ON NORMAL $K3$ SURFACES

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Abstract. We determine all possible configurations of rational double points on complex normal algebraic $K3$ surfaces, and on normal supersingular $K3$ surfaces in characteristic $p > 19$.

1. Introduction

In this paper, we mean by a $K3$ surface an *algebraic* $K3$ surface defined over an algebraically closed field, unless otherwise stated.

A $K3$ surface X is said to be *supersingular* (in the sense of Shioda [24]) if the rank of the Picard lattice S_X of X is 22. Supersingular $K3$ surfaces exist only when the characteristic of the base field is positive. Artin [3] showed that, if X is a supersingular $K3$ surface in characteristic $p > 0$, then the discriminant of S_X can be written as $-p^{2\sigma_X}$, where σ_X is an integer with $0 < \sigma_X \leq 10$. This integer σ_X is called the *Artin invariant* of X.

Let Λ_0 be an even unimodular $\mathbb{Z}$-lattice of rank 22 with signature $(3, 19)$. By the structure theorem for unimodular $\mathbb{Z}$-lattices (see, for example, Serre [16, Chapter V]), the $\mathbb{Z}$-lattice Λ_0 is unique up to isomorphisms. If X is a complex $K3$ surface, then $H^2(X, \mathbb{Z})$ regarded as a $\mathbb{Z}$-lattice by the cup-product is isomorphic to Λ_0. For an *odd* prime integer p and an integer σ with $0 < \sigma \leq 10$, we denote by $\Lambda_{p,\sigma}$ an even $\mathbb{Z}$-lattice of rank 22 with signature $(1, 21)$ such that the discriminant group $\mathrm{Hom}(\Lambda_{p,\sigma}, \mathbb{Z})/\Lambda_{p,\sigma}$ is isomorphic to $(\mathbb{Z}/p\mathbb{Z})^{\oplus 2\sigma}$. Rudakov and Shafarevich [14, Theorem in Section 1] showed that the $\mathbb{Z}$-lattice $\Lambda_{p,\sigma}$ is unique up to isomorphisms. If X is a supersingular $K3$ surface in characteristic p with Artin invariant σ, then S_X is p-elementary by [14, Theorem in Section 8] and of signature $(1, 21)$ by the Hodge index theorem, and hence S_X is isomorphic to $\Lambda_{p,\sigma}$.

The *primitive closure* of a sublattice M of a $\mathbb{Z}$-lattice L is $(M \otimes_{\mathbb{Z}} \mathbb{Q}) \cap L$, where the intersection is taken in $L \otimes_{\mathbb{Z}} \mathbb{Q}$. A sublattice $M \subset L$ is said to be *primitive* if $(M \otimes_{\mathbb{Z}} \mathbb{Q}) \cap L = M$ holds. For $\mathbb{Z}$-lattices L and L', we consider the following condition:

$\mathrm{Emb}(L, L')$: There exists a primitive embedding of L into L'.

We denote by $\mathcal{P}$ the set of prime integers. For a non-zero integer m, we denote by $\mathcal{D}(m) \subset \mathcal{P}$ the set of prime divisors of m. We consider the following arithmetic condition on a non-zero integer d, a prime integer $p \in \mathcal{P} \setminus \mathcal{D}(2d)$, and a positive integer $\sigma \leq 10$.

$$\mathrm{Arth}(p, \sigma, d) \quad : \quad \left(\frac{(-1)^{\sigma+1} d}{p} \right) = -1,$$

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where $\left(\frac{x}{p}\right)$ is the Legendre symbol. Remark the following:

(i) Suppose that $d/d' \in (\mathbb{Q}^\times)^2$. Then, for any $p \in \mathcal{P} \setminus \mathcal{D}(2dd')$ and any σ, the conditions $\mathrm{Arth}(p,\sigma,d)$ and $\mathrm{Arth}(p,\sigma,d')$ are equivalent.

(ii) For fixed σ and d, there exists a subset $T_{\sigma,d}$ of $(\mathbb{Z}/4d\mathbb{Z})^\times$ such that, for $p \in \mathcal{P} \setminus \mathcal{D}(2d)$, the condition $\mathrm{Arth}(p,\sigma,d)$ is true if and only if $p \bmod 4d \in T_{\sigma,d}$. The set $T_{\sigma,d}$ is empty if and only if $(-1)^{\sigma+1}d$ is a square integer. Otherwise, we have $|T_{\sigma,d}| = |(\mathbb{Z}/4d\mathbb{Z})^\times|/2$, and hence the set of $p \in \mathcal{P} \setminus \mathcal{D}(2d)$ for which $\mathrm{Arth}(p,\sigma,d)$ is true has the natural density $1/2$.

The main result of this paper is as follows.

Theorem 1.1. *Let M be an even $\mathbb{Z}$-lattice of rank $r = t_+ + t_-$ with signature (t_+, t_-) and of discriminant d_M. Suppose that $t_+ \le 1$ and $t_- \le 19$. Then, for a prime integer $p \in \mathcal{P} \setminus \mathcal{D}(2d_M)$ and a positive integer $\sigma \le 10$, the following hold.*

1. *If $2\sigma > 22 - r$, then $\mathrm{Emb}(M, \Lambda_{p,\sigma})$ is false.*
2. *If $2\sigma < 22 - r$, then $\mathrm{Emb}(M, \Lambda_{p,\sigma})$ and $\mathrm{Emb}(M, \Lambda_0)$ are equivalent.*
3. *If $2\sigma = 22 - r$, then $\mathrm{Emb}(M, \Lambda_{p,\sigma})$ is true if and only if both of $\mathrm{Emb}(M, \Lambda_0)$ and $\mathrm{Arth}(p,\sigma,d_M)$ are true.*

We shall present a geometric application of Theorem 1.1. A *Dynkin type* is a finite formal sum of symbols $A_l\,(l \ge 1)$, $D_m\,(m \ge 4)$ and $E_n\,(n = 6,7,8)$ with non-negative integer coefficients. For a Dynkin type

$$R = \sum a_l A_l + \sum d_m D_m + \sum e_n E_n,$$

we denote by Σ_R^+ the positive-definite root lattice of type R, and define $\mathrm{rank}(R)$ and $\mathrm{disc}(R)$ to be the rank and the discriminant of Σ_R^+:

$$\begin{aligned} \mathrm{rank}(R) &:= \sum a_l l + \sum d_m m + \sum e_n n, \\ \mathrm{disc}(R) &:= \prod (l+1)^{a_l} \cdot \prod 4^{d_m} \cdot 3^{e_6} \cdot 2^{e_7}. \end{aligned}$$

A *normal $K3$ surface* is a normal surface such that its minimal resolution is a $K3$ surface. It is known that a normal $K3$ surface has only rational double points as its singularities (Artin [1, 2]). We define the *Dynkin type R_Y of a normal $K3$ surface* Y to be the Dynkin type of the singular points on Y. A normal $K3$ surface is said to be *supersingular* if its minimal resolution is supersingular. The *Artin invariant σ_Y of a normal supersingular $K3$ surface* Y is defined to be the Artin invariant σ_X of the minimal resolution X of Y. Note that $\mathrm{rank}(R_Y)$ is equal to the total Milnor number of a normal $K3$ surface Y. In particular, we have $\mathrm{rank}(R_Y) \le 21$ for any Y, and $\mathrm{rank}(R_Y) > 19$ holds only when Y is supersingular.

Let R be a Dynkin type, p a prime integer, and σ a positive integer ≤ 10. We consider the following conditions.

$\mathrm{NK}(0,R)$: There exists a complex normal $K3$ surface Y with $R_Y = R$.

$\mathrm{NK}(p,\sigma,R)$: There exists a normal supersingular $K3$ surface Y in characteristic p such that $\sigma_Y = \sigma$ and $R_Y = R$.

$\mathrm{NK}'(p,\sigma,R)$: Every supersingular $K3$ surface X in characteristic p with $\sigma_X = \sigma$ is birational to a normal $K3$ surface Y with $R_Y = R$.

We have the following:

Proposition 1.2. *The conditions $\mathrm{NK}(p,\sigma,R)$ and $\mathrm{NK}'(p,\sigma,R)$ are equivalent.*

Theorem 1.3. *Let R be a Dynkin type with $r := \operatorname{rank}(R) \le 19$, and σ a positive integer ≤ 10. We put $d_R := (-1)^r \operatorname{disc}(R)$, and let p be an element of $\mathcal{P} \setminus \mathcal{D}(2d_R)$.*

1. *If $2\sigma > 22 - r$, then $\mathrm{NK}(p, \sigma, R)$ is false.*
2. *If $2\sigma < 22 - r$, then $\mathrm{NK}(p, \sigma, R)$ and $\mathrm{NK}(0, R)$ are equivalent.*
3. *If $2\sigma = 22 - r$, then $\mathrm{NK}(p, \sigma, R)$ is true if and only if both of $\mathrm{NK}(0, R)$ and $\mathrm{Arth}(p, \sigma, d_R)$ are true.*

For each $p \in \mathcal{P}$, a supersingular $K3$ surface in characteristic p with Artin invariant 1 is unique up to isomorphisms (Ogus [12, 13]). We denote by $X_p^{(1)}$ the supersingular $K3$ surface in characteristic p with Artin invariant 1.

Corollary 1.4. *The following conditions on a Dynkin type R with $r := \operatorname{rank}(R) \le 19$ are equivalent. We put $d_R := (-1)^r \operatorname{disc}(R)$.*

(i) *There exists a complex normal $K3$ surface Y with $R_Y = R$.*
(ii) *There exists a prime integer $p \in \mathcal{P} \setminus \mathcal{D}(2d_R)$ such that $X_p^{(1)}$ is birational to a normal $K3$ surface Y with $R_Y = R$.*
(iii) *For every $p \in \mathcal{P} \setminus \mathcal{D}(2d_R)$, the supersingular $K3$ surface $X_p^{(1)}$ is birational to a normal $K3$ surface Y with $R_Y = R$.*

Let Y be a normal supersingular $K3$ surface in characteristic p. It is proved in [18] that, if $\operatorname{rank}(R_Y) = 21$, then $p \in \mathcal{D}(2 \operatorname{disc}(R_Y))$ holds. It is proved in [22] that, if $\operatorname{rank}(R_Y) = 20$, then either $\sigma_Y = 1$ or $p \in \mathcal{D}(2 \operatorname{disc}(R_Y))$ holds. (In [22], we have also determined all Dynkin types R of rank 20 of rational double points that can appear on normal supersingular $K3$ surfaces in characteristic $p \notin \mathcal{D}(2 \operatorname{disc}(R))$ with the Artin invariant 1.) Therefore, if $\sigma_Y > 1$, then either $\operatorname{rank}(R_Y) \le 19$ or $p \in \mathcal{D}(2 \operatorname{disc}(R_Y))$ holds. Combining this consideration with Theorem 1.3, we obtain restrictions on Dynkin types of normal supersingular $K3$ surfaces with large Artin invariants.

Corollary 1.5. *Let Y be a normal supersingular $K3$ surface in characteristic p with $\sigma_Y = 10$. Then either one of the following holds.* (i) $\operatorname{rank}(R_Y) \le 1$ *(that is, Y is smooth or has only one ordinary node as its singularities),* (ii) $R_Y = A_2$ *and* $p \bmod 24 \in \{5, 11, 17, 23\}$, (iii) $R_Y = 2A_1$ *and* $p \bmod 8 \in \{3, 7\}$, *or* (iv) $p \in \mathcal{D}(2 \operatorname{disc}(R_Y))$.

Corollary 1.6. *Let Y be a normal supersingular $K3$ surface in characteristic p with $\sigma_Y = 9$. Then either one of the following holds.* (i) $\operatorname{rank}(R_Y) \le 3$, (ii) $R_Y = A_4$ *and* $p \bmod 40 \in \{3, 7, 13, 17, 23, 27, 33, 37\}$, (iii) $R_Y = A_1 + A_3$ *and* $p \bmod 8 \in \{3, 5\}$, (iv) $R_Y = 2A_1 + A_2$ *and* $p \bmod 24 \in \{5, 7, 17, 19\}$, *or* (v) $p \in \mathcal{D}(2 \operatorname{disc}(R_Y))$.

