of $E(G)$;

(b) $Z(E(G)) \leq Z(F(G)) = C_G(F^*(G))$ and $[S(G), E(G)] = 1$;

(c) every perfect 2-component is normal in $L_2(G)$, $L_2(G)$ is the irredundant product of the distinct perfect 2-components of $G$ and $J$ is a perfect 2-component of $G$ if and only if $J$ is a minimal perfect normal subgroup of $L_2(G)$;

(d) if $J$ is a perfect 2-component of $G$, then $J = O^2(O(G)J) = (O(G)J)^{[\infty]}$ and $[S(G), J] \leq O(J)$;

(e) if $J$ and $K$ are distinct perfect or solvable 2-components of $G$, then $[J, K] < O(J)$ and $O(K)$; and

(f) if $J$ and $K$ are distinct perfect 2-components of $G$, then the following three conditions are equivalent: (i) $[J, K] = 1$, (ii) $[J, K] \leq Z(J)$, (iii) $[J, K] \leq Z(K)$.

Proof. Clearly (a) and (b) follow from [5, §1], (c)–(e) follow from [18, §2] and (f) follows from Lemma 2.6(a).

Lemma 2.12. Let $N$ be a normal subgroup of the group $G$, let $H$ be a 2-quasisimple subgroup of $G$ such that $H \nsubseteq N$ and set $G = G/N$. Then the following three conditions hold.

(a) $H$ is 2-quasisimple and $H/Z^*(H) \cong H/Z^*(H)$;

(b) $O(H) = O(H)$; and

(c) $Z^*(H) = Z^*(H)$.

Proof. Clearly $N \cap H \leq Z^*(H)$, $H/HZ^*(H) = H/H$ and $H/Z^*(H) \cong H/Z^*(H)$ is simple. Also $O(H) \leq O(H)$ by Lemma 2.2(a). Thus $Z^*(H) \leq Z^*(H)$ and both (a) and (c) hold. Since $Z^*(H)/O(H)$ is a 2-group, (b) also holds and we are done.

Lemma 2.13. Let $G$ be a group such that $O^2(G)$ is 2-quasisimple. Set $M = O^2(G)$ and $\tilde{G} = G/S(G)$. Then the following three conditions hold.

(a) $S(G) = O(G)Z^*(M) = C_G(M/O(M)) = C_G(M/Z^*(M))$;

(b) $Z^*(M) = S(G) \cap M$ and $O^2(S(G)) = O(G)$; and

(c) $\tilde{M} = O^2(\tilde{G}) = F^*(\tilde{G})$ and $\tilde{M} = M/Z^*(M)$.

Proof. Clearly

$$S(G) \cap M = Z^*(M)$$

and

$$O(G)Z^*(M) \leq S(G) \leq C_G(M/O(M)) = C_G(M/Z^*(M)).$$

Also $C_G(M/O(M)) \cap M = Z^*(M) \unlhd G$, $|C_G(M/O(M))/Z^*(M)|$ is odd and $[C_G(M/O(M)), Z^*(M)] \leq O(M)$. Thus

$$C_G(M/O(M)) = O(G)Z^*(M) = S(G) \quad \text{and} \quad O^2(S(G)) = O(G).$$

Clearly $\tilde{M} = O^2(\tilde{G}) \cong M/Z^*(M)$ and $C_{\tilde{G}}(\tilde{M}) = 1$. Thus $F^*(\tilde{G}) = \tilde{M}$ and the proof is complete.
For the convenience of the reader, we restate [18, Theorem 3.1; 22, Proposition 1; 23, Proposition 1].

**Lemma 2.14.** Let $G$ be a group, let $M$ be a normal subgroup of $G$, let $B$ be a 2-subgroup of $G$, let $K$ be a 2-component of $C_G(B)$ and set $G = G/M$. Then the following three conditions hold.

(a) $L_2(N_G(B)) = L_2(C_G(B)) \leq L_2(G)$;
(b) if $K$ is perfect, then $K \leq M$ or $\overline{K}$ is a perfect 2-component of $C_{\overline{G}}(\overline{B})$; and
(c) if $K$ is solvable, then $O^2(K) \leq M$ or $O(C_{\overline{G}}(\overline{B}))\overline{K}$ is a solvable 2-component of $C_{\overline{G}}(\overline{B})$.

**Lemma 2.15.** Let $K$ be a perfect 2-component of the group $G$ and let $B$ be a 2-subgroup of $G$ such that $[K, B] \leq Z^*(K)$. Then $[K, B] \leq O(K)$, $O^2(C_K(B)) = C_K(B)^{\infty}$, $C_K(B)^{\infty}$ is a perfect 2-component of $C_G(B)$ such that

$$K = O(K)\left(C_K(B)^{\infty}\right) = \left(O(G)\left(C_K(B)^{\infty}\right)\right)^{\infty}$$

and

$$K/O(K) = C_K(B)^{\infty}/O\left(C_K(B)^{\infty}\right).$$

**Proof.** Set $\overline{G} = G/O(G)$. Then $\overline{K}$ is a perfect component of $\overline{G}$ and $[\overline{K}, \overline{B}] \leq Z(\overline{K})$. Thus $[\overline{K}, \overline{B}] = 1$ by Lemma 2.6(a) and hence $\overline{K}$ is a component of $C_{\overline{G}}(\overline{B})$ and $[K, B] \leq O(K)$. Set $X = O(G)K$. As $K \leq X$, we have $O^2(X) = X^{\infty} = K$. Hence

$$X = O(G)C_K(B) = O(G)\left(C_K(B)^{\infty}\right),$$

$$C_X(B)^{\infty} = C_K(B)^{\infty} = O^2(C_X(B)) = O^2(C_K(B)),$$

$$K = O(K)C_K(B)^{\infty}$$

and $C_K(B)^{\infty}$ is a perfect 2-component of $C_G(B)$. Thus

$$K = O(K)\left(C_K(B)^{\infty}\right) = \left(O(G)C_K(B)^{\infty}\right)^{\infty},$$

$$K/O(K) = C_K(B)^{\infty}/O\left(C_K(B)^{\infty}\right)$$

and we are done.

In the next three lemmas, let $B$ denote a 2-subgroup of the group $G$, let $N$ and $H$ be normal subgroups of the group $G$ with $N \leq Z^*(H)$ and set $\overline{G} = G/N$. Also let $M$ denote the full inverse image in $H$ of $C_H(B)$. Thus $\overline{M} = C_{\overline{G}}(\overline{B})$, $N \leq M = \{h \in H \mid [h, B] \leq N\}$, $C_H(B) \leq C_G(B)$, $C_N(B) \leq C_G(B)$ and $C_N(B) \leq C_H(B) = C_M(B)$.

**Lemma 2.16.** The following four conditions hold.

(a) $[H, N] \leq O(N) \leq G$;
(b) $O^2(M) = O(N)O^2(C_H(B))$;
(c) $O(M) = O(N)O(C_H(B))$; and
(d) $O(C_H(B)) = O(C_{\overline{H}}(\overline{B})) = O(\overline{M})$. 

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Proof. Clearly \([H, N] \leq O(H) \cap N = O(N) \leq G\), so that (a) holds. Also \(NC_H(B) \leq M = \{h \in H \mid [B, h] \leq N\}\) and \(N\) has a normal 2-complement. Set \(\tilde{G} = G/O(N)\) and note that \(O^2(M) = O^2(M)\), \(O^2(\tilde{M}) = O^2(M)\), \(N \leq O_2(Z(\tilde{H}))\) and \(C_H(\tilde{B}) = C_{\tilde{H}}(\tilde{B})\) by [16, Theorem 6.2.2]. Consequently, to prove (b), it suffices to assume that \(O(N) = 1\). Let \(\pi \in M\) with \(|\pi|\) odd. Then \(\pi\) stabilizes the chain \(BN \\ N \gg 1\). Hence \(\pi \in C_H(BN) = C_H(B)\) by [16, Theorem 5.3.2] and (b) holds. Then
\[O(M) = O(O^2(M)) = O(N)O(O^2(C_H(B))) = O(N)O(C_H(B))\]
and (c) holds. For (d), let \(L\) denote the inverse image in \(H\) of \(O(C_H(\tilde{B})) = O(\tilde{M})\). Then \(NO(C_H(\tilde{B})) = NO(M) \leq L \leq M, \leq L/N \leq O(N)\). By [16, Theorem 7.4.3], we conclude that \(L = O(L)N\). Since \([B, O(L)] \leq O(L) \cap N = O(N)\), we have \(O(L) = O(N)C_{OL}(L)\). As \(O(C_H(B)) \leq C_{OL}(L) \leq C_H(B)\), we have \(O(C_H(B)) = C_{OL}(L)\). Thus (d) holds and we are done.

Lemma 2.17. Let \(K\) be a 2-component of \(C_H(B)\). Then the following two conditions hold.

(a) \(K\) is a 2-component of \(C_H(B)\) and \(K/Z^*(K) \leq K/Z^*(K)\); and
(b) \(K = C_{NK}(B)^{\infty}\) if \(K\) is perfect and \(K = O^2(C_{NK}(B))\) if \(K\) is solvable.

Proof. As \(\tilde{K} \equiv K/(K \cap N)\) and \(K \cap N \leq Z^*(K)\), we have
\[K/Z^*(K) \equiv \tilde{K}/Z^*(\tilde{K})\].

Clearly \(K \leq C_H(B) \leq C_0(B), O^2(K) \not\leq N\) and \(O(C_H(\tilde{B})) = O(C_H(B)) \leq C_H(B)\) if \(K\) is solvable. Thus (a) follows from Lemma 2.14. Set \(X = C_{NK}(B) = C_{NK}(B)\). Since \(C_{NK}(B) \leq C_0(B)\), we have \(C_{NK}(B) \leq Z^*(C_H(B))\) and \([K, C_{NK}(B)] \leq O(K)\). Thus \(X^{\infty} = K\) if \(K\) is perfect. Suppose that \(K\) is solvable. Since \(O^2(C_N(B)) = O(C_N(B)) \leq O(C_H(B)) \leq K = O^2(K) \leq X\), we have \(K = O^2(X)\) and we are done.

Lemma 2.18. Let \(\tilde{J}\) be a 2-component of \(C_H(\tilde{B})\) and let \(K\) denote the full inverse image of \(\tilde{J}\) in \(H\). Set \(L = C_K(B)^{\infty}\) if \(\tilde{J}\) is perfect and \(L = O^2(C_K(B))\) if \(\tilde{J}\) is solvable. Then the following four conditions hold.

(a) \(\tilde{L} = \tilde{J}\) and \(L/Z^*(L) \equiv \tilde{J}/Z^*(\tilde{J})\);
(b) \(L\) is a perfect 2-component of \(C_H(B)\) if \(\tilde{J}\) is perfect;
(c) \(L\) is a solvable 2-component of \(C_H(B)\) if \(\tilde{J}\) is solvable; and
(d) if \(|N|\) is odd, then \(L/O(L) \equiv \tilde{J}/O(\tilde{J}), L = O^2(C_K(B))\) if \(\tilde{J}\) is perfect and \(O^2(C_K(B)) \leq L = C_K(B)\) if \(\tilde{J}\) is solvable.

Proof. Note that \([K, B] \leq N \leq K \leq M\) and \(K = NO^2(K)\) since \(O^2(J) = \tilde{J}\). Thus \(O(N) \leq O^2(K) \leq O^2(M) = O(N)O^2(C_H(B))\) by Lemma 2.16. Hence
\[O^2(K) = O(N)(O^2(K) \cap O^2(C_H(B))),\]
\[O^2(K), B \leq O^2(N), \quad \tilde{J} = O^2(K),\]
and
\[O^2(K) \cap C_0(B) = O^2(K) \cap O^2(C_H(B)).\]
Suppose that $\bar{J}$ is perfect and $L = C_K(B)$. Then $L \leq O^2(C_H(B)) \cap O^2(K)$, $L \leq C_M(B) = C_H(B) \leq C_B(B)$ and $L = (O^2(C_H(B)) \cap O^2(K))$. Hence

$$\bar{J} = \bar{J}^{(\infty)} = O^2(K) \cap O^2(C_B(B))^{(\infty)} = \bar{L}$$

and $K = NL$. Let $Y$ denote the subgroup of $L$ such that $N \cap L \leq Y < L$ and $\bar{Y} = O(\bar{L})$ and let $T \in \text{Syl}_2(N \cap L)$. Then $N \cap L = O(N \cap L)T$, $Y/N \cap L$ is odd, $[L, T] \leq O(N \cap L) \leq O(L)$ and $T \in \text{Syl}_2(Y)$. Applying [16, Theorem 7.4.3], we conclude that $Y = O(Y)T$. Hence $O(Y) = O(L)$, $[L, Y] \leq O(Y) \leq C_T(B)$ and $Y \leq Z^*(L) \leq S(L)$. As $L/Y \cong \bar{J}/O(\bar{J})$, which is quasisimple, $S(L)/O(L)$ is a 2-group and $[L, S(L)] < Y$. Then $L$ stabilizes the chain $S(L) \geq Y \geq O(L)$. Since $L = O^2(L)$, we have $[L, S(L)] \leq O(L)$ by [16, Theorem 5.3.2]. Thus $L$ is 2-quasisimple, $S(L) = Z^*(L)$ and $L/Z^*(L) \cong \bar{J}/Z^*(\bar{J})$.

Suppose that $\bar{J}$ is solvable and $L = O^2(C_K(B))$. Then $L \leq C_M(B) = C_H(B) \leq C_B(B)$, $L \leq O^2(K) \cap C_B(B) = O^2(K) \cap O^2(C_B(B)) \leq C_K(B)$ and hence

$$L = O^2(O^2(K) \cap O^2(C_B(B))).$$

Thus $\bar{J} = O^2(\bar{J}) = O^2(K) = O^2(O^2(K)) = \bar{L}$. Let $Y$ denote the subgroup of $L$ such that $N \cap L \leq Y < L$ and $\bar{Y} = O(\bar{L})$. Then, as above, $Y \leq C_B(B)$, $Y = O(L)T$ where $T \in \text{Syl}_2(N \cap L)$ and $[L, Y] \leq O(L)$. However $O(L) = O(C_B(B)) = O(C_B(B)) \cap H \leq C_K(B)$ since $O(C_B(B)) = O(C_B(B))$ and $\bar{J} = O(C_B(B))$. Hence $O(L) = O(C_B(B))$. Note that $L/Y \cong \bar{J}/O(\bar{J})$, which is isomorphic to PSL(2,3) or SL(2,3). Set $\bar{L} = L/O(L)$. Then $O^2(\bar{L}) = \bar{O}(\bar{L}) = \bar{L}$, $\bar{T} \leq O_2(\bar{Z}(\bar{L}))$ and Lemma 2.10 implies that $\bar{L}$ is isomorphic to PSL(2,3) or SL(2,3). Thus (a)–(c) hold.

For (d), assume that $|N|$ is odd. Then $K = NL$ implies that $C_K(B) = C_N(B)L$. Here both $|C_N(B)|$ and $|C_K(B)/L|$ are odd. Thus $L = O^2(C_B(B))$ if $\bar{J}$ is perfect and $L = C_K(B)$ if $\bar{J}$ is solvable. Also $L \cap N \leq O(L)$, $\bar{J} = \bar{L} \cong L/(L \cap N)$ and (d) is clear. The proof of this lemma is now complete.

**Lemma 2.19.** Let $z$ be an involution of the group $G$ and set $H = C_G(z)$. Let $L$ be a perfect 2-component of $G$ and let $J$ be a perfect 2-component of $H$. Then the following three conditions hold:

(a) if $L^z = L$, then every perfect 2-component of $C_L(z)$ is a perfect 2-component of $H$;

(b) if $L^z \neq L$, then $C_{LL^z}(z)^{(\infty)}$ is a perfect 2-component of $H$,

$$O(C_{LL^z}(z)) = O(G) \cap (C_{LL^z}(z))$$

and $C_{LL^z}(z)^{(\infty)}/O(C_{LL^z}(z)^{(\infty)})$ is a homomorphic image of $L/O(L)$; and

(c) there is a perfect 2-component $K$ of $G$ such that either (i) $K^z = K$ and $J$ is a perfect 2-component of $C_K(z)$, or (ii) $K^z \neq K$ and $J = C_{KK^z}(z)^{(\infty)}$. Also, in either case, $[J, K^z] = [J, L^z(G)] = (J^L(G)^{(z)}) = K^z$.

**Proof.** Suppose that $L^z = L$. Then $L \leq G$, $C_L(z) \leq H$ and (a) holds. Assume that $L^z \neq L$ and set $M = LL^z$ and $G = G/O(G)$. Note that $M \leq G$, $\bar{z} \in \mathbf{G}(G)$, $\bar{H} = C_G(\bar{z})$ and $L = O^2(O(G)L) = (O(G)L)^{(\infty)}$ by Lemma 2.18. Clearly
The intrinsic 2-component of Chevalley type

$\bar{L}$ and $\bar{L}'$ are distinct components of $\bar{G}$, $\bar{M} = L\bar{L}' = L'\bar{L} \leq G$ and $C_M(z) = C_M(\bar{z}) \leq H$. Moreover $L_2(C_M(\bar{z})) = C_M(\bar{z})^{(\infty)}$ and is a homomorphic image of $\bar{L} \cong L/O(L)$ by [17, Lemma 2.1] and $L_2(C_M(\bar{z}))$ is a component of $H$. Set $\mathcal{J} = C_M(z)^{(\infty)}$. Then $\mathcal{J} = C_M(\bar{z})^{(\infty)}$ and hence $O(G)\mathcal{J}$ is the full inverse image in $G$ of $L_2(C_M(\bar{z}))$. Since $\mathcal{J} \leq (O(G)\mathcal{J}) \cap C_G(z) = C_{O(G)}(z)\mathcal{J}$, we have $\mathcal{J} = (O(G)\mathcal{J} \cap C_G(z))^{(\infty)}$. Thus $\mathcal{J}$ is a 2-component of $H$ by Lemma 2.18. Also $\mathcal{J} = L_2(C_M(\bar{z}))$ and $\mathcal{J}$ is quasisimple. Thus $O(C_M(\bar{z})) \leq C_M(\mathcal{J})$, so that $O(C_M(\bar{z})) \cong Z(M) = Z(L)Z(L')$ by [17, Lemma 2.2]. Since $Z(L)$ is a 2-group, $O(C_M(z)) = O(G) \cap C_M(z)$ and (b) holds. Clearly the first part of (c) follows from (a), (b) and [18, Lemma 2.18 and Corollary 3.2]. Also $J' \subseteq L_2(G)$, so that $J \leq [J, KK'] \leq [J, L_2(G)] = \langle J^{LL'}G \rangle \leq KK'$ by Lemma 2.3. Thus $J \leq X = [J, KK'] \leq KK' = Y$ and $X$ is not solvable. Set $\bar{Y} = Y/S(Y)$. Clearly $K \leq Y$, $K' \leq Y$, $S(K) = Z^*(K) = S(Y) \cap K$, $S(K') = Z^*(K') = S(Y) \cap K'$, $K = (S(Y)K)^{(\infty)}$, $K' = (S(Y)K')^{(\infty)}$ and $1 \neq \bar{X} \leq \bar{Y} = KK'$ where $K \cong K/Z^*(K)$ and $K' \cong K'/Z^*(K')$ are simple. Suppose that $XS(Y) = KK'$. Then $(KK')^{(\infty)} = KK' = X^{(\infty)} \leq X$ and $X = KK'$. Thus to conclude the proof of the lemma, it suffices to assume that $K \neq K'$ and $\bar{Y} = \bar{K} \times \bar{K}'$. However if $\bar{X} = \bar{K}$, then $J = J^{(\infty)} \leq (KS(Y))^{(\infty)} = K$ and hence $K' = K$. Similarly $\bar{X} = \bar{K}'$ is impossible and the proof of this lemma is complete.

Our next result sharpens [1, Theorem 2(2)].

Lemma 2.20. Let $G$ be a group, let $z \in 3(G)$ and let $K$ be a 2-component of $C_G(z)$. Suppose that $L$ is a perfect 2-component of $G$ such that $L^z \neq L$. Then exactly one of the following two conditions holds.

(a) $[K, L] \leq O(L)$ and $[K, L^z] \leq O(L^z)$; or
(b) $K = C_L(L^z)^{(\infty)}$.

Proof. Assume that $G$ is a counterexample of minimal order to the lemma. Applying [1, Theorem 2] and Lemmas 2.17–2.19, we conclude that $O(G) = 1$, $G = (LL^z)(O(C_G(z)) \times z)$, $G^{(\infty)} = E(G) = L \times L^z$, $K \leq O^2(G) = LL^zO(C_G(z)) = N_G(L) = N_{G}(L^z)$ and $|G/O^2(G)| = 2$. Thus $K$ is solvable by Lemma 2.19. Clearly $O_2(G) = Z(L) \times Z(L^z) = Z(E(G)) = C_G(E(G))$ and $F^*(G) = E(G)$. Set $J = C_{E(G)}(z)^{(\infty)}$ and $\bar{G} = G/O_2(G)$. Thus $J$ is a perfect component of $C_G(z)$ with $O(J) = 1$ by Lemma 2.19 and hence $[K, J] = 1$. But $J_1 = \langle xx^z \mid x \in L \rangle \leq C_{E_G(z)}(z)$ and $J_1$ is a homomorphic image of $L$. Thus $J_1 \leq J$ and hence $[K, J_1] = 1$. Now [2, Lemma 2.5] implies that $K = O^2(K) \leq C_G(E(G)) = O_2(G)$. This contradiction completes the proof.

The next result is a slight refinement of [1, Theorem 2(4)].

Lemma 2.21. Let $z$ be an involution of the group $G$, let $H = C_G(z)$, let $L$ be a 2-component of $G$ and let $K$ be an intrinsic 2-component of $H = C_G(z)$. Then $[K, L] \leq O(L)$ or $O^2(K) \leq L$.

Proof. By [1, Theorem 2(4)], we have $[K, L] \leq O(G)$ or $O^2(K) \leq L$. Suppose that $[K, L] \leq O(G)$ and $O(G) \neq O(L)$. Then $L$ is perfect and $K \leq N_G(O(G)) \leq N_G(L)$ since $L = O^2(LO(G))$. Hence $[K, L] \leq O(G) \cap L = O(L)$ and we are done.
The next lemma utilizes J. G. Thompson’s concept of a critical subgroup of a $p$-group (cf. [16, pp. 185–186]) and extends [39, Lemma 4.1].

**Lemma 2.22.** Let $G$ be a group with $O(G) = 1$. Let $z \in \mathcal{S}(G)$ and let $K$ be a solvable 2-component of $C_G(z)$. Then exactly one of the following two conditions holds:

(a) $O^2(K) \leq E(G), [O^2(K), E(G)] \neq 1$ and $K \leq C_G(O_2(G));$

(b) $O^2(K) = [C_p(z), K]$ for every critical subgroup $P$ of $O_2(G)$.

**Proof.** Let $S \in \text{Syl}_2(K)$ and let $\rho$ be a 3-element of $N_K(S) - O(K)$. Thus

$$O(X_G(z))S \triangleleft K = O(C_G(z))\langle \rho^K \rangle = O(C_G(z))S\langle \rho \rangle.$$  

By [16, Theorem 5.3.4], we have $[O(C_G(z)), O_2(G)] = 1$. First, we suppose that $O^2(K) \leq C_G(E(G))$. Then $O_2(G) \neq 1$ since $F^*(G) = O_2(G)E(G)$ and $C_G(F^*(G)) = Z(O_2(G))$. Let $P$ be a critical subgroup of $O_2(G)$. Suppose that $[P, \langle \rho \rangle] = 1$. Then $\rho \in C_G(O_2(G)), K \leq C_G(O_2(G)), O^2(K) \leq C_G(F^*(G)) = Z(O_2(G))$ and $O^2(K) \leq \Omega_4(Z(O_2(G))) \cap C_G(z)$. Since $Z(O_2(G)) \leq P$, this is impossible. Thus $[P, \langle \rho \rangle] \neq 1$. Then $C_p(z), \langle \rho \rangle \neq 1$ by [16, Theorem 5.3.4] and (b) holds by [23, Lemma 2.8].

Finally, suppose that $[O^2(K), E(G)] \neq 1$. Then $O^2(K) \leq E(G)$ by [1, Theorem 2] and $O^2(K) \neq O_2(G)$. Hence $[O_2(G), z] = 1$ by [23, Lemma 2.8] and $O_2(G), O^2(K) = [O_2(G), K] = 1$. Thus (a) holds and we are done.

**Lemma 2.23.** Let $G$ be a group with $O(G) = 1$. Let $z \in \mathcal{S}(G)$ and let $K$ be an intrinsic solvable 2-component of $C_G(z)$ such that $O^2(K) \leq O_2(G)$. Then the following three conditions hold:

(a) $O(C_G(z)) = 1$ and $E(G) = E(C_G(z));$

(b) $K \triangleleft \triangleleft G;$ and

(c) if $M$ is a solvable or perfect 2-component of $C_G(z)$, then $M \triangleleft \triangleleft G$.

**Proof.** Let $P$ be a critical subgroup of $O_2(G)$ and let $Q$ be the unique Sylow 2-subgroup of $K$. Then $z \in Q' \leq P' \leq Z(P), P \leq C_G(Z(P)) \leq C_G(z), L_2(C_G(z)) = E(G) = E(C_G(z))$ by Lemma 2.19 and $[O(C_G(z)), P] = 1$. Thus

$$O(C_G(z)) \leq C_G(O_2(G)E(G)) = Z(O_2(G)),$$

(a) holds and $[K, E(G)] = 1$. Let $\rho$ be an element of order 3 in $K$. Thus $\rho \notin C_G(O_2(G))$ and hence $Q = [P, K] = [P, \langle \rho \rangle]$ and $[\Omega_4(Z(P)), \rho] = 1$ by [23, Lemma 2.6]. Hence $[Z(P), \langle \rho \rangle] = 1, K \leq C_G(Z(P)) \leq C_G(z)$ and (b) holds. For the proof of (c), it suffices to consider a solvable 2-component $M$ of $C_G(z)$ by (a). But then $[E(C_G(z)), M] = [E(G), M] = 1$ and $O^2(M) \leq P \leq C_G(z)$ by Lemma 2.22. Let $R$ be the unique Sylow 2-subgroup of $M$ and let $\nu$ be an element of $M$ of order 3. Suppose that $R' \neq 1$. Then $[Z(P), \langle \nu \rangle] = [Z(P), M] = 1$ by [23, Lemma 2.6] and hence $M \leq C_G(Z(P))$ and $M \triangleleft \triangleleft G$. Suppose that $R' = 1$. Then $P = R \times C_p(M)$ by [23, Lemma 2.5] and hence $P' \leq C_p(M)$. Since $z \in P' \leq Z(P)$, we have $M \leq C_G(P') \leq C_G(z)$ and $C_G(P') \leq G$. Thus $M \triangleleft \triangleleft G$ and we are done.

**Lemma 2.24.** Let $G$ be a group, let $z \in \mathcal{S}(G)$, let $L$ be a 2-component of $G$ such that $L^2 \neq L$ and let $K$ be a 2-component of $C_G(z)$ such that $[L, O^2(K)] \leq O(L)$. Then $[L, K] \leq O(L)$. 

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Proof. Assume that $[L, K] \not\in O(L)$. Since $K = O^2(K)$ if $K$ is perfect, it follows that $K$ is solvable. Also [1, Theorem 2] implies that $K \leq LL^2O(C_G(z))$ and $O^2(K) \leq LL^2$. Thus $K = (K \cap (LL^2))O(C_G(z))$ and

$$O^2(K) \leq C_K(L/O(L)) \cap C_K(L^2/O(L^2)) \cap (LL^2) = K \cap (Z^*(L)Z^*(L^2)).$$

It follows that a Sylow 2-subgroup of $K$ is abelian and $K$ acts trivially on $O^2(K)/O(K).$ This contradiction establishes the lemma.

Definition 2.1. A simple group $K$ is said to be $\theta$-balanced if every group $H$ such that $F^*(H) = K$ has the property that $(|O(CH(t))|, 3) = 1$ for all $t \in \mathfrak{I}(H)$.

Note that if a simple group $K$ is balanced (in the terminology of [7]) or is a simple Chevalley group over a field of characteristic 3 (cf. [9, Lemma]), then $K$ is $\theta$-balanced.

The next result was suggested by situations arising in [24].

Lemma 2.25. Let $G$ be a group and let $z \in \mathfrak{I}(G)$. Let $K$ be a solvable 2-component of $C_G(z)$ and let $L$ be a perfect 2-component of $G$. Suppose that the simple group $L/Z(L)$ is $\theta$-balanced. Also suppose that $K \leq N_G(L), [K, O^2(K)] \leq O(L)$ and that $O^2(K)$ is not contained in $L$. Then $O^2(K) \leq C_K(L/O(L))$.

Proof. By Lemma 2.24, we may assume that $L^2 = L$. Set $H = L(K(z))$. Then $C_H(z) \leq C_G(z), O(C_H(z)) \leq O(C_G(z)) = O(K)$ and $K$ is a solvable 2-component of $C_H(z)$. Thus we may assume that $G = H = L(K(z))$.

Suppose that $O(G) = 1$. Clearly $O^2(K) \leq C_G(L) = C_G(L/Z(L)) = S(G)$ and $S(G) \cap L = Z(L)$. If $z \in S(G)$, then $L$ is a perfect 2-component of $C_G(z)$ and hence $[L, K] = 1$. Thus we may assume that $z \not\in S(G)$. Set $\bar{G} = G/S(G)$. Then $F^*(\bar{G}) = \bar{L}$ is simple, $\bar{z} \in \mathfrak{I}(\bar{G})$ and $|\bar{K}|$ is odd. The inverse image of $C_G(\bar{z})$ in $G$ is

$$N_G(\langle z \rangle S(L)) = N_L(\langle z \rangle Z(L))K(z) = N_G(\langle z \rangle Z(L)).$$

Also $[Z(L), O^2(K)O(K)] = 1$ and $[C_G(L), K] = 1$ since $O^2(K) \not\in Z(L)$ by [23, Lemma 2.8]. Hence $[Z(L), K] = 1$ by [16, Theorem 5.3.4]. This implies that $K \leq C_G(\langle \bar{z} \rangle Z(L)) \leq N_G(\langle z \rangle Z(L)).$ Thus $S(G)K \leq N_G(\langle z \rangle S(G))$ and $\bar{K} \leq O(C_G(\bar{z}))$ since $|\bar{K}|$ is odd. Since $\bar{L}$ is $\theta$-balanced, it follows that $O^2(K) \leq S(G)$ and we are done in this case.

Suppose that $O(G) \neq 1$ and set $\bar{G} = G/O(G)$. Then $\bar{z} \in \mathfrak{I}(\bar{G}), \bar{L}$ is a perfect 2-component of $\bar{G}$ and is a solvable 2-component of $C_G(\bar{z}) = C_G(z)$ by Lemma 2.17. Since $O^2(\bar{K}) = O^2(K), O^3(\bar{K}) = O^3(K)$ and $|O(G)Z^*(L)/Z^*(L)|$ is odd, it is clear that the lemma follows from the above.

The next result was suggested by the proof of [24, Theorem 1].

Lemma 2.26. Let $G$ be a group and let $z \in \mathfrak{I}(G)$. Suppose that $C_G(z)$ contains 2-components $L_1$ and $L_2$ with $z \in L_2$. Assume also that $O(G)L_1$ is not subnormal in $G$ if $L_1$ is perfect and that $O(G)O^3(L_1)$ is not subnormal in $G$ if $L_1$ is solvable. Then $O^2(L_2)$ is contained in a unique perfect 2-component $K$ of $G$. Also $z \not\in Z^*(K), K$ is $C_G(z)$-invariant, $L_1 \leq K$ if $L_1$ is perfect and $[K, L^3(L_1)] = K$ if $L_1$ is solvable.
Proof. First suppose that \( O(G) = 1 \). Clearly \( O^2(L_2) \leq E(G) \) and \([L_2, O_2(G)] = 1\) by Lemmas 2.22 and 2.23. If \( z \in Z(E(G)) \), then \( L_2(C_G(z)) = E(C_G(z)) = E(G) \), \( L_1 \) is solvable and \( L_1 \leq C_G(E(G)) \leq C_G(z) \). Since \( L_1 \) is not subnormal in \( C_G(E(G)) \), it follows that \( z \notin Z(E(G)) \). Hence \([1, \text{Theorem 2(4)}]\) implies that there is a unique perfect component \( K \) of \( G \) such that \( O^2(L_2) \leq K \). Clearly \( z \notin Z(K) \) and \( C_G(z) \) normalizes \( K \). If \([L_1, K] = 1\), then \([L_1, C_G(E(G))] = [L_1, C_G(z)] \) since all components of \( E(G) \) with the exception of \( K \) are components of \( C_G(z) \) by Lemma 2.19. Since \( L_1 \) is not subnormal in \( C_G(E(G)) \), we have \([L_1, K] = K \). Thus \( L_1 \leq K \) if \( L_1 \) is perfect by Lemma 2.19. Suppose that \( L_1 \) is solvable and that \([K, O^3(L_1)] = 1\). Then \( O^3(L_1) \leq C_G(E(G)) \leq C_G(z) \) and \( O^3(L_1) \leq L_1 \), a contradiction. Thus \( O(G) \neq 1 \). Set \( G = G/O(G) \) and let \( J_i = O(G)L_i \) for \( i = 1, 2 \). Thus \( \tilde{J}_i \) and \( \tilde{J}_2 \) are 2-components of \( C_{G_i}(\tilde{z}) \), \( \tilde{z} \in Z(J_2) \), \( \tilde{J}_i \) is not subnormal in \( \tilde{G} \) if \( \tilde{J}_i \) is perfect and \( O^3(J_i) = O^3(L_i) = \tilde{O}^3(L_i) \) is not subnormal in \( \tilde{G} \) if \( \tilde{J}_i \) is solvable. Hence, by the above, \( O^2(J_i) = O^2(L_i) = \tilde{O}^2(L_i) \) is contained in a unique perfect component \( \tilde{K} \) of \( \tilde{G} \), etc. Let \( K_1 \) denote the inverse image of \( \tilde{K} \) in \( G \) and set \( K = K_1^{(\infty)} \). Then \( K = O^2(K_1) \) is a perfect 2-component of \( G \), \( K_1 = (G/K, O^2(L_2) \leq K_1, z \notin Z(K_1) \), \( K \) is \( C_G(z) \) invariant and is the unique perfect 2-component of \( G \) that contains \( O^2(L_2) \). If \( L_1 \) is perfect, then \( L_1 \leq K_1 \) and hence \( L \leq K = K_1^{(\infty)} \). Suppose that \( L_1 \) is solvable. Then \( \tilde{K} = [O^3(L_1), \tilde{K}] = [O^3(L_1), K] \) and hence \([O^3(L_1), K] = K \). The proof of this lemma is now complete.

The next result of this section is a compilation of results of various authors. For references, see \[13, \S 2; 19\].

**Lemma 2.27.** Let \( X \) be a simple Chevalley group over a finite field of order \( q \) where \( q = p^n \) for some odd prime \( p \) and positive integer \( n \). Then \( X \) has a universal covering group, \( \text{Cov}(X) \), and \( S(\text{Cov}(X)) = Z(\text{Cov}(X)) \). Set \( Y = \text{Cov}(X)/O(\text{Cov}(X)) \). Then exactly one of the following 16 conditions holds.

1. \( X \cong \text{PSL}(m, q) \cong A_{m-1}(q) \) for some integer \( m \geq 2 \) with \( (m, q) \neq (2, 3) \); \( Z(\text{SL}(m, q)) \cong Z_{(m, q-1)} \); if \( (m, q) \neq (2, 9) \), then \( O(\text{Cov}(X)) \cong \text{SL}(m, q) \) and if \( (m, q) = (2, 9) \), then \( O(\text{Cov}(X)) \cong Z_3 \) and \( Y \cong \text{SL}(2, 9) \);

2. \( X \cong \text{PSU}(m, q) \cong 2A_{m-1}(q) \) for some integer \( m \geq 3 \); \( Z(\text{SU}(m, q)) \cong Z_{(m, q+1)} \); if \( (m, q) \neq (4, 3) \), then \( O(\text{Cov}(X)) \cong \text{SU}(m, q) \) and if \( (m, q) = (4, 3) \), then \( O(\text{Cov}(X)) \cong Z_3 \times Z_3 \) and \( Y \cong \text{SU}(4, 3) \);

3. \( X \cong \text{PSp}(2m, q) \cong C_m(q) \) for some integer \( m \geq 2 \); \( Z(\text{Sp}(2m, q)) \cong Z_2 \) and \( \text{Cov}(X) \cong \text{Sp}(2m, q) \);

4. \( X \cong \text{PSO}(2m + 1, q) \cong B_m(q) \) for some integer \( m \geq 3 \); \( Z(\text{Spin}(2m + 1, q)) \cong Z_2 \); if \( (2m + 1, q) \neq (7, 3) \), then \( O(\text{Cov}(X)) \cong \text{Spin}(2m + 1, q) \) and if \( (2m + 1, q) = (7, 3) \), then \( O(\text{Cov}(X)) \cong Z_3 \) and \( Y \cong \text{Spin}(7, 3) \);

5. \( X \cong \text{PSO}(2m, q, 1) \cong D_m(q) \) for some even integer \( m \geq 4 \); \( Z(\text{Spin}(4m, q, 1)) \cong E_4 \) and \( \text{Cov}(X) \cong \text{Spin}(4m, q, 1) \);

6. \( X \cong \text{PSO}(2m, q, -1) \cong 2D_m(q) \) for some even integer \( m \geq 4 \); \( Z(\text{Spin}(2m, q, -1)) \cong Z_2 \) and \( \text{Cov}(X) \cong \text{Spin}(2m, q, -1) \);

7. \( X \cong \text{PSO}(2m, q, 1) \cong D_m(q) \) for some odd integer \( m \geq 5 \); \( Z(\text{Spin}(2m, q, 1)) \cong Z_{(4, q-1)} \) and \( \text{Cov}(X) \cong \text{Spin}(2m, q, 1) \);
(8) $X \cong P\Omega(2m, q, -1) \cong D_m(q)$ for some odd integer $m \geq 5$, $Z(\text{Spin}(2m, q, -1)) \cong Z_{4q+1}$ and $\text{Cov}(X) \cong \text{Spin}(2m, q, -1)$;
(9) $X \cong E_6(q)$ and $Z(\text{Cov}(X)) \cong Z_{3q-1}$;
(10) $X \cong E_7(q)$ and $Z(\text{Cov}(X)) \cong Z_2$;
(11) $X \cong E_8(q)$ and $Z(\text{Cov}(X)) \cong Z_3$;
(12) $X \cong F_4(q)$ and $Z(\text{Cov}(X)) \cong Z_3$;
(13) $X \cong G_2(q)$ if $q \neq 3$, then $X = \text{Cov}(X)$ and if $q = 3$, then $Z(\text{Cov}(X)) \cong Z_3$;
(14) $X \cong D_6(q)$ and $Z(\text{Cov}(X)) = (3, q+1)$; or
(15) $X \cong F_4(q)$ and $Z(\text{Cov}(X)) \cong (3, q+1)$.

Lemma 2.28. Let $N$ be a normal subgroup of the group $G$, let $H$ be a subgroup of $G$ that is of $\mathfrak{R}(p)$-type and set $\overline{G} = G/N$. Then $\mathfrak{R}(Z^*(H)) \subseteq N$ or $\overline{H}$ is of $\mathfrak{R}(p)$-type.

Proof. Assume that $t \in \mathfrak{R}(Z^*(H)) - N$. Suppose that $H/O(H) \cong SL(2, 3)$. Then $N \cap H \leq H$ and hence $N \cap H \leq O(H)$ and $\overline{H}/O(\overline{H}) \cong SL(2, 3)$. Thus we may assume that $H$ is 2-quasisimple. Then, by Lemma 2.12, $\overline{H}$ is 2-quasisimple, $\overline{H}/\overline{Z^*(H)} \cong H/Z^*(H)$, $t \in Z^*(\overline{H}) = \overline{Z^*(H)}$ and $t \in \mathfrak{R}(\overline{G})$. Suppose that $\overline{H}$ is not of $\mathfrak{R}(p)$-type. Then $H/Z^*(H)$ is isomorphic to $\text{PSL}(2n, p')$ or $\text{PSU}(2n, p')$ for some positive integers $n$ and $r$, $Z^*(H)$ has cyclic Sylow 2-subgroups and $|Z^*(H)|_2 < |\mathfrak{R}(H/Z^*(H))|_2$. As $Z^*(H) \cap N \leq Z^*(H)$, $|Z^*(H) \cap N|$ is even and $t \notin N$, we have a contradiction and the lemma holds.

3. Centralizers of involutions and semi-involutions in the classical linear groups over finite fields of odd characteristic. In this section, we shall review the survey of the conjugacy classes of involutions and semi-involutions and their centralizers in the classical linear groups over finite fields of odd order as presented in [12, Chapitre I, §§3, 4, 13 and 14] and add a few observations that we shall require at various points in the proofs in this paper.

Throughout this section, let $k$ denote a finite field of order $q = p^n$ where $p$ is an odd prime integer and $n$ is a positive integer. Also let $V$ be a finite dimensional vector space over $k$ with $\dim(V/k) = m$.

Suppose that $m = 1$. Then $\text{GL}(V/k) = \langle \lambda I \mid \lambda \in k^\times \rangle \cong k^\times$, $\text{SL}(V/k) = 1$ and consequently we shall usually assume that $m > 1$.

Before discussing the classical linear groups, we present two lemmas that we shall need in subsequent discussions.

