ON A STRONG FORM OF OLIVER'S p-GROUP CONJECTURE

DAVID J. GREEN, LÁSZLÓ HÉTHELYI, AND NADIA MAZZA

Abstract. We introduce a strong form of Oliver's p-group conjecture and derive a reformulation in terms of the modular representation theory of a quotient group. The Sylow p-subgroups of the symmetric group S_n and of the general linear group $GL_n(\mathbb{F}_q)$ satisfy both the strong conjecture and its reformulation.

1. Introduction

Bob Oliver proved the Martino–Priddy Conjecture, which states that the p-local fusion system of a finite group G uniquely determines the p-completion of its classifying space BG [10, 11]. Finite groups are not however the only source of fusion systems: the p-blocks of modular representation theory have fusion systems too, and there are other exotic examples as well. An open question in the theory of p-local finite groups claims that every fusion system has a unique p-completed classifying space – see [1] for a survey article on this field.

In [10], Oliver introduced the characteristic subgroup $\mathfrak{X}(S)$ of a finite p-group S. For odd primes he showed that unique existence of the classifying space would follow from the following conjecture. Recall that $J(S)$ denotes the Thompson subgroup of S generated by all elementary abelian subgroups of greatest rank.

Conjecture 1.1 (Oliver; Conjecture 3.9 of [10])**.** *Let p be an odd prime and S a finite p-group. Then $J(S) \leq \mathfrak{X}(S)$.*

In [4], the first two authors and Lilienthal obtained the following reformulation of Oliver's conjecture.

Conjecture 1.2 (Conjecture 1.3 of [4])**.** *Let p be an odd prime and G a finite p-group. If the faithful $\mathbb{F}_pG$ module V is an F-module, then there is an element $1 \neq g \in \Omega_1(Z(G))$ such that the minimal polynomial of the action of g on V divides $(X-1)^{p-1}$.*

Recall that V is by definition an F-module if there is an *offender*, i.e., an elementary abelian subgroup $1 \neq E \leq G$ such that $\dim(V) - \dim(V^E) \leq \operatorname{rank}(E)$. Theorem 1.2 of [4] states that Conjecture 1.1 holds for every p-group S with $S/\mathfrak{X}(S) \cong$

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G if and only if Conjecture 1.2 holds for G. Note that by [4, Lemma 2.3], every p-group G does occur as some $S/\mathfrak{X}(S)$.

In this paper we modify Oliver's construction of $\mathfrak{X}(S)$ slightly to obtain a new characteristic subgroup $\mathcal{Y}(S)$, with $\mathcal{Y}(S) \leq \mathfrak{X}(S)$ for p odd and $\mathcal{Y}(S) = S$ for $p = 2$: see §2. We therefore propose the following strengthening of Oliver's conjecture:

Conjecture 1.3. *Let p be a prime and S a finite p-group. Then $J(S) \leq \mathcal{Y}(S)$.*

This is indeed a strengthening: if $p = 2$ then $\mathcal{Y}(S) = S$ and so Conjecture 1.3 is true, whereas Oliver's conjecture is false in general; and for $p \geq 3$ we have $\mathcal{Y}(S) \leq \mathfrak{X}(S)$. We recently learnt that Justin Lynd raises the same question in his paper [8]; note that his $\mathfrak{X}_3(S)$ is our $\mathcal{Y}(S)$.

This conjecture admits a module-theoretic reformulation as well. An element $g \in G$ is said to be *quadratic* on the $\mathbb{F}_pG$-module V if its action has minimal polynomial $(X-1)^2$. Note that if V is faithful then quadratic elements must have order p.

Conjecture 1.4. *Let p be a prime and G a finite p-group. If the faithful $\mathbb{F}_pG$-module V is an F-module, then there are quadratic elements in $\Omega_1(Z(G))$.*

Observe that Conjecture 1.4 is a strengthening of Conjecture 1.2, and trivially true for $p = 2$. Our first actual result is the equivalence of the two new conjectures:

Theorem 1.5. *Let p be an odd prime and G a finite p-group. Then Conjecture 1.3 holds for every finite p-group S with $S/\mathcal{Y}(S) \cong G$ if and only if Conjecture 1.4 holds for every faithful $\mathbb{F}_pG$-module V.*

Proof. The proof of [4, Theorem 1.2] adapts easily to the present case, given the results on Y-series and on $\mathcal{Y}(G)$ in Lemma 2.1. □

Note that Conjecture 1.4 holds if G is metabelian or of (nilpotence) class at most four: for though [5, Theorem 1.2] only purports to verify the weaker Conjecture 1.2, the proof that is given there only uses the assumptions of Conjecture 1.4.

Our main result is the following:

Theorem 1.6. *For $n \geq 1$ and a prime p, let P be a Sylow p-subgroup of the symmetric group S_n. Then Conjecture 1.3 holds with $S = P$, and Conjecture 1.4 holds with $G = P$.*

Proof. For $p = 2$ there is nothing to prove, so assume that $p \geq 3$. It is well known (see [6, III.15]) that P is a direct product $P = \prod_{i=1}^m P_{r_i}$, where $r_i \geq 1$ for all i, and P_r is the iterated wreath product $C_p \wr C_p \wr \cdots \wr C_p$ with r factors C_p. Recall that the Sylow p-subgroups of S_{p^r} are isomorphic to P_r.

As $P_1 \cong C_p$ is abelian, and P_r satisfies Hypothesis 5.2 for $r \geq 2$ by Corollary 6.6, Lemma 5.3 tells us that $G = P$ satisfies Conjecture 1.4.

For Conjecture 1.3, observe that $J(G_1 \times G_2) = J(G_1) \times J(G_2)$ for any groups G_1, G_2. Huppert shows in [6, Satz III.15.4a)] that $J(P_r)$ is an abelian normal subgroup of P_r. Hence $J(P)$ is abelian and normal in P. So $J(P) \leq \mathcal{Y}(P)$ by Lemma 2.1 (3). $\square$

The fact that they provide the proper degree of generality for the proof of [5, Theorem 1.2] was not the only reason for introducing $\mathcal{Y}(S)$ and its companion Conjecture 1.4.

Theorem 1.7. *Let p be a prime and G a finite p-group. Suppose that G satisfies one of the following conditions:*

(1) *G is generated by its abelian normal subgroups; or more generally*
(2) *$\mathcal{Y}(G) = G$; or more generally*
(3) *$\Omega_1(Z(\mathcal{Y}(G))) = \Omega_1(Z(G))$.*

Then Conjecture 1.4 holds for G.

Proof. Clearly (2) $\Rightarrow$ (3). For (1) $\Rightarrow$ (2), note from Lemma 2.1 (3) that every abelian normal subgroup lies in $\mathcal{Y}(G)$.