Note that, if $p \in \mathcal{D}(2 \operatorname{disc}(R))$ with $\operatorname{rank}(R) \le 21$, then we have $p \le 19$. Therefore we obtain the following:

Corollary 1.7. *The total Milnor number of a normal supersingular $K3$ surface Y in characteristic $p > 19$ with Artin invariant σ_Y is at most $22 - 2\sigma_Y$.*

Let R and R' be Dynkin types. We write $R' < R$ if the Dynkin diagram of R' can be obtained from the Dynkin diagram of R by deleting some vertexes and the edges emitting from them. For a Dynkin type R, we denote by $S(R)$ the set of Dynkin types R' with $R' = R$ or $R' < R$. A $K3$ surface X is birational to a normal $K3$ surface Y with $R_Y = R$ if and only if there exists a configuration of (-2)-curves of type R on X. Hence, if $R' \in S(R)$, we have the following implications:

$$\mathrm{NK}(0, R) \Rightarrow \mathrm{NK}(0, R'), \qquad \mathrm{NK}(p, \sigma, R) \Rightarrow \mathrm{NK}(p, \sigma, R').$$

(rank 15) $A_4 + 11A_1$, $2A_2 + 11A_1$, $A_2 + 13A_1$,

(rank 16) $3D_4 + 2A_2$, $A_6 + A_2 + 8A_1$, $A_4 + 2A_2 + 8A_1$,

(rank 17) $E_8 + D_4 + 5A_1$, $E_6 + 2D_4 + 3A_1$, $E_6 + D_4 + A_2 + 5A_1$, $D_7 + 5A_2$, $D_5 + 5A_2 + 2A_1$, $3D_4 + A_4 + A_1$, $2D_4 + A_6 + A_3$, $2D_4 + A_6 + 3A_1$, $2D_4 + A_4 + A_3 + A_2$, $2D_4 + A_4 + A_2 + 3A_1$, $2D_4 + 3A_2 + 3A_1$, $D_4 + A_8 + 5A_1$, $D_4 + 2A_4 + 5A_1$, $D_4 + A_3 + 5A_2$, $D_4 + 4A_2 + 5A_1$, $A_{10} + 7A_1$, $A_4 + 5A_2 + 3A_1$, $A_3 + 5A_2 + 4A_1$, $7A_2 + 3A_1$, $5A_2 + 7A_1$, $17A_1$,

(rank 18) $E_8 + D_4 + 2A_3$, $E_6 + D_4 + 2A_3 + A_2$, $E_6 + 4A_3$, $D_5 + D_4 + 3A_3$, $D_4 + A_8 + 2A_3$, $D_4 + 2A_4 + 2A_3$, $A_7 + 5A_2 + A_1$, $2A_4 + 5A_2$, $A_4 + 7A_2$, $4A_3 + 3A_2$, $4A_3 + A_2 + 4A_1$,

(rank 19) $E_7 + 3A_4$, $E_7 + 3A_3 + A_2 + A_1$, $D_{12} + A_7$, $D_9 + 3A_3 + A_1$, $D_7 + D_5 + 2A_3 + A_1$, $D_6 + 2D_5 + A_3$, $D_6 + D_5 + 2A_3 + A_2$, $D_6 + 3A_4 + A_1$, $D_6 + 4A_3 + A_1$, $3D_5 + A_3 + A_1$, $D_5 + A_5 + 3A_3$, $D_5 + 3A_4 + A_2$, $D_4 + 4A_3 + 3A_1$, $A_7 + 3A_4$, $A_6 + 4A_3 + A_1$, $A_5 + 3A_4 + A_2$, $A_5 + 4A_3 + 2A_1$, $A_5 + 3A_3 + 2A_2 + A_1$, $3A_4 + 2A_3 + A_1$, $3A_4 + A_3 + A_2 + 2A_1$, $3A_4 + 2A_2 + 3A_1$, $A_4 + 4A_3 + A_2 + A_1$.

TABLE 1.1. Minimal Dynkin types R for which $\mathrm{NK}(0, R)$ is false

We have determined the Boolean value of $\mathrm{NK}(0, R)$ for each Dynkin type R with $\mathrm{rank}(R) \leq 19$, and obtained the following:

Theorem 1.8. *Let R be a Dynkin type of rank ≤ 19. Then* $\mathrm{NK}(0, R)$ *is true if and only if $S(R)$ does not contain any Dynkin type that appears in Table 1.1.*

Corollary 1.9. *Let R be a Dynkin type of rank ≤ 14. Then there exists a complex normal $K3$ surface Y with $R_Y = R$.*

Because $p \in \mathcal{D}(2\,\mathrm{disc}(R))$ with $\mathrm{rank}(R) \leq 21$ implies $p \leq 19$, Theorems 1.3 and 1.8 combined with the results of our previous papers [18] and [22] determine all possible configurations of rational double points on normal supersingular $K3$ surfaces in characteristic $p > 19$.

Since $17A_1$ appears in Table 1.1, we obtain the following result that was proved in Nikulin [9] for the complex case. See also Section 5.1 of this paper.

Corollary 1.10. (1) *There cannot exist seventeen disjoint (-2)-curves on a complex $K3$ surface.* (2) *There exist seventeen disjoint (-2)-curves on a supersingular $K3$ surface only in characteristic* 2.

Remark that, in characteristic 2, there exist twenty-one disjoint (-2)-curves on *every* supersingular $K3$ surface ([18, 19]).

The proof of Theorems 1.1 and 1.8 is based on the theory of discriminant forms due to Nikulin [10], and the theory of l-excess due to Conway and Sloane [6, Chapter 15]. The same method was used in [17] to determine the list of Dynkin types R_f of reducible fibers of complex elliptic $K3$ surfaces $f : X \to \mathbb{P}^1$ with a section and the torsion parts MW_f of their Mordell-Weil groups.

Remark 1.11. Lemma 5.2 in [17] is wrong. It should be replaced with (III) and (IV) in Section 3 of the present article. However, In the actual calculation of the list of all the pairs (R_f, MW_f) of complex elliptic $K3$ surfaces $f : X \to \mathbb{P}^1$ with a section, we used the correct version of [17, Lemma 5.2], and hence the list presented in [17] is valid. See Remark 4.3.

The plan of this paper is as follows. In Section 2, we prove Proposition 1.2 and deduce Theorem 1.3 from Theorem 1.1. In Section 3, we review the theory of l-excess and discriminant forms. In Section 4, we prove Theorems 1.1 and 1.8. We conclude the paper with two remarks in the last section. We give a simple proof of a theorem of Ogus [12, Theorem 7.10] on supersingular Kummer surfaces, and investigate, from our point of view, the reduction modulo p of a singular $K3$ surface (in the sense of Shioda and Inose [23]) defined over a number field.

Conventions

(1) Let D be a finite abelian group. The *length* of D is the minimal number of generators of D, and is denoted by $\mathrm{leng}(D)$.

(2) For $l \in \mathcal{P}$ and $x \in \mathbb{Q}_l^\times$, we denote by $\mathrm{ord}_l(x)$ the largest integer such that $l^{-\mathrm{ord}_l(x)} x \in \mathbb{Z}_l$. We put $\mathbb{Z}_\infty = \mathbb{Q}_\infty = \mathbb{R}$.

(3) For a divisor D on a $K3$ surface X, let $[D] \in S_X$ denote the class of D.

2. Geometric application

We prove Proposition 1.2 and deduce Theorem 1.3 from Theorem 1.1.

Let X be a $K3$ surface. A divisor H on X is called a *polarization* if H is nef, $H^2 > 0$, and the complete linear system $|H|$ has no fixed components. If H is a polarization of X, then $|H|$ is base-point free by Saint-Donat [15, Corollary 3.2], and hence $|H|$ defines a morphism $\Phi_{|H|}$ from X to a projective space of dimension $N := \dim |H| = H^2/2 + 1$. (See Nikulin [11, Proposition 0.1].) Let

$$X \longrightarrow Y_{|H|} \longrightarrow \mathbb{P}^N$$

be the Stein factorization of $\Phi_{|H|}$. Then $X \to Y_{|H|}$ is the minimal resolution of the normal $K3$ surface $Y_{|H|}$. Conversely, let $X \to Y$ be the minimal resolution of a normal $K3$ surface Y. Let H' be a hyperplane section of Y, and H the pull-back of H' to X. Then H is a polarization of X, and Y is isomorphic to $Y_{|H|}$.

Proposition 2.1. *An element v of S_X is the class of a polarization if and only if $(v,v) > 0$, v is nef, and the set $\{e \in S_X \mid (v,e) = 1, (e,e) = 0\}$ is empty.*

Proof. See Nikulin [11, Proposition 0.1], and the argument in the proof of (4)⇒(1) in Urabe [25, Proposition 1.7]. □

We put

$$\Xi_X := \{\, v \in S_X \;\mid\; (v,v) = -2 \,\} \quad \text{and} \quad \Gamma_X := \{\, x \in S_X \otimes_{\mathbb{Z}} \mathbb{R} \;\mid\; (x,x) > 0 \,\}.$$

For $d \in \Xi_X$, we define the *wall* $d^\perp$ associated with d by

$$d^\perp := \{\, x \in S_X \otimes_{\mathbb{Z}} \mathbb{R} \;\mid\; (x,d) = 0 \,\}.$$

Note that the family of walls $d^\perp$ are locally finite in Γ_X. We denote by

$${}^0\Gamma_X := \{\, x \in \Gamma_X \;\mid\; (x,d) \neq 0 \ \text{ for any } \ d \in \Xi_X \,\}$$

the complement of these walls in Γ_X. Let W_X be the subgroup of the orthogonal group $O(S_X)$ of S_X generated by the reflections $x \mapsto x + (x,d)d$ into the walls $d^\perp$ associated with the vectors $d \in \Xi_X$. Then the subgroup of $O(S_X)$ generated by W_X and $\{\pm 1\}$ acts on the set of connected components of ${}^0\Gamma_X$ transitively. Let $\mathcal{A}$ denote the connected component of ${}^0\Gamma_X$ containing the class of a very ample line bundle on X. Then a vector $v \in S_X$ is nef if and only if v is contained in the closure of $\mathcal{A}$ in $S_X \otimes_{\mathbb{Z}} \mathbb{R}$. Combining these considerations with Proposition 2.1, we obtain the following Corollary. See also [14, Proposition 3 in Section 3].

Corollary 2.2. *Let $v \in S_X$ be a vector such that $(v, v) > 0$. Then there exists an isometry $\phi \in O(S_X)$ such that $\phi(mv)$ is the class of a polarization of X for any integer $m \geq 2$.*

We introduce a notion from lattice theory. Let L be a negative-definite even $\mathbb{Z}$-lattice. A vector $v \in L$ is called a *root* if $(v, v) = -2$ holds. We denote by $\mathrm{Roots}(L)$ the set of roots in L. A subset F of $\mathrm{Roots}(L)$ is called a *fundamental system of roots in L* if F is a basis of the sublattice $\langle \mathrm{Roots}(L) \rangle \subset L$ generated by $\mathrm{Roots}(L)$ and each root $v \in \mathrm{Roots}(L)$ is written as a linear combination $v = \sum_{d \in F} k_d d$ of elements d of F with integer coefficients k_d all non-positive or all non-negative. Let $t : L \to \mathbb{R}$ be a linear form such that $t(d) \neq 0$ for any $d \in \mathrm{Roots}(L)$. We put

$$(\mathrm{Roots}(L))^+_t := \{\ d \in \mathrm{Roots}(L)\ \mid\ t(d) > 0\ \}.$$

An element $d \in (\mathrm{Roots}(L))^+_t$ is said to be *decomposable* if there exist vectors $d_1, d_2 \in (\mathrm{Roots}(L))^+_t$ such that $d = d_1 + d_2$; otherwise, we call d *indecomposable*. The following proposition is proved, for example, in Ebeling [7, Proposition 1.4].