Lemma 3.1. Suppose that $m > 1$. Let $H$ be a finite group and let $G$ be a subgroup of index 2 of $H$ such that $G \cong \text{GL}(V/k)$; thus $G' \cong \text{SL}(V/k)$ and $Z(G) = k^\times$. Assume that there is an element $\tau \in H - G$ such that $\tau^2 \in Z(G)$ and $\tau$ acting by conjugation on $G$ induces transpose-inverse on $G$ with respect to the basis $B = \{v_1, \ldots, v_n\}$ of $V/k$. Then the following two conditions hold.
(a) If $m = 2$ and $\alpha \in G$ has matrix $\begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$ with respect to $B$, then $C_H(G') = \langle Z(G), \alpha \tau \rangle$ and $(\alpha \tau)^2 = (-1_v) \tau^2$; and
(b) if $m > 2$, then $C_H(G') = Z(G)$. 

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Proof. Let \( M = C_H(G') \). By [25, Proposition 2], we have \( M \cap G = C_G(G') = Z(G) = \langle \lambda I_V | \lambda \in k^\times \rangle \), so that \( |M/Z(G)| \leq 2 \). First suppose that \( m = 2 \) and let \( \alpha \) be as in (a). Then \( \alpha \tau \in M - Z(G) \) and it is clear that (a) holds. Consequently we may suppose that \( m > 2 \) and \( |M/Z(G)| = 2 \). Thus there is an element \( \beta \in G \) such that \( \beta \tau \in M \).

For each integer \( 1 \leq i < m \), let \( u_i \) denote the unique element of \( G \) such that:

\[
\begin{align*}
u_i(v_j) &= v_j \quad \text{if } j \notin \{i, i + 1\}, \\
u_i(v_{i+1}) &= -v_i.
\end{align*}
\]

Clearly \( \langle u_i | 1 \leq i < m \rangle \leq G' \cap C_G(\tau) \leq C_G(\tau, \beta) \). Also, for each \( 1 \leq i < m \), let \( t_i \) denote the unique element of \( G \) such that:

\[
\begin{align*}t_i(v_j) &= v_j \quad \text{if } j \notin \{i, i + 1\}, \\
t_i(v_{i+1}) &= -v_{i+1}.
\end{align*}
\]

Clearly \( t_i \tau = t_i \in G' \) for all \( 1 \leq i < m \) and hence \( \beta \in C_G(\langle t_i | 1 \leq i < m \rangle) \cong \bigcap_{i=1}^m Stab_G(kv_i) \). Since \( \beta \in C_G(\langle u_i | 1 \leq i < m \rangle) \), we conclude that \( \beta \in Z(G) \) and hence \( M = \langle Z(G), \tau \rangle \). Since \( \tau \notin C_H(G') \), we have a contradiction and the proof of this lemma is complete.

Lemma 3.2. Suppose that \( m > 1 \) and \( n \) is even. Let \( H \) be a finite group and let \( G \) be a subgroup of index 2 of \( H \) such that \( G = \text{GL}(V/k) \); thus \( G' = \text{SL}(V/k) \) and \( Z(G) = k^\times \). Let \( \sigma \in \mathfrak{S}(\text{Aut}(k)) \) and suppose that there is an element \( \tau \in H - G \) such that \( \tau^2 \in Z(G) \) and \( \tau \) acting by conjugation on \( G \) induces a unitary automorphism (transpose-inverse-automorphism induced by \( \sigma \)) on \( G \) with respect to the basis \( B = \{v_1, \ldots, v_m\} \) of \( V/k \). Then \( C_H(G') = Z(G) \).

Proof. Let \( M = C_H(G') \), so that \( M \cap G = C_G(G') = Z(G) = \langle \lambda I_V | \lambda \in k^\times \rangle \) and \( |M/Z(G)| \leq 2 \). Assume that there is an element \( \beta \in G \) such that \( \beta \tau \in M \).

For each integer \( 1 \leq i < m \), let \( u_i \) and \( t_i \) be as in Lemma 3.1. First suppose that \( m > 2 \). Then, as in Lemma 3.1, it follows that \( \beta \in Z(G) \) and \( M = \langle Z(G), \tau \rangle \). Since \( \tau \notin C_H(G') \) we have a contradiction. Consequently, \( m = 2 \). Let \( C_k(\sigma) = k_0, q_0 = |k_0| \) and let \( N : k^\times \to k_0^\times \) denote the norm mapping of \( k/k_0 \). Clearly \( q_0^2 = q \) and \( |\text{Ker}(N)| = q_0 + 1 \) by [28, Lemma 8.5]. Hence there is an element \( c \in \text{Ker}(N) \) with \( c \notin \{1, -1\} \). Let \( x \in G \) be such that \( x(v_1) = cv_1 \) and \( x(v_2) = c^{-1}v_2 \). Then \( x \in G' \) and \( x^2 = x \). Hence \( \beta \in C_G(x) = Stab_G(kv_1) \cap Stab_G(kv_2) \). On the other hand, \( \beta \in C_G(u_i) \) and hence \( \beta \in Z(G) \). Thus \( M = \langle Z(G), \tau \rangle \) and since \( \tau \notin C_H(G') \), we have a contradiction to complete the proof.

3A. The general linear groups. Let \( G = \text{GL}(V/k), H = \text{SL}(V/k) \) and \( Z = Z(G) = \langle \lambda I_V | \lambda \in k^\times \rangle \) and \( |M/Z(G)| \leq 2 \). Assume that there is an element \( \beta \in G \) such that \( \beta \tau \in M \).

First assume that \( U \) is not cyclic. Then \( U = Z \times \langle w \rangle \) where \( w \in \mathfrak{S}(G - Z) \), \( w \neq -I_V \), \( C_G(U) = C_G(w) \), \( C_G(U) \subset \{w, -I_V w\} \) and \( |w| = |M/C_G(U)| \leq 2 \). Also as in [12, I, §3 and 4], we have \( V = V^+ \oplus V^- \) where:

\[
V^+ = C_V(w) \quad \text{and} \quad V^- = \{v \in V | w(v) = -v\} = [V, w].
\]
Also 1 ≤ \(\text{dim}(V^+/k)\) < \(m\), \(\det(w) = (-1)^{\text{dim}(V^-/k)}\) and \(U \notin Z \cdot H\) if and only if \(\text{dim}(V^-/k)\) is odd and \(-1 \notin (k^\times)^m\). Clearly \(G = HC_G(w)\), \(w^G = w^H\) and there is an isomorphism \(\alpha: C_G(U) \rightarrow \text{GL}(V^+/k) \times \text{GL}(V^-/k)\) with \(\alpha(Z) = \langle (\lambda I_{V^+}, \lambda I_{V^-}) \mid \lambda \in k^\times \rangle\) and \(\alpha(w) \in Z(\text{GL}(V^-/k))\). Clearly

\[
(\text{GL}(V^+/k) \times \text{GL}(V^-/k))' = \text{SL}(V^+/k) \times \text{SL}(V^-/k)
\]

and hence

\[
\alpha(C_{C_G(U)}(C_G(U)')) = \langle (\lambda I_{V^+}, \delta I_{V^-}) \mid \lambda, \delta \in k^\times \rangle \approx k^\times \times k^\times
\]

by [25, Proposition 2]. Suppose that \(|M/C_G(U)| = 2\). Then \(w \sim (-I_V)w\) in \(M\) and hence there is an involution \(g \in M\) such that \(g: C_V(w) \leftrightarrow [V, w]\), \(w^g = (-I_V)w\) and \(M = C_G(U)g = GL(V^+/k)\wr Z_2\).

The above discussion shows that if \(x, y \in \mathfrak{g}(G)\), then the following three conditions are equivalent: (i) \(x \sim y\) in \(G\); (ii) \(\text{dim}(C_V(x)/k) = \text{dim}(C_V(y)/k)\); (iii) \(x \sim y\) via \(H\). Also for any integer \(p\) with \(1 \leq p < m\), there is an involution \(z \in G - Z\) such that \(\text{dim}(C_V(z)/k) = p\).

Next assume that \(U\) is cyclic. Then \(U = \langle Z, w \rangle\) where \(w^2 = \gamma I_V\) for some \(\gamma \in k^\times - (k^\times)^2\). Hence \(X^2 - \gamma\) is irreducible in the polynomial ring \(k[X]\) and is the minimal polynomial of \(w\). Thus \(m\) is even, \((X^2 - \gamma)^{m/2}\) is the characteristic polynomial of \(w\) and \(\det(w) = (-\gamma)^{m/2}\). Consequently \(U \notin Z \cdot H\) if and only if \((-\gamma)^{m/2} \notin (k^\times)^m\). As in [12, I, §3], let \(K\) be a quadratic extension field of \(k\) such that \(K = k(\rho)\) where \(\rho^2 = \gamma\), so that \(\{1, \rho\}\) is a basis of \(K/k\). As in [12, I, §3], for \(v \in V\) and \(a, b \in k\), set \(v(a + bp) = va + w(v)b\). Then \(V\) becomes a vector space over \(K\) of dimension \(\frac{m}{2}\) and \(C_G(U) = GL(V/K)\). Let \(B = \{v_1, \ldots, v_m/2\}\) be a basis of \(V/K\) and let \(\text{Gal}(K/k) = \langle \tau \rangle\), so that \(B_1 = \{v_1, \ldots, v_{m/2}, v_1\rho, \ldots, v_{m/2}\rho\}\) is a basis of \(V/k\), for any \(1 \leq i \leq \frac{m}{2}\), \(w(v_2) = v_2\rho\) and \(w(v_i\rho) = v_i\gamma\), \(\tau \in \text{Aut}(k)\), \(|\tau| = 2\), \(\tau(\rho) = -\rho\) and \(C_K(\tau) = k\). For any \(v = \sum_{i=1}^{m/2} v_id_i\) with \(d_i \in K\) for \(1 \leq i \leq \frac{m}{2}\), set \(x(v) = \sum_{i=1}^{m/2} v_i\tau(d_i)\). Then \(x(GL(V/K)) = G\), \(\det(x) = (-1)^{m/2}\), \(|x| = 2\) and \(w^x = -w\) since \(xw(v) = x(v)\rho = v\tau(\rho) = -x(v)\rho = -(wx(v))\). Thus \(M = C_G(U)(x) \leq \Gamma L(V/K)\) and \(x\) acts like a field automorphism of order 2 on \(C_G(U) = GL(V/K)\). Since the norm \(N: K^\times \to k^\times\) is epimorphic, it is easy to see that \(G = C_G(U)H\) and hence \(w^G = w^H\). Also it is obvious that for every \(\delta \in (K^\times)^2\), there is an element \(w_1 \in wZ = U - Z\) such that \(w_1^2 = \delta I_V\). Consequently all cyclic subgroups \(X\) of \(G\) such that \(Z \leq X\) and \(|X/Z| = 2\) are conjugate via \(H\) because of the basis \(B_1\) of \(V/k\). Moreover, if \(m\) is even, there are cyclic subgroups \(X\) of \(G\) such that \(Z \leq X\) and \(|X/Z| = 2\) since there are elements \(w \in G\) such that \(w^2 = \gamma I_V\) for any \(\gamma \in k^\times -(k^\times)^2\).

3B. The symplectic groups. Suppose, in this section, that \(f: V \times V \to k\) is a bilinear symplectic scalar product that is nonsingular (cf. [25, §1; 29, §7; etc.]). Thus \(f(v_1, v_2) = -f(v_2, v_1)\) for all \(v_1, v_2 \in V\) and \(m = \text{dim}(V/k)\) is even. Let \(G = GSp(V/k)\) and \(H = \text{Sp}(V/k)\) be as defined in [12, I, §9]. Thus \(Z = \langle \lambda I_V \mid \lambda \in k^\times \rangle \leq G\), \(H = G'\), \(Z(G) = Z\) by [25, Proposition 3] and \(Z \cap H = \langle -I_V \rangle\). For each \(u \in G\), there is a unique element \(r_u \in k^\times\) such that \(f(u(v_1), u(v_2)) = r_u f(v_1, v_2)\) for all \(v_1, v_2 \in V\), \(r_u\) is called the multiplicator of \(u\) and the mapping \(\gamma: G \to k^\times\) defined
by \( \gamma(u) = r_u \) for \( u \in G \) is an epimorphism with \( \text{Ker}(\gamma) = H \) (cf. [25, Proposition 3]). Set \( \overline{G} = G/Z \). Then \( |\overline{G}/H| = 2 \) and the inverse image of \( H \) in \( G \) is \( Z \ast H = \{ u \in G | r_u \in (k^\times)^2 \} \).

For \( m = 2 \), we have, by [28, II, 9.12], \( G = \text{GL}(V/k) \), \( \gamma = \text{det} \) and \( H = \text{SL}(V/k) \).

Let \( u \in G - Z \) be such that \( u^2 = \gamma r_\gamma \) for some \( \gamma \in k^\times \), so that \( |\overline{u}| = 2 \). Let \( U = \langle u, Z \rangle \) and \( M = N_G(U) \). Thus \( U \) is abelian, \( U = \langle \overline{u} \rangle \cong U/Z \), \( C_G(U) = C_G(U) \), \( M \) is the inverse image in \( G \) of \( C_G(\overline{u}) \), \( U \subseteq Z \ast H \) if and only if \( |(U \cap H)/(Z \cap H)| = 2 \) and \( |M/C_G(U)| \leq 2 \) as in \( \S 3A \).

First assume that \( U \) is not cyclic. Then \( U = Z \times \langle w \rangle \) where \( w \in \mathcal{G}(G - Z) \), \( w \neq -I_V \), \( C_G(U) = C_G(w) \), \( w^M \subseteq \{ w, (-I_V)w \} \), \( |w^M| = |M/C_G(U)| \leq 2 \) and \( r_w^2 = 1 \).

Suppose that \( r_w = 1 \). Then \( w \in H \), \( U \cong Z \ast H \), \( V = V^+ \perp V^- \) where \( V^+ = C_V(w) \), \( V^- = \{ v \in V | w(v) = -v \} \) and the restrictions of \( f \) to \( V^+/k \) and \( V^-/k \) yield nonsingular symplectic vector spaces. Thus \( \dim(V^+ /k) \) is even, \( 2 \leq \dim(V^+ /k) < m \), \( C_G(U) \cong \{ (w_1, w_2) \in (GSp(V^+/k)) \times (GSp(V^-/k)) | r_{w_1} = r_{w_2} \} \), \( G = HC_G(U) \) and \( w^G = w^H \). Suppose that \( |M/C_G(U)| = 2 \). Then \( w \sim (-I_V)w \) in \( M \) and [29, Proposition 9.13] implies that there is an involution \( g \in M \cap H \) such that \( g: V^+ \leftrightarrow V^- \), \( w^g = (-I_V)w \) and \( M = C_G(U)/g \).

It now is clear that if \( x \), \( y \in \mathcal{G}(H) \), then the following three conditions are equivalent: (i) \( x \sim y \) in \( G \); (ii) \( \dim(C_V(x)/k) = \dim(C_V(y)/k) \); (iii) \( x \sim y \) in \( H \). Also for any even integer \( p \) with \( 2 \leq p < m \), there is an involution \( z \in G - Z \) such that \( \dim(C_V(z)/k) = p \).

Suppose that \( r_w = -1 \). Then \( w \notin H \), \( U \subseteq Z \ast H \) if and only if \( q \equiv 1 \) (mod \( 4 \)), \( V^+ = C_V(w) \) and \( V^- = \{ v \in V | w(v) = -v \} \) are totally isotropic subspaces of \( V \) with \( V = V^+ \oplus V^- \) and \( \dim(V^+ /k) = \dim(V^- /k) = \frac{m}{2} \). Also there are bases \( \{ v_i | 1 \leq i \leq \frac{m}{2} \} \) of \( V^+ /k \) and \( \{ v_{j+m/2} | 1 \leq j \leq \frac{m}{2} \} \) of \( V^- /k \) such that \( f(v_i, v_{j+m/2}) = \delta_{ij} \) for all \( 1 \leq i, j \leq \frac{m}{2} \). Suppose that \( x \in C_G(U) \). Then \( x \) leaves invariant both \( V^+ \) and \( V^- \) and \( f(x(v_1), x(v_2)) = r_s f(v_1, v_2) \) for all \( v_1 \in V^+ \) and \( v_2 \in V^- \). Conversely, if \( x \in \text{GL}(V/k) \) is such that \( x \) leaves invariant both \( V^+ \) and \( V^- \) and \( f(x(v_1), x(v_2)) = sf(v_1, v_2) \) for all \( v_1 \in V^+ \), \( v_2 \in V^- \) and for some fixed \( s \in k \), then \( x \in C_G(U) \) and \( r_s = s \). For \( (\lambda_1, \lambda_2) \in k^\times \times k^\times \), let \( (\lambda_1 I^+, \lambda_2 I^-)(v_1 + v_2) = \lambda_1 v_1 + \lambda_2 v_2 \) for all \( v_1 \in V^+ \) and \( v_2 \in V^- \). Then

\[
g(\langle \lambda_1 I^+, \lambda_2 I^- \rangle) = \lambda_1 \lambda_2 \text{ and } X = \langle \langle \lambda_1 I^+, \lambda_2 I^- \rangle | \lambda \in k^\times \rangle \subseteq C_G(U).
\]

Also for each \( g \in \text{GL}(V^+ /k) \), there is a unique element \( g^* \in \text{GL}(V^- /k) \) such that \( f(g(v_1), g^*(v_2)) = f(v_1, v_2) \) for all \( v_1 \in V^+ \) and \( v_2 \in V^- \). Hence the mapping \( \alpha: \text{GL}(V^+ /k) \to C_H(U) \) defined by \( \alpha(g)(v_1 + v_2) = g(v_1) + g^*(v_2) \) for all \( v_1 \in V^+ \), \( v_2 \in V^- \) and \( g \in \text{GL}(V^+ /k) \) induces an isomorphism of \( \text{GL}(V^+ /k) \) onto \( C_H(U) \).

Consequently

\[
C_G(U) = C_H(U) X = C_H(U) \ast X = C_H(U) \times \langle (I^+_V, \lambda I^-_V) | \lambda \in k^\times \rangle
\]

since \( C_G(U) \cap X = \langle (\lambda I^+_V, \lambda^{-1} I^-_V) | \lambda \in k^\times \rangle \). Note that \( C_G(U)^\gamma = \text{SL}(V^+ /k) \) and \( Z < X = C_G(U) C_G(U)^\gamma \). Let \( g \in \text{GL}(V/k) \) be such that \( v_i \leftrightarrow v_{i+m/2} \) for all \( 1 \leq i \leq \frac{m}{2} \). Then \( g \in \mathcal{G}(G) \) with \( r_g = -1 \), \( g w = (-I_V)wg \in H \), \( (gw)^2 = -I_V \), \( M = C_G(U)/g \) and it is easy to see that conjugation by \( g \) induces transpose inverse on
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$C_H(U) \cong \text{GL}(V^+/k)$ and that $g: \langle (\lambda I_{V^+}, I_{V^+}) | \lambda \in k^\times \rangle \leftrightarrow \langle (I_{V^+}, \lambda I_{V^+}) | \lambda \in k^\times \rangle$. Clearly $G = HCG(U)$, $w^G = w^H$ and it follows from the existence of the bases of $V^+/k$ and of $V^−/k$ described above that all involutions $w$ of $G$ with $r_w = -1$ are conjugate under $H$. Moreover, it is easy to see from [29, Proposition 9.13], that there are involutions $w \in G$ such that $r_w = -1$.

Next assume that $U$ is cyclic. Then $U = \langle Z, w \rangle$ where $w^2 = \gamma I_V$ for some $\gamma \in k^\times - (k^\times)^2$. Since $r_w^2 = \gamma^2$, we have $r_w = \pm \gamma$. Also, let $K = k(p), \rho, \tau, V/k, \text{etc.}$ be as in §3A and for any $v_1, v_2 \in V$, set $f_0(v_1, v_2) = \rho f(v_1, v_2) + f(v_1, w(v_2))$. Thus $f_0(v_2, v_1) = -\rho f(v_1, v_2) - r_w^{-1} f(v_1, w(v_2))$ for any $v_1, v_2 \in V$.

Suppose that $r_w = \gamma$. Then $f_0(v_1, v_2) = -f_0(v_2, v_1)$ for all $v_1, v_2 \in V$ and $f_0: V \times V \to K$ is a nonsingular bilinear symplectic scalar product on $V/K$. Hence $\dim(V/K) = \frac{f}{2}$ is even and $U \not\subset Z \ast H$ since $r_w = \gamma \not\in (k^\times)^2$. It readily follows that $C_G(U) = \{ x \in GSp(V/K) | r_x \in k^\times \}$ and hence $G = HCG(U)$ and $w^G = w^H$ by [25, Proposition 3]. Also by [29, Proposition 9.13], $V/K$ has a basis $B = \{ v^{(i)}_1, v^{(i)}_2 | 1 \leq i \leq \frac{f}{2} \}$ such that for all $1 \leq i, j \leq \frac{f}{2}$ and $1 \leq r, s \leq 2$, we have

$$f_0(v^{(i)}_1, v^{(j)}_2) = 0 \text{ if } i \neq j \text{ or } r = s \text{ and } f_0(v^{(i)}_1, v^{(j)}_2) = 1 = -f_0(v^{(i)}_2, v^{(j)}_1).$$

Consequently $B_i = \{ v^{(i)}_1, v^{(i)}_2, v^{(j)}_1, v^{(j)}_2 | 1 \leq i \leq \frac{f}{2} \}$ is a basis of $V/k$ such that for all $1 \leq i, j \leq \frac{f}{2}$ and $1 \leq r, s \leq 2$, we have

$$f(v^{(i)}_1, v^{(j)}_2) = f(v^{(i)}_1, v^{(j)}_2) = f(v^{(i)}_1, v^{(j)}_2) = 0 \text{ if } i \neq j \text{ or } r = s,$$

$$f(v^{(i)}_1, v^{(j)}_2) = f(v^{(i)}_1, v^{(j)}_2) = 0 \text{ and } f(v^{(i)}_1, v^{(j)}_2) = f(v^{(i)}_2, v^{(j)}_2) = +1.$$  

Clearly $w(v^{(i)}_1) = v^{(i)}_2$ and $w(v^{(i)}_1) = v^{(j)}_2$ for all $1 \leq i \leq \frac{f}{2}$. Let $x = \Gamma L(V/K)$ be induced by $\gamma$ with respect to the basis $B$ of $V/k$ as in §3A. Then $xw = (-I_V)xw, x \in \text{GSp}(V/K), x(v_1), x(v_2) = f(v_1, v_2)$ for all $v_1, v_2 \in V, x \in G, |x| = 2$ and $M = C_G(U) \langle x \rangle \leq \text{GSp}(V/K)$. Clearly every element $w_i \in wZ$ is such that $w_i^{-1} I_V$ with $w_i \in k^\times - (k^\times)^2$. Next suppose that $X$ is a cyclic subgroup of $G$ such that $Z \subset X, |X/Z| = 2$ and such that $X - Z$ contains an element $z$ with $z^2 = r_z I_V$. Then $r_z \not\in (k^\times)^2$ since $X$ is cyclic and we may assume that $r_z = \gamma$. The existence of the basis $B_i$ of $V/k$ above implies that $X$ and $U$ are conjugate via $H$. Moreover, when $\frac{f}{2}$ is even, there are such subgroups $X$ of $G$. To see this, let $\gamma \in k^\times - (k^\times)^2$, let $K = k(p)$ where $p^2 = \gamma$ as above, let $W/K$ be a vector space with dim$(W/K) = \frac{f}{2}$ and let $g: W \times W \to K$ be a $K$-bilinear nonsingular symplectic scalar product (cf. [29, Proposition 9.13]). Since $K = k + kp$, we conclude that $g = pg_1 + g_2$ where $g_i: W \times W \to k$ is a $k$-bilinear scalar product on $W/k$ for $i = 1, 2$. For each $0 \neq v \in W$, $g(v, W) = K = g(W, v)$ and $g(v, v) = 0$. Thus $g_1$ and $g_2$ are nonsingular symplectic scalar products on $W/k$. Since $g$ is $K$-bilinear, it follows that $g_1(v_1\rho, v_2) = g_1(v_1, v_2\rho)$ and hence $g_1(v_1\rho, v_2\rho) = \gamma g_1(v_1, v_2)$ for all $v_1, v_2 \in W$. Thus, if $m$ denotes multiplication by $\rho$ on $W/k$, then $m^2 = \gamma I_w, m \in \text{GSp}(W/k)$ and $r_m = \gamma$ with respect to the symplectic space $(W/k, g_1)$. Since $(V/k, f)$ and $(W/k, g_1)$ are isometric, our proof of the existence of such subgroups $X$ of $G$ is complete.

Suppose that $r_w = -\gamma$. Then $f_0(v_1, v_1) = \tau(f_0(v_1, v_2))$ for all $v_1, v_2 \in V$ and $f_0: V \times V \to K$ is a nonsingular $\tau$-bilinear Hermitian scalar product on $V/K$. Clearly
$U \leq Z \ast H$ if and only if $q \equiv -1 \pmod{4}$. Since the multiplicators of all elements of $GU(V/K)$ lie in $k^\times$, it follows that $C_G(U) = GU(V/K)$. Clearly $G = HC_G(U)$ and $w^G = w^H$ by [25, Proposition 4]. Also, by [29, Proposition 8.8], $V/K$ has a basis $B = \{v_i \mid 1 \leq i \leq \frac{n}{2}\}$ such that $f_0(v_i, v_j) = \delta_{i,j}$ for all $1 \leq i, j \leq \frac{n}{2}$. Consequently $B_1 = \{v_i, v_i\rho \mid 1 \leq i \leq \frac{n}{2}\}$ is a basis of $V/K$ such that for all $1 \leq i, j \leq \frac{n}{2}$ we have

$$f(v_i, v_j) = f(v_i, v_j\rho) = f(v_i\rho, v_j\rho) = 0 \quad \text{if} \ i \neq j$$

and

$$f(v_i, v_i) = f(v_i\rho, v_i\rho) = 0 \quad \text{and} \quad f(v_i, v_j\rho) = +1.$$  

Clearly $w(v_i) = v_i\rho$ and $w(v_i\rho) = v_i\gamma$ for all $1 \leq i \leq \frac{n}{2}$. Let $x \in \Gamma L(V/K)$ be induced by $\tau$ with respect to the basis $B$ of $V/K$ as above. Then $xw = (-I_{\tau})wx$, $x \in \Gamma U(V/K)$, $f(x(v_i), x(v_j)) = -f(v_i, v_j)$ for all $v_1, v_2 \in V$, $x \in G$, $|x| = 2$ and $M = C_G(U)(x) \leq \Gamma U(V/K)$. As above all cyclic subgroups $X$ of $G$ such that $Z \leq X$, $|X/Z| = 2$ and $X - Z$ contains an element $z$ with $z^2 = -r_{I_{\tau}}$ are conjugate under $H$. Moreover such subgroups $X$ of $G$ always exist. To see this, let $\gamma \in k^\times - (k^\times)^2$, let $K = k(\rho)$ where $\rho^2 = \gamma$ and let $\text{Gal}(K/k) = \langle \tau \rangle$ be as above. Let $W/K$ be a vector space of dimension $\frac{n}{2}$ and let $g: W \times W \to K$ be a nonsingular $\tau$-bilinear Hermitian scalar product on $W/K$. Since $K = k + k\rho$, we have $g = \rho g_1 + g_2$ where $g_i: W \times W \to k$ is a $k$-bilinear scalar product on $W/k$ for $i = 1, 2$. As above, it follows that $g_1$ is a nonsingular symplectic scalar product on $W/k$ and that $g_1(v_1\rho, v_2) = -g_1(v_1, v_2\rho)$ and hence $g_1(v_1\rho, v_2\rho) = -\gamma g_1(v_1, v_2)$ for all $v_1, v_2 \in W$. The existence of such subgroups $X$ of $G$ now follows as above.

3C. The unitary groups. Assume in this section that $n$ is even, so that $q = q_0^2$ where $q_0 = p^{n/2}$ and let $\sigma \in \text{Aut}(k)$ with $|\sigma| = 2$. Set $k_0 = C_k(\sigma)$, let $N: k^\times \to k_0^\times$ denote the norm mapping of $k/k_0$, and let $f: V \times V \to k$ be a $\sigma$-linear Hermitian scalar product that is nonsingular (cf. [25, §1; 29, §7; etc.]). Thus $f(v_1, v_2) = (f(v_2, v_1))$ for all $v_1, v_2 \in V$. Let $G = GU(V/k)$ and $H = U(V/k)$ be as defined in [12, I, §9]. Thus $Z = \langle \lambda I_{J_{V}} \mid \lambda \in k^\times \rangle = Z(G)$ by [25, Proposition 4]. For each $u \in G$, there is a unique element $r_u \in k_0^\times$ such that $f(u(v_1), u(v_2)) = r_u f(v_1, v_2)$ for all $v_1, v_2 \in V$, $r_u$ is called the multiplicator of $u$ and the mapping $\gamma: G \to k_0^\times$ defined by $\gamma(u) = r_u$ for $u \in G$ is an epimorphism with $\text{Ker}(\gamma) = H$, cf. [29, Proposition 4]. Also [29, Lemma 8.5] implies that $G = H \ast Z$.

Note that $U(V/k) \simeq U(m, q_0)$, $U(V/k) \cap \text{SL}(V/k) = \text{SU}(V/k) \simeq \text{SU}(m, q_0)$ and $PSU(V/k) \simeq \text{PSU}(m, q_0)$, etc. by our notational convention that adheres to [16, §17.1].

Suppose that $m = 2$. Then $V/k$ has a basis $B = \{v_1, v_2\}$ such that $f(v_1, v_1) = f(v_2, v_2) = 1$ and $f(v_1, v_2) = 0$. With matrices relative to the basis $B$, set

$$X = \left\{ \begin{pmatrix} a & b \\ -\sigma(b) & \sigma(a) \end{pmatrix} \right\} \mid a, b \in k \text{ and } N(a) + N(b) = \det \begin{pmatrix} a & b \\ -\sigma(b) & \sigma(a) \end{pmatrix} \neq 0 \right\}. $$

Then, as in [28, II, 8.8], it follows that $G = Z \ast X$ where $\gamma|_X = \det$ and $X \cap H = \text{SU}(V/k) \simeq \text{SL}(2, q_0)$. 

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Consequently, since $G = H \ast Z$, for greater simplicity we restrict our attention to $H = U(V/k)$. Note that $H' = SU(V/k)$. Set $Z_1 = Z \cap H = \langle \lambda I_V | \lambda \in \text{Ker}(N) \rangle \approx \text{Ker}(N)$ and $\bar{H} = H/Z_1$. Then $|\bar{H}/H^2| = (m, q_0 + 1)$, $\bar{H} \approx H'/(Z_1 \cap H') \approx \text{PSU}(V/k)$ and the inverse image of $\bar{H}$ in $H$ is $H' \ast Z_1 = \{ u \in H | \det(u) \in (\text{Ker}(N))^m \}$.

Let $u \in H - Z_1$ be such that $u^2 = \gamma I_V$ for some $\gamma \supset \text{er}(N)$, so that $|\bar{u}| = 2$. Let $U = \langle Z_1, u \rangle$ and $M = N_H(U)$. Thus $U$ is abelian, $\bar{U} = \langle \bar{u} \rangle$, $C_H(U) = C_H(u)$, $M$ is the inverse image in $H$ of $C_{\bar{H}}(\bar{u})$, $U \leq H' \ast Z$, if and only if

$$\frac{|(U \cap H')/(Z_1 \cap H')|}{|M/C_H(U)|} = 2$$

as in §3A.

First assume that $U$ is not cyclic. Then $U = Z_1 \times \langle w \rangle$ where $w \in \delta(H - Z_1)$, $w \neq -I_V$, $C_H(U) = C_H(w)$, $w^M \subseteq \{ w, (-I_V)w \}$ and $|w^M| = |M/C_H(U)|$. As above, we get $V = V^+ \perp V^-$ where $V^+ = C_V(w)$, $V^- = \{ v \in V | w(v) = -v \} = [V, w]$ and the restrictions of $f$ to $V^+/k$ and $V^-/k$ yield nonsingular unitary vector spaces. Thus there is an isomorphism

$$\alpha: C_H(U) \to U(V^+/k) \times U(V^-/k), \quad H = H' \ast C_H(U) \text{ and } w^H = w^H.$$

Clearly $U \leq Z_1 \ast H'$ if and only if $(-1)^{\text{dim}(V^-/k)} \in (\text{Ker}(N))^m$. If $|M/C_H(U)| = 2$, then [29, Proposition 8.8(b)] implies that there is an involution $g \in M$ such that $g: V^+ \leftrightarrow V^-$, $w^g = (-I_V)w$ and $M = C_H(U)(g) \approx U(V^+/k) \ast Z_2$.

It now is clear that if $x, y \in \delta(H)$, then the following three conditions are equivalent: (i) $x \sim y$ in $G = GU(V/k)$; (ii) $\dim(C_V(x)/k) = \dim(C_V(y)/k)$; (iii) $x \sim y$ in $H$. Also [29, Proposition 8.8] implies that for any integer $p$ with $1 \leq p < m$, there is an involution $z \in H - Z_1$ such that $\dim(C_V(z)/k) = p$.

Next assume that $U$ is cyclic. Then $u^2 = \gamma I_V$ where $\gamma \in \text{Ker}(N) - (\text{Ker}(N))^2$. Now $|k^x| = q - 1 = (q_0)^2 - 1$, $|\text{Ker}(N)| = q_0 + 1$ and $2|q_0 - 1|$. Hence there is an element $\lambda \in k^x$ such that $\lambda^2 = \gamma$. Set $u_0 = u(\lambda^{-1}I_V)$, so that $(u_0)^2 = I_V$, $u_0 \in GU(V/k)$, $C_H(u) = C_H(u_0)$ and $N_H(U) = N_H(\langle u_0 \rangle \times Z_1)$.

Clearly $r_{u_0} = N(\lambda^{-1}) \neq 1$ and $N(\lambda)^2 = N(\gamma) = 1$, so that $r_{u_0} = N(\lambda^{-1}) = -1$. Hence $m$ is even, $V = V^+ \oplus V^-$ where $V^+ = C_V(u_0)$ and $V^- = \{ v \in V | u_0(v) = -v \} = [V, u_0]$ are totally isotropic subspaces of $V$ with $\dim(V^+/k) = \dim(V^-/k) = \frac{m}{2}$. Since $\det(u) = (-\gamma)^{m/2}$ it follows that $U \leq Z_1 \ast H'$ if and only if $m_2 > |q_0 + 1|_2$ if $|m|_2 > 2$ and $q_0 \equiv 1$ (mod 4) if $|m|_2 = 2$. As in §3B, it follows that there is an isomorphism $\alpha: GL(V^+/k) \to C_H(u_0)$ and an involution $g \in H$ such that $gu = (-I_V)ug$, $N_H(U) = C_H(u)(g)$ and conjugation by $g$ induces a unitary automorphism on $U(\bar{H}) \approx GL(V^+/k)$. Note that $u(v) = \lambda v$ if $v \in V^+$ and $u(v) = -\lambda v$ if $v \in V^-$. Next suppose that $X$ is an arbitrary cyclic subgroup of $H$ such that $Z_1 \leq X$ and $|X/Z_1| = 2$. Then there is an element $z \in X - Z_1$ such that $z^2 = \gamma I_V$ and it is now clear that $X$ and $U$ are conjugate via $H$. Moreover, when $m$ is even, such subgroups $X$ of $H$ exist since then $V$ has complementarily totally isotropic subspaces each of dimension $\frac{m}{2}$ by [29, Proposition 9.14].

3D. The orthogonal groups. Assume in this section that $f: V \times V \to k$ is a bilinear symmetric (orthogonal) scalar product that is nonsingular (cf. [25, §1; 29, §7; etc.]).
Thus \( f(v_1, v_2) = f(v_2, v_1) \) for all \( v_1, v_2 \in V \). Also let \( g: V \to k \) be the associated quadratic form on \( V/k \) so that \( g(v) = \frac{1}{2} f(v, v) \) and \( f(v_1, v_2) = g(v_1 + v_2) - g(v_1) - g(v_2) \) for all \( v_1, v_2 \in V \) (cf. [29, §10]).

In this setting, there is associated (to \( V/k \) and \( f \)) a unique element \( D(V/k) \in k^\times/(k^\times)^2 \) called the discriminant (of \( (V/k, f) \)) (cf. [29, Definition 7.5]). Clearly if \( c \in k^\times \), then \( f: V \times V \to k \) is a bilinear nonsingular symmetric scalar product with discriminant \( c^m D(V/k) \).

Note that for any given dimension \( m = \text{dim}(V/k) \) and suitable \( f \), \( D(V/k) \) can be either of the two elements of \( k^\times/(k^\times)^2 \) and two orthogonal spaces over \( k \) are isometric if and only if they have the same dimension and discriminant (cf. [29, Proposition 8.9]).

Let \( G = GO(V/k) \) and \( H = O(V/k) \) be as defined in [12, I, §9]. Thus \( Z = \langle \lambda I_v | \lambda \in k^\times \rangle \leq Z(G) \) and \( Z \cap H = \langle -I_v \rangle \). Also for each \( u \in G \), there is a unique element \( r_u \in k^\times \) such that \( f(u(v_1), u(v_2)) = r_u f(v_1, v_2) \) for all \( v_1, v_2 \in V \) and \( r_u \) is called the multiplicator of \( u \). The mapping \( \gamma: G \to k^\times \) defined by \( \gamma(u) = r_u \) for \( u \in G \) is such that \( \text{Ker}(\gamma) = H \) and \( \gamma^{-1}(k^\times)^2 = Z \ast H \). \( \gamma \) maps \( G \) onto \( k^\times \) if \( m \) is even and onto \( (k^\times)^2 \) if \( m \) is odd by [25, Proposition 5(b)]. Set \( \Omega = H', K = SO(V/k) \) and \( \overline{G} = G/Z \). Then \( H \cong H/\langle -I_v \rangle \), \( \Omega \leq K \leq H \) and \( \text{det} \) maps \( H \) onto \( \langle -1 \rangle \) so that \( |H/K| = 2 \) by [29, Proposition 8.10].

By [29, Corollary 14.6], all maximal isotropic subspaces of \( V/k \) are conjugate under \( H = O(V/k) \) and the dimension of any such subspace of \( V/k \) is called the index of \( V \), \( \text{ind}(V/k) \). As in [29, Example 14.7], if \( m \) is odd, then

\[
\text{ind}(V/k) = (m - 1)/2
\]

and if \( m \) is even then either \( \text{ind}(V/k) = \frac{m}{2} \) and \( D(V/k) = (-1)^{m/2}(k^\times)^2 \) or \( \text{ind}(V/k) = \frac{m}{2} - 1 \) and \( D(V/k) = (-1)^{m/2}c(k^\times)^2 \) where \( c \in k^\times - (k^\times)^2 \). Thus the index distinguishes the two types of orthogonal vector spaces of the same even dimension.

From our notational convention (cf. [16, §17.11]), if \( m \) is even, we have \( P\Omega(V/k) \cong P\Omega(m, q, 1) \) if \( \text{ind}(V/k) = \frac{m}{2} \) and \( P\Omega(V/k) \cong P\Omega(m, q, -1) \) if \( \text{ind}(V/k) = \frac{m}{2} - 1 \).

As in [29, Proposition 20.2], there is a homomorphism \( \sigma: H = O(V/k) \to k^\times/(k^\times)^2 \) called the Spinornorm. The proof of [29, Proposition 20.10] yields \( \sigma(-I_v) = D(V/k)2^{-m}(k^\times)^2 \). If \( \text{ind}(V/k) > 0 \), then \( \sigma(K) = k^\times/(k^\times)^2 \) and \( \text{Ker}(\sigma) \cap K = \Omega \) by [29, Proposition 20.3 and Theorem 20.8]. If \( m \geq 3 \), then \( C_G(\Omega) = Z \) by [25, Proposition 5] and \( \text{ind}(V) > 0 \) and \( K' = H' = \Omega \) by [29, Propositions 9.2(b) and 20.9].

Suppose that \( m = \text{dim}(V/k) \) is odd for the moment. Then \( H = \langle -I_v \rangle \times K \) and \( G = Z \ast H = Z \times K \). Also, if \( c \in k^\times - (k^\times)^2 \), then \( \{(V/k, f), (V/k, cf)\} \) represents the two classes of nonsymmetric orthogonal spaces over \( k \) of dimension \( m \) and we have \( GO((V/k, f)) = GO((V/k, cf)) \), \( O(V/k, f) = O(V/k, cf) \), etc.

Next suppose that \( m = \text{dim}(V/k) \) is even and \( m \geq 4 \). Then \( |G/(Z \ast H)| = 2 \), \( Z(K) = \langle -I_v \rangle - I_v \in \Omega \) if and only if \( D(V/k) \in (k^\times)^2 \), \( K = \langle -I_v \rangle \times \Omega \) and \( H = \langle -I_v \rangle \times \text{Ker}(\sigma) \) when \( D(V/k) \notin (k^\times)^2 \) and \( Z(\Omega) = \langle -I_v \rangle \) when \( D(V/k) \in (k^\times)^2 \) by [25, Proposition 5].

We shall now discuss the cases with \( 1 \leq m \leq 6 \).

