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TORSION GROUPS OF A FAMILY OF ELLIPTIC CURVES OVER NUMBER FIELDS

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Abstract. We compute the torsion group explicitly over quadratic fields and number fields of degree coprime to 6 for a family of elliptic curves of the form $E\colon\ y^2 = x^3 + c$, where c is an integer.

Keywords: torsion group; elliptic curve; number field

MSC 2010: 14H52, 11R04

1. Introduction

Let K be a number field and E be an elliptic curve defined over K. Then by the Mordell-Weil theorem, the group $E(K)$ of K-rational points is a finitely generated abelian group. We have $E(K) \cong T \oplus \mathbb{Z}^r$ for some nonnegative integer r and for some torsion subgroup T. When $K = \mathbb{Q}$, by Mazur's theorem, see [9], it is well-known that the torsion subgroup of $E(\mathbb{Q})$ is either cyclic of order m for some integer $1 \leqslant m \leqslant 10$ or $m = 12$, or of the form $\mathbb{Z}/2\mathbb{Z} \oplus \mathbb{Z}/2m\mathbb{Z}$ for some integer $1 \leqslant m \leqslant 4$.

If K is a quadratic field, then, by a result of Kamienny in [6] and Kenku, Momose in [7], the torsion subgroup is isomorphic to one of $\mathbb{Z}/m\mathbb{Z}$ for $1 \leqslant m \leqslant 18$, $m \neq 17$ or one of $\mathbb{Z}/2\mathbb{Z} \oplus \mathbb{Z}/2m\mathbb{Z}$ for $1 \leqslant m \leqslant 6$ or one of $\mathbb{Z}/3\mathbb{Z} \oplus \mathbb{Z}/3m\mathbb{Z}$ for $m = 1, 2$ or $\mathbb{Z}/4\mathbb{Z} \oplus \mathbb{Z}/4\mathbb{Z}$. Moreover in [5], it has been proved that if we let the quadratic fields vary, then all of the 26 torsion subgroups described above appear infinitely often. However, when we fix a quadratic field, it is still unknown which of the 26 listed groups are actually appearing as torsion subgroup. Najman in [11] and [10] determined all possible torsion subgroups of $E(K)$ when K is a quadratic cyclotomic field, i.e. $K = \mathbb{Q}(\mathrm{i})$ or $\mathbb{Q}(\sqrt{-3})$.

Recently, Najman in [12] found all possible torsion subgroups of $E(K)$ for cubic field K and Enrique González-Jiménez [4] found all possible torsion subgroups of $E(K)$ for quintic number field K whenever E is defined over $\mathbb{Q}$.

The subject of torsion points on CM elliptic curves begins with a result of Olson, see [13]. He showed that the torsion subgroup of $E(\mathbb{Q})$ is isomorphic to one of: the trivial group, $\mathbb{Z}/2\mathbb{Z}$, $\mathbb{Z}/3\mathbb{Z}$, $\mathbb{Z}/4\mathbb{Z}$, $\mathbb{Z}/6\mathbb{Z}$ and $\mathbb{Z}/2\mathbb{Z}\times\mathbb{Z}/2\mathbb{Z}$ for any CM elliptic curve E over $\mathbb{Q}$. Then in [2], Bourdon, Clark and Stankewicz computed the torsion subgroup for CM elliptic curves defined over number fields of odd degree.

In this paper, we deal with a family of CM elliptic curves of the form $y^2 = x^3 + c$, where $c \in \mathbb{Q}$. By a rational transformation, it is enough to assume that c is an integer. For this family of curves, we derive precise torsion subgroup of $E(K)$ for any quadratic field K and for any number field K of degree coprime to 6.

2. The main results

For an elliptic curve $E\colon\ y^2 = x^3 + c$ with $c \in \mathbb{Z}$, we write $c = c_1 t^6$ for some sixth power-free integer c_1 and for some nonzero integer t. Then (x, y) is a point on the elliptic curve $E_1\colon\ y^2 = x^3 + c_1$ if and only if (t^2x, t^3y) is a point on E. Thus, it is enough to assume that c is a sixth power-free integer to compute the torsion subgroup of $E(K)$ for some number field K. We prove the following results.

