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ISOMETRY GROUPS AND MAPPING CLASS GROUPS OF SPHERICAL 3-ORBIFOLDS

MATTIA MECCHIA* AND ANDREA SEPPI**

ABSTRACT. We study the isometry group of compact spherical orientable 3-orbifolds S^3/G , where G is a finite subgroup of $\mathrm{SO}(4)$, by determining its isomorphism type and, when S^3/G is a Seifert fibered orbifold, by describing the action on the Seifert fibrations induced by isometric copies of the Hopf fibration of S^3 . Moreover, we prove that the inclusion of $\mathrm{Isom}(S^3/G)$ into $\mathrm{Diff}(S^3/G)$ induces an isomorphism of the π_0 groups, thus proving the π_0 -part of the natural generalization of the Smale Conjecture to spherical 3-orbifolds.

1. INTRODUCTION

Orbifolds are a generalization of manifolds, which had been introduced in different contexts by Satake [Sat56], by Thurston [Thu97, Chapter 13] and by Haefliger [Hae84] – useful references being also [BMP03, Cho12, Dun88]. The most standard example of an orbifold (of dimension n) is the quotient of a manifold M^n by a group Γ which acts properly discontinuously – but in general not freely – on M . If the action is not free, *singular points* appear in the quotient M/Γ , keeping track of the action of point stabilizers $\mathrm{Stab}_\Gamma(x)$ on a neighborhood of a fixed point $x \in M$. More generally, an orbifold is *locally* the quotient of a manifold by the action of a finite group.

Geometric 3-orbifolds had a large importance in Thurston’s geometrization program. These are *locally* the quotient of one of the eight Thurston’s model geometries by the properly discontinuous action of a group of isometries. The main object of this paper are compact *spherical* 3-orbifolds, which are *globally* the quotient of the 3-sphere S^3 by the action of a finite group G of isometries. Hence the quotient orbifold inherits a metric structure (which is a Riemannian metric of constant curvature 1 outside the singularities). The main purpose of this paper is to study the group of *isometries* of compact spherical 3-orbifolds $\mathcal{O} = S^3/G$, for G a finite subgroup of $\mathrm{SO}(4)$. Roughly speaking, an isometry of \mathcal{O} is a diffeomorphism which preserves both the induced metric and the type of singularities.

A widely studied problem concerning the isometry group of 3-manifolds is the *Smale Conjecture*, and its stronger version, called *Generalized Smale Conjecture*. The latter asserts that the natural inclusion of $\mathrm{Isom}(M)$, the group of isometries of a compact spherical 3-manifold M , into $\mathrm{Diff}(M)$ (its group of diffeomorphisms) is a homotopy equivalence. The original version was stated for $M = S^3$ by Smale. The π_0 -part of the original conjecture, namely the fact that the natural inclusion induces a bijection on the sets of path components, was proved by Cerf in [Cer68]. The full conjecture was then proved by Hatcher in [Hat83].

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The Generalized Smale Conjecture for spherical 3-manifolds was proven in many cases, but is still open in full generality [HKMR12]. The π_0 -part was instead proved in [McC02]. We will prove the π_0 -part of the analogous statement for spherical 3-orbifolds, namely:

Theorem (π_0 -part of the Generalized Smale Conjecture for spherical 3-orbifolds). *Let $\mathcal{O} = S^3/G$ be a compact spherical oriented orbifold. The inclusion $\text{Isom}(\mathcal{O}) \rightarrow \text{Diff}(\mathcal{O})$ induces a group isomorphism*

$$\pi_0 \text{Isom}(\mathcal{O}) \cong \pi_0 \text{Diff}(\mathcal{O}).$$

The proof uses both the algebraic description of the finite groups G acting on S^3 by isometries, and the geometric properties of *Seifert fibrations for orbifolds*.

In fact, the classification of spherical 3-orbifolds up to orientation-preserving isometries is equivalent to the classification of finite subgroups of $\text{SO}(4)$ up to conjugacy in $\text{SO}(4)$. Such algebraic classification was first given by Seifert and Threlfall in [TS31] and [TS33]; we will use the approach of in [DV64]. In the spirit of the paper [McC02], we provide an algebraic description of the isometry group of the spherical orbifold S^3/G once the finite subgroup $G < \text{SO}(4)$ is given. To perform the computation, we first understand the group of orientation-preserving isometries, which is isomorphic to the quotient of the normalizer of G in $\text{SO}(4)$ by G itself. We then describe the full group of isometries, when S^3/G has orientation-reversing isometries. Only part of the understanding of $\text{Isom}(S^3/G)$ is indeed necessary for the proof of the π_0 -part of the Generalized Smale Conjecture for orbifolds, but to the opinion of the authors it is worthwhile to report the isomorphism type of the isometry group for every spherical orbifold, as such list is not available in the literature. Moreover, by the main theorem above, this gives also the computation for the mapping class group of spherical orbifolds.

To prove that the homomorphism $\iota : \pi_0 \text{Isom}(\mathcal{O}) \rightarrow \pi_0 \text{Diff}(\mathcal{O})$ induced by the inclusion $\text{Isom}(\mathcal{O}) \rightarrow \text{Diff}(\mathcal{O})$ is an isomorphism, we will in fact prove that the composition

$$\pi_0 \text{Isom}^+(\mathcal{O}) \xrightarrow{\iota} \pi_0 \text{Diff}^+(\mathcal{O}) \xrightarrow{\alpha} \text{Out}(G),$$

is injective, where $\text{Out}(G) = \text{Aut}(G)/\text{Inn}(G)$. This implies that ι is injective, while surjectivity follows from [CZ92]. However, the injectivity of $\alpha \circ \iota$ does not hold in general, but will be proved when the singular locus of \mathcal{O} is nonempty and its complement is a Seifert fibered manifold, while the remaining cases were already treated in [McC02] and [CZ92]. In order to detect which orbifolds have this property and to prove injectivity in those cases, it is necessary to analyze the Seifert fibrations which a spherical orbifolds S^3/G may admit, in the general setting of Seifert fibrations for orbifolds. The methods to obtain such analysis were provided in [MS15].

