

Zero Divisors of Support Size 3 in Complex Group Algebras of Finite Groups

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ABSTRACT. It is proved that if $1 + x + y$ or $1 + x - y$ cannot occur as a zero divisor of the complex group algebra of a finite group G for any two distinct $x, y \in G \setminus \{1\}$, then G is solvable. We also characterize all finite abelian groups with the latter property. The motivation of studying such property for finite groups is to settle the existence of zero divisors with support size 3 in the integral group algebra of torsion free residually finite groups.

Keywords: Zero divisors, Complex group algebras, Finite groups.

2000 Mathematics subject classification: 20C07, 16S34.

1. INTRODUCTION

Let $\mathbb{C}[G]$ be the complex group algebra of a finite group G . In this paper we study finite groups G for which $\mathbb{C}[G]$ does not contain zero divisors of the form $1 + x + y$ or $1 + x - y$ for some distinct non-trivial elements $x, y \in G$. The motivation of studying such finite groups G is the following. There is a

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famous conjecture due to Kaplansky [7] saying that group algebras of torsion-free groups have no zero divisor. It is known that there is no zero divisor of support size 2 in the latter group algebras (see [8, Theorem 2.1]). The conjecture is still open and one of the important open cases is the validity of the conjecture for the integral group algebras (see e.g., Problem 1.3 of [9]). By [2, Theorem 1.1], every possible zero divisor of support size 3 in an integral group algebra of a torsion-free group Γ is a scalar multiple of elements of the form $1+x+y$ or $1+x-y$ for some distinct and non-trivial elements $x, y \in \Gamma$. On the other hand, the conjecture is even open for the group algebras of torsion-free residually finite groups (see e.g. [1] and [6, Question 7.2.6 and (C.29) of p. 60]). Note that the image of a zero divisor $\mathbb{C}[\Gamma]$ is still a zero divisor with the same support size in $\mathbb{C}[G]$ for arbitrary “sufficiently large” finite quotients G of a torsion-free residually finite group Γ .

Our main results are as follows.

Theorem 1.1. *Let G be a finite non-solvable group. Then*

- (a) $\mathbb{C}[G]$ has a zero divisor of the form $1+a+b$, for some non-trivial distinct elements $a, b \in G$.
- (b) $\mathbb{C}[G]$ has a zero divisor of the form $1+x-y$ for some non-trivial distinct elements $x, y \in G$.

Theorem 1.2. *Let G be a finite abelian group. Then*

- (a) $\mathbb{C}[G]$ has a zero divisor of the form $1+a+b$ for some non-trivial distinct elements $a, b \in G$ if and only if $3 \mid |G|$.
- (b) $\mathbb{C}[G]$ has a zero divisor of the form $1+x-y$ for some non-trivial distinct elements $x, y \in G$ if and only if $6 \mid |G|$.

In Section 2 we prove some preliminary results. In Section 3 we prove Theorem 1.1 and in Section 4 we prove Theorem 1.2.

2. PRELIMINARIES

Lemma 2.1. *Let G be a finite group. An element $z \in \mathbb{C}[G]$ is a zero divisor if and only if there exists a $\mathbb{C}[G]$ -module V and a non-zero element $v \in V$ such that $zv = 0$.*

Proof. Suppose that $z \in \mathbb{C}[G]$ is a zero divisor so that $zw = 0$ for some non-zero $w \in \mathbb{C}[G]$. Then as $\mathbb{C}[G]$ is a $\mathbb{C}[G]$ -module, we have done.