When \( m = 1 \), we have \( G = Z \), \( H = \langle -I_v \rangle \), \( K = \Omega = 1 \) and \( \sigma(-I_v) = 2^{-1}D(V/k)(k^\times)^2 \).
Suppose that $m = 2$ and $\text{ind}(V/k) > 0$. Then [29, Proposition 9.14] implies that $V/k$ has a basis $B = \{v_1, v_2\}$ such that $f(v_1, v_1) = f(v_2, v_2) = 0$ and $f(v_1, v_2) = 1$ (i.e. $V/k$ is a hyperbolic plane). Then $D(V/k) = (-1)(k^\times)^2$, the involution $t$ of $\text{GL}(V/k)$ such that $t: v_1 \mapsto v_2$ lies in $H - K$, $G = M(t)$ where $M = \text{Stab}_{\text{GL}(V/k)}(kv_1) \cap \text{Stab}_{\text{GL}(V/k)}(kv_2)$, $\gamma: G \to k^\times$ is an epimorphism, $\sigma: H \to k^\times/(k^\times)^2$ is an epimorphism by [29, Proposition 9.9], $K = \mathbb{Z}_{q-1}$, $t$ inverts $K$ and $H = K(t)$ is dihedral. Also, passing to matrices with respect to the basis $B$, it is easy to see that

$$H = \left\{ \begin{pmatrix} 0 & a \\ a^{-1} & 0 \end{pmatrix} \bigg| a \in k^\times \right\}, \quad K = \left\{ \begin{pmatrix} a & 0 \\ 0 & a^{-1} \end{pmatrix} \bigg| a \in k^\times \right\}$$

and that if $a \in k^\times$, then

$$\sigma\left( \begin{pmatrix} 0 & a \\ a^{-1} & 0 \end{pmatrix} \right) = -a(k^\times)^2 \quad \text{and} \quad \sigma\left( \begin{pmatrix} a & 0 \\ 0 & a^{-1} \end{pmatrix} \right) = a(k^\times)^2.$$

Suppose that $m = 2$ and $\text{ind}(V/k) = 0$. Then, as in the proof of [29, Lemma 15.1(b)], there is an element $c \in k^\times - (k^\times)^2$ such that $D(V/k) = -c(k^\times)^2$ and $V/k$ has a basis $B = \{v_1, v_2\}$ such that $g(a_1v_1 + a_2v_2) = a_1^2 - ca_2^2$ for all $a_1, a_2 \in k$. Also if $K/k$ is a quadratic extension field such that $K = k(\rho)$ where $\rho^2 = c$ and if $N: K^\times \to K^\times$ denotes the norm mapping of $K/k$, then there is a $k$-linear isomorphism $\epsilon: V \to K$ such that $N(\epsilon(v)) = g(v)$ for all $0 \neq v \in V$. Let $\tau$ denote the involution of $\text{Aut}(K)$, so that $C_K(\tau) = k$. Focusing attention on $(K/k, N)$, it follows that $\tau \in O(K/k) - SO(K/k)$, $|\tau| = 2$, $\tau$ inverts $SO(K/k) = \langle \lambda I_k | \lambda \in \text{Ker}(N) \rangle \cong \mathbb{Z}_{q^2-1}$, $H = O(K/k) = SO(K/k)/\langle \tau \rangle$ is dihedral, $G = GO(K/k) = \langle \lambda I_K | \lambda \in K^\times \rangle/\langle \tau \rangle$, $Z(G) = Z$, $\gamma: G \to k^\times$ is an epimorphism and $\sigma: H = O(K/k) \to k^\times/(k^\times)^2$ is an epimorphism since $N: K^\times \to k^\times$ is an epimorphism. Also, passing to matrices with respect to the bases $B = \{1, \rho\}$ of $K/k$, it is easy to see that

$$SO(K/k) = \left\{ \begin{pmatrix} a_1 & a_2 \\ ca_2 & a_1 \end{pmatrix} \bigg| a_1, a_2 \in k \text{ and } a_1^2 - ca_2^2 = 1 \right\},$$

$$\tau = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix},$$

$$O(K/k) - SO(K/k) = SO(K/k)\tau$$

$$= \left\{ \begin{pmatrix} a_1 & -a_2 \\ ca_2 & -a_1 \end{pmatrix} \bigg| a_1, a_2 \in k \text{ and } a_1^2 - ca_2^2 = 1 \right\}.$$
If \( b_1 = 1 \), then \( b_2 = 0 \), \( T = \tau = R_w \) for all \( w = a_1 + a_2 \rho \) with \( a_1 = 0 \neq a_2 \) and hence \( \sigma(T) = \sigma(\tau) = -c(k^\times)^2 \). If \( b_1 \neq 1 \), then it is easy to see that \( \sigma(T) = 2(1 - b_1)(k^\times)^2 \). Consequently

\[
\begin{pmatrix}
  b_1 & b_2 \\
  cb_2 & b_1
\end{pmatrix}

\]

for all \( \{b_1, b_2\} \subseteq k \) with \( b_1^2 - cb_2^2 = 1 \) and \( b_1 \neq 1 \). Note that \( \sigma \) maps \( S^2(K/k) \to \mathbb{A} : x \mapsto a_1, a_2 \in k \) and \( a_1^2 - ca_2^2 = 1 \) onto \( k^\times / (k^\times)^2 \). For \( \sigma((-1, 0)) = -c(k^\times)^2 \) and \( c \notin (k^\times)^2 \). Moreover, if \( -c \in (k^\times)^2 \), then \( \sigma(O(K/k)) = \sigma(SO(K/k)) = k^\times / (k^\times)^2 \) and the assertion is proved.

If \( m = 3 \), then \( H = \langle -I_\nu \rangle \times K \), \( K \cong \text{PGL}(2, q) \) and \( \Omega \cong \text{PSL}(2, q) \) by [29, Proposition 24.1].

If \( m = 4 \) and \( \text{ind}(V/k) = 1 \), then \( H' = \Omega \cong \text{PSL}(2, q^2) \) and \( H = \langle -I_\nu \rangle \times \text{Ker}(\sigma) \) where \( \text{Ker}(\sigma) \) is isomorphic to \( \text{PSL}(2, q^2) \) extended by a field automorphism of order 2 (cf. [29, Proposition 24.12]).

To discuss the case \( m = 4 \) and \( \text{ind}(V/k) = 2 \), we shall apply the methods of [29, Lemma 24.10 and Proposition 24.11]. Thus let \( W, W' \) be two vector spaces over \( k \) of dimension 2 with bases \( B = \{w_1, w_2\} \) and \( B' = \{w_1', w_2'\} \) respectively and let \( V = W \otimes \mathbb{F} W' \) so that \( B^* = \{v_i, j = w_i \otimes w'_j \mid 1 \leq i, j \leq 2\} \) is a basis of \( V/k \). Define

\[
g(\sum_{i,j=1}^2 c_{ij} v_{ij}) = c_{11} c_{22} - c_{12} c_{22} \quad \text{for all} \quad \{c_{ij} \mid 1 \leq i, j \leq 2\} \subseteq k
\]

Then \( V/k \) becomes a nonsingular orthogonal vector space of index 2 and \( V = (kv_{11} + kv_{22}) \perp (kv_{12} + kv_{21}) \) is an orthogonal sum of hyperbolic planes. Let \( A \in \text{GL}(W/k) \) and \( A' \in \text{GL}(W'/k) \), so that \( g(A \otimes A'(v)) = \det(A)\det(A')g(v) \) for all \( v \in V \) as in [29, Lemma 24.10]. Moreover, as in this reference, if \( H = \{(A, A') \mid A \in \text{GL}(W/k), A' \in \text{GL}(W'/k) \} \), then the mapping \( \gamma \) such that \( \gamma((A, A')) = A \otimes_k A' \) is an epimorphism of \( H \) onto \( \text{SO}(V/k) \) with \( \text{Ker}(\gamma) = \{(aI_w, a^{-1}I_w) \mid a \in k^\times \} \) and such that \( \gamma(\text{SL}(W/k) \times \text{SL}(W'/k)) = \Omega(V/k) \cong \text{SL}(2, q) \ast \text{SL}(2, q) \). Let \( T, T' \) have matrix \((1, 0, 0, 0)\) with respect to the bases \( B, B' \) of \( W/k \) and \( W'/k \) respectively and let \( x \) and \( y \) have matrices

\[
\begin{pmatrix}
  1 & 0 & 0 & 0 \\
  0 & -1 & 0 & 0 \\
  0 & 0 & -1 & 0 \\
  0 & 0 & 0 & 1
\end{pmatrix}
\quad \text{and} \quad
\begin{pmatrix}
  1 & 0 & 0 & 0 \\
  0 & 1 & 0 & 0 \\
  0 & 0 & 1 & 0 \\
  0 & 0 & 0 & 1
\end{pmatrix}
\]

with respect to the bases \( B^* \) of \( V/k \). Then

\[
\gamma(T \otimes T') = x \in 4(\text{SO}(V/k)) - \Omega(V/k),
\]

\( y \in 4(O(V/k) - \text{SO}(V/k)), xy = yx, O(V/k) = \Omega(V/k) \langle x, y \rangle, y \) interchanges the two 2-components of \( \Omega(V/k) \) and \( \text{SO}(V/k) = \Omega(V/k) \langle x \rangle \) normalizes the two 2-components of \( \Omega(V/k) \).

If \( m = 5 \), then \( \Omega \cong \text{PSp}(4, q) \) by [29, Proposition 24.13].

If \( m = 6 \) and \( \text{ind}(V/k) = 3 \), then \( D(V) = -1(k^\times)^2 \) and \( \Omega(V/k) \) is isomorphic to \( \text{SL}(4, k)/A \) where \( A \) is the unique central subgroup of \( \text{SL}(4, k) \) of order 2 by [29, Proposition 24.15].
If \( m = 6 \) and \( \text{ind}(V/k) = 2 \), then \( D(V) = -c(k^\times)^2 \) where \( c \in k^\times \) and \( \Omega(V/k) \) is isomorphic to \( \text{SU}(4, k)/B \) where \( B \) is the unique central subgroup of \( \text{SU}(4, k) \) of order 2 by [29, Proposition 24.15].

For the remainder of this section, assume that \( m > 7 \). Thus \( K' = H' = \Omega = \text{Ker}(\sigma) \cap K, C_H(\Omega) = \langle -I_\nu \rangle \), \( \sigma \) maps \( K \) onto \( k^\times/(k^\times)^2 \) and \( H/\Omega \cong E_4 \).

Let \( u \in G - Z \) be such that \( u^2 = \gamma I_\nu \) for some \( \gamma \in k^\times \), so that \( |\tilde{u}| = 2 \). Let \( U = \langle u, Z \rangle \) and \( M = N_H(U) \). Thus \( U \) is abelian, \( \tilde{U} = \langle \tilde{u} \rangle \cong U/Z, C_G(u) = C_G(U), M \) is the inverse image in \( H \) of \( C_{\tilde{H}}(\tilde{u}) \), and \( |M/C_H(U)| \leq 2 \).

First assume that \( U \) is not cyclic. Then \( U = Z \times \langle w \rangle \) where \( w \in \mathfrak{g}(G - Z, w \neq -I_\nu, C_G(U) = C_G(w), w^M \subseteq \{w, (-I_\nu w)\}, |w^M| = |M/C_H(U)| \leq 2 \) and \( r_w^2 = 1 \).

Suppose that \( r_w = 1 \). Then \( w \in H, U \cap H = \langle -I_\nu, w \rangle, U \leq Z \ast H, V = V^+ \perp V^- \) where \( V^+ = C_H(w) \), \( V^- = \{v \in V| w(v) = -v\} = [V, w] \) and the restrictions of \( f \) to \( V^+/k \) and \( V^-/k \) yield nonsingular orthogonal vector spaces such that \( D(V/k) = D(V^+/k)D(V^-/k) \). Thus

\[
C_G(U) = \{(w_1, w_2) \in (GO(V^+/k)) \times (GO(V^-/k)) | r_{w_1} = r_{w_2}\},
\]

\[
C_H(U) = O(V^+/k) \times O(V^-/k),
\]

\[
H = \Omega C_H(w) \quad \text{and} \quad w^H = w^\Omega.
\]

Also \( w \in \Omega \) if and only if \( \text{dim}(V^-/k) \) is even and \( D(V^-/k) \in (k^\times)^2 \) by [29, Lemma 20.6]. If \( |M/C_H(U)| = 2 \), then there is an involution \( g \in M \) such that \( g: V^+ \rightarrow V^- \), \( w^g = (-I_\nu w) \) and \( M = C_H(U) \langle g \rangle \cong O(V^+/k) \wr Z_2 \). Also [25, Proposition 5] implies that if \( m \) is odd, then \( G = H C_G(U) \) and if \( m \) is even, then \( G = H C_G(U) \) if \( \text{dim}(V^+/k) \) is even and \( |G/ (H C_G(U))| = 2 \) if \( \text{dim}(V^+/k) \) is odd.

Also if \( h \in G = GO(V/k) \), then \( w_1 = w^h = \mathfrak{g}(H, C_H(w_1) = h^{-1}(V^+), D(C_H(w_1))/k) = (r^h)^{\text{dim}(V^+/k)}D(V^+/k), \) \( [V, w_1] = h^{-1}(V^-) \) and \( D([V, w_1])/k) = (r^h)^{\text{dim}(V^-/k)}D(V^-/k). \) If \( x, y \in \mathfrak{g}(H), \) then it is clear that the following three conditions are equivalent: (i) \( x \sim y \) in \( H = O(V/k), \) (ii) \( x \sim y \) via \( \Omega; \) (iii) \( \text{dim}(C_H(x)/k) = \text{dim}(C_H(y)/k) \) and \( D(C_H(x)/k) = D(C_H(y)/k). \) Also for any integer \( p \) with \( 1 \leq p < m \) and any element \( a \in k^\times/(k^\times)^2 \) it is clear that there is an involution \( z \in H - Z \) such that \( \text{dim}(C_H(z)/k) = p \) and \( D(C_H(z)/k) = a \).

Suppose that \( r_w = -1 \). Then \( \mathfrak{w} \not\in H, U \leq Z \ast H \) if and only if \( q \equiv 1 \pmod{4}, V^+ = C_H(w) \) and \( V^- = \{v \in V | w(v) = -v\} = [V, w] \) are totally isotropic subspaces of \( V \) with \( V = V^+ \oplus V^- \), \( m \) is even, \( \text{dim}(V^+/k) = \text{dim}(V^-/k) = \frac{m}{2} \) and \( \text{ind}(V) = \frac{m}{2} \).

Suppose that \( q \equiv 1 \pmod{4} \) and let \( v \in k^\times \) be such that \( v^2 = -1 \). Also, as in §3B, choose bases \( \{v_i | 1 \leq i \leq \frac{m}{2}\} \) and \( \{v_{i+m/2} | 1 \leq i \leq \frac{m}{2}\} \) of \( V^+/k \) and \( V^-/k \) respectively such that \( f(v_i, v_{j+m/2}) = \delta_{ij} \) for all \( 1 \leq i, j \leq \frac{m}{2} \). Set \( H_L = kv_i + kv_{i+i+m/2} \) so that \( H_L \) is a hyperbolic plane for all \( 1 \leq i \leq \frac{m}{2} \) and \( V = H_L \perp \cdots \perp H_{m/2}. \) Then \( U \cap H = \langle (v I_\nu w) \rangle \) where \( ((v I_\nu w)^2 = -I_\nu, ((v I_\nu w)v_i = v v_i \) and \( ((v I_\nu w)v_{i+m/2} = -v v_{i+m/2} \) for all \( 1 \leq i \leq \frac{m}{2} \). Thus \( \sigma^{(v I_\nu w)} = \mu^{m/2}(k^\times)^2 \) by [29, Example 20.4 and Lemma 20.6]. Hence \( U \leq Z \ast \Omega \) if and only if \( \mu^{m/2} \in (k^\times)^2 \).

As in §3B, we have \( C_H(U) = GL(V^+/k), M = C_H(U) \langle g \rangle \) where \( g \in \mathfrak{g}(H) \) and conjugation by \( g \) induces transpose inverse on \( C_H(U) \cong GL(V^+/k), G = HC_G(U), w^G = w^H \) and all involutions with \( r_w = -1 \) are conjugate under \( H \). Moreover, when
$m$ is even and $\text{ind}(V) = \frac{m}{2}$, the existence of complementary totally isotropic subspaces of $V$ each of dimension $\frac{m}{2}$ by [29, Proposition 9.15] implies the existence of such subgroups $U$ of $G$.

Next assume that $U$ is cyclic. Thus $U = \langle Z, w \rangle$ where $w^2 = \gamma I_V$ for some $\gamma \not\in (k^\times)^2$. Thus $r_w = \pm \gamma$ since $r_w^2 = \gamma^2$ and $m$ is even. Also let $K = k(\rho)$, $\tau$, $V/k$, $N: K^\times \to k^\times$, etc. be as in §3A and, for any $v_1, v_2 \in V$, set $f_0(v_1, v_2) = \rho f(v_1, v_2) + f(v_1, w(v_2))$. Consequently

$$f_0(v_2, v_1) = \rho f(v_1, v_2) + \gamma r_w^{-1}f(v_1, w(v_2)).$$

Suppose that $r_w = \gamma$. Then $f_0(v_2, v_1) = f_0(v_1, v_2)$ for all $v_1, v_2 \in V$ and $f_0: V \times V \to K$ is a nonsingular $K$-bilinear symmetric scalar product on $V/K$. Also $U \not\subseteq Z \ast H$ since $r_w = \gamma \not\in (k^\times)^2$. It readily follows that $C_G(U) = \{x \in GO(V/K) | r_x \in k^\times \}$, $C_H(U) = O(V/K)$, $G = H \subseteq C_G(U)$ by [25, Proposition 5(b)] since $k^\times \subseteq (k^\times)^2$ and $w^G = w^H$. Let $\alpha = a + b\rho$ be any element of $D(V/K)$. Then [29, Proposition 8.9] implies that $V/K$ has a basis $B = \{v_i | 1 \leq i \leq \frac{m}{2}\}$ such that

$$f_0(v_i, v_j) = \begin{cases} 0 & \text{if } i \neq j, \\ 1 & \text{if } 1 \leq i = j < \frac{m}{2}, \\ \alpha & \text{if } i = j = \frac{m}{2}. \end{cases}$$

Consequently $B_1 = \{v_i, v_{i+\frac{m}{2}} | 1 \leq i \leq \frac{m}{2}\}$ is a basis of $V/k$ such that

$$f(v_i, v_j) = f(v_i, v_j, v_i) = f(v_i, v_i, v_i) = 0 \quad \text{if } i \neq j,$$

$$f(v_i, v_i) = f(v_i, v_i, v_i) = f(v_i, v_i, v_i) = 0 \quad \text{and } f(v_i, v_i) = 1 \quad \text{if } 1 \leq i < \frac{m}{2},$$

$$f(v_{m/2}, v_{m/2}) = b, \quad f(v_{m/2}, v_{m/2}) = \gamma b$$

and $f(v_{m/2}, v_{m/2}) = a$. Calculating the discriminant of $V/k$ using $B_1$ yields $(-1)^{m/2}N(\alpha) \in D(V/k)$. However $(k^\times)^2$ is the inverse image of $(k^\times)^2$ in $K^\times$ under $N$. Thus $D(V/K) = \alpha(k^\times)^2$ is uniquely determined. Clearly $w(v_i) = v_i\rho$ and $w(v_i, v_i) = v_i\gamma$ for all $1 \leq i \leq \frac{m}{2}$. Let $x \in GL(V/K)$ be induced by $\tau$ with respect to the basis $B$ of $B/K$. Then $xw = (-I_\rho)xw, x \in \Gamma(O(V/K)), f(x(v_i), x(v_j)) = -f(v_i, v_j)$ for all $v_1, v_2 \in V, x \in \Gamma, |x| = 2$ and $N_\tau(U) = C_G(U)(x)$. Suppose that $x$ is a cyclic subgroup of $G$ such that $Z \leq X, |X/Z| = 2$ and such that $X - Z$ contains an element with $z^2 = r_z I_V$. Then $r_z \not\in (k^\times)^2$ since $X$ is cyclic and we may assume that $r_z = \gamma$. The existence of the basis $B_1$ of $V/k$ and the discussion above imply that $X$ and $U$ are conjugate via $H$. Moreover, when $m$ is even, such subgroups $X$ of $G$ always exist. To see this, let $\gamma \in k^\times - (k^\times)^2$ and let $K = k(\rho)$ with $\rho^2 = \gamma, \tau, N: K^\times \to k^\times$, etc. be as above. Let $W/K$ be a vector space of dimension $\frac{m}{2}$ and let $g: W \times W \to k$ be a nonsingular orthogonal scalar product on $W/K$ such that if $\alpha \in D(W/K)$, then $(-1)^{m/2}N(\alpha) \in D(V/k)$. Since $K = k + k\rho$, we have $g = pg_1 + g_2$ where $g_i: W \times W \to k$ is a $k$-bilinear nonsingular orthogonal scalar product on $W/k$ for $i = 1, 2$. Also $g_1(v_1, v_2, v_2) = g_1(v_1, v_2, v_2)$ and hence $g_1(v_1, v_2, v_2) = g_1(v_1, v_2, v_2)$ for all $v_1, v_2 \in W$. Also, as above, we conclude that $D((W/k, g_1)) =$
D(V/k). Since \( \dim(W/k) = m \), we conclude that \((W/k, g_1)\) and \((V/k, f)\) are isometric. Then the existence of such subgroups \( X \) of \( G \) follows as in §3B.

Suppose that \( r_w = -\gamma \). Then \( f_0(v_2, v_1) = -\gamma (f_0(v_1, v_2)) \) and \( \rho^{-1}f_0: V \times V \to K \) is a nonsingular Hermitian scalar product on \( V/K \). Clearly \( U \leq Z \cdot H \) if and only if \( q \equiv -1 \pmod{4} \) and since the multiplicators of all elements of \( GU(V/K) \) lie in \( k^{\times} \), it follows that \( C_G(U) = GU(V/K) \), \( G = HC_G(U) \) and \( w^H = w^H \). Also [29, Proposition 8.8] implies that \( V/K \) has a basis \( B = \{v_i | 1 \leq i \leq \frac{m}{2}\} \) such that \( \rho^{-1}f_0(v_i, v_j) = \delta_{ij} \) for all \( 1 \leq i, j \leq \frac{m}{2} \). Consequently \( B_1 = \{v_i, v_i \rho \mid 1 \leq i \leq \frac{m}{2}\} \) is a basis of \( V/k \) such that \( f(v_i, v_j) = f(v_i, v_j \rho) = f(v_i \rho, v_j \rho) = 0 \) for all \( i \neq j \) with \( 1 \leq i, j \leq \frac{m}{2} \), \( f(v_i, v_j) = 1, f(v_i \rho, v_j \rho) = r_w \) and \( f(v_i, v_j) = 0 \) for all \( 1 \leq i \leq \frac{m}{2} \). Thus \((-\gamma)^{m/2} \in D(V/k), \text{ind}(V/k) = \frac{m}{2} \) if \( \frac{m}{2} \) is even and \( \text{ind}(V/k) = \frac{m}{2} - 1 \) if \( \frac{m}{2} \) is odd. Let \( x \in \Gamma \) be induced by \( \tau \) with respect to the basis \( B \) of \( V/K \). Then \( xw = (-I_v)xw, x \in H = O(V/k), |x| = 2 \) and \( N_G(U) = C_G(U)(x) \leq \Gamma U(V/K) \). It is easy to see that all cyclic subgroups \( X \) of \( G \) such that \( Z \leq X, |X/Z| = 2 \) and \( X - Z \) contains an element \( z \) with \( z^2 = -r_i I_v \) are conjugate under \( H \). Finally, when \( m \) is even, \( \text{ind}(V/k) = \frac{m}{2} \) if \( \frac{m}{2} \) is even and \( \text{ind}(V/k) = \frac{m}{2} - 1 \) if \( \frac{m}{2} \) is odd, such subgroups \( X \) of \( G \) always exist. To see this, let \( \gamma \in k^{\times} - (k^{\times})^2, K = k(\rho) \) with \( \rho^2 = \gamma, \tau, N: k^{\times} \to k^{\times} \), etc. be as above. Also let \( W/K \) be a vector space of dimension \( \frac{m}{2} \) and let \( g: W \times W \to K \) be a nonsingular skew-Hermitian scalar product on \( V/K \). Let \( g = g_1 + g_2 \) where \( g_1: W \times W \to k \) is a \( k \)-bilinear nonsingular scalar product on \( W/k \) for \( i = 1, 2 \). Then \( g_1(v_1, v_2) = g_1(v_2, v_1), g_1(v_1 \rho, v_2 \rho) = -g(v_1, v_2 \rho) \) and hence \( g_1(v_1 \rho, v_2) = -\gamma g_1(v_1, v_2) \) for all \( v, v \in W \). As above, we conclude that \((W/k, g_1)\) is a nonsingular orthogonal vector space with \( \dim(W/k) = m \) and \((-\gamma)^{m/2} \in D((W/k, g_1))\). Then by hypothesis, \( D(V/k) = D(W/k) \). Thus \((V/k, f)\) and \((W/k, g_1)\) are isometric by [29, Proposition 8.9] and the existence of such subgroups \( X \) of \( G \) follows as in §3B.

This concludes §3.

4. Applications of the theory of linear algebraic groups. In this section, we apply the theory of linear algebraic groups to survey the conjugacy classes of involutions and their centralizers in various Chevalley groups and their automorphism groups over finite fields of odd order. In some cases, since the machinery is at hand and for completeness, we derive more information than is actually required in this paper. However all of these results are utilized in [26] and are of independent interest.

We begin this section with some results on endomorphisms of linear algebraic groups that are slight reformulations of some results in [33, 35]. Then we combine these results with the methods and results of [30, 35]. The remainder of this section presents our applications of this material to the Chevalley groups over finite fields of odd order.

Our first results concern the following situation.

\( \bar{G} \) is a linear algebraic group and \( \sigma \) is an endomorphism of \( \bar{G} \) onto \( \bar{G} \) such that \( \bar{G}_o = C_{\bar{G}}(\sigma) = \{g \in \bar{G} \mid \sigma(g) = g\} \) is finite.

The basic results about the structure of \( \bar{G}_o \), conjugacy, etc. are contained in [35, §§10–15]. The first result in this context that we specifically mention is a consequence of [35, Corollary 10.9].
Lemma 4.1. Let $G$ be a connected linear algebraic group and let $\sigma$ be an endomorphism of $G$ onto $G$ such that $G_\sigma$ is finite and $\ker(\sigma) = 1$. Let $H = \langle \sigma \rangle$ (the semidirect product) and let $g \in G$. Then $g\sigma$ and $\sigma$ are conjugate via an element of $G$.

Lemma 4.2. Let $G$ be a connected linear algebraic group and let $\sigma: G \to G$ be an endomorphism of $G$ such that $\sigma$ is an automorphism of the underlying group. Let $n$ be a positive integer, set $F = G^{\sigma_n} = \{ g \in G | \sigma^n(g) = g \}$ and assume that $F$ is finite. Thus $G_\sigma = \{ g \in G | \sigma(g) = g \}$ is finite, $\sigma_0 = \sigma |_F$ induces an automorphism of $F$ and $\sigma_0^n = 1$. Set $H = F\langle \sigma_0 \rangle$ (the semidirect product). Let $f_\sigma_0 \in H$ with $f \in F$ and $| f_\sigma_0 | = n$. Then $f_\sigma_0$ and $\sigma_0$ are conjugate via an element of $F$.

Proof. Since $(f_\sigma_0)^n = (f\sigma(f)\sigma^2(f) \cdots \sigma^{n-1}(f))\sigma^n = 1$, we have $f\sigma(f) \cdots \sigma^{n-1}(f) = 1$. By [35, Theorem 10.1], there is an element $x \in G$ such that $x\sigma(x)^{-1} = f$. Hence $\sigma(x^{-1}) = x^{-1}f$, $\sigma^2(x^{-1}) = x^{-1}\sigma(f)$, etc. and $\sigma^{n}(x^{-1}) = x^{-1}\sigma(f) \cdots \sigma^{n-1}(f) = x^{-1}$. Thus $x \in F$, $x\sigma_0 x^{-1} = x\sigma(x)^{-1}\sigma_0 = f_\sigma_0$ and we are done.

Suppose that $A$ is a not necessarily finite group and that $\sigma$ is an endomorphism of $A$. Then $H^1(\sigma, A)$ denotes $A$ modulo the equivalence relation: $a \sim b$ if $a = c\sigma(c)^{-1}$ for some $c \in A$. As an example, if $\sigma$ is the identity on $A$, then $H^1(\sigma, A)$ is the set of conjugacy classes of $A$.

For the next two results, as above, we let $G$ be a linear algebraic group and let $\sigma$ be an endomorphism of $G$ onto $G$ such that $G_\sigma$ is finite. Consequently $\sigma(G^0) = G^0$ by [36, §1.13, Proposition 2(b)] (where $G^0$ denotes the irreducible component of $G$ that contains the identity of $G$). For convenience of the reader, we restate [33, I, 2.6].

Lemma 4.3. Suppose that $G$ is connected and that $A$ is a (closed) subgroup of $G$ fixed by $\sigma$. Then the natural map from $H^1(\sigma, A)$ into $H^1(\sigma, A/\sigma^0)$ is bijective.

The second result in this context that we present is a slight refinement of [33, I, 3.4(b)].

Lemma 4.4. Suppose that $m \in G$ is such that $\sigma(m) = m$ and $G = \langle G^0, m \rangle = G^0 \langle m \rangle$. Let $M = ccl_G(m)$ and let $A = C_{G^0}(m)$, so that $\sigma(A) \subseteq A$, $A = C_G(m) \cap G^0$ is a closed subgroup of $G$, $A/\sigma^0$ is a finite group and $C_G(m) = A \langle m \rangle$. Let $\mathfrak{A}$ be a set of representatives in $A$ of the cosets in a representative choice from the equivalence classes of $H^1(\sigma, A/\sigma^0)$ and suppose that $\mathfrak{A} = \{ \alpha_i \in A | 1 \leq i \leq n \}$ where $| \mathfrak{A} | = n$. For each $\alpha_i \in \mathfrak{A}$ with $1 \leq i \leq n$, choose (by [33, I, Theorem 2.2]) an element $g_i \in G^0$ such that $g_i \sigma(g_i)^{-1} = \alpha_i$. Then the following three conditions hold.

(a) $m^{g_i} \in G_\sigma$ for all $1 \leq i \leq n$;
(b) $\{ m^{g_i} | 1 \leq i \leq n \}$ is a set of representatives for the orbits of $G_\sigma$ on $M_\sigma = \{ x \in M | \sigma(x) = x \}$; and
(c) $C_{G_\sigma}(m^{g_i}) = C_{G^0}(m^{g_i})\langle m^{g_i} \rangle$ and

$$C_{G^0}(m^{g_i}) = \{ (x \in A | \alpha_i \sigma(x) \sigma^{-1}(x) = x) \}^{g_i} = (A_{\beta_i})^{g_i}$$

where $\beta_i$ denotes the inner automorphism of $G$ induced by $\alpha_i^{-1}$, for all $1 \leq i \leq n$. 

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Proof. Note that \( C_G(m) \) and hence \( A = C_G(m) \cap G^0 \) are closed subgroups of \( \tilde{G} \) by \([6, 1, (1.7), \text{Proposition (c)})\]. Clearly \( \sigma(m^g) = \sigma(g)^{-1}m\sigma(g) = g^{-1}a_{i\alpha}ma_{i\alpha}^{-1}g = m^g \) and (a) holds. Since \( C_G(m) = A\langle m \rangle \), it follows that \( G^0 \) acts transitively (by conjugation) on \( M \). Suppose that \( m^g_i = m^g_jh \) for some \( h \in \tilde{G}_a \) and \( 1 \leq i, j \leq n \). Since \( \tilde{G}_a = (G^0)_{\sigma}(m^g) \), we may assume that \( h \in (G^0)_{\sigma} \). Then \( g_jh_{g_i}^{-1} \in A = C_G(m) \) and \( g_jh = ag_i \) for some \( a \in A \). Thus \( (g_jh)^{-1}g_j(g_i)^{-1} = g_j\sigma(g_i)^{-1} = a_i = ag_i\sigma(g_i)^{-1}\sigma(a)^{-1} = aa_i\sigma(a)^{-1} \sim a_i \) and hence \( i = j \). Now \([33, 1, 3.4(b)]\) yields (b). Choose any \( i \) with \( 1 \leq i \leq n \). Clearly

\[
C_{\tilde{G}_a}(m^g) = C((\tilde{G}_a)_a(m^g)) \quad \text{and} \quad C_G(G^0(m^g)) = (C_{\tilde{G}_a}(m^g))_{\sigma} = (A^g)_{\sigma}.
\]

Let \( x \in A \). Since the following three conditions are equivalent: (i) \( x^g \in \tilde{G}_a \), (ii) \( g_i\sigma(g_i)^{-1}\sigma(x)\sigma(g_i)^{-1} = x \) and (iii) \( \alpha_i\sigma(x)\alpha_i^{-1} = x \), we also have (c). The proof of this lemma is now complete.

Next, we introduce some (standard) notation and results from \([30, 7]\).

Let \( p \) be a prime integer, let \( K \) be an algebraic closure of \( \mathbb{Z}/(p\mathbb{Z}) \), let \( \mathfrak{g} \) denote a complex semisimple Lie algebra and let \( \pi \) denote a faithful representation of \( \mathfrak{g} \). Let \( \tilde{G} = G_{\mathfrak{g}, K} \) denote the Chevalley group obtained from the triple \((\mathfrak{g}, \pi, K)\) (cf. \([7, \S 3]\)). In this construction and notation, \( \tilde{G} \) is a (connected) semisimple linear algebraic group, \( B \) is a Borel subgroup of \( \tilde{G} \), \( \tilde{H} \) is a maximal torus of \( \tilde{G} \), \( \tilde{U} = B_1 \) (the unipotent radical of \( B \)), \( \tilde{B} = \tilde{U}H \), \( \tilde{N} = N_{\tilde{G}}(\tilde{H}) \), \( W = \tilde{N}/\tilde{H} \), etc. (cf. \([34, \S 5; 7, \S 3]\)). Clearly, since \( \tilde{H} \) is abelian, \( W \) acts on \( \tilde{H} \) by conjugation.

Let \( P(\pi) \) denote the set of weights of \( \pi \) and let \( \Gamma_\pi \) denote the \( \mathbb{Z} \)-module generated by \( P(\pi) \). Then \( \tilde{H} \) can be described as follows.

\[
\text{for } x \in \text{Hom}(\Gamma_\pi, \tilde{K}^\times), \text{ associate to } x \text{ the automorphism of } V,
\]

\[
(4.1) \quad (\text{the representation space of } \pi), \text{ defined by:}
\]

\[
\tilde{h}(x)v = \chi(m)v \text{ for each } v \in V_m \text{ and } m \in P(\pi).
\]

Then the mapping \( x \rightarrow \tilde{h}(x) \) is an isomorphism of \( \text{Hom}(\Gamma_\pi, \tilde{K}^\times) \) onto \( \tilde{H} \).

Moreover, letting \( \Phi \) denote the root system of \( \mathfrak{g} \), we have

\[
\text{if } x \in \text{Hom}(\Gamma_\pi, \tilde{K}^\times), \alpha \in \Phi \text{ and } u \in K,
\]

\[
(4.2) \quad \text{ then } \tilde{h}(x)\alpha(u)\tilde{h}(x)^{-1} = \alpha(u) \tilde{h}(x)(\alpha)u.
\]

For \( \alpha \in \Phi \), set \( \tilde{x}_\alpha = \langle x_\alpha(u) | u \in K \rangle \), so that \( \tilde{H} \leq N_{\tilde{G}}(\tilde{x}_\alpha) \) and the mapping \( u \rightarrow x_\alpha(u) \) is an isomorphism of \((K, +)\) onto \( \tilde{x}_\alpha \). Then \( \tilde{U} = \langle \tilde{x}_\alpha | \alpha \in \Phi^+ \rangle \) and \( \tilde{U}^- = \langle \tilde{x}_\alpha | \alpha \in \Phi^- \rangle \) is the unipotent radical of the Borel subgroup that is “opposite” to \( \tilde{B} \) relative to \( \tilde{H} \) (cf. \([6, \text{IV, \S 14}]\)).

Note that every semisimple element of \( \tilde{G} \) is conjugate in \( \tilde{G} \) to an element of \( \tilde{H} \) by \([36, \S 2.12 \text{ and } 2.13]\) and \( W \) controls the \( \tilde{G} \)-fusion of elements of \( \tilde{H} \) by \([35, 6.3]\). Also if \( x \in \text{Hom}(\Gamma_\pi, \tilde{K}^\times) \), then \([30, \text{Proposition 1, (i)-(iii)}]\) holds and

\[
C_{\tilde{G}_\pi}(h(x))/\left(C_{\tilde{G}_\pi}(h(x))^\circright) = W_x/\left(W_x^0\right)
\]

where \( W_x^0 \) and \( W_x \) are as in \([30, \S 2]\).

Let \( E \) denote the \( G \)-module generated by \( \Phi \) and fix a \( W \)-invariant inner product \((*,*)\) on \( E \) and for any \( Z \)-submodule \( \Gamma \) of \( E \) set \( \Gamma^\perp = \{ x \in E | (x, y) \in Z \text{ for all } y \in \Gamma \} \). Also, as in \([30, \S 2]\), \( \text{ad} \) denotes the adjoint representation of \( \mathfrak{g} \) and \( \text{sc} \).
denotes the simply connected representation of \( \Theta \). Thus \( \Gamma_{ad} \leq \Gamma_\pi \leq \Gamma_{sc} \leq E \), \( \Gamma_{ad} \) is the \( Z \)-submodule of \( E \) generated by \( \Phi \), \( \Gamma_{sc} \) is the \( Z \)-submodule of \( E \) generated by all weights of \( \Theta \) and \( W \) stabilizes \( \Gamma_{sc} \), \( \Gamma_\pi \) and \( \Gamma_{ad} \). Also \( \Gamma_{sc} \), \( \Gamma_\pi \) and \( \Gamma_{ad} \) are \( W \)-stable and \( \Gamma_{sc} \leq \Gamma_\pi \leq \Gamma_{ad} \). With this action of \( W \) on \( \Gamma_\pi \) and with trivial action of \( W \) on \( K^\times \), the isomorphism of (4.1) becomes a \( W \)-isomorphism.

As a standard, if \( 0 \neq \beta \in E \), set \( \beta^* = 2\beta/(\beta, \beta) \) and for \( t \in K^\times \) and \( \alpha \in \Phi \), let

\[
 h_\alpha(t) = h(\chi) \quad \text{where } \chi \text{ is the unique element of } \\
\text{Hom}(\Gamma_\pi, K^\times) \text{ such that } \chi(m) = t^{(m, \alpha^*)} \text{ for any } m \in \Gamma_\pi. 
\]

We shall frequently be concerned with the following situation.

\( \tau \) is an (algebraic group) endomorphism of \( \tilde{G} = G_{\pi, K} \) onto itself that leaves \( \tilde{H} \) and \( \tilde{U} \) invariant and such that (i) \( \tilde{G} \) is finite or (ii) \( \tau \) is an automorphism of \( \tilde{G} \) as an algebraic group.

Suppose that \( \tau \) satisfies (i). Then, as noted above, [35, §§10–15] presents many basic results in this situation. Note also that if \( \gamma \) is any (algebraic group) endomorphism of \( \tilde{G} \) onto \( \tilde{G} \) such that \( \tilde{G} \) is finite then \( \gamma \) is conjugate via \( \text{Inn}(\tilde{G}) \) to an endomorphism of \( \tilde{G} \) that leaves \( \tilde{H} \) and \( \tilde{U} \) invariant by [35, Corollary 10.10].

Next suppose that \( \tau \), as above, satisfies (ii). Then [35, §§7–9] presents many basic results in this situation. In particular, \( C_\tilde{G}(\tau) \) is closed, \( C_\tilde{G}(\tau)^0 \) is reductive and contains every unipotent element of \( \tilde{G} \) and the structure of \( C_\tilde{G}(\tau)/C_\tilde{G}(\tau)^0 \) is given by [35, Lemma 9.2]. Also, if \( \tilde{G} \) is simply connected, then \( C_\tilde{G}(\tau) = C_\tilde{G}(\tau)^0 \) by [35, Theorem 8.2 and Corollary 9.4]. Clearly \( \tau \) fixes \( \tilde{U}^- \) and \( \tilde{N} \) and \( C_\tilde{G}(\tau)^0 = \langle \tilde{U}, \tilde{H}, (\tilde{U}^-) \rangle \) by [35, Lemma 9.2(a) and the proof of Theorem 8.2] and \( C_\tilde{G}(\tau) = \langle \tilde{U}, \tilde{N} \rangle \) by uniqueness in [35, 6.3]. For example, when \( \tau \) is the inner automorphism of \( G \) induced by the element \( x \in \text{Hom}(\Gamma_\pi, K^\times) \), then the structures of \( C_\tilde{G}(\tau), C_\tilde{G}(\tau)^0 \) and \( C_\tilde{G}(\tau)/(C_\tilde{G}(\tau)^0) \) are readily apparent (cf. [35, 8.3(c); 30, Proposition 1; 30, §8]). Note also that if \( \gamma \) is any semisimple automorphism of \( \tilde{G} \), then \( \gamma \) is conjugate via \( \text{Inn}(\tilde{G}) \) to a semisimple automorphism of \( \tilde{G} \) that leaves \( \tilde{H} \) and \( \tilde{U} \) invariant by [35, Theorem 7.5].

Let \( \lambda \) denote the element of \( \text{Aut}(K) \) such that \( \lambda(u) = u^p \) for all \( u \in K \), let \( n \) be an arbitrary positive integer and set \( q = p^n, \sigma = \lambda^n \) and \( k = C_K(\lambda) \). Then \( C_K(\lambda) \) is the prime subfield of \( K \) and \( k \) is the unique subfield of \( K \) of order \( q \).