Motivated by the relevance of the notion of Seifert fibration for spherical orbifolds, we decided to include in this paper a more explicit discussion of the action of the isometry group $\text{Isom}(S^3/G)$ on Seifert fibrations of S^3/G induced from some isometric copy of the standard Hopf fibration of S^3 (when any exists). We thus give a geometric interpretation of the action of the subgroup of $\text{Isom}(S^3/G)$ which preserves a Seifert fibration (such subgroup being always orientation-preserving, for general reasons).

Organization of the paper. In Section 2, we explain the algebraic classification of finite subgroups of $\mathrm{SO}(4)$ up to conjugacy, and we give an introduction of two- and three-dimensional orbifolds, with special attention to the spherical case. In Section 3, we compute the isometry group of spherical 3-orbifolds, by first computing the subgroup of orientation-preserving isometries and then the full isometry group. The results are reported in Tables 2, 3 and 4. In Section 4 we discuss the Seifert fibrations for spherical orbifolds and in Table 5 we describe the action of the isometry group on the base 2-orbifolds of the fibrations. Finally, in Section 5 we prove the π_0 -part of the Generalized Smale Conjecture for spherical orbifolds.

2. SPHERICAL THREE-ORBIFOLDS

Let $\mathbb{H} = \{a + bi + cj + dk \mid a, b, c, d \in \mathbb{R}\} = \{z_1 + z_2j \mid z_1, z_2 \in \mathbb{C}\}$ be the quaternion algebra. Given a quaternion $q = z_1 + z_2j$, we denote by $\bar{q} = \bar{z}_1 - z_2j$ its conjugate. Thus \mathbb{H} endowed with the positive definite quadratic form given by $q\bar{q} = |z_1|^2 + |z_2|^2$, is isometric to the standard scalar product on \mathbb{R}^4 . We will consider the round 3-sphere as the set of unit quaternions:

$$S^3 = \{a + bi + cj + dk \mid a^2 + b^2 + c^2 + d^2 = 1\} = \{z_1 + z_2j \mid |z_1|^2 + |z_2|^2 = 1\}.$$

The restriction of the product of \mathbb{H} induces a group structure on S^3 . For $q \in S^3$, $q^{-1} = \bar{q}$.

2.1. Finite subgroups of $\mathrm{SO}(4)$. In this subsection we present the classification of the finite subgroup of $\mathrm{SO}(4)$, which is originally due to Seifert and Threlfall ([TS31] and [TS33]). More details can be found in [DV64, CS03, MS15]; we follow the approach and the notation of [DV64]. We have to mention that in Du Val's list of finite subgroup of $\mathrm{SO}(4)$ there are three missing cases.

Let us consider the group homomorphism

$$\Phi : S^3 \times S^3 \rightarrow \mathrm{SO}(4)$$

which associates to the pair $(p, q) \in S^3 \times S^3$ the function $\Phi_{p,q} : \mathbb{H} \rightarrow \mathbb{H}$ with

$$\Phi_{p,q}(h) = phq^{-1},$$

which is an isometry of S^3 . The homomorphism Φ can be proved to be surjective and has kernel

$$\mathrm{Ker}(\Phi) = \{(1, 1), (-1, -1)\}.$$

Therefore Φ gives a 1-1 correspondence between finite subgroups of $\mathrm{SO}(4)$ and finite subgroups of $S^3 \times S^3$ containing the kernel of Φ . Moreover, if two subgroups are conjugate in $\mathrm{SO}(4)$, then the corresponding groups in $S^3 \times S^3$ are conjugate and vice versa. To give a classification of finite subgroups of $\mathrm{SO}(4)$ up to conjugation, one can thus classify the subgroups of $S^3 \times S^3$ which contain $\{(1, 1), (-1, -1)\}$, up to conjugation in $S^3 \times S^3$.

Let \tilde{G} be a finite subgroup of $S^3 \times S^3$ and let us denote by $\pi_i : S^3 \times S^3 \rightarrow S^3$, with $i = 1, 2$, the two projections. We use the following notations: $L = \pi_1(\tilde{G})$, $L_K = \pi_1((S^3 \times \{1\}) \cap \tilde{G})$, $R = \pi_2(\tilde{G})$, $R_K = \pi_2((\{1\} \times S^3) \cap \tilde{G})$. The projection π_1 induces an isomorphism

$$\bar{\pi}_1 : \tilde{G}/(L_K \times R_K) \rightarrow L/L_K,$$

and π_2 induces an isomorphism

$$\bar{\pi}_2 : \tilde{G}/(L_K \times R_K) \rightarrow R/R_K.$$

Let us denote by $\phi_{\tilde{G}} : L/L_K \rightarrow R/R_K$ the isomorphism

$$\phi_{\tilde{G}} = \bar{\pi}_1^{-1} \circ \bar{\pi}_2.$$

On the other hand, if we consider two finite subgroups L and R of S^3 , with two normal subgroups L_K and R_K such that there exists an isomorphism $\phi : L/L_K \rightarrow R/R_K$, we can define a subgroup \tilde{G} of $S^3 \times S^3$ such that $L = \pi_1(\tilde{G})$, $L_K = \pi_1((S^3 \times \{1\}) \cap \tilde{G})$, $R = \pi_2(\tilde{G})$, $R_K = \pi_2((\{1\} \times S^3) \cap \tilde{G})$ and $\phi = \phi_{\tilde{G}}$. The subgroup \tilde{G} of $S^3 \times S^3$ is determined uniquely by the 5-tuple (L, L_K, R, R_K, ϕ) .