Proposition-Definition 2.3. *The set F_t of indecomposable elements in $(\mathrm{Roots}(L))^+_t$ is a fundamental system of roots in L. We call F_t the* fundamental system of roots associated with *$t : L \to \mathbb{R}$.*

Let H be a polarization of a $K3$ surface X. The orthogonal complement $\langle [H] \rangle^\perp$ of $\langle [H] \rangle$ in S_X is a negative-definite even lattice. We put

$$\Xi_{(X,H)} := \mathrm{Roots}(\langle [H] \rangle^\perp) = \langle [H] \rangle^\perp \cap \Xi_X.$$

We denote by $F_{(X,H)}$ the set of classes of (-2)-curves that are contracted by the birational morphism $X \to Y_{|H|}$. It is obvious that $F_{(X,H)} \subset \Xi_{(X,H)}$.

Proposition 2.4. *The set $F_{(X,H)}$ is equal to the fundamental system of roots F_α in $\langle [H] \rangle^\perp$ associated with the linear form $\langle [H] \rangle^\perp \to \mathbb{R}$ given by $v \mapsto (v, \alpha)$, where α is a vector in the connected component $\mathcal{A}$ of ${}^0\Gamma_X$.*

Proof. We denote by $(\Xi_{(X,H)})^+_\alpha$ the set of $d \in \Xi_{(X,H)}$ such that $(d, \alpha) > 0$. By the Riemann-Roch theorem, an element $d \in \Xi_{(X,H)}$ is contained in $(\Xi_{(X,H)})^+_\alpha$ if and only if d is effective. Hence we have $F_{(X,H)} \subset (\Xi_{(X,H)})^+_\alpha$. Suppose that $[E] \in F_{(X,H)}$ were decomposable in $(\Xi_{(X,H)})^+_\alpha$, where E is a (-2)-curve contracted by $X \to Y_{|H|}$. Then there would exist $[D_1], [D_2] \in (\Xi_{(X,H)})^+_\alpha$ with D_1 and D_2 being effective such that $[E] = [D_1] + [D_2]$. Then we would have $D_1 + D_2 \in |E|$, which is absurd. Therefore $[E]$ is indecomposable in $(\Xi_{(X,H)})^+_\alpha$, and hence $F_{(X,H)} \subset F_\alpha$ is proved.

Conversely, let $[D_1], \dots, [D_m]$ be the elements of F_α. Since $F_\alpha \subset (\Xi_{(X,H)})^+_\alpha$, we can assume that $D_1, \dots, D_m$ are effective. We will show that each D_i is a (-2)-curve contracted by $X \to Y_{|H|}$. Let $D_i = F_i + M_i$ be the decomposition of D_i into the sum of the fixed part F_i and the movable part M_i. Since H is nef and $D_i H = 0$, we have $F_i H = 0$ and $M_i H = 0$. In particular, $[M_i]$ is contained in the negative-definite $\mathbb{Z}$-lattice $\langle [H] \rangle^\perp$. Therefore $M_i \neq 0$ would imply $M_i^2 < 0$, which contradicts the movability of M_i. Hence we have $D_i = F_i$. Consequently, the integral components $E_1, \dots, E_l$ of D_i are (-2)-curves. We have $D_i = a_1 E_1 + \dots + a_l E_l$, where $a_1, \dots, a_l$ are positive integers. Since H is nef and $D_i H = 0$, we have $E_1 H = \dots = E_l H = 0$, and hence $E_1, \dots, E_l$ are contracted by $\Phi_{|H|}$. Therefore $[E_1], \dots, [E_l]$ are elements of $F_{(X,H)} \subset F_\alpha$. Thus, for each $k = 1, \dots, l$, there exists j_k such that $[E_k] = [D_{j_k}]$. Then we have $[D_i] = a_1[D_{j_1}] + \cdots + a_l[D_{j_l}]$. Since $[D_1], \dots, [D_m]$ form a basis of the sublattice $\langle \Xi_{(X,H)} \rangle$ of $\langle [H] \rangle^\perp$, and $a_1, \dots, a_l$ are positive integers, we must have $l = 1$, $a_1 = 1$ and $j_1 = i$; that is, $D_i = E_1$. Hence $[D_i] \in F_{(X,H)}$ holds, and $F_\alpha \subset F_{(X,H)}$ is proved. □

Corollary 2.5. *The Dynkin type of the rational double points on* $Y_{|H|}$ *is equal to the Dynkin type of* $\mathrm{Roots}(\langle [H] \rangle^\perp)$.

Let L be a $\mathbb{Z}$-lattice. We denote by $L^\vee$ the *dual lattice* $\mathrm{Hom}(L, \mathbb{Z})$ of L. Then L is embedded in $L^\vee$ as a submodule of finite index, and there exists a natural $\mathbb{Q}$-valued symmetric bilinear form on $L^\vee$ that extends the $\mathbb{Z}$-valued symmetric bilinear form on L. An *overlattice* of L is a submodule L' of $L^\vee$ containing L such that the $\mathbb{Q}$-valued symmetric bilinear form on $L^\vee$ takes values in $\mathbb{Z}$ on L'. If L is embedded in a $\mathbb{Z}$-lattice L'' of the same rank, then L'' is naturally embedded in $L^\vee$ as an overlattice of L. Let L be a negative-definite even $\mathbb{Z}$-lattice. If L' is an even overlattice of L, then we have $\mathrm{Roots}(L') \supseteq \mathrm{Roots}(L)$. We put

$$\mathcal{E}(L) := \left\{ \; L' \;\middle|\; \begin{array}{l} L' \text{ is an even overlattice of } L \text{ such that} \\ \mathrm{Roots}(L') = \mathrm{Roots}(L) \text{ holds} \end{array} \right\}.$$

For a Dynkin type R, we denote by Σ_R^- the *negative-definite* root lattice of type R.

Proposition 2.6. *A* $K3$ *surface* X *is birational to a normal* $K3$ *surface* Y *with* $R_Y = R$ *if and only if there exists an* $M \in \mathcal{E}(\Sigma_R^-)$ *such that* $\mathrm{Emb}(M, S_X)$ *is true.*

Proof. Combining Corollaries 2.2 and 2.5, we see that a $K3$ surface X is birational to a normal $K3$ surface Y with $R_Y = R$ if and only if there exists a vector $v \in S_X$ with $(v, v) > 0$ such that $\mathrm{Roots}(\langle v \rangle^\perp)$ is of type R, where $\langle v \rangle^\perp$ is the orthogonal complement of $\langle v \rangle$ in S_X.

Suppose that such a vector $v \in S_X$ exists. Let $M_0 \subset S_X$ be the sublattice of S_X generated by $\mathrm{Roots}(\langle v \rangle^\perp)$. Then we have an isometry $\varphi : \Sigma_R^- \xrightarrow{\sim} M_0$. Let M be the overlattice of Σ_R^- corresponding by φ to the primitive closure of M_0 in S_X. Then $M \in \mathcal{E}(\Sigma_R^-)$ holds, and $\mathrm{Emb}(M, S_X)$ is true.

Conversely, suppose that there exists an $M \in \mathcal{E}(\Sigma_R^-)$ that admits a primitive embedding $M \hookrightarrow S_X$. Let N be the orthogonal complement of M in S_X. Since M is primitive in S_X, the orthogonal complement of N in S_X coincides with M. Hence a wall $d^\perp$ associated with $d \in \Xi_X$ contains $N \otimes_\mathbb{Z} \mathbb{R}$ if and only if $d \in \Xi_X \cap M = \mathrm{Roots}(M) = \mathrm{Roots}(\Sigma_R^-)$. We put

$$\Gamma_N := \Gamma_X \cap (N \otimes_\mathbb{Z} \mathbb{R}),$$

which is a non-empty open subset of $N \otimes_\mathbb{Z} \mathbb{R}$. The family of real hyperplanes

$$\{ \; d^\perp \cap (N \otimes_\mathbb{Z} \mathbb{R}) \;\mid\; d \in \Xi_X \setminus \mathrm{Roots}(\Sigma_R^-) \; \}$$

in $N \otimes_\mathbb{Z} \mathbb{R}$ is locally finite in Γ_N, and hence there exists $v \in \Gamma_N \cap N$ such that $v \notin d^\perp$ for any $d \in \Xi_X \setminus \mathrm{Roots}(\Sigma_R^-)$. Then $\mathrm{Roots}(\langle v \rangle^\perp) = \mathrm{Roots}(\Sigma_R^-)$ holds. □

Proposition 2.7. *The condition* $\mathrm{NK}(0, R)$ *is true if and only if there exists an* $M \in \mathcal{E}(\Sigma_R^-)$ *such that* $\mathrm{Emb}(M, \Lambda_0)$ *is true.*

Proof. Suppose that there exists a complex normal $K3$ surface Y with $R_Y = R$. Let X be the minimal resolution of Y. Then, by Proposition 2.6, there exists an $M \in \mathcal{E}(\Sigma_R^-)$ such that $\mathrm{Emb}(M, S_X)$ is true. Since S_X is primitive in $H^2(X, \mathbb{Z})$, and $H^2(X, \mathbb{Z})$ is $\mathbb{Z}$-isometric to Λ_0, we see that $\mathrm{Emb}(M, \Lambda_0)$ is true.

Conversely, suppose that there exists an $M \in \mathcal{E}(\Sigma_R^-)$ that admits a primitive embedding $M \hookrightarrow \Lambda_0$. We choose a vector $h \in \Lambda_0$ such that $(h, h) > 0$, and denote by S the primitive closure of the sublattice of Λ_0 generated by M and h. Since M is primitive in Λ_0, the embedding $M \hookrightarrow S$ is also primitive. Let T be the orthogonal complement of S in Λ_0. We put

$$\Omega_T := \{\ [\omega] \in \mathbb{P}_*(T \otimes_{\mathbb{Z}} \mathbb{C})\ \mid\ (\omega, \omega) = 0, (\omega, \bar{\omega}) > 0\ \},$$

where $[\omega] \subset T \otimes_{\mathbb{Z}} \mathbb{C}$ is the 1-dimensional linear subspace generated by $\omega \in T \otimes_{\mathbb{Z}} \mathbb{C}$. There exists $[\omega_0] \in \Omega_T$ such that $\{v \in T \mid (\omega_0, v) = 0\} = \{0\}$. Then we have

$$\{\ v \in \Lambda_0\ \mid\ (\omega_0, v) = 0\ \} = S. \tag{2.1}$$

By the surjectivity of the period mapping for complex analytic $K3$ surfaces (see, for example, [4, Chapter VIII]), there exist an analytic $K3$ surface X and an isometry

$$\phi : H^2(X, \mathbb{Z}) \xrightarrow{\sim} \Lambda_0$$

of $\mathbb{Z}$-lattices such that $\phi \otimes \mathbb{C}$ maps the 1-dimensional subspace $H^{2,0}(X) \subset H^2(X, \mathbb{C})$ to $[\omega_0]$. By (2.1), we have $\phi(S_X) = S$. Let $h_X \in S_X$ be the vector such that $\phi(h_X) = h$. Then we have $(h_X, h_X) > 0$, and hence X is algebraic. Since S and S_X is $\mathbb{Z}$-isometric, we see that $\mathrm{Emb}(M, S_X)$ is true. Then X is birational to a normal $K3$ surface Y with $R_Y = R$ by Proposition 2.6. □

Proof of Proposition 1.2 and Theorem 1.3. By [14, Theorem in Section 8] and [14, Theorem in Section 1] (with [14, Proposition in Section 5] for the case of characteristic 2), the Picard lattice of a supersingular $K3$ surface is determined, up to isomorphisms, by the characteristic of the base field and the Artin invariant. Hence Proposition 1.2 follows from Proposition 2.6.