Now suppose that there exists a $\mathbb{C}[G]$ -module V and a non-zero element $v \in V$ such that $zv = 0$. Since V is completely reducible, V is a direct sum of some irreducible $\mathbb{C}[G]$ -modules. It follows that there exists an irreducible $\mathbb{C}[G]$ -module W and a non-zero element $w \in W$ such that $zw = 0$. Since G is finite, there exists an irreducible $\mathbb{C}[G]$ -submodule M of $\mathbb{C}[G]$ such that W is

isomorphic to M as $\mathbb{C}[G]$ -modules. It follows that $zm = 0$ for some non-zero $m \in M$. This completes the proof. $\square$

Lemma 2.2. *Let G be a finite group, H a subgroup of G and $z \in \mathbb{C}[H]$. Then z is a zero divisor of $\mathbb{C}[G]$ if and only if z is a zero divisor of $\mathbb{C}[H]$.*

Proof. Let z be a zero divisor of $\mathbb{C}[G]$ so that $zw = 0$ for some non-zero $w \in \mathbb{C}[G]$. Suppose that $w' = \sum_{x \in G} w'_x x \in \mathbb{C}[G]$ is an element with minimum support size with respect to the properties: $zw' = 0$ and $1 \in \text{supp}(w') := \{x \in G \mid w'_x \neq 0\}$. It follows from [3, Lemma 2.5] that $\text{supp}(w') \subseteq \langle \text{supp}(z) \rangle \leq H$. Hence $w' \in \mathbb{C}[H]$ and so z is a zero divisor of $\mathbb{C}[H]$. $\square$

Lemma 2.3. *Let G be a finite group, N a normal subgroup of G and $z \in \mathbb{C}[G]$. Suppose that $\bar{\cdot}: \mathbb{C}[G] \rightarrow \mathbb{C}[\frac{G}{N}]$ is the induced ring homomorphism by the natural group homomorphism from G to $\frac{G}{N}$ sending x to xN . If $\bar{z} \in \mathbb{C}[\frac{G}{N}]$ is a zero divisor, then z is a zero divisor of $\mathbb{C}[G]$.*

Proof. Note that $\mathbb{C}[\frac{G}{N}]$ is a $\mathbb{C}[G]$ -module with the action $\alpha \cdot v = \bar{\alpha}v$ for all $\alpha \in \mathbb{C}[G]$ and $v \in \mathbb{C}[\frac{G}{N}]$. Now Lemma 2.1 completes the proof. $\square$

Theorem 2.4. *Let $p \geq 3$ be a prime and $G := \langle a, b \mid a^p = b^{p-1} = 1, b^{-1}ab = a^k \rangle$, where k is a primitive root of p . Then $1 + a \pm b$ is a zero divisor of G .*

Proof. Let $H := \langle a \rangle = G'$ and $\alpha = e^{\frac{2\pi i}{p}}$. Now $\mathbb{C}[G]$ acts on $\mathbb{C}[\frac{G}{H}]$ as follows

$$a \star b^m H = \alpha^{km} b^m H, b \star b^m H = b^{m+1} H,$$

where $0 \leq m \leq p-2$ is an integer. It is easy to see that $(\mathbb{C}[\frac{G}{H}], \star)$ is a $\mathbb{C}[G]$ -module. Now it follows from Lemma 2.1 that $1 + a \pm b$ is a zero divisor of $\mathbb{C}[G]$ if and only if there exist $c_0, c_1, \dots, c_{p-2} \in \mathbb{C}$ not all of them zero such that $(1 + a \pm b) \star (\sum_{m=0}^{p-2} c_m b^m H) = 0$. The latter is equivalent to $(1 + \alpha)(1 + \alpha^k)(1 + \alpha^{k^2}) \cdots (1 + \alpha^{k^{p-2}}) = 1$. Since k is a primitive root of p , $\{1, \alpha, \alpha^k, \dots, \alpha^{k^{p-2}}\}$ is the set of all roots of $x^p - 1 = 0$. Hence $\{1 + 1, 1 + \alpha, 1 + \alpha^k, \dots, 1 + \alpha^{k^{p-2}}\}$ is the set of roots of $(x - 1)^p - 1 = 0$. Thus $(1 + 1)(1 + \alpha) \cdots (1 + \alpha^{k^{p-2}})$ is the product of all roots of $(x - 1)^p - 1 = 0$. Therefore $(1 + 1)(1 + \alpha) \cdots (1 + \alpha^{k^{p-2}}) = 2$. This completes the proof. $\square$

Lemma 2.5. *The complex group algebra of the alternating group A_4 of degree 4 has a zero divisor of the form $1 + a - b$ for some non-trivial distinct elements $a, b \in A_4$.*