Theorem 1. *Let $E\colon\ y^2 = x^3 + c$ be an elliptic curve for some sixth power-free integer c and let $\mathbb{Q}(\sqrt{d})$ be a quadratic field for some square-free integer d. If T is the torsion subgroup of $E(\mathbb{Q}(\sqrt{d}))$, then T is isomorphic to one of the following groups.*

(1) $\mathbb{Z}/6\mathbb{Z}\begin{cases}\text{if } c = 1 \text{ and } d \neq -3,\\ \text{or } c = a^3 \text{ with } a \neq 1, -3 \text{ for some } a \in \mathbb{Z} \text{ and } d = a;\end{cases}$

(2) $\mathbb{Z}/3\mathbb{Z}\begin{cases}\text{if } c = 2t^3 \text{ with } t \neq 2, -6 \text{ for some } t \in \mathbb{Z} \text{ and}\\ \qquad d \text{ is square-free part of } 2t \text{ or } -6t,\\ \text{or } c = b^2 \neq 1, 16 \text{ for some } b \in \mathbb{Z},\\ \text{or } c = 16, -432 \text{ and } d \neq -3,\\ \text{or } c \text{ is neither a cube nor a square, } c \neq 2t^3 \text{ for any } t \in \mathbb{Z} \text{ and}\\ \qquad d \text{ is square-free part of } c;\end{cases}$

(3) $\mathbb{Z}/2\mathbb{Z}$ *if* $c = a^3$ *with* $a \neq 1$ *for some* $a \in \mathbb{Z}$ *and* $d \neq a$;

(4) $\mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/6\mathbb{Z}$ *if* $c = 1, -27$ *and* $d = -3$;

(5) $\mathbb{Z}/3\mathbb{Z} \times \mathbb{Z}/3\mathbb{Z}$ *if* $c = 16, -432$ *and* $d = -3$;

(6) $\mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/2\mathbb{Z}$ *if* $c = a^3$ *with* $a \neq 1, -3$ *for some* $a \in \mathbb{Z}$ *and* $d = -3$;

(7) $\{\mathcal{O}\}$, *otherwise.*

Theorem 2. *Let $E\colon\ y^2 = x^3 + c$ be an elliptic curve for some sixth power-free integer c and let K be a number field of degree coprime to 6. If T is the torsion subgroup of $E(K)$, then T is isomorphic to one of the following groups.*

(1) $\mathbb{Z}/6\mathbb{Z}$ *if* $c = 1$,
(2) $\mathbb{Z}/3\mathbb{Z}$ *if* $c \neq 1$ *is a square, or* $c = -432$,
(3) $\mathbb{Z}/2\mathbb{Z}$ *if* $c \neq 1$ *is a cube,*
(4) $\{\mathcal{O}\}$, *otherwise.*

3. Preliminaries

In this section, we provide some useful tools which are essential to prove the main results.

For any elliptic curve E over field L and for any positive integer n define

$$E(L)[n] = \{P = (x, y) \in E(L)\colon\ nP = \mathcal{O}\} \cup \{\mathcal{O}\}.$$

Remark 1. Let E be an elliptic curve defined over a number field K. Also let E^d be the d-quadratic twist of E for some $d \in K^*/(K^*)^2$. Then it is well-known that, for any odd positive integer n,

$$E(K(\sqrt{d}))[n] \cong E(K)[n] \times E^d(K)[n].$$

Proposition 1 ([4], Lemma 5)**.** *Let E be an elliptic curve defined over $\mathbb{Q}$ and let $R \in E(\mathbb{C})$ be a point of order n for some positive integer n. Then $[\mathbb{Q}(R) : \mathbb{Q}]$ divides $|\mathrm{GL}_2(\mathbb{Z}/n\mathbb{Z})|$, where $\mathrm{GL}_2(\mathbb{Z}/n\mathbb{Z})$ is the set of all 2×2 invertible matrices over $\mathbb{Z}/n\mathbb{Z}$ and the field $\mathbb{Q}(R)$ is the smallest field containing $\mathbb{Q}$, $x(R), y(R)$.*

Proposition 2 ([8], Lemma 5.12, page 149)**.** *Let $E\colon\ y^2 = x^3 + c$ be an elliptic curve for some nonzero integer c. Let $p \equiv 2 \pmod 3$ be an odd prime such that $p \nmid \Delta$, where Δ is the discriminant of E. Then we have*

$$|\overline{E}(\mathbb{F}_p)| = p + 1,$$

where $\overline{E}$ is the elliptic curve obtained by reducing E modulo p.