Since \( \tilde{G}, \tilde{H}, \tilde{N}, \tilde{U} \) and \( \tilde{U}^- \) are all defined over \( C_K(\lambda) \), both \( \lambda \) and \( \sigma \) induce, in a natural way, endomorphisms of \( \tilde{G} \) that leave invariant \( \tilde{H}, \tilde{N}, \tilde{U}, \tilde{U}^- \) and \( \tilde{B} = \tilde{U}H \) and that we shall also denote by \( \lambda \) and \( \sigma \), respectively. Thus \( \lambda^n = \sigma \) as endomorphisms of \( \tilde{G} \), \( \lambda \) and \( \sigma \) are automorphisms of \( \tilde{G} \) as a group, \( C_\tilde{G}(\lambda) = \tilde{G}_\lambda \leq C_\tilde{G}(\sigma) = \tilde{G}_\sigma \), \( \tilde{G}_\sigma \) is finite and \( \lambda \)-invariant, etc. Let \( G = \langle \tilde{U}, (\tilde{U}^-) \rangle \). Then \( G \) is the Chevalley group associated with the triple \( (\Theta, \pi, k), G = O^p(\tilde{G}_\sigma), \tilde{G}_\sigma = G(\tilde{H}_\sigma), \tilde{N}_\sigma = (\tilde{H}_\sigma)(\tilde{N}_\lambda), \tilde{N} = \tilde{H}(\tilde{N}_\lambda), \tilde{H}_\sigma \) is the image of \( \text{Hom}(\Gamma_\pi, K^\times) \) under the isomorphism of (4.1), \( \text{Hom}(\Gamma_\pi, K^\times) = \{ \chi \in \text{Hom}(\Gamma_\pi, K^\times) \mid \chi^{q-1} = 1 \} \) and \( \tilde{H}_\sigma = \{ h \in \tilde{H} \mid h^{q-1} = 1 \} \), etc. (cf. [35, §12; 7, §3]).
As on [30, p. F-5], we fix a generator $\mathfrak{g}$ of $k^\times$ and define a homomorphism $\Gamma_{\sigma}^\perp \to \text{Hom}(\Gamma_{\sigma}, k^\times)$ by
\begin{equation}
\lambda \to \chi_{\lambda} \quad \text{where } \chi_{\lambda}(\xi) = \mathfrak{g}^{(\lambda, \xi)} \text{ for } \xi \in \Gamma_{\sigma}.
\end{equation}

Clearly this yields an exact sequence of $W$-modules
\begin{equation}
1 \to (q - 1)\Gamma_{\sigma}^\perp \to \Gamma_{\sigma}^\perp \to \text{Hom}(\Gamma_{\sigma}, k^\times) \to 1.
\end{equation}

Next we impose the additional assumption that $\mathfrak{g}$ is a simple Lie algebra. Let $B = \{\alpha_1, \ldots, \alpha_l\}$ be a set of simple roots and let $\alpha_0$ denote the highest root of $\Phi$. Then $G$ is a simple linear algebraic group and $\alpha_0 = \sum_{i=1}^l m_i \alpha_i$ where each $m_i$ is a positive integer. As in [30, §3], set
\begin{equation}
\mathfrak{g}_{\sigma} = \{\xi \in E \mid 0 \leq \langle \alpha_i, \xi \rangle \text{ for all } 1 \leq i \leq l \text{ and } (\alpha_0, \xi) \leq q - 1\}.
\end{equation}

Then the remaining definitions and results of [30, §§3–5] yield the following three lemmas.

**Lemma 4.5.** Assume that $\mathfrak{g}$ is a simple Lie algebra and that $m$ is a positive divisor of $q - 1$. Then every element of $G$ of order $m$ is conjugate in $G$ to an element of $H_\alpha$ of the form $h(\chi_\lambda)$ for some $\lambda \in \mathfrak{g}_{\sigma} \cap \Gamma_{\sigma}^\perp$.

**Lemma 4.6.** Assume that $\mathfrak{g}$ is a simple Lie algebra and let $\beta, \gamma \in \mathfrak{g}_{\sigma} \cap \Gamma_{\sigma}^\perp$. Then the following four conditions are equivalent.
\begin{enumerate}
\item[(a)] $h(\chi_\beta) \sim h(\chi_\gamma)$ in $G$;
\item[(b)] $h(\chi_\beta) \sim h(\chi_\gamma)$ via $G$;
\item[(c)] $\beta \sim \gamma$ via $\mathfrak{g}_{\sigma}$; and
\item[(d)] $\beta \sim \gamma$ via $\Gamma_{\sigma}$.
\end{enumerate}

**Lemma 4.7.** Assume that $\mathfrak{g}$ is a simple Lie algebra. Then the following two conditions hold.
\begin{enumerate}
\item[(a)] $\Omega_{\sigma} = \mathfrak{g}_{\sigma}/\gamma \cong \Gamma_{\sigma}^\perp/\Gamma_{\sigma}^\perp \cong \Gamma_{\sigma}^\perp/\Gamma_{\sigma}^\perp$; and
\item[(b)] if $\beta \in \mathfrak{g}_{\sigma} \cap \Gamma_{\sigma}^\perp$, then $\Omega_{\sigma, \beta} \cong C_G(h(\chi_\beta))/\langle C_G(h(\chi_\beta))^0 \rangle$.
\end{enumerate}

Also, as in [30, §7], let $\{\mathfrak{g}_1, \ldots, \mathfrak{g}_l\}$ be the $Z$-basis of $\Gamma_{\sigma}^\perp$ such that $(\mathfrak{g}_i, \alpha_j) = \delta_{ij}$ for all $1 \leq i, j \leq l$. Then we have the following elementary extension of [30, Proposition 7].

**Lemma 4.8.** Assume that $\mathfrak{g}$ is a simple Lie algebra, let $\delta \in \mathfrak{g}_{\sigma} \cap \Gamma_{\sigma}^\perp$ and let $m$ be a positive divisor of $q - 1$. Then $h(\chi_\delta)$ is an element of $\overline{H}$ of order $m$ if and only if the following four conditions hold.
\begin{enumerate}
\item[(a)] $\delta = ((q - 1)/m)(\sum_{i=1}^l a_i \mathfrak{g}_i)$ for nonnegative integers $a_i$ with $1 \leq i \leq l$;
\item[(b)] $\sum_{i=1}^l a_i m_i \leq m$;
\item[(c)] $m(\delta, \Gamma_{\sigma}) \leq (q - 1)Z$; and
\item[(d)] if $f$ is a proper divisor of $m$, then $f(\delta, \Gamma_{\sigma}) \neq (q - 1)Z$.
\end{enumerate}

**Proof.** Clearly $|h(\chi_\delta)| = m$ if and only if (i) $\mathfrak{g}_m^{(\delta, \mu)} = 1$ for all $\mu \in \Gamma_{\sigma}$ and (ii) if $f$ is a proper divisor of $m$, then $\mathfrak{g}_f^{(\delta, \mu)} \neq 1$ for some $\mu \in \Gamma_{\sigma}$. Clearly (a)–(d) imply
\[ \delta \in \mathcal{G} \cap \Gamma_\pi^+ \text{ and } |h(\chi_\delta)| = m. \] Conversely, since \( \delta \in \Gamma_\pi^+ \leq \Gamma_{ad}^+ \), we have \( \delta = \sum_{i=1}^l c_i \delta_i \) for integers \( c_i \) with \( 1 \leq i \leq l \). Then \((q - 1)|mc_i\) for all \( 1 \leq i \leq l \) since \( \Gamma_{ad} \leq \Gamma_\pi \). From the fact that \( \delta \in \mathcal{G} \), we conclude (a) and (b). Since (c) and (d) follow from (i) and (ii), we are done.

Now utilizing the facts noted above, we shall derive various results that we require about Chevalley groups over finite fields of odd order. Consequently, for the remainder of this section, we assume that \( p \) is odd. Also let \( k_1 = C_k(\sigma^2) \) so that \( k \leq k_1 \) and \( k_1 \) is the unique subfield of \( K \) of order \( q^2 \).

As observed before, by our notational convention, if \( m \) is an even integer and \( V/k \) is an orthogonal finite dimensional vector space with \( \dim(V/k) = m \), then \( \Omega(V/k) = \Omega(m, q, 1) \) if \( \mathrm{ind}(V/k) = \frac{m}{2} \) and \( \Omega(V/k) = \Omega(m, q, -1) \) if \( \mathrm{ind}(V/k) = \frac{m}{2} - 1 \) (cf. §3D). Also, as is standard and throughout the remainder of this paper, we set \( \Omega(6, q, 1) = \text{PSL}(4, q) \), \( \text{Spin}(6, q, 1) = \text{SL}(4, q) \), \( \Omega(6, q, -1) = \text{PSU}(4, q) \), \( \text{Spin}(6, q, -1) = \text{SU}(4, q) \), \( \Omega(4, q, 1) = \text{PSL}(2, q) \times \text{PSL}(2, q) \), \( \text{Spin}(4, q, 1) = \text{SL}(2, q) \times \text{SL}(2, q) \), \( \Omega(4, q, -1) = \text{PSL}(2, q^2) \) and \( \text{Spin}(4, q, -1) = \text{SL}(2, q^2) \).

**Lemma 4.9.** Let \( X = \text{Cov}(E_7(q)) \). Then the following six conditions hold.

(a) \( Z(X) = \langle z \rangle \) where \( z \) is an involution;
(b) there is a unique conjugacy class \( \mathfrak{R} \) of involutions of \( X \) such that if \( \tau \in \mathfrak{R} \), then \( C_X(\tau) \) contains a 2-component \( J \) with \( \tau \in J \) and \( \tau \neq J \); 
(c) if \( \mathfrak{R} \), \( \tau \) and \( J \) are as in (b), then \( C_X(\tau) \) contains, besides \( J \), precisely one other 2-component \( J_1 \) and \( J_1 \cong \text{Spin}(12, q, 1) \) with \( Z(J_1) = \langle \tau, z \rangle \);
(d) \( \{ \tau, z, \tau z \} \) is a set of representatives of the conjugacy classes of involutions in \( X \); 
(e) there are elements \( \gamma_1, \gamma_2 \) of \( X \) such that \( \gamma_i^2 = z \) and \( L_{2i}(C_X(\gamma_i)) \) is a quotient of \( \text{SL}(8, q) \) if \( q \equiv 1 \pmod{4} \) and of \( \text{SU}(8, q) \) if \( q \equiv -1 \pmod{4} \) and \( \text{E}(C_X(\gamma_1)) \) is a quotient of \( \text{Cov}(E_6(q)) \) if \( q \equiv 1 \pmod{4} \) and of \( \text{Cov}(E_6(q)) \) if \( q \equiv -1 \pmod{4} \); and 
(f) all elements \( \gamma \) of \( X \) such that \( \gamma^2 = z \) are conjugate in \( X \) to \( \gamma_1 \) or \( \gamma_2 \).

**Proof.** Let \( \mathfrak{E} = E_7 \), let \( \pi \) denote the simply connected representation of \( \mathfrak{E} \), so that \( \hat{G} \) is a simply connected linear algebraic group, and let \( B = \{a_1, \ldots, a_7\} \) be as in [8, Planche VI]. Then \( \Gamma_{ad} = \sum_{i=1}^7 Z a_i \) and \( \Gamma_{\pi} = \Gamma_{sc} = \sum_{i=1}^7 Z \bar{a}_i \) where \( \{\bar{a}_1, \ldots, \bar{a}_7\} \) is as in [8, Planche VI]. Also \( \hat{G} \cong \hat{G}_0 \cong X \) by [35, Theorem 12.4] and \( C_G(h) \) is connected for all \( h \in \hat{H} \) by [35, Theorem 8.1]. Thus, we have \( \Omega_\pi = \bar{a}_1, \bar{a}_i = \bar{a}_i \) for all \( 1 \leq i \leq 7 \), \( \Gamma_{\pi} = \Gamma_{ad} = \Gamma_{\pi} \) and \( \bar{a}_0 = 2a_1 + 2a_2 + 3a_3 + 4a_4 + 3a_5 + 2a_6 + a_7 \). Then Lemmas 4.4–4.8 imply that \( \hat{G} \) and \( G \) each have three conjugacy classes of involutions represented by \( h(\chi_\lambda) \) for \( i = 1, 2, 3 \) where

\[ \lambda_i = \frac{q - 1}{2} \bar{a}_i, \quad \lambda_2 = \frac{q - 1}{2} \bar{a}_6 \quad \text{and} \quad \lambda_3 = \frac{q - 1}{2}(2\bar{a}_7) = (q - 1)\bar{a}_7. \]

Also (4.4) yields

\[ h(\chi_{\lambda_1}) = h_{a_1}(-1)h_{a_2}(-1)h_{a_3}(-1) = h_{a_0}(-1), \]
\[ h(\chi_{\lambda_2}) = h_{a_2}(-1)h_{a_3}(-1) \quad \text{and} \]
\[ h(\chi_{\lambda_3}) = h_{a_3}(-1)h_{a_4}(-1)h_{a_5}(-1). \]
Setting $L_1 = \langle x \pm a_i, 1 \leq i \leq 7 \rangle$, $L_2 = \langle x \pm a_i | 1 \leq i \leq 5 \rangle$, $L_3 = \langle x \pm a_i, 2 \leq i \leq 7 \rangle$, and $L_4 = \langle x \pm a_i \rangle$, for $i = 1, 2, L_j \leq C_{G}(h(x_{i}))$ for $j = 1, 2, 3, 4$, $L_1 \cong SL(2, K)$, $Z(L_1) = \langle h(x_{i}) \rangle$, $Z(L_2) = \langle h(x_{i}) \rangle$, $h(x_{i}) \cong E_4$ and $Z(L_4) = \langle h(x_{1}), h(x_{2}) \rangle$. Also $C_{G}(h(x_{i})) = C_{G}(h(x_{i}), h(x_{j}))$ and $Z(C_{G}(h(x_{i}))) = \langle h(x_{i}) \rangle$. Thus $h(x_{i}) h(x_{j}) \cong h(x_{i})$ in both $G$ and $G$. Moreover, setting $L_1 = C_{L_1}(\sigma)$ and $L_2 = C_{L_2}(\sigma)$, we have $L_1 \cong SL(2, K)$, $Z(L_1) = \langle h(x_{i}) \rangle$, $L_2 \cong Spin(12, K)$, $Z(L_2) = \langle h(x_{i}) \rangle$. Also,

$$C_{G}(h(x_{i})) = C_{G}(h(x_{i}), h(x_{j}))$$

Thus (a)–(d) hold.

For (e) and (f), let $v$ be an element of order $4$ in $K^\times$. Then Lemma 4.8 implies that $G$ contains precisely two conjugacy classes of elements $y$ such that $y^2 = z$ and these two conjugacy classes have representatives

$$y_1 = h(x_{i}) = h_{a_2}(v^3) h_{a_3}(v) h_{a_5}(-1) h_{a_6}(v^3)$$

and

$$y_2 = h(x_{i}) = h_{a_1}(v^3) h_{a_2}(v) h_{a_5}(-1) h_{a_6}(v) h_{a_7}(v^3)$$

where

$$\lambda_4 = \frac{q - 1}{4 (2\omega_2)} = \frac{q - 1}{2 \omega_2} \quad \text{and} \quad \lambda_5 = \frac{q - 1}{4 (2\omega_7)} = \frac{q - 1}{2 \omega_7}.$$

Thus $L_1$ is a quotient of $SL(8, K)$, $z \in L_1$, $\gamma_i \in L_1$ if and only if $8 \mid (q - 1)$, $L_2/Z(L_2) \cong E_6(K)$ and $z \notin L_2$. Suppose that $q \equiv 1 (mod 4)$. Then $y \in K^\times$, and we have (e) and (f) in this case.

Finally assume that $q \equiv -1 (mod 4)$. Then $v \notin K$ and $\sigma$ inverts both $y_1$ and $y_2$. Let $w$ be an element of $\overline{N}_G$ such that the $w$ induced automorphism $w$ of $\Phi$ satisfies $w$:

$$\alpha_1 \mapsto \alpha_6, \alpha_3 \mapsto \alpha_5, \alpha_7 \mapsto -\alpha_0 \text{ and } \text{fixes } \alpha_2 \text{ and } \alpha_4.$$

Then $w^2 \in \overline{H}$ and $w$ inverts $y_1$ and $y_2$. Letting $\beta$ denote the inner automorphism of $G$ induced by $w$, it follows that $\beta \sigma$ fixes both $y_1$ and $y_2$ and $\beta \sigma$ is conjugate via $Inn(G)$ to $\sigma$ by Lemma 4.1. Since $(\overline{L}_1)_{\beta \sigma}$ is a quotient of $SU(8, q)$ and $(\overline{L}_2)_{\beta \sigma}$ is a quotient of $Cov(2E_6(q))$ by $[35, \S 11]$, Lemma 4.4 implies (e) and (f) in this case also and we are done.

**Lemma 4.10.** Let $X = Spin(7, q)$ with $Z(X) = \langle z \rangle$ and let $S \in Syl_2(X)$. Then the following six conditions hold.

(a) $Z(S) = \langle z \rangle \cong Z_2$, $\Omega_1(S) = S$ and $S$ has a normal $4$-subgroup;

(b) all involutions of $X - Z(X)$ are conjugate in $X$;
(c) if \( t \in S(\langle \tau \rangle) \), then \( |X| \cdot C_X(t)|_2 = 2 \), \( C_X(t) \) contains precisely three 2-components \( J_1, J_2 \) and \( J_3 \). These 2-components may be indexed so that \( \text{SL}(2, q) = J_i < C_X(t) \) for all \( 1 \leq i \leq 3 \), \( Z(J_1) = \langle \tau \rangle \), \( Z(J_2) = \langle t \rangle \), \( Z(J_3) = \langle tz \rangle \) and \( C_X(J_1 \cdot J_2 \cdot J_3) = \langle z, t \rangle \). Also there is an involution \( \tau \in C_X(t) - (J_1 \cdot J_2 \cdot J_3) \) such that \( C_X(t) = (J_1 \cdot J_2 \cdot J_3)(\tau) \) and \( J_i(\tau) \) has semidihedral Sylow 2-subgroups for all \( 1 \leq i \leq 3 \);

(d) there are two elements \( \gamma_1, \gamma_2 \) of \( X \) such that \( \gamma_1^2 = z \) and \( L_2(C_X(\gamma_i)) = E(C_X(\gamma_i)) \) for \( i = 1, 2 \), \( E(C_X(\gamma_i)) = \text{Sp}(4, q) \) with \( Z(E(C_X(\gamma_2))) = \langle z \rangle \), \( E(C_X(\gamma_2)) = \text{SL}(4, q) \) if \( q \equiv 1 \text{ (mod 4)} \), \( E(C_X(\gamma_2)) = \text{SU}(4, q) \) if \( q \equiv -1 \text{ (mod 4)} \) and \( Z(E(C_X(\gamma_2))) = \langle \gamma_2 \rangle \);

(e) all elements \( \gamma \) of \( X \) such that \( \gamma^2 = z \) are conjugate in \( X \) to \( \gamma_1 \) or \( \gamma_2 \); and

(f) if \( E \) is a normal 4-subgroup of \( S \), then \( T = C_X(E) \) is a maximal subgroup of \( S \), \( \Omega_i(T) = T \), \( Z(T) = E \) and \( T \in \text{Syl}_2(C_X(E)) \).

Proof. Let \( \mathfrak{O} = B_3 \), let \( \pi \) denote the simply connected representation of \( \mathfrak{O} \), so that \( \tilde{G} \) is a simply connected linear algebraic group, and adopt the notation of [8, Planche II]. Let \( B = \{ a_1, a_2, a_3 \} \), so that \( \Gamma_{ad} = \Sigma_{i=1}^{3} Z a_i, \Gamma_\sigma = \Gamma_{ad} = \Sigma_{i=1}^{3} Z \omega_1 \) where \( \{ \omega_1, \omega_2, \omega_3 \} \) are as in [8, Planche II], \( a_0 = a_1 + 2a_2 + 2a_3, \omega_1 = \omega_2 \) for \( i = 1, 2 \), \( \omega_3 = 2\omega_2, \Gamma_\sigma = \Sigma_{i=1}^{3} Z \bar{\omega}_1 \). Then, as in Lemma 4.9, \( \tilde{G} \) and \( G \) have precisely two conjugacy classes of involutions represented by \( h(x_1), h(x_3) \) where

\[
\lambda_1 = \frac{q-1}{2} (2\omega_1) \quad \text{and} \quad \lambda_2 = \frac{q-1}{2} \omega_2.
\]

Also setting \( z = h(x_1, y) \) and \( t = h(x_3, y) \), we have \( z = (h_0(1), -1), t = h_0(-1) = h_0(-1)h_0(-1), Z(\tilde{G}) = Z(G) = \langle z \rangle \) and \( C_{\tilde{G}}(t) = (\tilde{J}_0 \cdot \tilde{J}_1 \cdot \tilde{J}_3 \tilde{H} \rangle \) where \( \tilde{J}_0 = \langle x \rangle = \langle 1 \rangle \) for all \( i \in \{ 0, 1, 3 \} \), \( Z(J_0) = \langle t \rangle \), \( Z(J_3) = \langle z \rangle \) and \( Z(J_1) = \langle tz \rangle \). Then, as in [30, §8], \( C_G(t) = C_G(t) = (J_0 \cdot J_1 \cdot J_3) \tilde{H} \langle \omega_0 \rangle \rangle \) where \( \text{SL}(2, k) \approx \langle \tilde{J}_0 \rangle = J_i \leq C_G(t) \langle t \rangle \) for all \( i \in \{ 0, 1, 3 \} \), \( Z(J_0) = \langle t \rangle \), \( Z(J_3) = \langle z \rangle \) and \( Z(J_1) = \langle tz \rangle \). Also

\[
|G| = q^9(q^2 - 1)(q^4 - 1)(q^6 - 1)
\]

by [34, §9], \( \tilde{H}_0 \cap J_1 = \langle h_0(3) \rangle \), \( \tilde{H}_0 \cap J_3 = \langle h_0(3) \rangle \), \( \tilde{H}_0 \cap J_3 = \langle h_0(3) \rangle \rangle \) where \( h_0(u) = h_0(u)h_0(u^2)h_0(u) \) for all \( u \in k^* \), \( |C_G(t) = (J_0 \cdot J_1 \cdot J_3) = 2 \) and \( |C_G(t) = q^9(q^2 - 1)^3 \). Thus (b) holds, \( C_G(t) = (J_0 \cdot J_1 \cdot J_3) \langle h_0(3) \rangle \) and \( |G : C_G(t) \rangle = 2 \).

Set \( M = C_X(t) \) and let \( \{ i, j, k \} = \{ 0, 1, 3 \} \). Then

\[
J_j \cdot J_k = J_j \times J_k \leq C_M(J_j) \leq C_M(\mathfrak{x}_a) \subseteq N_M(\mathfrak{x}_a) = J_j J_k \mathfrak{x}_a, \tilde{H}_a.
\]

Since \( C_{\tilde{H}_a}(x_a(1)) = \langle (\tilde{H}_a) \cap J_j \rangle \times \langle (\tilde{H}_a) \cap J_k \rangle \), we have \( C_M(\mathfrak{x}_a) = J_j \times J_k \times \mathfrak{x}_a, \) and \( C_M(J_j) = J_j \times J_k \). Thus \( C_X(J_0 \cdot J_1 \cdot J_3) = \langle t, z, \tau \rangle = Z(M) \) and \( M/C_M(J_j) \approx \text{PGL}(2, q) \). For \( r \in \{ 0, 1, 3 \} \), let \( \omega_\alpha \) be as in [34, p. 30, (R5)]. Then \( \omega_\alpha, \omega_\alpha, \omega_\alpha \) is abelian, \( \omega_\alpha^2 = t, \omega_\alpha^2 = tz \) and \( \omega_\alpha^2 = z \). Hence \( \lambda = \omega_\alpha, \omega_\alpha, \omega_\alpha \) is an involution and \( \lambda \) inverts \( h_\alpha(3) \). Thus \( \tau = h_\alpha(3) \lambda \in \Omega(t) \) and \( M = (J_0 \cdot J_1 \cdot J_3) \langle \tau \rangle \). Moreover, for \( r \in \{ 0, 1, 3 \} \), we have \( (J_r(\langle \tau \rangle))/Z(J_r) \approx \text{PGL}(2, q) \) and [27, Lemma 2.2] readily implies that \( J_r(\langle \tau \rangle) \) has semidihedral Sylow 2-subgroups. Thus (c) holds. Next let \( T \in \text{Syl}_2(M) \) and let \( T < V \in \text{Syl}_2(X) \). Then \( T = C_r(t), Z(T) = \langle t, z \rangle, \Omega_r(T) = T, |V : T| = 2 \) and \( Z(V) = \langle z \rangle \). Thus \( \langle t, z \rangle \leq V, T = C_r(\langle t, z \rangle) \) and (f) holds.
Clearly $N_{x}(\langle t, z \rangle) = MV$, $J_{3} \subseteq MV$ and $J_{0}^{MV} = J_{1}^{MV} = J_{2}^{MV} = \{ J_{0}, J_{1} \}$ since $t^{\nu} = t(z)$. By the discussion in §3D, there is an element $\alpha \in MV - M$ such that $\alpha^{2} \in \langle z \rangle$ and $[\alpha, J_{3}] \leq \langle z \rangle$. Hence $[\alpha, J_{3}] = 1$ and a Sylow 2-subgroup of $\langle J_{3}, \alpha \rangle$ is not quaternion. Thus $J_{3} \alpha$ contains an involution. Since $MV = M(\alpha)$, (a) also holds.

For (d) and (e), let $\nu$ be an element of order 4 in $K^{\times}$. Then Lemmas 4.5–4.7 imply that $\overline{G}$ contains precisely two conjugacy classes of elements $\gamma$ such that $\gamma^{2} = z$ and these two conjugacy classes have representatives

$$\gamma_{1} = h(\chi_{\lambda_{1}}) = h_{\alpha_{1}}(-1)h_{\alpha_{3}}(-\nu), \quad \text{where} \quad \lambda_{1} = \frac{q-1}{4}(2\delta_{3}) = \frac{q-1}{4}(4\delta_{3})$$

and

$$\gamma_{2} = h(\chi_{\lambda_{2}}) = h_{\alpha_{1}}(-1)h_{\alpha_{3}}(-\nu), \quad \text{where} \quad \lambda_{2} = \frac{q-1}{4}(2\delta_{1}) = \frac{q-1}{4}(2\delta_{1}).$$

Also by [30, Proposition 8], we have $C_{G}(\gamma_{2}) = L_{1}H$ and $C_{G}(\gamma_{2}) = L_{2}H$, where $\gamma_{1} \in L_{1} = \langle \bar{x}_{x_{a_{0}}}, \bar{x}_{x_{a_{1}}}, \bar{x}_{x_{a_{2}}} \rangle \cong SL(4, K)$ and $z \in L_{2} = \langle \bar{x}_{x_{a_{0}}}, \bar{x}_{x_{a_{1}}} \rangle \cong Sp(4, K)$. Suppose that $q \equiv 1 \pmod{4}$. Then $\nu \in k$, $\gamma_{1} \in C_{G}(\sigma) \cong SL(4, k)$, $z \in C_{L}(\sigma) \cong Sp(4, k)$ and we have (d) and (e) in this case. Finally, suppose that $q \equiv -1 \pmod{4}$. Then $\nu \not\in k$ and $\sigma$ inverts both $\gamma_{1}$ and $\gamma_{2}$. Let $\delta = \alpha_{1} + \alpha_{2} + \alpha_{3}$. Thus $\delta \in \Phi$ and $\omega_{8}$, as defined on [34, p. 30, (R5)], has coefficients in the prime subfield of $K$ and is such that $\omega_{8} \in \bar{N}$ and $(\omega_{8})^{2} = h_{\alpha_{i}}(-1)$. Set $w = \omega_{8}$. Then the $w$ induced automorphism $\tilde{w}$ of $\Phi$ satisfies: $\tilde{w}: \alpha_{i} \leftrightarrow -\alpha_{i}$ and $\tilde{w}(\alpha_{j}) = \alpha_{j}$ for $j = 2, 3$. Thus $w$ also inverts $\gamma_{1}$ and $\gamma_{2}$.

Letting $\beta$ denote the inner automorphism of $\overline{G}$ induced by $w$, it follows that $\beta\sigma$ fixes both $\gamma_{1}$ and $\gamma_{2}$ and $\beta\sigma$ is conjugate via $\text{Inn}(\overline{G})$ to $\sigma$ by Lemma 4.1. Since $(L_{1})_{\beta\sigma} \cong SU(4, k)$ and $(L_{2})_{\beta\sigma} \cong Sp(4, k)$ by [35, §11], we have (d) and (e) in this case also by Lemma 4.4 and our proof is complete.

**Lemma 4.11.** Let $X = \text{Spin}(7, q)$ and $Z(\langle z \rangle) = \langle z \rangle$ where $z$ is an involution. Let $\mathfrak{A} = \text{Aut}(X)$, $\mathfrak{B} = \text{Inn}(X)$ and let $\mathfrak{C}$ be an arbitrary subgroup of $\mathfrak{A}$ with $\mathfrak{B} \leq \mathfrak{C}$. Then the following nine conditions hold.

(a) $P\mathfrak{A}(7, q) \cong \mathfrak{A}(7, q) \cong \mathfrak{B} = \mathfrak{A} \cap \mathfrak{C} \leq \mathfrak{A} \cong \text{PGL}(7, q)$;

(b) $\mathfrak{A} / \mathfrak{B} \cong Z_{2} \times Z_{2}$;

(c) there are involutions $\alpha_{1}, \alpha_{2}, \alpha_{3}$ in $\mathfrak{A} - \mathfrak{B}$ such that $\mathfrak{B}\alpha_{1} = \mathfrak{B}\alpha_{2} = \mathfrak{B}\alpha_{3}$, $\mathfrak{B} \langle \alpha_{i} \rangle \cong SO(7, q) \cong \text{PGO}(7, q)$, $E(C_{X}(\alpha_{i})) = L_{2}(C_{X}(\alpha_{i}))$ and $Z(E(C_{X}(\alpha_{i}))) = \langle z \rangle$ for $i = 1, 2$ and $3$, $E(C_{X}(\alpha_{i})) \cong SU(4, q)$ if $q \equiv 1 \pmod{4}$, $E(C_{X}(\alpha_{i})) \cong SL(4, q)$ if $q \equiv -1 \pmod{4}$, $E(C_{X}(\alpha_{2})) \cong Sp(4, q)$ and $E(C_{X}(\alpha_{3}))$ contains precisely two components $J_{1}$ and $J_{2}$, $Z(J_{1}) = Z(J_{2}) = \langle z \rangle$ and $J_{1}$ and $J_{2}$ may be indexed so that $J_{1} \cong SL(2, q)$ and $J_{2} \cong SL(2, q^{2})$;

(d) all involutions in $\mathfrak{B} \alpha_{i}$ are conjugate via an element of $\mathfrak{B}$ to $\alpha_{1}, \alpha_{2}$ or $\alpha_{3}$;

(e) $\mathfrak{B}$ contains precisely one conjugacy class of involutions $\mathfrak{R}$ such that if $\tau \in \mathfrak{R}$, then $C_{\mathfrak{B}}(\tau)$ contains an intrinsic 2-component $J$ with $J / O(\langle J \rangle) \cong SL(2, q)$;

(f) if $\mathfrak{R}$, $\tau$ and $J$ are as in (e), then $O(C_{\mathfrak{B}}(\tau)) = O(C_{\mathfrak{B}}(\tau)) = 1$ and $C_{\mathfrak{B}}(\tau)$ contains, besides $J$, two other 2-components $J_{1}$ and $J_{2}$ such that $\tau \in J_{1} \cong SL(2, q), J_{2} \cong PSL(2, q)$ and $C_{\mathfrak{B}}(J * J_{1} * J_{2}) = \langle \tau \rangle$;

(g) if $n$ is odd, then $O^{2}(\mathfrak{A}) = \mathfrak{B} \langle \alpha_{1} \rangle$.
if \( n \) is even, then there is an involution \( \tau \in \mathfrak{A} - (\mathfrak{B} \langle \alpha_1 \rangle) \) such that \( C_X(\tau) \cong \text{Spin}(7, \sqrt{q}) \), \( Z(C_X(\tau)) = \langle z \rangle \), all involutions of \( \mathfrak{A} - \mathfrak{B} \langle \alpha_1 \rangle \) are conjugate via an element of \( \mathfrak{B} \langle \alpha_1 \rangle \) to \( \tau \) and \( \mathfrak{B}(\mathfrak{B} \tau \alpha_1) = \emptyset \); and

(i) if \( 4 \mid \mathfrak{C}/\mathfrak{B} \), then \( n \) is even and \( \mathfrak{B} \langle \tau \rangle \leq \mathfrak{C} \).

**Proof.** Observe that the natural epimorphism of \( X \) onto \( X/Z(X) \cong \Omega(7, q) \cong P\Omega(7, q) \) induces an isomorphism of \( \text{Aut}(X) \) onto \( \text{Aut}(X/Z(X)) \) by [21, Corollary 4.1].

Adopt the notation of the previous lemma. Note that \( Z(\tilde{G}) = \langle z \rangle \), set \( \tilde{G} = \tilde{G}/\langle z \rangle \) and observe that [6, II, Theorem 6.8] implies that \( \tilde{G} \) is a connected linear algebraic group and the natural epimorphism of \( \tilde{G} \) onto \( \tilde{G}/\langle z \rangle \) is a morphism of linear algebraic groups. Also \( \lambda \) and \( \sigma \) induce endomorphisms of \( \tilde{G} \), \( \tilde{G}_a = \tilde{X}K \) where \( \tilde{K} = \{ h \in \tilde{H} \mid \sigma(h)h^{-1} \in \langle z \rangle \} \), \( \tilde{X} = X/Z(X) \cong P\Omega(7, q) \cong \Omega(7, q) \), \( \tilde{X} = O^\sigma(\tilde{G}_a) = (\tilde{G}_a)' \) and \( \tilde{X}K/\tilde{X} = 2 \). Moreover \( \lambda \) leaves \( \tilde{G}_a \) invariant. Letting \( \lambda^* \) denote the restriction of \( \lambda \) to \( \tilde{G}_a \), it follows that \( \lambda^* \) induces an automorphism of \( \tilde{G}_a \) of order \( n \), \( C_{\tilde{G}_a}(\lambda^*)(\tilde{X}) = 1 \) and \( \tilde{G}_a(\lambda^*) \cong \text{Aut}(X) \) with \( \tilde{X} \) corresponding to \( \text{Inn}(X) \) (cf. [11, §12.5]). By [25, Proposition 5], \( | P\Gamma O(7, q) | = | \mathfrak{A} | \) and \( P\Gamma O(7, q) \) is isomorphic to a subgroup of \( \mathfrak{A} = \text{Aut}(X) \cong \text{Aut}(X/Z(X)) \). Thus (a) and (b) hold. Also Lemma 4.10 implies that \( \tilde{G} \) possesses three conjugacy classes of involutions which are represented by

\[
\tilde{t} = h_a(-1), \quad \tilde{t}_1 = h_a(-1)h_a(\nu^2) \quad \text{and} \quad \tilde{t}_2 = h_a(-1)h_a(\nu^2). \]

Let \( w \) be as in Lemma 4.10. Then \( w \in \tilde{N}_\lambda \), \( w \) inverts \( \gamma_1 \) and \( \gamma_2 \), \( w^2 = 1 \) and \( \tau^w = tw \).

Thus for any \( j \in \{ t, \gamma_1, \gamma_2 \} \), we have \( \tilde{j} \in \tilde{G}_a \) and

\[
C_{\tilde{G}}(j) = C_{\tilde{G}}(\tilde{w}) = N_{\tilde{G}}(\langle z, j \rangle), \quad \text{where} \quad C_{\tilde{G}}(j)^0 = C_{\tilde{G}}(j).
\]

Choose \( g \in \tilde{G} \) such that \( g\sigma(g)^{-1} = w \), so that \( g\sigma(g)^{-1} = \tilde{w} \).

Lemma 4.4 implies that \( \tilde{G}_a \) has 6 conjugacy classes of involutions represented by \( \{ \tilde{t}, \tilde{t}_1, \tilde{t}_2, \tilde{\gamma}_1, \tilde{\gamma}_2, \tilde{\gamma}_3 \} \) of which only three conjugacy classes lie in \( \tilde{X} \) by Lemma 4.10. Clearly \( J_0^* = J_1 \) and (e) holds. Also it is easy to see from §3D and [25, Proposition 5(d)] applied to \( P\Gamma O(7, q) \) that (e) and (f) hold. Alternatively (f) also follows easily from the proof of Lemma 4.10. For, with \( t, \tilde{J}_0, J_0 \), etc. as in Lemma 4.10, we have \( N_{\tilde{G}, \langle \lambda^* \rangle}(J_0 \cdot J_1 \cdot \tilde{J}_3) = C_{\tilde{G}}(t)(\lambda^*) \) and hence it suffices to study \( C_X(t)(\lambda^*) = (J_0 \cdot J_1 \cdot J_3)H_\lambda(\lambda^*) \). Set \( L \equiv C_X(t)(\lambda^*) \) and let \( \{ i, j, k \} = \{ 0, 1, 3 \} \). Then, as in Lemma 4.10,

\[
J_i \cdot J_k = J_i \times J_k \leq C_{L}(J_i) \leq C_{L}(\xi_{\alpha_i}) \leq N_{L}(\xi_{\alpha_i}) = J_i \cdot J_k \cdot \xi_{\alpha_i} \cdot H_\lambda(\lambda^*). \]

Also, since \( C_{H_\lambda}(\xi_{\alpha_i}) = (\tilde{H}_\alpha \cap J_i) \times (\tilde{H}_\alpha \cap J_k) \), we have \( C_{L}(\xi_{\alpha_i}) = (J_i \times J_k)\xi_{\alpha_i} \). Consequently \( C_{L}(J_i) = J_i \times J_k \) and \( C_{L}(J_0 \cdot J_i \cdot J_3) = \langle t, \tilde{z} \rangle \). Now Lemma 2.7 implies (f). Let \( \beta \) denote the inner automorphism of \( \tilde{G} \) induced by \( w \). Note that \( \beta \sigma = \sigma \beta \), \( \beta^2 = 1 \) and \( (\beta \sigma)^2 = \sigma^2 \) as endomorphisms of \( \tilde{G} \).

First let \( \tilde{A} = C_{\tilde{G}}(t) \). Then \( \tilde{A} = C_{\tilde{G}}(\langle z, t \rangle) \) and both \( \beta \) and \( \sigma \) leave \( \tilde{A} \) invariant. As in Lemma 4.10, \( \{ J_0, J_1, J_3 \} \) is the set of 2-components of \( C_X(t) = \tilde{A} \). Also \( C_X(\tau^g) = C_{\tilde{G}}(\tau^g) = \langle C_{\tilde{G}}(t)J_0 \rangle \rangle \), \( (\beta \sigma)(\tilde{J}_0) = \tilde{J}_1 \) and \( (\beta \sigma)(\tilde{J}_3) = \tilde{J}_2 \). Then Lemma 2.5 and [30, §8; 35, §11.6] imply that \( C_{\tilde{G}}(t)_{\beta \sigma} \) contains precisely two 2-components

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\$ j_1 \text{ and } j_2 \text{ and by suitable indexing we may assume that } j_3 = (j_3)_{\beta_0} \cong \text{SL}(2, k), \ Z(j_1) = \langle z \rangle, j_2 = C_{i \tilde{J} \cdot i \tilde{J}}(\beta_0) = \text{SL}(2, k_i) \text{ and } Z(j_2) = \langle z \rangle. \\

Next let \( \mathcal{A} = C_{\tilde{G}}(\gamma_1) = C_{\tilde{G}}(\gamma_1) \). Thus \( \beta \) and \( \sigma \) both leave \( \mathcal{A} \) invariant and, as above, \( \langle L_1 \rangle = \text{SL}(4, k), Z(\langle L_1 \rangle) = \langle \gamma \rangle \text{ if } 4 \mid (q - 1), Z(\langle L_1 \rangle) = \langle z \rangle \text{ if } 4 \mid (q - 1) \) and \( \langle L_1 \rangle \) is the unique 2-component of \( C_X(\gamma_1) = \mathcal{A} \). Also \( C_X(\gamma_1) = (A_{\beta_0}, (\beta_0)(L_1) = \tilde{L}_1 \) and, as above, \( Z(\langle L_1 \rangle) = \text{SU}(4, k), Z(\langle L_1 \rangle) = \langle \gamma \rangle \text{ if } 4 \mid (q - 1) \) and \( Z(\langle L_1 \rangle) = \langle z \rangle \text{ if } 4 \mid (q - 1) \).

Next set \( \mathcal{A} = C_{\tilde{G}}(\gamma_2) = C_{\tilde{G}}(\gamma_2) \). Thus \( \beta \) and \( \sigma \) both leave \( \mathcal{A} \) invariant, and, as above \( \langle L_2 \rangle = \text{Sp}(4, k), Z(\langle L_2 \rangle) = \langle z \rangle \).

Clearly (g) holds. Suppose that \( n \) is even, let \( m = \frac{n}{2} \) and set \( t^* = (X^*)^m, \) thus \( t^* \) is the restriction of \( \lambda^m \) to \( G_{\alpha} \), \( (\lambda^m)^2 = \sigma \) and \( C_X(\tau^*) = C_{\tilde{G}}(\lambda^m) = \text{Spin}(7, q^2) \). Also Lemma 4.2 implies that all involutions of \( (\tilde{G}_\alpha)^* \) are conjugate via \( G_{\alpha} \) to \( \tau^* \). Thus (h) and (i) hold. Finally (c) and (d) follow from the above and \$3D$ and the proof of this lemma is complete.

**Lemma 4.12.** Let \( X = \text{Spin}(2m + 1, q) \) with \( m \geq 4 \). Then the following five conditions hold.

(a) \( Z(X) = \langle z \rangle \) where \( z \) is an involution;
(b) there is an involution \( t \in X \setminus Z(X) \) such that \( C_X(t) \) contains 2-components \( J_1 \) and \( J_2 \) with \( J_1 = J_2 = \text{SL}(2, q) \), \( Z(J_1) = \langle t \rangle \) and \( Z(J_2) = \langle tz \rangle \);
(c) \( m \) is odd if and only if there is a conjugacy class \( S \) of involutions in \( X \) such that if \( \tau \in S \), then \( C_X(\tau) \) possesses a 2-component \( J \) with \( z \in J \) and \( J/0(J) = \text{SL}(2, q_1) \) with \( q_1 = p^r \) for some positive integer \( r \);
(d) if \( m \) is odd and \( S \), \( \tau \) and \( J \) are as in (c), then \( S \) is unique, \( q_1 = q, O(J) = 1 \) and \( C_X(\tau) \) possesses, besides \( J \), precisely one other 2-component \( j \) and \( j = \text{Spin}(2m - 1, q, 1) \) with \( Z(j) = \langle z, \tau \rangle \) and
(e) there is an involution \( J \in X \) such that \( C_X(j) \) contains a component \( J \) with \( \langle z, j \rangle = Z(J), J \cong \text{Spin}(2m, q, 1) \) if \( m \) is even and \( J \cong \text{Spin}(2m - 1, q, 1) \) if \( m \) is odd.

