# TWO RATIONAL NODAL QUARTIC THREEFOLDS

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Abstract. We prove that the quartic threefolds defined by

$$\sum_{i=0}^{5} x_i = \sum_{i=0}^{5} x_i^4 - t\left(\sum_{i=0}^{5} x_i^2\right)^2 = 0$$

in $\mathbb{P}^5$ are rational for $t = \frac{1}{6}$ and $t = \frac{7}{10}$.

## 1. Introduction

Consider the six-dimensional permutation representation $\mathbb{W}$ of the group $\mathfrak{S}_6$. Choose coordinates $x_0, \ldots, x_5$ in $\mathbb{W}$ so that they are permuted by $\mathfrak{S}_6$. Then $x_0 \ldots, x_5$ also serve as homogeneous coordinates in the projective space $\mathbb{P}^5 = \mathbb{P}(\mathbb{W})$.

Let us identify $\mathbb{P}^4$ with a hyperplane

$$x_0 + x_1 + x_2 + x_3 + x_4 + x_5 = 0$$

in $\mathbb{P}^5$. Denote by $X_t$ the quartic threefold in $\mathbb{P}^4$ that is given by the equation

$$x_0^4 + x_1^4 + x_2^4 + x_3^4 + x_4^4 + x_5^4 = t\Big(x_0^2 + x_1^2 + x_2^2 + x_3^2 + x_4^2 + x_5^2\Big)^2, \tag{1.1}$$

where $t$ is an element of the ground field, which we will always assume to be the field $\mathbb{C}$ of complex numbers. Then $X_t$ is singular for every $t \in \mathbb{C}$. Indeed, denote by $\Sigma_{30}$ the $\mathfrak{S}_6$-orbit of the point $[1 : 1 : \omega : \omega : \omega^2 : \omega^2]$, where $\omega = e^{\frac{2\pi i}{3}}$. Then $|\Sigma_{30}| = 30$, and $X_t$ is singular at every point of $\Sigma_{30}$ for every $t \in \mathbb{C}$ (see, for example, [12, Theorem 4.1]).

The possible singularities of the quartic threefold $X_t$ have been described by van der Geer in [12, Theorem 4.1]. To recall his description, denote by $\mathcal{L}_{15}$ the $\mathfrak{S}_6$-orbit of the line that passes through the points $[1 : 0 : -1 : 1 : 0 : -1]$ and $[0 : 1 : -1 : 0 : 1 : -1]$, and denote by $\Sigma_6$, $\Sigma_{10}$, and $\Sigma_{15}$ the $\mathfrak{S}_6$-orbits of the points $[-5 : 1 : 1 : 1 : 1 : 1]$, $[-1 : -1 : -1 : 1 : 1 : 1]$, and $[1 : -1 : 0 : 0 : 0 : 0]$, respectively. Then the curve $\mathcal{L}_{15}$ is a union of fifteen lines, while $|\Sigma_6| = 6$, $|\Sigma_{10}| = 10$, and $|\Sigma_{15}| = 15$. Moreover, one has

$$\mathrm{Sing}(X_t) = \begin{cases} \mathcal{L}_{15} \text{ if } t = \dfrac{1}{4}, \\ \Sigma_{30} \cup \Sigma_{15} \text{ if } t = \dfrac{1}{2}, \\ \Sigma_{30} \cup \Sigma_{10} \text{ if } t = \dfrac{1}{6}, \\ \Sigma_{30} \cup \Sigma_{6} \text{ if } t = \dfrac{7}{10}, \\ \Sigma_{30} \text{ otherwise.} \end{cases}$$

Furthermore, if $t \neq \frac{1}{4}$, then all singular points of the quartic threefold $X_t$ are isolated ordinary double points (nodes).

The threefold $X_{\frac{1}{2}}$ is classical. It is the so-called *Burkhardt quartic*. In [3], Burkhardt discovered that the subset $\Sigma_{30}\cup\Sigma_{15}$ is invariant under the action of the simple group $\mathrm{PSp}_4(\mathbf{F}_3)$ of order 25920. In [7], Coble proved that $\Sigma_{30}\cup\Sigma_{15}$ is the singular locus of the threefold $X_{\frac{1}{2}}$, and proved that $X_{\frac{1}{2}}$ is also $\mathrm{PSp}_4(\mathbf{F}_3)$-invariant. Later Todd proved in [22] that $X_{\frac{1}{2}}$ is rational. In [15], de Jong, Shepherd-Barron, and Van de Ven proved that $X_{\frac{1}{2}}$ is the unique quartic threefold in $\mathbb{P}^4$ with 45 singular points.

The quartic threefold $X_{\frac{1}{4}}$ is also classical. It is known as the *Igusa quartic* from its modular interpretation as the Satake compactification of the moduli space of Abelian surfaces with level 2 structure (see [12]). The projectively dual variety of the quartic threefold $X_{\frac{1}{4}}$ is the so-called *Segre cubic*. Since the Segre cubic is rational, $X_{\frac{1}{4}}$ is rational as well.

During *Kul!fest* conference dedicated to the 60th anniversary of Viktor Kulikov that was held in Moscow in December 2012, Alexei Bondal and Yuri Prokhorov posed

**Problem 1.2.** *Determine all $t\in\mathbb{C}$ such that $X_t$ is rational.*

Since $X_t$ is singular, we cannot apply Iskovskikh and Manin's theorem from [14] to $X_t$. Similarly, we cannot apply Mella's [18, Theorem 2] to $X_t$ either, because the quartic threefold $X_t$ is not $\mathbb{Q}$-factorial by [1, Lemma 2]. Nevertheless, Beauville proved

**Theorem 1.3** ([1])**.** *If $t\not\in\{\frac{1}{2},\frac{1}{4},\frac{1}{6},\frac{7}{10}\}$, then $X_t$ is non-rational.*

Both $X_{\frac{1}{2}}$ and $X_{\frac{1}{4}}$ are rational. The goal of this paper is to prove

**Theorem 1.4.** *The quartic threefolds $X_{\frac{1}{6}}$ and $X_{\frac{7}{10}}$ are also rational.*

Surprisingly, the proof of Theorem 1.4 goes back to two classical papers of Todd. Namely, we will construct an explicit $\mathfrak{A}_6$-birational map $\mathbb{P}^3\dashrightarrow X_{\frac{7}{10}}$ that is a special case of Todd's construction from [20]. Similarly, we will construct an explicit $\mathfrak{S}_5$-birational map $\mathbb{P}^3\dashrightarrow X_{\frac{1}{6}}$ that is a degeneration of Todd's construction from [21]. We emphasize that our proof is self-contained, i.e. it does not rely on the results proved in [20] and [21], but recovers the necessary facts in our particular situation using additional symmetries arising from group actions.

*Remark* 1.5. Todd proved in [22] that the Burkhardt quartic $X_{\frac{1}{2}}$ is determinantal (see also [19, §5.1]). The constructions of our birational maps $\mathbb{P}^3\dashrightarrow X_{\frac{7}{10}}$ and $\mathbb{P}^3\dashrightarrow X_{\frac{1}{6}}$ imply that both $X_{\frac{7}{10}}$ and $X_{\frac{1}{6}}$ are determinantal (see [19, Example 6.4.2] and [19, Example 6.2.1]). Yuri Prokhorov pointed out that the quartic threefold

$$\det\begin{pmatrix} y_0 & y_1 & y_2 & y_3\\ y_4 & y_0 & y_3 & y_4\\ y_2 & y_1 & y_1 & y_0\\ y_0 & y_3 & y_2 & y_4\end{pmatrix}=0$$

in $\mathbb{P}^4$ with homogeneous coordinates $y_0,\ldots,y_4$ has exactly 45 singular points. Thus, it is isomorphic to the Burkhardt quartic $X_{\frac{1}{2}}$ by [15]. It would be interesting to find similar determinantal equations of the threefolds $X_{\frac{7}{10}}$ and $X_{\frac{1}{6}}$.

The plan of the paper is as follows. In Section 2 we recall some preliminary results on representations of a central extension of the group $\mathfrak{S}_6$, and some of its subgroups.

In Section 3 we collect results concerning a certain action of the group $\mathfrak{A}_5$ on $\mathbb{P}^3$, and study $\mathfrak{A}_5$-invariant quartic surfaces; the reason we pay so much attention to this group is that it is contained both in $\mathfrak{A}_6$ and in $\mathfrak{S}_5$, and thus the information about its properties simplifies the study of the latter two groups. In Section 4 we collect auxiliary results about the groups $\mathfrak{S}_6$, $\mathfrak{A}_6$ and $\mathfrak{S}_5$, in particular about their actions on curves and their five-dimensional irreducible representations. In Section 5 we construct an $\mathfrak{A}_6$-equivariant birational map $\mathbb{P}^3 \dashrightarrow X_{\frac{7}{10}}$. Finally, in Section 6 we construct an $\mathfrak{S}_5$-equivariant birational map $\mathbb{P}^3 \dashrightarrow X_{\frac{1}{6}}$ and make some concluding remarks.

Throughout the paper, we denote a cyclic group of order $n$ by $\boldsymbol{\mu}_n$, and we denote a dihedral group of order $2n$ by $\mathrm{D}_{2n}$. In particular, one has $\mathrm{D}_{12} \cong \mathfrak{S}_3 \times \boldsymbol{\mu}_2$. By $F_{36}$ we denote a group isomorphic to $(\boldsymbol{\mu}_3 \times \boldsymbol{\mu}_3) \rtimes \boldsymbol{\mu}_4$, and by $F_{20}$ we denote a group isomorphic to $\boldsymbol{\mu}_5 \rtimes \boldsymbol{\mu}_4$.

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## 2. Representation theory

Recall that the permutation group $\mathfrak{S}_6$ has two central extensions $2^+\mathfrak{S}_6$ and $2^-\mathfrak{S}_6$ by the group $\boldsymbol{\mu}_2$ with the central subgroup contained in the commutator subgroup (see [8, p. xxiii] for details). We denote the first of them (i. e. the one where the preimages of a transposition in $\mathfrak{S}_6$ under the natural projection have order two) by $2.\mathfrak{S}_6$ to simplify notation. Similarly, for any group $\Gamma$ we denote by $2.\Gamma$ a non-split central extension of $\Gamma$ by the group $\boldsymbol{\mu}_2$.

We start with recalling some facts about four- and five-dimensional representations of the group $2.\mathfrak{S}_6$ we will be working with. A reader who is not interested in details here can skip to Corollary 2.1, or even to Section 4 where we reformulate everything in geometric language. Also, we will see in Section 4 that our further constructions do not depend much on the choice of representations, and all computations one makes for one of them actually apply to all others.

Let $\mathbb{I}$ and $\mathbb{J}$ be the trivial and the non-trivial one-dimensional representations of the group $\mathfrak{S}_6$, respectively. Consider the six-dimensional permutation representation $\mathbb{W}$ of $\mathfrak{S}_6$. One has

$$\mathbb{W} \cong \mathbb{I} \oplus \mathbb{W}_5 \otimes \mathbb{J}$$

for some irreducible representation $\mathbb{W}_5$ of $\mathfrak{S}_6$. We can regard $\mathbb{I}$, $\mathbb{J}$ and $\mathbb{W}_5$ as representations of the group $2.\mathfrak{S}_6$. Recall that there is a double cover $\mathrm{SL}_4(\mathbb{C}) \to \mathrm{SO}_6(\mathbb{C})$, see e.g. [10, Exercise 20.39]. Using it, we conclude that there is an embedding of the group $2.\mathfrak{S}_6$ into $\mathrm{SL}_4(\mathbb{C})$. This embedding gives rise to two four-dimensional representations of $2.\mathfrak{S}_6$ that differ by a tensor product with $\mathbb{J}$. We fix one of these two representations $\mathbb{U}_4$. Note that

$$\mathbb{I} \oplus \mathbb{W}_5 \cong \Lambda^2(\mathbb{U}_4).$$

Recall that there are coordinates $x_0, \ldots, x_5$ in $\mathbb{W}$ that are permuted by the group $\mathfrak{S}_6$. We will refer to a subgroup of $2.\mathfrak{S}_6$ fixing one of the corresponding points as a *standard* subgroup $2.\mathfrak{S}_5$; we denote any such subgroup by $2.\mathfrak{S}_5^{st}$. A subgroup of $2.\mathfrak{S}_6$ that is isomorphic to $2.\mathfrak{S}_5$ but is not conjugate to a standard $2.\mathfrak{S}_5$ will be called a *non-standard* subgroup $2.\mathfrak{S}_5$; we denote any such subgroup by $2.\mathfrak{S}_5^{nst}$. These agree with standard and non-standard subgroups of $\mathfrak{S}_6$ isomorphic to $\mathfrak{S}_5$, although outer automorphisms of $\mathfrak{S}_6$ do not lift to $2.\mathfrak{S}_6$. Any subgroup of $2.\mathfrak{S}_6$ that is isomorphic to $2.\mathfrak{A}_5$, $2.\mathfrak{S}_4$ or $2.\mathfrak{A}_4$ and is contained in $2.\mathfrak{S}_5^{st}$ is denoted by $2.\mathfrak{A}_5^{st}$, $2.\mathfrak{S}_4^{st}$ or $2.\mathfrak{A}_4^{st}$, respectively. Similarly, any subgroup of $2.\mathfrak{S}_6$ that is isomorphic to $2.\mathfrak{A}_5$, $2.\mathfrak{S}_4$ or $2.\mathfrak{A}_4$ and is contained in $2.\mathfrak{S}_5^{nst}$ is denoted by $2.\mathfrak{A}_5^{nst}$, $2.\mathfrak{S}_4^{nst}$ or $2.\mathfrak{A}_4^{nst}$, respectively.

The values of characters of important representations of the group $2.\mathfrak{S}_6$, and the information about some of its subgroups are presented in Table 1, cf. [8, p. 5]. The first two columns of Table 1 describe conjugacy classes of elements of the group $2.\mathfrak{S}_6$. The first column lists the orders of the elements in the corresponding conjugacy class, and the second column, except for the entries in the second and the third row, gives a cycle type of the image of an element under projection to $\mathfrak{S}_6$ (for example, $[3, 2]$ denotes a product of two disjoint cycles of lengths 3 and 2). By id we denote the identity element of $2.\mathfrak{S}_6$, and $z$ denotes the unique non-trivial central element of $2.\mathfrak{S}_6$. Note that the preimages of some of conjugacy classes in $\mathfrak{S}_6$ split into a union of two conjugacy classes in $2.\mathfrak{S}_6$. The next three columns list the values of the characters of the representations $\mathbb{W}$, $\mathbb{W}_5$ and $\mathbb{U}_4$ of $2.\mathfrak{S}_6$. Note that there is no real ambiguity in the choice of $\sqrt{-3}$ since we did not specify any way to distinguish the two conjugacy classes in $2.\mathfrak{S}_6$ whose elements are projected to cycles of length 6 in $\mathfrak{S}_6$ up to this point (note that the two ways to choose a sign here is exactly a tensor multiplication of the representation with $\mathbb{J}$, i.e. the choice between two homomorphisms of $2.\mathfrak{S}_6$ to $\mathrm{SL}_4(\mathbb{C})$ having the same image). The remaining columns list the numbers of elements from each of the conjugacy classes of $2.\mathfrak{S}_6$ in subgroups of certain types. By $2.F_{36}$ (respectively, by $2.F_{20}$, by $2.\mathrm{D}_{12}^{nst}$) we denote a subgroup of $2.\mathfrak{S}_6$ (respectively, of $2.\mathfrak{S}_6$, or of $2.\mathfrak{S}_5^{nst}$) isomorphic to a central extension of $F_{36}$ (respectively, of $F_{20}$, or of $\mathrm{D}_{12}$) by $\boldsymbol{\mu}_2$. A subgroup $2.F_{20}$ is actually contained in a subgroup $2.\mathfrak{S}_5^{st}$ and in a subgroup $2.\mathfrak{S}_5^{nst}$. Note that the intersection of a conjugacy class in a group with a subgroup may (and often does) split into several conjugacy classes in this subgroup.

