

Fourier–Mukai numbers of K3 categories of very general special cubic fourfolds

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Abstract

We give counting formulas for the number of Fourier–Mukai partners of the K3 category of a very general special cubic fourfold.

1 Introduction

The number of isomorphism classes of Fourier–Mukai partners of a very general complex algebraic K3 surface was computed by Oguiso [Ogu02, Proposition (1.10)]. The purpose of this paper is to establish similar counting formulas for the K3 category of a very general special cubic fourfold.

Let $X \subseteq \mathbb{P}^5$ be a cubic fourfold, namely, a smooth complex cubic hypersurface. Then the bounded derived category of coherent sheaves on X admits a semiorthogonal decomposition

$$D^b(X) = \langle \mathcal{A}_X, \mathcal{O}_X, \mathcal{O}_X(1), \mathcal{O}_X(2) \rangle.$$

The full triangulated subcategory \mathcal{A}_X , called the *K3 category of X* , is an example of a non-commutative K3 surface in the sense of [MS19, Definition 2.31]. In contrast to its common usage in the literature, we say two cubic fourfolds are *Fourier–Mukai partners*, or *FM-partners* for short, if their K3 categories are equivalent. It is known that the number of FM-partners of a cubic fourfold up to isomorphism is finite [Huy17, Theorem 1.1]. Moreover, this number is equal to 1 if the lattice

$$H^{2,2}(X, \mathbb{Z}) := H^4(X, \mathbb{Z}) \cap H^2(X, \Omega_X^2)$$

has rank 1 [Huy17, Theorem 1.5 (i)].

A cubic fourfold is called *special* if $H^{2,2}(X, \mathbb{Z})$ has rank at least 2, or equivalently, if there exists a rank 2 saturated sublattice $K \subseteq H^{2,2}(X, \mathbb{Z})$ containing the square of the hyperplane class $h := c_1(\mathcal{O}_X(1))$. In the moduli space of cubic fourfolds, special members marked by such a sublattice K with $\text{disc}(K) = d$ form an irreducible divisor \mathcal{C}_d , which is nonempty if and only if $d \geq 8$ and $d \equiv 0, 2 \pmod{6}$ [Has00, Theorem 1.0.1]. We say a special cubic fourfold $X \in \mathcal{C}_d$ is *very general* if it is away from a union of countably many divisors. Note that $H^{2,2}(X, \mathbb{Z})$ has rank exactly 2 for such an X .

To state the main theorem, let us first consider the ring \mathbb{Z}_{2d} of integers modulo $2d$ and denote the subset of square roots of unity as

$$(\mathbb{Z}_{2d}^\times)_2 := \{n \in \mathbb{Z}_{2d}^\times \mid n^2 \equiv 1 \pmod{2d}\}.$$

Using the Chinese remainder theorem, one can verify that

$$|(\mathbb{Z}_{2d}^\times)_2| = \begin{cases} 4 & \text{if } d = 2^{a+1} \\ 2^{k+1} & \text{if } d = 2p_1^{e_1} \cdots p_k^{e_k} \\ 2^{k+2} & \text{if } d = 2^{a+1}p_1^{e_1} \cdots p_k^{e_k} \end{cases}$$

where $a, k \geq 1$ and every p_i is an odd prime.

Theorem 1.1. *Let $X \in \mathcal{C}_d$ be a very general member and $\text{FM}(X)$ be the set of isomorphism classes of FM-partners of X .*

- *If $d \not\equiv 0 \pmod{3}$, then $|\text{FM}(X)| = \frac{1}{4} |(\mathbb{Z}_{2d}^\times)_2|$.*
- *If $d \equiv 0 \pmod{3}$ and $d \not\equiv 0 \pmod{9}$, then $|\text{FM}(X)| = \frac{1}{8} |(\mathbb{Z}_{2d}^\times)_2|$.*
- *If $d \equiv 0 \pmod{9}$ and $\frac{d}{18} \equiv 1 \pmod{3}$, then $|\text{FM}(X)| = \frac{1}{4} |(\mathbb{Z}_{2d}^\times)_2|$.*
- *If $d \equiv 0 \pmod{9}$ and $\frac{d}{18} \equiv 2 \pmod{3}$, then $|\text{FM}(X)| = \frac{1}{2} |(\mathbb{Z}_{2d}^\times)_2|$.*
- *If $d \equiv 0 \pmod{27}$, then $|\text{FM}(X)| = \frac{3}{4} |(\mathbb{Z}_{2d}^\times)_2|$.*

