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ON THE FIELDS OF 2-POWER TORSION OF CERTAIN ELLIPTIC CURVES

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Abstract. Let μ_{2^∞} denote the group of 2-power roots of unity. The outer pro-2 Galois representation on the projective line minus three points has a kernel whose fixed field, Ω_2, is a pro-2 extension of $\mathbb{Q}(\mu_{2^\infty})$, unramified away from 2. The fields of 2-power torsion of elliptic curves defined over $\mathbb{Q}$ possessing good reduction away from 2 are also pro-2 extensions of $\mathbb{Q}(\mu_{2^\infty})$, unramified away from 2. In this paper, we show that these fields are contained in Ω_2. An analogous result is shown for a certain family of elliptic curves defined over $\mathbb{Q}(\mu_{2^\infty})$.

1. Introduction

For a geometrically connected $\mathbb{Q}$-scheme X, the algebraic fundamental group is given by $\pi_1(X) := \varprojlim \mathrm{Aut}_X(X_i)$, where the $\{X_i\}$ are a collection of finite étale Galois coverings of X (see [4] for details). Hence, each element of $\pi_1(X)$ is a consistent choice of X-automorphisms of the X_i, and such an element in fact determines an X-automorphism of *any* finite étale covering of X. Conversely, any deck transformation τ of a covering $Z \to X$ can be lifted to an element $\tilde{\tau} \in \pi_1(X)$. Let ℓ be a fixed prime number. We may define, similarly, the pro-ℓ fundamental group, $\pi_1^\ell(X)$, by restricting to only those Galois étale coverings of X which have degree a power of ℓ.

In the case X is a curve defined over $k \subseteq \bar{\mathbb{Q}}$, the natural correspondence between morphisms of curves and extensions of function fields provides an alternative description for the fundamental group; $\pi_1(X)$ is isomorphic to $\mathrm{Gal}\big(K(X)^{\mathrm{unr}}/K(X)\big)$, where $K(X)^{\mathrm{unr}}$ is the maximal unramified extension of $K(X)$. Similarly,

$$\pi_1^\ell(X) \cong \mathrm{Gal}\left(K(X)^{\mathrm{unr,\ pro}-\ell}/K(X)\right), \tag{1}$$

where $K(X)^{\mathrm{unr,\ pro}-\ell}$ denotes the maximal pro-ℓ unramified extension of $K(X)$.

Now consider the case where $X = \mathbb{P}^1_{\mathbb{Q}} \smallsetminus \{0, 1, \infty\}$, and let $\bar{X} = X \otimes_{\mathbb{Q}} \bar{\mathbb{Q}}$. In this case, the pro-$\ell$ fundamental group of $\bar{X}$ is isomorphic to $\mathrm{Gal}\big(M/\bar{\mathbb{Q}}(t)\big)$, where M is the maximal pro-ℓ extension of $\mathbb{Q}(t)$ unramified away from $t = 0, 1, \infty$. There

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is an exact sequence of Galois groups

(2)

$$\begin{tikzcd} 1 \arrow[r] & \mathrm{Gal}\big(M/\bar{\mathbb{Q}}(t)\big) \arrow[r] & \mathrm{Gal}\big(M/\mathbb{Q}(t)\big) \arrow[r] & \mathrm{Gal}\big(\bar{\mathbb{Q}}(t)/\mathbb{Q}(t)\big) \arrow[r] & 1 , \\ & \pi_1^\ell\left(\bar{X}\right) \arrow[u, "\cong"'] & & \mathrm{Gal}(\bar{\mathbb{Q}}/\mathbb{Q}) \arrow[u, "\cong"'] & \end{tikzcd}$$

which determines an associated Galois representation

$$\rho_\ell \colon \mathrm{Gal}\left(\bar{\mathbb{Q}}/\mathbb{Q}\right) \longrightarrow \mathrm{Out}\left(\pi_1^\ell(\bar{X})\right). \tag{3}$$

The action of ρ_ℓ is given as follows. For any $\sigma \in \mathrm{Gal}\left(\bar{\mathbb{Q}}/\mathbb{Q}\right)$, we may choose a lift $\tilde{\sigma} \in \mathrm{Gal}\big(M/\mathbb{Q}(t)\big)$.Then conjugation by $\tilde{\sigma}$ is an automorphism of $\mathrm{Gal}\big(M/\bar{\mathbb{Q}}(t)\big)$, which is well-defined up to the choice of $\tilde{\sigma}$. But $\tilde{\sigma}$ is defined up to elements of $\mathrm{Gal}\big(M/\bar{\mathbb{Q}}(t)\big)$, and so this action is defined up to inner automorphism. This is the action of ρ_ℓ.