Now suppose that V is a faithful F-module. Timmesfeld's replacement theorem in the version given in [5, Theorem 4.1] states that there are quadratic elements in G. Hence by Lemma 8.1 there are quadratic elements which are *late* in the sense of §8. But Lemma 8.2 says that if a quadratic element is late then it lies in $\Omega_1(Z(\mathcal{Y}(G)))$. So if (3) holds then there are quadratic elements in $\Omega_1(Z(G))$. $\square$

For $p \geq 5$, this result has been obtained independently by Justin Lynd: see the remark after [8, Lemma 8]. One application of this result is the following:

Theorem 1.8. *Let $n \geq 1$, let p be a prime, and let q be any prime power. Let P be a Sylow p-subgroup of the general linear group $GL_n(\mathbb{F}_q)$. Then Conjecture 1.3 holds for $S = P$, and Conjecture 1.4 holds for $G = P$.*

Proof. First we consider the case where q is a power of p (defining characteristic). If we can show that P is generated by its abelian normal subgroups then we are done: for this is condition (1) of Theorem 1.7, which implies both condition (2) and the conclusion of that theorem. Now, we may choose P to be the group of upper triangular matrices with ones on the diagonal. This copy of P is generated by the collection of abelian normal subgroups $N_{i,j}$ for $1 \leq i < j \leq n$, where

$$N_{i,j} = \{A \in P \mid A_{aa} = 1;\ A_{ab} = 0 \text{ for } a \neq b \text{ whenever } a > i \text{ or } b < j\}\,.$$

See also [13].

Now we turn to the case where $(p, q) = 1$ (coprime characteristic). It was first shown by Weir [12] that P is a direct product of iterated wreath products $C_{p^r} \wr C_p \wr \cdots \wr C_p$, where the C_{p^r} is the "innermost" factor in the wreath product. These iterated wreath products satisfy Hypothesis 5.2 by Lemma 5.6 (1) and Proposition 6.1. The one exception is of course C_{p^r}, which is abelian. So any direct product of these groups satisfies Conjecture 1.4 by Lemma 5.3.

We now turn to Conjecture 1.3 in coprime characteristic. As $\mathcal{Y}(P) = P$ if $p = 2$, we may assume that p is odd. We shall show that $J(P)$ is abelian, from which $J(P) \leq \mathcal{Y}(P)$ follows by Lemma 2.1 (3). Since $J(G \times H) = J(G) \times J(H)$, we may assume that P is one iterated wreath product. Applying Lemma 5.4, we see that $J(P)$ is elementary abelian by induction on the number of iterations. □

The method of Theorem 1.7 can also be used to show the following:

Theorem 1.9. *Let p be a prime, G a finite p-group and V a faithful $\mathbb{F}_pG$-module with no quadratic elements in $\Omega_1(Z(G))$. Then the subgroup generated by all quadratic elements of G is a proper subgroup of G.*

Proof. Let $H \leq G$ be the subgroup generated by all *last* quadratic elements, c.f. §8. By Lemma 8.1 we know that $H \neq 1$. So $H \not\leq Z(G)$, for $Z(G)$ has no quadratic elements. Hence $C_G(H) \lneq G$. But $C_G(H)$ contains every quadratic element by Lemma 8.5. □

Structure of the paper. In Section 2 we construct and study the characteristic subgroup $\mathcal{Y}(G)$ of G. We then prove some orthogonality relations in §3 and study weakly closed elementary abelian subgroups in §4. Then in Section 5 we introduce a hypothesis which constitutes a strengthening of Conjecture 1.4 for groups with cyclic centre. In Section 6 we demonstrate the key property of this hypothesis: it remains valid when passing from a group P to the wreath product $P \wr C_p = P^p \rtimes C_p$.

In Section 7 we introduce the notions of deepest commutators and locally deepest commutators. In Section 8 we use late and last quadratics to demonstrate some lemmas which are required by the proofs of Theorem 1.7 and 1.9. Finally we show in §9 that powerful p-groups satisfy Conjecture 1.4.

2. A modification of Oliver's construction

Definition. Let p be a prime, S a finite p-group and $N \trianglelefteq S$ a normal subgroup. A *Y-series* in S for N is a sequence $1 = Y_0 \leq Y_1 \leq \cdots \leq Y_n = N$ of normal subgroups $Y_i \trianglelefteq S$ such that

$$[\Omega_1(C_S(Y_{i-1})), Y_i; 2] = 1$$

holds for each $1 \leq i \leq n$. The unique largest normal subgroup N which admits a Y-series is denoted $\mathcal{Y}(S)$.

Lemma 2.1. *Let p be a prime and S a finite p-group.*

1. *If $1 = Y_0 \leq Y_1 \leq \cdots \leq Y_n = N$ is a Y-series in S and $M \trianglelefteq S$ also admits a Y-series, then there is a Y-series for MN starting with $Y_0, \ldots, Y_n$.*
2. *There is indeed a unique largest normal subgroup $\mathcal{Y}(S)$ admitting a Y-series. Moreover, $\mathcal{Y}(S)$ is characteristic in S.*
3. *Every abelian normal subgroup of S lies in $\mathcal{Y}(S)$. In particular, $\mathcal{Y}(S)$ is centric in S.*

(4) *If p is odd then $\mathcal{Y}(S) \leq \mathfrak{X}(S)$. If $p = 3$ then $\mathcal{Y}(S) = \mathfrak{X}(S)$.*
(5) *If $p = 2$ then $\mathcal{Y}(S) = S$.*

Proof. (1) See the corresponding proof for Q-series, at the bottom of p. 334 in [10].
(2) Unique existence follows from the first part. It is characteristic because it is unique.
(3) The proof of [10, Lemma 3.2] works for $\mathcal{Y}(S)$ as well, even for $p = 2$.
(4) If $p \geq 3$ then every Y-series is a Q-series. If $p = 3$ then the two notions coincide.
(5) If not, then $\mathcal{Y}(S) < S$. Choose $T > \mathcal{Y}(S)$ such that $T/\mathcal{Y}(S)$ is cyclic of order 2 and contained in $\Omega_1(Z(S/\mathcal{Y}(S)))$. Then $T \trianglelefteq S$, and we must have $[\Omega_1(Z(\mathcal{Y}(S))), T; 2] \neq 1$, since $\mathcal{Y}(S)$ is centric and the Y-series for $\mathcal{Y}(S)$ cannot be extended to include T.

As $\mathcal{Y}(S)$ has index 2 in T, we have $t^2 \in \mathcal{Y}(S)$ for each $t \in T$. Hence by Eqn (2.2) of [5] we have

$$[\Omega_1(Z(\mathcal{Y}(S))), t; 2] = [\Omega_1(Z(\mathcal{Y}(S))), t^2] = 1\,,$$

a contradiction. □

Example. Oliver remarks in [10, p. 335] that $\mathfrak{X}(S) = C_S(\Omega_1(S))$ for any finite 2-group S. So if S is dihedral of order 8, then $\mathfrak{X}(S) = Z(S)$ is cyclic of order 2, whereas $\mathcal{Y}(S) = S$ has order 8. Hence $\mathfrak{X}(S) < J(S) = \mathcal{Y}(S) = S$ in this case.