The special case when $d \not\equiv 0 \pmod{9}$ were proved in our earlier work [FL23, Proposition 2.6], where the formulas were used to help us find new examples of rational cubic fourfolds. Because of this, we need to treat only the case when $d \equiv 0 \pmod{9}$ here. This assumption implies that $d \equiv 0 \pmod{18}$ and we will mostly work with

$$d' := \frac{d}{18}$$

instead of d in this paper. By the theorem, if $d \equiv 0 \pmod{27}$, then $|\text{FM}(X)| = 3 \cdot 2^n$ for some $n \geq 0$; otherwise, $|\text{FM}(X)|$ is a power of 2. It would be interesting to understand the origin of the factor 3 from a geometric perspective. We remark that the case when X has an associated K3 surface was studied previously by Pertusi [Per21, Theorem 1.1].

Our proof of the theorem is mainly based on the works of Addington–Thomas [AT14] and Huybrechts [Huy17] as these works turn the original problem into the counting of certain overlattices. In Section 2, we briefly review these background materials and set up necessary notations. In Section 3, we introduce the overlattices arising naturally from FM-partners and explain their roles in the counting problem. In Section 4, we count the number of those overlattices and finish the proof of the main theorem.

Acknowledgements The second author was supported by the ERC Synergy Grant HyperK (ID: 854361).

2 Mukai lattices of the K3 categories

The topological K-theory $K_{\text{top}}(X)$ of a cubic fourfold is a free abelian group equipped with a natural integral bilinear pairing $\chi(\cdot, \cdot)$. It contains the subgroup

$$K_{\text{top}}(\mathcal{A}_X) := \{\kappa \in K_{\text{top}}(X) \mid \chi([\mathcal{O}_X(i)], \kappa) = 0 \text{ for } i = 0, 1, 2\},$$

called the *Mukai lattice of \mathcal{A}_X* , and it has a polarized Hodge structure of K3 type. Indeed, the pairing $\chi(\cdot, \cdot)$ is symmetric on $K_{\text{top}}(\mathcal{A}_X)$ and so turns it into a lattice. On the other hand, the Mukai vector defines an embedding

$$K_{\text{top}}(X) \hookrightarrow H^*(X, \mathbb{Q}) : E \mapsto \text{ch}(E) \cdot \sqrt{\text{td}(X)}$$

which endows a Hodge structure on $K_{\text{top}}(\mathcal{A}_X)$ by taking the restriction of the Hodge structure on $H^4(X, \mathbb{Z})$. By [Huy17, Theorem 1.5 (iii)] and [LPZ23, Theorem 1.3], two very general special cubic fourfolds are FM-partners if and only if there exists a Hodge isometry between their Mukai lattices.

Following our previous work [FL23], we define $\tilde{H}(\mathcal{A}_X, \mathbb{Z}) := K_{\text{top}}(\mathcal{A}_X)(-1)$. As an abstract lattice, it is unimodular of signature $(4, 20)$, so we have

$$\tilde{H}(\mathcal{A}_X, \mathbb{Z}) \cong E_8(-1)^{\oplus 2} \oplus U^{\oplus 4} \quad \text{where} \quad U = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}. \quad (2.1)$$