The kernel of ρ_ℓ is a normal subgroup of $\mathrm{Gal}(\bar{\mathbb{Q}}/\mathbb{Q})$, and we denote its fixed field by Ω_ℓ. Anderson and Ihara have demonstrated that Ω_ℓ is the field generated by the "higher circular ℓ-units" [1]. It is a pro-ℓ extension of $\mathbb{Q}\left(\mu_{\ell^\infty}\right)$, unramified outside of ℓ. Ihara has asked if Ω_ℓ is the maximal such extension [3].

In this article, we consider specifically the case $\ell = 2$. If Ihara's question has an affirmative answer, then any pro-2 extension of $\mathbb{Q}\left(\mu_{2^\infty}\right)$, unramified away from 2, will appear as a subfield of Ω_2. Such fields occur quite naturally. Let E be an elliptic curve defined over $\mathbb{Q}$, with good reduction away from 2, satisfying

$$\mathbb{Q}\left(E[2]\right) \subseteq \mathbb{Q}\left(\mu_{2^\infty}\right). \tag{4}$$

Then $\mathbb{Q}\left(E[2^\infty]\right)$ is a pro-2 extension of $\mathbb{Q}\left(\mu_{2^\infty}\right)$ unramified away from 2. In fact, equation (4) holds for all 24 elliptic curves over $\mathbb{Q}$ with good reduction away from 2. Our main result is the following.

Theorem 1.1. *Let $E/\mathbb{Q}$ be an elliptic curve with good reduction away from 2. Then $\mathbb{Q}\left(E[2^\infty]\right) \subseteq \Omega_2$.*

The key to the proof is to demonstrate these elliptic curves provide 2-covers for $\bar{X}$. We say a morphism $f\colon Y \to Z$ is an **ℓ-cover** of Z if f is unramified and the Galois closure of f has degree a power of ℓ. In particular, an ℓ-cover is not assumed to be Galois itself. For convenience, we will also call a morphism $\varphi\colon C \to \mathbb{P}^1$ an ℓ-cover of $\bar{X}$ if φ can be restricted to an ℓ-cover of $\bar{X}$.

Once a 2-cover $g_0\colon E \to \mathbb{P}^1$ of $\bar{X}$ has been constructed, one may demonstrate that a Galois element σ cannot act trivially through ρ_2 while acting non-trivially on $E[2^\infty]$. This implies the containment $\mathbb{Q}(E[2^\infty]) \subseteq \Omega_2$.

In §2, we will assume the existence of g_0 and give the proof of Theorem 1.1. In §3, we will demonstrate the construction of g_0 for each of the elliptic curves in question. In §4 we will extend the result, by demonstrating an infinite family of elliptic curves which provide 2-covers of $\bar{X}$, and which therefore satisfy $\mathbb{Q}(E[2^\infty]) \subseteq \Omega_2$.

2. Proof of Theorem 1.1

We begin the proof of Theorem 1.1 with the following lemma. Let ζ_8 be a primitive 8th root of unity.

Lemma 2.1. *Let $E/\mathbb{Q}$ be an elliptic curve with good reduction outside 2. Then*

1. *E has a minimal model of the form $y^2 = (x-e_1)(x-e_2)(x-e_3)$, with $e_1 \in \mathbb{Z}$, $e_2, e_3 \in \mathbb{Z}[\zeta_8]$,*
2. *$\mathbb{Q}(E[2]) \subseteq \mathbb{Q}(\zeta_8)$,*
3. *E has a point R of exact order 4 which is Ω_2-rational.*

Proof. The work is entirely by computation. The only nontrivial calculation is in the construction of R. To demonstrate R is Ω_2-rational, we use the description of Ω_2 as the higher circular 2-units. Anderson and Ihara have shown ([1, §2]) that Ω_2 is generated by the sets $f^{-1}(\{0,1,\infty\})$ of ramification of all *elementary* 2-covers $f\colon \mathbb{P}^1 \to \mathbb{P}^1$ of $\bar{X}$. For example, to demonstrate the membership

$$\theta = \sqrt{1-i} \in \Omega_2, \tag{5}$$

we note $\theta \mapsto 1$ under the elementary 2-cover $\mathbb{P}^1 \to \mathbb{P}^1$ of $\bar{X}$ given by $x \mapsto (x^2-1)^4$.

Table 1 demonstrates the results for all 24 elliptic curves over $\mathbb{Q}$ with good reduction away from 2, as enumerated in Cremona's tables [2]. The first column gives the designation and equation for the elliptic curve, and the second column gives the field generated by the 2-torsion of E. The third column gives a rational point P of E of exact order 2 (hence, determining e_1), and the fourth column gives a point R, of exact order 4, rational over Ω_2. □

Before proceeding to the proof of Theorem 1.1, we prove the following lemma.