Proposition 3 ([14], Theorem 4.12, page 103)**.** *For any prime p let $|E(\mathbb{F}_p)| = p + 1 - a$ with $|a| \leqslant 2\sqrt{p}$. Let $X^2 - aX + p = (X - \alpha)(X - \beta)$ be a quadratic equation for some complex numbers α, β. Then*

$$|E(\mathbb{F}_{p^n})| = p^n + 1 - (\alpha^n + \beta^n)$$

for all $n \geqslant 1$.

Corollary 1. *Let $E\colon\ y^2 = x^3 + c$ be an elliptic curve for some nonzero integer c. Let $p \equiv 2 \pmod 3$ be an odd prime such that $p \nmid \Delta$, where Δ is the discriminant of E. Then we have*

$$|\overline{E}(\mathbb{F}_{p^n})| = \begin{cases} p^n + 1 & \text{if } n \text{ is odd,} \\ (p^{n/2}+1)^2 & \text{if } n \equiv 2 \pmod 4. \end{cases}$$

Proof. We know that $|\overline{E}(\mathbb{F}_p)| = p + 1 - a$ for some integer a with $|a| \leqslant 2\sqrt{p}$. Hence, by Proposition 2, we have $a = 0$ as $p \equiv 2 \pmod 3$. Consider the factorization of the quadratic equation over $\mathbb{C}$ as

$$X^2 + p = (X - \mathrm{i}\sqrt{p})(X + \mathrm{i}\sqrt{p}).$$

By setting $\alpha = \mathrm{i}\sqrt{p}$ and $\beta = -\mathrm{i}\sqrt{p}$ and by Proposition 3, we have

$$|\overline{E}(\mathbb{F}_{p^n})| = \begin{cases} p^n + 1 & \text{if } n \text{ is odd,} \\ (p^{n/2}+1)^2 & \text{if } n \equiv 2 \pmod 4. \end{cases}$$

□

Proposition 4 ([3], Proposition 4). *Let $E\colon\ y^2 = x^3 + bx + c$ be an elliptic curve for some integers b and c. Let T be the torsion subgroup of $E(K)$ for some number field K. Also let $\mathcal{O}_K$ be the ring of integers in K and $\mathcal{P}$ be a prime ideal lying above odd prime p in $\mathcal{O}_K$. If E has good reduction at $\mathcal{P}$, then let φ be the reduction modulo $\mathcal{P}$ map on T. Then the reduction map φ is an injective homomorphism except for finitely many prime ideals $\mathcal{P}$.*

Proposition 5 ([8], Theorem 5.3, page 134). *Let $E\colon\ y^2 = x^3 + c$ be an elliptic curve for some sixth power-free integer c. If T is the torsion subgroup of $E(\mathbb{Q})$, then T is isomorphic to one of the following groups.*

(1) $\mathbb{Z}/6\mathbb{Z}$ *if* $c = 1$,
(2) $\mathbb{Z}/3\mathbb{Z}$ *if* $c \neq 1$ *is a square, or* $c = -432$,
(3) $\mathbb{Z}/2\mathbb{Z}$ *if* $c \neq 1$ *is a cube,*
(4) $\{\mathcal{O}\}$, *otherwise.*

4. Proof of Theorem 1

To prove Theorem 1, we need to formulate several lemmas.

Lemma 1. *There does not exist any element of order* 4 *in* T.

Proof. Let P be an element of order 4 in T. In that case, T contains an element of order 2 which forces c to be a cube, say, a^3 for some nonzero integer a.

Note that if $P=(x,y)$ is an element of order 4, then $y(2P)=0 \Leftrightarrow x^6+20cx^3-8c^2=0 \Leftrightarrow x^3=-10c\pm 6c\sqrt{3}$. Hence, for $d=3$ we have $x=(-1\pm\sqrt{3})a\in\mathbb{Z}[\sqrt{3}]$. Therefore for $d\neq 3$ there does not exist any element of order 4.