Let us further define $N(\mathcal{A}_X) := \tilde{H}^{1,1}(\mathcal{A}_X, \mathbb{Z})$ and $T(\mathcal{A}_X) := N(\mathcal{A}_X)^{\perp \tilde{H}(\mathcal{A}_X, \mathbb{Z})}$. The projections of the classes $[\mathcal{O}_{\text{line}}(1)]$ and $[\mathcal{O}_{\text{line}}(2)]$ to $K_{\text{top}}(\mathcal{A}_X)$ induces two elements $\lambda_1, \lambda_2 \in N(\mathcal{A}_X)$ which span the sublattice

$$A_2(X) := \langle \lambda_1, \lambda_2 \rangle \cong \begin{pmatrix} 2 & -1 \\ -1 & 2 \end{pmatrix} \subseteq N(\mathcal{A}_X).$$

By [AT14, Proposition 2.3], there is a commutative diagram of Hodge structures

$$\begin{array}{ccc} A_2(X)^{\perp \tilde{H}(\mathcal{A}_X, \mathbb{Z})} & \xrightarrow{\sim} & \langle h^2 \rangle^{\perp H^4(X, \mathbb{Z})(-1)} = H^4(X, \mathbb{Z})_{\text{prim}}(-1) \\ \uparrow & & \uparrow \\ T(\mathcal{A}_X) & \xrightarrow{\sim} & H^{2,2}(X, \mathbb{Z})^{\perp H^4(X, \mathbb{Z})(-1)} \end{array}$$

where the horizontal maps are isomorphisms.

From now on, we fix a very general $X \in \mathcal{C}_d$ with $d \equiv 0 \pmod{9}$. Let us denote for short that $T := T(\mathcal{A}_X)$ and $S := N(\mathcal{A}_X) \cap A_2(X)^{\perp N(\mathcal{A}_X)}$. Then a direct computation using the fact that $d \equiv 0 \pmod{6}$ gives

$$H^{2,2}(X, \mathbb{Z}) \cong \begin{pmatrix} 3 & 0 \\ 0 & 6d' \end{pmatrix} \quad \text{whence} \quad N(\mathcal{A}_X) \cong \begin{pmatrix} 2 & -1 & 0 \\ -1 & 2 & 0 \\ 0 & 0 & -6d' \end{pmatrix}.$$

Denote by $\{\lambda_1, \lambda_2, \ell\}$ the standard basis for $N(\mathcal{A}_X)$ so that $\ell^2 = -6d'$. Then

$$S = \langle \ell \rangle \quad \text{whence} \quad S^*/S = \left\langle \frac{\ell}{6d'} \right\rangle \cong \mathbb{Z}_{6d'}. \quad (2.2)$$

Let us also give an explicit formula for the discriminant group of T .

Lemma 2.1. *There exists $t_1, t_2 \in T$ with $t_1^2 = -6$, $t_2^2 = 6d'$, and $t_1 t_2 = 0$ such that*

$$T^*/T = \left\langle \frac{t_1}{3} \right\rangle \oplus \left\langle \frac{t_2}{6d'} \right\rangle \cong \mathbb{Z}_3 \oplus \mathbb{Z}_{6d'}.$$

Proof. As a result of [Nik79, Theorem 1.14.4], we can fix an isomorphism (2.1) such that the basis elements for $N(\mathcal{A}_X)$ are identified as

$$\lambda_1 = e_1 + f_1, \quad \lambda_2 = e_2 + f_2 - e_1, \quad \ell = e_3 - (3d')f_3$$

where $\{e_i, f_i\}$, $i = 1, 2, 3$, are the standard bases for the last three copies of U . This isomorphism identifies T with the sublattice $E_8(-1)^{\oplus 2} \oplus U \oplus A_2(-1) \oplus \mathbb{Z}(6d')$ where

$$A_2(-1) = \langle e_1 - f_1 - e_2, e_2 - f_2 \rangle \quad \text{and} \quad \mathbb{Z}(6d') = \langle e_3 + (3d')f_3 \rangle.$$

Take $t_1 := e_1 - f_1 - 2e_2 + f_2$ and $t_2 := e_3 + (3d')f_3$ respectively from these factors. Then a direct computation shows that they satisfy the requirements. \square

3 FM-partners and two types of overlattices

Let us retain the setting from the previous section and define $\mathcal{M}_{S,T}$ to be the set of even overlattices $L \supseteq S \oplus T$ with $\text{disc}(L) = 3$ such that $S, T \subseteq L$ are both saturated. Our goal is to turn the original counting problem to the counting on the set $\mathcal{M}_{S,T}$. Let us start by showing that the elements of $\mathcal{M}_{S,T}$ can be divided into two types.