It is immediate to see from Table 1 that $\mathbb{U}_4$ is an irreducible representation of the group $2.\mathfrak{S}_6$. Using the information provided by Table 1, we immediately obtain the following results.

**Corollary 2.1.** *Let $\Gamma$ be a subgroup of $2.\mathfrak{S}_6$. After restriction to the subgroup $\Gamma$ the $2.\mathfrak{S}_6$-representation $\mathbb{U}_4$*

- (i) *remains irreducible, if $\Gamma$ is one of the subgroups $2.\mathfrak{A}_6$, $2.\mathfrak{S}_5^{nst}$, $2.\mathfrak{A}_5^{nst}$, $2.\mathfrak{S}_4^{nst}$, $2.F_{36}$, or $2.F_{20}$;*
- (ii) *splits into a sum of two non-isomorphic irreducible two-dimensional representations, if $\Gamma$ is one of the subgroups $2.\mathfrak{A}_5^{st}$, $2.\mathfrak{A}_4^{nst}$, or $2.\mathrm{D}_{12}^{nst}$.*

*Proof.* Compute inner products of the corresponding characters with themselves, and keep in mind that neither of the groups $2.\mathfrak{A}_5^{st}$, $2.\mathfrak{A}_4^{nst}$, and $2.\mathrm{D}_{12}^{nst}$ has an irreducible three-dimensional representation with a non-trivial action of the central subgroup. □

*Remark* 2.2. By Corollary 2.1(i), the $2.\mathfrak{S}_5^{nst}$-representation $\mathbb{U}_4$ is irreducible. One can check that it is not induced from any proper subgroup of $2.\mathfrak{S}_5^{nst}$, i.e. it defines a primitive

TABLE 1. Characters and subgroups of the group $2.\mathfrak{S}_6$

| ord | type | $\mathbb{W}$ | $\mathbb{W}_5$ | $\mathbb{U}_4$ | $2.\mathfrak{S}_6$ | $2.\mathfrak{A}_6$ | $2.\mathfrak{S}_5^{nst}$ | $2.\mathfrak{A}_5^{st}$ | $2.\mathfrak{A}_5^{nst}$ | $2.\mathfrak{S}_4^{nst}$ | $2.\mathfrak{A}_4^{nst}$ | $2.F_{36}$ | $2.F_{20}$ | $2.\mathrm{D}_{12}^{nst}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | id | 6 | 5 | 4 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 2 | $z$ | 6 | 5 | $-4$ | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 2 | [2] | 4 | $-3$ | 0 | 30 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | [2, 2] | 2 | 1 | 0 | 90 | 90 | 30 | 30 | 30 | 6 | 6 | 18 | 10 | 6 |
| 4 | [2, 2, 2] | 0 | 1 | 0 | 30 | 0 | 20 | 0 | 0 | 12 | 0 | 0 | 0 | 8 |
| 6 | [3] | 3 | 2 | 2 | 40 | 40 | 0 | 20 | 0 | 0 | 0 | 4 | 0 | 0 |
| 3 | [3] | 3 | 2 | $-2$ | 40 | 40 | 0 | 20 | 0 | 0 | 0 | 4 | 0 | 0 |
| 6 | [3, 2] | 1 | 0 | 0 | 120 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | [3, 2] | 1 | 0 | 0 | 120 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | [3, 3] | 0 | $-1$ | $-1$ | 40 | 40 | 20 | 0 | 20 | 8 | 8 | 4 | 0 | 2 |
| 3 | [3, 3] | 0 | $-1$ | 1 | 40 | 40 | 20 | 0 | 20 | 8 | 8 | 4 | 0 | 2 |
| 8 | [4] | 2 | $-1$ | 0 | 180 | 0 | 60 | 0 | 0 | 12 | 0 | 0 | 20 | 0 |
| 8 | [4, 2] | 0 | $-1$ | 0 | 180 | 180 | 0 | 0 | 0 | 0 | 0 | 36 | 0 | 0 |
| 10 | [5] | 1 | 0 | 1 | 144 | 144 | 24 | 24 | 24 | 0 | 0 | 0 | 4 | 0 |
| 5 | [5] | 1 | 0 | $-1$ | 144 | 144 | 24 | 24 | 24 | 0 | 0 | 0 | 4 | 0 |
| 12 | [6] | 0 | 1 | $\sqrt{-3}$ | 120 | 0 | 20 | 0 | 0 | 0 | 0 | 0 | 0 | 2 |
| 12 | [6] | 0 | 1 | $-\sqrt{-3}$ | 120 | 0 | 20 | 0 | 0 | 0 | 0 | 0 | 0 | 2 |

subgroup isomorphic to $2.\mathfrak{S}_5$ in $\mathrm{GL}_4(\mathbb{C})$. Note that this subgroup is not present in the list given in [9, §8.5]. It is still listed by some other classical surveys, see e.g. [2, §119].

**Corollary 2.3.** *Let $\Gamma$ be a subgroup of $2.\mathfrak{S}_6$. After restriction to the subgroup $\Gamma$ the $2.\mathfrak{S}_6$-representation $\mathbb{W}_5$*

(i) *remains irreducible, if $\Gamma$ is one of the subgroups $2.\mathfrak{A}_6$, $2.\mathfrak{S}_5^{nst}$, or $2.\mathfrak{A}_5^{nst}$;*
(ii) *splits into a sum of the trivial and an irreducible four-dimensional representation if $\Gamma$ is a subgroup $2.\mathfrak{A}_5^{st}$;*
(iii) *splits into a sum of the trivial and two different irreducible two-dimensional representations if $\Gamma$ is a subgroup $2.\mathrm{D}_{12}^{nst}$.*

In the sequel we will denote the restrictions of the $2.\mathfrak{S}_6$-representations $\mathbb{U}_4$ and $\mathbb{W}_5$ to various subgroups by the same symbols for simplicity. The next two corollaries are implied by direct computations (we used GAP software [11] to perform them).

**Corollary 2.4.** *The following assertions hold:*

(i) *the $\mathfrak{A}_6$-representation $\mathrm{Sym}^2(\mathbb{U}_4^\vee)$ does not contain one-dimensional subrepresentations;*
(ii) *the $\mathfrak{A}_6$-representation $\mathrm{Sym}^4(\mathbb{U}_4^\vee)$ does not contain one-dimensional subrepresentations;*
(iii) *the $\mathfrak{A}_5^{nst}$-representation $\mathrm{Sym}^2(\mathbb{U}_4^\vee)$ splits into a sum of two different irreducible three-dimensional representations and one irreducible four-dimensional representation;*
(iv) *the $2.\mathfrak{A}_5^{nst}$-representation $\mathrm{Sym}^3(\mathbb{U}_4^\vee)$ does not contain one-dimensional subrepresentations;*
(v) *the $\mathfrak{A}_5^{nst}$-representation $\mathrm{Sym}^4(\mathbb{U}_4^\vee)$ has a unique two-dimensional subrepresentation, and this subrepresentation splits into a sum of two trivial representations of $\mathfrak{A}_5^{nst}$.*

Recall that all representations of a symmetric group are self-dual. Therefore, to study invariant hypersurfaces in $\mathbb{P}(\mathbb{W}_5)$ we will use the following result.

**Corollary 2.5.** *Let $\Gamma$ be one of the groups $\mathfrak{S}_6$, $\mathfrak{A}_6$ or $\mathfrak{S}_5^{nst}$. Then*

(i) *the $\Gamma$-representation $\mathrm{Sym}^2(\mathbb{W}_5)$ has a unique one-dimensional subrepresentation;*
(ii) *the $\Gamma$-representation $\mathrm{Sym}^4(\mathbb{W}_5)$ has a unique two-dimensional subrepresentation, and this subrepresentation splits into a sum of two trivial representations of $\Gamma$.*

We conclude this section by recalling some information about several subgroups of $2.\mathfrak{S}_6$ that are smaller than those listed in Table 1. Namely, we list in Table 2 orders, types and numbers of elements in certain subgroups of $2.\mathfrak{A}_5^{nst}$. We keep the notation used in Table 1. By $2.\mathfrak{S}_3'$ we denote a subgroup of $2.\mathfrak{A}_5^{nst}$ isomorphic to $2.\mathfrak{S}_3$. Note that the preimage in $2.\mathfrak{S}_6$ of any subgroup $\boldsymbol{\mu}_5 \subset \mathfrak{S}_6$ is isomorphic to $\boldsymbol{\mu}_{10}$.

Looking at Table 2 (and keeping in mind character values provided by Table 1) we immediately obtain the following.

**Corollary 2.6.** *Let $\Gamma$ be a subgroup of $2.\mathfrak{A}_5^{nst} \subset 2.\mathfrak{S}_6$. After restriction to $\Gamma$ the $2.\mathfrak{S}_6$-representation $\mathbb{U}_4$*

(i) *splits into a sum of two non-isomorphic irreducible two-dimensional representations if $\Gamma$ is a subgroup $2.\mathrm{D}_{10}$;*
(ii) *splits into a sum of an irreducible two-dimensional representation and two non-isomorphic one-dimensional representations if $\Gamma$ is a subgroup $2.\mathfrak{S}_3'$;*

TABLE 2. Subgroups of $2.\mathfrak{A}_5^{nst}$

| ord | type | $2.\mathrm{D}_{10}$ | $2.\mathfrak{S}_3'$ | $2.(\boldsymbol{\mu}_2 \times \boldsymbol{\mu}_2)$ | $\boldsymbol{\mu}_{10}$ |
|---|---|---|---|---|---|
| 1 | id | 1 | 1 | 1 | 1 |
| 2 | $z$ | 1 | 1 | 1 | 1 |
| 4 | $[2,2]$ | 10 | 6 | 6 | 0 |
| 6 | $[3,3]$ | 0 | 2 | 0 | 0 |
| 3 | $[3,3]$ | 0 | 2 | 0 | 0 |
| 10 | $[5]$ | 4 | 0 | 0 | 4 |
| 5 | $[5]$ | 4 | 0 | 0 | 4 |

(iii) *splits into a sum of two isomorphic irreducible two-dimensional representations if* $\Gamma$ *is a subgroup* $2.(\boldsymbol{\mu}_2 \times \boldsymbol{\mu}_2)$*;*
(iv) *splits into a sum of four pairwise non-isomorphic one-dimensional representations if* $\Gamma$ *is a subgroup* $\boldsymbol{\mu}_{10}$*.*

## 3. Icosahedral group in three dimensions

In this section, we consider the action of the group $\mathfrak{A}_5$ on the projective space $\mathbb{P}^3$ arising from a non-standard embedding of $\mathfrak{A}_5 \hookrightarrow \mathfrak{S}_6$. Namely, we identify $\mathbb{P}^3$ with the projectivization $\mathbb{P}(\mathbb{U}_4)$, where $\mathbb{U}_4$ is the restriction of the four-dimensional irreducible representation of the group $2.\mathfrak{S}_6$ introduced in Section 2 to a subgroup $2.\mathfrak{A}_5^{nst}$ (which we will refer to as just $2.\mathfrak{A}_5$ in this section). Recall from Corollary 2.1(i) that $\mathbb{U}_4$ is an irreducible representation of $2.\mathfrak{A}_5$.

*Remark* 3.1 (see e. g. [8, p. 2]). Let $\Gamma$ be a proper subgroup of $\mathfrak{A}_5$ such that the index of $\Gamma$ is at most 15. Then $\Gamma$ is isomorphic either to $\mathfrak{A}_4$, or to $\mathrm{D}_{10}$, or to $\mathfrak{S}_3$, or to $\boldsymbol{\mu}_5$, or to $\boldsymbol{\mu}_2 \times \boldsymbol{\mu}_2$. In particular, if $\mathfrak{A}_5$ acts transitively on the set of $r < 15$ elements, then $r \in \{5, 6, 10, 12\}$.

**Lemma 3.2.** *Let* $\Omega$ *be an* $\mathfrak{A}_5$*-orbit of length* $r \leqslant 15$ *in* $\mathbb{P}^3$*. Then either* $r = 10$*, or* $r = 12$*. Moreover,* $\mathbb{P}^3$ *contains exactly two* $\mathfrak{A}_5$*-orbits of length* 10 *and exactly two* $\mathfrak{A}_5$*-orbits of length* 12*.*

*Proof.* By Remark 3.1 one has $r \in \{1, 5, 6, 10, 12, 15\}$. The case $r = 1$ is impossible since $\mathbb{U}_4$ is an irreducible $2.\mathfrak{A}_5$-representation. Restricting $\mathbb{U}_4$ to subgroups of $2.\mathfrak{A}_5$ isomorphic to $2.\mathfrak{A}_4$, $2.\mathrm{D}_{10}$, and $2.(\boldsymbol{\mu}_2 \times \boldsymbol{\mu}_2)$, and applying Corollaries 2.1(ii) and 2.6(i),(iii), we see that $r \notin \{5, 6, 15\}$.

Restricting $\mathbb{U}_4$ to a subgroup of $2.\mathfrak{A}_5$ isomorphic to $2.\mathfrak{S}_3$, applying Corollary 2.6(ii) and keeping in mind that there are ten subgroups isomorphic to $\mathfrak{S}_3$ in $\mathfrak{A}_5$, we see that $\mathbb{P}^3$ contains exactly two $\mathfrak{A}_5$-orbits of length 10.

Finally, restricting $\mathbb{U}_4$ to a subgroup of $2.\mathfrak{A}_5$ isomorphic to $\boldsymbol{\mu}_{10}$, applying Corollary 2.6(iv) and keeping in mind that there are six subgroups isomorphic to $\boldsymbol{\mu}_5$ in $\mathfrak{A}_5$, we see that $\mathbb{P}^3$ contains exactly two $\mathfrak{A}_5$-orbits of length 12. □

**Lemma 3.3.** *There are no* $\mathfrak{A}_5$*-invariant surfaces of degree at most three in* $\mathbb{P}^3$*.*

*Proof.* Apply Corollary 2.4(iii),(iv). □

By Corollary 2.1(ii), the subgroup $\mathfrak{A}_4 \subset \mathfrak{A}_5$ leaves invariant two disjoint lines in $\mathbb{P}^3$, say $L_1$ and $L_1'$. Let $L_1, \ldots, L_5$ be the $\mathfrak{A}_5$-orbit of the line $L_1$, and let $L_1', \ldots, L_5'$ be the $\mathfrak{A}_5$-orbit of the line $L_1'$.

**Lemma 3.4.** *The lines $L_1, \ldots, L_5$ (respectively, the lines $L_1', \ldots, L_5'$) are pairwise disjoint.*

*Proof.* Suppose that some of the lines $L_1, \ldots, L_5$ have a common point. Since the action of $\mathfrak{A}_5$ on the set $\{L_1, \ldots, L_5\}$ is doubly transitive, this implies that every two of the lines $L_1, \ldots, L_5$ have a common point. Therefore, either all lines $L_1, \ldots, L_5$ are coplanar, or all of them pass through one point. Both of these cases are impossible since the $2.\mathfrak{A}_5$-representation $\mathbb{U}_4$ is irreducible by Corollary 2.1(i). Therefore, the lines $L_1, \ldots, L_5$ are pairwise disjoint. A similar argument applies to the lines $L_1', \ldots, L_5'$. □

**Corollary 3.5.** *Any $\mathfrak{A}_5$-orbit contained in the union $L_1 \cup \ldots \cup L_5$ has length at least* 20.

*Proof.* Corollary 2.1(ii) implies that the stabilzier $\Gamma \cong \mathfrak{A}_4$ of the line $L_1$ acts on $L_1$ faithfully. Therefore, the length of any $\Gamma$-orbit contained in $L_1$ is at least four. Thus the required assertion follows from Lemma 3.4. □

We are going to describe the configuration formed by the lines $L_1, \ldots, L_5, L_1', \ldots, L_5'$.