Lemma 2.2. *Suppose $g_0\colon E \to \mathbb{P}^1$ is a 2-cover of $\bar{X}$, defined over $\mathbb{Q}(\mu_{2^\infty})$. Then for any $n \geq 1$, the morphism $g_n := g_0 \circ [2^n]$ is also a 2-cover of $\bar{X}$, defined over $\mathbb{Q}(\mu_{2^\infty})$.*

Proof. Let $\bar{\mathbb{Q}}(t) \hookrightarrow K_1$ be the inclusion of function fields corresponding to g_0. Let $\tilde{K}_1/K_1$ be the extension corresponding to the morphism $[2^n]$. Let L be the Galois closure of $K_1/\bar{\mathbb{Q}}(t)$, and let $\tilde{L}$ be the Galois closure of $\tilde{K}_1/\bar{\mathbb{Q}}(t)$. We must show that $[\tilde{L} : \bar{\mathbb{Q}}(t)]$ is a power of 2.

Let $\tilde{K}_2, \ldots, \tilde{K}_s$ be the Galois conjugates of $\tilde{K}_1$ in $\tilde{L}$. Since $\tilde{K}_1/K_1$ is Galois, there are corresponding Galois extensions $\tilde{K}_i/K_i$, for each i, within $\tilde{L}$. Because $L/\bar{\mathbb{Q}}(t)$ is Galois of degree a power of 2, and each of the K_i appear within L, it follows that L/K_i is Galois with degree a power of 2 also. Hence for each i, the Galois extensions $\tilde{K}_i/K_i$ and L/K_i form a compositum $L\tilde{K}_i/K_i$ which is Galois and whose degree must also be a power of 2.

Further, each $L\tilde{K}_i$ contains $\tilde{K}_i$, and so the compositum of the $L\tilde{K}_i$ must contain $\tilde{L}$. But the compositum of the Galois extensions $L\tilde{K}_i/\bar{\mathbb{Q}}(t)$ must have a degree dividing the product of the degrees of the extensions. Hence this compositum, as well as the sub-extension $\tilde{L}$, has degree a power of 2 over $\bar{\mathbb{Q}}(t)$.

TABLE 1. Data for the Proof of Lemma 2.1

Let $u = -1 + \sqrt{2}$, $\beta = 1 + i$, and let ζ be a primitive 8th root of unity.

E	$\mathbb{Q}(E[2])$	$P \in E[2]$	$R \in E[4]$
32A1 : $y^2 = x^3 + 4x$	$\mathbb{Q}(\sqrt{-2})$	$(0,0)$	$(2,4)$
32A2 : $y^2 = x^3 - x$	$\mathbb{Q}$	$(0,0)$	$(i, 2\beta^{-1})$
32A3 : $y^2 = x^3 - 11x - 14$	$\mathbb{Q}(\sqrt{2})$	$(-2,0)$	$(-1, 2i)$
32A4 : $y^2 = x^3 - 11x + 14$	$\mathbb{Q}(\sqrt{2})$	$(2,0)$	$(1,2)$
64A1 : $y^2 = x^3 - 4x$	$\mathbb{Q}$	$(0,0)$	$(2i, 2^{5/2}\beta^{-1})$
64A2 : $y^2 = x^3 - 44x - 112$	$\mathbb{Q}(\sqrt{2})$	$(-4,0)$	$(-6, 8i)$
64A3 : $y^2 = x^3 - 44x + 112$	$\mathbb{Q}(\sqrt{2})$	$(4,0)$	$(6,8)$
64A4 : $y^2 = x^3 + x$	$\mathbb{Q}(i)$	$(0,0)$	$(1, 2^{1/2})$
128A1 : $y^2 = x^3 + x^2 + x + 1$	$\mathbb{Q}(i)$	$(-1,0)$	$(u, 2u^{1/2})$
128A2 : $y^2 = x^3 + x^2 - 9x + 7$	$\mathbb{Q}(\sqrt{2})$	$(1,0)$	$(1 + 2i, 4i\beta^{1/2})$
128B1 : $y^2 = x^3 + x^2 + 3x - 5$	$\mathbb{Q}(\sqrt{-2})$	$(1,0)$	$(1 + 2\sqrt{2}, 2^{5/2}u^{-1/2})$
128B2 : $y^2 = x^3 + x^2 - 2x - 2$	$\mathbb{Q}(\sqrt{2})$	$(-1,0)$	$(-2\beta^{-1}, 2\beta^{-1/2})$
128C1 : $y^2 = x^3 - x^2 + x - 1$	$\mathbb{Q}(i)$	$(1,0)$	$(u^{-1}, 2u^{-1/2})$
128C2 : $y^2 = x^3 - x^2 - 9x - 7$	$\mathbb{Q}(\sqrt{2})$	$(-1,0)$	$(-1 + 2i, 2^{5/2}\beta^{-1/2})$
128D1 : $y^2 = x^3 - x^2 + 3x + 5$	$\mathbb{Q}(\sqrt{-2})$	$(-1,0)$	$(-1 + 2\sqrt{2}, 2^{5/2}u^{1/2})$
128D2 : $y^2 = x^3 - x^2 - 2x + 2$	$\mathbb{Q}(\sqrt{2})$	$(1,0)$	$(\beta, i2^{1/2}\beta^{1/2})$
256A1 : $y^2 = x^3 + x^2 - 3x + 1$	$\mathbb{Q}(\sqrt{2})$	$(1,0)$	$(u^{-1}, 2^{5/4}u^{-1/2})$
256A2 : $y^2 = x^3 + x^2 - 13x - 21$	$\mathbb{Q}(\sqrt{2})$	$(-3,0)$	$(-u^2, i2^{11/4}u^{1/2})$
256B1 : $y^2 = x^3 - 2x$	$\mathbb{Q}(\sqrt{2})$	$(0,0)$	$(i2^{1/2}, \zeta^3 2^{5/4})$
256B2 : $y^2 = x^3 + 8x$	$\mathbb{Q}(\sqrt{-2})$	$(0,0)$	$(2^{3/2}, 2^{11/4})$
256C1 : $y^2 = x^3 + 2x$	$\mathbb{Q}(\sqrt{-2})$	$(0,0)$	$(2^{1/2}, 2^{5/4})$
256C2 : $y^2 = x^3 - 8x$	$\mathbb{Q}(\sqrt{2})$	$(0,0)$	$(i2^{3/2}, \zeta^3 2^{11/4})$
256D1 : $y^2 = x^3 - x^2 - 3x - 1$	$\mathbb{Q}(\sqrt{2})$	$(-1,0)$	$(u, i2^{5/4}u^{1/2})$
256D2 : $y^2 = x^3 - x^2 - 13x + 21$	$\mathbb{Q}(\sqrt{2})$	$(3,0)$	$(u^{-2}, 2^{11/4}u^{-1/2})$