Using $[S^* : S] = 6d'$ and $[T^* : T] = 18d'$, one can deduce from the chain of inclusions

$$S \oplus T \subseteq L \subseteq L^* \subseteq S^* \oplus T^*$$

that $[L : S \oplus T] = [S^* \oplus T^* : L^*] = 6d'$. Now, as $S, T \subseteq L$ are saturated, the projections

$$L^*/(S \oplus T) \longrightarrow S^*/S \cong \mathbb{Z}_{6d'} \tag{3.1}$$

$$L^*/(S \oplus T) \longrightarrow T^*/T \cong \mathbb{Z}_3 \oplus \mathbb{Z}_{6d'} \tag{3.2}$$

are both surjective. In particular, the second map is an isomorphism as the orders of the two groups are both $18d'$. Hence, there exist integers b_1 and b_2 such that

$$L^*/(S \oplus T) = \left\langle \frac{b_1 \ell + t_1}{3} \right\rangle \oplus \left\langle \frac{b_2 \ell + t_2}{6d'} \right\rangle \tag{3.3}$$

where ℓ, t_1, t_2 are as in (2.2) and Lemma 2.1.

The subgroup $L/(S \oplus T) \subseteq L^*/(S \oplus T)$ has index 3, so its image under (3.2) followed by the projection to the factor $\mathbb{Z}_{6d'}$ is either $\mathbb{Z}_{2d'}$ or $\mathbb{Z}_{6d'}$. We can use (3.3) to deduce an explicit expression for $L/(S \oplus T)$ in each of the two cases as follows:

(I) If the image is $\mathbb{Z}_{2d'}$, then

$$L/(S \oplus T) = \left\langle \frac{b_1 \ell + t_1}{3} \right\rangle \oplus \left\langle \frac{b_2 \ell + t_2}{2d'} \right\rangle.$$

In view of the surjectivity of (3.1), we may assume that

$$0 \leq b_1 < 3 \quad \text{and} \quad 0 \leq b_2 < 2d' \quad \text{with} \quad \gcd(b_1, 3) = \gcd(b_2, 2d') = 1. \tag{3.4}$$

(II) If the image is $\mathbb{Z}_{6d'}$, then

$$L/(S \oplus T) = \left\langle \frac{kt_1}{3} + \frac{b_3\ell + t_2}{6d'} \right\rangle \quad \text{for some } 0 \leq k < 3.$$

Here $b_3 = 2d'kb_1 + b_2$. In view of the surjectivity of (3.1), we may assume that

$$0 \leq b_3 < 6d' \quad \text{with} \quad \gcd(b_3, 6d') = 1. \quad (3.5)$$

In order to relate the set $\mathcal{M}_{S,T}$ to the set of FM-partners, let us consider the set $\widetilde{\text{FM}}(X)$ of triples (Y, ϕ, ψ) where

- $Y \in \text{FM}(X)$,
- $\phi: S \longrightarrow S_Y := N(\mathcal{A}_Y) \cap A_2(Y)^{\perp N(\mathcal{A}_Y)}$ is an isometry of rank 1 lattices,
- $\psi: T \longrightarrow T_Y := T(\mathcal{A}_Y)$ is a Hodge isometry.

Lemma 3.1. *The forgetful map*

$$\widetilde{\text{FM}}(X) \longrightarrow \text{FM}(X) : (Y, \phi, \psi) \longmapsto Y$$

is 4-to-1. Therefore, we have $|\text{FM}(X)| = \frac{1}{4}|\widetilde{\text{FM}}(X)|$.