**Definition 3.6.** Let $T_1, \ldots, T_5, T_1', \ldots, T_5'$ be different lines in a projective space. We say that they form a *double five configuration* if the following conditions hold:

- the lines $T_1, \ldots, T_5$ (respectively, the lines $T_1', \ldots, T_5'$) are pairwise disjoint;
- for every $i$ the lines $T_i$ and $T_i'$ are disjoint;
- for every $i \neq j$ the line $T_i$ meets the line $T_j'$.

**Lemma 3.7.** *The lines $L_1, \ldots, L_5, L_1', \ldots, L_5'$ form a double five configuration. Moreover, the only line in $\mathbb{P}^3$ that intersects all lines of $L_1, \ldots, L_5$ but $L_i$ is the line $L_i'$, and the only line in $\mathbb{P}^3$ that intersects all lines of $L_1', \ldots, L_5'$ but $L_i'$ is the line $L_i$.*

*Proof.* For any $i$ the lines $L_i$ and $L_i'$ are disjoint by construction. The lines $L_1, \ldots, L_5$ (respectively, the lines $L_1', \ldots, L_5'$) are pairwise disjoint by Lemma 3.4.

Since any three pairwise skew lines in $\mathbb{P}^3$ are contained in a smooth quadric surface, and an intersection of two different quadric surfaces in $\mathbb{P}^3$ cannot contain three pairwise skew lines, we see that for any three indices $1 \leqslant i < j < k \leqslant 5$ there is a unique quadric surface $Q_{ijk}$ in $\mathbb{P}^3$ passing through the lines $L_i$, $L_j$ and $L_k$. Moreover, the quadric $Q_{ijk}$ is smooth. Note also that the quadric $Q_{ijk}$ is not $\mathfrak{A}_5$-invariant by Lemma 3.3. This implies that all five lines $L_1, \ldots, L_5$ are not contained in a quadric.

Therefore, we may assume that the quadric $Q_{123}$ does not contain the line $L_4$. It is well-known that in this case either there is a unique line $L$ meeting all four lines $L_1, \ldots, L_4$, or there are exactly two lines $L$ and $L'$ meeting $L_1, \ldots, L_4$. In the latter case the stabilizer $\Gamma \subset \mathfrak{A}_5$ of the quadruple $L_1, \ldots, L_4$ (i.e. the stabilizer of the line $L_5$) preserves the lines $L_5$, $L$ and $L'$. On the other hand, the lines $L$ and $L'$ are different from $L_5$ since $L_5$ meets neither of the lines $L_1, \ldots, L_4$; moreover, the group $\Gamma \cong \mathfrak{A}_4$ fixes both $L$ and $L'$. But $\Gamma$ cannot fix three different lines in $\mathbb{P}^3$ by Corollary 2.1(ii). The contradiction shows that there is a unique line $L$ meeting $L_1, \ldots, L_4$. Again we see that $L \neq L_5$, so that $L = L_5'$ by Corollary 2.1(ii).

Since the group $\mathfrak{A}_5$ permutes the lines $L_1, \ldots, L_5$ transitively, we conclude that the only line in $\mathbb{P}^3$ that intersects all lines of $L_1, \ldots, L_5$ except $L_i$ is the line $L_i'$. Similarly, we see that the only line in $\mathbb{P}^3$ that intersects all lines of $L_1', \ldots, L_5'$ except $L_i'$ is the line $L_i$. In particular, the lines $L_1, \ldots, L_5, L_1', \ldots, L_5'$ form a double five configuration. □

**Lemma 3.8.** *Every $\mathfrak{A}_5$-invariant curve of degree at most three in $\mathbb{P}^3$ is a twisted cubic. Moreover, there are exactly two $\mathfrak{A}_5$-invariant twisted cubic curves in $\mathbb{P}^3$.*

*Proof.* Let $C$ be an $\mathfrak{A}_5$-invariant curve of degree at most three in $\mathbb{P}^3$. Since the $2.\mathfrak{A}_5$-representation $\mathbb{U}_4$ is irreducible, we conclude that $C$ is a twisted cubic.

By Corollary 2.4(iii), one has

$$\mathrm{Sym}^2(\mathbb{U}_4) \cong \mathbb{V}_3 \oplus \mathbb{V}_3' \oplus \mathbb{V}_4, \tag{3.9}$$

where $\mathbb{V}_3$, $\mathbb{V}_3'$, and $\mathbb{V}_4$, are irreducible representations of the group $\mathfrak{A}_5$ of dimensions 3, 3, and 4, respectively. Note that $\mathbb{V}_3$ and $\mathbb{V}_3'$ are not isomorphic.

Denote by $\mathcal{Q}$ and $\mathcal{Q}'$ the linear systems of quadrics in $\mathbb{P}^3$ that correspond to $\mathbb{V}_3$ and $\mathbb{V}_3'$, respectively. Since $\mathbb{P}^3$ does not contain $\mathfrak{A}_5$-orbits of lengths less or equal to eight by Lemma 3.2, we see that the base loci of $\mathcal{Q}$ and $\mathcal{Q}'$ contain $\mathfrak{A}_5$-invariant curves $\mathscr{C}^1$ and $\mathscr{C}^2$, respectively. The degrees of these curves must be less than four, so that they are twisted cubic curves. This also implies that the base loci of $\mathcal{Q}$ and $\mathcal{Q}'$ are exactly the curves $\mathscr{C}^1$ and $\mathscr{C}^2$, respectively.

Now take an arbitrary $\mathfrak{A}_5$-invariant twisted cubic curve $C$ in $\mathbb{P}^3$. The quadrics in $\mathbb{P}^3$ passing through $C$ define a three-dimensional $\mathfrak{A}_5$-subrepresentation in $\mathrm{Sym}^2(\mathbb{U}_4)$. Moreover, different $\mathfrak{A}_5$-invariant twisted cubics give different $\mathfrak{A}_5$-subrepresentations of $\mathrm{Sym}^2(\mathbb{U}_4)$. Thus, (3.9) implies that $C$ coincides either with $\mathscr{C}^1$ or with $\mathscr{C}^2$. □

Keeping in mind Lemma 3.8, we will denote the two $\mathfrak{A}_5$-invariant twisted cubic curves in $\mathbb{P}^3$ by $\mathscr{C}^1$ and $\mathscr{C}^2$ throughout this section.

*Remark* 3.10. The curves $\mathscr{C}^1$ and $\mathscr{C}^2$ are disjoint. Indeed, otherwise, their intersection would contain at least 12, which is impossible, since a twisted cubic curve is an intersection of quadrics.

The lines in $\mathbb{P}^3$ that are tangent to the curves $\mathscr{C}^1$ and $\mathscr{C}^2$ sweep out quartic surfaces $\mathcal{S}^1$ and $\mathcal{S}^2$, respectively. These surfaces are $\mathfrak{A}_5$-invariant. The singular loci of $\mathcal{S}^1$ and $\mathcal{S}^2$ are the curves $\mathscr{C}^1$ and $\mathscr{C}^2$, respectively. In particular, the surfaces $\mathcal{S}^1$ and $\mathcal{S}^2$ are different. Their singularities along these curves are locally isomorphic to a product of $\mathbb{A}^1$ and an ordinary cusp.

Denote by $\mathcal{P}$ the pencil of quartics in $\mathbb{P}^3$ generated by $\mathcal{S}^1$ and $\mathcal{S}^2$.

**Lemma 3.11.** *All $\mathfrak{A}_5$-invariant quartic surfaces in $\mathbb{P}^3$ are contained in the pencil $\mathcal{P}$.*

*Proof.* This follows from Corollary 2.4(v). □

We proceed by describing the base locus of the pencil $\mathcal{P}$. This was done in [4, Remark 2.6], but we reproduce the details here for the convenience of the reader.

**Lemma 3.12.** *The base locus of the pencil $\mathcal{P}$ is an irreducible curve $B$ of degree* 16*. It has* 24 *singular points, these points are in a union of two $\mathfrak{A}_5$-orbits of length* 12*, and each of them is an ordinary cusp of the curve $B$. The curve $B$ contains a unique $\mathfrak{A}_5$-orbit of length* 20*.*

*Proof.* Denote by $B$ the base curve of the pencil $\mathcal{P}$. Let us show that the curves $\mathscr{C}^1$ and $\mathscr{C}^2$ are not contained in $B$. Since $\mathscr{C}^1$ is projectively normal, there is an exact sequence of $2.\mathfrak{A}_5$-representations

$$0 \to H^0(\mathcal{I}_{\mathscr{C}^1} \otimes \mathcal{O}_{\mathbb{P}^3}(4)) \to H^0(\mathcal{O}_{\mathbb{P}^3}(4)) \to H^0(\mathcal{O}_{\mathscr{C}^1} \otimes \mathcal{O}_{\mathbb{P}^3}(4)) \to 0,$$

where $\mathcal{I}_{\mathscr{C}^1}$ is the ideal sheaf of $\mathscr{C}^1$. The $2.\mathfrak{A}_5$-representation $H^0(\mathcal{O}_{\mathscr{C}^1}\otimes\mathcal{O}_{\mathbb{P}^3}(4))$ contains a one-dimensional subrepresentation corresponding to the unique $\mathfrak{A}_5$-orbit of length 12 in $\mathscr{C}^1\cong\mathbb{P}^1$. This shows that $\mathcal{P}$ contains a surface that does not pass through $\mathscr{C}^1$, so that $\mathscr{C}^1$ is not contained in $B$. Similarly, we see that $\mathscr{C}^2$ is not contained in $B$.

Let $\rho\colon \hat{\mathcal{S}}^1\to\mathcal{S}^1$ be the normalization of the surface $\mathcal{S}^1$, and let $\hat{\mathscr{C}}^1$ be the preimage of the curve $\mathscr{C}^1$ via $\rho$. Then the action of the group $\mathfrak{S}_5$, and in particular of its subgroup $\mathfrak{A}_5$, lifts to $\hat{\mathcal{S}}^1$. One has $\hat{\mathcal{S}}^1\cong\mathbb{P}^1\times\mathbb{P}^1$, and $\rho^*(\mathcal{O}_{\mathcal{S}^1}\otimes\mathcal{O}_{\mathbb{P}^3}(1))$ is a divisor of bi-degree $(1,2)$. This shows that $\hat{\mathscr{C}}^1$ is of bi-degree $(1,1)$. Thus, the action of $\mathfrak{A}_5$ on $\hat{\mathcal{S}}$ is diagonal by [6, Lemma 6.4.3(i)].

Denote by $\hat{B}$ be the preimage of the curve $B$ via $\rho$. Then $\hat{B}$ is a divisor of bi-degree $(4,8)$. Hence, the curve $\hat{B}$ is irreducible by [6, Lemma 6.4.4(i)], so that the curve $B$ is irreducible as well.

Note that the curve $\hat{B}$ is singular. Indeed, the intersection $\mathcal{S}^1\cap\mathscr{C}^2$ is an $\mathfrak{A}_5$-orbit $\Sigma_{12}$ of length 12, because $\mathscr{C}^2$ is not contained in $\mathcal{S}^1$. Similarly, we see that the intersection $\mathcal{S}^2\cap\mathscr{C}^1$ is also an $\mathfrak{A}_5$-orbit $\Sigma'_{12}$ of length 12. These $\mathfrak{A}_5$-orbits $\Sigma_{12}$ and $\Sigma'_{12}$ are different by Remark 3.10. Since $B$ is the scheme theoretic intersection of the surfaces $\mathcal{S}^1$ and $\mathcal{S}^2$, it must be singular at every point of $\Sigma_{12}\cup\Sigma'_{12}$. Denote by $\hat{\Sigma}_{12}$ and $\hat{\Sigma}'_{12}$ the preimages via $\rho$ of the $\mathfrak{A}_5$-orbits $\Sigma_{12}$ and $\Sigma'_{12}$, respectively. Then $\hat{B}$ is singular in every point of $\hat{\Sigma}'_{12}$.

The curve $\hat{B}$ is smooth away of $\hat{\Sigma}'_{12}$, because its arithmetic genus is 21, and the surface $\hat{\mathcal{S}}^1$ does not contain $\mathfrak{A}_5$-orbits of length less than 12. On the other hand, we have

$$\hat{B}\cap\hat{\mathscr{C}}^1=\hat{\Sigma}_{12},$$

because $\hat{B}\cdot\hat{\mathscr{C}}^1=12$ and $\hat{\Sigma}_{12}\subset\hat{B}$. This shows that $B$ is an irreducible curve whose only singularities are the points of $\Sigma_{12}\cup\Sigma'_{12}$, and each such point is an ordinary cusp of the curve $B$. In particular, the genus of the normalization of the curve $B$ is 9. By [6, Lemma 5.1.5], this implies that $B$ contains a unique $\mathfrak{A}_5$-orbit of length 20. □

The following classification of $\mathfrak{A}_5$-invariant quartic surfaces in $\mathbb{P}^3$ was obtained in [4, Theorem 2.4].

**Lemma 3.13.** *The pencil $\mathcal{P}$ contains two surfaces $\mathcal{R}^1$ and $\mathcal{R}^2$ with ordinary double singularities, such that the singular loci of $\mathcal{R}^1$ and $\mathcal{R}^2$ are $\mathfrak{A}_5$-orbits of length* 10*. Every surface in $\mathbb{P}^3$ different from $\mathcal{S}^1$, $\mathcal{S}^2$, $\mathcal{R}^1$ and $\mathcal{R}^2$ is smooth.*

*Proof.* Let $S$ be a surface in $\mathcal{P}$ that is different from $\mathcal{S}^1$ and $\mathcal{S}^2$. It follows from Lemma 3.3 that $S$ is irreducible. Assume that $S$ is singular.

We claim that $S$ has isolated singularities. Indeed, suppose that $S$ is singular along some $\mathfrak{A}_5$-invariant curve $Z$. Taking a general plane section of $S$, we see that the degree of $Z$ is at most three. Thus, one has either $Z=\mathscr{C}^1$ or $Z=\mathscr{C}^2$ by Lemma 3.8. Since neither of these curves is contained in the base locus of $\mathcal{P}$ by Lemma 3.12, this would imply that either $S=\mathcal{S}^1$ or $S=\mathcal{S}^2$. The latter is not the case by assumption.

We see that the singularities of $S$ are isolated. Hence, $S$ contains at most two non-Du Val singular points by [23, Theorem 1] applied to the minimal resolution of singularities of the surface $S$. Since the set of all non-Du Val singular points of the surface $S$ must be $\mathfrak{A}_5$-invariant, we see that $S$ has none of them by Lemma 3.2. Thus, all singularities of $S$ are Du Val.

By [6, Lemma 6.7.3(iii)], the surface $S$ has only ordinary double singularities, the set $\mathrm{Sing}(S)$ consists of one $\mathfrak{A}_5$-orbit, and

$$\big|\mathrm{Sing}(S)\big| \in \big\{5, 6, 10, 12, 15\big\}.$$

Since $\mathbb{P}^3$ does not contain $\mathfrak{A}_5$-orbits of lengths 5, 6, and 15 by Lemma 3.2, we see that $\mathrm{Sing}(S)$ is either an $\mathfrak{A}_5$-orbit of length 10 or an $\mathfrak{A}_5$-orbit of length 12.

Suppose that the singular locus of $S$ is an $\mathfrak{A}_5$-orbit $\Sigma_{12}$ of length 12. Then $S$ does not contain other $\mathfrak{A}_5$-orbits of length 12 by [6, Lemma 6.7.3(iv)]. Since $\mathscr{C}^1$ is not contained in the base locus of $\mathcal{P}$ by Lemma 3.12, and $\mathscr{C}^1$ is contained in $\mathcal{S}^1$, we see that $\mathscr{C}^1 \not\subset S$. Since

$$S \cdot \mathscr{C}^1 = 12$$

and $\Sigma_{12}$ is the only $\mathfrak{A}_5$-orbit of length at most 12 in $\mathscr{C}^1 \cong \mathbb{P}^1$, we have $S \cap \mathscr{C}^1 = \Sigma_{12}$. Thus,

$$12 = S \cdot \mathscr{C}^1 \geqslant \sum_{P \in \Sigma_{12}} \mathrm{mult}_P(S) = 2|\Sigma_{12}| = 24,$$

which is absurd.