Finally, we note that for an elliptic curve E defined over $\mathbb{Q}$, the morphism $[2]$ is also defined over $\mathbb{Q}$. Hence, the morphism g_n is defined over $\mathbb{Q}(\mu_{2^\infty})$ if g_0 is. $\square$

In the next section, we will construct a 2-cover $g_0 \colon E \to \mathbb{P}^1$ of $\bar{X}$, defined over $\mathbb{Q}(\mu_{2^\infty})$, for each of the 24 curves. The following proposition finishes the proof of Theorem 1.1. See also [1, Prop. 3.8.1] for a more general result regarding when the Jacobian of a curve appearing as an ℓ-cover of $\bar{X}$ has ℓ-power torsion rational over Ω_ℓ.

Proposition 2.3. *Let $E/\mathbb{Q}$ be an elliptic curve with good reduction away from 2. Suppose there exists $g_0 \colon E \to \mathbb{P}^1$, a 2-cover of $\bar{X}$, defined over $\mathbb{Q}(\mu_{2^\infty})$. Let $\sigma \in \mathrm{Gal}(\bar{\mathbb{Q}}/\mathbb{Q})$ be such that σ acts non-trivially on $E[2^\infty]$. Then $\sigma \notin \ker \rho_2$.*

Proof. By assumption, there exists $n \geq 1$ and $P \in E[2^n]$ such that $P^\sigma \neq P$. We have demonstrated above that the morphism $g_n \colon E \to \mathbb{P}^1$ is a 2-cover of $\bar{X}$, defined over $\mathbb{Q}(\mu_{2^\infty})$. Let C be the Galois closure of (E, g_n). Let t_P denote the deck transformation of g_n given by translation-by-P. It is an $\bar{X}$-automorphism of (E, g_n), and necessarily extends to some $\bar{X}$-automorphism $\tilde{t}_P$ of C.

If σ does not fix $\mathbb{Q}(\mu_{2^\infty})$, then σ cannot fix Ω_2, and so $\sigma \notin \ker \rho_2$. Hence, we may assume σ fixes $\mathbb{Q}(\mu_{2^\infty})$, and so $g_n^\sigma = g_n$. Let $\bar{\mathbb{Q}}(t, y)$ be the function field of (E, g_n). We choose a lift $\tilde{\sigma} \in \mathrm{Gal}(M/\mathbb{Q}(t))$ such that under $\tilde{\sigma}$, $t \mapsto t$ and $y \mapsto y$. Suppose that $\sigma \in \ker \rho_2$. Then there exists $\varphi \in \pi_1^2(\bar{X})$ such that for every $\eta \in \pi_1^2(\bar{X})$,

$$\rho(\sigma)(\eta) = \eta^{\tilde{\sigma}} = \varphi\eta\varphi^{-1}. \tag{6}$$

That is to say, $\tilde{\sigma}$ must act as some inner automorphism of $\pi_1^2(\bar{X}) \cong \mathrm{Gal}\left(M/\bar{\mathbb{Q}}(t)\right)$. Further, this equality holds for deck transformations of C; in particular, it holds for $\tilde{t}_P$.