To consider the classification up to conjugacy, one uses the following straightforward lemma, which is implicitly used in [DV64].

Lemma 1. *Let $\tilde{G} = (L, L_K, R, R_K, \phi)$ and $\tilde{G}' = (L', L'_K, R', R'_K, \phi')$ be finite subgroups of $S^3 \times S^3$ containing $\text{Ker}(\Phi)$. An element $(g, f) \in S^3 \times S^3$ conjugates \tilde{G} to \tilde{G}' if and only if the following three conditions are satisfied:*

- (1) $g^{-1}Lg = L'$ and $f^{-1}Rf = R'$;
- (2) $g^{-1}L_Kg = L'_K$ and $f^{-1}R_Kf = R'_K$;
- (3) *the following diagram commutes:*

$$\begin{array}{ccc} L/L_K & \xrightarrow{\phi} & R/R_K \\ \downarrow \alpha & & \downarrow \beta \\ L'/L'_K & \xrightarrow{\phi'} & R'/R'_K \end{array} \quad (1)$$

where $\alpha(xL_K) = g^{-1}xgL'_K$ and $\beta(yR_K) = f^{-1}y f R'_K$.

Observe that the diagonal subgroup Δ in $S^3 \times S^3$ is the subgroup which preserves the antipodal points 1 and -1 , and thus also preserves the equatorial S^2 which is equidistant from 1 and -1 . Thus one obtains a map

$$\Phi : \Delta \cong S^3 \rightarrow \text{SO}(3)$$

which associates to $q \in S^3$ the isometry $h \mapsto qhq^{-1}$. By means of this map, and the classification of finite subgroups of $\text{SO}(3)$ one shows that the finite subgroups of S^3 are:

$$\begin{aligned} C_n &= \{ \cos\left(\frac{2\alpha\pi}{n}\right) + i \sin\left(\frac{2\alpha\pi}{n}\right) \mid \alpha = 0, \dots, n-1 \} & n \geq 1 \\ D_{2n}^* &= C_n \cup C_{n,j} & n \geq 3 \\ T^* &= \bigcup_{r=0}^2 \left(\frac{1}{2} + \frac{1}{2}i + \frac{1}{2}j + \frac{1}{2}k\right)^r D_4^* \\ O^* &= T^* \cup \left(\sqrt{\frac{1}{2}} + \sqrt{\frac{1}{2}}j\right) T^* \\ I^* &= \bigcup_{r=0}^4 \left(\frac{1}{2}\tau^{-1} + \frac{1}{2}\tau j + \frac{1}{2}k\right)^r T^* \quad \left(\text{where } \tau = \frac{\sqrt{5}+1}{2}\right) \end{aligned}$$

The group C_n is cyclic of order n , and contains the center -1 if and only if n is even. The group D_{2n}^* is a generalized quaternion group of order $2n$. The group D_{2n}^* is called also

binary dihedral and it is a central extension of the dihedral group by a group of order 2. Observe that for $n = 2$, one has $D_4^* = \{\pm 1, \pm j\}$, which is conjugate to $C_4 = \{\pm 1, \pm i\}$. For this reason, the groups D_{2n}^* are considered with indices $n \geq 3$. The case $n = 3$ is also a well-known group, in fact $D_8^* = \{\pm 1, \pm i, \pm j, \pm k\}$ is also called quaternion group. The groups T^* , O^* and I^* are central extensions of the tetrahedral, octahedral and icosahedral group, respectively, by a group of order two; they are called binary tetrahedral, octahedral and icosahedral, respectively.

Using Lemma 1, one can thus obtain a classification (up to conjugation) of the finite subgroups of $S^3 \times S^3$ which contain $\text{Ker}(\Phi)$, in terms of the finite subgroups of S^3 . We report the classification in Table 1.

For most cases the group is completely determined up to conjugacy by the first four data in the 5-tuple (L, L_K, R, R_K, ϕ) and any possible isomorphism ϕ gives the same group up to conjugacy. So we use Du Val's notation where the group (L, L_K, R, R_K, ϕ) is denoted by $(L/L_K, R/R_K)$, using a subscript only when the isomorphism has to be specified. This is the case for Families 1, 1', 11, 11', 26', 26'', 31, 31', 32, 32', 33 and 33'.

Recalling that ϕ is an isomorphism from L/L_K to R/R_K , in the group $(C_{2mr}/C_{2m}, C_{2nr}/C_{2n})_s$ the isomorphism is

$$\phi_s : (\cos(\pi/mr) + i \sin(\pi/mr))C_{2m} \mapsto (\cos(s\pi/nr) + i \sin(s\pi/nr))C_{2n}.$$

In the group $(C_{mr}/C_m, C_{nr}/C_n)_s$ the situation is similar and the isomorphism is

$$\phi_s : (\cos(2\pi/mr) + i \sin(2\pi/mr))C_m \mapsto (\cos(2s\pi/nr) + i \sin(2s\pi/nr))C_n.$$

For Families 11 and 11' we extend the isomorphisms ϕ_s to dihedral or binary dihedral groups sending simply j to j . If $L = D_{4mr}^*$, $R = D_{4nr}^*$, $L_K = C_{2m}$ and $R_K = C_{2n}$, then these isomorphisms cover all the possible cases except when $r = 2$ and $m, n > 1$. In this case we have to consider another isomorphism $f : D_{4mr}^*/C_{2m} \rightarrow D_{4nr}^*/C_{2n}$ such that:

$$f : \begin{cases} (\cos(\pi/2m) + i \sin(\pi/2m))C_{2m} \mapsto jC_{2n} \\ jC_{2m} \mapsto (\cos(\pi/2n) + i \sin(\pi/2n))C_{2n} \end{cases}.$$

This is due to the fact that, if $r > 2$, the quotients L/L_K and R/R_K are isomorphic to a dihedral group of order greater than four where the index two cyclic subgroup is characteristic, while if $r = 2$ the quotients are dihedral groups of order four and extra isomorphisms appear. The isomorphism f gives another class of groups (the number 33 in our list), this family is one of the missing case in Du Val's list. However, when $m = 2$ or $n = 2$, one has $L = D_8^*$ (or $R = D_8^*$), and it is possible to conjugate $jC_2 = \{\pm j\}$ to $iC_2 = \{\pm i\}$ in S^3 (for instance by means of $(i + j)/\sqrt{2}$). Therefore for $m = 1$ or $n = 1$, the isomorphism f is equivalent to the trivial isomorphism.