Note that $d_R = (-1)^r \operatorname{disc}(R)$ is the discriminant of Σ_R^-. If M is an element of $\mathcal{E}(\Sigma_R^-)$ with discriminant d_M, then we have $\mathcal{D}(2d_M) \subset \mathcal{D}(2d_R)$, and, for any $p \in \mathcal{P} \setminus \mathcal{D}(2d_R)$, the conditions $\mathrm{Arth}(p, \sigma, d_M)$ and $\mathrm{Arth}(p, \sigma, d_R)$ are equivalent, because $d_R/d_M = |M/\Sigma_R^-|^2$ is a square integer. Therefore Theorem 1.3 follows from Propositions 2.6 and 2.7 and Theorem 1.1. □

3. The theory of l-excess and discriminant forms

See Cassels [5], Conway and Sloane [6, Chapter 15] and Nikulin [10] for the details of the results reviewed in this section.

Let R be $\mathbb{Z}$, $\mathbb{Q}$, $\mathbb{Z}_l$ or $\mathbb{Q}_l$, where $l \in \mathcal{P} \cup \{\infty\}$. An *$R$-lattice* is a free R-module L of finite rank equipped with a non-degenerate symmetric bilinear form

$$(\ ,\ )\ :\ L \times L \to R.$$

We say that R-lattices L and L' are *R-isometric* and denote $L \cong L'$ if there exists an isomorphism of R-modules $L \xrightarrow{\sim} L'$ that preserves the symmetric bilinear form. We sometimes express an R-lattice L of rank n by an $n \times n$ symmetric matrix with components in R by choosing a basis of L. For example, for $a \in R$ with $a \neq 0$, we denote by $[a]$ the R-lattice of rank 1 generated by a vector g such that $(g, g) = a$. For R-lattices L and L', we denote by $L \oplus L'$ the *orthogonal* direct-sum of L and

L'. For $s \in R \setminus \{0\}$, we denote by sL the R-lattice obtained from an R-lattice L by multiplying the symmetric bilinear form with s. Suppose that an R-lattice L is expressed by a symmetric matrix M with respect to a certain basis of L. Then

$$\operatorname{disc}(L) := \det(M) \bmod (R^\times)^2 \quad \in \quad R/(R^\times)^2$$

dose not depend on the choice of the basis of L. We say that L is *unimodular* if $\operatorname{disc}(L) \in R^\times/(R^\times)^2$.

The following is proved in [5, Theorem 1.2 in Chapter 9].

Theorem 3.1. *Let n be a positive integer, and d a non-zero integer. Suppose that, for each $l \in \mathcal{P} \cup \{\infty\}$, we are given a $\mathbb{Z}_l$-lattice L_l of rank n such that $\operatorname{disc}(L_l)$ is equal to d in $\mathbb{Z}_l/(\mathbb{Z}_l^\times)^2$. If there exists a $\mathbb{Q}$-lattice W such that $W \otimes_{\mathbb{Q}} \mathbb{Q}_l$ is $\mathbb{Q}_l$-isometric to $L_l \otimes_{\mathbb{Z}_l} \mathbb{Q}_l$ for each $l \in \mathcal{P} \cup \{\infty\}$, then there exists a $\mathbb{Z}$-lattice L such that $L \otimes_{\mathbb{Z}} \mathbb{Z}_l$ is $\mathbb{Z}_l$-isometric to L_l for each $l \in \mathcal{P} \cup \{\infty\}$.*

Let L be an R-lattice, where $R = \mathbb{Z}$ or $\mathbb{Z}_l$ with $l \in \mathcal{P}$, and let k be the quotient field of R. We put

$$L^\vee := \operatorname{Hom}_R(L, R).$$

We have a natural embedding $L \hookrightarrow L^\vee$ of R-modules, and a natural k-valued symmetric bilinear form on $L^\vee$ that extends the R-valued symmetric bilinear form on L. We define the *discriminant group* D_L of L by

$$D_L := L^\vee/L.$$

If L is a $\mathbb{Z}$-lattice, then $\operatorname{disc}(L) = (-1)^{s_-}|D_L|$ holds in $\mathbb{Z}/(\mathbb{Z}^\times)^2 = \mathbb{Z}$.

Suppose that L is a $\mathbb{Z}_l$-lattice. We have an orthogonal direct-sum decomposition

$$L = \bigoplus\nolimits_{\nu \geq 0} l^\nu L_\nu, \tag{3.1}$$

where each L_ν is a unimodular $\mathbb{Z}_l$-lattice. The decomposition (3.1) is called the *Jordan decomposition* of L. The discriminant group D_L of L is then isomorphic to the direct product $\prod_{\nu \geq 1} (\mathbb{Z}/l^\nu\mathbb{Z})^{\operatorname{rank}(L_\nu)}$. In particular, we have

$$|D_L| = l^{\sum \nu \operatorname{rank}(L_\nu)} \quad \text{and} \quad \operatorname{leng}(D_L) = \operatorname{rank}(L) - \operatorname{rank}(L_0).$$

We define the *reduced discriminant* of L by

$$\operatorname{reddisc}(L) := \prod\nolimits_{\nu \geq 0} \operatorname{disc}(L_\nu) = \operatorname{disc}(L)/|D_L| \quad \in \quad \mathbb{Z}_l^\times/(\mathbb{Z}_l^\times)^2.$$

Suppose that $l \neq 2$. Then we have an orthogonal direct-sum decomposition

$$L \;\cong\; \bigoplus l^{\nu_i}[a_i] \qquad (a_i \in \mathbb{Z}_l^\times). \tag{3.2}$$

For $a \in \mathbb{Z}_l^\times$, we define

$$l\text{-excess}(l^\nu[a]) := \begin{cases} (l^\nu - 1) \bmod 8 & \text{if } \nu \text{ is even or } a \in (\mathbb{Z}_l^\times)^2, \\ (l^\nu + 3) \bmod 8 & \text{if } \nu \text{ is odd and } a \notin (\mathbb{Z}_l^\times)^2, \end{cases}$$

and define $l\text{-excess}(L) \in \mathbb{Z}/8\mathbb{Z}$ to be the sum of the l-excesses of the direct summands in (3.2). It has been proved that $l\text{-excess}(L)$ does not depend on the choice of the orthogonal direct-sum decomposition (3.2). Note that, if L is unimodular, then $l\text{-excess}(L) = 0$.

Suppose that $l = 2$. Every unimodular $\mathbb{Z}_2$-lattice is $\mathbb{Z}_2$-isometric to an orthogonal direct-sum of copies of the following $\mathbb{Z}_2$-lattices:

$$[a] \quad (a \in \mathbb{Z}_2^\times), \qquad U := \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \quad \text{or} \quad V := \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix}.$$

Hence L has an orthogonal direct-sum decomposition

$$L \;\cong\; \bigoplus 2^{\nu_i}[a_i] \oplus \bigoplus 2^{\nu_j} U \oplus \bigoplus 2^{\nu_k} V, \tag{3.3}$$

where $a_i \in \mathbb{Z}_2^\times$. We put

$$2\text{-excess}(2^\nu[a]) := \begin{cases} (1-a) \bmod 8 & \text{if } \nu \text{ is even or } a \equiv \pm 1 \bmod 8, \\ (5-a) \bmod 8 & \text{if } \nu \text{ is odd and } a \equiv \pm 3 \bmod 8, \end{cases}$$

$$2\text{-excess}(2^\nu U) := 2 \bmod 8, \qquad 2\text{-excess}(2^\nu V) := (4 - (-1)^\nu 2) \bmod 8,$$

and define $2\text{-excess}(L) \in \mathbb{Z}/8\mathbb{Z}$ to be the sum of the 2-excesses of the direct summands in (3.3). It has been proved that $2\text{-excess}(L)$ does not depend on the choice of the orthogonal direct-sum decomposition (3.3). The 2-excess of a unimodular $\mathbb{Z}_2$-lattice need not be 0.

For the following, see Conway and Sloane [6, Theorem 8 in Chapter 15].

Theorem 3.2. *Let n be a positive integer, and d a non-zero integer. Suppose that, for each $l \in \mathcal{P} \cup \{\infty\}$, we are given a $\mathbb{Z}_l$-lattice L_l of rank n such that*

$$\mathrm{disc}(L_l) = d \mod (\mathbb{Z}_l^\times)^2 \tag{3.4}$$

holds in $\mathbb{Z}_l/(\mathbb{Z}_l^\times)^2$. Then there exists a $\mathbb{Q}$-lattice W such that $W \otimes_{\mathbb{Q}} \mathbb{Q}_l$ is $\mathbb{Q}_l$-isometric to $L_l \otimes_{\mathbb{Z}_l} \mathbb{Q}_l$ for each $l \in \mathcal{P} \cup \{\infty\}$ if and only if

$$s_+ - s_- + \textstyle\sum_{l \in \mathcal{P}} l\text{-excess}(L_l) \;\equiv\; n \mod 8 \tag{3.5}$$

holds, where (s_+, s_-) is the signature of the $\mathbb{R}$-lattice L_∞.

Remark 3.3. If $l \notin \mathcal{D}(2d)$ and $l \neq \infty$, then the condition (3.4) implies that the $\mathbb{Z}_l$-lattice L_l is unimodular. Hence the summation in (3.5) is in fact finite.

Definition 3.4. A *finite quadratic form* is a pair (D, q) of a finite abelian group D and a map $q : D \to \mathbb{Q}/2\mathbb{Z}$ such that (i) $q(nx) = n^2 q(x)$ for $n \in \mathbb{Z}$ and $x \in D$, and (ii) the map $b : D \times D \to \mathbb{Q}/\mathbb{Z}$ defined by $b(x,y) := (q(x+y) - q(x) - q(y))/2$ is bilinear. A finite quadratic form (D, q) is said to be *non-degenerate* if the symmetric bilinear form b is non-degenerate.

Remark 3.5. Let (D, q) be a finite quadratic form. Suppose that D is an l-group, where $l \in \mathcal{P}$. Then the image of q is contained in the subgroup

$$(\mathbb{Q}/2\mathbb{Z})_l := \{\, t \in \mathbb{Q}/2\mathbb{Z} \;\mid\; l^\nu t = 0 \text{ for a sufficiently large } \nu \,\} = 2\mathbb{Z}[1/l]/2\mathbb{Z}$$

of $\mathbb{Q}/2\mathbb{Z}$. On the other hand, the canonical homomorphism $\mathbb{Q}/2\mathbb{Z} \to (\mathbb{Q}/2\mathbb{Z}) \otimes_{\mathbb{Z}} \mathbb{Z}_l = \mathbb{Q}_l/2\mathbb{Z}_l$ induces an isomorphism $(\mathbb{Q}/2\mathbb{Z})_l \xrightarrow{\sim} \mathbb{Q}_l/2\mathbb{Z}_l$. Hence we can consider q as a map to $\mathbb{Q}_l/2\mathbb{Z}_l$.

Definition 3.6. For a non-degenerate finite quadratic form (D, q) and $l \in \mathcal{P}$, let

$$D_l := \{\, t \in D \;\mid\; l^\nu t = 0 \text{ for a sufficiently large } \nu \,\}$$

denote the l-part of D, and q_l the restriction of q to D_l. We call $(D, q)_l := (D_l, q_l)$ the *l-part* of (D, q). If $l \notin \mathcal{D}(|D|)$, then $(D_l, q_l) = (0, 0)$. We have a decomposition

$$(D, q) = \textstyle\bigoplus_{l \in \mathcal{D}(|D|)} (D_l, q_l)$$

that is orthogonal with respect to the symmetric bilinear form b.

Let R be $\mathbb{Z}$ or $\mathbb{Z}_l$ with $l \in \mathcal{P}$, and k the quotient field of R. An R-lattice L is said to be *even* if $(v, v) \in 2R$ holds for every $v \in L$. Note that, if l is odd, then any $\mathbb{Z}_l$-lattice is even. Note also that a $\mathbb{Z}$-lattice L is even if and only if the $\mathbb{Z}_2$-lattice $L \otimes_{\mathbb{Z}} \mathbb{Z}_2$ is even, and that a $\mathbb{Z}_2$-lattice L is even if and only if the component L_0 of the Jordan decomposition $L = \bigoplus 2^\nu L_\nu$ is $\mathbb{Z}_2$-isometric to an orthogonal direct-sum of copies of U and V.