Lemma 2.4. *Under these assumptions, $\varphi(E) = E$.*

Proof. To see this, let $\tau \in \mathrm{Gal}(C/E)$. We also denote by τ its lift to an element of $\mathrm{Gal}(M/\bar{\mathbb{Q}}(t))$. Our choice of $\tilde{\sigma}$ satisfies $\tilde{\sigma}^{-1}\left(\bar{\mathbb{Q}}(E)\right) \subseteq \bar{\mathbb{Q}}(E)$, as $\tilde{\sigma}$ fixes t and y. Hence, $\tilde{\sigma}^{-1}(s) \in \bar{\mathbb{Q}}(E)$ for any $s \in \bar{\mathbb{Q}}(E)$, and so $\tilde{\sigma}^{-1}(s)$ is necessarily fixed by τ. Then

$$\begin{aligned} \tau\left(\varphi^{-1}(s)\right) &= \varphi^{-1}\left(\varphi\left(\tau\left(\varphi^{-1}(s)\right)\right)\right) \\ &= \varphi^{-1}\left(\tilde{\sigma}\left(\tau\left(\tilde{\sigma}^{-1}(s)\right)\right)\right) \\ &= \varphi^{-1}\left(\tilde{\sigma}\left(\tilde{\sigma}^{-1}(s)\right)\right) = \varphi^{-1}(s). \end{aligned} \tag{7}$$

So $\varphi^{-1}(s)$ is fixed by all $\tau \in \mathrm{Gal}(C/E)$. Hence, $\varphi^{-1}(s) \in \bar{\mathbb{Q}}(E)$ for every $s \in \bar{\mathbb{Q}}(E)$, and so $\varphi(E) = E$. $\square$

In particular, for $\tilde{t}_P$ we have $\tilde{t}_P^{\tilde{\sigma}} = \varphi\tilde{t}_P\varphi^{-1}$. Since $\tilde{\sigma}(E) = E$,

$$\begin{aligned} \tilde{t}_P^{\tilde{\sigma}}\big|_E &= \tilde{\sigma} \circ \tilde{t}_P \circ \tilde{\sigma}^{-1}\big|_E \\ &= \tilde{\sigma} \circ \tilde{t}_P\big|_E \circ \tilde{\sigma}^{-1}\big|_E = \tilde{\sigma} t_P \tilde{\sigma}^{-1}\big|_E . \end{aligned} \tag{8}$$

Similarly, $\varphi\tilde{t}_P\varphi^{-1}\big|_E = \varphi t_P \varphi^{-1}\big|_E$. Hence, the action of $\tilde{\sigma}$ on $\tilde{t}_P$ descends, and we know that on E,

$$t_P^{\tilde{\sigma}} = \varphi t_P \varphi^{-1}. \tag{9}$$

Then φ cannot be the identity morphism on E, since for an arbitrary $T \in E$,

$$\begin{aligned} t_P^{\tilde{\sigma}}(T) &= \tilde{\sigma}\left(t_P\left(\tilde{\sigma}^{-1}(T)\right)\right) = t_P(T^{\sigma^{-1}})^\sigma \\ &= (P + T^{\sigma^{-1}})^\sigma = P^\sigma + T \neq P + T = t_P(T). \end{aligned} \tag{10}$$

So $\varphi|_E$ is a nontrivial $\bar{X}$-automorphism of E. But *any* curve automorphism of E must be a composition of a translation and a group isomorphism, so we may write $\varphi = t_Q \circ \varphi'$. One quickly sees that $\varphi t_P \varphi^{-1} = \varphi' t_P \varphi'^{-1}$, and so without loss of generality, we may assume that φ is a group isomorphism of E.

However, φ also represents an element of $\mathrm{Gal}(E/\bar{X})$, which by assumption has order a power of 2. So as an element of $\mathrm{Aut}(E)$, φ must have order a power of 2. Since we are in characteristic 0, the only possibilities are that φ or φ^2 is the automorphism $-1 \in \mathrm{Aut}(E)$ ([6, pg. 103]). We consider the two possible cases.