**Proof.** Let \( G_{\alpha} = B_m \), let \( \pi \) denote the simply connected representation of \( G_{\alpha} \) so that \( G_{\alpha} \) is a simply connected linear algebraic group and adopt the notation of [8, Planche II]. Thus \( B = \{\alpha_1, \alpha_2, \ldots, \alpha_m\}, \Gamma_{ad} = \sum_{i=1}^m Z\alpha_i, \Gamma_s = \sum_{i=1}^m Z\omega_i, \alpha_0 = \alpha_1 + \sum_{i=2}^m 2\alpha_i, \delta_0 = \omega, \) for all \( 1 \leq i \leq m - 1, \) \( \delta_m = 2\omega_m, \) \( \Gamma_m = \sum_{i=1}^m Z\delta_i < \Gamma_{ad}, \Gamma_{ad} = \sum_{i=1}^m Z\delta_i, X = G = \tilde{G}_{\alpha} \) and \( \Omega_{s} = 1, \) etc. Then, as in Lemma 4.9, \( G_{\alpha} \) and \( G \) have precisely \( 1 + [\frac{m}{2}] \) conjugacy classes of involutions which are represented by

\[
\left\{ h(\lambda_1) \mid \lambda = \frac{q - 1}{2}\omega, \text{with } j \text{ odd and } 2 \leq j \leq m - 1 \right\} \\
\cup \left\{ h(\lambda_1), h(\lambda_2) \mid \lambda_1 = \frac{q - 1}{2}(2\omega_1) \text{ and } \lambda_2 = \frac{q - 1}{2}(2\omega_m) \text{ if } m \text{ is even} \right\}.
\]

Then, as in Lemma 4.9, we have \( Z(G) = \langle h(\lambda_1) \rangle, h(\lambda_1) = h_{\alpha_0}(-1) \) and \( h_{\alpha_0}(z) = h(\chi_1) \) with \( \lambda = \frac{q - 1}{2}\omega_2. \) Also \( t = h_{\alpha_0}(-1) \) satisfies (b) and it is easy to see, as in Lemma 4.9, that (c)–(e) hold.
Lemma 4.13. Let $X = \text{Spin}(8, q, 1)$. Then the following three conditions hold.

(a) $Z(X) \cong \mathbb{E}_4$ and $Z(X) = \{t_1, t_2\}$ where $t_1$ and $t_2$ are distinct commuting involutions;

(b) all involutions in $X - Z(X)$ are conjugate in $X$; and

(c) if $\tau \in \mathfrak{g}(X - Z(X))$, then $C_X(\tau)$ possesses precisely four 2-components $J_1, J_2, J_3, J_4$. Also the 2-components of $C_X(\tau)$ can be indexed so as to satisfy the following conditions:

(i) $J_1 \cong \text{SL}(2, q)$ and $Z(J_1) = \langle \tau \rangle$;

(ii) $J_2 \cong \text{SL}(2, q)$ and $Z(J_2) = \langle \tau t_1 \rangle$;

(iii) $J_3 \cong \text{SL}(2, q)$ and $Z(J_3) = \langle \tau t_2 \rangle$; and

(iv) $J_4 \cong \text{SL}(2, q)$ and $Z(J_4) = \langle \tau t_1 t_2 \rangle$.

Proof. Let $\mathfrak{g} = D_4$, let $\sigma$ denote the simply connected representation of $\mathfrak{g}$ so that $\overline{G}$ is a simply connected linear algebraic group and adopt the notation of [8, Planche IV]. Thus $B = \{\alpha_1, \alpha_2, \alpha_3, \alpha_4\}$, $\Gamma_{\text{ad}} = \sum_{i=1}^4 Z \alpha_i$, $\Gamma_{\alpha} = \Gamma_{\text{sc}} = \sum_{i=1}^4 Z \alpha_i$, $\alpha_0 = \alpha_1 + 2\alpha_2 + \alpha_3 + \alpha_4$, $\overline{\alpha}_i = \overline{\alpha}_i$ for all $1 \leq i \leq 4$, $\Gamma_{\text{ad}} = \Gamma_{\alpha}$, $G = \overline{G}_0 \cong X$ and $\Omega_{\alpha} = 1$, etc. Then, as in Lemma 4.9, $\overline{G}$ and $G$ have precisely 4 conjugacy classes of involutions represented by

$$\left\{ h(x_{\lambda_i}) \mid \lambda_1 = \frac{q-1}{2} \overline{\omega}_2, \lambda_2 = \frac{q-1}{2} (2 \overline{\omega}_1), \lambda_3 = \frac{q-1}{2} (2 \overline{\omega}_3), \lambda_4 = \frac{q-1}{2} (2 \overline{\omega}_4) \right\}.$$ 

Also, as in Lemma 4.9, we have

$$X \cong G = \overline{G}_0, \quad h(x_{\lambda_1}) = h_{\alpha_0}(-1) = h_{\lambda_1}(-1)h_{\lambda_2}(-1)h_{\lambda_3}(-1),$$

$$h(x_{\lambda_2}) = h_{\lambda_2}(-1)h_{\lambda_3}(-1), \quad h(x_{\lambda_3}) = h_{\lambda_3}(-1)h_{\lambda_4}(-1),$$

$$h(x_{\lambda_4}) = h_{\lambda_4}(-1)h_{\lambda_1}(-1), \quad Z(G) = \langle h(x_{\lambda_1}), h(x_{\lambda_3}) \rangle$$

and (a) and (b) hold. Also, setting $\tau = h_{\alpha_0}(-1)$ and observing that $h_{\alpha_1}(-1) = \tau h_{\alpha_1}(-1)h_{\alpha_2}(-1)$, $h_{\alpha_2}(-1) = \tau h_{\alpha_2}(-1)h_{\alpha_2}(-1)$ and $h_{\alpha_3}(-1) = \tau h_{\alpha_3}(-1)h_{\alpha_3}(-1)$, it readily follows, as in Lemma 4.9, that (c) holds and we are done.

Lemma 4.14. Let $X = \text{Spin}(8, q, -1)$. Then the following four conditions hold.

(a) $Z(X) = \langle z \rangle$ where $z$ is an involution;

(b) all involutions in $X - Z(X)$ are conjugate in $X$;

(c) if $\tau \in \mathfrak{g}(X - Z(X))$, then $C_X(\tau)$ possesses precisely three 2-components $J_1, J_2, J_3$. Also the 2-components of $C_X(\tau)$ can be indexed so as to satisfy the following three conditions:

(i) $J_1 \cong \text{SL}(2, q^2)$ and $Z(J_1) = \langle \tau \rangle$;

(ii) $J_2 \cong \text{SL}(2, q)$ and $Z(J_2) = \langle \tau \rangle$; and

(iii) $J_3 \cong \text{SL}(2, q)$ and $Z(J_3) = \langle \tau \rangle$; and

(d) if $y \in X$ is such that $y^2 = z$, then $C_X(y)$ contains a unique 2-component $L$ with $L \cong \text{SL}(4, q)$ or $L \cong \text{SU}(4, q)$.

Proof. Assume the notation of Lemma 4.13 and let $\rho$ denote the graph automorphism of order 2 of the root system of $D_4$ such that $\rho(\alpha_i) = \alpha_i$ for $i = 1, 2$ and $\rho(\alpha_3) = \alpha_4$. Then $\rho$ induces a semisimple automorphism of $\overline{G}$, which we shall also denote by $\rho$, such that if $\alpha \in \Phi$ and $u \in K$, then $\rho(x_{\alpha}(u)) = x_{\rho(u)}(\alpha)$. Also, as
endomorphisms of \( \overline{G} \), we have \( \sigma \rho = \rho \sigma \) and \( (\sigma \rho)^2 = \sigma^2 \) and we may take \( \overline{X} = \overline{G}_{\sigma \rho} = C_{\overline{G}}(\sigma \rho) \). Then (a) with \( z = h_{a_0}(-1)h_{a_0}(-1) \) and (b) follow from Lemma 4.13. Also \( \tau = h_{a_0}(-1) \in \mathfrak{g}(X - Z(X)) \) and \( C_X(\tau) = C_{\overline{G}}(\tau_{\sigma \rho}) \). Since \( C_{\overline{G}}(\tau) = \overline{LH} \) where \( \overline{L} = J_{\mathfrak{g}} * J_1 * J_5 * J_6 \) and \( SL(2, K) \cong \overline{J}_i = \langle \overline{x}_{a_i}, \overline{x}_{-a_i} \rangle \cong C_{\overline{G}}(t) \) for all \( i \in \{0, 1, 3, 4\} \), the methods of [30, §§2 and 8] imply that \( C_X(\tau) = (\overline{J}_{\mathfrak{g}} * \overline{J}_1 * \overline{J}_5)H \) where \( H = C_{\overline{G}}(\sigma \rho) \), \( SL(2, q) = C_{\overline{G}}(\sigma) = C_{\overline{G}}(\rho) \) where \( \overline{J}_1 \) is the conjugacy class of involutions \( \tau \). \( Z(\overline{J}_1) = \langle \tau \rangle \). \( SL(2, q^2) = C_{\overline{G}}(\sigma \rho) \) is \( \langle \overline{x}_{a_0}(u)x_{a_4}(\sigma(u)), x_{-a_4}(u)x_{-a_0}(\sigma(u)) \rangle \) \( u \in k_1 \rangle \) and \( Z(\overline{J}_1) = \langle \overline{h}_{a_0}(-1)h_{a_0}(-1) \rangle = \langle \overline{z} \rangle \). Thus (c) holds.

For (d), let \( v \) be an element of order 4 in \( K^\times \). Lemma 4.8 implies that \( \overline{G} \) contains precisely two conjugacy classes of elements \( \gamma \) of order 4 such that \( \gamma^2 = z \) and these two conjugacy classes have representatives

\[
\gamma_1 = h(x_{\lambda_1}) = h_{a_0}(-1)h_{a_0}(v^3)h_{a_4}(v^3),
\]

where \( \lambda_1 = \frac{q-1}{4}(2\overline{w}_3 + 2\overline{w}_4) = \frac{q-1}{2}(\overline{w}_3 + \overline{w}_4) \) and

\[
\gamma_2 = h(x_{\lambda_2}) = h_{a_0}(-1)h_{a_0}(-1)h_{a_4}(v)h_{a_4}(v), \quad \text{where} \quad \lambda_2 = \frac{q-1}{4}(2\overline{w}_1) = \frac{q-1}{2}\overline{w}_1.
\]

Also we have \( C_{\overline{G}}(\gamma_1) = \overline{L}_1 \overline{H} \) and \( C_{\overline{G}}(\gamma_2) = \overline{L}_2 \overline{H} \) where \( \gamma_1 \in \overline{L}_1 = \langle \overline{x}_{\pm a_0}, \overline{x}_{\pm a_3}, \overline{x}_{\pm a_4} \rangle \cong SL(4, K), \gamma_2 \not\in \overline{L}_2 = \langle \overline{x}_{\pm a_1}, \overline{x}_{\pm a_2}, \overline{x}_{\pm a_3}, \overline{x}_{\pm a_4} \rangle \) is of type \( A_3 \) and \( z \in L_2 \).

Suppose that \( q \equiv 1 \pmod{4} \). Then \( v \in k, \gamma_1 \in C_{L_1}(\rho \sigma) \cong SL(4, q) \) and \( z \in C_{L_2}(\rho \sigma) \cong SU(4, q) \) by [35, §11]. It follows that (d) holds in this case. Finally, suppose that \( q \equiv -1 \pmod{4} \). Then \( v \not\in k \) and \( \rho \sigma \) inverts both \( \gamma_1 \) and \( \gamma_2 \). Also, from [8, Planche IV], it follows that there is an element \( w \in \overline{N} \) with coefficients in the prime field of \( K \) such that \( w^2 \in \overline{H} \) and such that the \( w \) induced automorphism \( \tilde{w} \) of \( \Phi \) satisfies \( \tilde{w}: \alpha_i \mapsto -\alpha_0, \tilde{w}(\alpha_2) = \alpha_2 \) and \( \tilde{w}: \alpha_3 \mapsto \alpha_4 \). Then, by [34, p. 30], we have \( \gamma_i^w = \gamma_i^{-1} \) for \( i = 1, 2 \).

Letting \( \beta \) denote the inner automorphism of \( \overline{G} \) induced by conjugation by \( w \), it follows that \( \beta \rho \sigma \) fixes both \( \gamma_1 \) and \( \gamma_2 \) and \( \beta \rho \sigma \) is conjugate via \( \text{Inn}(\overline{G}) \) to \( \rho \sigma \) by Lemma 4.1. Since \( (\overline{L}_1)_{\beta \rho \sigma} \cong SU(4, q) \) and \( (\overline{L}_2)_{\beta \rho \sigma} \cong SL(4, q) \) by [35, §11], we have (d) in this case also.

**Lemma 4.15.** Let \( X = \text{Spin}(2m, q, 1) \) for some even integer \( m \geq 6 \). Then the following three conditions hold.

(a) \( Z(\mathfrak{g}) = E_4 \) and \( Z(\mathfrak{g}) = \langle t_1, t_2 \rangle \) where \( t_1 \) and \( t_2 \) are distinct commuting involutions of \( \mathfrak{g} \); 

(b) there is a unique conjugacy class of involutions \( \mathfrak{S} \) of \( X \) such that if \( \tau \in \mathfrak{S} \), then \( C_X(\tau) \) possesses a 2-component \( J \) with \( \tau \in J \) and \( O(J) = SL(2, q) \); and

(c) if \( \mathfrak{S} \) and \( \tau \) are as in (b), then \( O(J) = 1, J \) is the unique 2-component of \( C_X(\tau) \) that contains \( \tau \), \( C_X(\tau) \) contains precisely two other 2-components \( J_1 \) and \( J_2 \) such that, by appropriate indexing, we may assume: \( J_1 \cong SL(2, q) \) and \( J_2 \cong \text{Spin}(2m - 4, q, 1) \) and, by appropriate indexing of \( Z(\mathfrak{g})^\mathfrak{S} \), we may also assume: \( Z(J_1) = \langle \tau t_1 \rangle \) and \( Z(J_2) = \langle \tau t_2, t_1 \rangle \).

**Proof.** Let \( \mathfrak{G} = D_m \), let \( \pi \) denote the simply connected representation of \( \mathfrak{G} \) so that \( \overline{G} \) is a simply connected linear algebraic group and let \( B = \{a_1, \ldots, a_m\} \) be as in [8,
Planche IV]. Then $\Gamma_{\text{ad}} = \Sigma_{i=1}^{m} \mathcal{Z} \alpha_i$, and $\Gamma_{\mathcal{Z}} = \Gamma_{\text{sc}} = \Sigma_{i=1}^{m} \mathcal{Z} \bar{\omega}_i$, where $\{\bar{\omega}_i\} | 1 \leq i \leq m \}$ is as given in [8, Planche IV], $\varepsilon_i = \bar{\omega}_i$ for all $1 \leq i \leq m$, $\Gamma_{\text{ad}} = \Gamma_{\mathcal{Z}}$, $G = G_{\mathcal{Z}} \cong X$, $\Omega_{\mathcal{Z}} = 1$ and $\alpha_0 = \alpha_1 + \sum_{j=2}^{m-2} \alpha_j + \alpha_{m-1} + \alpha_m$, etc. Then, as in Lemma 4.9, $\tilde{G}$ and $G$ have precisely $3 + (m - 2)/2$ conjugacy classes of involutions represented by

$$\mathfrak{B} = \left\{ (\chi_{\lambda}) | \lambda = \frac{q - 1}{2} \bar{\omega}_i \text{ with } i \text{ even and } 2 \leq i \leq m - 2 \right\}$$

$$\cup \left\{ (\chi_{\lambda}) | \lambda = \frac{q - 1}{2} (2\bar{\omega}_i) \text{ with } i \in \{1, m - 1, m \} \right\}.$$

Also $Z(G) \cong E_4$, $h(\chi_{\lambda}) = h_{\alpha_{m-1}}(-1)h_{\alpha_m}(-1)$, $h(\chi_{\lambda_{m-1}}) = h_{\alpha_1}(-1)h_{\alpha_3}(-1) \cdots h_{\alpha_{m-1}}(-1)h_{\alpha_m}(-1)^{m/2}h_{\alpha_m}(-1)^{(m-2)/2}$, $h(\chi_{\lambda_m}) = h(\chi_{\lambda_{m-1}})h(\chi_{\lambda_m})$ and $Z(G) = \langle h(\chi_{\lambda}), h(\chi_{\lambda_{m-1}}) \rangle$. In addition, it is easy to see that $\mu = h(\chi_{\lambda})$ with $\lambda = \frac{q - 1}{2} \bar{\omega}_2$ is the unique involution of $\mathfrak{B}$ satisfying the conditions required in (b) and that the conditions of (c) hold in $C_{\mathcal{G}}(\mu) = (C_{\mathcal{G}}(\mu))_\ast$.

**Lemma 4.16.** Let $X = \text{Spin}(2m, q, -1)$ for some even integer $m \geq 6$. Then the following five conditions hold.

(a) $Z(X) = \langle z \rangle$ where $z$ is an involution;

(b) there is a unique conjugacy class $\mathfrak{K}_1$ of involutions in $X$ such that if $\tau \in \mathfrak{K}_1$, then $C_X(\tau)$ possesses a 2-component $J$ with $\tau \in J$ and $O(J) \cong \text{SL}(2, q)$;

(c) if $\mathfrak{K}_1$, $\tau$ and $J$ are as in (b), then $O(J) = 1$, $J$ is the unique 2-component of $C_X(\tau)$ that contains $\tau$ and $C_X(\tau)$ contains, besides $J$, precisely two other 2-components $J_1$ and $J_2$ which may be indexed so that $J_1 \cong \text{SL}(2, q)$, $J_2 \cong \text{Spin}(2m - 4, q, -1)$, $Z(J_1) = \langle \tau z \rangle$ and $Z(J_2) = \langle z \rangle$;

(d) there is a unique conjugacy class $\mathfrak{K}_2$ of involutions in $X$ such that if $\tau \in \mathfrak{K}_2$, then $C_X(\tau)$ possesses a 2-component $J$ with $z \in J$ and $O(J) \cong \text{SL}(2, q_1)$ where $q_1 = q^r$ for some positive integer $r$; and

(e) if $\mathfrak{K}_2$, $\tau$ and $J$ are as in (d), then $O(J) = 1$, $q_1 = q^2$ and the following two conditions hold:

(i) $C_X(\tau)$ possesses, besides $J$, exactly one other 2-component $\mathfrak{J}$; and

(ii) $\mathfrak{J} \cong \text{Spin}(2m - 4, q, 1)$ and $Z(\mathfrak{J}) = \langle \tau, z \rangle$.

**Proof.** Assume the notation of Lemma 4.15 and let $\rho$ denote the graph automorphism of order 2 of the root system of $D_m$ (cf. [11, §12.2]). Then $\rho$ induces a semisimple automorphism of $\tilde{G}$, which we shall also denote by $\rho$, such that if $\alpha \in \Phi$ and $u \in K$, then $\rho(x_{\alpha}(u)) = x_{\rho(\alpha)}(u)$. Also as endomorphisms of $\tilde{G}$, we have $\rho \sigma = \sigma \rho$ and $(\rho \sigma)^2 = \sigma^2$ and we may take $X = G_{\rho \sigma}$. Note that $Z(\tilde{G}) = \langle h(\chi_{\lambda}), h(\chi_{\lambda_{m-1}}) \rangle$, $Z(\tilde{G})_{\rho \sigma} = \langle h(\chi_{\lambda}) \rangle$ and for each even integer $i$ with $2 \leq i \leq m - 2$ and for $\lambda_i = \frac{q - 1}{2} \bar{\omega}_i$, we have

$$h(\chi_{\lambda_i}) = h_{\alpha_1}(-1)h_{\alpha_3}(-1) \cdots h_{\alpha_{m-1}}(-1)(h_{\alpha_{m-1}}(-1)h_{\alpha_m}(-1))^{i/2}.$$

Thus $Z(X) = \langle z \rangle$ where $z = h(\chi_{\lambda_1}) = h_{\alpha_{m-1}}(-1)h_{\alpha_m}(-1)$ and $X$ possesses precisely $1 + (m - 2)/2$ conjugacy classes of involutions represented by $\mathfrak{B} = \{ (\chi_{\lambda}) | \lambda = \frac{q - 1}{2} \bar{\omega}_i \text{ with } i \text{ even and } 2 \leq i \leq m - 2 \} \cup \{ z \}$. Thus (a) holds and it follows via arguments similar to those above that $h(\chi_{\lambda_i}) = h_{\alpha_0}(-1)$ is the unique involution of $\mathfrak{B}$ satisfying the conditions required in (b), that $h(\chi_{\lambda_{m-2}})$ is the unique involution of $\mathfrak{B}$ satisfying the conditions required in (d) and that (c) and (e) also hold.
Lemma 4.17. Let $X = \text{Spin}(2m, q, 1)$ for some odd integer $m \geq 5$. Also let $Z(X) = \langle \gamma \rangle$ where $|\gamma| = (4, q - 1)$ and let $z$ be the unique involution in $Z(X)$. Then the following three conditions hold.

(a) There is a unique conjugacy class $\mathcal{S}$ of involutions of $X$ such that if $\tau \in \mathcal{S}$, then $C_X(\tau)$ contains a 2-component $J$ with $\tau \in J$ and $J/O(J) \cong SL(2, q)$;

(b) if $\mathcal{S}$, $\tau$ and $J$ are as in (a), then $O(J) = 1$, $J$ is the unique 2-component of $C_X(\tau)$ that contains $\tau$ and $C_X(\tau)$ contains, besides $J$, precisely two 2-components $J_1$ and $J_2$. Also by suitable indexing we may assume $J_1 = \text{SL}(2, q)$, $J_2 = \text{Spin}(2m - 4, q, 1)$, $Z(J_1) = \langle \tau z \rangle$, $Z(J_2) = \langle z \rangle$ if $q \equiv -1 \pmod{4}$ and $Z(J_2) = \langle \tau \gamma \rangle$ if $q \equiv 1 \pmod{4}$; and

(c) there does not exist an involution $\tau \in X$ such that $C_X(\tau)$ possesses a 2-component $J$ with $z \in J$ and $J/O(J) \cong SL(2, q^2)$.

Proof. Let $\mathcal{S} = D_m$, let $\pi$ denote the simply connected representation of $\mathcal{S}$ so that $G$ is a simply connected linear algebraic group and let $B = \{a_1, \ldots, a_m\}$ be as in [8, Planche IV]. Then $\Gamma_{ad} = \sum_{i=1}^{m} Z(a_i)$ and $\Gamma_\pi = \Gamma_{sc} = \sum_{i=1}^{m} Z(\tilde{\omega}_i)$ where $\tilde{\omega}_i$ is as given in [8, Planche IV], $\epsilon_i = \tilde{\omega}_i$ for all $1 \leq i \leq m$, $\Gamma_{ad} = \Gamma_{sc}$, $G = G_\pi \cong X$, $\Omega_\pi = 1$ and $\alpha_0 = \alpha_1 + \sum_{j=2}^{m-2} 2\alpha_j + \alpha_{m-1} + \alpha_m$, etc. Let $v$ be an element of order 4 in $K^\times$. Then $Z(G) = \langle h(\lambda) \rangle \cong Z_4$ where $\beta = q^{-1}(4\tilde{\omega}_m) = (q - 1)\tilde{\omega}_m$,

$$h(\lambda) = h_{a_1}(-1)h_{a_2}(-1) \cdots h_{a_{m-1}}(-1)h_{a_m}(\mu)$$

and $h(\chi_\beta)^2 = h_{a_{m-1}}(-1)h_{a_m}(-1)$. Also $Z(G) = Z(G)$ if $4 \mid (q - 1)$ and $Z(G) = \langle h(\lambda)^2 \rangle$ if $4 \nmid (q - 1)$. Moreover, as in Lemma 4.9, $\overline{G}$ and $G$ have precisely $2 + (m - 3)/2$ conjugacy classes of involutions represented by

$$B = \left\{ h(\lambda_i) \mid \lambda = \frac{q - 1}{2} \tilde{\omega}_i \text{ with } i \text{ even and } 2 \leq i \leq m - 3 \right\}$$

$$\cup \left\{ h(\lambda_1), h(\lambda_2) \mid \lambda_1 = \frac{q - 1}{2}(2\tilde{\omega}_1) \text{ and } \lambda_2 = \frac{q - 1}{2}(\tilde{\omega}_{m-1} + \tilde{\omega}_m) \right\}.$$ Here $h(\chi_\lambda) = h_{a_{m-1}}(-1)h_{a_m}(-1) = h(\chi_\beta)^2$ and $\mu = h(\chi_\lambda)$ with $\lambda = \frac{q - 1}{2}\tilde{\omega}_2$ is the unique involution of $B$ satisfying the conditions required in (a). Finally, since $\mu = h_{a_1}(-1)h(\chi_\beta)^2 = h_{a_0}(-1)$, both (b) and (c) readily follow.

Lemma 4.18. Let $X = \text{Spin}(2m, q, -1)$ for some odd integer $m \geq 5$. Also let $Z(X) = \langle \gamma \rangle$ where $|\gamma| = (4, q + 1)$ and let $z$ be the unique involution in $Z(X)$. Then the following three conditions hold.

(a) There is a unique conjugacy class $\mathcal{S}$ of involutions of $X$ such that if $\tau \in \mathcal{S}$, then $C_X(\tau)$ contains a 2-component $J$ with $\tau \in J$ and $J/O(J) \cong SL(2, q)$;

(b) if $\mathcal{S}$, $\tau$ and $J$ are as in (a), then $O(J) = 1$, $J$ is the unique 2-component of $C_X(\tau)$ that contains $\tau$ and $C_X(\tau)$ contains, besides $J$, precisely two 2-components $J_1$ and $J_2$. Also by suitable indexing we may assume $J_1 = \text{SL}(2, q)$, $J_2 = \text{Spin}(2m - 4, q, -1)$, $Z(J_1) = \langle \tau z \rangle$, $Z(J_2) = \langle z \rangle$ if $q \equiv 1 \pmod{4}$ and $Z(J_2) = \langle \tau \gamma \rangle$ if $q \equiv -1 \pmod{4}$; and

(c) there does not exist an involution $\tau \in X$ such that $C_X(\tau)$ possesses a 2-component $J$ with $z \in J$ and $J/O(J) \cong SL(2, q^2)$.
Proof. Assume the notation of Lemma 4.17, let \( \rho \) denote the graph automorphism of order 2 of the root system of \( D_m \) (cf. [11, §12.2]) and assume that \( \rho \) induces an automorphism of \( \tilde{G} \) as in the previous lemmas, etc. Then we may take \( X = \tilde{G}_{\rho} \), \( Z(X) = \langle h_{\sigma_1}, \ldots, h_{\sigma_{m-3}} \rangle \) if \( q \equiv 1 \) (mod 4) and \( Z(X) = \langle h(\chi_{\rho}) \rangle \) if \( q \equiv -1 \) (mod 4) and both \( \tilde{G} \) and \( X \) have precisely \( 2 + (m-3)/2 \) conjugacy classes of involutions with representatives as in the proof of Lemma 4.17. Also the methods of the proof of Lemma 4.14 and the information in the proof of Lemma 4.17 readily yield (a)–(c).

Lemma 4.19. Let \( X = E_6(q) \), let \( \mathfrak{A} = \text{Aut}(X) \) and let \( \mathfrak{B} = \text{Inn}(X) \). Then the following five conditions hold.

(a) \( \mathfrak{A} = \mathfrak{B} A \) where \( A \cap \mathfrak{B} = 1, X \cong \mathfrak{B} = \mathfrak{A}' \) and \( A \) is the subgroup of \( \mathfrak{A} \) induced by \( \text{Aut}(k) \), so that \( A \cong \text{Aut}(k) \cong Z_n \);

(b) \( \mathfrak{B} \) contains involutions \( t \) and \( v \) such that \( C_{\mathfrak{B}}(t) \) possesses precisely two 2-components \( J_1 \) and \( J_2 \) and by appropriate indexing we may assume that \( Z(J_1) = Z(J_2) = \langle t \rangle \), \( J_1 = \text{SL}(2, q) \), \( J_2 = \text{Cov}(E_7(q)) \), \( |C_{\mathfrak{B}}(t)/(J_1 \ast J_2)| = 2 \) and \( C_{\mathfrak{B}}(J_1 \ast J_2) = \langle t \rangle \) and such that \( Z(C_{\mathfrak{B}}(v)) = \langle v \rangle \), \( C_{\mathfrak{B}}(v) \) is a proper quotient of \( \text{Spin}(16, q, 1) \), \( |C_{\mathfrak{B}}(v)/C_{\mathfrak{B}}'(v)| = 2 \) and \( C_{\mathfrak{B}}(C_{\mathfrak{B}}'(v)) = \langle v \rangle \);

(c) \( \{t, v\} \) is a set of representatives for the conjugacy classes of involutions of \( \mathfrak{B} \);

(d) if \( n \) is odd, then \( O^2(\mathfrak{B}) = \mathfrak{B} \) and

(e) if \( n \) is even, then the unique involution \( \tau \in A \) is such that \( C_{\mathfrak{B}}(\tau) \cong E_6(\sqrt{q}) \) and \( \mathfrak{B}(A - B) = \tau^\mathfrak{B} \).

Proof. Clearly (a), (d) and (e) follow from Lemma 4.2, [35, Theorem 12.4; 11, Theorem 12.5.1]. Also (b) and (c) follow from [30, §9 and Proposition 9(ii)] or the methods of this section.

The same references in the proof just above yield

Lemma 4.20. Let \( X = E_7(q) \), let \( \mathfrak{A} = \text{Aut}(X) \) and let \( \mathfrak{B} = \text{Inn}(X) \). Then the following five conditions hold.

(a) \( \mathfrak{A} = \mathfrak{B} A \) where \( A \cap \mathfrak{B} = 1, X \cong \mathfrak{B} = \mathfrak{A}' \) and \( A \) is the subgroup of \( \mathfrak{A} \) induced by \( \text{Aut}(k) \), so that \( A \cong \text{Aut}(k) \cong Z_n \);

(b) \( \mathfrak{B} \) contains involutions \( t \) and \( v \) such that \( C_{\mathfrak{B}}(t) \) possesses precisely two 2-components \( J_1 \) and \( J_2 \) and by appropriate indexing we may assume that \( Z(J_1) = Z(J_2) = \langle t \rangle \), \( J_1 = \text{SL}(2, q) \), \( J_2 = \text{Sp}(6, q) \), \( |C_{\mathfrak{B}}(t)/(J_1 \ast J_2)| = 2 \) and \( C_{\mathfrak{B}}(J_1 \ast J_2) = \langle t \rangle \);

(c) \( \{t, v\} \) is a set of representatives for the conjugacy classes of involutions of \( \mathfrak{B} \);

(d) if \( n \) is odd, then \( O^2(\mathfrak{B}) = \mathfrak{B} \) and

(e) if \( n \) is even, then the unique involution \( \tau \in A \) is such that \( C_{\mathfrak{B}}(\tau) \cong E_7(\sqrt{q}) \) and \( \mathfrak{B}(A - B) = \tau^\mathfrak{B} \).

Lemma 4.21. Let \( X = 3D_4(q) \), let \( \mathfrak{A} = \text{Aut}(X) \) and let \( \mathfrak{B} = \text{Inn}(X) \). Also let \( k_2 = C_{\mathfrak{B}}(\sigma^3) \), so that \( |k_2| = q^3 \). Then the following four conditions hold.

(a) \( \mathfrak{A} = \mathfrak{B} A \) where \( A \cap \mathfrak{B} = 1, X \cong \mathfrak{B} = \mathfrak{A}' \) and \( A \) is the subgroup of \( \mathfrak{A} \) induced by \( \text{Aut}(k_2) \), so that \( A \cong \text{Aut}(k_2) \cong Z_3 \);

(b) \( \mathfrak{B} \) has one conjugacy class of involutions and if \( t \in \mathfrak{B} \), then the structure of \( C_{\mathfrak{B}}(t) \) is as given in [14]; in particular, \( C_{\mathfrak{B}}(t) \) has exactly two 2-components \( J_1 \) and \( J_2 \).
which may be indexed so that $Z(J_1) = Z(J_2) = \langle t \rangle$, $J_1 \cong \text{SL}(2, q)$, $J_2 \cong \text{SL}(2, q^3)$, $| C_{\mathfrak{g}}(t)/(J_1 \ast J_2)| = 2$ and $C_{\mathfrak{g}}(J_1 \ast J_2) = \langle t \rangle$;

(c) if $n$ is odd, then $O^2(\mathfrak{H}) = \mathfrak{B}$; and

(d) if $n$ is even, then the unique involution $\tau \in A$ is such that $C_{\mathfrak{g}}(\tau) \cong D_4(\sqrt{q})$ and $\mathfrak{g}(\mathfrak{H} - \mathfrak{B}) = \tau^\mathfrak{B}$. 

**Proof.** Clearly $X \equiv \mathfrak{B}$ and (b) follows from the methods above or [14, Theorem and (2A)(iii)]. Also (a) follows from results of R. Steinberg, [34, Theorem 36]. Thus (c) holds. Suppose that $n = 2n_1$ for some integer $n_1$ and $\tau$ is the unique involution of $A$. Then $C_{\mathfrak{g}}(\tau) \cong D_4(\sqrt{q})$ and $\tau$ is induced from the field automorphism of $k_2$ of order 2. Let $\mathfrak{B} = \mathfrak{B}(\langle \tau \rangle)$, so that $\mathfrak{g}(\mathfrak{H} - \mathfrak{B}) = \mathfrak{g}(\mathfrak{H} - \mathfrak{B})$.

To conclude the proof, we shall apply Lemma 4.2 as follows. Let $\mathfrak{H} = D_4$, let $\pi$ denote the adjoint representation of $\mathfrak{H}$ and let $G$ denote the Chevalley group obtained from $(\mathfrak{H}, \pi, K)$. Let $q_0 = p^{n_1}$ and $\rho_0 = \lambda^{n_1} \in \text{Aut}(K)$ so that $\sigma_0(u) = u^{q_0}$ for any $u \in K$ and denote the $\sigma_0$-induced endomorphism of $G$ also by $\sigma_0$. Then $\rho_0^2 = \sigma$ and $C_K(\sigma_0) = k_0$ has order $q_0$. Also let $\rho$ denote the element of $\text{Aut}(G)$ induced by the graph automorphism of order 3 (cf. [35, §11; 11, Proposition 12.2.3]). Then $\rho^3 = 1$, $\rho_0^2 = \sigma_0\rho$ as endomorphisms of $G$ (cf. [11, p. 225]), $(\rho_0^2)^2 = \rho_0\rho$, $(\rho\sigma_0)^3 = \sigma^3$, $C_G(\rho_0) \cong C_G(\rho\sigma) < C_G(\rho^2) < C_G(\rho) < C_G(\sigma^3)$ and $(\sigma_0\sigma)^2 = \sigma^3$. Also $C_G(\rho_0) \cong D_4(q)$ by [34, §11, Theorem 35 and Corollary] and Lemma 4.2 now implies that $\mathfrak{g}(\mathfrak{H} - \mathfrak{B}) = \tau^\mathfrak{B}$. The proof of this lemma is now complete.

**Lemma 4.22.** Let $X = G_2(q)$, let $\mathfrak{H} = \text{Aut}(X)$ and let $\mathfrak{B} = \text{Inn}(X)$. Then the following four conditions hold.

(a) $X \equiv \mathfrak{B} = \mathfrak{A}'$ and $\mathfrak{A}/\mathfrak{B}$ is cyclic;

(b) $\mathfrak{B}$ has one conjugacy class of involutions and if $t \in \mathfrak{g}(\mathfrak{B})$, then $C_{\mathfrak{g}}(t)$ has precisely two 2-components $J_1$ and $J_2$ and by appropriate indexing we may assume that $Z(J_1) = Z(J_2) = \langle t \rangle$, $J_1 \cong J_2 \cong \text{SL}(2, q)$, $| C_{\mathfrak{g}}(t)/(J_1 \ast J_2)| = 2$ and $C_{\mathfrak{g}}(J_1 \ast J_2) = \langle t \rangle$;

(c) if $p \neq 3$, then $\mathfrak{H} = \mathfrak{B} A$ where $\mathfrak{B} \cap \mathfrak{H} = 1$ and $A$ is the subgroup of $\mathfrak{H}$ induced by $\text{Aut}(k)$, so that $A \equiv \text{Aut}(k) \equiv Z_n$, $O^2(\mathfrak{H}) = \mathfrak{B}$ when $n$ is odd and, when $n$ is even, the unique involution $\tau \in A$ is such that $C_{\mathfrak{g}}(\tau) \cong G_2(\sqrt{q})$ and $\mathfrak{g}(\mathfrak{A} - \mathfrak{B}) = \tau^\mathfrak{B}$; and

(d) if $p = 3$, then $\mathfrak{H} = \mathfrak{B} A$ where $\mathfrak{B} \cap \mathfrak{H} = 1$, $A \equiv Z_2n$ and the unique involution $\tau \in A$ is such that $\mathfrak{g}(\mathfrak{A} - \mathfrak{B}) = \tau^\mathfrak{B}$, $C_{\mathfrak{g}}(\tau) \cong G_2(\sqrt{q})$ if $n$ is even and $C_{\mathfrak{g}}(\tau) \cong G_2(q)$ if $n$ is odd where $G_2(q) \equiv \text{Aut}(\text{PSL}(2, q))$.

**Proof.** Clearly $X \equiv \mathfrak{B}$ and (b) follows from [30, §9 and Proposition 9(ii)] or [14, §2]. Suppose that $p \neq 3$. Then Lemma 4.2 and the proof of [11, Theorem 12.5.1] imply (c). Suppose that $p = 3$. Then [11, Proposition 12.4.1, Theorem 12.5.1 and p. 225] imply that $\mathfrak{H} = \mathfrak{B} A$ where $\mathfrak{B} \cap \mathfrak{H} = 1$ and $A \equiv \langle g \rangle$ where $g^2$ is the automorphism of $X$ induced by $\lambda \in \text{Aut}(K)$. Since $\text{Aut}(k) = \langle \lambda \rangle \cong Z_n$, we have (d) when $n$ is even. When $n$ is odd, then Lemma 4.2, [11, p. 225 and Lemma 14.1.1; 31, Theorem 7.8 and (8.4); 11, Proposition 12.4.1 and p. 268, Note] and the fact that a Sylow 3-subgroup of $G_2(3)$ is nonabelian by [31, (5.5)] yield (d). Clearly (a) holds and we are done.
Lemma 4.23. Suppose that \( q = 3^n \) where \( n = 2m + 1 \) for some integer \( m \geq 1 \). Let \( X = \mathbb{G}_2(q) \), let \( \mathbb{A} = \text{Aut}(X) \) and let \( \mathbb{B} = \text{Inn}(X) \). Then the following two conditions hold.

(a) \( \mathbb{A} = \mathbb{B} A \) where \( A \cap \mathbb{B} = 1 \), \( X \cong \mathbb{A} = \mathbb{A}' = O^2(\mathbb{A}) \) and \( A \) is the subgroup of \( \mathbb{A} \) induced by \( \text{Aut}(k) \), so that \( A \cong \text{Aut}(k) \cong Z_n \); and

(b) \( \mathbb{B} \) has one conjugacy class of involutions and if \( t \in \mathcal{Y}(\mathbb{B}) \), then \( C_{\mathbb{B}}(t) = \langle t \rangle \times J \) where \( J \cong \text{PSL}(2, q) \).

Proof. Clearly [31, Theorem 9.1] implies (a) and (b) is well known (cf. [16, §16.6] or [10, Appendix 1]).

Lemma 4.24. Let \( X = E_7(q) \), let \( \mathbb{A} = \text{Aut}(X) \) and let \( \mathbb{B} = \text{Inn}(X) \). Then the following four conditions hold.