Definition 3.7. For an even R-lattice L, we can define a map

$$q_L : D_L \to k/2R$$

by $q_L(\bar{x}) := (x, x) \bmod 2R$, where $x \in L^\vee$ and $\bar{x} := x \bmod L$. When $R = \mathbb{Z}_l$, we consider q_L as a map to $\mathbb{Q}/2\mathbb{Z}$ by the isomorphism $\mathbb{Q}_l/2\mathbb{Z}_l \cong (\mathbb{Q}/2\mathbb{Z})_l \subset \mathbb{Q}/2\mathbb{Z}$ in Remark 3.5. It is easy to see that the finite quadratic form (D_L, q_L) is non-degenerate. We call (D_L, q_L) the *discriminant form* of L.

We have $\operatorname{leng}(D_L) \le \operatorname{rank}(L)$. If L is unimodular, then $(D_L, q_L) = (0, 0)$ holds. If $b_L(\bar{x}, \bar{y}) := (q_L(\bar{x} + \bar{y}) - q_L(\bar{x}) - q_L(\bar{y}))/2$ is the symmetric bilinear form of (D_L, q_L), then we have $b_L(\bar{x}, \bar{y}) = (x, y) \bmod \mathbb{Z}$. The following is obvious:

Proposition 3.8. *Let L be an even $\mathbb{Z}$-lattice, and l a prime integer. Then the homomorphism $D_L \to D_{L\otimes_{\mathbb{Z}}\mathbb{Z}_l}$ induced from the natural homomorphism $L^\vee \to L^\vee \otimes_{\mathbb{Z}} \mathbb{Z}_l = (L \otimes_{\mathbb{Z}} \mathbb{Z}_l)^\vee$ yields an isomorphism from the l-part $(D_L, q_L)_l$ of (D_L, q_L) to $(D_{L\otimes_{\mathbb{Z}}\mathbb{Z}_l}, q_{L\otimes_{\mathbb{Z}}\mathbb{Z}_l})$.*

Let $(D^{(l)}, q^{(l)})$ be a non-degenerate quadratic form on a finite abelian l-group $D^{(l)}$, and n a positive integer. We denote by $\mathbb{L}^{(l)}(n, D^{(l)}, q^{(l)})$ the set of even $\mathbb{Z}_l$-lattices L of rank n such that (D_L, q_L) is isomorphic to $(D^{(l)}, q^{(l)})$. We then denote by $\mathcal{L}^{(l)}(n, D^{(l)}, q^{(l)}) \subset \mathbb{Z}/8\mathbb{Z} \times \mathbb{Z}_l^\times/(\mathbb{Z}_l^\times)^2$ the image of the map

$$\begin{array}{ccc} \mathbb{L}^{(l)}(n, D^{(l)}, q^{(l)}) & \to & \mathbb{Z}/8\mathbb{Z} \times \mathbb{Z}_l^\times/(\mathbb{Z}_l^\times)^2 \\ L & \mapsto & \tau^{(l)}(L) := [\, l\text{-excess}(L), \operatorname{reddisc}(L)\,]. \end{array}$$

Let (D, q) be a non-degenerate finite quadratic form, and let

$$\mathcal{L}^{\mathbb{Z}}(n, D, q) := \textstyle\prod_{l \in \mathcal{D}(2|D|)} \mathcal{L}^{(l)}(n, D_l, q_l)$$

be the Cartesian product of the sets $\mathcal{L}^{(l)}(n, D_l, q_l)$, where (D_l, q_l) is the l-part of (D, q) and l runs through the prime divisors of $2|D|$. Let (s_+, s_-) be a pair of non-negative integers such that $s_+ + s_- = n$. We denote by $\mathbb{L}^{\mathbb{Z}}((s_+, s_-), D, q)$ the set of even $\mathbb{Z}$-lattices L of rank n with signature (s_+, s_-) such that (D_L, q_L) is isomorphic to (D, q). By Proposition 3.8, we can define a map

$$\begin{array}{ccc} \mathbb{L}^{\mathbb{Z}}((s_+, s_-), D, q) & \to & \mathcal{L}^{\mathbb{Z}}(n, D, q) \\ L & \mapsto & \tau^{\mathbb{Z}}(L) := (\, \tau^{(l)}(L \otimes_{\mathbb{Z}} \mathbb{Z}_l) \mid l \in \mathcal{D}(2|D|)\,). \end{array}$$

Theorem 3.9. *We put $d := (-1)^{s_-}|D|$. Then the image of $\tau^{\mathbb{Z}}$ coincides with the set of elements $(\,[\sigma_l, \rho_l] \mid l \in \mathcal{D}(2d)\,)$ of $\mathcal{L}^{\mathbb{Z}}(n, D, q)$ satisfying the following:*

(i) $\rho_l = d/l^{\operatorname{ord}_l(d)} \bmod (\mathbb{Z}_l^\times)^2$ *for each $l \in \mathcal{D}(2d)$, and*

(ii) $s_+ - s_- + \sum_{l \in \mathcal{D}(2d)} \sigma_l \equiv n \bmod 8$.

In particular, the set $\mathbb{L}^{\mathbb{Z}}((s_+, s_-), D, q)$ is non-empty if and only if there exists an element $(\,[\sigma_l, \rho_l] \mid l \in \mathcal{D}(2|D|)\,) \in \mathcal{L}^{\mathbb{Z}}(n, D, q)$ that satisfies (i) *and* (ii).

Let $l \in \mathcal{P}$ be an odd prime. We choose a non-square element $v_l \in \mathbb{Z}_l^\times$, and put $\bar{v}_l := v_l \bmod (\mathbb{Z}_l^\times)^2$, so that $\mathbb{Z}_l^\times/(\mathbb{Z}_l^\times)^2 = \{1, \bar{v}_l\}$ holds. We then define $\mathbb{Z}_l$-lattices $S_n^{(l)}$ and $N_n^{(l)}$ of rank n by

$$\begin{aligned} S_n^{(l)} &:= [1] \oplus \cdots \oplus [1] \oplus [1], \\ N_n^{(l)} &:= [1] \oplus \cdots \oplus [1] \oplus [v_l]. \end{aligned}$$

It is easy to see that $[v_l] \oplus [v_l]$ is $\mathbb{Z}_l$-isometric to $[1] \oplus [1]$. Therefore, if T is a unimodular $\mathbb{Z}_l$-lattice of rank n, then we have

$$T \cong \begin{cases} S_n^{(l)} & \text{if } \mathrm{disc}(T) = 1, \\ N_n^{(l)} & \text{if } \mathrm{disc}(T) = \bar{v}_l. \end{cases}$$

Proof of Theorem 3.9. We denote by (D_l, q_l) the l-part of (D, q). Suppose that $L \in \mathbb{L}^{\mathbb{Z}}((s_+, s_-), D, q)$. Then $\mathrm{disc}(L) = d$ holds. Since $\mathrm{disc}(L \otimes_{\mathbb{Z}} \mathbb{Z}_l) = d \bmod (\mathbb{Z}_l^\times)^2$ and $|D_{L\otimes_{\mathbb{Z}}\mathbb{Z}_l}| = |D_l| = l^{\mathrm{ord}_l(d)}$ by Proposition 3.8, we have

$$\mathrm{reddisc}(L \otimes_{\mathbb{Z}} \mathbb{Z}_l) \;=\; d/l^{\mathrm{ord}_l(d)} \bmod (\mathbb{Z}_l^\times)^2$$

for each $l \in \mathcal{D}(2d)$. Since l-$\mathrm{excess}(L \otimes_{\mathbb{Z}} \mathbb{Z}_l) = 0$ for every $l \notin \mathcal{D}(2d)$, we have

$$s_+ - s_- + \textstyle\sum_{l\in\mathcal{D}(2d)} l\text{-excess}(L \otimes_{\mathbb{Z}} \mathbb{Z}_l) \;\equiv\; n \mod 8$$

by Theorem 3.2. Hence $\tau^{\mathbb{Z}}(L)$ satisfies (i) and (ii).

Conversely, suppose that $([\sigma_l, \rho_l] \,|\, l \in \mathcal{D}(2d)) \in \mathcal{L}^{\mathbb{Z}}(n, D, q)$ satisfies (i) and (ii). For each $l \in \mathcal{D}(2d)$, we have an even $\mathbb{Z}_l$-lattice $L^{(l)} \in \mathbb{L}^{(l)}(n, D_l, q_l)$ such that l-$\mathrm{excess}(L^{(l)}) = \sigma_l$ and $\mathrm{reddisc}(L^{(l)}) = \rho_l$. Then we have

$$\mathrm{disc}(L^{(l)}) = \mathrm{reddisc}(L^{(l)}) \cdot |D_l| = d \bmod (\mathbb{Z}_l^\times)^2$$

by the condition (i) and $|D_l| = l^{\mathrm{ord}_l(d)}$. For $l \in \mathcal{P} \setminus \mathcal{D}(2d)$, we put

$$L^{(l)} := \begin{cases} S_n^{(l)} & \text{if } d \in (\mathbb{Z}_l^\times)^2, \\ N_n^{(l)} & \text{if } d \notin (\mathbb{Z}_l^\times)^2. \end{cases}$$

Then $L^{(l)} \in \mathbb{L}^{(l)}(n, D_l, q_l) = \mathbb{L}^{(l)}(n, 0, 0)$ and $\mathrm{disc}(L^{(l)}) = d \bmod (\mathbb{Z}_l^\times)^2$ hold. We put $L^{(\infty)}$ to be an $\mathbb{R}$-lattice of rank n with signature (s_+, s_-). Then we have $\mathrm{disc}(L^{(\infty)}) = d \bmod (\mathbb{R}^\times)^2$. Since l-$\mathrm{excess}(L^{(l)}) = 0$ for $l \in \mathcal{P}\setminus\mathcal{D}(2d)$, the condition (ii) and Theorem 3.2 imply that there exists a $\mathbb{Q}$-lattice W of rank n such that $W \otimes_{\mathbb{Q}} \mathbb{Q}_l$ is $\mathbb{Q}_l$-isometric to $L^{(l)} \otimes_{\mathbb{Z}_l} \mathbb{Q}_l$ for any $l \in \mathcal{P} \cup \{\infty\}$. By Theorem 3.1, there exists a $\mathbb{Z}$-lattice L of rank n such that $L \otimes_{\mathbb{Z}} \mathbb{Z}_l$ is $\mathbb{Z}_l$-isometric to $L^{(l)}$ for any $l \in \mathcal{P} \cup \{\infty\}$. Looking at the places $l = 2$ and $l = \infty$, we see that L is even and of signature (s_+, s_-). For each $l \in \mathcal{P}$, the l-part of (D_L, q_L) is isomorphic to $(D_{L^{(l)}}, q_{L^{(l)}}) \cong (D_l, q_l)$ by Proposition 3.8. Therefore (D_L, q_L) is isomorphic to (D, q). □

We fix $l \in \mathcal{P}$, and explain how to calculate the set $\mathcal{L}^{(l)}(n, D, q)$ for a non-degenerate quadratic form (D, q) on a finite abelian l-group D.

Definition 3.10. An orthogonal direct-sum decomposition

$$(D, q) = (D', q') \oplus (D'', q'')$$

is said to be *liftable* if, for any even $\mathbb{Z}_l$-lattice L with an isomorphism $\varphi : (D_L, q_L) \xrightarrow{\sim} (D, q)$, there exists an orthogonal direct-sum decomposition $L = L' \oplus L''$ such that $\mathrm{rank}(L')$ is equal to $\mathrm{leng}(D')$ and that φ maps $D_{L'} \subset D_L$ to D'. If this is the case,

φ induces isomorphisms $(D_{L'}, q_{L'}) \xrightarrow{\sim} (D', q')$ and $(D_{L''}, q_{L''}) \xrightarrow{\sim} (D'', q'')$. Therefore we have $\tau^{(l)}(L') \in \mathcal{L}^{(l)}(\text{leng}(D'), D', q')$ and $\tau^{(l)}(L'') \in \mathcal{L}^{(l)}(n - \text{leng}(D'), D'', q'')$.