Case I: $\varphi = -1$. In this case, we note

$$P^\sigma = \sigma t_P \sigma^{-1}(O) = \varphi t_P \varphi^{-1}(O) = \varphi(P) = -P. \tag{11}$$

But this must hold for any $P \in E[2^\infty]$ not fixed by σ. Hence, $P^\sigma = \pm P$ for every $P \in E[2^\infty]$. However, this is only possible if $P^\sigma = -P$ for every P, or if σ acts trivially on $E[2^\infty]$. Indeed, if $P, Q \in E[2^\infty] \setminus E[2]$ are such that $P^\sigma = P, Q^\sigma = -Q$, then $(P+Q)^\sigma \neq \pm(P+Q)$.

Since σ does not fix all of $E[2^\infty]$, we know $P^\sigma = -P$ for every $P \in E[2^\infty]$. But by Lemma 2.1, there is an $R \in E[4]$ rational over Ω_2, and so $R^\sigma = R$! This is a contradiction, and so $\sigma \notin \ker \rho_2$.

Case II: $\varphi^2 = -1$. In this case, φ is given by

$$(x, y) \mapsto (\zeta^2 x, \zeta^3 y), \qquad \zeta \in \mu_4. \tag{12}$$

Since σ fixes Ω_2, $\zeta^\sigma = \zeta$, and so φ and σ commute in their action on the points of E. As in Case I, we see that $P^\sigma = \varphi(P)$ for every $P \in E[2^\infty]$ not fixed by σ. Hence, $P^{\sigma^2} = \varphi^2(P) = -P$ or $P^{\sigma^2} = P$ for every $P \in E[2^\infty]$. It follows that σ^2 must act as -1 on all of $E[2^\infty]$. The existence of $R \in E[4]$ fixed by σ^2 again provides a contradiction, and so $\sigma \notin \ker \rho_2$. $\square$

Corollary 2.5. *For every elliptic curve $E/\mathbb{Q}$ which has good reduction away from 2, $\mathbb{Q}(E[2^\infty]) \subseteq \Omega_2$.*

Proof. Proposition 2.3 shows that if σ does not fix $\mathbb{Q}(E[2^\infty])$, then σ does not fix Ω_2. This is equivalent to saying that every σ fixing Ω_2 also fixes $\mathbb{Q}(E[2^\infty])$, or equivalently, that $\mathbb{Q}(E[2^\infty]) \subseteq \Omega_2$. $\square$

3. Construction of the 2-Cover g_0

We now demonstrate that for each of the 24 elliptic curves $E/\mathbb{Q}$ with good reduction away from 2, there exists a 2-cover $g_0 \colon E \to \mathbb{P}^1$ of $\bar{X}$, defined over $\mathbb{Q}(\mu_{2^\infty})$. That is, we will construct a morphism $g_0 \colon E \to \mathbb{P}^1$, unramified away from $\{0, 1, \infty\}$, whose Galois closure has degree a power of 2. In fact, the cover g_0 that we construct will be a composition of degree 2 morphisms. In this case, the degree of the Galois closure will automatically be a power of 2. We remind the reader of the proof.

Lemma 3.1. *Let $F = K_0 \subseteq K_1 \subseteq \cdots \subseteq K_n = K$ be a tower of quadratic field extensions. Then the Galois closure of K/F has degree a power of 2.*

Proof. We proceed by induction. The base case $n = 1$ is trivial. Suppose that the Galois closure of K_{n-1}/F, K_{n-1}^g, has degree a power of 2 over F. We label by $K_n = K_n^1, \ldots, K_n^k$ the Galois conjugates of K_n. Each K_n^i contains a Galois conjugate of K_{n-1}, denoted K_{n-1}^i.

Since K_{n-1}^g and K_n^1 are both Galois over K_{n-1}, the compositum $K_n^1 K_{n-1}^g$ is Galois over K_{n-1} also, and has degree a power of 2 over K_{n-1}. But this compositum contains the field K_{n-1}^2, and so must be Galois and degree a power of 2 over K_{n-1}^2. Hence, the compositum $K_n^2 K_n^1 K_{n-1}^g$ is likewise Galois and degree a power of 2 over K_{n-1}^g. Continuing in this fashion, we see that the compositum $K_n^k \cdots K_n^1 K_{n-1}^g$ is Galois and has degree a power of 2 over K_{n-1}^g. But this compositum clearly contains all the Galois conjugates of K_n, and so also contains K_n^g, the Galois closure of K_n. Thus, the Galois closure of K_n also has degree a power of 2 over F. $\square$

We now set out to construct the covers g_0. We begin by selecting a degree 2 morphism $f\colon E \to \mathbb{P}^1$, which necessarily branches over a 4-point set. We will then use the arithmetic properties of E to prove that f may be extended by degree 2 morphisms $\mathbb{P}^1 \to \mathbb{P}^1$ that collapses the branching to the set $\{0, 1, \infty\}$.