Therefore, we see that the singular locus of $S$ is an $\mathfrak{A}_5$-orbit $\Sigma_{12}$ of length 10. Vice versa, if an $\mathfrak{A}_5$-invariant quartic surface passes through an $\mathfrak{A}_5$-orbit of length 10, then it is singular by [6, Lemma 6.7.1(ii)]. We know from Lemma 3.2 that there are exactly two $\mathfrak{A}_5$-orbits of length 10 in $\mathbb{P}^3$, and it follows from Lemma 3.12 that they are not contained in the base locus of $\mathcal{P}$. Thus there are two surfaces $\mathcal{R}^1$ and $\mathcal{R}^2$ that are singular exactly at the points of these two $\mathfrak{A}_5$-orbits, respectively. The above argument shows that every surface in $\mathcal{P}$ except $\mathcal{S}^1$, $\mathcal{S}^2$, $\mathcal{R}^1$ and $\mathcal{R}^2$ is smooth. □

Keeping in mind Lemma 3.13, we will denote by $\mathcal{R}^1$ and $\mathcal{R}^2$ the two nodal surfaces contained in the pencil $\mathcal{P}$ until the end of this section.

**Lemma 3.14.** *There is a unique $\mathfrak{A}_5$-invariant quartic surface in $\mathbb{P}^3$ that contains the lines $L_1, \ldots, L_5$ (respectively, the lines $L_1', \ldots, L_5'$). Moreover, this surface is smooth, and it does not contain the lines $L_1', \ldots, L_5'$ (respectively, $L_1, \ldots, L_5$).*

*Proof.* Put $\mathcal{L} = \sum_{i=1}^5 L_i$ and $\mathcal{L}' = \sum_{i=1}^5 L_i'$. Corollary 2.1(ii) implies that the stabilizer in $\mathfrak{A}_5$ of a general point of $L_1$ is trivial. Therefore, there exists a surface $S \in \mathcal{P}$ that contains all lines $L_1, \ldots, L_5$. By Lemma 3.12 such surface $S$ is unique.

We claim that $S \neq \mathcal{S}^1$. Indeed, all lines contained in $\mathcal{S}^1$ are tangent to the curve $\mathscr{C}^1$, and there are no $\mathfrak{A}_5$-orbits of length five in $\mathscr{C}^1 \cong \mathbb{P}^1$. Similarly, one has $S \neq \mathcal{S}^2$.

We claim that $S$ is not one of the two nodal surfaces $\mathcal{R}^1$ and $\mathcal{R}^2$ contained in the pencil $\mathcal{P}$. Indeed, suppose that $S = \mathcal{R}^1$. Since the singular locus of $\mathcal{R}^1$ is an $\mathfrak{A}_5$-orbit of length 10 by Lemma 3.13, we see that the lines $L_1, \ldots, L_5$ are contained in the smooth locus of $\mathcal{R}^1$ by Corollary 3.5. On the other hand, one has $\mathcal{L}^2 = -10$ by Lemma 3.4. This means that $\mathrm{rk}\,\mathrm{Pic}(S)^{\mathfrak{A}_5} \geqslant 2$, which is impossible by [6, Lemma 6.7.3(i),(ii)].

We see that the surface $S$ is different from $\mathcal{R}^1$. A similar argument shows that $S$ is different from $\mathcal{R}^2$. Hence, $S$ is smooth by Lemma 3.13.

Let us show that $S$ does not contain the lines $L_1', \ldots, L_5'$. Suppose that it does. By Lemma 3.4 one has

$$\mathcal{L} \cdot \mathcal{L} = \mathcal{L}' \cdot \mathcal{L}' = -10.$$

By [6, Lemma 6.7.1(i)], we have $\mathrm{rk}\,\mathrm{Pic}(S)^{\mathfrak{A}_5}=2$. Let $\Pi_S$ be the class of a plane section of $S$. Then the determinant of the matrix

$$\begin{pmatrix}\mathcal{L}\cdot\mathcal{L} & \mathcal{L}\cdot\mathcal{L}' & \Pi_S\cdot\mathcal{L}\\ \mathcal{L}\cdot\mathcal{L}' & \mathcal{L}'\cdot\mathcal{L}' & \Pi_S\cdot\mathcal{L}'\\ \Pi_S\cdot\mathcal{L} & \Pi_S\cdot\mathcal{L}' & \Pi_S\cdot\Pi_S\end{pmatrix}=\begin{pmatrix}-10 & 20 & 5\\ 20 & -10 & 5\\ 5 & 5 & 4\end{pmatrix}$$

must vanish. This is a contradiction, because it equals 12.

Applying similar arguments, we see that the lines $L_1',\ldots,L_5'$ are contained in a unique $\mathfrak{A}_5$-invariant quartic surface, this surface is smooth and does not contain the lines $L_1,\ldots,L_5$. □

*Remark* 3.15. One can use the properties of the pencil $\mathcal{P}$ to give an alternative proof of Lemma 3.7. Namely, we know from Lemma 3.14 that there are two (different) smooth $\mathfrak{A}_5$-invariant quartic surfaces $S$ and $S'$ containing the lines $L_1,\ldots,L_5$ and $L_1',\ldots,L_5'$, respectively. By Lemma 3.12, the base locus of the pencil $\mathcal{P}$ is an irreducible curve $B$ that contains a unique $\mathfrak{A}_5$-orbit $\Sigma$ of length 20. By Corollary 3.5, this implies that $\Sigma$ is contained in the union $L_1\cup\ldots\cup L_5$, because

$$B\cdot(L_1+\ldots+L_5)=20$$

on the surface $S$. Similarly, we see that $\Sigma$ is contained in $L_1'\cup\ldots\cup L_5'$. These facts together with Lemma 3.4 easily imply that the lines $L_1,\ldots,L_5$ and $L_1',\ldots,L_5'$ form a double five configuration.

Now we will obtain some restrictions on low degree $\mathfrak{A}_5$-invariant curves in $\mathbb{P}^3$.

**Lemma 3.16.** *Let $C$ be an irreducible $\mathfrak{A}_5$-invariant curve in $\mathbb{P}^3$ of degree $d\leqslant 10$. Denote by $g$ the genus of the normalization of the curve $C$. Then*

$$g\leqslant\frac{d^2}{8}+1-|\mathrm{Sing}(C)|.$$

*Proof.* Since $\mathbb{U}_4$ is an irreducible $2.\mathfrak{A}_5$-representation, the curve $C$ is not contained in a plane in $\mathbb{P}^3$. This implies that a stabilizer in $\mathfrak{A}_5$ of a general point of the curve $C$ is trivial. In particular, the $\mathfrak{A}_5$-orbit of a general point of $C$ has length $|\mathfrak{A}_5|=60$.

Let $S$ be a surface in the pencil $\mathcal{P}$ that passes through a general point of $C$. Then the curve $C$ is contained in $S$, because otherwise one would have

$$60\leqslant|S\cap C|\leqslant S\cdot C=4d\leqslant 40,$$

which is absurd. Since the assertion of the lemma clearly holds for the twisted cubic curves $\mathscr{C}^1$ and $\mathscr{C}^2$, we may assume that $C$ is different from these two curves.

Suppose that $S=\mathcal{S}^1$. Let us use the notation of the proof of Lemma 3.12. Denote by $\hat{C}$ the preimage of the curve $C$ via $\rho$. Then $\hat{C}$ is a divisor of bi-degree $(a,b)$ for some non-negative integers $a$ and $b$ such that $d=2a+b$. On the other hand, one has

$$|\hat{C}\cap\hat{\mathscr{C}}^1|\leqslant\hat{C}\cdot\hat{\mathscr{C}}^1=a+b\leqslant 2a+b=d\leqslant 10,$$

which is impossible, since the curve $\hat{\mathscr{C}}^1\cong\mathscr{C}^1\cong\mathbb{P}^1$ does not contain $\mathfrak{A}_5$-orbits of length less than 12.

We see that $S\neq\mathcal{S}^1$. Similarly, we see that $S\neq\mathcal{S}^2$. By Lemma 3.13, either $S$ is a smooth quartic $K3$ surface, or $S$ is one of the surfaces $\mathcal{R}^1$ and $\mathcal{R}^2$. Denote by $\Pi_S$ a plane section of $S$. Then

$$\det\begin{pmatrix} \Pi_S^2 & \Pi_S\cdot C \\ \Pi_S\cdot C & C^2 \end{pmatrix} = \det\begin{pmatrix} 4 & d \\ d & C^2 \end{pmatrix} = 4C^2 - d^2 \leqslant 0$$

by the Hodge index theorem.

Suppose that $C$ is contained in the smooth locus of the surface $S$. Denote by $p_a(C)$ the arithmetic genus of the curve $C$. Then

$$C^2 = 2p_a(C) - 2.$$

by the adjunction formula. Thus, we get

$$p_a(C) \leqslant \frac{d^2}{8} + 1.$$

Since $g \leqslant p_a(C) - |\mathrm{Sing}(C)|$, this implies the assertion of the lemma.

To complete the proof, we may assume that $C$ contains a singular point of the surface $S$. By Lemma 3.13, this means that either $S = \mathcal{R}^1$ or $S = \mathcal{R}^2$. The singularities of the surface $S$ are ordinary double points, and its singular locus is an $\mathfrak{A}_5$-orbit of length 10. In particular, the curve $C$ contains the whole singular locus of $S$. By [6, Theorem 6.7.1], one has $\mathrm{Pic}(S)^{\mathfrak{A}_5} \cong \mathbb{Z}$. Since $\Pi_S^2 = 4$ and the self-intersection of any Cartier divisor on the surface $S$ is even, we see that the group $\mathrm{Pic}(S)^{\mathfrak{A}_5}$ is generated by $\Pi_S$.

Suppose that $C$ is a Cartier divisor on $S$. Then either $C \sim \Pi_S$ or $C \sim 2\Pi_S$, because $d \leqslant 10$. Since the restriction map

$$H^0\big(\mathcal{O}_{\mathbb{P}^3}(n)\big) \to H^0\big(\mathcal{O}_S(n\Pi_S)\big)$$

is an isomorphism for $n \leqslant 3$, we conclude that there is an $\mathfrak{A}_5$-invariant quadric in $\mathbb{P}^3$. This is not the case by Lemma 3.3.

Therefore, we see that $C$ is not a Cartier divisor on $S$. Since $S$ has only ordinary double points, the divisor $2C$ is Cartier. Thus

$$2C \sim l\Pi_S,$$

for some odd positive integer $l$. Since

$$2d = 2C\cdot\Pi_S = l\Pi_S\cdot\Pi_S = 4l,$$

we see that $l = \frac{d}{2}$. In particular, $d$ is even and $l \leqslant 5$.

Let $\theta\colon \tilde{S} \to S$ be the minimal resolution of singularities of the surface $S$. Denote by $\tilde{C}$ the proper transform of the curve $C$ on the surface $\tilde{S}$, and denote by $\Theta_1, \ldots, \Theta_{10}$ the exceptional curves of $\theta$. Then

$$2\tilde{C} \sim \theta^*(l\Pi_S) - m\sum_{i=1}^{10}\Theta_i,$$

for some positive integer $m$. Moreover, $m$ is odd, because $C$ is not a Cartier divisor. We have

$$4\tilde{C}^2 = \Pi_S^2 l^2 - 20m^2 = 4l^2 - 20m^2,$$

which implies that $\tilde{C}^2 = l^2 - 5m^2$. Since $\tilde{C}^2$ is even, $m$ is odd and $l \leqslant 5$, we see that either $l = 3$ or $l = 5$.

Denote by $p_a(\tilde{C})$ the arithmetic genus of the curve $\tilde{C}$. Then

$$l^2 - 5m^2 = \tilde{C}^2 = 2p_a(\tilde{C}) - 2.$$

by the adjunction formula. In particular, we have

$$25-5m^2 \geqslant l^2-5m^2 \geqslant -2,$$

so that $l \in \{3,5\}$ and $m=1$. The latter means that $C$ is smooth at every point of $\mathrm{Sing}(S)$, so that

$$|\mathrm{Sing}(\tilde{C})| = |\mathrm{Sing}(C)|.$$

If $l=\frac{d}{2}=3$, then $p_a(\tilde{C})=3$. This gives

$$g \leqslant p_a(\tilde{C}) - |\mathrm{Sing}(\tilde{C})| = 3 - |\mathrm{Sing}(C)| \leqslant \frac{d^2}{8} + 1 - |\mathrm{Sing}(C)|.$$

Similarly, if $l=\frac{d}{2}=5$, then $p_a(\tilde{C})=11$. This gives

$$g \leqslant p_a(\tilde{C}) - |\mathrm{Sing}(\tilde{C})| = 11 - |\mathrm{Sing}(C)| \leqslant \frac{d^2}{8} + 1 - |\mathrm{Sing}(C)|.$$

□

Recall from [6, Lemma 5.4.1] that there exists a unique smooth irreducible curve of genus 4 with a faithful action of the group $\mathfrak{A}_5$. This curve is known as the Bring's curve. Its canonical model is a complete intersection of a quadric and a cubic in a three-dimensional projective space. However, this sextic curve does not appear in our $\mathbb{P}^3=\mathbb{P}(\mathbb{U}_4)$ by

**Lemma 3.17.** *Let $C$ be a smooth irreducible $\mathfrak{A}_5$-invariant curve in $\mathbb{P}^3$ of degree $d \leqslant 6$ and genus $g$. Then $g \neq 4$.*

*Proof.* Suppose that $g=4$. Denote by $\Pi_C$ the plane section of the curve $C$. Then

$$h^0(\mathcal{O}_C(\Pi_C)) = d-3+h^0(\mathcal{O}_C(K_C-\Pi_C))$$

by the Riemann–Roch theorem. Since $C$ is not contained in a plane, this implies that $\Pi_C \sim K_C$. Therefore, the projective space $\mathbb{P}^3$ is identified with a projectivization of an $\mathfrak{A}_5$-representation $H^0(\mathcal{O}_C(K_C))^\vee$, i.e. of a representation of the group $2.\mathfrak{A}_5$ where the center of $2.\mathfrak{A}_5$ acts trivially. The latter is not the case by construction of $\mathbb{U}_4$. □

**Lemma 3.18.** *Let $C$ be an irreducible smooth $\mathfrak{A}_5$-invariant curve in $\mathbb{P}^3$ of degree $d=10$ and genus $g$. Then $g \neq 10$.*

*Proof.* Suppose that $g=10$. By Lemma 3.12, the base locus of the pencil $\mathcal{P}$ is an irreducible curve $B$ of degree 16. In particular, there exists a surface $S \in \mathcal{P}$ that does not contain $C$. Thus, the intersection $S \cap C$ is an $\mathfrak{A}_5$-invariant set that consists of

$$C \cdot S = 4d = 40$$

points (counted with multiplicities). On the other hand, by [6, Lemma 5.1.5], any $\mathfrak{A}_5$-orbit in $C$ has length 12, 30, or 60. □

## 4. Large subgroups of $\mathfrak{S}_6$

In this section we collect some auxiliary results about the groups $\mathfrak{S}_6$, $\mathfrak{A}_6$ and $\mathfrak{S}_5$. We start with recalling some general properties of the group $\mathfrak{A}_6$.

*Remark* 4.1 (see e. g. [8, p. 4]). Let $\Gamma$ be a proper subgroup of $\mathfrak{A}_6$ such that the index of $\Gamma$ is at most 15. Then $\Gamma$ is isomorphic either to $\mathfrak{A}_5$, or to $F_{36}$, or to $\mathfrak{S}_4$. In particular, if $\mathfrak{A}_6$ acts transitively on the set of $r<15$ elements, then either $r=6$ or $r=10$.

We will need the following result about possible actions of the group $\mathfrak{A}_6$ on curves of small genera (cf. [5, Theorem 2.18] and [6, Lemma 5.1.5]).