For elements $\tau := [\sigma, \rho]$ and $\tau' := [\sigma', \rho']$ of $\mathbb{Z}/8\mathbb{Z} \times \mathbb{Z}_l^\times/(\mathbb{Z}_l^\times)^2$, we put

$$\tau * \tau' := [\sigma + \sigma', \rho\rho'].$$

The following is obvious from $\tau^{(l)}(L' \oplus L'') = \tau^{(l)}(L') * \tau^{(l)}(L'')$.

Lemma 3.11. *If an orthogonal direct-sum decomposition $(D, q) = (D', q') \oplus (D'', q'')$ is liftable, then $\mathcal{L}^{(l)}(n, D, q)$ is equal to*

$$\{ \tau * \tau' \mid \tau \in \mathcal{L}^{(l)}(\text{leng}(D'), D', q'),\ \tau' \in \mathcal{L}^{(l)}(n - \text{leng}(D'), D'', q'') \}.$$

Lemma 3.12. *The decomposition $(D, q) = (D, q) \oplus (0, 0)$ is liftable.*

Proof. Let L be an even $\mathbb{Z}_l$-lattice with an isomorphism $(D_L, q_L) \xrightarrow{\sim} (D, q)$, and let $L = \bigoplus_{\nu \geq 0} l^\nu L_\nu$ be the Jordan decomposition of L. We put

$$L_{\geq 1} := \bigoplus\nolimits_{\nu \geq 1} l^\nu L_\nu.$$

Then we have $\text{rank}(L_{\geq 1}) = \text{leng}(D)$ and $(D_L, q_L) = (D_{L_{\geq 1}}, q_{L_{\geq 1}})$. Hence the orthogonal direct-sum decomposition $L = L_{\geq 1} \oplus L_0$ has the required property. □

Lemma 3.13. *An orthogonal direct-sum decomposition $(D, q) = (D', q') \oplus (D'', q'')$ with D' being cyclic is liftable.*

Proof. Let l^ν be the order of D', and γ a generator of D'. Since (D, q) is non-degenerate, so is (D', q'), and hence the order of $b'(\gamma, \gamma)$ in $\mathbb{Q}/\mathbb{Z}$ is l^ν, where b' is the symmetric bilinear form of (D', q'). Let L be an even $\mathbb{Z}_l$-lattice with an isomorphism $\varphi : (D_L, q_L) \xrightarrow{\sim} (D, q)$. We choose an element $x \in L^\vee$ such that $\varphi(\bar{x}) = \gamma$, where $\bar{x} := x \bmod L$, and put $v := l^\nu x \in L$. Since $(x, x) \bmod \mathbb{Z}_l$ is of order l^ν in $\mathbb{Q}_l/\mathbb{Z}_l$, we see that $(v, x) = l^\nu(x, x)$ is in $\mathbb{Z}_l^\times$. We put $a := (v, x)^{-1} \in \mathbb{Z}_l^\times$. Since (w, x) is in $\mathbb{Z}_l$ and $w - a(w, x)v$ is orthogonal to v for any $w \in L$, we have an orthogonal direct-sum decomposition $L = \langle v \rangle \oplus \langle v \rangle^\perp$ that induces $(D, q) = (D', q') \oplus (D'', q'')$ via φ. □

Definition 3.14. Suppose that $l = 2$. A non-degenerate finite quadratic form (D, q) is said to be *of even type* if D is isomorphic to $\mathbb{Z}/2^\nu\mathbb{Z} \times \mathbb{Z}/2^\nu\mathbb{Z}$ and the order of $b(\gamma, \gamma)$ in $\mathbb{Q}/\mathbb{Z}$ is strictly smaller than 2^ν for any $\gamma \in D$.

Remark 3.15. Let L be an even $\mathbb{Z}_2$-lattice of rank 2 with $D_L \cong \mathbb{Z}/2^\nu\mathbb{Z} \times \mathbb{Z}/2^\nu\mathbb{Z}$. Then (D_L, q_L) is of even type if and only if L is $\mathbb{Z}_2$-isometric to $2^\nu U$ or to $2^\nu V$.

Lemma 3.16. *Suppose that $l = 2$. Then an orthogonal direct-sum decomposition $(D, q) = (D', q') \oplus (D'', q'')$ with (D', q') being of even type is liftable.*

Proof. Suppose that D' is isomorphic to $\mathbb{Z}/2^\nu\mathbb{Z} \times \mathbb{Z}/2^\nu\mathbb{Z}$, and let γ_1, γ_2 be elements of D' of order 2^ν such that $D' = \langle \gamma_1 \rangle \times \langle \gamma_2 \rangle$. Since (D', q') is of even type, the orders of $b'(\gamma_1, \gamma_1)$ and $b'(\gamma_2, \gamma_2)$ in $\mathbb{Q}/\mathbb{Z}$ are $< 2^\nu$. Since (D', q') is non-degenerate, the order of $b'(\gamma_1, \gamma_2)$ in $\mathbb{Q}/\mathbb{Z}$ must be equal to 2^ν. Let L be an even $\mathbb{Z}_2$-lattice with an isomorphism $\varphi : (D_L, q_L) \xrightarrow{\sim} (D, q)$. We choose vectors $x_1, x_2 \in L^\vee$ such that $\varphi(\bar{x}_i) = \gamma_i$ for $i = 1, 2$, where $\bar{x}_i := x_i \bmod L$, and put $v_i := 2^\nu x_i \in L$. Then there exist $S, T, U \in \mathbb{Z}_2$ with $T \in \mathbb{Z}_2^\times$ such that

$$\begin{bmatrix} (v_1, v_1) & (v_1, v_2) \\ (v_2, v_1) & (v_2, v_2) \end{bmatrix} = 2^\nu \begin{bmatrix} 2S & T \\ T & 2U \end{bmatrix}.$$

Since $4SU - T^2 \in \mathbb{Z}_2^\times$, the components ξ_1, ξ_2 of the vector

$$\begin{bmatrix} \xi_1 \\ \xi_2 \end{bmatrix} := \begin{bmatrix} 2S & T \\ T & 2U \end{bmatrix}^{-1} \begin{bmatrix} (w, x_1) \\ (w, x_2) \end{bmatrix}$$

are elements of $\mathbb{Z}_2$ for any $w \in L$. Moreover, $w - \xi_1 v_1 - \xi_2 v_2$ is orthogonal to the sublattice $\langle v_1, v_2 \rangle$ of L. Thus we obtain an orthogonal direct-sum decomposition $L = \langle v_1, v_2 \rangle \oplus \langle v_1, v_2 \rangle^\perp$ that induces $(D, q) = (D', q') \oplus (D'', q'')$ via φ. □

Lemma 3.17. *If l is odd, then (D, q) is an orthogonal direct-sum of finite quadratic forms on cyclic groups. If $l = 2$, then (D, q) is an orthogonal direct-sum of finite quadratic forms (D_i, q_i), where, for each i, D_i is cyclic or (D_i, q_i) is of even type.*

Proof. We proceed by induction on $r := \operatorname{leng}(D)$. The case where $r = 1$ is trivial. Suppose that $r > 1$, and that D is isomorphic to $\mathbb{Z}/l^{\nu_1}\mathbb{Z} \times \cdots \times \mathbb{Z}/l^{\nu_r}\mathbb{Z}$ with $\nu_1 \geq \cdots \geq \nu_r$. If there exists an element $\gamma \in D$ such that the order of $b(\gamma, \gamma)$ in $\mathbb{Q}/\mathbb{Z}$ is l^{ν_1}, then $\langle \gamma \rangle$ is of order l^{ν_1}, and we have an orthogonal direct-sum decomposition

$$(D, q) = (\langle \gamma \rangle, q|\langle \gamma \rangle) \oplus (\langle \gamma \rangle^\perp, q|\langle \gamma \rangle^\perp)$$

with $\operatorname{leng}(\langle \gamma \rangle^\perp) = r - 1$. Suppose that the order of $b(\gamma, \gamma)$ in $\mathbb{Q}/\mathbb{Z}$ is strictly smaller than l^{ν_1} for any $\gamma \in D$. Since (D, q) is non-degenerate, there exist elements $\gamma_1, \gamma_2 \in D$ such that $b(\gamma_1, \gamma_2) \in \mathbb{Q}/\mathbb{Z}$ is of order l^{ν_1}. If $l \neq 2$, then the order of $b(\gamma_1 + \gamma_2, \gamma_1 + \gamma_2)$ in $\mathbb{Q}/\mathbb{Z}$ would be l^{ν_1}. Therefore we have $l = 2$. We put $D' := \langle \gamma_1 \rangle \times \langle \gamma_2 \rangle$. Then $(D', q|D')$ is non-degenerate. We then put $D'' := D'^\perp$. Then we have an orthogonal direct-sum decomposition

$$(D, q) = (D', q|D') \oplus (D'', q|D''),$$

with $(D', q|D')$ being of even type and $\operatorname{leng}(D'') = r - 2$. □

Combining all the results, we can calculate the set $\mathcal{L}^{(l)}(n, D, q)$ for a positive integer n and a non-degenerate quadratic form (D, q) on a finite abelian l-group D from the following tables.

(I) We have

$$\mathcal{L}^{(l)}(n, D, q) = \emptyset \quad \text{if } n < \operatorname{leng}(D).$$

(II) Recall that $\mathbb{Z}_l^\times/(\mathbb{Z}_l^\times)^2 = \{1, \bar{v}_l\}$ for an odd prime l. We also have $\mathbb{Z}_2^\times/(\mathbb{Z}_2^\times)^2 = \{1, 3, 5, 7\}$. When $n > 0$, we have

$$\mathcal{L}^{(l)}(n, 0, 0) = \begin{cases} \{[0, 1], [0, \bar{v}_l]\} & \text{if } l \text{ is odd}, \\ \emptyset & \text{if } l = 2 \text{ and } n \text{ is odd}, \\ \{[n, 1], [n, 5]\} & \text{if } l = 2 \text{ and } n \equiv 0 \bmod 4, \\ \{[n, 3], [n, 7]\} & \text{if } l = 2 \text{ and } n \equiv 2 \bmod 4. \end{cases}$$

(III) *Discriminant forms on cyclic groups.* Let $\langle \gamma \rangle$ be a cyclic group of order $l^\nu > 1$ generated by γ, and q a non-degenerate quadratic form on $\langle \gamma \rangle$. Since q is non-degenerate, we can write $q(\gamma) \in \mathbb{Q}/2\mathbb{Z}$ as $a/l^\nu \bmod 2\mathbb{Z}$, where a is an integer prime to l. Suppose that l is odd. Then we have

$$\mathcal{L}^{(l)}(1, \langle \gamma \rangle, q) = \begin{cases} \{[l^\nu - 1, 1]\} & \text{if } \lambda_l(a) = 1, \\ \{[l^\nu - 1, \bar{v}_l]\} & \text{if } \nu \text{ is even and } \lambda_l(a) = -1, \\ \{[l^\nu + 3, \bar{v}_l]\} & \text{if } \nu \text{ is odd and } \lambda_l(a) = -1, \end{cases}$$

where $\lambda_l : \mathbb{F}_l^\times \to \{\pm 1\}$ is the Legendre symbol. When $l = 2$, we have

$$\mathcal{L}^{(2)}(1, \langle\gamma\rangle, q) = \begin{cases} \{[1-a, a]\} & \text{if } \nu \text{ is even,} \\ \{[1-a, a]\} & \text{if } \nu \text{ is odd, } \nu \geq 2, \text{ and } a \equiv \pm 1 \bmod 8, \\ \{[5-a, a]\} & \text{if } \nu \text{ is odd, } \nu \geq 2, \text{ and } a \equiv \pm 3 \bmod 8, \\ \{[0,1],[0,5]\} & \text{if } \nu = 1 \text{ and } a \equiv 1 \bmod 4, \\ \{[2,3],[2,7]\} & \text{if } \nu = 1 \text{ and } a \equiv 3 \bmod 4. \end{cases}$$