(a) \( \mathbb{A} = \mathbb{B} A \) and there is a subgroup \( \mathcal{C} \) of \( \mathbb{A} \) such that \( \mathbb{B} \subset \mathcal{C} \), \( |\mathcal{C}/\mathbb{B}| = 2 \), \( \mathcal{C} = \langle \delta(\mathcal{C}) \rangle \) and \( \mathcal{A} = \mathcal{C} A \) where \( \mathcal{C} \cap A = 1 \) and \( A \) is the subgroup of \( \mathbb{A} \) induced by \( \text{Aut}(k) \), so that \( A \cong \text{Aut}(k) \cong Z_n \);

(b) if \( n \) is odd, then \( O^2(\mathbb{A}) = \mathcal{C} \);

(c) if \( n \) is even, then the unique involution \( \tau \in \mathbb{A} \) is such that \( C_{\mathbb{B}}(\tau) \cong E_{n/2}(\sqrt{q}) \) and \( \delta(\mathcal{A} - \mathcal{C}) = \tau^2 \); and

(d) \( \mathcal{C} \) contains five conjugacy classes of involutions which may be represented by \( \{t_i|1 \leq i \leq 5\} \) such that

1. \( t_1 \in \mathcal{B}, C_{\mathbb{B}}(t_1) \) contains precisely two 2-components \( J_1 \) and \( J_2 \) which may be indexed so that \( Z(J_1) = Z(J_2) = \langle t_1 \rangle \), \( J_1 \cong \text{SL}(2, q) \), \( J_2 \) is a proper quotient of \( \text{Spin}(12, q) \), \( | C_{\mathbb{B}}(t_1)/(J_1 \ast J_2) | = 2 \) and \( C_{\mathbb{B}}(J_1 \ast J_2) = \langle t_1 \rangle \);

2. \( t_2 \in \mathcal{B}, C_{\mathbb{B}}(t_2) \) contains exactly one 2-component \( J \) such that \( J \) is a quotient of \( \text{SL}(8, q) \) if \( q \equiv 1 \) (mod 4) and of \( \text{SU}(8, q) \) if \( q \equiv -1 \) (mod 4) and \( C_{\mathbb{B}}(t_2) \cap C_{\mathcal{C}}(J) \) is cyclic;

3. \( t_3 \in \mathcal{B}, C_{\mathbb{B}}(t_3) \) contains exactly one 2-component \( J \) such that \( J \) is a quotient of \( \text{Cov}(E_6(q)) \) if \( q \equiv 1 \) (mod 4) and of \( \text{Cov}(2E_6(q)) \) if \( q \equiv -1 \) (mod 4) and \( C_{\mathbb{B}}(t_3) \cap C_{\mathcal{C}}(J) \) is cyclic;

4. \( t_4 \in \mathcal{C} - \mathcal{B}, C_{\mathbb{B}}(t_4) \) contains exactly one 2-component \( J \) such that \( J \) is a quotient of \( \text{SU}(8, q) \) if \( q \equiv 1 \) (mod 4) and of \( \text{SL}(8, q) \) if \( q \equiv -1 \) (mod 4) and \( C_{\mathbb{B}}(t_4) \cap C_{\mathcal{C}}(J) \) is cyclic; and

5. \( t_5 \in \mathcal{C} - \mathcal{B}, C_{\mathbb{B}}(t_5) \) contains exactly one 2-component \( J \) such that \( J \) is a quotient of \( \text{Cov}(2E_6(q)) \) if \( q \equiv 1 \) (mod 4) and of \( \text{Cov}(E_6(q)) \) if \( q \equiv -1 \) (mod 4) and \( C_{\mathbb{B}}(t_5) \cap C_{\mathcal{C}}(J) \) is cyclic.

Proof. Let \( \mathcal{G} = E_7 \), let \( \pi \) denote the adjoint representation of \( \mathcal{G} \) and let \( \mathcal{G} \) denote the linear algebraic group obtained from the triple \( (\mathcal{G}, \pi, K) \). Note that \( G = O^0(\mathcal{G}_0) = X, \mathcal{G}_0 = G/H_0, \mathcal{G}_0/G \cong H_0/(G \cap H_0) \cong Z_2 \) by [35, Corollary 12.6(b)], \( H_0 \cong \text{Hom}(\Gamma_{ad}, k^*) \) and \( G \cap H_0 \) corresponds by [11, Theorem 7.1.1] to \( \text{Im}(\text{Res}) \) where \( \text{Res}: \text{Hom}(\Gamma_{ad}, k^*) \to \text{Hom}(\Gamma_{ad}, k^*) \) denotes restriction to \( \Gamma_{ad} \). Letting \( \lambda^* \) denote the restriction of \( \lambda \) to \( \mathcal{G}_0 \), it follows that \( \lambda^* \) induces an automorphism of \( G \) of order \( n \), \( C_{\mathcal{G}_0}(\lambda^*)(G) = 1 \) and \( \mathcal{A} = \text{Aut}(E_7(q)) = \mathcal{G}_0(\lambda^*) \) (cf. [11, §12.5]). Let \( B = \{\alpha_1, \ldots, \alpha_7\}, \{\bar{\omega}_1, \ldots, \bar{\omega}_7\}, \) etc. be as in [8, Planche VI]. Also let \( \bar{\omega} \in \bar{\mathcal{N}}_b \) be such that the \( \bar{\omega} \) induced automorphism \( \bar{w} \) of \( \Phi \) satisfies \( \bar{w}: \alpha_1 \leftrightarrow \alpha_6, \alpha_3 \leftrightarrow \alpha_5, \alpha_7 \leftrightarrow -\alpha_0 \) and
intrinsric 2-component of chevalley type

fixes $\alpha_2$ and $\alpha_4$; thus $w^2 \in \tilde{H}_\lambda$. Here $\Gamma_{ad} = \sum_{i=1}^7 Z\alpha_i$, $\Gamma_{ad}^\perp = \Gamma_{sc} = \sum_{i=1}^7 Z\omega_i$, $|\Gamma_{sc}/\Gamma_{\pi}| = 2$, $\epsilon_i = \omega_i$ for all $1 \leq i \leq 7$ and $\alpha_0 = 2\alpha_1 + 2\alpha_2 + 3\alpha_3 + 4\alpha_4 + 3\alpha_5 + 2\alpha_6 + \alpha_7$.

Also by [30, Proposition 3], $Z_2 = \Omega_\alpha = \langle T_{(q-1)e_i} \rangle$. Then it follows that $\tilde{G}$ has three conjugacy classes of involutions represented by $t_i = h(\chi_{Z_2})$ for $i = 1, 2, 3$ where

$$\lambda_1 = \frac{q-1}{2} \omega_1, \quad \lambda_2 = \frac{q-1}{2} \omega_2, \quad \lambda_3 = \frac{q-1}{2} \omega_3,$$  

$$t_1 = h_{\alpha_1}(-1)h_{\alpha_2}(-1)h_{\alpha_3}(-1)h_{\alpha_4}(-1),$$  

$$t_2 = h_{\alpha_2}(v^3)h_{\alpha_3}(v)h_{\alpha_4}(-1)h_{\alpha_5}(v^3),$$  

$$t_3 = h_{\alpha_1}(-1)h_{\alpha_2}(v^3)h_{\alpha_3}(-1)h_{\alpha_4}(v)h_{\alpha_5}(v^3)$$

for some element $v \in K^\times$ of order 4. Also $t_i \in \tilde{G}_\alpha = G$ for $i = 1, 2, 3$ and $C_G(t_i) = (\tilde{L}_i \ast \tilde{L}_2)H$ where $\tilde{L}_1 = \langle \tilde{x}_{\pm a_0} \rangle \cong \text{SL}(2, K)$, $\tilde{L}_2 = \langle \tilde{x}_{\pm a_i} | 2 \leq i \leq 7 \rangle$ is a proper quotient of Spin(12, K) and $Z(\tilde{L}_1) = Z(\tilde{L}_2) = \langle \tilde{t}_i \rangle$, $C_G(t_2) = (\tilde{L}_3 \tilde{H}) \langle w \rangle$ where $\tilde{L} = \langle \tilde{x}_{\pm a_i} | i \in \{0, 1, 3, 4, 5, 6, 7\} \rangle$ is a quotient of SL(8, K) and $C_G(t_3) = (\tilde{L}_4 \tilde{H}) \langle w \rangle$ where $\tilde{L}_4 = \langle \tilde{x}_{\pm a_i} | 1 \leq i \leq 6 \rangle$ is a quotient of Cov(Spin(12, K)).

Next we apply Lemma 4.2. Let $g \in \tilde{G}$ be such that $g\sigma(g)^{-1} = w$. Then $G \cong \tilde{G}_\alpha$ has five conjugacy classes of involutions represented by $\{t_1, t_2, t_3, t_4, t_5\}$. Also if $\beta$ denotes the inner automorphism of $\tilde{G}$ induced by $w^{-1}$, then $C_G(t_i \beta) = (C_G(t_i)_{\beta})^\sigma$ for $i = 2, 3$. Now Lemmas 4.2 and 4.9 yield (a)–(c).

As in [30, §8], we have $C_G(t_1) = (J_1 \ast J_2)H_\alpha$ where $J_1 = \langle \tilde{x}_{\pm a_0} \rangle \cong \text{SL}(2q)$, $J_2 = \langle \tilde{x}_{\pm a_i} | 2 \leq i \leq 7 \rangle$ is a proper quotient of Spin(12, q, 1) and $Z(J_1) = Z(J_2) = \langle \tilde{t}_i \rangle$. Clearly $|C_G(t_1)/(J_1 \ast J_2)| = 2$ and

$$C_G(J_1 \ast J_2) = C_G(t_1) \cap C_G(J_1 \ast J_2) = C_{\tilde{H}}(J_1 \ast J_2) \leq C_H(\langle \tilde{x}_{\pm a_0} \rangle \ast \langle \tilde{x}_{\pm a_i} | 2 \leq i \leq 7 \rangle) = \langle t_1 \rangle;$$

thus part (1) of (d) holds.

Similarly $C_G(t_2) = (J_3 \tilde{H}_\alpha)\langle w \rangle$ where $J_3 = \langle \tilde{x}_{\pm a_i} | i \in \{0, 1, 3, 4, 5, 6, 7\} \rangle$ is a quotient of $\text{SL}(8, q)$. Also, it is clear that $C_G(t_2) \cap C_G(J_3) = C_{\tilde{H}}(J_3)$. Since $\tilde{H}, J_3 = \tilde{L}_3 \tilde{H}$, we have $\langle t_2 \rangle \leq C_{\tilde{H}}(J_3) \leq C_{\tilde{H}}(\tilde{L}_3) = \langle t_2 \rangle$. Thus $C_G(t_2) \cap C_G(J_3) = \langle t_2 \rangle$.

Note that $C_G(t_3 \beta) = C_G(t_2 \beta) = (J_3 \tilde{H}_{\beta})\langle w \rangle$ where $J_3^0 = O^\sigma((\tilde{L}_3)_{\beta})$ is a quotient of $\text{SU}(8, q)$ by [35, §11.6]. Also, it is easy to see that $\langle \tilde{H}, J_3^0 \rangle = \tilde{L}_3 \tilde{H}$. Since $C_G(t_2 \beta) \cap C_G(J_3^0) = \tilde{H}_{\beta} \cap \tilde{H}$ and $C_{\tilde{H}}(\tilde{L}_3) = \langle t_3 \rangle$, we conclude from Lemma 4.9 that (2) and (4) of (d) hold.

Also, as above, $C_G(t_3) = (J_4 \tilde{H}_\alpha)\langle w \rangle$ where $J_4 = \langle \tilde{x}_{\pm a_i} | 1 \leq i \leq 6 \rangle$ is a quotient of Cov(E_6(q)) and $C_G(t_3) \cap C_G(J_4) = C_{\tilde{H}}(J_4)$. Here $\langle \tilde{H}, J_4 \rangle = \tilde{L}_4 \tilde{H}$ and

$$C_{\tilde{H}}(\tilde{L}_4) = \{ \chi \in \text{Hom}(\Gamma_{\pi}, K^\times) | \chi(\alpha_i) = 1 \text{ for all } 1 \leq i \leq 6 \} \cong K^\times,$$

so that $C_G(t_3) \cap C_G(J_4)$ is cyclic.

Finally, as above, $C_G(t_4 \beta) = C_G(t_3 \beta) = (J_3^0(\tilde{H}_{\beta}))\langle w \rangle$ where $J_3^0 = O^\sigma((\tilde{L}_3)_{\beta})$ is a quotient of Cov^2(E_6(q)) and $\langle \tilde{H}, J_3^0 \rangle = \tilde{L}_4 \tilde{H}$. Since $C_G(t_3 \beta) \cap C_G(J_3^0) = \tilde{H}_{\beta}$, we conclude that (3) and (5) of (d) hold and we are done.
Lemma 4.25. Let \( X = E_6(q) \), let \( \mathfrak{A} = \text{Aut}(X) \) and let \( \mathfrak{B} = \text{Inn}(X) \). Then the following five conditions hold.

(a) \( \mathfrak{A} = \mathfrak{A}'(A \times \langle \tau^* \rangle) \) where \( \mathfrak{A}' \cap (A \times \langle \tau^* \rangle) = 1 \), \( A \) is the subgroup of \( \mathfrak{A} \) induced by \( \text{Aut}(k) \), so that \( A \cong \text{Aut}(k) \cong \mathbb{Z}_n \), and where \( \tau^* \) is the automorphism of \( X \) of order 2 induced by the graph automorphism of order 2 of the root system of type \( E_6 \), \( \mathfrak{B} = O^2(\mathfrak{A}') \), \( |\mathfrak{A}' / \mathfrak{B}| = (3, q - 1) \), \( \tau^* \) inverts \( \mathfrak{A}' \) and \( A \times \langle \tau^* \rangle \cong \mathbb{Z}_n \times \mathbb{Z}_2 \);

(b) \( \mathfrak{A}' \) and \( \mathfrak{B} \) have precisely two conjugacy classes of involutions which may be represented by involutions \( t \) and \( v \) such that \( t \in \mathfrak{C}_q(t') \cong \text{Spin}(10, q, 1) \) and \( \mathfrak{C}_q(\mathfrak{C}_q(t')) \) is cyclic and such that \( \mathfrak{C}_q(v) \) possesses precisely two 2-components \( J_1 \) and \( J_2 \) which, by appropriate indexing may be assumed to satisfy: \( J_1 = \text{SL}(2, q) \), \( J_2 \) is a quotient of \( \text{SL}(6, q) \), \( Z(J_1) = Z(J_2) = \langle v \rangle \) and \( \mathfrak{C}_q(J_1 * J_2) = \langle v \rangle \);

(c) \( \mathfrak{A}' \langle \tau^* \rangle \) is \( \mathfrak{A} \)-invariant and \( \mathfrak{C}_q(\langle \tau^* \rangle) \) decomposes into two \( \mathfrak{A} \)-orbits (under conjugacy by elements of \( \mathfrak{A} \)), these two \( \mathfrak{A} \)-orbits may be represented by \( \tau^* \) and \( h \tau^* \) for some involution \( h \in \mathfrak{C}_q(\langle \tau^* \rangle \times A) \) where \( \mathfrak{C}_q(\tau^*) \cong F_4(q) \) and \( \mathfrak{C}_q(h \tau^*) \) is a quotient of \( \text{Sp}(8, q) \);

(d) if \( n \) is odd, then \( O^2(\mathfrak{A}) = \mathfrak{A}' \langle \tau^* \rangle \); and

(e) if \( n \) is even and \( \varphi \) denotes the unique involution of \( A \), then \( \mathfrak{C}_q(\langle \tau^* \rangle) = \varphi \mathfrak{C}_q(\mathfrak{A}' \langle \tau^* \rangle) \).

Proof. Let \( \mathfrak{B} = E_6 \), let \( \pi \) denote the adjoint representation of \( \mathfrak{B} \) and let \( \widetilde{G} \) denote the linear algebraic group obtained from the triple \((\mathfrak{B}, \pi, K)\). Let \( \tau \) denote the automorphism of \( \widetilde{G} \) induced by the graph automorphism \( \tilde{\tau} \) of \( \Phi \) (of order 2) such that \( \tau(x_{\alpha}(u)) = x_{\pi(\alpha)}(u) \) for all \( u \in K \) and all \( \alpha \in \Phi \). Clearly \( \lambda \tau = \lambda \tau \) as endomorphisms of \( \widetilde{G} \), both \( \tau \) and \( \lambda \) leave invariant \( \mathfrak{g}_\alpha \), \( G = O^2(\mathfrak{g}_\alpha) \cong X \), \( \mathfrak{g}_\alpha = \mathfrak{g}/(G \cap \mathfrak{h}) \) and \( G = (\mathfrak{g}_\alpha) \).

Letting \( \lambda^* \) and \( \tau^* \) denote the restrictions of \( \lambda \) and \( \tau \) to \( \mathfrak{g}_\alpha \), respectively, it follows that \( \lambda^* \) and \( \tau^* \) induce commuting automorphisms of \( G \) of orders \( n \) and \( 2 \), respectively; \( C_{\mathfrak{G}_\alpha(\langle \lambda^* \times \langle \tau^* \rangle \rangle)}(G) = 1 \) and \( \mathfrak{A} = \text{Aut}(E_6(q)) \equiv \mathfrak{G}_\alpha(\langle \lambda^* \rangle \times \langle \tau^* \rangle \rangle) \) (cf. [11, §12.5]). Let \( B = \{ \alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5, \alpha_6 \} \), \( \{ \omega_1, \omega_2, \omega_3, \omega_4, \omega_5, \omega_6 \} \), etc., be as in [8, Planche V]. Then \( \Gamma_\text{ad} = \sum_{i=1}^6 Z \alpha_i \), \( \Gamma_{\text{ad}} = \Gamma_{\text{sc}} = \sum_{i=1}^3 Z \omega_i \), \( \{ \Gamma_\text{ad} / \Gamma_{\text{ad}} \} = 3 \), \( e_i = \omega_i \) for all \( 1 \leq i \leq 6 \), \( \alpha_0 = \alpha_1 + 2 \alpha_2 + 2 \alpha_3 + 3 \alpha_4 + 2 \alpha_5 + \alpha_6 \) and it follows that \( \widetilde{G} \) has two conjugacy classes of involutions represented by \( t_i = h(\chi_{\alpha_i}) \) for \( i = 1, 2 \) where \( \lambda_1 = \frac{q-1}{2} (\omega_1 + \omega_5) \), \( t_1 = h(\alpha_1(-1)h(\alpha_5(-1)) \), \( \lambda_2 = \frac{-q-1}{2} \omega_2 \) and \( t_2 = h(\alpha_4(-1)h(\alpha_4(-1)) = h(\alpha_5(-1)) \). Also \( t_i \in \mathfrak{g}_\text{ad} \) for \( i = 1, 2 \), \( C_G(t_1) = \tilde{L}_1 \tilde{H} \) where \( \tilde{L}_1 = \langle \tilde{\mathfrak{g}}_{\alpha_i} \mid i \in \{0, 2, 3, 4, 5, 6\} \rangle \), \( \tilde{t}_1 \in \tilde{L}_1 \), \( \tilde{L}_1 \cong \text{Spin}(10, K) \) and \( C_{\tilde{G}}(t_2) = \langle \tilde{L}_2 \rangle \tilde{H} \) where \( \tilde{L}_2 = \langle \tilde{\mathfrak{g}}_{\omega_i} \rangle \cong \text{SL}(2, K) \), \( \tilde{t}_2 = \langle \tilde{\mathfrak{g}}_{\omega_i} \mid i \in \{1, 3, 4, 5, 6\} \rangle \), is a quotient of \( \text{SL}(6, K) \) and \( \mathfrak{Z}(\tilde{L}_2) = \langle \tilde{t}_2 \rangle = Z(\tilde{L}_2) \).

As in [30, §8], we have \( C_{\tilde{G}}(t_1) = J_1(\mathfrak{h}_\text{ad}) \) where \( t_1 \in J_1 = \langle \tilde{\mathfrak{g}}_{\alpha_i} \mid i \in \{0, 2, 3, 4, 5\} \rangle = (\tilde{L}_1)_\alpha \cong \text{Spin}(10, q, 1) \) by [35, Theorem 12.4]. Clearly \( C_{\mathfrak{G}_\alpha}(J_1) = C_{\mathfrak{H}_\text{ad}}(J_1) \) and \( \langle \tilde{H}, J_1 \rangle = \tilde{L}_1 \tilde{H} = C_{\tilde{G}}(t_1) \).

Since \( C_{\tilde{G}}(\tilde{L}_1) \cong \{ \chi \in \text{Hom}(\Gamma_\text{ad}, \mathfrak{K}) \mid \chi(\alpha_i) = 1 \text{ for all } i \in \{0, 2, 3, 4, 5\} \} \)

\( \cong \{ \chi \in \text{Hom}(\Gamma_\text{ad}, \mathfrak{K}) \mid \chi(\alpha_i) = 1 \text{ for all } 2 \leq i \leq 5 \text{ and } \chi(\alpha_i) = \chi(\alpha_i)^{-1} \} \)

\( \cong \mathfrak{K} \),

it follows that \( C_{\mathfrak{G}_\alpha}(J_1) \) is cyclic.
Similarly, we have \( C_G(t_2) = (J_2 \ast J_3)(\overline{H}_\alpha) \) where \( J_2 = \langle \xi \pm a_i | i \in \{1,3,4,5,6\} \rangle \) is a quotient of \( SL(6, q) \) and \( Z(J_2) = \langle t_2 \rangle \).

Clearly \( C_G(J_2 \ast J_3) = C_H(t_2 \ast J_3) \) and \( \langle \overline{H}, J_2, J_3 \rangle = (L_2 \ast L_3)\overline{H} = C_G(t_2) \). As above, it follows that \( C_H(L_2 \ast L_3) = \langle t_2 \rangle = C_G(J_2 \ast J_3) \).

Let \( \pi^* \) denote the simply connected representation of \( \mathfrak{g} \) and let \( G^* \) denote the simply connected linear algebraic group obtained from the triple \( (\mathfrak{g}, \pi^*, K) \). Also let \( \Delta: G^* \rightarrow \overline{G} \) be the universal covering of \( \overline{G} \) and extend \( \lambda, \tau \) and \( \sigma = \lambda^\sigma \) to endomorphisms of \( G^* \) in the obvious way so that \( \lambda, \tau \) and \( \sigma \) are compatible with \( \Delta \).

Clearly \( (4.1) \) and \( (4.2) \) imply that \( Ker(\Delta) \cong \text{Hom}(\Gamma_{sc}/\Gamma_e, K^\times) \) where \( |\Gamma_{sc}/\Gamma_e| = 3 \).

Thus, if \( p = 3 \), then \( Ker(\Delta) = 1 \) and if \( p \neq 3 \) and \( v \) is an element of order 3 in \( K^\times \), then \( Ker(\Delta) = \langle f \rangle \cong Z_3 \) where \( f = h_{a_1}(v)h_{a_2}(v^{-1})h_{a_3}(v)h_{a_4}(v^{-1}) \). Note that \( \tau \) inverts \( Ker(\Delta) \) and \( Ker(\Delta) \leq (G^*)_e \) if and only if \( 3 \mid (q - 1) \).

Now the proof of [35, Corollary 12.6(b)] implies that \( G_\sigma/G \cong Z_3(q-1) \) and \( \tau \) inverts \( G_\sigma/G \). Thus \( (G_\sigma(\langle \lambda^* \rangle \times \langle \tau^* \rangle))^e = G_\sigma \) and both (a) and (b) hold.

For (c), observe that \( \overline{G}(\tau) \) is a linear algebraic group and that \( \overline{G} \) is a normal closed subgroup of \( G(\tau) \) by [6, Chapter I, 1.11]. Since \( \overline{G} \) is a simple group (cf. [7, §3.2(3)]), it follows that \( (\overline{G}(\tau))^0 = \overline{G} \) by [6, Chapter I, (1.2), Proposition]. Also \( \sigma \) induces an endomorphism of \( \overline{G}(\tau) \) with \( (\overline{G}(\tau))^o = \overline{G}(\tau) \). On the other hand, every involution of \( \overline{G}(\tau) \) is conjugate via \( \overline{G} \) to an element of \( N_{\overline{G}(\tau)}(\overline{B}) \cap N_{\overline{G}(\tau)}(\overline{H}) = \overline{H}(\tau) \) by [35, Theorem 7.5; 36, §2.12, Corollary 2 and §2.8, Theorem 2(c)]. Note that \( \tau: \alpha_1 \leftrightarrow \alpha_6, \alpha_3 \leftrightarrow \alpha_5 \) and fixes \( \alpha_2 \) and \( \alpha_4 \).

For each \( 1 \leq i \leq 6, \) let \( \tilde{H}_i = \{ h(\chi) | \chi(\alpha_i) = 1 \} \) for all \( j \neq i \) with \( 1 \leq j \leq 6 \), so that \( \tilde{H}_i \) is a subgroup of \( \tilde{H} \). Then \( \tilde{H} = \bigoplus_{i=1}^6 \tilde{H}_i, \) \( \tilde{H}_1 = \tilde{H}_6, \tilde{H}_2 = \tilde{H}_5, \) and \( \tau(\tilde{H} \times \tilde{H}) = 1 \). For \( j \in \{2,4\} \), let \( h_j = h(\chi) \in \tilde{H}_j \) be such that \( \chi(\alpha_j) = -1 \), so that \( h_j \) is the unique involution of \( \tilde{H}_j \). Also \( h_2 = h_{a_1}(-1)h_{a_2}(-1)h_{a_3}(-1) \) and \( h_4 = h_{a_4}(-1) \). Then Lemma 2.5 implies that every involution of \( \overline{H} \) is conjugate via \( \overline{H} \) to an involution in \( \langle h_2, h_4 \rangle \tau \).

Clearly \( \langle h_2, h_4, \xi \pm a_2, \xi \pm a_4 \rangle \leq C_G(\tau) \) and \( \langle h_2, h_4 \rangle \leq \overline{H} \). For \( j \in \{2,4\} \), let \( \omega_j = a \) be as defined in [34, p. 30, (R5)]. Then

\[ \langle \omega_2, \omega_4 \rangle \leq C_G(\tau) \cap \tilde{N}_\lambda \leq C_G(\tau) \cap \tilde{N}_\sigma \text{ and } (h_2 \tau)^{\omega_2} = h_2 h_4 \tau = (h_4 \tau)^{\omega_2} h_{a_6}(-1) \].

Consequently every involution of \( \overline{G}(\tau) \) is conjugate via \( \overline{G} \) to an element of \( \{ \tau, h_2 \tau \} \leq (\overline{G}(\tau))^0 = \overline{G}(\tau) \). Also, [35, (9.4) and (9.8)] imply that \( C_G(\tau) \) and \( C_G(h_2 \tau) \) are connected and reductive linear algebraic groups. Hence Lemma 4.32 implies that \( \gamma(\overline{G}(\tau)) = (\tau^* \overline{G}) \cup (h_2 \tau^* \overline{G}) \).

The methods of [11, Chapter 13] can be used to determine the structure of \( C_G(\tau) \) and \( C_G(h_2 \tau) \). For this process, let \( S \) denote the set of orbits of \( \tau \) on \( \Phi \) and for each orbit \( \Theta \in S \), let \( a_\Theta = (\sum_{a \in \Theta} a)/|\Theta| \) denote the average of the vectors in \( \Theta \).

Then \( \{ a_\Theta | \Theta \in S \} \) is the corresponding root system for \( C_G(\tau) \) and \( \{ \alpha_2, \alpha_4, (\alpha_1 + \alpha_6)/2, (\alpha_3 + \alpha_5)/2 \} \) is a base for this root system. Since each element of \( (\tilde{N}/\tilde{H}) \) can be represented by an element of \( \tilde{N} \), as follows from [35, §8.2(5)], we conclude that \( C_G(\tau) = \langle \langle \tilde{x} | \alpha \in \Phi \text{ and } \tilde{\tau}(\alpha) = \alpha \rangle, \langle x(a) x_\tau(a)(u) | u \in K \rangle \rangle \cong F_4(K) \) and \( (C_G(\tau))^o = C_G(\tau)^{\pi^*} \cong F_4(k) \).
Note that $h_2 = h(\chi)$ for the element $\chi \in \text{Hom}(\Gamma_{ad}, K^\times)$ such that $\chi(\alpha_i) = 1$ for all $1 \leq i \leq 6$ with $i \neq 2$ and $\chi(\alpha_2) = -1$. Let $S_1 = \{0 \in S \mid |0| = 1$ and $\chi(\alpha) = 1$ for $\alpha \in \mathcal{E}\}$, let $S_2 = \{0 \in S \mid |0| = 2$ and $\chi(\alpha) = 1$ for $\alpha \in \mathcal{E}\}$ and let $S_3 = \{0 \in S \mid |0| = 2$ and $\chi(\alpha) = -1$ for $\alpha \in \mathcal{E}\}$. Then $\{0 \mid 0 \in S_1 \cup S_2 \cup S_3\}$ is the corresponding root system for $C_\mathbb{Q}(h_2 \tau)$, is of type $C_4$ and has base

$$
\left\{ \alpha_4, \frac{\alpha_1 + \alpha_6}{2}, \frac{\alpha_3 + \alpha_5}{2}, \frac{2\alpha_2 + \alpha_3 + 2\alpha_4 + \alpha_5}{2} \right\}.
$$

Then [35, (9.2), (9.3), (9.8) and the proof of (8.2)] imply that $C_\mathbb{Q}(h_2 \tau) = \langle \widetilde{H}_{h_2 \tau}, L \rangle$ where $L = \langle \langle \widetilde{x}_v \mid \{v\} \in S_1 \rangle, \langle x_v(\alpha) \rangle \mid u \in K \rangle \in S_2 \rangle, \langle x_v(\alpha) \rangle \mid u \in K \rangle \in S_2 \rangle \rangle \rangle$. Hence $((C_\mathbb{Q}(h_2 \tau)_u) = C_{\mathbb{Q}}(h_2 \tau)$ and $C_{\mathbb{Q}}(h_2 \tau)$ is a quotient of $\text{Sp}(4, k)$. This completes the proof of (c), and (d) is immediate. Finally, suppose that $n$ is even and let $\varphi$ be as in (e). Then $\varphi$ corresponds to $(\lambda^*)^{n/2} = (\lambda^{n/2})^\mathbb{Q}$ since $(\lambda^{n/2})^2 = \sigma$ and $(\lambda^{n/2})^2 = \sigma$. Lemma 4.2 implies that $\varphi = C_{\mathbb{Q}}(\lambda^{n/2})^\mathbb{Q}$ and $\varphi = C_{\mathbb{Q}}(\lambda^{n/2})^\mathbb{Q}$ clearly $C_{\mathbb{Q}}((\lambda^{n/2})^\mathbb{Q}) = C_{\mathbb{Q}}((\lambda^{n/2})^\mathbb{Q})$ and $C_{\mathbb{Q}}((\lambda^{n/2})^\mathbb{Q}) = C_{\mathbb{Q}}((\lambda^{n/2})^\mathbb{Q})$. Thus (e) holds and we are done.

**Lemma 4.26.** Let $X = 2E_6(q)$, let $\mathbb{L} = \text{Aut}(X)$ and let $\mathbb{B} = \text{Inn}(X)$. Then the following three conditions hold.

(a) $\mathbb{L} = \mathbb{L}' \mathbb{A}$ where $\mathbb{L}' \cap \mathbb{A} = 1$ and $\mathbb{A}$ is the subgroup of $\mathbb{L}$ induced by $\text{Out}(k_1)$, so that $\mathbb{A} = \text{Out}(k_1) \cong Z_{2n}$, $\mathbb{B} \leq \mathbb{L}'$ and $|\mathbb{L}'/\mathbb{B}| = (3, q + 1)$;

(b) $\mathbb{L}'$ and $\mathbb{B}$ have precisely two conjugacy classes of involutions which may be represented by involutions $t$ and $v$ such that $t \in C_{\mathbb{L}'}(v)^\mathbb{Q} \cong \text{Spin}(10, q, -1)$ and $C_{\mathbb{L}'}(C_{\mathbb{B}}(v))^\mathbb{Q}$ is cyclic and such that $C_{\mathbb{L}'}(v)$ possesses precisely two 2-components $J_1$ and $J_2$ which by appropriate indexing may be assumed to satisfy: $J_1 = \text{SL}(2, q)$, $J_2$ is a quotient of $\text{SU}(6, q)$, $Z(J_1) = Z(J_2) = \langle v \rangle$ and $C_{\mathbb{L}'}(J_1 \cdot J_2) = \langle v \rangle$; and

(c) if $\varphi$ denotes the unique involution of $A$, then $\mathbb{L}' = \langle \varphi \rangle = \langle \varphi(\mathbb{L}') \rangle$ and $\varphi(\mathbb{L}')$ decomposes into two $\mathbb{L}'$-orbits (under conjugacy by elements of $\mathbb{L}'$), these two $\mathbb{L}'$-orbits may be represented by $\varphi$ and $\varphi h$ for some involution $h \in \mathbb{L}'(A)$ where $\mathbb{L}'(\varphi) = F_6(q)$ and $\mathbb{L}'(\varphi h)$ is a quotient of $\text{Sp}(8, q)$.

**Proof.** We use the notation of the previous lemma except that we consider $\widetilde{G}_{\sigma\tau}$ and set $G = O^+(\widetilde{G}_{\sigma\tau})$. Then $(\widetilde{G}_{\sigma\tau})' = G \cong X, \lambda$ and $\tau$ leave $\widetilde{G}_{\sigma\tau}$ invariant, $\widetilde{G}_{\sigma\tau} = GH_{\sigma\tau} \leq \widetilde{G}_{\sigma\tau}$ and $\widetilde{G}_{\sigma\tau}/G \cong \widetilde{H}_{\sigma\tau}/(G \cap \widetilde{H}_{\sigma\tau})$. Letting $\lambda^* \tau^*$ denote the restrictions of $\lambda$ and $\tau$ to $\widetilde{G}_{\sigma\tau}$, we have $\langle \lambda^* \rangle = \tau^* = \sigma |_{\widetilde{G}_{\sigma\tau}}, |\lambda^*| = 2n$, $C_{\widetilde{G}_{\sigma\tau}}(\lambda^*) = 1$ and $\mathbb{L} = \text{Out}(2E_6(q)) = \widetilde{G}_{\sigma\tau}(\lambda^*)$ (cf. [34, Theorem 36]). Note that [35, Corollary 12.6(b)] and the proof of Lemma 4.25 readily imply that $|\widetilde{G}_{\sigma\tau}/G| = (3, q + 1)$ and that $\tau$ inverts $\widetilde{G}_{\sigma\tau}/G$. Clearly $\langle t_1, t_2 \rangle \leq G$. Then Lemma 4.4 implies that $\widetilde{G}_{\sigma\tau}$ has two conjugacy classes of involutions represented by $t_1$ and $t_2$. Also, as above, $C_{\widetilde{G}_{\sigma\tau}}(t_1) = \langle L_{t_1}, J_1 \rangle$ where $t_1 = J_1 = \langle \langle x_\alpha(u) \mid u \in k, \alpha \in \{±\alpha_2, ±\alpha_0, ±\alpha_4\}, \langle x_\alpha(u) x_\alpha(\sigma(u)) \rangle \mid u \in k_1 \rangle \rangle \rangle$. Clearly $C_{\widetilde{H}_{\sigma\tau}}(J_1) = C_{\widetilde{H}_{\sigma\tau}}(J_1)$ and $\widetilde{H}_{\sigma\tau} = L_{t_1} H = C_{\widetilde{G}_{\sigma\tau}}(t_1)$, so that $C_{\widetilde{G}_{\sigma\tau}}(J_1)$ is cyclic. Similarly, we have $C_{\widetilde{G}_{\sigma\tau}}(t_2) = \langle J_2 \rangle$ where $J_2 = \langle \langle x_{±\alpha_4} \rangle \rangle \rangle \rangle$ and $Z(J_2) = \langle t_2 \rangle$, $J_3 = \langle \langle x_{±\alpha_4} \rangle \rangle$ is a quotient of $\text{SU}(6, q)$ and $Z(J_3) = \langle t_2 \rangle$. Since $\langle H, J_2, J_3 \rangle = (L_2 \ast L_3) H$, we conclude, as above, that $C_{\widetilde{G}_{\sigma\tau}}(J_2 \ast J_3) = \langle t_2 \rangle$. Thus both (a) and (b) hold.
For (c), as in the preceding lemma, we have \( \langle G, \tau \rangle = (\tau) G \cup (h_2 \tau) G \), \( C_G(\tau) = C_G(h_2 \tau) = F(h) \) and \( C_G(h_2 \tau) = C_G(h_2 \tau) G \). However \( h_2 \in C_G(h_2 \tau) G \) and \( C_G(h_2 \tau) G \) is connected. Thus \( C_G(h_2 \tau) G = C_G(h_2 \tau) G = C_G(h_2 \tau) G \) where \( \beta \) denotes the inner automorphism of \( C_G(h_2 \tau) G \) induced by conjugation by \( h_2 \). Now (c) follows from Lemma 4.25 and our proof is complete.

The information about Aut(PSL(2, q)) that we require appears in [14, §1]. For the remaining cases we present

**Lemma 4.27.** Let \( X = PSL(m, q) \) for some integer \( m \geq 3 \), let \( \mathfrak{A} = Aut(X) \) and \( \mathfrak{B} = \text{Inn}(X) \). Then the following four conditions hold.

(a) \( \mathfrak{A} = Aut(A \times (\tau^*)) \) where \( \mathfrak{A} \cap (A \times (\tau^*)) = 1, \) \( A \) is the subgroup of \( \mathfrak{A} \) induced by \( Aut(k) \), so that \( A \geq Aut(k) \) and \( \tau^* \) is the graph automorphism of order 2 induced by the graph automorphism of order 2 of the root system of type \( A_{m-1} \), \( \mathfrak{B} = \mathfrak{B} \)'s PGL(m, q) ⊆ \( \mathfrak{A} \) and \( \tau^* \) inverts \( \mathfrak{B} \) ≅ Z(m, q-1);

(b) if \( m \) is odd then \( Aut(PSL(m, q)) = (\tau^*)^6 \) and if \( m \) is even, then \( Aut(PSL(m, q)) \) decomposes into three orbits under conjugation by \( \mathfrak{B} \);

(c) if \( n \) is odd, then \( O^2(\mathfrak{A}) = \mathfrak{A} (\tau^*) \); and

(d) if \( n \) is even and \( \varphi \) denotes the unique involution of \( A \), then \( Aut(PSL(m, q)) = (\tau^*)^6 \) and \( \mathfrak{A} \) ≅ PGL(m, \sqrt{q}) and \( \mathfrak{A} (\tau^* \varphi) = PU(m, \sqrt{q}) \).

**Proof.** Let \( \mathfrak{B} = A_{m-1} \), let \( \pi \) denote the adjoint representation of \( \mathfrak{B} \) and let \( G \) denote the linear algebraic group obtained from the triple \((\mathfrak{B}, \pi, K)\). Let \( \tau \) denote the automorphism of \( \bar{G} \) induced by the graph automorphism \( \bar{\tau} \) of \( \Phi \) or order 2 such that \( \tau(k(u)) = k(\bar{w}(u)) \) for all \( u \in K \) and all \( k \in \Phi \). Clearly \( \tau \lambda = \lambda \tau \) as endomorphisms of \( \bar{G} \), both \( \tau \) and \( \lambda \) leave invariant \( \bar{G} \) ≅ PGL(m, q), \( \bar{G} \) = PSL(m, q) and \( \bar{G} = Z(m, q-1) \). Letting \( \lambda^* \) and \( \tau^* \) denote the restrictions of \( \lambda \) and \( \tau \) to \( \bar{G} \), respectively, it follows that \( \lambda^* \) and \( \tau^* \) induce commuting automorphisms of \( \bar{G} \) of orders \( n \) and 2, respectively,

\[
C_{\bar{G}_d}(\lambda^* \times (\tau^*)) \cap (G) = 1 = \bar{G}_d \cap \langle \lambda^* \rangle \times \langle \tau^* \rangle
\]

and

\[
\mathfrak{A} = \text{Aut}(PSL(m, q)) = \bar{G}_d \langle \lambda^* \rangle \times \langle \tau^* \rangle
\]

(cf. [11, §12.5]). Let \( B = \{a_1, \ldots, a_{m-1}\}, \{w_1, \ldots, w_{m-1}\}, \ldots \), etc., be as in [8, Planche I]. Thus, we may assume that \( \bar{\tau} \equiv \alpha_{m-1} \) for all \( 1 \leq \alpha \leq (m-1)/2 \) and \( \bar{\tau} \) fixes \( \alpha_{m/2} \) if \( m-1 \) is odd. Then, from [8, Planche I], we conclude that \( \bar{\tau} \) inverts \( \Gamma_{sc} \Gamma_{ad} \). Note that \( \bar{G}_d = G(\bar{H}_d), \bar{G}_d = \bar{H}_d \langle G \cap \bar{H}_d \rangle \approx Z(m, q-1), \Gamma_{sc} = Z \bar{w}_1 + \Gamma_{ad} \) and \( \bar{\tau}(\bar{w}_1) = -\bar{w}_1 + r \) for some \( r \in \Gamma_{ad} \). As in Lemma 4.25, it is easy to see that \( \tau^* \) inverts \( \bar{G}_d \). This may also be demonstrated as follows. If \( \chi \in \text{Hom}(\Gamma_{sc}, k^\times) \), then \( \chi \chi^\tau \) extends to an element of \( \text{Hom}(\Gamma_{sc}, k^\times) \) by defining

\[
(\chi \chi^\tau)(zw + s) = \chi(r) \chi(s) \chi^\tau(s) \quad \text{for all } z \in Z \text{ and } s \in \Gamma_{ad}.
\]

Now [11, Theorem 7.1.1] implies that \( \tau^* \) inverts \( \bar{H}_d \cap \bar{H}_d \) and \( \bar{G}_d \). Thus (a) and (c) hold. Also (d) follows from Lemma 4.2 and [35, §11.6]. For any \( 1 \leq i \leq m-1 \), let \( \bar{H}_i = \{h(\chi) | \chi(a_j) = 1 \} \) for all \( j \neq i \) with \( 1 \leq j \leq m-1 \), so that \( \bar{H}_i \) is a
subgroup of $\bar{H}$ and $\bar{H}_i \cong K^\times$. Clearly $\bar{H} = \bigoplus_{i=1}^{m-1} \bar{H}_i$ and Lemma 2.5 implies that $\delta(\bar{H}) = \tau^H$ if $m - 1$ is even and $\delta(\bar{H}) = \tau^H \cup (h)^H$ where $h$ is the unique involution of $\bar{H}_{m/2}$ if $m - 1$ is odd. As in Lemma 4.25, we observe that $\bar{G}(\tau)$ is a linear algebraic group and $(\bar{G}(\tau))^0 = \bar{G}$. Also $\sigma$ induces an endomorphism of $\bar{G}(\tau)$ with $(\bar{G}(\tau))^0 = \bar{G}_{\bar{a}}(\tau)$, and $\bar{C}_{\bar{G}}(\tau)$ is a connected linear algebraic group by [35, 8.3(b)]. Thus, by Lemma 4.4, we may assume that $m - 1$ is odd. Since $|\bar{C}_{\bar{G}}(h\tau)/(\bar{C}_{\bar{G}}(h\tau))^0| = 2$ (cf. [10, §4.3]), (b) follows from Lemma 4.4 and we are done.