For $d=3$, since $x\in\mathbb{Z}[\sqrt{3}]$ and $y^2=x^3+c\in\mathbb{Z}[\sqrt{3}]$, we have $y\in\mathbb{Z}[\sqrt{3}]$. Let $y=t_1+t_2\sqrt{3}$ for some nonzero integers t_1 and t_2. Since $y^2=x^3+c$, we get two relations which are $t_1^2+3t_2^2=-9c$ and $t_1t_2=\pm 3c$. These two relations together imply $t_1^2+3t_2^2\mp 3t_1t_2=0$. Putting $t=t_1/t_2\in\mathbb{Q}$, we have

$$t^2\mp 3t+3=0 \implies t=\frac{\pm 3\pm\sqrt{-3}}{2},$$

a contradiction as $t\in\mathbb{Q}$. Hence, we conclude that there does not exist any element of order 4 in T. $\square$

Lemma 2. *Let* $q>3$ *be any prime. Then there does not exist any element of order* q *in* T.

Proof. From Proposition 5 we see that $E(\mathbb{Q})$ does not have any element of order q. Therefore $E(\mathbb{Q})[q]=\{\mathcal{O}\}$. Now, we consider the d-quadratic twist of E which is $E^d\colon y^2=x^3+cd^3$. Again by Proposition 5, $E^d(\mathbb{Q})$ does not have any element of order q. Therefore $E^d(\mathbb{Q})[q]=\{\mathcal{O}\}$. Hence, by Remark 1, we have $E(\mathbb{Q}(\sqrt{d}))[q]=\{\mathcal{O}\}$, which proves the lemma. $\square$

Lemma 3. *There does not exist any element of order* 9 *in* T.

Proof. From Proposition 5 we see that $E(\mathbb{Q})$ does not have any element of order 9. Therefore $E(\mathbb{Q})[9]\cong\mathbb{Z}/3\mathbb{Z}$ or $E(\mathbb{Q})[9]=\{\mathcal{O}\}$. Also by Proposition 5, $E^d(\mathbb{Q})$ does not have any element of order 9. Therefore $E^d(\mathbb{Q})[9]\cong\mathbb{Z}/3\mathbb{Z}$ or $E^d(\mathbb{Q})[9]=\{\mathcal{O}\}$. Hence, by Remark 1, we conclude that $E(\mathbb{Q}(\sqrt{d}))[9]$ is isomorphic to one of $\mathbb{Z}/3\mathbb{Z}\times\mathbb{Z}/3\mathbb{Z}$, $\mathbb{Z}/3\mathbb{Z}$ and $\{\mathcal{O}\}$. Thus, there does not exist any element of order 9 in T. $\square$

Lemma 4. *Let $P = (x, y)$ be a point of order 2 in $T \subseteq E(\mathbb{Q}(\sqrt{d}))$. Then $c = a^3$ for some nonzero square-free integer a and*

$$P = \begin{cases} (-a, 0) & \text{for } d \neq -3, \\ (-a, 0), (-a\omega, 0), (-a\omega^2, 0) & \text{for } d = -3, \end{cases}$$

where ω is a cube root of unity.

Proof. Note that $P = (x, y)$ is a point of order 2 in $T \Leftrightarrow P \neq \mathcal{O}$ and $2P = \mathcal{O}$ $\Leftrightarrow P \neq \mathcal{O}$ and $P = -P \Leftrightarrow y = 0 \Leftrightarrow x^3 + c = 0$. Hence, $[\mathbb{Q}(x) : \mathbb{Q}] \leqslant 3$. Since $x \in \mathbb{Q}(\sqrt{d})$ and $[\mathbb{Q}(\sqrt{d}) : \mathbb{Q}] = 2$, we conclude that $[\mathbb{Q}(x) : \mathbb{Q}] \leqslant 2$. Hence the polynomial $x^3 + c$ is reducible over $\mathbb{Q}$ and so it has an integer root. Therefore $c = a^3$ for some nonzero integer a.