In Family 11' the behaviour is similar. In fact if $r > 2$ the isomorphisms ϕ_s give all the possible groups up to conjugacy, if $r = 2$ and $m, n > 1$ the quotients are quaternion groups of order 8 and a further family has to be considered. This is the second missing case in [DV64] and Family 33' in our list where f is the following isomorphism:

$$f : \begin{cases} (\cos(\pi/m) + i \sin(\pi/m))C_m \mapsto jC_n \\ jC_m \mapsto (\cos(\pi/n) + i \sin(\pi/n))C_n \end{cases}.$$

The third family of groups not in Du Val's list is Family 34 in Table 1. Note that D_{4n}^*/C_n is cyclic of order 4 if and only if n is odd. If m is even while n is odd, then $(C_{4m}/C_m, D_{4n}^*/C_n)$ does not contain the kernel of Φ , but if m is odd, a new family appears.

The other groups in the list defined by a non trivial automorphism between L/L_K and R/R_K are the groups 26'', 32 and 32'. In the first case f is the identity on the subgroup T^* and maps x to $-x$ in the complement $O^* \setminus L^*$. For the group 32 (resp. 32') the automorphism f can be chosen between the automorphism of I^*/C_2 (resp. I^*) that are not inner (see [Dun94, page 124]), in particular we choose f of order two; this choice turns out to be useful when we compute the full isometry group in Subsection 3.2.

Finally we remark that the groups (L, L_K, R, R_K, ϕ) and $(R, R_K, L, L_K, \phi^{-1})$ are not conjugate unless L and R are conjugate in S^3 , so the corresponding groups in $\text{SO}(4)$ are in general not conjugate in $\text{SO}(4)$. If we consider conjugation in $\text{O}(4)$ the situation changes, because the orientation-reversing isometry of S^3 , sending each quaternion $z_1 + z_2j$ to its inverse $\bar{z}_1 - z_2j$, conjugates the two subgroups of $\text{SO}(4)$ corresponding to (L, L_K, R, R_K, ϕ) and $(R, R_K, L, L_K, \phi^{-1})$. For this reason, in Table 1 only one family between (L, L_K, R, R_K, ϕ) and $(R, R_K, L, L_K, \phi^{-1})$ is listed.

2.2. Two and three-dimensional orbifolds. Roughly speaking an orbifold \mathcal{O} of dimension n is a paracompact Hausdorff topological space X together with an atlas of open sets $(U_i, \varphi_i : \tilde{U}_i/\Gamma_i \rightarrow U_i)$ where \tilde{U}_i are open subsets of \mathbb{R}^n , Γ_i are finite groups acting effectively on U_i and φ_i are homeomorphisms. The orbifold is smooth if the coordinate changes $\varphi_i \circ \varphi_j^{-1}$ can be lifted to diffeomorphisms $\tilde{U}_i \rightarrow \tilde{U}_j$. There is a well-defined notion of *local group* for every point x , namely the smallest possible group which gives a local chart for x , and points with trivial local group are *regular points* of \mathcal{O} . Points with non-trivial local group are *singular points*. The set of regular points of an orbifold is a smooth manifold. The topological space X is called the *underlying topological space* of the orbifold. An orbifold is *orientable* if there is an orbifold atlas such that all groups Γ in the definition act by orientation-preserving diffeomorphisms, and the coordinate changes are lifted to orientation-preserving diffeomorphisms. For details see [BMP03], [Cho12] or [Rat06].

A compact orbifold is *spherical* if there is an atlas as above, such that the groups Γ_i preserve a Riemannian metric \tilde{g}_i on \tilde{U}_i of constant sectional curvature 1 and the coordinate changes are lifted to isometries $(\tilde{U}_i, \tilde{g}_i) \rightarrow (\tilde{U}_j, \tilde{g}_j)$. An (orientation-preserving) diffeomorphism (resp. isometry) between spherical orbifolds $\mathcal{O}, \mathcal{O}'$ is an homeomorphism of the underlying topological spaces which can be locally lifted to an (orientation-preserving) diffeomorphism (resp. isometry) $\tilde{U}_i' \rightarrow \tilde{U}_j'$. It is known that any compact spherical orbifold can be seen as a global quotient of S^n , i.e. if \mathcal{O} is a compact spherical orbifold of dimension n , then there exists a finite group of isometries of S^n such that \mathcal{O} is isometric to S^n/G (see [Rat06, Theorem 13.3.10]); if the spherical orbifold is orientable G is a subgroup of $\text{SO}(n+1)$. By a result of de Rham [dR64] two diffeomorphic spherical orbifolds are isometric.