(IV) *Discriminant forms of even type.* Suppose that $l = 2$. Let $\langle\gamma_1\rangle$ and $\langle\gamma_2\rangle$ be cyclic groups of order 2^ν generated by γ_1 and γ_2, where $\nu > 0$, and q a non-degenerate quadratic form on $\langle\gamma_1\rangle \times \langle\gamma_2\rangle$ of even type. There exist integers u, v and w such that

$$q(\gamma_1) = \frac{2u}{2^\nu} \bmod 2\mathbb{Z}, \quad q(\gamma_2) = \frac{2w}{2^\nu} \bmod 2\mathbb{Z}, \quad \text{and} \quad b(\gamma_1, \gamma_2) = \frac{v}{2^\nu} \bmod \mathbb{Z}.$$

Since q is non-degenerate, the integer v is odd. Then we have

$$\mathcal{L}^{(2)}(2, \langle\gamma_1\rangle \times \langle\gamma_2\rangle, q) = \begin{cases} \{[2,7]\} & \text{if } uw \text{ is even,} \\ \{[2,3]\} & \text{if } \nu \text{ is even and } uw \text{ is odd,} \\ \{[6,3]\} & \text{if } \nu \text{ is odd and } uw \text{ is odd.} \end{cases}$$

4. Proof of Main Theorems

Proposition 4.1. *Let p be an odd prime. Then $\Lambda_{p,\sigma} \otimes_{\mathbb{Z}} \mathbb{Z}_2$ is $\mathbb{Z}_2$-isometric to $U^{\oplus 11}$, and $\Lambda_{p,\sigma} \otimes_{\mathbb{Z}} \mathbb{Z}_p$ is $\mathbb{Z}_p$-isometric to*

$$\begin{cases} S^{(p)}_{22-2\sigma} \oplus pN^{(p)}_{2\sigma} & \text{if } p \equiv 3 \bmod 4 \text{ and } \sigma \equiv 0 \bmod 2, \\ N^{(p)}_{22-2\sigma} \oplus pS^{(p)}_{2\sigma} & \text{if } p \equiv 3 \bmod 4 \text{ and } \sigma \equiv 1 \bmod 2, \\ N^{(p)}_{22-2\sigma} \oplus pN^{(p)}_{2\sigma} & \text{if } p \equiv 1 \bmod 4. \end{cases}$$

Proof. Note that $\mathrm{disc}(\Lambda_{p,\sigma}) = -p^{2\sigma}$. For simplicity, we put $\Lambda^{(l)} := \Lambda_{p,\sigma} \otimes_{\mathbb{Z}} \mathbb{Z}_l$. Since $U \oplus U$ and $V \oplus V$ are $\mathbb{Z}_2$-isometric, the even unimodular $\mathbb{Z}_2$-lattice $\Lambda^{(2)}$ is $\mathbb{Z}_2$-isometric to $U^{\oplus 11}$ or to $U^{\oplus 10} \oplus V$. Since $p^{2\sigma} \in (\mathbb{Z}_2^\times)^2$, we have $\mathrm{disc}(\Lambda^{(2)}) = -1$ in $\mathbb{Z}_2/(\mathbb{Z}_2^\times)^2$ and hence $\Lambda^{(2)} \cong U^{\oplus 11}$. Therefore we obtain $2\text{-excess}(\Lambda^{(2)}) = 6$. Since $D_{\Lambda_{p,\sigma}} \cong (\mathbb{Z}/p\mathbb{Z})^{\oplus 2\sigma}$, the $\mathbb{Z}_p$-lattice $\Lambda^{(p)}$ is $\mathbb{Z}_p$-isometric to $X \oplus pY$, where X is either $S^{(p)}_{22-2\sigma}$ or $N^{(p)}_{22-2\sigma}$, and Y is either $S^{(p)}_{2\sigma}$ or $N^{(p)}_{2\sigma}$. We have

$$p\text{-excess}(\Lambda^{(p)}) = \begin{cases} 2\sigma(p-1) & \bmod 8 \quad \text{if } Y = S^{(p)}_{2\sigma}, \\ 2\sigma(p-1) + 4 & \bmod 8 \quad \text{if } Y = N^{(p)}_{2\sigma}. \end{cases}$$

On the other hand, from the equality

$$1 - 21 + 2\text{-excess}(\Lambda^{(2)}) + p\text{-excess}(\Lambda^{(p)}) \equiv 22 \mod 8$$

in Theorem 3.9, we obtain $p\text{-excess}(\Lambda^{(p)}) = 4$. Therefore we have

$$Y = \begin{cases} S^{(p)}_{2\sigma} & \text{if } 2\sigma(p-1) \equiv 4 \bmod 8, \\ N^{(p)}_{2\sigma} & \text{if } 2\sigma(p-1) \equiv 0 \bmod 8. \end{cases}$$

From the equality

$$-1 = \mathrm{reddisc}(\Lambda^{(p)}) = \mathrm{disc}(X)\,\mathrm{disc}(Y) = \begin{cases} 1 & \text{if } \mathrm{disc}(X) = \mathrm{disc}(Y), \\ \bar{v}_p & \text{if } \mathrm{disc}(X) \neq \mathrm{disc}(Y) \end{cases}$$

in $\mathbb{Z}_p^\times/(\mathbb{Z}_p^\times)^2$, we obtain the required result. $\square$

Proposition 4.2. *Let p be an odd prime, and let $(D_{p,\sigma}, q_{p,\sigma})$ be the discriminant form of $\Lambda_{p,\sigma}$. Then*

$$\mathcal{L}^{(p)}(n, D_{p,\sigma}, q_{p,\sigma}) = \begin{cases} \emptyset & \text{if } n < 2\sigma, \\ \{[4,1]\} & \text{if } n = 2\sigma \text{ and } \sigma(p-1) \equiv 2 \bmod 4, \\ \{[4,\bar{v}_p]\} & \text{if } n = 2\sigma \text{ and } \sigma(p-1) \equiv 0 \bmod 4, \\ \{[4,1],[4,\bar{v}_p]\} & \text{if } n > 2\sigma. \end{cases}$$

Proof. Let $\langle\gamma\rangle$ be a cyclic group of order p generated by γ, and let q_1 and q_v be the quadratic forms on $\langle\gamma\rangle$ with values in $\mathbb{Q}_p/2\mathbb{Z}_p = \mathbb{Q}_p/\mathbb{Z}_p$ such that $q_1(\gamma) = 1/p \bmod \mathbb{Z}_p$ and $q_v(\gamma) = v_p/p \bmod \mathbb{Z}_p$, respectively. (Let $\tilde{v}_p \in \mathbb{Z}$ be an integer such that $\tilde{v}_p \bmod p = v_p \bmod p\mathbb{Z}_p$. As a quadratic form with values in $\mathbb{Q}/2\mathbb{Z}$, we have $q_1(\gamma) = (p+1)/p \bmod 2\mathbb{Z}$, and

$$q_v(\gamma) = \begin{cases} \tilde{v}_p/p \bmod 2\mathbb{Z} & \text{if } \tilde{v}_p \text{ is even}, \\ (\tilde{v}_p + p)/p \bmod 2\mathbb{Z} & \text{if } \tilde{v}_p \text{ is odd}. \end{cases}$$

See Remark 3.5.) Then $(\langle\gamma\rangle, q_1)$ is isomorphic to the discriminant form of the $\mathbb{Z}_p$-lattice $p[1]$, and $(\langle\gamma\rangle, q_v)$ is isomorphic to the discriminant form of the $\mathbb{Z}_p$-lattice $p[v_p]$. By Proposition 4.1, we see that $(D_{p,\sigma}, q_{p,\sigma})$ is isomorphic to

$$\begin{cases} (\langle\gamma\rangle, q_1)^{\oplus 2\sigma} & \text{if } \sigma(p-1) \equiv 2 \bmod 4, \\ (\langle\gamma\rangle, q_1)^{\oplus 2\sigma - 1} \oplus (\langle\gamma\rangle, q_v) & \text{if } \sigma(p-1) \equiv 0 \bmod 4. \end{cases}$$

Hence $\mathcal{L}^{(p)}(n, D_{p,\sigma}, q_{p,\sigma}) = \emptyset$ for $n < 2\sigma$ by (I), and $\mathcal{L}^{(p)}(2\sigma, D_{p,\sigma}, q_{p,\sigma})$ is equal to

$$\begin{cases} \{[p-1,1]^{*2\sigma}\} = \{[4,1]\} & \text{if } \sigma(p-1) \equiv 2 \bmod 4, \\ \{[p-1,1]^{*(2\sigma-1)} * [p+3,\bar{v}_p]\} = \{[4,\bar{v}_p]\} & \text{if } \sigma(p-1) \equiv 0 \bmod 4, \end{cases}$$

by Lemmas 3.11 and 3.13 and (III). If $n > 2\sigma$, then $\mathcal{L}^{(p)}(n, D_{p,\sigma}, q_{p,\sigma})$ is equal to

$$\{\ \tau * \tau' \ \mid\ \tau \in \mathcal{L}^{(p)}(2\sigma, D_{p,\sigma}, q_{p,\sigma}), \tau' \in \mathcal{L}^{(p)}(n-2\sigma, 0, 0)\ \} = \{[4,1],[4,\bar{v}_p]\}$$

by Lemmas 3.11 and 3.12 and (II). Thus we obtain the required result. $\square$

Proof of Theorem 1.1. By Nikulin [10, Proposition 1.5.1], the condition $\mathrm{Emb}(M, \Lambda_0)$ is true if and only if

$$\mathbb{L}^{\mathbb{Z}}((3-t_+, 19-t_-), D_M, -q_M) \neq \emptyset. \tag{4.1}$$

Since $p \notin \mathcal{D}(2d_M)$, the condition $\mathrm{Emb}(M, \Lambda_{p,\sigma})$ is true if and only if

$$\mathbb{L}^{\mathbb{Z}}((1-t_+, 21-t_-), D_M \oplus D_{p,\sigma}, -q_M \oplus q_{p,\sigma}) \neq \emptyset. \tag{4.2}$$

Remark that

$$(-1)^{19-t_-}|D_M| = -d_M \quad \text{and} \quad (-1)^{21-t_-}|D_M \oplus D_{p,\sigma}| = -p^{2\sigma} d_M.$$

By Theorem 3.9, the condition (4.1) is true if and only if there exists

$$(\,[\sigma_l, \rho_l] \mid l \in \mathcal{D}(2d_M)\,) \in \mathcal{L}^{\mathbb{Z}}(22-r, D_M, -q_M)$$

satisfying

(c1) $\rho_l = -d_M/l^{\mathrm{ord}_l(d_M)} \bmod (\mathbb{Z}_l^\times)^2$ for each $l \in \mathcal{D}(2d_M)$, and

(c2) $-16 - t_+ + t_- + \sum_{l \in \mathcal{D}(2d_M)} \sigma_l \ \equiv\ 22 - r \quad \bmod 8$, and the condition (4.2) is true if and only if there exist

$$([\sigma'_l, \rho'_l]) \in \mathcal{L}^{\mathbb{Z}}(22-r, D_M, -q_M) \quad \text{and} \quad [\sigma_p, \rho_p] \in \mathcal{L}^{(p)}(22-r, D_{p,\sigma}, q_{p,\sigma})$$

satisfying

(s1) $\rho'_l = -p^{2\sigma} d_M / l^{\mathrm{ord}_l(d_M)} \bmod (\mathbb{Z}_l^\times)^2$ for each $l \in \mathcal{D}(2d_M)$, and
$\rho_p = -d_M \bmod (\mathbb{Z}_p^\times)^2$, and

(s2) $-20 - t_+ + t_- + \sum_{l \in \mathcal{D}(2d_M)} \sigma'_l + \sigma_p \;\equiv\; 22 - r \mod 8.$

Note that, for $l \in \mathcal{D}(2d_M)$, the condition $\rho'_l = -p^{2\sigma} d_M / l^{\mathrm{ord}_l(d_M)} \bmod (\mathbb{Z}_l^\times)^2$ is equivalent to the condition $\rho'_l = -d_M / l^{\mathrm{ord}_l(d_M)} \bmod (\mathbb{Z}_l^\times)^2$, because $p^{2\sigma} \in (\mathbb{Z}_l^\times)^2$. By Proposition 4.2, if $[\sigma_p, \rho_p] \in \mathcal{L}^{(p)}(22-r, D_{p,\sigma}, q_{p,\sigma})$, then $\sigma_p = 4$. Therefore the condition ((s1) and (s2)) is equivalent to the condition

$$\text{(c1) and (c2) and } [4, -d_M] \in \mathcal{L}^{(p)}(22-r, D_{p,\sigma}, q_{p,\sigma}).$$

By Proposition 4.2, we have $[4, -d_M] \in \mathcal{L}^{(p)}(22-r, D_{p,\sigma}, q_{p,\sigma})$ if and only if $2\sigma < 22 - r$ holds, or $2\sigma = 22 - r$ and

$$(4.3) \qquad \begin{array}{l} (\ \sigma(p-1) \equiv 2 \bmod 4 \quad \text{and} \quad \lambda_p(-d_M) = 1\ ) \ \text{ or} \\ (\ \sigma(p-1) \equiv 0 \bmod 4 \quad \text{and} \quad \lambda_p(-d_M) = -1\ ) \end{array}$$

hold, where $\lambda_p : \mathbb{F}_p^\times \to \{\pm 1\}$ is the Legendre symbol. Since (4.3) is equivalent to $\mathrm{Arth}(p, \sigma, d_M)$, Theorem 1.1 is proved. □

Proof of Theorem 1.8. For each Dynkin type R with $r := \mathrm{rank}(R) \le 19$, we make the following calculation.