Example. Let $S = C_5^3 \rtimes C_5$ be the semidirect product in which the cyclic group on top acts via a (3×3) Jordan block (with eigenvalue 1) on the rank three elementary abelian on the bottom. Then $C_5^3 = J(S) = \mathcal{Y}(S) \lneq \mathfrak{X}(S) = S$.

Remark. Let p be an odd prime. The proof of [4, Lemma 2.3] also shows that for every p-group G there is a p-group S with $S/\mathcal{Y}(S) \cong G$.

3. Orthogonality

Notation. Suppose that p is an odd prime, that G is a non-trivial p-group, and that V is a faithful (right) $\mathbb{F}_pG$-module. Let I be the kernel of the structure map $\mathbb{F}_pG \to \mathrm{End}(V)$. Recall from [5, Section 2] that $[v, g] = v(g-1)$ for all $v \in V$, $g \in G$. Hence $[V, g, h] = 0$ if and only if $(g-1)(h-1) \in I$.

For elements $g, h \in G$ we write $g \perp_V h$ or simply $g \perp h$ if $[g, h] = 1$ and $(g-1)(h-1) \in I$. Note that $\perp_V$ is a symmetric relation on G. We write

$$g^\perp := \{h \in G \mid g \perp h\}\,.$$

Observe that $1 \neq g \in G$ is quadratic if and only if $g \perp g$.

Lemma 3.1. *Let V be a faithful $\mathbb{F}_pG$-module, where G is a non-trivial p-group. For any $g, h, x \in G$ we have:*
(1) *g is quadratic if and only if $g \in g^\perp$.*

(2) *The relation $h \in g^{\perp}$ is symmetric.*
(3) *The set $g^{\perp}$ is a subgroup of $C_G(g)$.*
(4) *For any integer r coprime to p, we have that $(g^r)^{\perp} = g^{\perp}$ and therefore*

$$g^r \text{ quadratic} \iff g \text{ quadratic}.$$

(5) *Assume that p is odd. If g, h are both quadratic and $[g, h] = 1$ then*

$$gh \text{ is quadratic} \iff g \perp h\,.$$

(6) *Assume that p is odd. If g is quadratic and $[g, g^x] = 1$ then*

$$g \perp g^x \iff [g, x] \text{ is quadratic}.$$

Proof. Parts (1) and (2) are clear. Part (3): Obviously $g \perp 1$. If $g \perp h$ and $g \perp k$, then

$$(g-1)(hk-1) = (g-1)(h-1) + h(g-1)(k-1)$$

and so $g \perp hk$. Inverses follow, since G is finite.

Part (4): If $g = 1$ then there is nothing to prove. If $g \neq 1$ then r is a unit modulo the order of g. So it suffices to show the inclusion $g^{\perp} \leq (g^r)^{\perp}$. As g^r only depends on the residue class of r modulo the order of g, we may assume that $r \geq 1$. Then

$$g^r - 1 = a(g-1) \quad \text{for } a = \sum_{i=0}^{r-1} g^i\,.$$

So if $(g-1)(h-1)$ lies in the kernel I of the representation, then so does $(g^r - 1)(h-1)$.

Part (5): From $(gh-1) = (g-1) + g(h-1)$, we get that

$$(gh-1)^2 = (g-1)^2 + 2g(g-1)(h-1) + g^2(h-1)^2$$

because $[g, h] = 1$. So since $2g$ is invertible and $(g-1)^2$, $(h-1)^2 \in I$, we see that $(gh-1)^2 \in I$ if and only if $(g-1)(h-1) \in I$.

Part (6): By (4) we see that g^{-1} is quadratic if and only if g is; and by (3) we have $g^{-1} \in (g^x)^{\perp}$ if and only if $g \in (g^x)^{\perp}$. But $[g, x] = g^{-1}g^x$. Now apply (5). □

Corollary 3.2. *Let p be an odd prime, G a non-trivial p-group, and V a faithful $\mathbb{F}_pG$-module. If $E = \langle g_1, g_2, \ldots, g_r \rangle \leq G$ is elementary abelian then the following three statements are equivalent:*

(1) *Every element $1 \neq g \in E$ is quadratic.*
(2) *$g \perp h$ for all $g, h \in E$.*
(3) *$g_i \perp g_j$ for all $i, j \in \{1, \ldots, r\}$.*

Notation. Recall that an elementary abelian subgroup $E \leq G$ is called *quadratic* (for V) if it satisfies the equivalent conditions of Corollary 3.2.

Proof. Clearly the second statement implies the first. The first implies the third, by Lemma 3.1 (5). Now assume the third condition holds. Then $E \leq (g_i)^\perp$ for every i, since $(g_i)^\perp$ is a group (Lemma 3.1 (3)) and contains each g_j. So $g \perp g_i$ for each i and for each $g \in E$. Hence $g_i \in g^\perp$ for every i. Therefore $E \leq g^\perp$. So $g \perp h$ for all $g, h \in E$, and the second condition holds. □

Lemma 3.3. *Suppose that $g, h \in G$ with $g \neq 1$ and $g \perp h$. Suppose further that C is a subgroup of $C_G(h)$ which contains g and has cyclic centre. Then*

$$\Omega_1(Z(C)) \leq h^\perp .$$

Proof. We proceed by induction on the smallest integer $r \geq 1$ with $g \in Z_r(C)$. If $r = 1$ then $\Omega_1(Z(C)) \leq \langle g \rangle$, and we are done since $\langle g \rangle \leq h^\perp$. If $g \in Z_{r+1}(C)$, then there is an $x \in C$ such that $1 \neq y := [g, x] \in Z_r(C)$. By induction it suffices to show that $y \perp h$. Since $x \in C$ we have $[h, x] = 1$ and therefore $x^{-1}(g-1)(h-1)x = (g^x-1)(h-1)$, showing that $g^x \perp h$. So $y \in \langle g, g^x \rangle \leq h^\perp$. □

We close this section by recalling without proof a key lemma from [4].

Lemma 3.4 (Lemma 4.1 of [4])**.** *Suppose that p is an odd prime, that G is a non-trivial p-group, and that V is a faithful (right) $\mathbb{F}_pG$-module. Suppose that $A, B \in G$ are such that $C := [B, A]$ is a nontrivial element of $C_G(A, B)$. If B is quadratic, then so is C.* □

4. Weakly closed subgroups

This section is related to work of Chermak and Delgado [2], especially the case $\alpha = 1$ of their Theorem 2.4.

Notation. For the sake of brevity we will say that an abelian subgroup A of G is *weakly closed* if A is weakly closed in $C_G(A)$ with respect to G. That is, $A \leq G$ is weakly closed if $[A, A^g] \neq 1$ holds for every G-conjugate $A^g \neq A$.

Remark. Every maximal elementary abelian subgroup M of G is weakly closed, since if $M^g \neq M$ but $[M, M^g] = 1$ then $\langle M, M^g \rangle$ is elementary abelian and strictly larger. Hence every elementary abelian subgroup is contained in a weakly closed one. If the normal closure of E is non-abelian, then every weakly closed elementary abelian subgroup containing E is non-normal.