Let us now explain the local models of 2-orbifolds. The underlying topological space of a 2-orbifold is a 2-manifold with boundary. If x is a singular point, a neighborhood of x is modelled by D^2/Γ where the local group Γ can be a cyclic group of rotations (x is called a cone point), a group of order 2 generated by a reflection (x is a mirror reflector) or a dihedral group generated by an index 2 subgroup of rotations and a reflection (in this case x is called a corner reflector). The local models are presented in Figure 1, a cone point or

	\tilde{G}	order of G	
1.	$(C_{2mr}/C_{2m}, C_{2nr}/C_{2n})_s$	$2mnr$	$\gcd(s, r) = 1$
1'.	$(C_{mr}/C_m, C_{nr}/C_n)_s$	$(mnr)/2$	$\gcd(s, r) = 1 \gcd(2, n) = 1$ $\gcd(2, m) = 1 \gcd(2, r) = 2$
2.	$(C_{2m}/C_{2m}, D_{4n}^*/D_{4n}^*)$	$4mn$	
3.	$(C_{4m}/C_{2m}, D_{4n}^*/C_{2n})$	$4mn$	
4.	$(C_{4m}/C_{2m}, D_{8n}^*/D_{4n}^*)$	$8mn$	
5.	$(C_{2m}/C_{2m}, T^*/T^*)$	$24m$	
6.	$(C_{6m}/C_{2m}, T^*/D_8^*)$	$24m$	
7.	$(C_{2m}/C_{2m}, O^*/O^*)$	$48m$	
8.	$(C_{4m}/C_{2m}, O^*/T^*)$	$48m$	
9.	$(C_{2m}/C_{2m}, I^*/I^*)$	$120m$	
10.	$(D_{4m}^*/D_{4m}^*, D_{4n}^*/D_{4n}^*)$	$8mn$	
11.	$(D_{4mr}^*/C_{2m}, D_{4nr}^*/C_{2n})_s$	$4mnr$	$\gcd(s, r) = 1$
11'.	$(D_{2mr}^*/C_m, D_{2nr}^*/C_n)_s$	mnr	$\gcd(s, r) = 1 \gcd(2, n) = 1$ $\gcd(2, m) = 1 \gcd(2, r) = 2$
12.	$(D_{8m}^*/D_{4m}^*, D_{8n}^*/D_{4n}^*)$	$16mn$	
13.	$(D_{8m}^*/D_{4m}^*, D_{4n}^*/C_{2n})$	$8mn$	
14.	$(D_{4m}^*/D_{4m}^*, T^*/T^*)$	$48m$	
15.	$(D_{4m}^*/D_{4m}^*, O^*/O^*)$	$96m$	
16.	$(D_{4m}^*/C_{2m}, O^*/T^*)$	$48m$	
17.	$(D_{8m}^*/D_{4m}^*, O^*/T^*)$	$96m$	
18.	$(D_{12m}^*/C_{2m}, O^*/D_8^*)$	$48m$	
19.	$(D_{4m}^*/D_{4m}^*, I^*/I^*)$	$240m$	
20.	$(T^*/T^*, T^*/T^*)$	288	
21.	$(T^*/C_2, T^*/C_2)$	24	
21'.	$(T^*/C_1, T^*/C_1)$	12	
22.	$(T^*/D_8^*, T^*/D_8^*)$	96	
23.	$(T^*/T^*, O^*/O^*)$	576	
24.	$(T^*/T^*, I^*/I^*)$	1440	
25.	$(O^*/O^*, O^*/O^*)$	1152	
26.	$(O^*/C_2, O^*/C_2)$	48	
26'.	$(O^*/C_1, O^*/C_1)_{Id}$	24	
26''.	$(O^*/C_1, O^*/C_1)_f$	24	
27.	$(O^*/D_8^*, O^*/D_8^*)$	192	
28.	$(O^*/T^*, O^*/T^*)$	576	
29.	$(O^*/O^*, I^*/I^*)$	2880	
30.	$(I^*/I^*, I^*/I^*)$	7200	
31.	$(I^*/C_2, I^*/C_2)_{Id}$	120	
31'.	$(I^*/C_1, I^*/C_1)_{Id}$	60	
32.	$(I^*/C_2, I^*/C_2)_f$	120	
32'.	$(I^*/C_1, I^*/C_1)_f$	60	
33.	$(D_{8m}^*/C_{2m}, D_{8n}^*/C_{2n})_f$	$8mn$	$m \neq 1 \ n \neq 1.$
33'.	$(D_{8m}^*/C_m, D_{8n}^*/C_n)_f$	$4mn$	$\gcd(2, n) = 1 \gcd(2, m) = 1$ $m \neq 1 \text{ and } n \neq 1.$
34.	$(C_{4m}/C_m, D_{4n}^*/C_n)$	$2mn$	$\gcd(2, n) = 1 \gcd(2, m) = 1$

TABLE 1. Finite subgroups of $SO(4)$

a corner reflector is labelled by its singularity index, i.e. an integer corresponding to the order of the subgroup of rotations in Γ . We remark that the boundary of the underlying topological space consists of mirror reflectors and corner reflectors, and the singular set might contain in addition some isolated points corresponding to cone points. If X is a 2-manifold without boundary we denote by $X(n_1, \dots, n_k)$ the 2-orbifold with underlying topological space X and with k cone points of singularity index n_1, \dots, n_k . If X is a 2-manifold with non-empty connected boundary we denote by $X(n_1, \dots, n_k; m_1, \dots, m_h)$ the 2-orbifold with k cone points of singularity index n_1, \dots, n_k and with h corner reflectors of singularity index m_1, \dots, m_h .