Proof. For each $Y \in \text{FM}(X)$, there are exactly two isometries $\phi: S \longrightarrow S_Y$ which are different by a sign. On the other hand, there exists a Hodge isometry $\psi: T \longrightarrow T_Y$ due to [Huy17, Theorem 1.5 (iii)]. Because the only Hodge isometries on T are ± 1 [Huy16, Corollary 3.3.5], the only Hodge isometries from T to T_Y are $\pm\psi$. This shows that the preimage over $Y \in \text{FM}(X)$ consists of $(Y, \pm\phi, \pm\psi)$, so the statement follows. \square

For each $(Y, \phi, \psi) \in \widetilde{\text{FM}}(X)$, one can verify that the pullback

$$L_{(Y, \phi, \psi)} := (\phi \oplus \psi)^* \left(A_2(Y)^{\perp \tilde{H}(\mathcal{A}_Y, \mathbb{Z})} \right) \subseteq S^* \oplus T^*$$

is an element of $\mathcal{M}_{S,T}$. This defines a map

$$\widetilde{\text{FM}}(X) \longrightarrow \mathcal{M}_{S,T} : (Y, \phi, \psi) \longmapsto L_{(Y, \phi, \psi)}. \quad (3.6)$$

Due to the Torelli theorem [Voi86], if (Y, ϕ, ψ) and (Y', ϕ', ψ') have the same image under this map, then $Y \cong Y'$. Hence, the forgetful map in Lemma 3.1 factors as

$$\begin{array}{ccc} \widetilde{\text{FM}}(X) & \xrightarrow{L_\bullet} & \mathcal{M}_{S,T} \\ & \searrow 4:1 & \downarrow \\ & & \text{FM}(X). \end{array}$$

This shows that every fiber of (3.6) is contained in a fiber of the forgetful map. Moreover, the map is surjective due to the surjectivity of the period map [Laz10, Theorem 1.1]; see the end of [FL23, Proof of Lemma 2.7] for the details.

Lemma 3.2. *The map (3.6) is 2-to-1. As a result, we have $|\text{FM}(X)| = \frac{1}{2}|\mathcal{M}_{S,T}|$.*

Proof. It is easy to see that $L_{(Y,\phi,\psi)} = L_{(Y,-\phi,-\psi)}$ for every $(Y, \phi, \psi) \in \widetilde{\text{FM}}(X)$. As a consequence, the fiber $\{(Y, \pm\phi, \pm\psi)\} \subseteq \widetilde{\text{FM}}(X)$ over each $Y \in \text{FM}(X)$ is mapped by (3.6) as the set $\{L_{(Y,\phi,\psi)}, L_{(Y,-\phi,\psi)}\}$. To prove the statement, it suffices to verify $L_{(Y,\phi,\psi)} \neq L_{(Y,-\phi,\psi)}$, that is, one gets a different lattice after replacing ℓ with $-\ell$.

First suppose that $L := L_{(Y,\phi,\psi)}$ satisfies (I). Assume, to the contrary, that L remains the same after replacing ℓ with $-\ell$. This assumption implies that

$$\frac{b_1\ell + t_1}{3} = \pm \left(\frac{-b_1\ell + t_1}{3} \right)$$

within the \mathbb{Z}_3 factor of $L/(S \oplus T) \cong \mathbb{Z}_3 \oplus \mathbb{Z}_{2d'}$, which gives $\frac{2b_1}{3}\ell = 0$ or $\frac{2}{3}t_1 = 0$. Note that the latter case does not occur. In the former case, we get $b_1 \equiv 0 \pmod{3}$, but this contradicts the fact that $\gcd(b_1, 3) = 1$.

Now suppose that L satisfies (II). Assume again to the contrary that L remains the same after replacing ℓ with $-\ell$. In this case, we get

$$\frac{kt_1}{3} + \frac{b_3\ell + t_2}{6d'} = \pm \left(\frac{kt_1}{3} + \frac{-b_3\ell + t_2}{6d'} \right) \in L/(S \oplus T) \cong \mathbb{Z}_{6d'},$$

which implies $\frac{b_3}{3d'}\ell = 0$ or $\frac{2k}{3}t_1 + \frac{2}{3d'}t_2 = 0$. The latter case does not occur. In the former case, we get $b_3 \equiv 0 \pmod{3d'}$, but this contradicts the fact that $\gcd(b_3, 6d') = 1$.