Then $(-a, 0)$ is the only point of order 2 in T for $d \neq -3$. For $d = -3$, $(-a, 0)$, $(-a\omega, 0)$ and $(-a\omega^2, 0)$ are the only points of order 2 in T. Hence the lemma. □

Lemma 5. *Let $P = (x, y)$ be a point of order 3 in $T \subseteq E(\mathbb{Q}(\sqrt{d}))$. If $c \neq 2t^3$ for any integer t, then*

$$P = \begin{cases} (0, \pm\sqrt{c}) & \textit{if } c \textit{ is a square}, \\ (0, \pm\sqrt{c}) & \textit{if } c \textit{ is not a square and } d \textit{ is square-free part of } c. \end{cases}$$

Proof. Note that $P = (x, y)$ is a point of order 3 in $T \Leftrightarrow P \neq \mathcal{O}$ and $3P = \mathcal{O} \Leftrightarrow P \neq \mathcal{O}$ and $2P = -P$.

Hence, if P is a point of order 3 in T, then

$$x(2P) = x(-P) \;\Leftrightarrow\; \frac{x(x^3 - 8c)}{4(x^3 + c)} = x \;\Leftrightarrow\; x(x^3 + 4c) = 0.$$

If $x^3 + 4c = 0$, then $[\mathbb{Q}(x) : \mathbb{Q}] \leqslant 3$. Since $x \in \mathbb{Q}(\sqrt{d})$ and $[\mathbb{Q}(\sqrt{d}) : \mathbb{Q}] = 2$, we see that $[\mathbb{Q}(x) : \mathbb{Q}] \leqslant 2$. Hence the polynomial $x^3 + 4c$ is reducible over $\mathbb{Q}$ and so it has an integer root. Therefore $4c = z^3$ for some nonzero integer z. Hence, we conclude that $c = 2t^3$ for some nonzero square-free integer t, which is a contradiction. So, $x^3 + 4c \neq 0$. Therefore $x = 0$ and $y = \pm\sqrt{c}$.

If c is a square, say $c = b^2$ for some nonzero integer b, then $(0, \pm b)$ are the only points of order 3 in T for any d. If c is not a square, then $(0, \pm\sqrt{c})$ are the only points of order 3 in T when d is square-free part of c. Hence the lemma. □

Lemma 6. *Let $P = (x, y)$ be a point of order 3 in $T \subseteq E(\mathbb{Q}(\sqrt{d}))$. If $c = 2t^3$ for some square-free integer t, then*

$$P = \begin{cases} (0, \pm 4) \quad \textit{if } t = 2 \textit{ and } d \neq -3, \\ (0, \pm 4),\ (-4, \pm 4\sqrt{-3}),\ (-4\omega, \pm 4\sqrt{-3}) \\ \qquad \textit{and } (-4\omega^2, \pm 4\sqrt{-3}) \quad \textit{if } t = 2 \textit{ and } d = -3, \\ (12, \pm 36) \quad \textit{if } t = -6 \textit{ and } d \neq -3, \\ (0, \pm 12\sqrt{-3}),\ (12, \pm 36),\ (12\omega, \pm 36) \\ \qquad \textit{and } (12\omega^2, \pm 36) \quad \textit{if } t = -6 \textit{ and } d = -3, \\ (0, \pm t\sqrt{2t}) \quad \textit{if } t \neq 2 \textit{ and } d \textit{ is square-free part of } 2t, \\ (-2t, \pm t\sqrt{-6t}) \quad \textit{if } t \neq -6 \textit{ and } d \textit{ is square-free part of } -6t. \end{cases}$$

Proof. Note that if P is a point of order 3 in T, then $x(x^3 + 4c) = 0$. If $x = 0$, then $y = \pm\sqrt{c} = \pm t\sqrt{2t}$. If $2t$ is a square, then $t = 2$ as t is square-free. In this case, $(0, \pm 4)$ are points of order 3 for any d. Though for $d = -3$ we have 8 points of order 3. If $2t$ is not a square, then $(0, \pm t\sqrt{2t})$ are the only points of order 3 when d is square-free part of $2t$.