(1) We denote by (D_R, q_R) the discriminant form of Σ_R^-, and by Γ_R the image of the natural homomorphism $O(\Sigma_R^-) \to O(q_R)$. (See [17, Section 6] for the description of the group Γ_R.) We make the list of isotropic subgroups of (D_R, q_R) up to the action of Γ_R. By means of Nikulin [10, Proposition 1.4.1], the list of even overlattices of Σ_R^- up to the action of Γ_R is obtained. Then, by the method described in [20], we make the list $\mathcal{E}(\Sigma_R^-)$ up to the action of Γ_R.

(2) For each $M \in \mathcal{E}(\Sigma_R^-)$, we see whether $\mathbb{L}_M := \mathbb{L}^{\mathbb{Z}}((3, 19-r), D_M, -q_M)$ is empty or not by Theorem 3.9. If we find $M \in \mathcal{E}(\Sigma_R^-)$ such that $\mathbb{L}_M \ne \emptyset$, then $\mathrm{NK}(0, R)$ is true. If $\mathbb{L}_M = \emptyset$ for every $M \in \mathcal{E}(\Sigma_R^-)$, then $\mathrm{NK}(0, R)$ is false. □

Remark 4.3. Let R be a Dynkin type with $r := \mathrm{rank}(R) \le 18$, and MW a finite abelian group. By [17, Theorem 7.1], the following are equivalent:

(i) There exists a complex elliptic $K3$ surface $f : X \to \mathbb{P}^1$ with a section such that the Dynkin type R_f of reducible fibers of f is equal to R and that the torsion part MW_f of the Mordell-Weil group of f is isomorphic to MW.

(ii) There exists an element $M \in \mathcal{E}(\Sigma_R^-)$ such that $M/\Sigma_R^- \cong MW$ and that $\mathbb{L}^{\mathbb{Z}}((2, 18-r), D_M, -q_M) \ne \emptyset$.

Therefore, once we have made the list $\mathcal{E}(\Sigma_R^-)$ for each Dynkin type R of rank ≤ 19, it is an easy task to verify the list of all possible pairs (R_f, MW_f) given in [17].

Remark 4.4. Let $\langle h \rangle$ denote a $\mathbb{Z}$-lattice of rank 1 generated by a vector h with $(h, h) = 2$. For a Dynkin type R with $r := \mathrm{rank}(R) \le 19$, we denote by $\mathcal{Y}(R)$ the set of even overlattices M of $\Sigma_R^- \oplus \langle h \rangle$ with the following properties:

(1) $\mathrm{Roots}(\langle h \rangle_M^\perp) = \mathrm{Roots}(\Sigma_R^-)$, where $\langle h \rangle_M^\perp$ is the orthogonal complement of $\langle h \rangle$ in M, and

(2) $\{e \in M \mid (h,e)=1, (e,e)=0\} = \emptyset$.

By Yang [26], the following are equivalent:

(i) There exists a complex reduced plane curve $C \subset \mathbb{P}^2$ of degree 6 with only simple singularities such that the Dynkin type of $\mathrm{Sing}(C)$ is equal to R.

(ii) There exists an element $M \in \mathcal{Y}(R)$ such that $\mathbb{L}^{\mathbb{Z}}((2, 19-r), D_M, -q_M) \neq \emptyset$.

During the proof of Theorem 1.8, we have also calculated the set $\mathcal{Y}(R)$ for each R, and confirmed the validity of Yang's list [26] of configurations of singular points of complex sextic curves with only simple singularities.

5. Concluding remarks

5.1. **Kummer surfaces.** We work over an algebraically closed field of characteristic $p > 0$ with $p \neq 2$. Let A be an abelian surface, and $\iota : A \to A$ the inversion. Then $Y_A := A/\langle\iota\rangle$ is a normal $K3$ surface with $R_{Y_A} = 16A_1$. The minimal resolution $\mathrm{Km}(A)$ of Y_A is called the *Kummer surface*. We give a simple proof of the following theorem due to Ogus [12, Theorem 7.10].

Theorem 5.1. *A supersingular $K3$ surface is a Kummer surface if and only if the Artin invariant is 1 or 2.*

Proof. Since $\mathrm{NK}(0, 16A_1)$ is true and $\mathrm{Arth}(p, 3, (-1)^{16}2^{16})$ is false, Theorem 1.3 implies that $\mathrm{NK}(p, \sigma, 16A_1)$ is true if and only if $\sigma \leq 2$. Thus the "only if" part of Theorem 5.1 is proved. To show the "if" part, it is enough to prove that the minimal resolution of a normal $K3$ surface Y with $R_Y = 16A_1$ is a Kummer surface. For this purpose, we use the following Lemma, which can be checked easily by using a computer:

Lemma 5.2. *Let $\mathcal{C}$ be a binary linear code of length 16 with dimension ≥ 5 such that the weight $\mathrm{wt}(w)$ of every word w satisfies $\mathrm{wt}(w) \equiv 0 \bmod 4$ and $\mathrm{wt}(w) \neq 4$. Then there exists a word of weight 16 in $\mathcal{C}$.*

We consider subgroups of the discriminant group $D_{16A_1} \cong \mathbb{F}_2^{\oplus 16}$ of $\Sigma^-_{16A_1}$ as binary linear codes of length 16.

Lemma 5.3. *If $M \in \mathcal{E}(\Sigma^-_{16A_1})$ satisfies $\mathrm{leng}(D_M) \leq 6$, then $M/\Sigma^-_{16A_1} \subset D_{16A_1}$ contains a word of weight 16.*

Proof. Let $\mathcal{C} \subset D_{16A_1}$ be a linear code. Then $\mathcal{C}$ is isotropic with respect to q_{16A_1} if and only if $\mathrm{wt}(w) \equiv 0 \bmod 4$ for every $w \in \mathcal{C}$. Suppose that $\mathcal{C}$ is isotropic. Then the corresponding even overlattice $M_{\mathcal{C}}$ of $\Sigma^-_{16A_1}$ satisfies $\mathrm{Roots}(M_{\mathcal{C}}) = \mathrm{Roots}(\Sigma^-_{16A_1})$ if and only if $\mathrm{wt}(w) \neq 4$ for every $w \in \mathcal{C}$. Because $\mathrm{leng}(D_{M_{\mathcal{C}}}) = 16 - 2\dim\mathcal{C}$ by Nikulin [10, Proposition 1.4.1], we obtain Lemma 5.3 from Lemma 5.2. $\square$

Suppose that Y is a normal $K3$ surface with $R_Y = 16A_1$, and $X \to Y$ the minimal resolution. We denote by Σ_X the sublattice of S_X generated by the classes of the (-2)-curves $E_1, \dots, E_{16}$ contracted by $X \to Y$, and let M_X be the primitive closure of Σ_X in S_X. Then we have $M_X \in \mathcal{E}(\Sigma_X)$ by Proposition 2.4. Moreover we have $\mathrm{leng}(D_{M_X}) \leq 6$, because $\mathrm{Emb}(M_X, \Lambda_{p,\sigma})$ is true, where $\sigma = \sigma_X$, and hence $\mathcal{L}^{(2)}(22 - \mathrm{rank}(M_X), D_{M_X}, -q_{M_X}) \neq \emptyset$. By Lemma 5.3, there exists a word of weight 16 in the code M_X/Σ_X. Hence we have $([E_1] + \cdots + [E_{16}])/2 \in M_X$. Therefore there exists a double covering $A' \to X$ whose branch locus is $E_1 \cup \cdots \cup E_{16}$. Then the contraction of (-1)-curves on A' yields an abelian surface A, and X is isomorphic to the Kummer surface $\mathrm{Km}(A)$. (See [12, Lemma 7.12]). $\square$

Remark 5.4. In fact, a linear code $\mathcal{C} \subset \mathbb{F}_2^{\oplus 16}$ with the properties described in Lemma 5.2 is unique up to isomorphisms. See Nikulin [9] for the description of this code in terms of 4-dimensional affine geometry over $\mathbb{F}_2$.

5.2. **Singular $K3$ surfaces.** A complex $K3$ surface X is called *singular* (in the sense of Shioda and Inose [23]) if S_X is of rank 20. Let X be a singular $K3$ surface, and T_X the transcendental lattice of X. Then T_X possesses a canonical orientation η_X determined by the holomorphic 2-form on X. Shioda and Inose [23] showed that the mapping $X \mapsto (T_X, \eta_X)$ induces a bijection from the set of isomorphism classes of singular $K3$ surfaces to the set of $SL_2(\mathbb{Z})$-equivalence classes of positive-definite even binary forms.

In [23], it is also shown that every singular $K3$ surface X can be defined over a number field F. (See Inose [8] for an explicit defining equation.) For a maximal ideal $\mathfrak{p}$ of the integer ring $\mathcal{O}_F$ of F, let $X(\mathfrak{p})$ denote the reduction of X at $\mathfrak{p}$.

Proposition 5.5. *Suppose that a singular $K3$ surface X is defined over a number field F. Let $\mathfrak{p}$ be a maximal ideal of $\mathcal{O}_F$ with residue characteristic p. Suppose that p is prime to $2\operatorname{disc}(T_X)$, and that $X(\mathfrak{p})$ is a supersingular $K3$ surface. Then the Artin invariant of $X(\mathfrak{p})$ is 1, and we have*

$$\left(\frac{-\operatorname{disc}(T_X)}{p}\right) = -1. \tag{5.1}$$

Proof. Since the signature of S_X is $(1, 19)$, we have $\operatorname{disc}(S_X) = -\operatorname{disc}(T_X)$. Let σ be the Artin invariant of $X(\mathfrak{p})$. The reduction induces an embedding $S_X \hookrightarrow S_{X(\mathfrak{p})}$. Let M be the primitive closure of S_X in $S_{X(\mathfrak{p})}$. Then $\operatorname{Emb}(M, \Lambda_{p,\sigma})$ is true. Since M is of rank 20 and $\operatorname{disc}(S_X)/\operatorname{disc}(M)$ is a square integer, it follows from Theorem 1.1 that $\sigma = 1$, and that $\operatorname{Arth}(p, 1, \operatorname{disc}(S_X))$ is true. Therefore we obtain (5.1). □

Remark 5.6. A converse of Proposition 5.5 is proved in [21].

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