**Lemma 4.2.** *Suppose that $C$ is a smooth irreducible curve of genus $g \leqslant 15$ with a non-trivial action of the group $\mathfrak{A}_6$. Then $g = 10$.*

*Proof.* Let $\Omega \subset C$ be an $\mathfrak{A}_6$-orbit. Then a stabilizer of a point in $\Omega$ is a cyclic subgroup of $\mathfrak{A}_6$, which implies that

$$|\Omega| \in \big\{72, 90, 120, 180, 360\big\}.$$

From the classification of finite subgroups of $\mathrm{Aut}(\mathbb{P}^1) \cong \mathrm{PGL}_2(\mathbb{C})$ we know that $g \neq 0$. Also, it follows from the non-solvability of the group $\mathfrak{A}_6$ that $g \neq 1$.

Put $\bar{C} = C/\mathfrak{A}_6$. Then $\bar{C}$ is a smooth curve. Let $\bar{g}$ be the genus of the curve $\bar{C}$. The Riemann–Hurwitz formula gives

$$2g - 2 = 360\big(2\bar{g} - 2\big) + 180a_{180} + 240a_{120} + 270a_{90} + 288a_{72},$$

where $a_k$ is the number of $\mathfrak{A}_6$-orbits in $C$ of length $k$.

Since $a_k \geqslant 0$ and $2 \leqslant g \leqslant 15$, one has $\bar{g} = 0$. Thus, we obtain

$$2g - 2 = -720 + 180a_{180} + 240a_{120} + 270a_{90} + 288a_{72}.$$

Going through the values $2 \leqslant g \leqslant 15$, and solving this equation case by case we see that the only possibility is $g = 10$. □

We proceed by recalling some general properties of the group $\mathfrak{S}_5$.

*Remark* 4.3 (see e. g. [8, p. 2]). Let $\Gamma$ be a proper subgroup of $\mathfrak{S}_5$ such that the index of $\Gamma$ is less than 12. Then $\Gamma$ is isomorphic either to $\mathfrak{A}_5$, or to $\mathfrak{S}_4$, or to $F_{20}$, or to $\mathfrak{A}_4$, or to $\mathrm{D}_{12}$. In particular, if $\mathfrak{S}_5$ acts transitively on the set of $r < 12$ elements, then $r \in \{2, 5, 6, 10\}$.

**Lemma 4.4.** *The group $\mathfrak{S}_5$ cannot act faithfully on a smooth irreducible curve of genus 5.*

*Proof.* Suppose that $C$ is a curve of genus 5 with a faithful action of $\mathfrak{S}_5$. Considering the action of the subgroup $\mathfrak{A}_5 \subset \mathfrak{S}_5$ on $C$ and applying [6, Lemma 5.4.3], we see that $C$ is hyperelliptic. This gives a natural homomorphism

$$\theta\colon \mathfrak{S}_5 \to \mathrm{Aut}(\mathbb{P}^1) \cong \mathrm{PGL}_2(\mathbb{C})$$

whose kernel is either trivial or isomorphic to $\boldsymbol{\mu}_2$. Thus $\theta$ is injective, which gives a contradiction. □

Now we will prove some auxiliary facts about actions of the groups $\mathfrak{S}_6$, $\mathfrak{A}_6$ and $\mathfrak{S}_5$ on the four-dimensional projective space.

*Remark* 4.5. The group $\mathfrak{S}_6$ has exactly four irreducible five-dimensional representations (see e. g. [8, p. 5]). Starting from one of them, one more can be obtained by a twist by an outer automorphism of $\mathfrak{S}_6$, and two remaining ones are obtained from these two by a tensor product with the sign representation. Although these four representations are not isomorphic, the images of $\mathfrak{S}_6$ in $\mathrm{PGL}_5(\mathbb{C})$ under them are the same. Every irreducible five-dimensional representation of $\mathfrak{S}_6$ restricts to an irreducible representation of the subgroup $\mathfrak{A}_6 \subset \mathfrak{S}_6$, and restricts to an irreducible representation of the *some* of the subgroups $\mathfrak{S}_5 \subset \mathfrak{S}_6$. The group $\mathfrak{A}_6$ has exactly two irreducible five-dimensional representations, each of them arising this way (see e. g. [8, p. 5]). Similarly, the group $\mathfrak{S}_5$ has exactly two irreducible five-dimensional representations, each of them arising this way (see e. g. [8, p. 2]). Note also that every five-dimensional representation of a group $\mathfrak{A}_6$ or $\mathfrak{S}_5$ that does not contain one-dimensional subrepresentations is irreducible.

Let $\mathbb{V}_5$ be an irreducible five-dimensional representation of the group $\mathfrak{S}_6$. Put $\mathbb{P}^4 = \mathbb{P}(\mathbb{V}_5)$. Keeping in mind Remark 4.5, we see that the image of the corresponding homomorphism $\mathfrak{S}_6$ to $\mathrm{PGL}_5(\mathbb{C})$ is the same for any choice of $\mathbb{V}_5$, and thus the $\mathfrak{S}_6$-orbits and $\mathfrak{S}_6$-invariant hypersurfaces in $\mathbb{P}^4$ do not depend on $\mathbb{V}_5$ either.

Remark 4.5 implies that there are six linear forms $x_0, \ldots, x_5$ on $\mathbb{P}^4$ that are permuted by the group $\mathfrak{S}_6$ (cf. Sections 1 and 2). Indeed, up to a twist by an outer automorphoism of $\mathfrak{S}_6$ and a tensor product with the sign representation, $\mathbb{V}_5$ is a subrepresentation of the six-dimensional representation $\mathbb{W}$ of $\mathfrak{S}_6$, so that one can take restricitions of the natural coordinates in $\mathbb{W}$ to be these linear forms. Let $Q$ be the three-dimensional quadric in $\mathbb{P}^4$ given by equation

$$x_0^2 + x_1^2 + x_2^2 + x_3^2 + x_4^2 + x_5^2 = 0. \tag{4.6}$$

The quadric $Q$ is smooth and $\mathfrak{S}_6$-invariant. Note also that equation (1.1) makes sense in our $\mathbb{P}^4$.

We will use the notation introduced above until the end of the paper.

**Lemma 4.7.** *Let $\Gamma$ be either the group $\mathfrak{S}_6$, or its subgroup $\mathfrak{A}_6$, or a subgroup $\mathfrak{S}_5$ of $\mathfrak{S}_6$ such that $\mathbb{V}_5$ is an irreducible representation of $\Gamma$. Then the only $\Gamma$-invariant quadric threefold in $\mathbb{P}^4$ is the quadric $Q$. Similarly, every (reduced) $\Gamma$-invariant quartic threefold in $\mathbb{P}^4$ is given by equation (1.1) for some $t \in \mathbb{C}$.*

*Proof.* Apply Corollary 2.5. □

By a small abuse of notation we will refer to the points in $\mathbb{P}^4$ using $x_i$ as if they were homogeneous coordinates, i.e. a point in $\mathbb{P}^4$ will be encoded by a ratio of six linear forms $x_i$. As in Section 1, let $\Sigma_6$ and $\Sigma_{10}$ are the $\mathfrak{S}_6$-orbits of the points $[-5 : 1 : 1 : 1 : 1 : 1]$ and $[-1 : -1 : -1 : 1 : 1 : 1]$, respectively. Looking at equation (4.6), we obtain

**Corollary 4.8.** *The quadric $Q$ does not contain the $\mathfrak{S}_6$-orbits $\Sigma_6$ and $\Sigma_{10}$.*

Now we will have a look at the action of the group $\mathfrak{A}_6$ on $\mathbb{P}^4$. Note that $\mathbb{V}_5$ is an irreducible $\mathfrak{A}_6$-representation by Remark 4.5.

**Lemma 4.9.** *There are no $\mathfrak{A}_6$-orbits of length less than six in $\mathbb{P}^4$. Moreover, the only $\mathfrak{A}_6$-orbit of length six in $\mathbb{P}^4$ is $\Sigma_6$.*

*Proof.* The only subgroup of $\mathfrak{A}_6$ of index less than six is $\mathfrak{A}_6$ itself (cf. Remark 4.1), so that the first assertion of the lemma follows from irreducibility of the $\mathfrak{A}_6$-representation $\mathbb{V}_5$. Also, the only subgroups of $\mathfrak{A}_6$ of index six are $\mathfrak{A}_5^{st}$ and $\mathfrak{A}_5^{nst}$, so that the second assertion of the lemma also follows from Corollary 2.3. □

**Lemma 4.10.** *Let $X$ be an $\mathfrak{A}_6$-invariant quartic threefold in $\mathbb{P}^4$ that contains an $\mathfrak{A}_6$-orbit of length at most six. Then $X = X_{\frac{7}{10}}$.*

*Proof.* By Lemma 4.7, one has $X = X_t$ for some $t \in \mathbb{C}$, and by Lemma 4.9 the $\mathfrak{A}_6$-orbit $\Sigma_6$ is contained in $X_t$. Since $\Sigma_6$ is not contained in the quadric $Q$ by Corollary 4.8, we see that there is a unique $t \in \mathbb{C}$ such that $\Sigma_6$ is contained in a quartic given by equation (1.1). Therefore, we conclude that $t = \frac{7}{10}$. □

Now we will make a couple of observations about the action of the group $\mathfrak{S}_5$ on $\mathbb{P}^4$. We choose $\mathfrak{S}_5$ to be a subgroup of $\mathfrak{S}_6$ such that $\mathbb{V}_5$ is an irreducible $\mathfrak{S}_5$-representation (cf. Remark 4.5 and Corollary 2.3).

**Lemma 4.11.** *Let $P \in \mathbb{P}^4$ be a point such that its stabilizer in $\mathfrak{S}_5$ contains a subgroup isomorphic to* $\mathrm{D}_{12}$*. Then the $\mathfrak{S}_5$-orbit of $P$ is $\Sigma_{10}$.*

*Proof.* By Corollary 2.3(iii), the point in $\mathbb{P}^4$ fixed by a subgroup $\mathrm{D}_{12} \subset \mathfrak{S}_5$ is unique. On the other hand, it is straightforward to check that a stabilizer in $\mathfrak{S}_5$ of a point of $\Sigma_{10}$ contains a subgroup isomorphic to $\mathrm{D}_{12}$. It remains to notice that the latter stabilizer is actually isomorphic to $\mathrm{D}_{12}$, since the only subgroups of $\mathfrak{S}_5$ that contain $\mathrm{D}_{12}$ are $\mathrm{D}_{12}$ and $\mathfrak{S}_5$ itself, while $\mathfrak{S}_5$ has no fixed points on $\mathbb{P}^4$. □

**Lemma 4.12.** *Let $X$ be an $\mathfrak{S}_5$-invariant quartic threefold in $\mathbb{P}^4$ that contains $\Sigma_{10}$. Then $X = X_{\frac{1}{6}}$.*

*Proof.* By Lemma 4.7, one has $X = X_t$ for some $t \in \mathbb{C}$. Since $\Sigma_{10}$ is not contained in the quadric $Q$ by Corollary 4.8, we see that there is a unique $t \in \mathbb{C}$ such that $\Sigma_{10}$ is contained in a quartic given by equation (1.1). Therefore, we conclude that $t = \frac{1}{6}$. □

## 5. Rationality of the quartic threefold $X_{\frac{7}{10}}$

In this section we will construct an explicit $\mathfrak{A}_6$-equivariant birational map $\mathbb{P}^3 \dashrightarrow X_{\frac{7}{10}}$. Implicitly, the construction of this map first appeared in the proof of [5, Theorem 1.20]. Here we will present a much simplified proof of its existence.

We identify $\mathbb{P}^3$ with the projectivization $\mathbb{P}(\mathbb{U}_4)$, where $\mathbb{U}_4$ is the restriction of the four-dimensional irreducible representation of the group $2.\mathfrak{S}_6$ introduced in Section 2 to the subgroup $2.\mathfrak{A}_6$. By Corollary 2.1(i), the $2.\mathfrak{A}_6$-representation $\mathbb{U}_4$ is irreducible.

**Lemma 5.1.** *There are no $\mathfrak{A}_6$-invariant surfaces of odd degree in $\mathbb{P}^3$, and no $\mathfrak{A}_6$-invariant pencils of surfaces of odd degree in $\mathbb{P}^3$. Moreover, there are no $\mathfrak{A}_6$-invariant quadric and quartic surfaces in $\mathbb{P}^3$.*

*Proof.* Recall that the only one-dimensional representation of the group $2.\mathfrak{A}_6$ is the trivial representation. Therefore, any $\mathfrak{A}_6$-invariant surface of odd degree $d$ in $\mathbb{P}^3$ gives rise to a trivial $2.\mathfrak{A}_6$-subrepresentation in $R_d = \mathrm{Sym}^d(\mathbb{U}_4)$. On the other hand, the non-trivial central element $z$ of $2.\mathfrak{A}_6$ acts on $R_d$ by a scalar matrix with diagonal entries equal to $-1$, which shows that $R_d$ does not contain trivial $2.\mathfrak{A}_6$-representations. Also, since the only two-dimensional representation of $2.\mathfrak{A}_6$ is the sum of two trivial representations, this implies that there are no $\mathfrak{A}_6$-invariant pencils of surfaces of odd degree in $\mathbb{P}^3$.

The last assertion of the lemma follows from Corollary 2.4(i),(ii). □

**Lemma 5.2.** *Let $\Omega$ be an $\mathfrak{A}_6$-orbit in $\mathbb{P}^3$. Then $|\Omega| \geqslant 16$.*

*Proof.* Lemma 5.1 implies that there are no $\mathfrak{A}_6$-orbits of odd length in $\mathbb{P}^3$. Thus, if $\Omega$ is an $\mathfrak{A}_6$-orbit in $\mathbb{P}^3$ of length at most 15, then by Remark 4.1 a stabilizer of its general point is isomorphic either to $\mathfrak{A}_5$ or to $F_{36}$. Both of these cases are impossible by Corollary 2.1. □

Actually, the minimal degree of an $\mathfrak{A}_6$-invariant surface in $\mathbb{P}^3$ equals 8 (see [5, Lemma 3.7]), and the minimal length of an $\mathfrak{A}_6$-orbit in $\mathbb{P}^3$ equals 36 (see [5, Lemma 3.8]), but we will not need this here.

**Lemma 5.3** (cf. [5, Lemma 4.26]). *Let $C$ be a smooth irreducible $\mathfrak{A}_6$-invariant curve of degree 9 and genus $g$ in $\mathbb{P}^3$. Then $g \neq 10$.*

*Proof.* Suppose that $g = 10$. Then it follows from [13, Example 6.4.3] that either $C$ is contained in a unique quadric surface in $\mathbb{P}^3$, or $C$ is a complete intersection of two cubic surfaces in $\mathbb{P}^3$. The former case is impossible, since there are no $\mathfrak{A}_6$-invariant quadrics in $\mathbb{P}^3$ by Lemma 5.1. The latter case is impossible, because there are no $\mathfrak{A}_6$-invariant pencils of cubic surfaces in $\mathbb{P}^3$ by Lemma 5.1. □

Recall that the group $\mathfrak{A}_6$ contains six standard subgroups isomorphic to $\mathfrak{A}_5$ and six non-standard subgroups isomorphic to $\mathfrak{A}_5$ (see the conventions made in Section 2). Denote the former ones by $H_1', \ldots, H_6'$, and denote the latter ones by $H_1, \ldots, H_6$. By Corollary 2.1(ii), each group $H_i'$ leaves invariant two lines $L_i^1$ and $L_i^2$ in $\mathbb{P}^3$. Note that each group $H_i$ permutes transitively the lines $L_1^1, \ldots, L_6^1$ (respectively, $L_1^2, \ldots, L_6^2$).

Put $\mathcal{L}^1 = L_1^1 + \ldots + L_6^1$ and $\mathcal{L}^2 = L_1^2 + \ldots + L_6^2$. Then the curves $\mathcal{L}^1$ and $\mathcal{L}^2$ are $\mathfrak{A}_6$-invariant, and the curve $\mathcal{L}^1 + \mathcal{L}^2$ is $\mathfrak{S}_6$-invariant.