Remark 4.1. Note that if $A \leq G$ is an abelian subgroup and $g \in G$ then

$$[A, A^g] = 1 \iff [A, [A, g]] = 1 \iff [g, A, A] = 1 .$$

In particular, if A is weakly closed (in our sense), then $Z_2(G) \leq N_G(A)$: for if $g \in Z_2(G)$ then $[A, g] \leq Z(G)$ and therefore $[A, [A, g]] = 1$. Hence $[A, A^g] = 1$ and so $A = A^g$, that is $g \in N_G(A)$.

Remark 4.2. Using GAP [3], the authors have constructed the following examples:

- The Sylow 3-subgroup G of the symmetric group S_{27} contains a rank four weakly closed elementary abelian E with $E \cap Z(G) = 1$.

- The Sylow 3-subgroup G of the symmetric group S_{81} contains a rank six weakly closed elementary abelian E with $E \cap Z_2(G) = 1$.

The GAP code is available from the first author on request.

Lemma 4.3. *Suppose that G is a finite p-group and that the elementary abelian subgroup E of G is weakly closed. Then $N_G(E) = N_G(C_G(E))$. So if E is not central in G then $N_G(E) \gneq C_G(E)$.*

Proof. $N_G(E)$ always normalizes $C_G(E)$. If $x \in G$ normalizes $C_G(E)$ then as $E \leq C_G(E)$ we have that $E^x \leq C_G(E)$ and therefore $[E, E^x] = 1$. So $E^x = E$, for E is weakly closed. Hence $x \in N_G(E)$. Last part: G is a nilpotent group. So if $C_G(E)$ is a proper subgroup of G, then it is properly contained in its normalizer. □

Notation. Let G be a finite group, $H \leq G$ a subgroup, and V a faithful $\mathbb{F}_pG$-module. Following Meierfrankenfeld and Stellmacher [9] we set

$$j_H(V) := \frac{|H| \cdot |C_V(H)|}{|V|} \in \mathbb{Q}\,.$$

This means that an elementary abelian subgroup E of G is an offender if and only if $E \neq 1$ and $j_E(V) \geq 1 = j_1(V)$.

Lemma 4.4 (Lemma 2.6 of [9])**.** *Let G be a finite group and V a faithful $\mathbb{F}_pG$-module. Let H, K be subgroups of G with $\langle H, K\rangle = HK$. Then*

$$j_{HK}(V) j_{H\cap K}(V) \geq j_H(V) j_K(V)\,,$$

with equality if and only if $C_V(H \cap K) = C_V(H) + C_V(K)$. □

Remark. As some readers may find the article [9] by Meierfrankenfeld and Stellmacher hard to obtain, we reproduced the proof of this result in our earlier paper [5, Lemma 3.1] – though unfortunately we accidentally omitted the necessary assumption that $\langle H, K\rangle = HK$.

Recall that a faithful $\mathbb{F}_pG$-module V is called an *F-module* if it has at least one offender.

Proposition 4.5. *Suppose that the faithful $\mathbb{F}_pG$-module V is an F-module. Set*

$$j_0 = \max\{j_E(V) \mid E \text{ an offender}\}\,.$$

Then there is a weakly closed quadratic offender E with $j_E(V) = j_0$.

Moreover if $D \leq G$ is any offender with $j_D(V) = j_0$, then there is such an E which is a subgroup of the normal closure of D.

Proof. Let D be an offender with $j_D(V) = j_0$. Then D has a subgroup $C \leq D$ which is minimal by inclusion amongst the offenders with $j_C(V) = j_0$. By maximality of j_0, the version of Timmesfeld's replacement theorem in [5, Theorem 4.1] then tells us that C is a quadratic offender.

Suppose first that $j_0 > 1$. We shall show that C is weakly closed. If not, then $A := \langle C, C^g\rangle$ is elementary abelian for some $g \in G$ with $C^g \neq C$. Then

$j_A(V) \leq j_0$ by maximality of j_0. And since $j_0 > 1 = j_1(V)$, we have that $j_{C\cap C^g}(V) < j_0$ by maximality of j_0 and minimality of C. But by Lemma 4.4, this means that

$$j_0^2 > j_A(V) j_{C\cap C^g}(V) \geq j_C(V) j_{C^g}(V) = j_0^2\,,$$

a contradiction. So $E = C \leq D$ has the required properties.

Now suppose that $j_0 = 1$. Let $g \in G$ be such that $C^g \neq C$ and $[C, C^g] = 1$. As $\langle C, C^g\rangle$ and $C \cap C^g$ both have $j \leq 1$, Lemma 4.4 means that both have $j = 1$, and (by equality) $C_V(C\cap C^g) = C_V(C) + C_V(C^g)$. Furthermore, minimality of C means that $C \cap C^g = 1$, and so $C_V(C) + C_V(C^g) = V$. As in the proof of [5, Lemma 4.3], this means that $[V, C, C^g] = 0$. Let $T \subseteq G$ be a subset maximal with respect to the condition that $E := \langle C^g \mid g \in T\rangle$ is abelian (and therefore elementary abelian). Applying the above argument to any $g, h \in T$ with $C^g \neq C^h$ we deduce that $[V, C^g, C^h] = 0$. So since each C^g is quadratic, we deduce that E is quadratic too. Finally, a repeated application of Lemma 4.4 coupled with the fact that j never exceeds 1 tells us that $j_E(V) = 1$ too. But by construction, E is weakly closed and contained in the normal closure of D. □

It follows from Proposition 4.5 that Conjecture 1.4 holds for (G, V) if the following conjecture does.

Conjecture 4.6. *Let p be a prime, G a finite p-group, and V a faithful $\mathbb{F}_pG$-module. If there is an elementary abelian subgroup $1 \neq E \leq G$ which is both quadratic on V and weakly closed in $C_G(E)$ with respect to G, then there are quadratic elements in $\Omega_1(Z(G))$.*

We establish Theorem 1.6 by demonstrating that the Sylow subgroups of the symmetric groups satisfy Conjecture 4.6.

5. An inductive hypothesis

We now present the inductive hypothesis (Hypothesis 5.2) that will be used in Section 6 to verify Conjecture 1.4 for an iterated wreath product. First though, we need a few auxilliary lemmas.

Lemma 5.1. *Suppose that G is a direct product of the form $G = H \times P$, where H and P are p-groups. Let $E \leq G$ be an elementary abelian subgroup which is weakly closed (in $C_G(E)$ with respect to G). Set*

$$F = \{g \in P \mid \exists h \in H\ (h, g) \in E\} \leq P\,,$$

and set $N = N_P(F)$. Then the following hold:

1. *F is weakly closed (in $C_P(F)$ with respect to P).*
2. *$1 \times [F, N] \leq E$.*
3. *If $E \not\leq H \times Z(P)$, then $[F, N] \neq 1$ and therefore $E \cap (1 \times P) \neq 1$.*

Proof. (1) If $x \in P$ and $F^x \neq F$ then $E^{(1,x)} \neq E$ and therefore $[E, E^{(1,x)}] \neq 1$. But $[E, E^{(1,x)}] = 1 \times [F, F^x]$. So $[F, F^x] \neq 1$.