If $x \neq 0$, then $x^3 = -4c = -8t^3$ and hence x is one of $-2t$, $-2t\omega$, $-2t\omega^2$, where ω is a cube root of unity. In this case, $y = \pm t\sqrt{-6t}$. If $-6t$ is a square, then $t = -6$ as t is square-free. In this case, $(12, \pm 36)$ are points of order 3 for any d. Though for $d = -3$ we have 8 points of order 3. If $-6t$ is not a square, then $(12, \pm t\sqrt{-6t})$ are the only points of order 3 when d is square-free part of $-6t$. $\square$

Now we are ready to prove Theorem 1.

Proof of Theorem 1. By Lemma 1, Lemma 2 and Lemma 3 we see that the only possible orders for the nontrivial torsion points in T are $2, 3$ and 6.

Case 1. c is a cube and a square.

In this case, $c = 1$ as c is sixth power-free.

If $d \neq -3$, then $(0, \pm 1)$ are the only points of order 3 by Lemma 5 and $(1, 0)$ is the only point of order 2 by Lemma 4. Since T is abelian, it has an element of order 6. Hence, $T \cong \mathbb{Z}/6\mathbb{Z}$.

If $d = -3$, then $(0, \pm 1)$ are the only points of order 3 by Lemma 5 and $(1, 0)$, $(\omega, 0)$, $(\omega^2, 0)$ are the only points of order 2 in T by Lemma 4. Since T is abelian, it has an element of order 6. Hence, $T \cong \mathbb{Z}/6\mathbb{Z} \times \mathbb{Z}/2\mathbb{Z}$.

Case 2. c is a cube, but not a square.

Write $c = a^3$ for some nonzero square-free integer $a \neq 1$.

For $d = -3$, $(-a, 0)$, $(-a\omega, 0)$, $(-a\omega^2, 0)$ are the only points of order 2 in T by Lemma 4. If $a \neq -3$, then there does not exist any element of order 3 for $d = -3$

by Lemma 5. Hence, $T \cong \mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/2\mathbb{Z}$. If $a = -3$, then $c = -27$. In that case, $(0, \pm 3\sqrt{-3})$ are the only points of order 3 for $d = -3$ by Lemma 5. Since T is abelian, it has an element of order 6. Hence, $T \cong \mathbb{Z}/6\mathbb{Z} \times \mathbb{Z}/2\mathbb{Z}$.

For $d \neq -3$, $(-a, 0)$ is the only point of order 2 in T by Lemma 4. If $-3 \neq d = a$, then $(0, \pm a\sqrt{a})$ are the only points of order 3 by Lemma 5. Since T is abelian, it has an element of order 6. Hence, $T \cong \mathbb{Z}/6\mathbb{Z}$. If $-3 \neq d \neq a$, then there does not exist any element of order 3 in T by Lemma 5. Hence, $T \cong \mathbb{Z}/2\mathbb{Z}$.

Case 3. c is a square, but not a cube.

If $c = 2t^3$ for some square-free integer t, then $c = 16$ as c is a square. In this case, there does not exist any element of order 2 in T by Lemma 4. For $d = -3$, T has 8 points of order 3 by Lemma 6. Hence, $T \cong \mathbb{Z}/3\mathbb{Z} \times \mathbb{Z}/3\mathbb{Z}$. For $d \neq -3$, $(0, \pm 4)$ are the only points of order 3 by Lemma 6. Hence, $T \cong \mathbb{Z}/3\mathbb{Z}$.

If $c \neq 2t^3$ for any integer t, then write $c = a^2$ for some integer a. Therefore $(0, \pm a)$ are the only points of order 3 in T by Lemma 5. Also there does not exist any element of order 2 by Lemma 4. Hence, $T \cong \mathbb{Z}/3\mathbb{Z}$.

Case 4. c is neither a square nor a cube.

If $c = 2t^3$ for some square-free integer t, then $t \neq 2$ as c is not a square. Hence there does not exist any element of order 2 in T by Lemma 4. Now by Lemma 6, we conclude that for $t = -6$, $T \cong \mathbb{Z}/3\mathbb{Z} \times \mathbb{Z}/3\mathbb{Z}$ for $d = -3$ and $T \cong \mathbb{Z}/3\mathbb{Z}$ for $d \neq -3$. Also for $t \neq -6$, $T \cong \mathbb{Z}/3\mathbb{Z}$ if d is square-free part of $2t$ or $-6t$ by Lemma 6.