Let E be one of the 24 elliptic curves over $\mathbb{Q}$ with good reduction away from 2. We note that $\mathbb{Q}(\zeta_8)$ has class number 1, and in its ring of integers, there is a unique prime ideal over 2, generated by $\pi = 1 - \zeta_8$. We will use the minimal model of E, together with the properties noted in Lemma 2.1, to construct g_0. We note the discriminant of E,

$$\Delta = 2^4(e_1 - e_2)^2(e_1 - e_3)^2(e_2 - e_3)^2, \tag{13}$$

must have the form $\Delta = u \cdot \pi^k$, for some unit $u \in \mathbb{Z}[\zeta_8]^\times$. For any $\wp \nmid 2$, $v_\wp(\Delta) = 0$. Since the $e_i - e_j$ are all algebraic integers, it follows that $v_\wp(e_i - e_j) = 0$ also.

Now of the quantities $e_i - e_j$, any one can be written as a difference of the other two. Hence, at least two of the valuations $v_\pi(e_i - e_j)$ must be equal. Let us relabel the e_i such that

$$v_\pi(e_1 - e_2) = v_\pi(e_1 - e_3). \tag{14}$$

Now the morphism $f\colon E \to \mathbb{P}^1$ given by

$$f(x, y) = \frac{x - e_1}{e_2 - e_1} \tag{15}$$

has degree 2 and branches over the set $\{0, 1, \infty, \alpha\}$, where

$$\alpha = \frac{e_3 - e_1}{e_2 - e_1}. \tag{16}$$

By (14) and the reduction type of E, α has valuation 0 with respect to every prime ideal in $\mathbb{Q}(\zeta_8)$. Hence, α is a unit in the ring of integers of $\mathbb{Q}(E[2]) \subseteq \mathbb{Q}(\zeta_8)$. For 10 of the curves in the table, the field generated by $E[2]$ has a unit group with rank 0, and so α must be a root of unity. Those curves are 32A1, 32A2, 64A1, 64A4, 128A1, 128B1, 128C1, 128D1, 256B2, and 256C1. For any of these curves, then, the composition

$$g_0 = (x \mapsto x^{2^k}) \circ f, \qquad k \leq 2, \tag{17}$$

gives a morphism $g_0 \colon E \to \mathbb{P}^1$, ramified only over $\{0, 1, \infty\}$, which is a composition of degree 2 morphisms. This is a 2-cover of $\bar{X}$, defined over $\mathbb{Q}$.

The remaining curves have 2-torsion which generates a field with a unit group of positive rank. However, for two of these curves, 256B1 and 256C2, computation shows $\alpha = -1$, and so the morphism $g_0 = (x \mapsto x^2) \circ f$ provides a 2-cover $E \to \mathbb{P}^1$ of $\bar{X}$, defined over $\mathbb{Q}$.

For the eight curves 128A2, 128B2, 128C2, 128D2, 256A1, 256A2, 256D1, and 256D2, computation reveals $\alpha = \pm u^2$, where u is a unit which generates the torsion-free part of the unit group of $\mathbb{Q}(E[2]) = \mathbb{Q}(\sqrt{2})$. Hence, the morphism $\frac{1}{u} \cdot f$ ramifies over the set $\{0, \infty, \frac{1}{u}, u\}$ or $\{0, \infty, \frac{1}{u}, -u\}$, where $u = 1 + \sqrt{2}$ or $u = -1 + \sqrt{2}$. We note the following degree 2 morphisms are unramified:

$$
\begin{array}{llr}
A_1 \colon \mathbb{P}^1 \smallsetminus \{0, \infty, \pm 1 + \sqrt{2}\} \longrightarrow \mathbb{P}^1 \smallsetminus \{0, 1, 2, \infty\} & & x \mapsto (x - \sqrt{2})^2 \\
A_2 \colon \mathbb{P}^1 \smallsetminus \{0, \infty, \pm 1 - \sqrt{2}\} \longrightarrow \mathbb{P}^1 \smallsetminus \{0, 1, 2, \infty\} & & x \mapsto (x + \sqrt{2})^2 \\
A_3 \colon \mathbb{P}^1 \smallsetminus \{0, \infty, -1 \pm \sqrt{2}\} \longrightarrow \mathbb{P}^1 \smallsetminus \{0, 1, 2, \infty\} & & x \mapsto (x + 1)^2 \\
A_4 \colon \mathbb{P}^1 \smallsetminus \{0, \infty, \ \ 1 \pm \sqrt{2}\} \longrightarrow \mathbb{P}^1 \smallsetminus \{0, 1, 2, \infty\} & & x \mapsto (x - 1)^2 \\
B \colon \mathbb{P}^1 \smallsetminus \{0, 1, 2, \infty\} \longrightarrow \mathbb{P}^1 \smallsetminus \{0, 1, \infty\} & & x \mapsto 2x - x^2
\end{array}
\tag{18}
$$

Hence, for these eight curves, a composition of the form $B \circ A_i \circ \frac{1}{u} f$ gives a 2-cover $g_0 \colon E \to \mathbb{P}^1$ of $\bar{X}$, defined over $\mathbb{Q}(\zeta_8)$.