(2) Let $f \in F$ and $n \in N$. Pick $h \in H$ such that $(h, f) \in E$. Since $[F, F^n] = [F, F] = 1$, we have $[E, E^{(1,n)}] = 1$ by the proof of the first part. Hence $E^{(1,n)} = E$, and therefore $(1, [f, n]) = [(h, f), (1, n)] \in E$.
(3) F is weakly closed by the first part, and non-central by assumption. Hence $1 \neq [F, N] \leq F$ by Lemma 4.3. Done by the second part. □

Hypothesis 5.2. Let P be a p-group with the following properties:

- P is nonabelian with cyclic centre.
- Suppose that H is a p-group and that V is a faithful $\mathbb{F}_p G$-module, where $G = H \times P$. If $E \leq G$ is a weakly closed quadratic elementary abelian such that $E \nleq H \times Z(P)$, then $1 \times \Omega_1(Z(P)) \leq Z(G)$ is quadratic.

At the end of this section (Corollary 5.7) we give some first examples of groups that satisfy this hypothesis. In the next section (Corollary 6.6) we shall show that the Sylow p-subgroups of S_{p^n} also satisfy it. First though we explain the significance of the hypothesis for Oliver's conjecture.

Lemma 5.3. *Suppose that the finite p-group G is a direct product $G = \prod_{r=1}^n H_r$, where each H_r is either abelian or satisfies Hypothesis 5.2. Then G satisfies Conjectures 1.4 and 4.6.*

Proof. For $1 \leq r \leq n$, we shall denote by K_r the product $\prod_{i \neq r} H_i$. Hence $G = K_r \times H_r$ for each r. Note that $Z(G) = \prod_r Z(H_r)$.

Conjecture 4.6 implies Conjecture 1.4 by Proposition 4.5, and so we assume that there is a weakly closed quadratic elementary abelian subgroup E of G with $E \neq 1$. If $E \leq Z(G)$ then every element $1 \neq g \in E$ is a quadratic element of $\Omega_1(Z(G))$. If $E \nleq Z(G) = \prod_r Z(H_r)$ then for some $1 \leq r \leq n$ we have $E \nleq K_r \times Z(H_r)$. It follows that H_r cannot be abelian, and so by assumption it satisfies Hypothesis 5.2: which means that the subgroup $1 \times \Omega_1(Z(H_r))$ of $\Omega_1(Z(G))$ is quadratic. □

We are particularly interested in wreath products of the form $G = P \wr C_p$, where P is a p-group. Recall that this means that G is the semidirect product $G = P^p \rtimes C_p$, where the C_p on top acts on the base $P^p = \prod_1^p P$ by permuting the factors cyclically. In particular, this means that we may view P^p as a subgroup of G.

We start with a minor diversion. The following result generalizes [6, Satz III.15.4a)] slightly and is presumably well known. It is needed for the proof of Theorem 1.8.

Lemma 5.4. *Suppose that p is an odd prime and that P is a p-group such that $J(P)$ is elementary abelian. Then $J(P \wr C_p)$ is elementary abelian too. In particular, if $P \neq 1$ then $J(P \wr C_p)$ is the copy of $J(P)^p$ in the base subgroup $P^p \leq P \wr C_p$.*

Proof. If $P = 1$ then $P \wr C_p = C_p$ is elementary abelian and we are done. So we may assume that $P \neq 1$, which means that $r \geq 1$, where r is the p-rank of P. Note that $J(P) \cong C_p^r$ by assumption.

Consider the base subgroup P^p, which has index p in $P \wr C_p = P^p \rtimes C_p$. Since $J(G_1 \times G_2) = J(G_1) \times J(G_2)$, we see that $J(P^p) = J(P)^p$, which is elementary abelian of rank pr. So if $J(P \wr C_p)$ is not elementary abelian then $P^p \rtimes C_p$ must contain an elementary abelian subgroup E of rank $\geq pr$ with $E \nleq P^p$. We set $E' = E \cap P^p$. Since P^p has index p in $P \wr C_p$, it follows that $|E \colon E'| = p$ and therefore that $E' \leq P^p$ is elementary abelian of rank $\geq pr - 1$. Furthermore there is an element $g \in (P \wr C_p) \setminus P^p$ with $E = \langle E', g \rangle$ and therefore $[E', g] = 1$.

We split P^p as $P^p = A \times B$, where $A, B \leq P^p$ are given by

$$A = \{(a_1, 1, \dots, 1) \mid a_1 \in P\} \qquad B = \{(1, a_2, \dots, a_p) \mid a_i \in P\}\,.$$

Note that $E' \cap B$ must be trivial: for no non-trivial element of B can commute with $g \in (P \wr C_p) \setminus P^p$. Hence the projection of E' onto A is injective. As $A \cong P$ has rank r, this means that $pr - 1 \leq r$. This is impossible with p odd and $r \geq 1$. □

Now we derive a property of wreath products which will be useful for verifying the hypothesis.

Lemma 5.5. *Suppose that G is the wreath product $P \wr C_p$, where P is a finite p-group. Suppose that E is a weakly closed elementary abelian subgroup of G and that either of the following properties is satisfied:*

(1) *E is not contained in the base subgroup P^p of G.*
(2) *$Z(P)$ is cyclic, E is non-central, and E lies in an abelian normal subgroup of G.*

Then $\Omega_1(Z(G)) \leq [E, N_G(E)]$.

Proof. The group $\Omega_1(Z(G))$ is cyclic of order p. It is generated by $(z, \dots, z) \in P^p$ for any element $z \in \Omega_1(Z(P))$ with $z \neq 1$.

Suppose first that (2) holds. As E lies in an abelian normal subgroup of G and is weakly closed, we deduce that $E \trianglelefteq G$. So $[E, N_G(E)] = [E, G]$ is normal too. Moreover, $[E, G]$ is nontrivial, because E is non-central. Since $|\Omega_1(Z(G))| = p$, it follows that $\Omega_1(Z(G)) \leq [E, G] = [E, N_G(E)]$.

Now suppose that (1) holds. Pick an element $z \in \Omega_1(Z(P))$ with $z \neq 1$. It suffices to show that $(z, \dots, z) \in [E, N_G(E)]$. We start by showing that $c = (1, z, z^2, \dots, z^{p-1})$ satisfies $c \in Z_2(G)$.

If $g \in P^p$ then $[g, c] = 1$, since $c \in Z(P^p)$. If $g \in G \setminus P^p$ then $g = h\sigma$, where $h \in P^p$ and σ is a cyclic permutation of the p factors of P^p. Hence

$$[g, c] = [\sigma, c] = (c^\sigma)^{-1} c = (z, z, \dots, z)^r \in Z(G) \quad \text{for some } 1 \leq r \leq p - 1.$$

Therefore $c \in Z_2(G)$ as claimed. By Remark 4.1 if follows that $c \in N_G(E)$.