**Lemma 5.4.** *The lines $L_1^1, \ldots, L_6^1$ (respectively, the lines $L_1^2, \ldots, L_6^2$) are pairwise disjoint. Moreover, the curves $\mathcal{L}^1$ and $\mathcal{L}^2$ are disjoint.*

*Proof.* We use an argument similar to one in the proof of Lemma 3.4. Suppose that some of the lines $L_1^1, \ldots, L_6^1$ have a common point. Since the action of $\mathfrak{A}_6$ on the set $\{L_1^1, \ldots, L_6^1\}$ is doubly transitive, this implies that any two of the lines $L_1^1, \ldots, L_6^1$ have a common point. Therefore, either all lines $L_1^1, \ldots, L_6^1$ are coplanar, or all of them pass through one point. Both of these cases are impossible since $\mathbb{U}_4$ is an irreducible $2.\mathfrak{A}_6$-representation (see Corollary 2.1(i)). Therefore, the lines $L_1^1, \ldots, L_6^1$ are pairwise disjoint. A similar argument applies to the lines $L_1^2, \ldots, L_6^2$.

Suppose that some of the lines $L_1^1, \ldots, L_6^1$, say, $L_1^1$, intersects some of the lines $L_1^2, \ldots, L_6^2$. Since the lines $L_1^1$ and $L_2^1$ are disjoint by construction, we may assume that $L_1^1$ intersects $L_2^2$. Since the stabilizer $H_1' \subset \mathfrak{A}_6$ of $L_1^1$ acts transitively on the lines $L_2^2, \ldots, L_6^2$, we conclude that all five lines $L_2^2, \ldots, L_6^2$ intersect $L_1^1$. Therefore, the line $L_1^1$ contains a subset of at most five points that is invariant with respect to the group $H_1' \cong \mathfrak{A}_5$, which is a contradiction. Thus, $\mathcal{L}^1$ and $\mathcal{L}^2$ are disjoint. □

**Lemma 5.5.** *Let $C$ be an $\mathfrak{A}_6$-invariant curve in $\mathbb{P}^3$ of degree $d \leqslant 10$. Then either $C = \mathcal{L}^1$ or $C = \mathcal{L}^2$.*

*Proof.* Suppose first that $C$ is reducible. We may assume that $\mathfrak{A}_6$ permutes the irreducible components of $C$ transitively. Thus, $C$ has either 6 or 10 irreducible components by Remark 4.1, and these irreducible components are lines. By Remark 4.1 and Corollary 2.1 the latter case is impossible, and in the former case one has either $C = \mathcal{L}^1$ or $C = \mathcal{L}^2$.

Therefore, we assume that the curve $C$ is irreducible. Let $g$ be the genus of the normalization of the curve $C$. We have

$$g \leqslant \frac{d^2}{8} + 1 - |\mathrm{Sing}(C)| \leqslant 13 - |\mathrm{Sing}(C)| \tag{5.6}$$

by Lemma 3.16. This implies that the curve $C$ is smooth, because $\mathbb{P}^3$ does not contain $\mathfrak{A}_6$-orbits of length less than 16 by Lemma 5.2.

If $d \leqslant 8$, then (5.6) gives $g \leqslant 9$. This is impossible by Lemma 4.2

If $d = 9$, then (5.6) gives $g \leqslant 11$, so that $g = 10$ by Lemma 4.2. This is impossible by Lemma 5.3.

Therefore, we see that $d = 10$. Thus, (5.6) gives $g \leqslant 13$, so that $g = 10$ by Lemma 4.2. The latter is impossible by Lemma 3.18. □

Denote by $\mathcal{M}$ the linear system on $\mathbb{P}^3$ consisting of all quartic surfaces passing through the lines $L_1^1, \ldots, L_6^1$. Then $\mathcal{M}$ is not empty. In fact, its dimension is at least four by parameter count. Moreover, the linear system $\mathcal{M}$ does not have base components by Lemma 5.1.

**Lemma 5.7.** *The base locus of $\mathcal{M}$ does not contain curves except the lines $L_1^1, \ldots, L_6^1$. Moreover, a general surface in $\mathcal{M}$ is smooth at a general point of each of the lines $L_1^1, \ldots, L_6^1$.*

*Proof.* Denote by $Z$ the union of the curves that are contained in the base locus of $\mathcal{M}$ and are different from the lines $L_1^1, \ldots, L_6^1$. Then $Z$ is a (possibly empty) $\mathfrak{A}_6$-invariant curve. Denote its degree by $d$. Pick two general surfaces $M_1$ and $M_2$ in $\mathcal{M}$. Then

$$M_1 \cdot M_2 = Z + m\mathcal{L}^1 + \Delta,$$

where $m$ is a positive integer, and $\Delta$ is an effective one-cycle on $\mathbb{P}^3$ that contains none of the lines $L_1^1, \ldots, L_6^1$. Note that $\Delta$ may contain irreducible components of the curve $Z$. Let $\Pi$ be a plane in $\mathbb{P}^3$. Then

$$16 = \Pi \cdot M_1 \cdot M_2 = \Pi \cdot Z + m\Pi \cdot \mathcal{L}^1 + \Pi \cdot \Delta = d + 6m + \Pi \cdot \Delta \leqslant d + 6m,$$

which implies that $m \leqslant 2$ and $d \leqslant 10$. By Lemma 5.5, we have $d = 0$, so that $Z$ is empty. Since

$$2 \geqslant m \geqslant \mathrm{mult}_{L_i^1}(M_1)\mathrm{mult}_{L_i^1}(M_2),$$

we see that a general surface in $\mathcal{M}$ is smooth at a general point of $L_i^1$. □

Let $\alpha\colon U \to \mathbb{P}^3$ be a blow up along the lines $L_1^1, \ldots, L_6^1$. Then $-K_U^3 = 4$, and the action of $\mathfrak{A}_6$ lifts to $U$. Denote by $E_1, \ldots, E_6$ the $\alpha$-exceptional surfaces that are mapped to $L_1^1, \ldots, L_6^1$, respectively.

**Lemma 5.8.** *The action of the stabilizer $H_i' \cong \mathfrak{A}_5$ in $\mathfrak{A}_6$ of the line $L_i^1$ on the surface $E_i \cong \mathbb{P}^1 \times \mathbb{P}^1$ is twisted diagonal, i.e., $E_i$ is identified with $\mathbb{P}(\mathbb{U}_2) \times \mathbb{P}(\mathbb{U}_2')$, where $\mathbb{U}_2$ and $\mathbb{U}_2'$ are different two-dimensional irreducible representations of the group $2.\mathfrak{A}_5$.*

*Proof.* This follows from Corollary 2.1(ii). □

Let us denote by $\mathcal{M}_U$ the proper transform of the linear system $\mathcal{M}$ on the threefold $U$. Then $\mathcal{M}_U \sim -K_U$ by Lemma 5.7.

**Lemma 5.9.** *The linear system $\mathcal{M}_U$ is base point free.*

*Proof.* Let us first show that $\mathcal{M}_U$ is free from base curves. Suppose that the base locus of the linear system $\mathcal{M}_U$ contains some curves. Then each of these curves is contained in some of the $\alpha$-exceptional surfaces by Lemma 5.7. Denote by $Z$ the union of all such curves that are contained in $E_1$. Then $Z$ is an $H_1'$-invariant curve. For some non-negative integers $a$ and $b$, one has

$$Z \sim as + bl,$$

where $s$ is a section of the natural projection $E_1 \to L_1^1$ such that $s^2 = 0$ on $E_1$, and $l$ is a fiber of this projection. On the other hand, we have

$$\mathcal{M}_U|_{E_1} \sim -K_U|_{E_1} \sim s + 3l.$$

This gives $a \leqslant 1$ and $b \leqslant 3$. Since the action of $H_1'$ on the surface $E_1$ is twisted diagonal by Lemma 5.8, the latter is impossible by [6, Lemma 6.4.2(i)] and [6, Lemma 6.4.11(o)].

We see that $\mathcal{M}_U$ is free from base curves. Since $\mathcal{M}_U \sim -K_U$, the linear system $\mathcal{M}_U$ cannot have more than $-K_U^3 = 4$ base points. By Lemma 5.2, this implies that $\mathcal{M}_U$ is base point free. □

**Corollary 5.10.** *The base locus of the linear system $\mathcal{M}$ consists of the lines $L_1^1, \ldots, L_6^1$.*

By Lemma 5.9, the divisor $-K_U$ is nef. Since $-K_U^3 = 4$, it is also big. Thus, we have

$$h^1\Big(\mathcal{O}_U\big(-K_U\big)\Big) = h^2\Big(\mathcal{O}_U\big(-K_U\big)\Big) = 0$$

by the Kawamata–Viehweg vanishing theorem (see [17]). Hence, the Riemann–Roch formula gives

$$h^0(\mathcal{O}_U(-K_U)) = 5. \tag{5.11}$$

In particular, we see that $|-K_U| = \mathcal{M}_U$.

**Lemma 5.12.** *The $\mathfrak{A}_6$-representation $H^0(\mathcal{O}_U(-K_U))$ is irreducible.*

*Proof.* By Lemma 5.1, there are no $\mathfrak{A}_6$-invariant quartic surfaces in $\mathbb{P}^3$. This implies that $H^0(\mathcal{O}_U(-K_U))$ does not contain one-dimensional subrepresentations. Hence it is irreducible by Remark 4.5. □

Lemma 5.9 together with (5.11) implies that there is an $\mathfrak{A}_6$-equivariant commutative diagram

$$\begin{array}{ccc} & U & \\ {\scriptstyle\alpha}\swarrow & & \searrow{\scriptstyle\beta} \\ \mathbb{P}^3 & \overset{\phi}{\dashrightarrow} & \mathbb{P}^4, \end{array} \tag{5.13}$$

where $\phi$ is a rational map given by $\mathcal{M}$, and $\beta$ is a morphism given by the anticanonical linear system $|-K_U|$. By Lemma 5.12 the projective space $\mathbb{P}^4$ in (5.13) is a projectivization of an irreducible $\mathfrak{A}_6$-representation.

Recall from Lemma 3.8 that $\mathbb{P}^3$ contains exactly two $H_1$-invariant twisted cubic curves $\mathscr{C}_1^1$ and $\mathscr{C}_1^2$.

**Lemma 5.14.** *The curve $\mathcal{L}^1$ intersects exactly one curve among $\mathscr{C}_1^1$ and $\mathscr{C}_1^2$. Moreover, each line among $L_1^1, \ldots, L_6^1$ contains two points of this intersection. Similarly, the curve $\mathcal{L}^2$ intersects exactly one curve among $\mathscr{C}_1^1$ and $\mathscr{C}_1^2$, and this curve is different from the one that intersects $\mathcal{L}^1$.*

*Proof.* By Remark 3.1, the stabilizer in $H_1$ of the curve $L_1^1$ is isomorphic to $\mathrm{D}_{10}$, and thus it has an orbit of length 2 on $L_1^1$. Thus, the curve $\mathcal{L}^1$ contains an $H_1$-orbit $\Sigma_{12}^1$ of length 12 by Lemma 3.2. Similarly, the curve $\mathcal{L}^2$ contains an $H_1$-orbit $\Sigma_{12}^2$ of length 12. By Lemma 5.4, one has $\Sigma_{12}^1 \neq \Sigma_{12}^2$. Moreover, $\Sigma_{12}^1$ and $\Sigma_{12}^2$ are the only $H_1$-orbits in $\mathbb{P}^3$ of length 12 by Lemma 3.2. Since $\mathscr{C}_1^1$ and $\mathscr{C}_1^2$ are disjoint by Remark 3.10, and each of them contains an $H_1$-orbit of length 12, we see that either $\Sigma_{12}^1 \subset \mathscr{C}_1^1$ and $\Sigma_{12}^2 \subset \mathscr{C}_1^2$, or $\Sigma_{12}^2 \subset \mathscr{C}_1^1$ and $\Sigma_{12}^1 \subset \mathscr{C}_1^2$. Since a line cannot have more than two common points with a twisted cubic, this also implies the last assertion of the lemma. □

Without loss of generality, we may assume that the curve $\mathcal{L}^1$ intersects $\mathscr{C}_1^1$, and the curve $\mathcal{L}^2$ intersects $\mathscr{C}_1^2$. Let $\mathscr{C}_1^1, \ldots, \mathscr{C}_6^1$ be the $\mathfrak{A}_6$-orbit of the curve $\mathscr{C}_1^1$, and let $\mathscr{C}_1^2, \ldots, \mathscr{C}_6^2$ be the $\mathfrak{A}_6$-orbit of the curve $\mathscr{C}_1^2$. By Lemma 3.8, the curves $\mathscr{C}_i^1$ and $\mathscr{C}_i^2$ are the only twisted cubic curves in $\mathbb{P}^3$ that are $H_i$-invariant. By Lemma 5.14, we have

**Corollary 5.15.** *Every twisted cubic curve $\mathscr{C}_i^1$ intersects each line among $L_1^1, \ldots, L_6^1$ by two points. Similarly, every twisted cubic curve $\mathscr{C}_i^2$ intersects each line among $L_1^2, \ldots, L_6^2$ by two points.*

Denote by $\widetilde{\mathscr{C}}_1^1, \ldots, \widetilde{\mathscr{C}}_6^1$ the proper transforms on $U$ of the curves $\mathscr{C}_1^1, \ldots, \mathscr{C}_6^1$, respectively.

**Lemma 5.16.** *One has $-K_U \cdot \widetilde{\mathscr{C}}_1^1 = \ldots = -K_U \cdot \widetilde{\mathscr{C}}_6^1 = 0$.*

*Proof.* This follows from Corollary 5.15. □

We see that each curve $\widetilde{\mathscr{C}}_i^1$ is contracted by $\beta$ to a point. Since the $\mathfrak{A}_6$-orbit of $\widetilde{\mathscr{C}}_1^1$ consists of six curves, we also obtain the following.

**Corollary 5.17.** *The image of the morphism $\beta$ contains an $\mathfrak{A}_6$-orbit of length at most six.*

Since $-K_U^3 = 4$, the image of $\beta$ is either an $\mathfrak{A}_6$-invariant quartic threefold or an $\mathfrak{A}_6$-invariant quadric threefold. Using results of [24], one can show that the latter case is impossible. However, this immediately follows from Corollary 5.17. Indeed, an $\mathfrak{A}_6$-orbit of length at most six cannot be contained in the $\mathfrak{A}_6$-invariant quadric by Corollary 4.8 and Lemma 4.9.

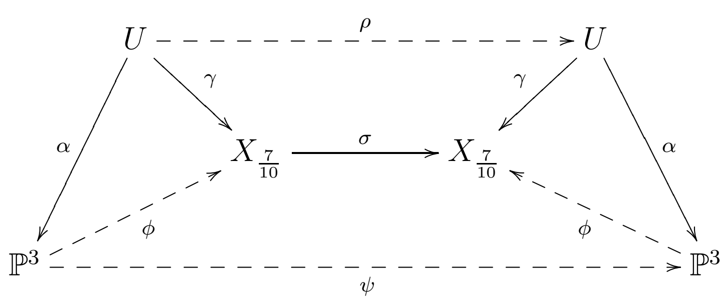
**Corollary 5.18.** *The morphism $\beta$ is birational onto its image, and its image is a quartic threefold.*

Now Lemma 4.10 implies that the image of $\beta$ is the quartic $X_{\frac{7}{10}}$. This proves

**Corollary 5.19.** *The threefold $X_{\frac{7}{10}}$ is rational.*

Let us conclude this section by recalling two related results proved in [5, §4]. The commutative diagram (5.13) can be extended to an $\mathfrak{A}_6$-equivariant commutative diagram

(5.20)



Here $\sigma$ is an automorphism of the quartic threefold $X_{\frac{7}{10}}$ given by an odd permutation in $\mathfrak{S}_6$ acting on $\mathbb{P}^4$, cf. Remark 4.5. The birational map $\rho$ is a composition of Atiyah flops in 36 curves contracted by $\gamma$, and the birational map $\psi$ is not regular.