We have proved the first statement, which gives $|\widetilde{\text{FM}}(X)| = 2|\mathcal{M}_{S,T}|$. It then follows from Lemma 3.1 that $|\text{FM}(X)| = \frac{1}{4}|\widetilde{\text{FM}}(X)| = \frac{1}{2}|\mathcal{M}_{S,T}|$. \square

4 Counting the number of overlattices

It remains to count the number of elements in $\mathcal{M}_{S,T}$, or more precisely, to count the number of lattices of the forms (I) and (II) which are even. Let us start by proving a basic property about square roots of unity.

Lemma 4.1. *Let n be a positive integer. Then the number of integers $0 \leq b < 2n$ which satisfy $b^2 \equiv 1 \pmod{4n}$ is equal to $\frac{1}{2} |(\mathbb{Z}_{4n}^\times)_2|$.*

Proof. For each b satisfying the hypothesis, the integers b and $b + 2n$ represent distinct elements in $(\mathbb{Z}_{4n}^\times)_2$. This proves the statement. \square

Let us first count even overlattices of Type (I).

Lemma 4.2. *Elements in $\mathcal{M}_{S,T}$ of Type (I) exist only if $d' \equiv 2 \pmod{3}$. If this condition holds, then there are $|(\mathbb{Z}_{4d'}^\times)_2|$ many of them.*

Proof. An overlattice of Type (I) has the form

$$L = S + T + \left\langle \frac{b_1\ell + t_1}{3} \right\rangle + \left\langle \frac{b_2\ell + t_2}{2d'} \right\rangle$$

where (b_1, b_2) are as in (3.4). Such a lattice is even, that is, belongs to $\mathcal{M}_{S,T}$, if and only if

$$\left(\frac{b_1\ell + t_1}{3}\right)^2 = -\frac{2}{3}(b_1^2 d' + 1) \in 2\mathbb{Z} \quad \iff \quad d' \equiv 2 \pmod{3}$$

and

$$\left(\frac{b_2\ell + t_2}{2d'}\right)^2 = -\frac{3}{2d'}(b_2^2 - 1) \in 2\mathbb{Z} \quad \iff \quad b_2^2 \equiv 1 \pmod{4d'}.$$

Note that the first equivalence follows from the condition $\gcd(b_1, 3) = 1$ in (3.4). From here, we see that even overlattices of Type (I) exist only if $d' \equiv 2 \pmod{3}$. In this situation, the number of such lattices equals the number of pairs (b_1, b_2) which satisfy

$$b_1 \in \{1, 2\} \quad \text{and} \quad 0 \leq b_2 < 2d' \quad \text{with} \quad b_2^2 \equiv 1 \pmod{4d'}.$$

By Lemma 4.1, the number of choices for b_2 is equal to $\frac{1}{2} |(\mathbb{Z}_{4d'}^\times)_2|$. Since there are two choices for b_1 , the number of desired (b_1, b_2) is equal to $|(\mathbb{Z}_{4d'}^\times)_2|$. \square

Recall that an overlattice of Type (II) has the form

$$L = S + T + \left\langle \frac{b_3\ell + 2d'kt_1 + t_2}{6d'} \right\rangle$$

where $0 \leq k < 3$ and b_3 is as in (3.5). This lattice is even if and only if

$$\left(\frac{b_3\ell + 2d'kt_1 + t_2}{6d'}\right)^2 = -\frac{1}{6d'}(b_3^2 + 4d'k^2 - 1) \in 2\mathbb{Z}. \quad (4.1)$$

Let us count the number of such overlattices case-by-case.