Now by assumption $E \nleq P^p$, and so E contains some $g = h\sigma$ in $G \setminus P^p$. So replacing g by a suitable power if necessary, we may suppose that $r = 1$, and so $(z, \dots, z) = [g, c] \in [E, c] \leq [E, N_G(E)]$. □

The following lemma gives one way of verifying that the hypothesis is satisfied.

Lemma 5.6. *Let P be a non-abelian p-group with cyclic centre. Suppose that for every non-central weakly closed elementary abelian subgroup F of P we have that $[F, N_P(F)] \cap Z_2(P) \neq 1$. Then P satisfies Hypothesis 5.2.*

Proof. Let $G = H \times P$ for a p-group H, and let E be a weakly closed quadratic elementary abelian subgroup of G with $E \not\leq H \times Z(P)$. We need to show that $1 \times \Omega_1(Z(P))$ is quadratic.

Consider the elementary abelian subgroup $F \leq P$ defined by $F = \{g \in P \mid \exists h \in H \ (h, g) \in E\}$. Then F is weakly closed (in $C_P(F)$ with respect to P) by Lemma 5.1 (1). Moreover, $F \not\leq Z(P)$, since $[F, N_P(F)] \neq 1$ by Lemma 5.1 (3). So by assumption we may pick $g \in Z_2(P) \cap [F, N_P(F)]$ with $g \neq 1$. Since $g \in [F, N_P(F)]$, we have $(1, g) \in E$ by Lemma 5.1 (2). Hence $(1, g)$ is quadratic and of order p. If $g \in Z(P)$ then we are done, since $Z(P)$ is cyclic.

If $g \in Z_2(P) \setminus Z(P)$ then $1 \neq [g, x]$ generates $\Omega_1(Z(P))$ for some $x \in P$. But then $(1, [g, x]) = [(1, g), (1, x)]$ is quadratic by Lemma 3.4. □

Corollary 5.7. *Let p be a prime and P a finite p-group. Assume that either of the following holds:*

(1) *P is a wreath product of the form $P = C_{p^r} \wr C_p$ for $r \geq 1$;*
(2) *$Z(P)$ is cyclic, and P has nilpotence class two or three.*

Then Hypothesis 5.2 holds for P.

Proof. In both cases, P is nonabelian and has cyclic centre. Let $F \leq P$ be a non-central elementary abelian subgroup which is weakly closed in $C_P(F)$ with respect to P. By Lemma 5.6 it suffices to show that $Z_2(P) \cap [F, N_P(F)] \neq 1$.

(1) We prove that $\Omega_1(Z(P)) \leq [F, N_P(F)]$. The case $F \not\leq C_{p^r}^p$ is covered by Lemma 5.5 (1). Since $C_{p^r}^p$ is normal abelian, the case $F \leq C_{p^r}^p$ is accounted for by Lemma 5.5 (2).
(2) Since F is weakly closed and non-central we have $C_P(F) \lneq N_P(F)$ by Lemma 4.3. Hence $[F, N_P(F)] \neq 1$. And as the (nilpotence) class of P is at most three we have $[F, N_P(F), P] \leq Z(P)$, whence $[F, N_P(F)] \leq Z_2(P)$. □

6. Wreath products

We saw in Lemma 5.3 that Conjecture 1.4 holds for the direct product $H_1 \times \cdots \times H_n$ if each p-group H_r is abelian or satisfies Hypothesis 5.2. In Corollary 5.7 we saw our first examples of groups which satisfy the hypothesis. We now demonstrate that if P satisfies the hypothesis, then so does the wreath product $P \wr C_p$. This is the key step in proving that the Sylow subgroups of a symmetric group satisfy Conjecture 1.4.

Proposition 6.1. *If the p-group P satisfies Hypothesis 5.2 then so does the wreath product $Q = P \wr C_p$.*

Proof. Certainly Q is nonabelian with cyclic centre. Let H be a p-group, and V a faithful module for $G = H \times Q$. Recall that Q is a semidirect product, with base subgroup $K := \prod_1^p P$ on which C_p acts by permuting the factors cyclically. Let $E \leq G$ be a quadratic elementary abelian subgroup which is weakly closed in $C_G(E)$ with respect to G, and also satisfies $E \nleq H \times Z(Q)$. We have to show that $1 \times \Omega_1(Z(Q))$ is quadratic.

Let $F = \{g \in Q \mid \exists h \in H \ (h,g) \in E\}$. Then F is a non-central elementary abelian subgroup of Q; and by Lemma 5.1 it is weakly closed (in $C_Q(F)$ with respect to Q).

Suppose first that $E \nleq H \times K$. Then $F \nleq K$, and so by Lemma 5.5 (1) we have $\Omega_1(Z(Q)) \leq [F, N_Q(F)]$. The same thing happens if $E \leq H \times Z(K)$: for then $F \leq Z(K)$, which is an abelian normal subgroup of Q. Hence $\Omega_1(Z(Q)) \leq [F, N_Q(F)]$ by Lemma 5.5 (2). In both cases we then deduce from Lemma 5.1 (2) that $1 \times \Omega_1(Z(Q))$ lies in E and is therefore quadratic.

So from now on we may assume that $E \leq H \times K$ but $E \nleq H \times Z(K)$. That is, F is a subgroup of $K = \prod_1^p P$, but $F \nleq Z(K) = Z(P)^p$. Define a subset $T(F) \subseteq \{1, 2, \ldots, p\}$ by

$$i \in T(F) \iff F \nleq P \times P \times \cdots \times Z(P) \times \cdots \times P \,,$$

where the factor $Z(P)$ occurs in the ith copy of P. Since $F \nleq Z(P)^p$, we have $T(F) \neq \emptyset$.

For $1 \leq i \leq p$ we define subgroups $L_i, P(i) \leq H \times K$ as follows:

$$L_i = H \times (P \times P \times \cdots \times 1 \times \cdots \times P) \quad P(i) = 1 \times (1 \times 1 \times \cdots \times P \times \cdots \times 1) \,,$$

where the brackets enclose K and the one distinguished factor occurs in the ith factor of $K = P^p$. Then $H \times K = L_i \times P(i)$ for each i. Observe that

$$i \in T(F) \iff E \nleq L_i \times Z(P(i)) \,. \tag{6.2}$$

Pick $1 \neq \zeta \in \Omega_1(Z(Q))$. We need to show that $(1, \zeta) \in Z(G)$ is quadratic. Note that $\zeta = (z, z, \ldots, z) \in K$ for some $1 \neq z \in \Omega_1(Z(P))$. That is, $\zeta = z_1 z_2 \cdots z_p$, where for $1 \leq i \leq p$ we define $z_i \in Z(K)$ by

$$z_i = (1, \ldots, z, \ldots, 1) \quad (z \text{ at the } i\text{th place}).$$

Now, the group $P(i) \cong P$ satisfies Hypothesis 5.2 by assumption. Applying the hypothesis to the direct product group $L_i \times P(i) = H \times K$, we see from Eqn (6.2) that $(1, z_i)$ is quadratic for every $i \in T(F)$. As $T(F)$ is nonempty and all the z_i are conjugate in Q under the cyclic permutation of the factors of $K = P^p$, it follows that *every* $(1, z_i)$ is quadratic.