The diagram (5.20) is a so-called $\mathfrak{A}_6$-Sarkisov link. The subgroup $\mathfrak{A}_6 \subset \mathrm{Aut}(\mathbb{P}^3)$ together with $\psi \in \mathrm{Bir}^{\mathfrak{A}_6}(\mathbb{P}^3)$ generates a subgroup isomorphic to $\mathfrak{S}_6$. Moreover, the subgroup

$$\mathrm{Aut}^{\mathfrak{A}_6}(\mathbb{P}^3) \subset \mathrm{Bir}^{\mathfrak{A}_6}(\mathbb{P}^3)$$

is also isomorphic to $\mathfrak{S}_6$. By [5, Theorem 1.24], the whole group $\mathrm{Bir}^{\mathfrak{A}_6}(\mathbb{P}^3)$ is a free product of these two copies of $\mathfrak{S}_6$ amalgamated over the original $\mathfrak{A}_6$.

## 6. Rationality of the quartic threefold $X_{\frac{1}{6}}$

In this section we will construct an explicit $\mathfrak{S}_5$-equivariant birational map $\mathbb{P}^3 \dashrightarrow X_{\frac{1}{6}}$. We identify $\mathbb{P}^3$ with the projectivization $\mathbb{P}(\mathbb{U}_4)$, where $\mathbb{U}_4$ is the restriction of the four-dimensional irreducible representation of the group $2.\mathfrak{S}_6$ introduced in Section 2 to a subgroup $2.\mathfrak{S}_5^{nst}$, and denote the latter subgroup simply by $2.\mathfrak{S}_5$. By Corollary 2.1(i), the $2.\mathfrak{S}_5$-representation $\mathbb{U}_4$ is irreducible.

**Lemma 6.1.** *Let $\Omega$ be an $\mathfrak{S}_5$-orbit in $\mathbb{P}^3$. Then $|\Omega| \geqslant 12$.*

*Proof.* Apply Remark 4.3 together with Corollary 2.1. ☐

**Lemma 6.2.** *Let $C$ be an $\mathfrak{S}_5$-invariant curve in $\mathbb{P}^3$ of degree $d$. Then $d \geqslant 6$.*

*Proof.* Suppose that $d \leqslant 5$. To start with, assume that $C$ is reducible and denote by $r$ the number of its irreducible components. We may assume that $\mathfrak{S}_5$ permutes the irreducible components of $C$ transitively. Thus, either $r = 2$ or $r = 5$ by Remark 4.3. If $r = 5$, the irreducible components of $C$ are lines, so that this case is impossible by Remark 4.3 and Corollary 2.1(i). Hence, we have $r = 2$, and the stabilizer of each of the two irreducible components $C_1$ and $C_2$ of $C$ is the subgroup $\mathfrak{A}_5 \subset \mathfrak{S}_5$. Moreover, in this case one has

$$\deg(C_1) = \deg(C_2) \leqslant 2,$$

which is impossible by Lemma 3.8.

Therefore, we assume that the curve $C$ is irreducible. Let $g$ be the genus of the normalization of the curve $C$. Then

$$g \leqslant \frac{d^2}{8} + 1 - |\mathrm{Sing}(C)|$$

by Lemma 3.16, so that $g \leqslant 5 - |\mathrm{Sing}(C)|$. This implies that $C$ is smooth, because there are no $\mathfrak{S}_5$-orbits of length less than 12 by Lemma 6.1.

Since $\mathfrak{S}_5$ does not act faithfully on $\mathbb{P}^1$, we see that $g \neq 0$. Thus, either $g = 4$ or $g = 5$ by [6, Lemma 5.1.5]. The former case is impossible by Lemma 3.17, while the latter case is impossible by Lemma 4.4. ☐

Recall from Section 3 that the subgroup $\mathfrak{A}_4 \subset \mathfrak{A}_5 \subset \mathfrak{S}_5$ fixes two disjoint lines $L_1$ and $L_1'$. As before, we consider the $\mathfrak{A}_5$-orbit $L_1, \ldots, L_5$ of the line $L_1$ and the $\mathfrak{A}_5$-orbit $L_1', \ldots, L_5'$ of the line $L_1'$. By Lemma 3.7 the lines $L_1, \ldots, L_5, L_1', \ldots, L_5'$ form a double five configuration (see Definition 3.6). Corollary 2.1(i) implies that the $\mathfrak{S}_5$-orbit of the line $L_1$ is $L_1, \ldots, L_5, L_1', \ldots, L_5'$.

*Remark* 6.3. Any subgroup $F_{20} \subset \mathfrak{S}_5$ permutes the ten lines $L_1, \ldots, L_5, L_1', \ldots, L_5'$ transitively. Indeed, let $c \in F_{20}$ be an element of order five. Then $c$ is not contained in a stabilizer of the line $L_1$, so that the orbit of $L_1$ with respect to the group $\Gamma \cong \boldsymbol{\mu}_5$ generated by $c$ is $L_1, \ldots, L_5$. Similarly, the $\Gamma$-orbit of the line $L_1'$ is $L_1', \ldots, L_5'$. Also, the group $F_{20}$ is not contained in $\mathfrak{A}_5$, so that the $F_{20}$-orbit of $L_1$ contains some of the lines $L_1', \ldots, L_5'$, and thus contains all the ten lines $L_1, \ldots, L_5, L_1', \ldots, L_5'$.

Let $\mathcal{M}$ be the linear system on $\mathbb{P}^3$ consisting of all quartic surfaces passing through all lines $L_1, \ldots, L_5$ and $L'_1, \ldots, L'_5$. Then $\mathcal{M}$ is not empty. In fact, Lemma 3.7 and parameter count imply that its dimension is at least four. Moreover, the linear system $\mathcal{M}$ does not have base components by Lemma 3.3.

**Lemma 6.4.** *The base locus of $\mathcal{M}$ does not contain curves that are different from the lines $L_1, \ldots, L_5, L'_1, \ldots, L'_5$. Moreover, general surface in $\mathcal{M}$ is smooth in a general point of each of these lines. Furthermore, two general surfaces in $\mathcal{M}$ intersect transversally at a general point of each of these lines.*

*Proof.* Denote by $Z$ the union of all curves that are contained in the base locus of the linear system $\mathcal{M}$ and are different from the lines $L_1, \ldots, L_5, L'_1, \ldots, L'_5$. Then $Z$ is a (possibly empty) $\mathfrak{S}_5$-invariant curve. Denote its degree by $d$. Pick two general surfaces $M_1$ and $M_2$ in $\mathcal{M}$. Then

$$M_1 \cdot M_2 = Z + m\sum_{i=1}^{5} L_i + m\sum_{i=1}^{5} L'_i + \Delta,$$

where $m$ is a positive integer, and $\Delta$ is an effective one-cycle on $\mathbb{P}^3$ that contains none of the lines $L_1, \ldots, L_5$ and $L'_1, \ldots, L'_5$. Note that $\Delta$ may contain irreducible components of the curve $Z$. Note also that $\Delta \neq 0$, because $\mathcal{M}$ is not a pencil.

Let $\Pi$ be a plane in $\mathbb{P}^3$. Then

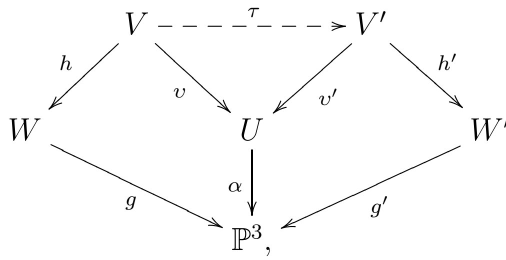
$$16 = \Pi \cdot Z + m\sum_{i=1}^{5} \Pi \cdot L_i + m\sum_{i=1}^{5} \Pi \cdot L'_i + \Pi \cdot \Delta = d + 10m + \Pi \cdot \Delta > d + 10m,$$

which implies that $m = 1$ and $d \leqslant 5$. By Lemma 6.2, we have $d = 0$, so that $Z$ is empty. Since

$$1 \geqslant m \geqslant \mathrm{mult}_{L_i}\big(M_1 \cdot M_2\big) \geqslant \mathrm{mult}_{L_i}\big(M_1\big)\mathrm{mult}_{L_i}\big(M_2\big),$$

we see that a general surface in $\mathcal{M}$ is smooth at a general point of $L_i$, and two general surfaces in $\mathcal{M}$ intersect transversally at a general point of $L_i$. Similarly, we see that a general surface in $\mathcal{M}$ is smooth at a general point of $L'_i$, and two general surfaces in $\mathcal{M}$ intersect transversally at a general point of $L'_i$. □

Let $g\colon W \to \mathbb{P}^3$ be a blow up along the lines $L_1, \ldots, L_5$, and let $g'\colon W' \to \mathbb{P}^3$ be a blow up along the lines $L'_1, \ldots, L'_5$, Denote by $\widetilde{L}'_1, \ldots, \widetilde{L}'_5$ (respectively, $\widetilde{L}_1, \ldots, \widetilde{L}_5$) the proper transforms of the lines $L'_1, \ldots, L'_5$ on the threefold $W$ (respectively, on the threefold $W'$). Let $h\colon V \to W$ be a blow up along the curves $\widetilde{L}'_1, \ldots, \widetilde{L}'_5$, and let $h'\colon V' \to W'$ be a blow up along the curves $\widetilde{L}_1, \ldots, \widetilde{L}_5$. Finally, let $\alpha\colon U \to \mathbb{P}^3$ be a blow up of the (singular) curve that is a union of all lines $L_1, \ldots, L_5, L'_1, \ldots, L'_5$. Then $U$ has twenty nodes by Lemma 3.7, and there exists a commutative diagram



where $\upsilon$ and $\upsilon'$ are small resolutions of singularities of the threefold $U$, and $\tau$ is a composition of twenty Atiyah flops.

*Remark* 6.5. By construction, the action of group $\mathfrak{A}_5$ lifts to the threefolds $W$, $W'$, $V$, $V'$, and $U$. Similarly, the action of the group $\mathfrak{S}_5$ lifts to the threefold $U$, but this action does not lift to $W$ and $W'$. On the threefolds $V$ and $V'$, the group $\mathfrak{S}_5$ acts biregularly outside of the curves flopped by $\tau$ and $\tau^{-1}$, respectively.

Denote by $E_1, \ldots, E_5$ the $g$-exceptional surfaces that are mapped to $L_1, \ldots, L_5$, respectively. Similarly, denote by $E_1', \ldots, E_5'$ the $g'$-exceptional surfaces that are mapped to $L_1', \ldots, L_5'$, respectively. Then all surfaces $E_1, \ldots, E_5, E_1', \ldots, E_5'$ are isomorphic to $\mathbb{P}^1 \times \mathbb{P}^1$.

Denote by $\hat{E}_1', \ldots, \hat{E}_5'$ the $h$-exceptional surfaces that are mapped to the curves $\widetilde{L}_1', \ldots, \widetilde{L}_5'$, respectively. Similarly, denote by $\check{E}_1, \ldots, \check{E}_5$ the $h'$-exceptional surfaces that are mapped to the curves $\widetilde{L}_1, \ldots, \widetilde{L}_5$, respectively. Denote by $\hat{E}_1, \ldots, \hat{E}_5$ the proper transforms on $V$ of the surfaces $E_1, \ldots, E_5$, respectively. Finally, denote by $\check{E}_1', \ldots, \check{E}_5'$ the proper transforms on $V'$ of the surfaces $E_1', \ldots, E_5'$, respectively. Then $\tau$ maps the surfaces $\hat{E}_1, \ldots, \hat{E}_5$ to the surfaces $\check{E}_1, \ldots, \check{E}_5$, respectively, and it maps the surfaces $\hat{E}_1', \ldots, \hat{E}_5'$ to the surfaces $\check{E}_1', \ldots, \check{E}_5'$, respectively.

Denote by $\mathcal{M}_W$, $\mathcal{M}_V$, $\mathcal{M}_{W'}$, $\mathcal{M}_{V'}$, and $\mathcal{M}_U$ the proper transforms of the linear system $\mathcal{M}$ on the threefolds $W$, $V$, $W'$, $V'$, and $U$, respectively. Then it follows from Lemma 6.4 that

$$\mathcal{M}_W \sim -K_W, \quad \mathcal{M}_V \sim -K_V, \quad \mathcal{M}_{W'} \sim -K_{W'}, \quad \mathcal{M}_{V'} \sim -K_{V'},$$

and $\mathcal{M}_U \sim -K_U$.

**Lemma 6.6.** *The base locus of the linear system $\mathcal{M}_W$ does not contain curves that are different from the curves $\widetilde{L}_1', \ldots, \widetilde{L}_5'$. Similarly, the base locus of $\mathcal{M}_{W'}$ does not contain curves that are different from the curves $\widetilde{L}_1, \ldots, \widetilde{L}_5$.*

*Proof.* It is enough to prove the first assertion of the lemma. Suppose that the base locus of the linear system $\mathcal{M}_W$ contains an irreducible curve $Z$ that is different from the curves $\widetilde{L}_1', \ldots, \widetilde{L}_5'$. Then $Z$ is contained in one of the surfaces $E_1, \ldots, E_5$ by Lemma 6.4.

By Lemma 6.4, the curve $Z$ is a fiber of some of the natural projections $E_i \to L_i$, because otherwise two general surfaces in $\mathcal{M}_W$ would be tangent in a general point of $L_i$. In particular, the only curves in the base locus of the linear system $\mathcal{M}_W$ are $\widetilde{L}_i'$ and possibly some fibers of the projections $E_i \to L_i$. This shows that $-K_W$ is nef. Indeed, $-K_W$ has positive intersections with the fibers of the projections $E_i \to L_i$, it has trivial intersection with all curves $\widetilde{L}_1', \ldots, \widetilde{L}_5'$, and $-K_W \sim \mathcal{M}_W$ has non-negative intersection with any other curve.

Let $Z_1 = Z, Z_2, \ldots, Z_r$ be the $\mathfrak{A}_5$-orbit of the curve $Z$. Then $r \geqslant 20$ by Corollary 3.5. Pick two general surfaces $M_1$ and $M_2$ in the linear system $\mathcal{M}_W$. By Lemma 6.4, one has

$$M_1 \cdot M_2 = \sum_{i=1}^{5} \widetilde{L}_i' + m \sum_{i=1}^{r} Z_i + \Delta$$

for some positive integer $m$ and some effective one-cycle $\Delta$ whose support contains none of the curves $\widetilde{L}_1',\ldots,\widetilde{L}_5'$ and $Z_1,\ldots,Z_r$. Hence

$$14=-K_W^3=-K_W\cdot M_1\cdot M_2=-K_W\cdot\Big(\sum_{i=1}^{5}\widetilde{L}_i'+m\sum_{i=1}^{r}Z_i+\Delta\Big)=$$
$$=-5K_W\cdot\widetilde{L}_1'-mrK_W\cdot Z-K_W\cdot\Delta=mr-K_W\cdot\Delta\geqslant mr\geqslant r\geqslant 20,$$

which is absurd. □

**Lemma 6.7.** *The linear system $\mathcal{M}_V$ is base point free.*

*Proof.* It is enough to show that $\mathcal{M}_V$ is free from base curves. Indeed, if the base locus of the linear system $\mathcal{M}_V$ does not contain base curves, then $\mathcal{M}_V$ cannot have more than $-K_V^3=4$ base points, because $\mathcal{M}_V\sim -K_V$. On the other hand, $V$ does not contain $\mathfrak{S}_5$-orbits of length less than 12, because there are no $\mathfrak{S}_5$-orbits of such length on $\mathbb{P}^3$ by Lemma 6.1.