Proof. Let $G := A_4$, $H := G'$, $a := (3, 2, 1)$ and $b := (4, 2, 1)$. Then $G := \langle a, b \rangle$ and $\mathbb{C}[G]$ acts on $\mathbb{C}[\frac{G}{H}]$ as follows

$$\begin{aligned} a \star H &:= aH, a \star aH &:= -bH, a \star bH &:= -H, \\ b \star H &:= bH, b \star aH &:= -H, b \star bH &:= -aH. \end{aligned}$$

It is easy to see that $(\mathbb{C}[\frac{G}{H}], \star)$ is a $\mathbb{C}[G]$ -module. Since $(1 + a - b) \star (H - aH) = 0$, Lemma 2.1 completes the proof. $\square$

3. SOLVABILITY OF FINITE GROUPS WHOSE COMPLEX GROUP ALGEBRAS NOT CONTAINING ZERO DIVISORS OF THE FORM $1 + x + y$ OR $1 + x - y$

Proof of Theorem 1.1 (a). Since G is non-solvable, there exist normal subgroups M and N of G such that $M/N \cong S \times \cdots \times S$, where $k \geq 1$ is an integer and S is a non-abelian finite simple group. From Lemmas 2.2 and 2.3, it is enough to show that S has a zero divisor of the form $1 + a + b$. If $3 \mid |S|$, we have done. Thus we assume that $3 \nmid |S|$. Hence by [5, Remarks 3.7, p. 188] $S \cong \text{Sz}(q)$ is the Suzuki simple group, where $q = 2^{2m+1}$ for some $m \in \mathbb{N}$. Since $\text{Sz}(2)$ is the Frobenius group of order 20 and $\text{Sz}(q)$ has $\text{Sz}(2)$ as a subgroup, Theorem 2.4 and Lemma 2.2 imply that S has a zero divisor of the form $1 + a + b$. This completes the proof. $\square$

Proof of Theorem 1.1 (b). Similar to Theorem 1.1, it is enough to show that a simple non-abelian group S has a zero divisor of the form $1 + a - b$. If there exists a section H of S such that $H \cong S_3$, then by Theorem 2.4 and Lemmas 2.2 and 2.3, we have done. Hence we may assume that S is non-abelian finite simple S_3 -free group. It follows from [4, Corollary 3] one of the following cases occurs:

Case 1. S is a simple Suzuki group. Then similar to Theorem 1.1, there exists a subgroup K of S which is a Frobenius group of order 20, and so Theorem 2.4 completes the proof.

Case 2. $S \cong \text{PSL}_2(3^{2m+1})$ the projective special linear group of dimension 2 over field with 3^{2m+1} for some $m \in \mathbb{N}$. Since $A_4 \cong \text{PSL}_2(3)$, S contains a subgroup isomorphic to A_4 and so Lemma 2.5 completes the proof. $\square$

4. FINITE ABELIAN GROUPS WHOSE COMPLEX GROUP ALGEBRAS CONTAINING ZERO DIVISORS OF THE FORM $1 + x + y$ OR $1 + x - y$

Lemma 4.1. *Let G be a finite group, $z \in \mathbb{C}[G]$, λ a linear complex character of G and $e_\lambda = \frac{1}{|G|} \sum_{g \in G} \lambda(g^{-1})g$ be the idempotent element of $\mathbb{C}[G]$ defined by λ . Then $ze_\lambda = 0$ if and only if $\lambda(z) = 0$.*

Proof. Now let h be an arbitrary element of G . Then

$$\begin{aligned} he_\lambda &= h \left(\frac{1}{|G|} \sum_{g \in G} \lambda(g^{-1})g \right) = \\ &= \frac{1}{|G|} \sum_{g \in G} \lambda(g^{-1})hg = \frac{\lambda(h)}{|G|} \sum_{g \in G} \lambda(h^{-1}g^{-1})hg = \\ &= \frac{\lambda(h)}{|G|} \sum_{g \in G} \lambda((hg)^{-1})hg = \lambda(h)e_\lambda. \end{aligned}$$