If $c \neq 2t^3$ for any integer t, then there does not exist any element of order 2 in T by Lemma 4 and $(0, \pm\sqrt{c})$ are the only points of order 3 in T when d is square-free part of c by Lemma 5. Hence, $T \cong \mathbb{Z}/3\mathbb{Z}$.

Thus, combining all the cases, Theorem 1 follows. $\square$

5. Proof of Theorem 2

Throughout this section, we denote by $\mathcal{O}_K$ a ring of integers in K. To prove Theorem 2, we require the following lemmas.

Lemma 7. *For any odd prime $q > 3$ there does not exist any element of order q in T.*

P r o o f. Suppose there exists an element of order q in T. Hence, q divides $|T|$. Then, by Dirichlet theorem on primes in arithmetic progression [1], we can choose a good prime p with $p \equiv q^2 + 1 \pmod{3q}$ as $(q^2 + 1, 3q) = 1$. Let $p\mathcal{O}_K = \mathcal{P}_1^{e_1}\mathcal{P}_2^{e_2}\ldots\mathcal{P}_r^{e_r}$ be the ideal decomposition in $\mathcal{O}_K$, where $\mathcal{P}_1, \mathcal{P}_2, \ldots, \mathcal{P}_r$ are prime ideals in $\mathcal{O}_K$ lying above p and e_i's are ramification indices for $\mathcal{P}_i$'s. Also, we know that $\sum_{i=1}^{r} e_i f_i = n$, where f_i's are residual degrees for $\mathcal{P}_i$'s.

Since n is odd, there exists at least one f_i which is odd. Let $\mathcal{P}_i$ be the corresponding prime ideal and consider the reduction modulo $\mathcal{P}_i$ map. Since $|\mathcal{O}_K/\mathcal{P}_i| = p^{f_i}$ and f_i is odd, we have $|\overline{E}(\mathcal{O}_K/\mathcal{P}_i)| = p^{f_i} + 1$ by Corollary 1 as $p \equiv 2 \pmod 3$. Hence by Proposition 4, we conclude that $q \mid p^{f_i} + 1$. But we also have $p \equiv 1 \pmod q$, which implies $p^{f_i} + 1 \equiv 2 \pmod q$, which is a contradiction as $q \nmid 2$. Hence the lemma. $\square$

Lemma 8. *There does not exist any element of order* 4 *in* T.

Proof. Suppose there exists an element of order 4 in T. Then 4 divides $|T|$. Therefore, by Dirichlet theorem on primes in arithmetic progression, see [1], we can choose a good prime p with $p \equiv 5 \pmod{12}$. Let $p\mathcal{O}_K = \mathcal{P}_1^{e_1}\mathcal{P}_2^{e_2}\ldots\mathcal{P}_r^{e_r}$ be the ideal decomposition in $\mathcal{O}_K$, where $\mathcal{P}_1, \mathcal{P}_2, \ldots, \mathcal{P}_r$ are prime ideals in $\mathcal{O}_K$ lying above p and e_i's are ramification indices for $\mathcal{P}_i$'s. Also, we know that $\sum\limits_{i=1}^{r} e_i f_i = n$, where f_i's are residual degrees for $\mathcal{P}_i$'s.

Since n is odd, there exists at least one f_i which is odd. Let $\mathcal{P}_i$ be the corresponding prime ideal and consider the reduction modulo $\mathcal{P}_i$ map. Since $|\mathcal{O}_K/\mathcal{P}_i| = p^{f_i}$ and f_i is odd, we have $|\overline{E}(\mathcal{O}_K/\mathcal{P}_i)| = p^{f_i} + 1$ by Corollary 1 as $p \equiv 2 \pmod 3$. Hence by Proposition 4, we conclude that $4 \mid p^{f_i} + 1$. But we also have $p \equiv 1 \pmod 4$, which implies $p^{f_i} + 1 \equiv 2 \pmod 4$, which is a contradiction. Therefore there does not exist any element of order 4 in $|T|$. $\square$

Lemma 9. *Let* $P = (x, y)$ *be a point of order* 2 *in* T. *Then* $c = a^3$ *for some nonzero square-free integer* a *and* $P = (-a, 0)$.