From Lemma 5.1 (3) and Eqn (6.2) it follows that for every $i \in T(F)$ there is some $1 \neq g_i \in P$ such that $(1, k_i) \in E$ for $k_i = (1, \ldots, g_i, \ldots, 1) \in K$. Now suppose that $i, j \in T(F)$ are distinct. Then $(1, k_i) \perp (1, k_j)$, as they both lie in E. Applying Lemma 3.3 with $C = P(i)$, we have that $(1, z_i) \perp (1, k_j)$. Applying this lemma a second time, but now with $C = P(j)$, we deduce that

$$(1, z_i) \perp (1, z_j) \tag{6.3}$$

holds for all $i, j \in T(F)$. We have already seen that it always holds for $i = j$.

As Q is the wreath product $P \wr C_p$, we may pick an element $x \in Q \setminus K$ such that $(h_1, \ldots, h_p)^x = (h_p, h_1, \ldots, h_{p-1})$ holds for all $(h_1, \ldots, h_p) \in P^p = K$. Then $T(F^x) = \sigma(T(F))$, where σ is the p-cycle $(1\,2\,\ldots\,p)$. Hence $T(F^{x^m}) = \sigma^m(T(F))$. We claim that

$$\forall\, 0 \leq m \leq p-1 \qquad \sigma^m(T(F)) \cap T(F) \neq \emptyset\,. \tag{6.4}$$

For if $\sigma^m(T(F)) \cap T(F) = \emptyset$, then $[F^{x^m}, F] = 1$ by definition of $T(F)$. But F is weakly closed, and so $[F^{x^m}, F] = 1$ implies that $F^{x^m} = F$. But then $\sigma^m(T(F)) = T(F^{x^m}) = T(F)$, and so $\sigma^m(T(F)) \cap T(F) = T(F) \neq \emptyset$, a contradiction.

So Eqn (6.4) is proved. We may rephrase it as follows:

$$\forall\, 0 \leq m \leq p-1 \quad \exists\, a, b \in T(F) \quad b \equiv a + m \pmod{p}\,. \tag{6.5}$$

Now pick any $i, j \in \{1, 2, \ldots, p\}$. By Eqn (6.5) there are $a, b \in T(F)$ with $b - a \equiv j - i \pmod{p}$. Define r to be the integer $0 \leq r < p$ such that $r \equiv i - a \pmod{p}$. Then

$$i = a + r \pmod{p} \qquad \text{and} \qquad j = b + r \pmod{p}\,.$$

Hence

$$(1, z_i) = (1, z_a)^{(1, x^r)} \qquad \text{and} \qquad (1, z_j) = (1, z_b)^{(1, x^r)}\,.$$

But $(1, z_a) \perp (1, z_b)$, as this is one of the cases for which we have already demonstrated Eqn (6.3). So we deduce that $(1, z_i) \perp (1, z_j)$: that is, Eqn (6.3) holds for all i, j. From $\zeta = z_1 z_2 \cdots z_p$ we therefore deduce by Corollary 3.2 that $(1, \zeta) \perp (1, \zeta)$, that is $(1, \zeta)$ is quadratic, as required. □

Corollary 6.6. *The Sylow p-subgroups of the symmetric group S_{p^n} satisfy Hypothesis 5.2 for every $n \geq 2$.*

Proof. By induction on n. It is well known that the Sylow p-subgroups P_n of S_{p^n} are isomorphic to the iterated wreath product $C_p \wr C_p \wr \cdots \wr C_p$, with n copies of C_p. So $P_2 = C_p \wr C_p$ satisfies the hypothesis by Corollary 5.7 (1). If P_r satisfies the hypothesis, then so does $P_{r+1} = P_r \wr C_p$ by Proposition 6.1. □

7. Deepest commutators

In this and the subsequent section we assemble the tools needed for the proof of Theorems 1.7 and 1.9.

Notation. Let G be a p-group and $g \in G$ a non-central element. Let $r_0 = \max\{r \mid \exists k \in K_r(G)\colon [g, k] \neq 1\}$. This exists by nilpotence, since g is not central.

If $k \in K_{r_0}(G)$ and $[g, k] \neq 1$, then we call $[g, k]$ a *deepest commutator* of g.

Remark. Observe that $r_0(g) = r_0(g^x)$ for every $x \in G$.

Lemma 7.1. *Let G be a p-group and $g \in G$ a non-central element.*

1. *g has at least one deepest commutator, and $[g,[g,k]] = 1$ holds for every deepest commutator $[g,k]$ of g.*
2. *Suppose that k is any element of G such that $y = [g,k]$ satisfies $[g,y] = 1$. Then the order of y divides the order of g.*
   In particular if $y \neq 1$ and g has order p, then so does y.

Proof. Deepest commutators exist, and commute with g by maximality of r_0. If $1 \neq y = [g,k]$ commutes with g, then $g^k = gy$ and so $(g^{p^n})^k = (gy)^{p^n} = g^{p^n} y^{p^n}$. So if $g^{p^n} = 1$ then $y^{p^n} = 1$. □

The concept "deepest commutator of g" depends not only on the element g, but also on the ambient group G. When we need to stress the group G we shall use the phrase "deepest commutator in G".

Notation. Let G be a p-group, g an element of G, and N a normal subgroup of G. If $y, x \in L := C_G(g)N$ are such that $y = [g,x]$ is a deepest commutator of g in L, then we call y a *(G,N)-locally deepest commutator* of g. A *locally deepest* commutator is a (G,N)-locally deepest commutator for some N.

Remark. Since N is normal, L is a group. By the existence of deepest commutators, g has a (G,N)-locally deepest commutator if and only if $N \not\leq C_G(g)$.

Lemma 7.2. *If y is an (G,N)-locally deepest commutator of $g \in G$, then $y = [g,x]$ for some $x \in N$.*

Proof. We have that $y = [g,x']$ for some $x' \in C_G(g)N$, and so $x' = ax$ for some $a \in C_G(g)$, $x \in N$. But then $g^{x'} = g^x$ and so $[g,x] = y$. □

8. Late and last quadratics

Throughout this section, G is a finite p-group and V a faithful $\mathbb{F}_pG$-module. Recall that an element $g \in G$ is called *quadratic* if its action on V has minimal polynomial $(X-1)^2$.

Notation. Suppose that $g \in G$ is quadratic. We call g *late* quadratic if every locally deepest commutator of g is non-quadratic. We call g *last* quadratic if every iterated commutator $z = [g, h_1, h_2, \ldots, h_r]$ with $r \geq 1$ and $h_1, \ldots, h_r \in G$ is non-quadratic.

Remark. An element $g \in G$ can only fail to have any locally deepest commutators if $g \in Z(G)$, for it is only if $g \in Z(G)$ that $N \leq C_G(g)$ holds for every $N \trianglelefteq G$. In particular, every quadratic element in $Z(G)$ is late quadratic.