It follows that $ze_\lambda = 0$ if and only if $\lambda(z) = 0$. $\square$

Proof of Theorem 1.2 (a). Suppose that $3 \mid |G|$. Then there exists $a \in G$ of order 3. Hence $(1 + a + a^2)(1 - a) = 0$. Thus $1 + a + a^2$ is a zero divisor of G . Now suppose that $a, b \in G \setminus \{1\}$, $a \neq b$ and $1 + a + b$ is a zero divisor of G . Thus using Lemma 2.1, there exist an irreducible $\mathbb{C}[G]$ -module V and $0 \neq v \in V$ such that $(1 + a + b)v = 0$. Therefore for some $\lambda \in \text{Irr}(G) = \text{Lin}(G)$, $V = V_\lambda = e_\lambda \mathbb{C}[G]$ where V_λ is an irreducible $\mathbb{C}[G]$ -module and $\dim_{\mathbb{C}} V_\lambda = \lambda(1) = 1$. Hence $V_\lambda = \mathbb{C}e_\lambda$. Thus by Lemma 4.1, $1 + \lambda(a) + \lambda(b) = 0$. Now assume that $o(a) = m$ and $o(b) = n$. Thus for some $s \in \{1, \dots, m-1\}$ and some $t \in \{1, \dots, n-1\}$, $1 + e^{\frac{2\pi si}{m}} + e^{\frac{2\pi ti}{n}} = 0$, where $i^2 = -1$. Hence
$$\begin{cases} \sin \frac{2\pi s}{m} = -\sin \frac{2\pi t}{n} \\ \cos \frac{2\pi s}{m} + \cos \frac{2\pi t}{n} = -1 \end{cases}.$$
 It follows that $\frac{s}{m} - \frac{t}{n} \in \{2k \pm \frac{1}{3}, 2k \pm \frac{2}{3} \mid k \in \mathbb{Z}\}$. Thus $3 \mid mn$ and so $3 \mid |G|$. $\square$

Proof of Theorem 1.2 (b). We first assume that $6 \mid |G|$. Since G is abelian, there exists $a \in G$ of order 6. Thus $(1 - a + a^2)(1 + a)(1 - a^3) = 0$. Hence $1 - a + a^2$ is a zero divisor of $\mathbb{C}[G]$. Now suppose that there exist $a, b \in G \setminus \{1\}$, $a \neq b$ and $1 + a - b$ is a zero divisor of $\mathbb{C}[G]$. Thus using Lemma 2.1, there exist an irreducible $\mathbb{C}[G]$ -module V and $0 \neq v \in V$ such that $(1 + a - b)v = 0$. Therefore for some $\lambda \in \text{Irr}(G) = \text{Lin}(G)$, $V = V_\lambda = e_\lambda \mathbb{C}[G]$ where V_λ is an irreducible $\mathbb{C}[G]$ -module and $\dim_{\mathbb{C}} V_\lambda = \lambda(1) = 1$. Hence $V_\lambda = \mathbb{C}e_\lambda$. Thus by Lemma 4.1, $1 + \lambda(a) - \lambda(b) = 0$. Now let $o(a) = m$ and $o(b) = n$. Thus there exists $s \in \{1, \dots, m-1\}$ and $t \in \{1, \dots, n-1\}$ such that $1 + e^{\frac{2\pi si}{m}} - e^{\frac{2\pi ti}{n}} = 0$, where $i^2 = -1$. Therefore
$$\begin{cases} \sin \frac{2\pi s}{m} = \sin \frac{2\pi t}{n} \\ \cos \frac{2\pi s}{m} - \cos \frac{2\pi t}{n} = -1 \end{cases}.$$
 It follows that $\frac{s}{m} + \frac{t}{n} \in \{2k \pm \frac{1}{6}, 2k + 1 \pm \frac{1}{6} \mid k \in \mathbb{Z}\}$. Therefore $6 \mid mn$ and so $6 \mid |G|$. $\square$

ACKNOWLEDGMENTS

This research was supported in part by a grant from School of Mathematics, Institute for Research in Fundamental Sciences (IPM).

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