Remark 4.28. Let $G = GL(m, k)$ for some integer $m \geq 3$, the group of nonsingular $m \times m$ matrices over $k$. Let $H = SL(m, k) = \{x \in G | \det(x) = 1\}$ and let $\tau$ denote the transpose-inverse automorphism of $G$. Then $G = H' = G(\infty)$ and [29, Proposition 8.9] implies that $C_G(\tau) \approx O((V/k, f))$ and $C_H(\tau) \approx SO((V/k, f))$ where $(V/k, f)$ is a nonsingular orthogonal vector space of dimension $m$ with $D((V/k, f)) = (k^\times)^2$. Also if $c \in k^\times - (k^\times)^2$ and $h$ denotes the inner automorphism of $G$ induced by the $m \times m$ diagonal matrix with $c$ in position $m$ and $1$ in the remaining (diagonal) positions, then $\tau h = h^{-1}\tau$ and $(h^2)^2 = \tau^2 = I_G$. Also, by [29, Proposition 8.9], $C_G(h\tau) \approx O((V/k, f))$ and $C_H(h\tau) \approx SO((V/k, f))$ where $(V/k, f)$ is a nonsingular orthogonal vector space of dimension $m$ with $D((V/k, f)) = c(k^\times)^2$. Suppose that $m$ is even and let $g$ denote the inner automorphism of $G$ induced by the matrix $A$ on [11, p. 3]. Then $\tau g \approx g \tau, g^2 \approx I_G \neq g$ and $C_H(\tau g) = Sp(V/k)$ where $V/k$ is a nonsingular symplectic vector space of dimension $m$ by [29, Proposition 9.13]. Suppose that $n$ is even and let $\sigma_0 = \lambda^{n/2}$, so that $\sigma_0^2 = \sigma$. Clearly $\lambda$ and $\sigma_0$ induce automorphisms, in the natural way, of $G$ which we shall also denote by $\lambda$ and $\sigma_0$. Then $\lambda^{n/2} = \sigma_0 \neq I_G = \sigma_0^2$ and $\sigma_0 = \sigma_0^4$, etc. Letting $C_{k_0}(\sigma_0) = C_k(\sigma_0) = k_0$, we have $C_G(\sigma_0) = GL(m, k_0)$ and $C_H(\sigma_0) = SL(m, k_0)$. Also, by [29, Proposition 8.8], we have $C_G(\sigma_0 \tau) = U(V/k)$ and $C_H(\sigma_0 \tau) = SU(V/k)$ where $V/k$ is a nonsingular unitary vector space of dimension $m$.

Lemma 4.29. Assume that $n$ is even and let $X = PSU(m, \sqrt{q})$ for some integer $m \geq 3$, let $\mathcal{A} = Aut(X)$ and let $\mathcal{B} = Inn(X)$. Then the following two conditions hold.

(a) $\mathcal{A} = \mathcal{C}A$ where $\mathcal{C} \unlhd \mathcal{A}, \mathcal{C} \cap A = 1, A$ is the subgroup of $\mathcal{A}$ induced by $Aut(k)$, so that $A = Aut(k) \cong Z_n, \mathcal{B} = \mathcal{C}'$, $PU(m, \sqrt{q}) \cong \mathcal{C} \subseteq \mathcal{A} \cong PUU(m, \sqrt{q})$, and $\mathcal{C}/\mathcal{B} \cong Z(m, \sqrt{q} + 1)$; and

(b) if $\phi$ denotes the unique involution in $A$, then $\delta(\mathcal{C} \phi)$ decomposes under conjugation by $\mathcal{C}$ into one orbit if $m$ is odd and into three orbits if $m$ is even.

Proof. Utilize the notation of Lemma 4.27 and set $\sigma_0 = \lambda^{n/2}$ and $G = O^p(\bar{G}_{\sigma_0 \tau})$. Clearly $\sigma_0^2 = \sigma, \tau \sigma_0 = \sigma_0 \tau, (\tau \sigma_0)^2 = \sigma,$

$$\bar{G}_{\sigma_0 \tau} \cong PU(m, \sqrt{q}), G = \bar{G}_{\sigma_0 \tau} \cong PSU(m, \sqrt{q})$$

and

$$\bar{G}_{\sigma_0 \tau} \subseteq \bar{G}_{\sigma} \cong PGL(m, q).$$
Let \( \lambda^*, \tau^* \), \( \sigma_0^* \) denote the restrictions of \( \lambda \), \( \tau \) and \( \sigma_0 \) to \( \overline{G}_{\sigma_0} \), respectively. Then 
\[ \tau^* = \sigma_0^* = \left( \lambda^* \right)^n/2, \quad \left( \lambda^* \right)^n = I_{G^*}, \quad C_{G^*}^{\sigma_0^*}(\lambda^*)(G) = 1 \quad \text{and} \quad \mathfrak{A} = \text{Aut}(\text{PSU}(m, \sqrt{q})) \approx \overline{G}_{\sigma_0^*}(\lambda^*) \] (cf. [34, Theorem 36]). Thus (a) holds. Clearly \( \sigma_0^* \) induces an endomorphism of the linear algebraic group \( \overline{G}(\tau) \), \( \overline{G}(\tau) \approx \overline{G}_{\sigma_0^*}(\tau) \) and (b) follows as in Lemma 4.27.

Remark 4.30. Suppose that \( n \) is even and let \( \sigma_0 = \lambda^{n/2} \) and \( k_0 = C_k(\sigma_0) \). Let 
\( (V/k, f) \) be a nonsingular unitary vector space of dimension \( m \). Then [29, Proposition 8.8] implies that \( V/k \) has a basis \( B = \{ v_1, \ldots, v_m \} \) such that \( f(v_i, v_j) = \delta_{ij} \) for all \( 1 \leq i, j \leq m \). Then \( W = \sum_{i=1}^m k_0 v_i \) is a vector space over \( k_0 \) of dimension \( m \) and \( (W/k_0, f|_{W/k_0}) \) is a nonsingular orthogonal vector space with \( D(W/k_0) = (k_0^\times)^2 \) by [29, Proposition 8.9]. If \( \alpha_B : U(V/k) \to \text{GL}(m, k) \) denotes the monomorphism defined via the basis \( B \), then \( \text{Im}(\alpha_B) \) is invariant under \( \sigma_0 \), \( \text{Im}(\alpha_B)_{\sigma_0} = \text{O}(W/k_0) \) and \( \alpha_B(\text{SO}(V/k))_{\sigma_0} = \text{SO}(W/k_0) \). Next let \( N : k^\times \to k^\times \) denote the norm map, let \( c \in k^\times \) be such that \( N(c) \notin (k_0^\times) \), let \( v'_i = v_i \) for all \( 1 \leq i < m - 1 \) and \( v'_m = cv_m \), let \( B' = \{ v'_1, \ldots, v'_m \} \) and let \( W' = \sum_{i=1}^m k_0 v'_i \). Then \( B' \) is a basis of \( V/k \) such that \( f(v'_i, v'_j) = \delta_{ij} \) for all \( 1 \leq i, j \leq m \) with \( i \neq m \) or \( j 
eq m \) and \( f(v'_m, v'_m) = N(c) \). \( W' \) is a vector space over \( k_0 \) of dimension \( m \) and \( (W'/k_0, f|_{W'/k_0}) \) is a nonsingular orthogonal vector space with \( D(W/k_0) = N(c)(k_0^\times)^2 \) by [29, Proposition 8.9]. If \( \alpha_B' : U(V/k) \to \text{GL}(m, k) \) denotes the monomorphism defined via the basis \( B' \) then \( \text{Im}(\alpha_{B'}) \) is invariant under \( \sigma_0 \), \( \text{Im}(\alpha_{B'})_{\sigma_0} = \text{O}(W'/k_0) \) and \( \alpha_B'(\text{SO}(V/k))_{\sigma_0} = \text{SO}(W'/k_0) \). Next, suppose that \( m \) is also even. By [29, Proposition 9.14], \( V/k \) has a basis \( B^* = \{ w_1^{(i)}, w_2^{(i)} \mid 1 \leq i \leq m \} \) such that \( f(w_1^{(i)}, w_2^{(i)}) = f(w_2^{(i)}, w_1^{(i)}) = 1 \) for all \( 1 \leq i \leq \frac{m}{2} \) and \( f(w_1^{(i)}, w_2^{(j)}) = 0 \) if \( i \neq j \) or \( r = s \) with \( 1 \leq i, j \leq \frac{m}{2} \) and \( 1 \leq r, s \leq 2 \). Let \( d \in k^\times \) be such that \( \sigma_0(d) = -d \) and set \( f^* = df \). Then \( W^* = \sum_{i=1}^m k_0 w_1^{(i)} + \sum_{i=1}^m k_0 w_2^{(i)} \) is a vector space over \( k_0 \) of dimension \( m \) and \( (W^*/k_0, f^*|_{W^*/k_0}) \) is a nonsingular symplectic vector space by [29, Proposition 9.13]. If \( \alpha_{B^*} : U(V/k) \to \text{GL}(n, k) \) denotes the monomorphism defined via the bases \( B^* \), then \( \text{Im}(\alpha_{B^*}) \) is invariant under \( \sigma_0 \) and \( \text{Im}(\alpha_{B^*})_{\sigma_0} = \text{Sp}(W^*/k_0) = \alpha_{B^*}(\text{SO}(V/k))_{\sigma_0} \).

Clearly, the following two results are easy consequences of the methods utilized in this section.

Lemma 4.31. Let \( X = \text{PSp}(2m, q) \) for some integer \( m \geq 2 \), let \( \mathfrak{A} = \text{Aut}(X) \) and let \( \mathfrak{B} = \text{Inn}(X) \). Then the following three conditions hold.

\( \mathfrak{A}' = \mathfrak{B}, \mathfrak{A} = \mathfrak{C} A \) where \( \mathfrak{B} \leq \mathfrak{C} \leq \mathfrak{A} \), \( | \mathfrak{C}/\mathfrak{B} | = 2 \), \( A \cap \mathfrak{C} = 1 \) and \( A \) is the subgroup of \( \mathfrak{B} \) induced by \( \text{Aut}(k) \), so that \( A \approx \text{Aut}(k) \approx Z_n^* \);

(a) if \( n \) is odd, then \( O^2(\mathfrak{A}) = \mathfrak{C} \);

(b) if \( n \) is even, then the unique involution \( \tau \in \mathfrak{A} \) is such that \( C_{\mathfrak{A}}(\tau) \approx \text{PGSp}(2m, \sqrt{q}) \) and \( \mathfrak{S}(\mathfrak{A} - \mathfrak{C}) = \tau \mathfrak{C} \).

Lemma 4.32. Let \( X = \text{PGO}(m, q) \) for some odd integer \( m \geq 7 \), let \( \mathfrak{A} = \text{Aut}(X) \) and let \( \mathfrak{B} = \text{Inn}(X) \). Then the following three conditions hold.

\( \mathfrak{A}' = \mathfrak{B}, \mathfrak{A} = \mathfrak{C} A \) where \( \mathfrak{B} \leq \mathfrak{C} \leq \mathfrak{A} \), \( \mathfrak{C} \equiv \text{PGO}(m, k) \equiv \text{SO}(m, q), \) \( | \mathfrak{C}/\mathfrak{B} | = 2 \), \( A \cap \mathfrak{C} = 1 \) and \( A \) is the subgroup of \( \mathfrak{A} \) induced by \( \text{Aut}(k) \), so that \( A \approx \text{Aut}(k) \approx Z_n^* \);
(b) if \( n \) is odd, then \( O^2(\mathbb{A}) = \mathbb{C} \); and
(c) if \( n \) is even, then the unique involution \( \tau \in A \) is such that \( C_\varphi(\tau) \approx SO(m, \sqrt{q}) \) and \( \varphi(\mathbb{A} - \mathbb{C}) = \tau \).

**Lemma 4.33.** Let \( X = \Phi(2m, q, 1) \) for some integer \( m \geq 4 \), let \( \mathbb{A} = \text{Aut}(X) \) and let \( \mathfrak{B} = \text{Inn}(X) \). Then the following seven conditions hold.

(a) There is a normal subgroup \( \mathbb{C} \) of \( \mathbb{A} \) such that \( \mathbb{C}' = \mathbb{B} \), \( \mathbb{C}/\mathbb{B} \approx E_4 \) if \( m \) is even and \( \mathbb{C}/\mathbb{B} \approx Z_{(4, q-1)} \) if \( m \) is odd;
(b) \( \mathbb{A} \) contains a subgroup \( A \) induced by \( \text{Aut}(k) \), so that \( A \approx \text{Aut}(k) = Z_n \);
(c) \( C_\varphi(A) \) contains a subgroup \( B \) such that \( B \cap A = 1 \), \( |B| = 2 \) if \( m \neq 4 \) and \( B = \Sigma_3 \) if \( m = 4 \) and \( \mathbb{A} = \mathbb{C}(B \times A) \) with \( \mathbb{C} \cap (B \times A) = 1 \);
(d) \( \mathbb{C}/\mathfrak{B} \approx \Sigma_4 \) if \( m = 4 \), \( \mathbb{C}/\mathfrak{B} \approx D_8 \) if \( m \) is even or \( m \) is odd and \( q \equiv 1 \) (mod 4) and \( \mathbb{C}/\mathfrak{B} \approx E_4 \) if \( m \) is odd and \( q \equiv -1 \) (mod 4);
(e) if \( \tau \in \mathfrak{B}(B) \), then \( \mathfrak{G}(\langle \tau \rangle) = \text{PGO}(2m, q, 1) \);
(f) if \( n \) is odd, then \( O^2(\mathbb{A}) = \mathbb{C} \); and
(g) if \( n \) is even and \( \varphi \) denotes the unique involution of \( A \) and if \( \tau \in \mathfrak{B}(B) \), then
\[
\varphi(\mathbb{C} \varphi) = \varphi \varphi, \quad \varphi(\mathbb{C} \tau \varphi) = (\tau \varphi)^\varphi, \quad C_\varphi(\varphi)' = \Phi(2m, \sqrt{q}, 1)
\]
and \( C_\varphi(\tau \varphi)' = \Phi(2m, \sqrt{q}, -1) \).

**Proof.** Let \( \mathfrak{G} = D_m \), let \( \pi \) denote the linear algebraic group obtained from the triple \((\mathfrak{G}, \pi, K)\). Let \( B \) denote the group of automorphisms of \( \mathfrak{G} \) induced by the group of graph automorphisms of \( \Phi \), as in Lemma 4.27. Thus \( B \approx \Sigma_3 \) if \( m = 4 \) and \( |B| = 2 \) otherwise and \( [B, \lambda] = 1 \) as endomorphisms of \( \mathfrak{G} \). Also \( B \) and \( \lambda \) leave invariant \( \mathfrak{G}_0 \) and \( G = \mathcal{O}(\mathfrak{G}_0) = (\mathfrak{G}_0)' \approx X \). Let \( \lambda^* = \lambda |_G \) and for \( b \in B \), let \( b^* = b |_G \). Then, as endomorphisms of \( G \), \( |\lambda^*| = n, \lambda^* \) commutes with \( B^* = \langle b^* | b \in B \rangle \), \( B^* \approx B \), \( \mathfrak{G}_0(\langle \lambda^* \rangle \times B^*)(G) = 1 = \mathfrak{G}_0 \cap (\langle \lambda^* \rangle \times B^*) \) and \( \mathfrak{A} = \mathfrak{G}_0(\langle \lambda^* \rangle \times B^*) \) by [11, Theorem 12.5.1]. Also from [8, Planche IV], we have \( \Gamma_{sc}/\Gamma_{ad} \approx E_4 \) if \( m \) is even and \( \Gamma_{sc}/\Gamma_{ad} \approx Z_4 \) if \( m \) is odd. Note that \( \mathfrak{G}_0 = \mathfrak{G}(\mathfrak{H}_a) \) and \( \mathfrak{G}_0/\mathfrak{G} \approx \mathfrak{H}_a/\mathfrak{H}_a \approx \text{Hom}(\Gamma_{sc}/\Gamma_{ad}, k^\times) \) by [11, Theorem 7.1.1]. Applying [35, Corollary 12.6(b)] and the proofs of Lemmas 4.13, 4.15 and 4.17 (as in Lemma 4.25), we conclude that (a)–(d) and (f) hold. Note that \( \Phi(2m, q, 1) \) is isomorphic to a subgroup of \( \mathfrak{A} \) and if \( |\mathfrak{A}| 
eq |\Phi(2m, q, 1)| \), then \( m = 4 \) and \( |\mathfrak{A}| = 3 |\Phi(2m, q, 1)| \). Thus we may assume that \( n \) is even and \( q \equiv 1 \) (mod 4). Let \( \varphi = (\lambda^*)^{n/2} \) and let \( \tau \in \mathfrak{B}(B^*) \). Then (g) holds by Lemma 4.4 and [35, §11.6]. Note that \( \langle \mathfrak{G}(\Phi(2m, q, 1)) \rangle = \mathfrak{G}(\Phi(2m, q, 1)) \) and that \( \langle \mathfrak{G}(\Phi(2m, q, 1)) \rangle = \mathfrak{G}(\Phi(2m, q, 1)) \) from §3D. Thus there is a monomorphism \( \delta: \Phi(2m, q, 1) \rightarrow \mathcal{C} \langle \tau, \varphi \rangle = \mathcal{C} \cup \mathcal{C} \tau \cup \mathcal{C} \varphi \cup \mathcal{C} \tau \varphi \). Then §3D and (g) imply that \( \delta(\Phi(2m, q, 1)) \subset \mathcal{C} \langle \tau \rangle \). Since \( |\Phi(2m, q, 1)| = |\mathcal{C} \langle \tau \rangle| \), we have \( \delta(\Phi(2m, q, 1)) = \mathcal{C} \langle \tau \rangle \) and we are done.

**Lemma 4.34.** Assume that \( n \) is even and let \( X = \Phi(2m, \sqrt{q}, -1) \) for some integer \( m \geq 4 \), let \( \mathfrak{A} = \text{Aut}(X) \) and let \( \mathfrak{B} = \text{Inn}(X) \). Then the following five conditions hold.
(a) There is a normal subgroup \( \mathbb{C} \) of \( \mathfrak{A} \) such that \( \mathbb{C}' = \mathfrak{B} \), \( |\mathbb{C}/\mathfrak{B}| = 2 \) if \( m \) is even, and \( \mathbb{C}/\mathfrak{B} \approx Z_{(4, \sqrt{q}^2 + 1)} \) if \( m \) is odd;
(b) \( \mathfrak{A} \) contains a subgroup \( A \) induced by \( \text{Aut}(k) \), so that \( A \approx \text{Aut}(k) \approx Z_n \).
(c) $\mathfrak{H} = \mathfrak{C}A$ and $\mathfrak{C} \cap A = 1$;
(d) $\mathfrak{H} \cong \Gamma O(2m, \sqrt{q}, -1)$; and
(e) if $\varphi$ denotes the unique involution of $A$, then $\mathfrak{C}<\varphi> \cong \Gamma O(2m, \sqrt{q}, -1)$ and $\varphi$ inverts $\mathfrak{C}/\mathfrak{B}$.

\textbf{Proof.} Utilize the notation of Lemma 4.33 but let $\tau \in G(B)$ and set $a_0 = \lambda^\alpha/2$ and $G = O^\tau(G_{a_0})$. Clearly $a_0 = \sigma$, $\tau \lambda = \lambda \tau$ and $(\tau a_0)^2 = \sigma$. Thus $\lambda$ and $\tau$ leave $G_{a_0}$ invariant, $G = (G_{a_0})' = X$, $a_0 |G_{a_0} = \tau |G_{a_0}$, and $G_{a_0}/G \cong H_{a_0}/(G \cap H_{a_0})$. Applying [35, Corollary 12.6(b)] and the proofs of Lemmas 4.13, 4.15 and 4.17, we conclude that $|G_{a_0}/G| = 2$ if $m$ is even and $G_{a_0}/G \cong Z(4, \sqrt{q}+1)$ if $m$ is odd. Also $\tau$ inverts $G_{a_0}/G$ in all cases. Let $\lambda^* = \lambda |G_{a_0}$. Then

$$\left(\lambda^*\right)^{n/2} = a_0 | G_{a_0} \neq \tau | G_{a_0} \neq I_{G_{a_0}}, \quad C_{G_{a_0}\langle \lambda^* \rangle}(G) = 1$$

and

$$\mathfrak{H} \cong G_{a_0}\langle \lambda^* \rangle$$

by [34, Theorem 36]. Thus (a)–(c) hold. Since $\Gamma O(2m, \sqrt{q}, -1)$ is isomorphic to a subgroup of $\mathfrak{H}$ and $|\Gamma O(2m, \sqrt{q}, -1)| = |\mathfrak{H}|$, we have (d). Since

$$\langle\{\Gamma O(2m, \sqrt{q}, -1)\} \rangle = \Gamma O(2m, \sqrt{q}, -1)$$

by §3D, $|\Gamma O(2m, \sqrt{q}, -1)| = 2 |G_{a_0}|$ and $(G_{a_0}\langle \lambda^* \rangle)/G_{a_0} \cong Z_n$, we have (e) also and we are done.

Finally, we note that §§3A–3D and Lemmas and Remarks 4.27–4.34 give a complete survey of the conjugacy classes of involutions in the automorphism groups of the classical linear groups over finite fields of odd order that extends [12].

5. Additional preliminary results. In this section, we utilize our previous work to derive further results that are required in our proofs of Theorems 1–3 (as presented in §§6–8, respectively).

Throughout this section, $p$ will denote an odd prime integer and $q = p^n$ for some positive integer $n$.

\textbf{Lemma 5.1.} Let $X$ be a simple Chevalley group over a finite field of order $q$. Let $z \in \mathfrak{S}(X)$ and set $H = C_{\mathfrak{S}}(z)$. Then the following seven conditions hold:

(a) every 2-component $H$ is a Chevalley group over a finite field of order $q$, $q^2$, $q^3$ or $q^4$ and $E(H) = L_2(q)$;
(b) $H/E(H)$ is solvable;
(c) if $q = 3$, then $O(H) = 1$;
(d) if $H$ possesses a solvable 2-component, then $q = 3$;
(e) $H$ does not contain a 2-component $J$ with $z \in J$ and $J \cong \text{Spin}(7, p^r)$ for any positive integer $r$;
(f) if $q \neq 3$, then $S(H) = C_H(E(H))$ and $S(H)$ is cyclic or dihedral; and
(g) if $q = 3$ and $E_z(H)$ denotes the product of all solvable 2-components of $H$, then $C_H(E(H)E_z(H))$ is cyclic or dihedral.
Proof. Clearly [9, Lemma (c)] yields (c). Applying Lemmas 4.19–4.26, it follows that we may assume that $X$ is a classical linear group. Then Lemmas 3.1–3.2, [25, Propositions 2–5] and §§3A–3D yield the result.

Lemma 5.2. Let $K$ be a 2-quasisimple group such that $K/Z^*(K)$ is a simple Chevalley group over a finite field of order $q$. Then exactly one of the following three conditions holds.

(a) There exists an involution $t \in K$ such that $C_K(t)$ possesses an intrinsic 2-component $J$ with $J/\text{O}(J) \cong \text{SL}(2,q)$;

(b) $K/\text{O}(K) \cong \text{PSL}(2,q)$; or

(c) $p = 3$, $n$ is odd, $n \geq 3$ and $K/\text{O}(K) \cong 2G_2(q)$.

Proof. Let $K$ be a counterexample of minimal order to this lemma. Then $O(K) = 1$ by Lemma 2.19 and hence $Z^*(K) \cong Z(K) = O_2(K)$. Let $L = \text{Cov}(K)$. Then $L = \text{Cov}(K/Z^*(K))$ by Corollary 2.7.1 and there is an epimorphism $\pi: L \to K$ such that $O(L) \leq \text{Ker}(\pi) \leq Z(L)$. Now Lemmas 2.14, 2.27, 4.9, 4.10, 4.12–4.26 and §§3A–3D force the conclusion of this lemma.

Lemma 5.3. Let $K$ be a 2-quasisimple group such that $K/Z^*(K)$ is a simple Chevalley group over a finite field of order $q$. Then exactly one of the following five conditions holds.

(a) $K/\text{O}(K) \cong \text{PSL}(2,q)$;

(b) $p = 3$, $n$ is odd, $n \geq 3$ and $K/\text{O}(K) \cong 2G_2(q)$;

(c) $q = 3$ and $K/\text{O}(K)$ is isomorphic to $\text{PSL}(3,3)$, $\text{PSU}(3,3)$, $\text{PSL}(4,3)$, $\text{PSU}(4,3)$, $\text{PSp}(4,3)$, $G_2(3)$, $P\Omega(7,3)$, $P\Omega(8,3,1)$ or $P\Omega(8,3,-1)$;

(d) $q = 3$, $|Z^*(K)|_2 = 2$ and $K/Z^*(K) \cong \text{PSU}(4,3)$; or

(e) $K$ contains an involution $t$ such that $C_K(t)$ possesses a perfect intrinsic 2-component of $\mathfrak{M}(p)$-type.

Proof. Let $K$ be a counterexample of minimal order to this lemma. Then, as in the previous lemma, we have $O(K) = 1$. Moreover, we must have $q = 3$ by the previous lemma. Suppose that $K$ is simple. Then Lemmas 4.19–4.26, Lemma 2.14 and §§3A–3D yield a contradiction. Thus $S(K) = Z(K) = O_2(K) \neq 1$. Since $K = C_K(j)$ for any involution $j \in Z(K)$, we conclude that $K$ is a proper quotient of $\text{SL}(2m,3)$ or of $\text{SU}(2m,3)$ for some integer $m \geq 2$. However Lemma 2.14 and §§3A and 3C yield a contradiction in this case also and we are done.

Lemma 5.4. Let $K$ be a 2-quasisimple group such that $K/Z^*(K)$ is isomorphic to a simple Chevalley group over a finite field of order $q$. Assume that $t$ is an involution in $Z^*(K)$ and that $K/Z^*(K)$ is not isomorphic to $\text{PSL}(2,q)$. Then there is an involution $z \in K - Z^*(K)$ such that $C_K(z)$ possesses a 2-component $J$ with $z \in Z(J)$ and $J/\text{O}(J) \cong \text{SL}(2,q)$ and at least one other 2-component $L$ of $\mathfrak{M}(p)$-type with $L/Z^*(L)$ isomorphic to a Chevalley group over a finite field of order $q$. Moreover, if $K$ is of $\mathfrak{M}(p)$-type, then $L$ may be chosen to satisfy $Z(L) \cap \{t,z\} \neq \emptyset$ also.

Proof. As above, we may assume that $O(K) = 1$. Then §§3A–3C and Lemmas 2.14, 2.27, 4.9, 4.10 and 4.12–4.18 imply the desired conclusions.

Our next result is clearly a consequence of §§3A and 3C.
Lemma 5.5. Let $X = \text{PSL}(2m, q)$ or $X = \text{PSU}(2m, q)$ for some positive integer $m \geq 2$. Let $z \in \mathcal{Z}(X)$, let $H = C_X(z)$ and let $L$ be a 2-component of $H$. Then the following two conditions hold.

(a) If $L$ is a 2-component of $H$, then either $L$ is isomorphic to $\text{SL}(j, q)$ or to $\text{SU}(j, q)$ for some integer $j$ with $2 \leq j \leq 2m - 1$ or $L/Z(L) \cong \text{PSL}(m, q^2)$; and

(b) if $L$ is a perfect 2-component of $H$ such that $|Z^*(L)| \neq |\mathfrak{R}(L/Z^*(L))|_2$, then $L/Z(L) \cong \text{PSL}(m, q^2)$ and $L$ is the unique 2-component of $H$.

Lemma 5.6. Let $X$ be a simple Chevalley group over a finite field of characteristic $p$ such that $|\mathfrak{R}(X)|$ is even. Assume that $X$ contains an involution $z$ such that $H = C_X(z)$ contains distinct solvable or perfect 2-components $J$ and $L$ such that $z \in L$ and $J/O(J) \cong \text{PSL}(2, q)$. Then $O(J) = 1$, $|\mathfrak{R}(X)| = 2$ and exactly one of the following six conditions holds.

(a) $n \geq 7$, and $L = \text{SL}(2, q)$;

(b) $X \cong \text{PSL}(2m + 1, q)$ for some integer $m > 4$, $L \cong \beta(2m - 2, q, 1)$ if $m$ is odd or $L \cong \beta(2m - 2, q, -1)$ if $m$ is even and $q \equiv 1 \pmod{4}$ and $L \cong \Omega(2m - 2, q, -1)$ if $m$ is even and $q \equiv -1 \pmod{4}$;

(c) $n$ is even, $X \cong P\Omega(8, r, -1)$, $r^2 = q$ and $L = \text{SL}(2, r)$;

(d) $n$ is even, $X \cong P\Omega(2m, r, -1)$ for some even integer $m \geq 6$, $r^2 = q$ and $L \cong \Omega(2m - 4, r, 1)$;

(e) $n$ is even, $X \cong P\Omega(2m, r, 1)$ for some odd integer $m \geq 5$, $r^2 = q$, $r \equiv -1 \pmod{4}$ and $L \equiv \Omega(2m - 4, r, -1)$; or

(f) $n$ is even, $X \cong P\Omega(2m, r, -1)$ for some odd integer $m \geq 5$, $r^2 = q$, $r \equiv 1 \pmod{4}$ and $L \equiv \Omega(2m - 4, r, 1)$.

Proof. Applying Lemmas 2.27 and 4.24 and §§3A–3C, we conclude that $X \cong P\Omega(m, p^n)$ for positive integers $m$ and $s$ with $m \geq 7$. Since $\Omega(3, q) \cong \text{PSL}(2, q)$ and $\Omega(4, q, -1) \cong \text{PSL}(2, q^2)$, it is easy to see that this result follows from §3D.

Lemma 5.7. Let $G$ be a group such that $O^2(G)$ is 2-quasisimple and $O^2(G)/O(O^2(G))$ is a Chevalley group over a finite field of order $q$. Assume that $G$ contains an involution $z$ such that $H = C_G(z)$ possesses a solvable 2-component $J$ such that $O^2(J)$ is not contained in $Z^*(O^2(G))$. Then $q = 3$, $z \in S(G)$, $O(H) \leq O(G)$ and $O^2(G) \cap H$ contains a solvable 2-component $J_1$ such that $J_1 \leq H$, $J = O(H)J_1$ and $O^2(J) = O^2(J_1)$.

Proof. Let $G$ be a counterexample of minimal order to this result and set $M = O^2(G)$.

Suppose that $z \in Z^*(M)$. Then $K = C_M(z^{(\infty)})$ is a perfect 2-component of $H$ such that $M = O(M)K = (O(G)K)^{(\infty)}$ by Lemma 2.15. Since $[J, K] \leq O(K) \leq O(M)$ by Lemma 2.11, we have $[J, M] \leq O(M)$ and hence $J \leq S(G) = O(G)Z^*(M)$ by Lemma 2.13. Since $O^2(S(G)) = O^2(Z^*(M))$, we have a contradiction. Thus $z \notin S(G)$ since $Z^*(M) = S(G) \cap M$.

Next observe that $q = 3$ implies $O(H) \leq O(G)$. To see this, set $\overline{G} = G/S(G)$. Then $\overline{z} \in \mathcal{Z}(\overline{G})$, $F^*(\overline{G}) = \overline{M} = O^2(\overline{G})$ and $O(C_{\overline{G}}(\overline{z})) = 1$ by Lemma 2.13 and [9,
Lemma (c)]. Since $O(H) \leq O(C_G(\bar{z}))$ by [18, Proposition 3.11], we have $O(H) \leq O^2(S(G)) = O(G)$ and our assertion is proved.

Suppose that $O(M) \neq 1$. Set $\overline{G} = G/O(M)$. Then $O^2(\overline{G}) = M/O(M)$, $Z^*(M) = Z^*(\overline{M})$, $\bar{z} \in \mathcal{N}(\overline{G})$, $\overline{H} = C_{\overline{G}}(\bar{z})$, $O(\overline{H}) = O(\overline{G})$ and $\overline{J}$ is a solvable 2-component of $\overline{H}$ by Lemmas 2.2, 2.12, 2.16 and 2.17. Since $|G| < |\overline{G}|$, we have $q = 3$, $O(\overline{H}) \leq O(\overline{G}) = O(G)$ and there is a solvable 2-component $J_1$ of $C_M(z)$ such that $\overline{J} = O(\overline{H}) \overline{J}_1$ by Lemma 2.18. Hence $O(M)J = O(M)O(H)J_1$. As $C_{O(M)}(z) \leq O(H)$, we have $J = O(H)J_1$. Also, since $J_1 \leq \mathcal{Z}J$, we have $O^2(J) = O^2(J_1)$. Thus $O(M) = 1$, $S(G) = O(G) \times Z(M) = C_G(M)$ and $M$ is quasisimple.

Suppose that $O(G) \neq 1$. Set $\overline{G} = G/O(G)$. Then, as above, we conclude that $q = 3$, $\overline{H} = C_{\overline{G}}(\bar{z})$, $O(\overline{H}) \leq O(G)$ and $(O(G) \times M) \cap H$ possess a solvable 2-component $\overline{J}$ such that $\overline{J} = O(\overline{H})\overline{J}_1$. As $O(G) \leq H$ since $z \in M$, we have $O(H) = O(G)$ and $J = \overline{J}_1$. Thus $J = O(G) \times (M \cap J)$. Set $J_1 = M \cap J$. Then $J_1 \leq H, J_1 \leq M \cap H, J_1 \leq J, O(M \cap H) \leq O(H) \cap M = 1, J_1$ is a solvable 2-component of $M \cap H$ and $O^2(J) = O^2(J_1)$. Consequently $O(G) = 1$ and $S(G) = Z(M) = O_2(M)$.

Suppose that $S(G) \neq 1$. Set $\overline{G} = G/S(M)$. Then $O(C_{\overline{G}}(\bar{z}))\overline{J}$ is a solvable 2-component of $C_{\overline{G}}(\bar{z})$ by Lemma 2.14 since $O^2(J) \neq S(G)$. Thus $q = 3$, $O(H) = 1$, $O(C_{\overline{G}}(\bar{z})) \leq O(G) = 1$ and $\overline{J} \leq \overline{M} = O^2(\overline{G})$. Thus $J$ is a solvable 2-component of $M \cap H$. This contradiction implies that $S(G) = 1, F^*(G) = M$ and $M$ is simple.

Let $R = O^2(J)$. Then $R \leq H \cap M, H \cap M \leq H, E(H) = L_2(\mathbb{F}) = E(H \cap M)$ and $[R, E(H)] = [R, E(H \cap M)] = 1$ by Lemmas 2.11 and 5.1. Let $T \in \text{Syl}_2(R)$, so that either $T \cong \mathbb{F}_8$ or $T \cong E_4$ and $z \not\in T$. Thus $q = 3$ by Lemma 5.1(f) and $O(H) = 1$ by [9, Lemma (c)]. Let $E_4(H \cap M)$ denote the product of all solvable 2-components of $H \cap M$. Suppose that $J$ is not a solvable 2-component of $H \cap M$. Then

$$[R, E(H \cap M)E_4(H \cap M)] \leq [J, E(H \cap M)E_4(H \cap M)] = 1$$

by Lemma 2.11 and Lemma 5.1(g) yields a contradiction since $\langle z, R \rangle \leq C_{H \cap M}(E(H \cap M)E_4(H \cap M))$. Thus $J \leq H \cap M$ which is also a contradiction and the proof is complete.

**Lemma 5.8.** Let $W$ be a 4-subgroup of the group $G$ and let $W^* = \{z_1, z_2, z_3\}$. Suppose that $C_G(W)$ contains solvable or perfect 2-components $L_1$ and $L_2$ such that $z_1 \in L_1, z_2 \in L_2$ and $L_1/O(L_1) \cong SL(2, q)$. Assume that $O(C_G(z_1)L_1)$ is not subnormal in $C_G(z_1)$ if $L_1$ is perfect and that $O(C_G(z_1)L_1)O^3(L_1)$ is not subnormal in $C_G(z_1)$ if $L_1$ is solvable. Then there is a unique perfect 2-component $K$ of $C_G(z_1)$ such that $O^2(L_2) \leq K$. Moreover the following two conditions hold.

(a) $z_3 \not\in Z^*(K), C_G(W) \leq N_G(K), L_1 \neq L_2, L_1 \leq K$ if $q \neq 3$ and $[K, O^3(L_1)] = K$ if $q = 3$; and

(b) if $K/Z^*(K)$ is a simple Chevalley group over a finite field of characteristic $p$, then $z_1 \in Z(K)$ and exactly one of the following four conditions holds:

(i) $K/O(K) \cong \text{Spin}(7, q), C_K(z_2)$ contains unique 2-components $J_1, J_2, J_3$ such that $z_i \in J_i, J_i \leq C_K(W)$ and $J_i/O(J_i) \cong SL(2, q)$ for $i = 1, 2, 3$. Also, for $i \in \{1, 2\}$, we have $J_i = L_i$ if $q \neq 3$ and $J_i \leq L_i = O(C_G(W))J_i$ if $q = 3$;
(ii) $K/O(K) \cong \text{Spin}(2m + 1, q)$ for some odd integer $m \geq 5$; $W \leq L_2 \leq C_G(W)$, $L_2/O(L_2) \cong \text{Spin}(2(m - 1), q, 1)$, $L_2$ is a 2-component of $C_K(z_2)$ and $C_K(z_2)$ contains exactly one other 2-component $J$. Moreover, $z_1 \in J \leq C_G(W)$, $J = L_1$ if $q \neq 3$ and $L_1 = O(C_G(W))J$ if $q = 3$;

(iii) $n$ is even, $K/O(K) \cong \text{Spin}(8, r, -1)$ where $q = r^2$, $L_1 \leq C_G(W)$, $L_1$ is a 2-component of $C_K(z_2)$ and $C_K(z_2)$ contains precisely two other 2-components $J_2$ and $J_3$. Moreover, $J_i \leq C_G(W)$ and $J_i/O(J_i) \cong \text{SL}(2, r)$ for $i = 2, 3$ and, by appropriate indexing, we may assume that $z_2 \in J_2$, $z_3 \in J_3$, $J_2 = L_2$ if $r \neq 3$ and $L_2 = O(C_G(W))J_2$ if $r = 3$; or

(iv) $n$ is even, $K/O(K) \cong \text{Spin}(2m, r, -1)$ for some even integer $m \geq 6$, $q = r^2$; $\{L_1, L_2\}$ is the set of 2-components of $C_K(z_2)$, $L_2/O(L_2) \cong \text{Spin}(2(m - 2), r, 1)$, $W \leq L_2 \leq C_G(W)$ and $L_1 \leq C_G(W)$.

**Proof.** Set $H = C_G(z_1)$. As $O_2(Z(L_1)) = \langle z_1 \rangle$, we have $L_1 \neq L_2$. Clearly $C_G(W) = C_H(z_2)$ and Lemma 2.26 implies that $O^2(L_2)$ is contained in a unique perfect 2-component $K$ of $H$. Moreover Lemma 2.26 yields $z_2 \notin Z^*(K)$, $C_G(W) \leq N_G(K)$, $C_K(z_2) \leq C_G(W)$, $L_1 \leq K$ if $q \neq 3$ and $[K, O^3(L_1)] = K$ if $q = 3$. Thus, for the remainder of this proof, we may assume that $K/Z^*(K)$ is a simple Chevalley group over a finite field of order $q_1 = p^r$ for some positive integer $r$. Recall that $K/Z^*(K)$ is $\theta$-balanced when $p = 3$. Thus [1, Theorem 2(3)] and Lemma 2.25 imply that $O^2(L_1) \leq K$ and $z_1 \in Z(K)$. Set $M = KL_1L_2$. Then $M^{(w)} = O^2(M) = K$ and $C_M(z_2) = C_K(z_2)L_1L_2$. Clearly $O^2(L_1)$ and $O^2(L_2)$ are not contained in $Z^*(K)$. Also, if $L_i$ is solvable for $i = 1$ or 2, then $O(L_i) = O(C_G(W)) \leq O(C_M(z_2)) \leq C_H(z_2) \leq C_G(W)$ and hence $O(C_G(W)) = O(L_i) = O(C_M(z_2))$. Consequently, $L_1$ and $L_2$ are 2-components of $C_M(z_2)$ and $q_1 = 3$ if $L_1$ or $L_2$ is solvable by Lemma 5.7. Also, Lemma 5.7 implies that $C_K(z_2)$ contains 2-components $J_1$ and $J_2$ such that $J_i \leq C_M(z_2) \leq C_G(W)$, $O^2(L_i) = O^2(J_i)$, $J_i = L_i$ if $L_i$ is perfect and $L_i = O(C_G(W))J_i$ if $L_i$ is solvable for $i = 1$ and 2. Since $O(K) = O(H) \cap K$ and $z_2 \notin Z^*(K)$, we may assume that $G = H = K$. Then Lemmas 2.16–2.18 and induction imply that we may assume that $O(G) = 1$ and hence that $S(G) = Z(G) = O_2(G)$.

Set $\overline{G} = G/Z(G)$. Then $|\mathfrak{M}(\overline{G})|$ is even since $z_1 \in Z(G)$ and $\overline{z}_2 \in \mathfrak{g}(\overline{G})$. Clearly $L_1 \cap Z(G) = \langle z_1 \rangle$, $\overline{L}_1/O(\overline{L}_1) \cong \text{PSL}(2, q)$, $\overline{z}_2 \in \overline{L}_2$ and $\overline{L}_1$ and $\overline{L}_2$ are 2-components of $C_G(\overline{z}_2)$ by Lemma 2.17. Then Lemma 5.6 implies that $Z(G) = \langle z_1 \rangle$ and $\overline{G}$ satisfies one of conditions (a)–(f) of Lemma 5.6. Then Lemmas 4.10, 4.12, 4.14, 4.16, 4.17 and 4.18 combine to complete this proof.

6. A proof of Theorem 1. We begin this section with an extension of a portion of [3, Corollary III] that is the solvable 2-component case of Theorem 1.