Proof. If $P = (x, y)$ is a point of order 2, then $x(P) = x(-P) \Leftrightarrow y = 0 \Leftrightarrow x^3 + c = 0$. Hence, $[\mathbb{Q}(x) : \mathbb{Q}] \leqslant 3$. Since $x \in K$ and $[K : \mathbb{Q}]$ is coprime to 6, we conclude that x is an integer. Hence, $c = a^3$ for some nonzero square-free integer a. In this case, $(-a, 0)$ is the only point of order 2 in T. Hence the lemma. $\square$

Lemma 10. *Let* $P = (x, y)$ *be a point of order* 3 *in* T. *Then*

$$P = \begin{cases} (0, \pm\sqrt{c}) & \text{if } c \text{ is a square,} \\ (12, \pm 36) & \text{if } c = -432. \end{cases}$$

Proof. If P is a point of order 3 in T, then

$$x(2P) = x(-P) \ \Leftrightarrow\ \frac{x(x^3 - 8c)}{4(x^3 + c)} = x \ \Leftrightarrow\ x(x^3 + 4c) = 0.$$

If $x = 0$, then $y = \pm\sqrt{c}$. Since K is a number field of odd degree, we see that y must be an integer and hence c is a square.

If $x \neq 0$, then $x^3 + 4c = 0$. Hence, $[\mathbb{Q}(x) : \mathbb{Q}] \leqslant 3$. Since $x \in K$ and $[K : \mathbb{Q}]$ is coprime to 6, we conclude that x is an integer. Hence $c = 2t^3$ for some nonzero square-free integer t. Therefore $y = \pm t\sqrt{-6t}$. Since $y \in K$ and K is a number field of odd degree, we conclude that y must be an integer. Hence, $-6t$ must be a square. Since t is a square-free integer, we have $t = -6$. Hence, for $c = -432$, $(12, \pm 36)$ are the only points of order 3 in T. Hence the lemma. □

Lemma 11. *There does not exist any element of order* 9 *in* T.

Proof. Let $P = (x, y)$ be a point of order 9 in T. By Proposition 1, $[\mathbb{Q}(P) : \mathbb{Q}]$ divides $|\mathrm{GL}_2(\mathbb{Z}/9\mathbb{Z})| = 3^5(3^2 - 1)(3 - 1) = 2^4 3^5$, which is a contradiction because $\mathbb{Q}(P)$ is a subfield of K and $[K : \mathbb{Q}]$ is coprime to 6. □

Now we are ready to prove Theorem 2.

Proof of Theorem 2. By Lemma 7, Lemma 8 and Lemma 11, we see that the only possible orders for the nontrivial torsion points in T are $2, 3$ and 6.

Case 1. c is a cube and a square.

In this case, $c = 1$ as c is sixth power-free. Hence, $(0, \pm 1)$ are the only points of order 3 in T by Lemma 10 and $(1, 0)$ is the only point of order 2 in T by Lemma 9. Since T is abelian, it has an element of order 6. Hence, $T \cong \mathbb{Z}/6\mathbb{Z}$.

Case 2. c is a cube, but not a square.

Write $c = a^3$ for some nonzero square-free integer $a \neq 1$. In this case, $(-a, 0)$ is the only point of order 2 in T by Lemma 9. There does not exist any element of order 3 in T by Lemma 10. Hence, $T \cong \mathbb{Z}/2\mathbb{Z}$.

Case 3. c is a square, but not a cube.

Suppose $c = a^2$ for some nonzero integer $a \neq 1$. In this case, there does not exist any element of order 2 in T by Lemma 9. Also $(0, \pm a)$ are the only points of order 3 in T by Lemma 10. Hence, $T \cong \mathbb{Z}/3\mathbb{Z}$.

Case 4. c is neither a square, nor a cube.

In this case, there does not exist any element of order 2 in T by Lemma 9. If $c = -432$, then $(12, \pm 36)$ are the only points of order 3 in T by Lemma 10. Hence, $T \cong \mathbb{Z}/3\mathbb{Z}$ for $c = -432$. If $c \neq -432$, then there does not exist any element of order 3 in T by Lemma 10. Hence, $T = \{\mathcal{O}\}$ for $c \neq -432$.

Thus, combining all the cases, Theorem 2 follows. □

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