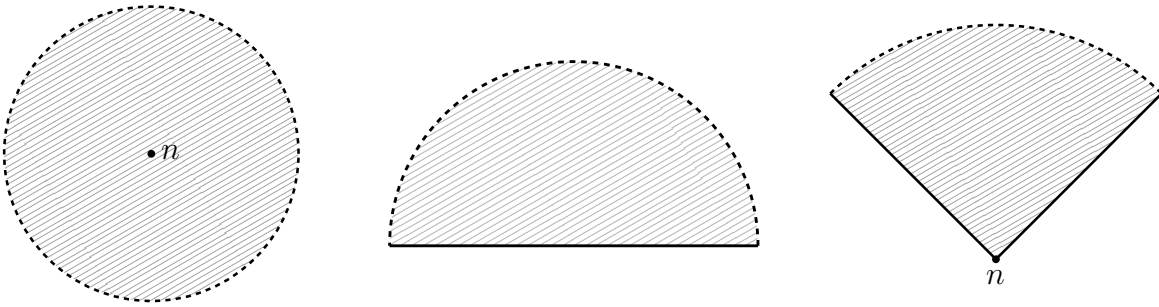


FIGURE 1. Local models of 2-orbifolds. On the left, cone point. In the middle, mirror reflector. On the right, corner point.

Let us now turn the attention to 3-orbifolds. We will only consider orientable 3-orbifolds. The underlying topological space of an orientable 3-orbifold is a 3-manifold and the singular set is a trivalent graph. The local models are represented in Figure 2. Excluding the vertices of the graph, the local group of a singular point is cyclic; an edge of the graph is labelled by its singularity index, that is the order of the related cyclic local groups.

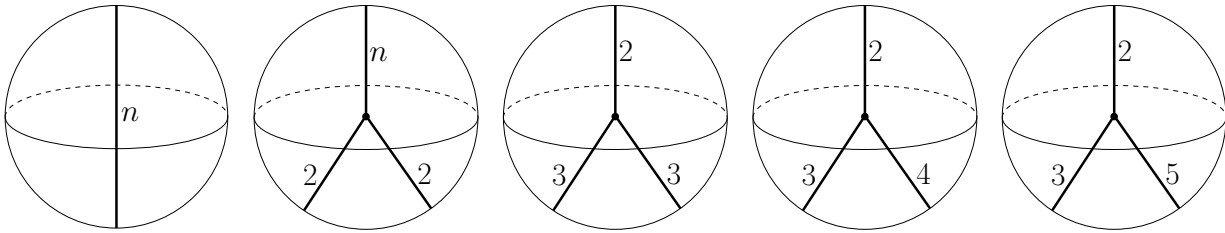


FIGURE 2. Local models of 3-orbifolds.

In this paper we deal with spherical 2-orbifolds and orientable spherical 3-orbifolds, namely orbifolds \mathcal{O} which are obtained as the quotient of S^2 (resp. S^3) by a finite group $G < \text{O}(3)$ (resp. $G < \text{SO}(4)$) of isometries. An isometry between two spherical 3-orbifolds $\mathcal{O} = S^3/\Gamma$ and $\mathcal{O}' = S^3/\Gamma'$ can thus be lifted to an isometry of S^3 which conjugates Γ to Γ' . If the isometry between the orbifolds is orientation-preserving, then the lift to S^3 is orientation-preserving. For this reason, the classification of spherical orientable 3-orbifolds S^3/G up to orientation-preserving isometries corresponds to the algebraic classification of finite subgroups of $\text{SO}(4)$ up to conjugation in $\text{SO}(4)$.

3. ISOMETRY GROUPS OF SPHERICAL THREE-ORBIFOLDS

The purpose of this section is to determine the isometry group of the spherical three-orbifolds S^3/G , once the finite subgroup $G < \text{SO}(4)$ in the list of Table 1 is given.

3.1. Orientation-preserving isometries. We start by determining the index 2 subgroup of orientation-preserving isometries. By the same argument as the last paragraph of Section 2, the subgroup of orientation-preserving isometries of S^3/G , which we denote by $\text{Isom}^+(S^3/G)$, is isomorphic to $\text{Norm}_{\text{SO}(4)}(G)/G$. The latter is in turn isomorphic to the quotient $\text{Norm}_{S^3 \times S^3}(\tilde{G})/\tilde{G}$.

A special case of Lemma 1 is the following:

Lemma 2. *Let $\tilde{G} = (L, L_K, R, R_K, \phi)$ be a finite subgroup of $S^3 \times S^3$ containing $\text{Ker}(\Phi)$. An element $(g, f) \in S^3 \times S^3$ is contained in the normalizer $N_{S^3 \times S^3}(G)$ if and only if the following three conditions are satisfied:*

- (1) $(g, f) \in N_{S^3}(L) \times N_{S^3}(R)$;
- (2) $(g, f) \in N_{S^3}(L_K) \times N_{S^3}(R_K)$;
- (3) *the following diagram commutes:*

$$\begin{array}{ccc} L/L_K & \xrightarrow{\phi} & R/R_K \\ \downarrow \alpha & & \downarrow \beta \\ L/L_K & \xrightarrow{\phi} & R/R_K \end{array} \quad (2)$$

where $\alpha(xL_k) = g^{-1}xgL_k$ and $\beta(yR_k) = f^{-1}yfR_k$.

First, it is necessary to understand the normalizers of the finite subgroups of S^3 . These are listed for instance in [McC02]. We report a list here:

$$\begin{aligned} \text{Norm}_{S^3}(C_n) &= O(2)^* & \text{if } n > 2 \\ \text{Norm}_{S^3}(C_2) &= S^3 & \text{if } n = 2 \\ \text{Norm}_{S^3}(D_{4n}^*) &= D_{8n}^* & \text{if } n > 2 \\ \text{Norm}_{S^3}(D_8^*) &= O^* & \text{if } n = 2 \\ \text{Norm}_{S^3}(T^*) &= O^* \\ \text{Norm}_{S^3}(O^*) &= O^* \\ \text{Norm}_{S^3}(I^*) &= I^* \end{aligned} \quad (3)$$

We split the computation in several cases, including in each case those groups for which the techniques involved are comparable. Families 1, 1', 11, 11' are treated in a systematic way in Case 9, although for some special values of the indices, they should in principle fall in the categories of some of the previous cases. In the following we denote by D_n the dihedral group of order n and O is the octahedral group (that is isomorphic to O^*/C_2 , and also to the symmetric group on 4 elements).