Note that every last quadratic element is late quadratic. We shall see in Lemma 8.2 that each late quadratic element has elementary abelian normal closure in G. Hence all the non-trivial iterated commutators of a last quadratic element have order p.

Lemma 8.1. *If G has quadratic elements, then it has both late quadratic and last quadratic elements.*

Proof. As there are quadratic elements we may set

$$t_0 := \max\{t \mid K_t(G) \text{ contains a quadratic element}\}\,.$$

Pick a quadratic element $g \in K_{t_0}(G)$ and observe that every commutator lies in $K_{t_0+1}(G)$. By the maximality of t_0, we see that g is both last and late quadratic. □

Lemma 8.2. *Every late quadratic element g of G lies in $\Omega_1(Z(\mathcal{Y}(G)))$ and therefore satisfies $\mathcal{Y}(G) \leq C_G(g)$.*

Proof. We have already observed that all quadratic elements have order p. As $\mathcal{Y}(G)$ is a centric subgroup of G (Lemma 2.1), it suffices to show that each quadratic element g of G lies in $C_G(\mathcal{Y}(G))$. Let $1 = Y_0 \leq \cdots \leq Y_n = \mathcal{Y}(G)$ be a Y-series, so

$$Y_r \trianglelefteq G \qquad \text{and} \qquad [\Omega_1(C_G(Y_{r-1})), Y_r; 2] = 1\,. \tag{8.3}$$

We show that $g \in C_G(Y_r)$ by induction on r. If $r = 0$, this is clear. Suppose $r \geq 1$ and $g \in C_G(Y_{r-1})$. If $g \notin C_G(Y_r)$ then by Lemma 7.2, g has a (G, Y_r)-locally deepest commutator $y = [g, x]$ with $x \in Y_r$. Then $[y, g] = 1$ by Lemma 7.1, and $[y, x] = [g, x, x] = 1$ by Eqn (8.3). So, as g is quadratic, y is too by Lemma 3.4. But y cannot be quadratic, since y is a locally deepest commutator of the late quadratic element $g \in G$. □

Remark 8.4. If we were attempting to prove Conjecture 1.4 by induction on $|G|$ then we could assume that it holds for $G/\mathcal{Y}(G)$. By Theorem 1.5 this would mean that $J(G) \leq \mathcal{Y}(G)$. It would then follow from Lemma 8.2 that every late quadratic element lies in $\Omega_1(Z(J(G)))$, the intersection of all the greatest rank elementary abelian subgroups of G.

Lemma 8.5. *Let $H \leq G$ be the subgroup generated by all last quadratic elements. Then every quadratic element of G lies in $C_G(H)$.*

Proof. If not then $[g, h] \neq 1$ for some elements $g, h \in G$, with g last quadratic and h quadratic. By nilpotency $[g, h; r] \neq 1$ and $[g, h; r+1] = 1$ for some $r \geq 1$. Let $k = [g, h; r-1]$. As the normal closure of g in G is abelian (Lemma 8.2), all the iterated commutators of g commute, and so $[[k, h], k] = 1$. Also $[[k, h], h] = [g, h; r+1] = 1$. Lemma 3.4 therefore says that $1 \neq [k, h]$ is quadratic, since h is. But $[k, h] = [g, h; r]$ cannot be quadratic, for g is last quadratic. Contradiction. □

9. Powerful p-groups

We use L. Wilson's paper [14] as a reference on powerful p-groups. Recall from [14, Definition 1.3] that for an odd prime p, a finite p-group G is called *powerful* if $G' \leq G^p := \langle g^p \mid g \in G\rangle$. As in the proof of Proposition 4.5, recall that

Timmesfeld's Replacement Theorem tells us that if V is a faithful F-module for G, then there is an elementary abelian subgroup E of G which is a quadratic offender. Our first result improves [5, Theorem 6.2].

Proposition 9.1. *Let p be an odd prime and G a finite p-group. If $G' \cap \Omega_1(G)$ is abelian then G satisfies Conjecture 1.4.*

Proof. Suppose that V is a faithful $\mathbb{F}_p G$-module with no quadratic elements in $\Omega_1(Z(G))$. We must show that there are no quadratic offenders. So suppose that the elementary abelian subgroup $E \leq G$ is a quadratic offender. Then $[G', E] \neq 1$ by [5, Theorem 1.5(2)]. Moreover, $G'E \trianglelefteq G$. Hence $G'E \cap \Omega_1(G) \trianglelefteq G$. By the Dedekind Lemma [7, X.3], we have $G'E \cap \Omega_1(G) = E(G' \cap \Omega_1(G))$, since $E \leq \Omega_1(G)$. Therefore $Z(E(G' \cap \Omega_1(G)))$ is an abelian normal subgroup of G, and so by [5, Theorem 1.5(1)] it cannot contain E. This means that $G' \cap \Omega_1(G)$ is not centralized by E. So there must be an $a \in E$ such that $[G' \cap \Omega_1(G), a] \neq 1$. But then $a \in \Omega_1(G)$, and so $N := G'\langle a \rangle \cap \Omega_1(G) = \langle a \rangle (G' \cap \Omega_1(G))$ is a normal subgroup of G. Since $G' \cap \Omega_1(G)$ is abelian, a well-known result (quoted as [5, Lemma 6.1]) says that the commutator subgroup of $N = \langle a \rangle (G' \cap \Omega_1(G))$ consists of commutators in a. But $N \trianglelefteq G$, and by choice of a we have $N' \neq 1$. Hence N' has nontrivial intersection with $\Omega_1(Z(G))$. So $1 \neq [a, x] \in \Omega_1(Z(G))$ for some $x \in G' \cap \Omega_1(G)$. Since a is quadratic, Lemma 3.4 says that $[a, x] \in \Omega_1(Z(G))$ is too. This contradicts our assumption that there are no quadratic elements in $\Omega_1(Z(G))$. So G satisfies the conjecture. □

Theorem 9.2. *Let p be an odd prime. Every powerful p-group G satisfies Conjecture 1.4.*

Proof. We refer to Wilson's paper [14]. His Theorem 4.7 says that G^p is powerful, and hence his Corollary 4.11 applied with $P = G$ shows that $\Omega_1(G^p)$ is powerful. On the other hand, his Theorem 3.1 says that $\Omega_1(G)$ has exponent p, and so $\Omega_1(G^p) = \Omega_1(G) \cap G^p$. So $\Omega_1(G) \cap G^p$ is powerful and of exponent p, which means it must be abelian. As $G' \leq G^p$, it follows that $\Omega_1(G) \cap G'$ is abelian. So G satisfies the conjecture, by Proposition 9.1 above. □

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Department of Mathematics, Friedrich-Schiller-Universität Jena, 07737 Jena, Germany

E-mail address: `david.green@uni-jena.de`

Department of Algebra, Budapest University of Technology and Economics, Budapest, Hungary

Department of Mathematics and Statistics, Fylde College, Lancaster University, Lancaster LA1 4YF, United Kingdom