**Lemma 6.1.** Let $G$ be a group such that $O^2(G)$ is 2-quasisimple. Suppose that $z \in \mathfrak{g}(G)$ and $H = C_G(z)$ possesses an intrinsic solvable 2-component $J$. Then the following three conditions hold.

(a) $O(H) \leq O(G)$;

(b) there is an intrinsic solvable 2-component $J_1$ of $H \cap O^2(G)$ such that $J_1 \leq H$, $O^2(J) = O^2(J)$ and $J = O(H)J$; and

(c) either $G = O(G)O^2(G)$ and $G/O(G) \cong M_{11}$ or $O^2(G)/O(O^2(G))$ is a Chevalley group over a field of 3 elements.
Proof. Assume that \( G \) is a counterexample of minimal order to this lemma and set \( M = O^2(G) \). Suppose that \( z \in Z^*(M) = S(G) \cap M \). Then \( K = C_M(z)^{\infty} \) is a perfect 2-component of \( H \) and \( M = O(M)K \). Thus \( [J, M] \leq O(M) \) and \( J \leq C_O(M/O(M)) = S(G) = O(G)Z^*(M) \) by Lemmas 2.11 and 2.3. As \( J = O^2(J) \), this is impossible. Thus \( z \notin S(G) \) and \( S(G) \cap J \leq O(J) \).

Suppose that \( S(G) \neq 1 \) and set \( \tilde{G} = \bar{G}/S(G) \). Then \( F^*(\tilde{G}) = \tilde{M} \approx M/Z^*(M) \), \( \tilde{z} \in \mathfrak{z}(\tilde{J}) \) and \( O(C_{\tilde{G}}(\tilde{z})) \) is a solvable 2-component of \( \tilde{G} \) by Lemmas 2.13 and 2.14. Hence \( O(H) \leq O(C_{\tilde{G}}(\tilde{z})) \) is 1 by [18, Proposition 3.11], and \( \tilde{M} = \tilde{M} \approx M_{11} \) or \( \tilde{M} \) is a Chevalley group over a field of 3 elements. Thus \( O(H) \leq O^2(S(G)) = O(G) \) and Lemma 5.7 implies that \( \tilde{G} = \tilde{M} \approx M_{11} \). Then \( Z^*(M) = O(M) \) since \( |\mathfrak{z}(M_{11})| = 1 \) (cf. [13, §2]) and \( S(G) = O(G) \). Then \( G = O(G)M, M/O(M) \approx M_{11} \) and \( J \) is the unique 2-component of \( C_O(z) = H \) by [4, Table 1]. Also we conclude that \( C_M(z) \) contains a unique 2-component \( K \) from Lemma 2.18. Moreover \( K \) is solvable, \( K \leq \mathfrak{z} J, z \in K \) and \( \tilde{J} = \tilde{K} \). Hence \( O(G)J = O(G)K \). Since \( C_O(G)(z) = O(H) \), we have \( J = O(H)K \) and \( O^2(J) = O^2(K) \) by Lemma 2.1. Thus \( S(G) = 1 \) and \( F^*(G) = M \) is simple. Then [3, Corollary III; 4, Table 1] imply that \( G = M \approx M_{11} \) or \( M \) is a Chevalley group over a finite field of order \( 3 \). Consequently Lemma 5.7 implies \( G = M \approx M_{11} \). Thus \( O(H) = 1 \) by [4, Table 1] and we have a contradiction, which concludes our proof of this result.

We now commence to prove Theorem 1. Thus let \( G, L, z \) and \( p \) be as in the hypotheses of Theorem 1 and assume that \( G \) is a counterexample of minimal order to the theorem.

Thus \( L \) is perfect by Lemma 6.1, \( L \leq O^2(G) = G \) and Lemmas 2.12–2.14 imply that \( O(G) = 1 \). Consequently \( O_2(G) = Z(G) = C_O(O^2(G)) = S(G) \) and \( z \notin Z(G) \) since \( G \neq L \).

Suppose that \( Z(G) \neq 1 \) and set \( \tilde{G} = G/Z(G) \). Then \( \tilde{G} \) is simple, \( |\tilde{G}| = |G| \), \( \tilde{z} \in \mathfrak{z}(\tilde{G}) \) and \( \tilde{L} \) is an intrinsic perfect 2-component of \( C_{\tilde{G}}(\tilde{z}) \) of \( \mathfrak{M}(p) \)-type by Lemmas 2.12 and 2.28. Then, by induction, \( \tilde{G} \approx M_{11} \) or \( \tilde{G} \) is isomorphic to a Chevalley group over a finite field of characteristic \( p \). Since \( |\mathfrak{M}(M_{11})| = 1 \), we have a contradiction. Thus \( Z(G) = 1 \) and \( G \) is simple. Then [3, Corollary III] and Lemma 5.1 imply that \( G \) does not contain an involution \( u \) such that \( C_G(u) \) contains an intrinsic 2-component \( J \) with \( J/O(J) = SL(2, p^k) \) for some integer \( k \geq 1 \).

Suppose that \( W \) is a 4-subgroup of \( G \) with \( W^* = \{z_1, z_2, z_3\} \) and such that \( C_G(W) \) contains 2-components \( L_1, L_2 \) such that \( z_1 \in L_1, z_2 \in L_2, L_1/O(L_1) \approx SL(2, p^k) \) for some integer \( k \geq 1 \) and \( L_2 \) is of \( \mathfrak{M}(p) \)-type.

Applying Lemma 5.8, we obtain a unique perfect 2-component \( K \) of \( C_G(z_1) \) such that \( O^2(L_2) \leq K, z_2 \notin Z^*(K), C_G(W) \leq N_G(K), L_1 \leq K \) if \( p^k \neq 3 \) and \( [K, O^3(L_1)] = K \) if \( p^k = 3 \). Set \( X = K \mathcal{L}_2 \). Then \( X \leq C_G(z_1) \leq G, O^2(X) = K, L_2 \leq \mathfrak{z} \leq C_X(z_2) = C_K(z_2)L_2 \leq \mathfrak{z} \leq C_G(W), O(L_2) \leq O(C_X(z_2)) \leq O(C_G(W)) \) and hence \( L_2 \) is an intrinsic 2-component of \( C_X(z_2) \) of \( \mathfrak{M}(p) \)-type. We conclude, by induction, that \( K/O(K) \) is a Chevalley group over a finite field of characteristic \( p \) or \( X = O(X)K \) and \( X/O(X) \approx K/O(K) \approx M_{11} \). Also, when \( p^k = 3, K/O(K) \) is always \( \theta \)-balanced since \( M_{11} \) is balanced. Then [1, Theorem 2(3)] and Lemma 2.25 imply that \( O^2(L_1) \leq K \). Thus \( z_1 \in Z(K), K/Z^*(K) \) is a simple Chevalley group over a finite field of order \( p^n \) for some integer \( n \geq 1 \) and Lemma 5.8 yields a great
deal of information about this situation. In particular, $L_2/O(L_2)$ is not isomorphic to $\text{Spin}(7, p^n)$ for any positive integer $r$.

Set $H = C_G(z)$, $Q = C_H(L/O(L))$ and $\overline{H} = H/O(H)$.

First suppose that $L/O(L) = \text{Spin}(7, q)$, where $q = p^n$ for some positive integer $n$. Let $1 \neq B$ be a 2-subgroup of $Q$. Then Lemma 2.15 implies that $J = C_G(B) = O^2(C_L(B))$ is a 2-component of $C_G(B(z))$ with $z \in J$, $L = O(L)J$ and $J/O(J) \cong L/O(L)$. Hence $J$ is contained in a unique 2-component $K$ of $C_G(B)$ by Lemma 2.19. Thus $J$ is a 2-component of $C_K(z)$ and hence $\overline{K} = K/Z^*(K)$ is a simple Chevalley group over a finite field of characteristic $p$ by induction since $K \leq C_G(B) < G$. Assume that $z \notin Z^*(K)$. Then $\bar{z} \in \mathfrak{z}(\bar{J})$, $J$ is a 2-component of $C_K(z)$ and $J/O(J) \cong \text{Spin}(7, q)$ since $Z^*(J) = O(H) \times \langle z \rangle$. Then Lemma 5.1(e) yields a contradiction. Thus $z \in Z^*(K)$, $J = C_K(z) = O(K)J = (O_C(B))/J$ and $K/O(K) \cong J/O(J) \cong L/O(L) \cong \text{Spin}(7, q)$ by Lemma 2.15. Let $j \in \mathfrak{z}(H - L)$ be such that $C_H(j)$ contains an intrinsic 2-component $J$ with $J/O(J) \cong \text{SL}(2, p^n)$ for some positive integer $r$. Then Lemma 2.21 implies that $[J, L] \leq O(L)$ since $j \in J - L$. Hence $j \in J \leq Q$ and the remarks above with $W = \langle j, z \rangle$ yield a contradiction. Thus, if $j \in \mathfrak{z}(H - L)$, then $C_H(j)$ does not contain an intrinsic 2-component $J$ with $J/O(J) \cong \text{SL}(2, p^n)$ for some positive integer $r$. Hence, if $K$ is a perfect 2-component of $H$ with $K \neq L$ and $K/O(K)$ isomorphic to a Chevalley group over a finite field of order $q = p^n$ for some positive integers $s$, then $K/O(K) = \text{PSL}(2, q)$ and $q \neq 3$ or $p = 3$, $s$ is odd, $s \geq 3$ and $K/O(K) \cong 2G_2(q)$ by Lemma 5.2. Thus $L \text{char } H$ and $Q \text{ char } H$.

Let $S \in \text{Syl}_2(H)$. Thus $S \cap Q \leq S$, $S \cap L \leq S$, $S \cap Q \cap L = \langle z \rangle < Z(S)$ and $[S \in Q, S \cap L] = 1$. Note that all involutions of $L - \langle z \rangle$ are conjugate in $L$ and $z^Q \cap S \neq \{ z \}$ by Glauberman's $Z^*$-theorem [15, Corollary 1].

Let $\tau \in \mathfrak{z}(S - L)$ be such that $C_G(\tau)$ contains an intrinsic 2-component $K$ with $K/O(K) \cong L/O(L)$. Suppose that $C_G(\tau)$ contains a perfect 2-component $J$ such that $z \in J$ and $J/O(J)$ is isomorphic to one of the following groups: Spin$(7, q)$, Spin$(4, q)$, SU$(4, q)$, SL$(2, q^2)$, Sp$(4, q)$ or $n$ is even and $J/O(J) \cong \text{Spin}(7, \sqrt{q})$. Then $z \in Z(J)$, $J$ is a perfect 2-component of $C_G(\tau, z)$ and $J$ is contained in a unique perfect 2-component $Y$ of $C_G(\tau)$ by Lemma 2.19. Since $J$ is a perfect 2-component of $C_G(\tau)$, we conclude by induction that $Y/O(Y)$ is a Chevalley group over a finite field of characteristic $p$. Clearly $Y \neq K$ by Lemma 4.10 and hence $X = C_K(z)^{\infty} = O^2(C_K(z))$ is a perfect 2-component of $C_G(\tau, z) = C_H(\tau)$ such that $\tau \in X$ and $X/O(X) \cong K/O(K)$ by Lemma 2.15. Then $X$ is contained in a unique perfect 2-component of $C_Y^G(\tau, z)$ of $H$. By induction, $\mathfrak{z}^G/O(G)$ is isomorphic to a Chevalley group over a finite field characteristic of $p$. Hence $\mathfrak{z} = L$, $\mathfrak{z} = O(\mathfrak{z})X$ and $\tau \in X \leq \mathfrak{z} = L$. Since $\tau \notin L$, we have a contradiction. Moreover as $C_H(\mathfrak{L}) = \mathfrak{Q} \leq \mathfrak{H}$, we may apply Lemmas 4.10--4.11 to the quotient $\mathfrak{H}/\mathfrak{Q}$ to conclude that $\tau = \tau_1 \tau_2$ where $\tau_1 \in \mathfrak{z}(S \cap Q)$ and $\tau_2 \in \mathfrak{z}((S \cap L) - \langle z \rangle)$. Then $\mathfrak{C}_L(\mathfrak{C}_G(\tau)) = \mathfrak{C}_L(\langle \tau, \tau_1 \rangle) \leq \mathfrak{O}(L)$ and $\mathfrak{C}_L(\langle \tau, \tau_2 \rangle)$ contains a 2-component $X$ such that $z \in X$ and $X/O(X) \cong \text{SL}(2, q)$ by Lemma 4.10. Thus $\mathfrak{C}_G(\langle \tau, \tau \rangle)$ contains a 2-component $J$ such that $z \in J$ and $J/O(J) \cong \text{SL}(2, q)$. Suppose that $[K, z] \leq O(K)$. Then Lemma 2.15 implies that $Y = C_K(z)^{\infty} = O^2(C_K(z))$ is a 2-component of $C_G(\langle \tau, z \rangle)$ such that $\tau \in Y$ and $Y/O(Y) \cong L/O(L)$. Applying an observation
above with $W = \langle \tau, z \rangle$ yields a contradiction. Thus $[K, z] = K$ and Lemma 2.21 implies that $z \in K$. Then Lemma 4.10 implies that $C_G(\langle \tau, z \rangle)$ contains a 2-component $J_1$ such that $\tau \in J_1$ and $J_1/O(J_1) \cong SL(2, q)$. As noted above, this implies that $\tau \in L$ and we have a contradiction.

We have shown that if $\tau \in \mathfrak{g}(S)$ is such that $C_G(\tau)$ contains an intrinsic 2-component $K$ such that $K/O(K) \cong L/O(L)$, then $\tau \in L$. Hence $z^G \cap S = \mathfrak{g}(S \cap L)$, $z^G \cap H = \mathfrak{g}(L)$, $\langle z^G \cap H \rangle = L$ and $S \in \text{Syl}_2(G)$ since $Z(S \cap L) = \langle z \rangle$ and $S \cap L = \langle \mathfrak{g}(S \cap L) \rangle$ by Lemma 4.10(a).

Let $z_1 \in \mathfrak{g}(L - \langle z \rangle)$ and let $z_1 = z^g$ for $g \in G$. Then $z_1 \sim z_1 z$ in $L$, $z^G \cap H^g = \mathfrak{g}(L^g)$, $\langle z^G \cap H^g \rangle = L^g$ and $z \sim z_1 z$ in $L^g$. Hence $N_G(\langle z, z_1 \rangle)/C_G(\langle z, z_1 \rangle) = \Sigma_3$. Note that $\overline{Q} \cdot C_G(\overline{z}_1) \leq C_G(\overline{z}_1) = C_H(\overline{z}_1)$, $Q = O(H)C_G(z_1)$, $C_G(\overline{z}_1) = C_L(\overline{z}_1)$, $LC_H(z_1) = H$, $|L : C_L(z_1)|_2 = 2 = |H : C_H(z_1)|_2$ and $\langle z, z_1 \rangle$ is the center of a Sylow 2-subgroup of $C_G(z_1)$ by Lemma 4.10. Also $C_L(z_1)$ contains precisely three 2-components $J_1, J_2, J_3$ such that $z \in J_1, z_1 \in J_2, z_1 z \in J_3, O(J) \leq O(L)$ and $J/O(J) \cong SL(2, q)$ for $i = 1, 2, 3$. Set $E = \langle z, z_1 \rangle$, $M = C_G(E) = C_H(z_1)$, $\overline{J}_i = J_i$ if $q \neq 3$ and $\overline{J}_i = O(M)J_i$ if $q = 3$ for $i = 1, 2, 3$. Thus, as $C_L(z_1) \leq M$, we have $J_1 \leq M$ and $\overline{J}_i$ is a 2-component of $M$ for $i = 1, 2, 3$. Suppose that $\mathfrak{X} = \mathfrak{g}$ is a 2-component of $M$ such that $z_1 \in \mathfrak{X}$ and $\mathfrak{X}/O(\mathfrak{X}) \cong SL(2, q)$. Then we conclude from Lemma 2.21 that $O^2(\mathfrak{X}) \leq L$. If $q \neq 3$, then $\mathfrak{X} = O^2(\mathfrak{X}) \leq L$ and $\mathfrak{X} = J_2 = \overline{J}_2$. Suppose that $q = 3$ and $\mathfrak{X} \leq C_G(z_1)$. Theorem 3.11 and Lemma 4.11(f) to the group $\overline{H}/\overline{Q}$, we conclude that $O(C_G(\overline{z}_1)) \leq \overline{Q} \leq \overline{M} = C_H(\overline{z}_1)$ and hence $O(M) = M \cap O(H)$. This implies that $\overline{J}_i \leq \overline{M}$ and $\overline{J}_i \cong SL(2, q)$ for $i = 1, 2, 3$. Also $C_M(\overline{J}_1, \overline{J}_2, \overline{J}_3) = \overline{Q} \times \langle \overline{z}_1 \rangle$ by Lemma 4.11(f). Moreover Lemma 4.10 implies that one may choose $z_1$ such that $z_1 \in S \cap L$, $z_1^T = z_1(z)$, $C_G(z_1) = T \in \text{Syl}_2(M)$, $Z(T \cap L) = E \leq S$ and $|S : T| = 2$. By the Frattini argument, there is a 3-element $\pi \in N_G(T) \cap N_G(E)$ such that $\pi$ acts transitively on $E^\ast$ and on $\overline{J}_1, \overline{J}_2, \overline{J}_3$. Thus

$$\langle S, \pi \rangle \leq N_G((S \cap Q) \times \langle z_1 \rangle) \leq N_G(T) \cap N_G(E)$$

since $S \cap Q = T \cap Q$. Suppose that $S \cap Q \neq \langle z \rangle$. Then $(S \cap Q) \cap ((S \cap Q)') \neq 1$. Since $S \cap Q \cap E = \langle z \rangle$, we have

$$((S \cap Q)') \cap E = \langle z' \rangle \quad \text{and} \quad (S \cap Q) \cap ((S \cap Q)') \cap E = 1.$$  

Let $\tau \in \mathfrak{g}((S \cap Q) \cap ((S \cap Q)'))$. Then $X = C_G(\tau)$ is a 2-component of $C_G(\tau, z)$ such that $S \cap L \leq X$, $Z^*(X) = O(X) \times \langle z \rangle$ and $X/O(X) = \text{Spin}(7, q)$. Also $Y = C_G(\tau, z')$ is a 2-component of $C_G(\tau, z')$ such that $E = \langle z, z' \rangle \leq Y$, $Z^*(Y) = O(Y) \times \langle z' \rangle$ and $Y/O(Y) \cong \text{Spin}(7, q)$. A previous observation implies that $\langle z, z' \rangle = E \leq L_2(C_G(\tau))$. Since $X \leq L_2(C_G(\tau))$, we have $X, z' \leq O(L_2(C_G(\tau))) \cap X = O(X)$. Hence $z' \in Z^*(X) = O(X) \times \langle z \rangle$. Since $z' \neq z$, we conclude that $S \cap Q = \langle z \rangle$, $Q = O(H) \times \langle z \rangle$, $H' \leq O(H)L$ by Lemma 4.11, $S' \leq S \cap L$ and $T' \leq T \cap L$.

Applying [32, Theorem 3.4], we conclude that $S \cap L \neq S$. Then, Lemma 4.11 applied to $\overline{H}/\overline{Q} = \overline{H}/\langle \overline{z} \rangle$ yields the existence of a normal subgroup $V$ of $S$ such
that $S \cap L \leq V \leq S$, $|V/(S \cap L)| \leq 2$, $S/V$ is cyclic, \( \{v \in V \mid v^2 \in \langle z \rangle \} \subseteq S \cap L \) and $S \neq V$ if and only if there is an element $x \in S - L$ such that $x^2 \in \langle z \rangle$. Since $\Omega(S) = \Omega(S \cap L) = \langle z \rangle$, it follows that $\Omega(S) = \Omega(S \cap L) = \langle z \rangle$. By [20, Corollary 2.1.2], Note that $T \cap L \in \text{Syl}_2(C_H(z))$, $Z(T \cap L) = E$, $\Omega(T \cap L) = T \cap L$ and $\Omega(S \cap L) = S \cap L$ by Lemma 4.10. Hence $T \cap L$ and $S \cap L$ are weakly closed in $T$ and $S$ respectively.

Moreover, $S = (S \cap L)T$ since $H = LM$, $S \cap L \in \text{Syl}_2(L)$ and $T \in \text{Syl}_2(M)$. Also $|(S \cap L)/(T \cap L)| = 2$, $T \cap L \triangleleft S$, $S \cap L \triangleleft S \in \text{Syl}_2(N_C(T) \cap N_C(E))$, $[S, T] \leq T^*[S \cap L, T] \leq T \cap L$ and $(N_C(T) \cap N_C(E))/N_{2s}(T) \cong \Sigma_3$ imply that $\langle S, \pi \rangle$ acts trivially on $T/(T \cap L)$.

As $H/(O(H)L)$ is abelian, we have $O(H)LV \triangleleft H$. Suppose that $Z(V) \neq \langle z \rangle$. Then $V \neq S \cap L$ and there is a subgroup $F \leq Z(V)$ such that $z \in F$ and $|F| = 4$. Since $\{v \in V \mid v^2 \in \langle z \rangle\} = \{v \in S \cap L \mid v^2 \in \langle z \rangle\}$, we have $F \leq S \cap L$. Since $Z(S \cap L) = \langle z \rangle$, this is impossible. Thus $Z(V) = \langle z \rangle$. Also $V = (S \cap L)(T \cap V)$, so that $|V/(V \cap T)| = 2$ and $V \cap T \in \text{Syl}_2(M \cap (O(H)LV))$.

We shall now demonstrate the following condition.

\[ (*) \text{ If } G \subseteq \{S \cap L, V - (S \cap L), S - V\} \text{ and } x \in G, \text{ then } x \text{ is conjugate in } G \text{ to an element } y \in G \text{ such that } \Omega_t(\langle y \rangle) = \langle z \rangle. \]

For, if $x$ and $G$ satisfy the hypotheses of $(*)$, we may clearly assume that $\Omega_t(\langle x \rangle) = \langle j \rangle$ for some involution $j \in S - \langle z \rangle$. Then $j \in S \cap L$ and by Lemma 4.10, there is an element $g \in H$ such that $j^g = z_1$ and $x^g \in T \cap G$ since $T \in \text{Syl}_2(C_H(z_1))$, $T \cap V \in \text{Syl}_2(O(H)LV) \cap C_H(z_1)$ and $T \cap L \in \text{Syl}_2(C_L(z_1))$.

However, $(S, \pi) \triangleleft N_C(T) \cap N_C(T \cap L)$ and $\langle S, \pi \rangle$ acts trivially on $T/(T \cap L)$ and $T \cap L \triangleleft T \cap V \triangleleft T$. Thus there is an element $h \in \langle S, \pi \rangle$ such that $j^{zh} = z$ and $x^g \in G$. We have established condition $(*)$ above.

Suppose that $V \neq S$. Then there is an element $x \in S - V$ such that $x^2 = z$. By [20, Corollary 2.1.2], $x$ is conjugate in $G$ to an element $x_1$ in $V$. By condition $(*)$, $x_1$ is conjugate in $G$ to an element $y \in V$ such that $y^2 = z$. Thus $x \sim y$ in $G$. Since $y^2 = z = x^2$, we have $x \sim y$ in $H$. However $x \notin O(H)LV \triangleleft H$ and we have a contradiction. Thus $V = S$ and $|S/(S \cap L)| = 2$.

Choose an element $x \in S - (S \cap L)$ of minimal order. Since $\Omega(S) = \Omega(S \cap L)$, $|x| \geq 2$. Also $ccl_G(x^{2i}) \cap S \leq S \cap L$ for all integers $i \geq 1$. Then [20, Corollary 2.1.2] and condition $(*)$ imply that there are elements $w$ and $v$ in $ccl_G(x)$ such that $w \in S - (S \cap L)$, $v \in S \cap L$ and $\Omega_t(\langle w \rangle) = \Omega_t(\langle v \rangle) = \langle z \rangle$. Thus $w \sim v$ in $H$. Since $w \notin O(H)LV \triangleleft H$, we have a contradiction. We conclude that $L/O(L)$ is not isomorphic to $\text{Spin}(7, q)$.

In the general case, Lemma 5.4 implies that there is an involution $u \in L - Z^*(L)$ such that $C_L(u)$ possesses 2-components $J_1$ and $J_2$ such that $u \in J_1$, $J_1/O(J_1) \cong \text{SL}(2, q)$, $\{z, uz\} \cap J_2 \neq \emptyset$, $J_2$ is of $\Omega(\langle p \rangle)$-type and $J_2/Z^*(J_2)$ is isomorphic to a Chevalley group over a finite field of order $q$. Set $W = \langle u, z \rangle$, $M = C_G(W)$, $\frac{J_1}{J_1}$, if $J_i$ is perfect and $\frac{J_1}{O(M)J_i}$ if $J_i$ is solvable for $i = 1, 2$. Then $\frac{J_1}{J_2}$ and $\frac{J_2}{J_2}$ are 2-components of $M$, $u \in \frac{J_1}{J_1}$, $\frac{J_1}{O(J_1)} \cong \text{SL}(2, q)$, $\{z, uz\} \cap \frac{J_2}{J_2} \neq \emptyset$, $\frac{J_2}{J_2}$ is of $\Omega(\langle p \rangle)$-type and $\frac{J_2}{Z^*(J_2)} \cong J_2/Z^*(J_2)$. From an observation above, we conclude that $C_L(u)$ contains a unique perfect 2-component $K$ such that $M \leq N_C(K)$, $\langle O^2(\frac{J_1}{J_1}), O^2(\frac{J_2}{J_2}) \rangle \leq K$, $u \in Z(K)$, $z \in K - Z^*(K)$ and $K/Z^*(K)$ is a simple
Chevalley group over a finite field of characteristic $p$. Note that $\frac{f_1}{O(f_1)}$ and $\frac{f_2}{O(f_2)}$ are both isomorphic to Chevalley groups over a finite field of order $q$. Consequently Lemma 5.8 implies that $K/O(K) \cong \text{Spin}(2m + 1, q)$ for some odd integer $m \geq 3$. From the preceding discussion and Lemma 5.8, we must have $m \geq 5$, $J_2 = \frac{f_2}{O(J_2)} \cong \text{Spin}(2(m - 1), q, 1)$ and $Z^*(K) = O(K) \times \langle u \rangle$. Consequently we may assume that $L/O(L) \cong \text{Spin}(2r + 1, q)$ for some odd integer $r \geq 5$. Thus Lemma 4.12 implies that we may assume that $J_1/O(J_1) \cong J_2/O(J_2) \cong \text{SL}(2, q)$. Since $\text{SL}(2, q)$ and $\text{Spin}(2(m - 1), q, 1)$ are not isomorphic, we have a contradiction and our proof of Theorem 1 is complete.

### 7. A proof of Theorem 2

We now commence to prove Theorem 2. Thus let $G$, $W$, $W^* = \{z_1, z_2, z_3\}$, $L_1$, $L_2$, $p_1$ and $p_2$ satisfy the hypotheses of Theorem 2 and assume that $G$ is a counterexample of minimal order to the theorem.

Assume that $O(G) \neq 1$. Set $\bar{G} = G/O(G)$. Then $z_i \in L_i$, $L_i$ is a 2-component of $C_G(W)$ and $\bar{L}_i$ is of $G(p_i)$-type by Lemmas 2.17 and 2.28. Hence, since $|\bar{G}| = |G|$, either (a) $O^2(\bar{L}_i) = O^2(L_i) \leq \leq G$ or (b) $O^2(\bar{L}_i) = O^2(L_i)$ is contained in a unique perfect 2-component $K_i$ of $\bar{G}$ such that $K_i \cong M_{11}$ or $K_i$ is isomorphic to a perfect Chevalley group over a finite field of characteristic $p_i$ for $i = 1$ and 2. Let $i \in \{1, 2\}$. Thus (b) holds and Lemma 2.18 yields a contradiction. Hence $O(G) = 1$.

Suppose that $L_1$ and $L_2$ are both solvable. Thus $p_1 = p_2 = 3$. Let $M = C_G(z_1)$ and $J_1 = O(M)O^3(L_1)$. Thus $O^2(L_1) \leq O^2(J_1)$ by Lemma 2.9. Assume, for the moment, that $J_1 \leq \leq M$. Suppose that $O^2(J_1) \neq O_2(G)$. Then $O(M) = 1$, $E(G) = E(M)$ and $J_1 = O^3(L_1) \leq \leq G$ by Lemma 2.23. Since $O^2(J_1) = O^2(L_1)$, we have $O^2(L_1) \leq \leq G$. Suppose that $O^2(J_1) \neq O_2(G)$. Then Lemmas 2.21 and 2.22 imply that there is a unique perfect component $K$ of $G$ such that $O^2(L_1) \leq O^2(J_1) \leq K$. Clearly $J_1 \leq N_G(K)$ and $z_1 \notin Z(K)$. Then Lemma 6.1 applied to $KL_1$ implies that $K \cong M_{11}$ or $K$ is a Chevalley group over a field of 3 elements. Now assume that $J_1$ is not subnormal in $M$. Then Lemma 2.26 implies that $O^2(L_2)$ is contained in a unique perfect 2-component $K$ of $M$. Also $z_2 \notin Z^*(K)$, $K = C_G(W) = C_M(z_2)$-invariant and $[K, O^3(L_1)] = K$. Applying Lemma 6.1 to $KL_2$, we conclude that $K/O(K) \cong M_{11}$ or $K/O(K)$ is a Chevalley group over a field of order 3. Then Lemma 2.25 implies that $O^2(L_1) \leq K$ and $z_1 \in K$. Also Lemma 5.8(b) implies that $K$ is of $G(3)$-type. By Lemma 2.19, $K$ is contained in a unique component $K$ of $G$. Then $O^2(L_i) \mid i = 1, 2 \leq G$ and Theorem 1 eliminates this case. A similar argument applied to $C_G(z_2)$ now yields a contradiction. Thus, by symmetry, we may assume that $L_1$ is perfect.

Set $M = C_G(z_1)$ and $J_1 = O(M)L_1$. Assume, for the moment, that $J_1 \leq \leq M$. Then there is a unique perfect component $K$ of $G$ such that $L_1 \leq J_1^{(\infty)} \leq K$. Then, since $J_1^{(\infty)} = O(J_1^{(\infty)})L_1$ is a 2-component of $C_K(z_1)$, Theorem 1 implies that $K$ is a Chevalley group over a finite field of characteristic $p_1$. Suppose that $O^2(L_2)$ is contained in a perfect 2-component $K_2$ of $M = C_G(z_1)$. Then $O^2(L_2)$ is not contained in $Z^*(K_2)$, $K_2$ is unique, $K_2 = [L_2(M), O^2(L_2)]$ and $L_2 \leq N_G(K_2)$. Then Theorem 1 applied to the group $K_2L_2$ implies that $K_2/O(K_2) \cong M_{11}$ or $K_2/O(K_2)$ is isomorphic to a Chevalley group over a finite field of characteristic $p_2$. Suppose that $K_2 \leq K$. If $z_1 \in Z(K_2)$, then $K_1 = K_2$ and $p_1 = p_2$ which is impossible. Thus $z_1 \notin Z(K_1)$. Set $\bar{K}_1 = K_1/Z(K_1)$. Then $\bar{K}_2$ is a perfect 2-component of
$C_K(\tilde{z}_1), p_1 = p_2$ and $\tilde{K}_2$ is a Chevalley group over a field of characteristic $p_1$ by Lemma 5.1. As $\langle O^2(L_1), O^2(L_2) \rangle \leq K_1$, this is impossible. Hence, since $z_1 \in K_1, K_2$ is contained in a unique component $X$ of $G$ with $X \neq K_1$ by Lemma 2.19. Since $[K_1, X] = 1, X = K_2$ and again we have a contradiction. Consequently $O^2(L_2)$ is not contained in a perfect 2-component of $M$ and hence $L_2$ is a solvable 2-component of $C_M(z_2) = C_G(W)$ by Lemma 2.19. But then Lemmas 2.21–2.23 imply that $O(C_G(W)) \leq O(M)$, $J_2 = O(M)L_2$ is a solvable 2-component of $M$ and $[J_2, X] = 1$ for all components $X$ of $G$ with $X \neq K_1$. However $O^2(L_2) \leq O^2(J_2)$ and $J_2 \leq N_G(K_1)$. Suppose that $O^2(J_2) \leq K_1$. Then Lemma 5.7 applied to the group $K_1J_2$ implies that $p_2 = 3 = p_1$. Since $O^2(L_2) \leq O^2(J_2)$, this is impossible. Hence $O^2(J_2) \neq K_1$ and [1, Theorem 2(3)] implies that $[O^2(J_2), E(G)] = 1$. Consequently $O^2(J_2) \leq O_2(G)$ by Lemma 2.22. Then $O^2(L_2) = O^2(J_2) \leq G$, which is impossible. Consequently $J_1 = O(M)L_1$ is not subnormal in $M$.

Now Lemma 2.26 implies that $O^2(L_2)$ is contained in a unique perfect 2-component $K$ of $M$. Also $z_2 \notin Z^*(K), K = C_G(W) = C_M(z_2)$-invariant and $L_1 \leq K$. Thus $z_1 \in Z(K), \bar{K} = K/Z^*(K)$ is a Chevalley group over a field of characteristic $p_2$ by Theorem 1 applied to $KL_2$. Since $\bar{K}$ is a perfect 2-component of $C_K(\tilde{z}_2)$, we have $p_1 = p_2$ by Lemma 5.1. Also $K$ is contained in a unique component of $\mathcal{X}$ of $G$ by Lemma 2.19, $L_2 \leq K$ if $L_2$ is perfect and $C_K(z_2)$ contains a solvable 2-component $X_2$ such that $L_2 = O(L_2)X_2, O^2(L_2) = O^2(X_2)$ and $O(C_K(z_2)) \leq O(K)$ if $L_2$ is solvable by Lemma 5.7. Moreover, $K$ is properly contained in a unique component $\mathcal{X}$ of $G$. Then, Theorem 1 implies that $K$ is not of $\mathfrak{S}(p_1)$-type. Thus $\bar{K} \cong PSL(2r, q)$ or $\bar{K} \cong PSU(2r, q)$ where $r$ is an integer, $r \geq 2$ and $q = p_1^s$ for some positive integer $s$. Note that $\bar{L}_1$ is a perfect component of $C_{\bar{K}}(\tilde{z}_2)$ with $|Z(\bar{L}_1)|_2 \neq |\mathfrak{S}(\bar{L}_1/Z(\bar{L}_1))|_2$ since $z_1 \in Z(L_1) \cap Z(K)$. Then Lemma 5.5 implies that $\bar{L}_1 = \bar{L}_2$ and $\bar{L}_1/Z(\bar{L}_1) \cong PSL(r, q^2)$. Hence $L_1 = L_2$ by Lemma 2.18. Since $L_1/Z^*(L_1) \cong \bar{L}_1/Z(\bar{L}_1)$, the Sylow 2-subgroups of $Z^*(L_1)$ are cyclic. Hence $z_1 = z_2$. This contradiction completes our proof of Theorem 2.

We remark that Theorem 1 follows easily from Theorem 2. For, assume Theorem 2 and let $G, z, L$ and $p$ be as in the hypotheses of Theorem 1. Then $O^2(G)$ is 2-quasisimple and, by Lemma 6.1, we may assume that $L$ is perfect. Then, by Lemma 5.4, there is an involution $t \in L - Z^*(L)$ such that $C_L(t)$ contains 2-components $J$ and $K$ of $\mathfrak{S}(p)$-type with $t \in J$ and $Z(K) \cap \{z, tz\} \neq \emptyset$. Set $W = \langle t, z \rangle$. Then Theorem 2 yields the conclusion of Theorem 1.

8. A proof of Theorem 3. We now present a proof of Theorem 3. Thus let $G, W, L, p$ and $w$ satisfy the hypotheses of Theorem 3 and assume that $G$ is a counterexample to Theorem 3.

Set $H = C_G(w), \bar{H} = H/O(H)$ and $K = \langle L^{L_z(H)} \rangle$ and let $t \in W - \langle w \rangle$. Thus $\bar{L}$ is a perfect 2-component of $C_{\bar{K}}(i)$ and $K = K_1K_2$ where $K_1$ and $K_2$ are distinct 2-components of $H$ by Lemma 2.20. Also $\bar{K} = \bar{K}_1 \ast \bar{K}_2, \bar{L} = \langle \bar{k}_1 \bar{k}_2 \mid k_1 \in \bar{K}_1 \rangle$ and the mapping $\bar{k}_1 \rightarrow \bar{k}_1 \bar{k}_2$ is a homomorphism of $\bar{K}_1$ onto $\bar{L}$ by [17, Lemma 2.1]. Consequently $K_1$ and $K_2$ are of $\mathfrak{S}(p)$-type by Lemma 2.28. Thus $w \notin K_1 \cup K_2$ by Theorem 1.
Suppose that $\overline{K}_1 \cap \overline{K}_2 = 1$. Then there is an involution $k_1 \in Z^*(K_1)$ such that $w = k_1 k_1^i$, $k_1 \neq k_1^i$, $[k_1, k_1^i] = 1$ and it is clear from Lemma 2.15 that Theorem 2 applies to the 4-subgroup $\langle k_1, k_1^i \rangle$ of $G$ to yield a contradiction. Thus $\overline{K}_1 \cap \overline{K}_2 \neq 1$.

Hence there is an involution $k \in Z^*(K_1) \cap Z^*(K_2) \cap C_H(t)$. Since $kk^i = 1$, we conclude from Lemma 2.27 that
$$L/Z^*(L) \cong K_1/Z^*(K_1) \cong K_2/Z^*(K_2) \cong P\Omega(m, p^n, \pm 1)$$
for some positive integers $m$, $n$, with $m$ even and $m \geq 8$, $|Z^*(L)|_2 = 2 < |\Omega(L/Z^*(L))|_2 = |Z^*(K_1)|_2 = |Z^*(K_2)|_2$ since $w \in K_1 \cup K_2$. Moreover there is an element $v_1 \in Z^*(K_1)$ such that $v_1^2 \in \langle k \rangle$, $v_1, k \in Syl_2(Z^*(K_1))$, $v_1^i \neq v_1$, $[v_1, v_1^i] = 1$ and $w = v_1 v_1^i$. Set $v_2 = v_1^i$, $M = C_G(k)$, $M = M/(O(M) \times \langle k \rangle)$ and $J_i = C_K(k)^{(\infty)} = O^2(C_K(k))$ for $i = 1, 2$.

Then Lemmas 2.14 and 2.15 imply that $J_i$ is a 2-component of $C_M(w)$ with $K_i = O(K_i)J_i$ and $\langle v_1, k \rangle \in Syl_2(Z^*(J_i))$ for $i = 1, 2$, $O(\tilde{M}) = 1$, $\tilde{w} \in \tilde{G}(\tilde{M})$ and $\tilde{J}_i$ is a 2-component of $C_{\tilde{M}}(\tilde{w})$ such that $\langle \tilde{v}_1 \rangle \in Syl_2\big(Z^*(\tilde{J}_i)\big)$ and $\tilde{J}_i/Z^*(\tilde{J}_i) \cong L/Z^*(L)$ for $i = 1, 2$. Also $w \in \langle \tilde{v}_1, \tilde{v}_2 \rangle \cong E_4$. Set $B = \langle v_1, v_2, k \rangle$. Thus $B$ is abelian of order 8, $w \in B$, $\tilde{B} \cong E_4$ and $[K_i, B] \leq O(K_i)$ and $[J_i, O(J_i)] \leq O(J_i)$ for $i = 1, 2$. Set $J_i = C_B(j_i)^{(\infty)} = O^2(j_i)$ and $j_i$ is a 2-component of $C_B(j_i) = C_M(j_i)$ such that $Z^*(j_i) = O(j_i) \times \langle k, v_i \rangle$ for $i = 1, 2$. Also $J_i$ is a 2-component of $C_{\tilde{M}}(\tilde{B})$ such that $Z^*(\tilde{j}_i) = O(j_i) \times \langle \tilde{v}_i \rangle$ and $\tilde{j}_i/Z^*(\tilde{j}_i) \cong \tilde{j}_i/Z^*(\tilde{j}_i) \cong \tilde{j}_i/Z^*(\tilde{j}_i) \cong L/Z^*(L)$ for $i = 1, 2$ by Lemmas 2.12 and 2.14. If $\tilde{j}_i \leq M$, then $O(M) \tilde{j}_i \leq \tilde{M}$ and Theorem 1 yields a contradiction for $i = 1$ or 2. Thus Theorem 2 and Lemmas 2.17–2.18 imply that $J_i$ is contained in a unique perfect 2-complete $\mathcal{K}$ of $M$ such that $\mathcal{K}/O(\mathcal{K})$ is a Chevalley group over a finite field of characteristic $p$. Since $J_i = O(J_i)J_i$, we have $J_i \leq \mathcal{K}$. If $[\mathcal{K}, w] \leq Z^*(\mathcal{K})$, then $\mathcal{K} = O(\mathcal{K})J_1$ and Theorem 1 yields a contradiction since $k \in \mathcal{K}$. Thus $[\mathcal{K}, w] = \mathcal{K}$ and $w \leq B \leq L_2(C_M(w)) \leq L_2(M)$ so that $w$ acts as an inner automorphism on $\mathcal{K} = \mathcal{K}/Z^*(\mathcal{K})$. However $J_i$ is a perfect 2-component of $C_{\mathcal{K}}(w)$ such that $J_i/Z^*(J_i) \cong L/Z^*(L)$ and $\mathcal{K}$ is not of $\Omega(p)$-type by Theorem 1 since $k \in \mathcal{K}$. Consequently we have $\mathcal{K} \cong PSL(2r, q)$ or $\mathcal{K} \cong PSU(2r, q)$ where $r$ is an integer with $r \geq 2$ and $q = p^s$ for some positive integer $s$. Then Lemma 5.5 and the fact that $J_i/Z^*(J_i) \cong P\Omega(m, p^n, \pm 1)$ for positive integers $m$, $n$, with $m \geq 8$ yield a contradiction. This completes our proof of Theorem 3.

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