Case 1. \tilde{G} is a product, i.e. $L = L_K$ and $R = R_K$.

In this case L/L_K and R/R_K are trivial groups, hence the conditions of Lemma 2 are trivially satisfied. Therefore $\text{Norm}_{S^3 \times S^3}(\tilde{G}) = \text{Norm}_{S^3}(L) \times \text{Norm}_{S^3}(R)$. Hence $\text{Isom}^+(S^3/G) =$

$(\text{Norm}_{S^3}(L)/L) \times (\text{Norm}_{S^3}(R)/R)$. This is the case of Families 2, 5, 7, 9, 10, 14, 15, 19 and Groups 20, 23, 24, 25, 29, 30 of Table 1.

Case 2. $L/L_K \cong R/R_K \cong \mathbb{Z}_2$ and L_K, R_K are not generalized quaternion groups.

It turns out that, for the pairs $(L, L_K) = (C_{4n}, C_{2n}), (D_{4n}^*, C_{2n}), (O^*/T^*)$, the normalizer $\text{Norm}_{S^3}(L)$ also normalizes L_K (or analogously for R and R_K). In this case, the condition of commutativity of the diagram (2) is trivially satisfied, since the identity is the only automorphism of \mathbb{Z}_2 . Hence $\text{Norm}_{S^3 \times S^3}(\tilde{G}) = \text{Norm}_{S^3}(L) \times \text{Norm}_{S^3}(R)$. This shows that, for Families 3, 8, 16 and Group 28 one has $\text{Norm}_{S^3 \times S^3}(\tilde{G}) = \text{Norm}_{S^3}(L) \times \text{Norm}_{S^3}(R)$.

To understand the isomorphism type of the orientation-preserving isometry group, for instance for the group in Family 3, namely

$$\tilde{G} = (C_{4m}/C_{2m}, D_{4n}^*/C_{2n}),$$

we consider

$$\text{Isom}^+(S^3/G) = \text{Norm}_{S^3 \times S^3}(\tilde{G})/\tilde{G} = ((O(2)^* \times D_{8n}^*)/(C_{2m} \times C_{2n})) / (\tilde{G}/(C_{2m} \times C_{2n})).$$

Therefore we get

$$\text{Isom}^+(S^3/G) \cong (O(2) \times D_4)/\mathbb{Z}_2$$

and, observing that $D_4 \cong \mathbb{Z}_2 \times \mathbb{Z}_2$, one concludes that

$$\text{Isom}^+(S^3/G) \cong O(2) \times \mathbb{Z}_2.$$

Case 3. $L/L_K \cong R/R_K \cong \mathbb{Z}_2$ and L_K or R_K is a generalized quaternion group.

When $(L, L_K) = (D_{8n}^*, D_{4n}^*)$, D_{4n}^* is not normal in $\text{Norm}_{S^3}(L) = D_{16n}^*$, and the normalizer of D_{4n}^* is D_{8n}^* . This is the case of Families 4, 12, 13 and 17. Basically, here one has to consider

$$\text{Norm}_{S^3 \times S^3}(\tilde{G}) = (\text{Norm}_{S^3}(L) \cap \text{Norm}_{S^3}(L_K)) \times (\text{Norm}_{S^3}(R) \cap \text{Norm}_{S^3}(R_K))$$

and apply the above strategy to successively compute $\text{Isom}(S^3/G)$. For instance, for Family 13,

$$\tilde{G} = (D_{8m}^*/D_{4m}^*, D_{4n}^*/C_{2n}),$$

we have

$$\text{Norm}_{S^3 \times S^3}(\tilde{G}) = D_{8m}^* \times D_{8n}^*.$$

Hence one gets

$$\text{Isom}^+(S^3/G) \cong (\mathbb{Z}_2 \times D_4)/\mathbb{Z}_2 \cong \mathbb{Z}_2 \times \mathbb{Z}_2.$$

Case 4. $L/L_K \cong R/R_K \cong \mathbb{Z}_3$.

This case includes Family 6 and Group 22. For Group 22, namely

$$\tilde{G} = (T^*/D_8^*, T^*/D_8^*),$$

we have $\text{Norm}_{S^3}(L) = \text{Norm}_{S^3}(R) = O^*$, and $L_K = R_K = D_8^*$ is normal in O^* . The induced action of the elements of T^* on $T^*/D_8^* = \mathbb{Z}_3$ is the identity, hence the normalizer of \tilde{G} contains $T^* \times T^*$. Moreover, the induced action of elements of $O^* \setminus T^*$ on \mathbb{Z}_3 is dihedral, hence elements of $O^* \setminus T^*$ on the left side have to be paired to elements of $O^* \setminus T^*$ on the right side to make the diagram (2) commutative. Hence

$$\text{Norm}_{S^3 \times S^3}(\tilde{G}) = (O^*/T^*, O^*/T^*)$$

and the isometry group is D_6 . By a similar argument, one checks that the normalizer of

$$\tilde{G} = (C_{6m}/C_{2m}, T^*/D_8^*)$$

is

$$\text{Norm}_{S^3 \times S^3}(\tilde{G}) = (O(2)^*/S^1, O^*/T^*).$$

Finally, one can compute

$$\begin{aligned} \text{Isom}^+(S^3/G) &= ((O(2)^*/S^1, O^*/T^*)/(C_{2m} \times D_8^*)) / ((C_{6m}/C_{2m}, T^*/D_8^*)/(C_{2m} \times D_8^*)) \\ &\cong \text{Dih}(S^1 \times \mathbb{Z}_3)/\mathbb{Z}_3 \cong O(2). \end{aligned}$$

Case 5. $L/L_K \cong R/R_K \cong D_6$.