Suppose that the base locus of the linear system $\mathcal{M}_V$ contains an irreducible curve $Z$. If $Z$ is not contained in any of the surfaces $\hat{E}_1',\ldots,\hat{E}_5'$, then the curve $h(Z)$ is a base curve of the linear system $\mathcal{M}_W$ and $h(Z)$ is different from the curves $\widetilde{L}_1',\ldots,\widetilde{L}_5'$. This is impossible by Lemma 6.6. Similarly, if $Z$ is not contained in any of the surfaces $\hat{E}_1,\ldots,\hat{E}_5$, then the curve $h'\circ\tau(Z)$ is a base curve of the linear system $\mathcal{M}_{W'}$ that is different from the curves $\widetilde{L}_1,\ldots,\widetilde{L}_5$. This is again impossible by Lemma 6.6. Thus, $Z$ is contained in one of the surfaces $\hat{E}_1,\ldots,\hat{E}_5$, and in one of the surfaces $\hat{E}_1',\ldots,\hat{E}_5'$. In particular, the curves flopped by $\tau$ are not contained in the base locus of $\mathcal{M}_V$.

Without loss of generality, we may assume that $Z=\hat{E}_1\cap\hat{E}_2'$. Let $C$ be the curve flopped by $\tau$ that is contained in $\hat{E}_1$ and intersects $\hat{E}_2'$. Then $C$ intersects $Z$ by one point. On the other hand, we have $-K_V\cdot C=0$. Since $\mathcal{M}_V\sim -K_V$, this implies that $C$ is disjoint from a general surface in $\mathcal{M}_V$. This is impossible, because $C\cap Z\neq\varnothing$, while $Z$ is contained in the base locus of the linear system $\mathcal{M}_V$. □

**Corollary 6.8.** *The linear systems $\mathcal{M}_{V'}$, and $\mathcal{M}_U$ are also base point free.*

*Proof.* Recall that $\mathcal{M}_V\sim -K_V$. Thus, the general surface of $\mathcal{M}_V$ is disjoint from all curves flopped by $\tau$, because $\mathcal{M}_V$ is base point free by Lemma 6.7. □

**Corollary 6.9.** *The base locus of $\mathcal{M}$ consists of the lines $L_1,\ldots,L_5,L_1',\ldots,L_5'$.*

By Lemma 6.7 and Corollary 6.8, the divisors $-K_V$, $-K_{V'}$, and $-K_U$ are nef. Since

$$-K_V^3=-K_{V'}^3=-K_U^3=4,$$

these divisors are also big. Thus, the Kawamata–Viehweg vanishing theorem and the Riemann–Roch formula give

$$h^0\Big(\mathcal{O}_V\big(-K_V\big)\Big)=h^0\Big(\mathcal{O}_{V'}\big(-K_{V'}\big)\Big)=h^0\Big(\mathcal{O}_U\big(-K_U\big)\Big)=4. \qquad (6.10)$$

In particular, one has $|-K_V|=\mathcal{M}_V$, $|-K_V'|=\mathcal{M}_{V'}$, and $|-K_U|=\mathcal{M}_U$.

**Lemma 6.11.** *The $\mathfrak{S}_5$-representation $H^0(\mathcal{O}_U(-K_U))$ is irreducible.*

*Proof.* By Lemma 3.14, there are no $\mathfrak{S}_5$-invariant quartic surfaces in $\mathbb{P}^3$ that pass through the ten lines $L_1,\ldots,L_5,L_1',\ldots,L_5'$. This implies that $H^0(\mathcal{O}_U(-K_U))$ does not contain one-dimensional subrepresentations. Hence it is irreducible by Remark 4.5. □

Lemma 6.7 together with (6.10) implies that there is an $\mathfrak{S}_5$-equivariant commutative diagram

(6.12)
$$\begin{array}{ccc} & U & \\ {}^{\alpha}\swarrow & & \searrow^{\beta} \\ \mathbb{P}^3 & \overset{}{\underset{\phi}{\dashrightarrow}} & \mathbb{P}^4, \end{array}$$

where $\phi$ is a rational map given by $\mathcal{M}$, and $\beta$ is a morphism given by the anticanonical linear system $|-K_U|$. By Lemma 6.11 the projective space $\mathbb{P}^4$ in (6.12) is a projectivization of an irreducible $\mathfrak{S}_5$-representation.

For $1 \leqslant i < j \leqslant 5$, let $\Lambda_{ij}$ be the intersection line of the plane spanned by $L_i$ and $L_j'$ with the plane spanned by $L_i'$ and $L_j$. Note that the stabilizer of $\Lambda_{ij}$ in $\mathfrak{S}_5$ contains a subgroup isomorphic to $\mathrm{D}_{12}$. Actually, this implies that the stabilizer of $\Lambda_{ij}$ in $\mathfrak{S}_5$ is isomorphic to $\mathrm{D}_{12}$, since $\mathrm{D}_{12}$ is a maximal proper subgroup in $\mathfrak{S}_5$ (see Remark 4.3) and there are no $\mathfrak{S}_5$-invariant lines in $\mathbb{P}^3$ by Corollary 2.1(i). Denote by $\hat{\Lambda}_{ij}$ the proper transform of the line $\Lambda_{ij}$ on the threefold $V$, and denote by $\overline{\Lambda}_{ij}$ its proper transform on $U$. Then

$$-K_V \cdot \hat{\Lambda}_{ij} = 0.$$

Since $\upsilon$ is a small birational morphism, we also obtain $-K_U \cdot \overline{\Lambda}_{ij} = 0$.

We see that each curve $\overline{\Lambda}_{ij}$ is contracted by $\beta$ to a point. Note that the stabilizer of $\Lambda_{ij}$ in $\mathfrak{S}_5$ is isomorphic to $\mathrm{D}_{12}$. Since $-K_U^3 = 4$, the image of $\beta$ is either an $\mathfrak{S}_5$-invariant quartic threefold or an $\mathfrak{S}_5$-invariant quadric threefold. Applying Corollary 4.8 together with Lemma 4.11, we obtain the following.

**Corollary 6.13.** *The morphism $\beta$ is birational on its image, and its image is a quartic threefold.*

Now Lemmas 4.11 and 4.12 imply that the image of $\beta$ is the quartic $X_{\frac{1}{6}}$. This proves

**Corollary 6.14.** *The threefold $X_{\frac{1}{6}}$ is rational.*

*Remark* 6.15. An alternative approach to the rationality of the quartic threefold $X_{\frac{1}{6}}$ was suggested in [16]. Unfortunately, its implementation seems to contradict the existence of the commutative diagram (6.12). Indeed, the paper [16] studies the action of the subgroup $F_{20} \subset \mathfrak{S}_6$ on the threefold $X_{\frac{1}{6}}$. Since all such subgroups in $\mathfrak{S}_6$ are conjugate, one may identify $F_{20}$ with a subgroup of our $\mathfrak{S}_5$. By Remark 6.3, the group $F_{20}$ permutes the ten lines $L_1, \ldots, L_5, L_1', \ldots, L_5'$ transitively. This means that $\gamma$ is an $F_{20}\mathbb{Q}$-factorialization of the quartic threefold $X_{\frac{1}{6}}$. Thus, the application of $F_{20}$-Minimal Model Program to $U$ must give the birational map $\alpha\colon U \to \mathbb{P}^3$. However, [16, Lemma 2.10], [16, Lemma 2.12] and [16, Lemma 2.13] exclude this possibility.

Ten curves $\overline{\Lambda}_{ij}$ are mapped by $\gamma$ to ten singular points of the threefold $X_{\frac{1}{6}}$. Twenty singular points of $U$ are mapped by $\gamma$ to another twenty singular points of $X_{\frac{1}{6}}$. Let us describe the curves in $U$ that are contracted by $\gamma$ to the remaining ten singular points of the threefold $X_{\frac{1}{6}}$. To do this, we need

**Lemma 6.16.** *Let $\ell_1$, $\ell_2$, $\ell_3$ and $\ell_4$ be pairwise skew lines in $\mathbb{P}^3$. Suppose that there is a unique line $\ell \subset \mathbb{P}^3$ that intersects $\ell_1$, $\ell_2$, $\ell_3$ and $\ell_4$. Let $\pi\colon Y \to \mathbb{P}^3$ be a blow up of the* *line $\ell$, and $E \cong \mathbb{P}^1 \times \mathbb{P}^1$ be the exceptional divisor of $\pi$. Denote by $\tilde{\ell}_1$, $\tilde{\ell}_2$, $\tilde{\ell}_3$ and $\tilde{\ell}_4$ the proper transforms on $Y$ of the lines $\ell_1$, $\ell_2$, $\ell_3$ and $\ell_4$, respectively. Then there exists a unique curve $C \subset E$ of bi-degree $(1,1)$ that intersects the curves $\tilde{\ell}_1$, $\tilde{\ell}_2$, $\tilde{\ell}_3$ and $\tilde{\ell}_4$.*

*Proof.* The lines $\ell_1$, $\ell_2$, and $\ell_3$ are contained in a unique quadric surface $S \subset \mathbb{P}^3$. Note that $S$ is smooth, because $\ell_1$, $\ell_2$, and $\ell_3$ are disjoint. Furthermore, the line $\ell$ is contained in $S$, because $\ell$ intersects the lines $\ell_1$, $\ell_2$, and $\ell_3$ by assumption. Moreover, the line $\ell_4$ is tangent to $S$, since otherwise there would be either two or infinitely many lines in $\mathbb{P}^3$ that intersect $\ell_1$, $\ell_2$, $\ell_3$ and $\ell_4$. Denote by $\tilde{S}$ the proper transform on $Y$ of the quadric surface $S$. Then $\tilde{S}$ contains the curves $\tilde{\ell}_1$, $\tilde{\ell}_2$, and $\tilde{\ell}_3$. Moreover, $\tilde{S}$ intersects the curve $\tilde{\ell}_4$. Thus $\tilde{S}|_E$ is the required curve $C$. □

By Lemmas 3.7 and 6.16, each surface $E_i \cong \mathbb{P}^1 \times \mathbb{P}^1$ contains a unique smooth rational curve $C_i$ of bi-degree $(1,1)$ that passes through all four points of the intersection of $E_i$ with the curves $\widetilde{L}'_1, \ldots, \widetilde{L}'_5$ (recall that $E_i \cap \widetilde{L}'_i = \varnothing$). Similarly, each surface $E'_i \cong \mathbb{P}^1 \times \mathbb{P}^1$ contains a unique smooth rational curve $C'_i$ of bi-degree $(1,1)$ that passes through all four points of the intersection of $E'_i$ with the curves $\widetilde{L}_1, \ldots, \widetilde{L}_5$. Denote by $\hat{C}_1, \ldots, \hat{C}_5$ the proper transforms on the threefold $V$ of the curves $C_1, \ldots, C_5$, respectively. Similarly, denote by $\check{C}'_1, \ldots, \check{C}'_5$ the proper transforms on the threefold $V'$ of the curves $C'_1, \ldots, C'_5$, respectively. Then

$$-K_V \cdot \hat{C}_i = -K_{V'} \cdot \check{C}'_i = 0.$$

This implies that the proper transforms of the curves $\hat{C}_1, \ldots, \hat{C}_5$ on the threefold $V'$ are $(-2)$-curves on the surfaces $\check{E}_1, \ldots, \check{E}_5$, respectively. Similarly, the proper transforms of the curves $\check{C}'_1, \ldots, \check{C}'_5$ on the threefold $V$ are $(-2)$-curves on the surfaces $\hat{E}'_1, \ldots, \hat{E}'_5$, respectively. Thus, all surfaces $\hat{E}'_1, \ldots, \hat{E}'_5, \check{E}_1, \ldots, \check{E}_5$ are isomorphic to the Hirzebruch surface $\mathbb{F}_2$.

Denote by $\overline{C}_1, \ldots, \overline{C}_5, \overline{C}'_1, \ldots, \overline{C}'_5$ the images of the curves $\hat{C}_1, \ldots, \hat{C}_5, \check{C}'_1, \ldots, \check{C}'_5$ on the threefold $U$, respectively. Then

$$-K_U \cdot \overline{C}_i = -K_U \cdot \overline{C}'_i = 0,$$

because $-K_V \cdot \hat{C}_i = -K_{V'} \cdot \check{C}'_i = 0$, and $\upsilon$ and $\upsilon'$ are small birational morphisms. Thus, the ten curves $\overline{C}_1, \ldots, \overline{C}_5, \overline{C}'_1, \ldots, \overline{C}'_5$ are contracted by the morphism $\beta$ to ten singular points of $X_{\frac{1}{6}}$.

It would be interesting to extend the commutative diagram (6.12) to an $\mathfrak{S}_5$-Sarkisov link similar to the $\mathfrak{A}_6$-Sarkisov link (5.20).

## References

[1] A. Beauville, *Non-rationality of the $\mathfrak{S}_6$-symmetric quartic threefolds*, Rend. Sem. Mat. Univ. Politec. Torino **71** (2013), 385–388.

[2] H. Blichfeldt, *Finite Collineation Groups*, University of Chicago Press, Chicago, 1917.

[3] H. Burkhardt, *Untersuchungen aus dem Gebiete der hyperelliptischen Modulfunctionen*, Math. Ann. **38** (1891), 161–224.

[4] I. Cheltsov, V. Przyjalkowski, C. Shramov, *Quartic double solids with icosahedral symmetry*, to appear in European J. of Math.

[5] I. Cheltsov, C. Shramov, *Five embeddings of one simple group*, Trans. of the AMS **366** (2014), 1289–1331.

[6] I. Cheltsov, C. Shramov, *Cremona groups and the icosahedron*, CRC Press, 2015.

[7] A. Coble, *An invariant condition for certain automorphic algebraic forms*, Amer. J. Math. **28** (1906), 333–366.

[8] J. Conway, R. Curtis, S. Norton, R. Parker, R. Wilson, *Atlas of finite groups*, Clarendon Press, Oxford, 1985.

[9] W. Feit, *The current situation in the theory of finite simple groups*, Actes du Congres International des Mathematiciens, Gauthier-Villars, Paris (1971), 55–93.

[10] W. Fulton, J. Harris, *Representation Theory. A First Course*, Graduate Texts in Mathematics **129**, New York: Springer-Verlag (1991).

[11] The GAP Group, GAP — Groups, Algorithms, and Programming, Version 4.7.4; 2014. http://www.gap-system.org

[12] G. van der Geer, *On the geometry of a Siegel modular threefold*, Math. Ann. **260** (1982), 317–350.

[13] R. Hartshorne, *Algebraic Geometry*, Graduate Texts in Mathematics **52** (1977) Springer-Verlag, New York-Heidelberg.

[14] V. Iskovskikh, Yu. Manin, *Three-dimensional quartics and counterexamples to the Lüroth problem*, Math. USSR-Sb. **15** (1971), 141–166.

[15] A. de Jong, N. Shepherd-Barron, A. Van de Ven, *On the Burkhardt quartic*, Math. Ann. **286** (1990), 309–328.

[16] I. Karzhemanov, *Rationality of an $S_6$-invariant quartic* 3*-fold*, preprint, arXiv:1510.00092v1 (2015).

[17] Y. Kawamata, *A generalization of Kodaira–Ramanujam's vanishing theorem*, Math. Ann. **261** (1982), 43–46.

[18] M. Mella, *Birational geometry of quartic 3-folds. II. The importance of being $\mathbb{Q}$-factorial*, Math. Ann. **330** (2004), 107–126.

[19] K. Pettersen, *On nodal determinantal quartic hypersurfaces in $\mathbb{P}^4$*, Ph.D. Thesis, University of Oslo, 1998.

[20] J. Todd, *Configurations defined by six lines in space of three dimensions*, Math. Proc. of the Cambridge Phil. Soc. **29** (1933), 52–68.

[21] J. Todd, *A note on two special primals in four dimensions*, Q. J. Math. **6** (1935) 129–136.

[22] J. Todd, *On a quartic primal with forty-five nodes, in space of four dimensions*, Q. J. Math. **7** (1935) 168–174.

[23] Y. Umezu, *On normal projective surfaces with trivial dualizing sheaf*, Tokyo J. Math. **4** (1981), 343–354.

[24] D. Vazzana, *Invariants and projections of six lines in projective space*, Trans. Amer. Math. Soc. **353** (2001), 2673–2688.

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