Unfortunately, for the remaining four curves, the unit α is the fourth power of a fundamental unit in $\mathbb{Q}(\sqrt{2})$, and the author could not find a composition of degree 2 morphisms that could extend f to an appropriate 2-cover in these cases. However, the situation is quickly remedied by considering a different morphism $E \to \mathbb{P}^1$ to start. The morphism $h \colon E \to \mathbb{P}^1$ given by

$$h(x, y) = \frac{y}{x - e_1} \tag{19}$$

is of degree 2. One calculates its branch set to be $\{\delta_2 \pm \delta_3, -\delta_2 \pm \delta_3\}$, where

$$\delta_i = \sqrt{e_1 - e_i}. \tag{20}$$

For the four remaining curves, 32A3, 32A4, 64A2, 64A3, one sees that δ_2, δ_3 are algebraic integers in $\mathbb{Q}(\zeta_8)$, and for these curves, the set of branch points of h has the form $\{\pm\gamma, \pm\gamma\sqrt{2}\}$, for some $\gamma \in \mathbb{Q}(\zeta_8)$. Hence, the composition

$$g_0 = B \circ (x \mapsto x^2) \circ \frac{1}{\gamma} h \tag{21}$$

gives a 2-cover $g_0 \colon E \to \mathbb{P}^1$ of $\bar{X}$, defined over $\mathbb{Q}(\zeta_8)$. This completes the construction of g_0 for each of the 24 elliptic curves, and we conclude the following.

Proposition 3.2. *For every elliptic curve $E/\mathbb{Q}$ with good reduction away from 2, there exists a 2-cover $g_0 \colon E \to \mathbb{P}^1$ of $\bar{X}$, defined over $\mathbb{Q}(\mu_{2^\infty})$.*

4. Curves Over $\mathbb{Q}(\mu_{2^\infty})$

We finish this article with an extension of the main theorem, and an example of an infinite family of elliptic curves defined over $\mathbb{Q}(\mu_{2^\infty})$ whose 2-power torsion is Ω_2-rational.

Theorem 4.1. *Let ζ be a primitive 2^n-th root of unity, and suppose that E is an elliptic curve defined over $\mathbb{Q}(\zeta)$, with a minimal model of the form*

$$y^2 = (x - e_1)(x - e_2)(x - e_3), \qquad e_i \in \mathbb{Z}[\zeta]. \tag{22}$$

Further, suppose that E has good reduction away from $(\pi) = (1-\zeta)$, and that E possesses a point R of exact order 4 which is Ω_2-rational. If there exists a 2-cover $g_0 \colon E \to \mathbb{P}^1$ of $\bar{X}$, defined over $\mathbb{Q}(\mu_{2^\infty})$, then $\mathbb{Q}\left(E[2^\infty]\right) \subseteq \Omega_2$.

Proof. Under these hypotheses, we may follow the proof of Theorem 1.1 directly, and so $\mathbb{Q}(E[2^\infty]) \subseteq \Omega_2$. □

Now, for any 2^n-th root of unity ζ, let E_ζ be the elliptic curve given by

$$y^2 = x(x+\zeta)(x-\pi), \qquad \pi = 1-\zeta. \tag{23}$$

We check with Tate's algorithm (see [5] or [7]) that this equation gives a global minimal model for E_ζ over $\mathbb{Q}(\zeta)$. The discriminant is $\Delta = 16\zeta^2\pi^2$, and so E_ζ has good reduction away from (π). Let η be a root of unity satisfying $\zeta = \eta^2$. Then the point $R = \left(\eta - \eta^2, i(\eta - \eta^2)\right)$ has exact order 4, and clearly is rational over Ω_2. We note that $f \colon E \to \mathbb{P}^1$, given by $f(x, y) = x + \zeta$, branches over the set $\{0, 1, \infty, \zeta\}$, and so

$$g_0 = (x \mapsto x^{2^n}) \circ f \tag{24}$$

gives a 2-cover $E \to \mathbb{P}^1$ of $\bar{X}$, defined over $\mathbb{Q}(\mu_{2^\infty})$. Applying Theorem 4.1, we have $\mathbb{Q}\left(E_\zeta[2^\infty]\right) \subseteq \Omega_2$.

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