Lemma 4.3. *There are $\frac{1}{2} |(\mathbb{Z}_{12d'}^\times)_2|$ many elements in $\mathcal{M}_{S,T}$ of Type (II) with $k = 0$.*

Proof. When $k = 0$, condition (4.1) reduces to

$$-\frac{1}{6d'}(b_3^2 - 1) \in 2\mathbb{Z} \quad \iff \quad b_3^2 \equiv 1 \pmod{12d'}.$$

By Lemma 4.1, the number of choices for b_3 is equal to $\frac{1}{2} |(\mathbb{Z}_{12d'}^\times)_2|$. \square

Now we consider the cases when $k = 1, 2$.

Lemma 4.4. *Elements in $\mathcal{M}_{S,T}$ of Type (II) with $k = 1$ exist only if $d' \equiv 0 \pmod{3}$. If this holds, then there are $\frac{1}{2} |(\mathbb{Z}_{4d'}^\times)_2|$ many of them. The same statement holds for $k = 2$.*

Proof. When $k = 1$ (resp. $k = 2$), condition (4.1) is equivalent to

$$b_3^2 + 4d' - 1 \equiv 0 \pmod{12d'}. \quad (4.2)$$

Recall from (3.5) that $\gcd(b_3, 6d') = 1$, whence $b_3^2 \equiv 1 \pmod{3}$, and the above relation modulo 3 gives $d' \equiv 0 \pmod{3}$. Now write

$$b_3 = b_4 + 2d'm \quad \text{with} \quad 0 \leq b_4 < 2d'.$$

Then (3.5) holds if and only if $m \in \{0, 1, 2\}$ and $\gcd(b_4, 2d') = 1$. From (4.2), we get

$$b_4^2 + 4d' - 1 \equiv b_4^2 + 4d'(mb_4 + d'm^2 + 1) - 1 \equiv 0 \pmod{12d'}. \quad (4.3)$$

This relation modulo $4d'$ gives

$$b_4^2 \equiv 1 \pmod{4d'}. \quad (4.4)$$

We claim that for each such b_4 , whether $m = 0, 1, 2$ is uniquely determined. Indeed, if we write $b_4^2 = 1 + 4d'r$ with r an integer, then

$$b_4^2 + 4d'(mb_4 + d'm^2 + 1) - 1 = 4d'(r + mb_4 + d'm^2 + 1).$$

Inserting this into (4.3) with $d' \equiv 0 \pmod{3}$ in mind reduces the relation to

$$r + mb_4 + 1 \equiv 0 \pmod{3}.$$

Then the claim follows as $b_4 \not\equiv 0 \pmod{3}$. By Lemma 4.1, the number of $0 \leq b_4 < 2d'$ satisfying (4.4) is equal to $\frac{1}{2} |(\mathbb{Z}_{4d'}^\times)_2|$. This completes the proof. \square

Proof of Theorem 1.1. By Lemmas 4.2, 4.3, 4.4, the numbers of elements in $\mathcal{M}_{S,T}$ of different types and values of d' can be organized into a table:

| | $d' \equiv 0 \pmod{3}$ | $d' \equiv 1 \pmod{3}$ | $d' \equiv 2 \pmod{3}$ |
|-----------------------|--|--|--|
| (I) | 0 | 0 | $ (\mathbb{Z}_{4d'}^\times)_2 $ |
| (II) with $k = 0$ | $\frac{1}{2} (\mathbb{Z}_{12d'}^\times)_2 $ | $\frac{1}{2} (\mathbb{Z}_{12d'}^\times)_2 $ | $\frac{1}{2} (\mathbb{Z}_{12d'}^\times)_2 $ |
| (II) with $k = 1$ | $\frac{1}{2} (\mathbb{Z}_{4d'}^\times)_2 $ | 0 | 0 |
| (II) with $k = 2$ | $\frac{1}{2} (\mathbb{Z}_{4d'}^\times)_2 $ | 0 | 0 |
| $ \mathcal{M}_{S,T} $ | $\frac{3}{2} (\mathbb{Z}_{4d'}^\times)_2 $ | $ (\mathbb{Z}_{4d'}^\times)_2 $ | $2 (\mathbb{Z}_{4d'}^\times)_2 $ |

The formulas can then be deduced from Lemma 3.2 and a direct computation. \square

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