For Group 27, in a very similar fashion as Group 22, the normalizer in $S^3 \times S^3$ is $(O^*/T^*, O^*/T^*)$ and thus the orientation-preserving isometry group is isomorphic to \mathbb{Z}_3 . The other groups to be considered here are those in Family 18, namely

$$\tilde{G} = (D_{12m}^*/C_{2m}, O^*/D_8^*).$$

Again, arguing similarly to Case 4, one sees that

$$\text{Norm}_{S^3 \times S^3}(\tilde{G}) = (D_{24m}^*/C_{4m}, O^*/D_8^*).$$

Therefore the orientation-preserving isometry group is \mathbb{Z}_2 .

Case 6. $L/L_K \cong R/R_K \cong T, T^*, O, O^*, I$ or I^* .

We start by considering Group 21, i.e. $\tilde{G} = (T^*/C_2, T^*/C_2)$. We have $\text{Norm}_{S^3}(L) = \text{Norm}_{S^3}(R) = O^*$. On the other hand, observing that the centre of O^* is precisely C_2 , the normalizer of \tilde{G} turns out to be $(O^*/C_2, O^*/C_2)$. In fact, in order to satisfy Lemma 2, any element of the form $(g, 1)$ which normalizes \tilde{G} must have $g \in C_2$. Hence the orientation-preserving isometry group is \mathbb{Z}_2 .

By analogous considerations, since $\text{Norm}_{S^3}(O^*) = O^*$ and $\text{Norm}_{S^3}(I^*) = I^*$, the orientation-preserving isometry groups for Groups 26 and 31 are trivial. Group 32, namely $\tilde{G} = (I^*/C_2, I^*/C_2)_f$, is defined by means of a non-inner automorphism of I^* . However, since any automorphism preserves the centre and O^*/C_2 has trivial centre, the same argument applies and the orientation-preserving isometry group is trivial.

For Group 21', namely $\tilde{G} = (T^*/C_1, T^*/C_1)$, the normalizer is again $(O^*/C_2, O^*/C_2)$, since the centre of O^* is C_2 . The orientation-preserving isometry group is $\mathbb{Z}_2 \times \mathbb{Z}_2$. Finally, the normalizer of Groups 26' and 26'' is Group 26, the normalizer of Group 31' is Group 31, and the normalizer of Group 32' is Group 32. Therefore Groups 26', 26'', 31' and 32' have orientation-preserving isometry groups isomorphic to \mathbb{Z}_2 .

Case 7. $L/L_K \cong R/R_K \cong \mathbb{Z}_4, \mathbb{Z}_2 \times \mathbb{Z}_2$ or D_8^* .

This is the case of Families 33, 33' and 34. The definition of Family 33, namely

$$\tilde{G} = (D_{8m}^*/C_{2m}, D_{8n}^*/C_{2n})_f,$$

makes use of a non-trivial automorphism of $\mathbb{Z}_2 \times \mathbb{Z}_2$. One can easily check that in $\text{Norm}_{S^3}(L) \times \text{Norm}_{S^3}(R) = D_{16m}^* \times D_{16n}^*$, it is not possible to obtain a pair (g, f) which makes the diagram (2) commute, unless (g, f) is already in \tilde{G} . This is essentially due to the fact that the non-trivial automorphism of $D_4 \cong \mathbb{Z}_2 \times \mathbb{Z}_2$ cannot be extended to an automorphism of D_8 .

	\tilde{G}	$\text{Isom}^+(S^3/G)$	$\text{Isom}_0(S^3/G)$	$\pi_0\text{Isom}^+(S^3/G)$
1.	$(C_{2mr}/C_{2m}, C_{2nr}/C_{2n})_s$	$\text{Dih}(S^1 \times S^1)$	$S^1 \times S^1$	\mathbb{Z}_2
1'.	$(C_{mr}/C_m, C_{nr}/C_n)_s$	$\text{Dih}(S^1 \times S^1)$	$S^1 \times S^1$	\mathbb{Z}_2
2.	$(C_{2m}/C_{2m}, D_{4n}^*/D_{4n}^*)$	$O(2) \times \mathbb{Z}_2$	S^1	$\mathbb{Z}_2 \times \mathbb{Z}_2$
3.	$(C_{4m}/C_{2m}, D_{4n}^*/C_{2n})$	$O(2) \times \mathbb{Z}_2$	S^1	$\mathbb{Z}_2 \times \mathbb{Z}_2$
4.	$(C_{4m}/C_{2m}, D_{8n}^*/D_{4n}^*)$	$O(2)$	S^1	\mathbb{Z}_2
5.	$(C_{2m}/C_{2m}, T^*/T^*)$	$O(2) \times \mathbb{Z}_2$	S^1	$\mathbb{Z}_2 \times \mathbb{Z}_2$
6.	$(C_{6m}/C_{2m}, T^*/D_8^*)$	$O(2)$	S^1	\mathbb{Z}_2
7.	$(C_{2m}/C_{2m}, O^*/O^*)$	$O(2)$	S^1	\mathbb{Z}_2
8.	$(C_{4m}/C_{2m}, O^*/T^*)$	$O(2)$	S^1	\mathbb{Z}_2
9.	$(C_{2m}/C_{2m}, I^*/I^*)$	$O(2)$	S^1	\mathbb{Z}_2
10.	$(D_{4m}^*/D_{4m}^*, D_{4n}^*/D_{4n}^*)$	$\mathbb{Z}_2 \times \mathbb{Z}_2$	$\{1\}$	$\mathbb{Z}_2 \times \mathbb{Z}_2$
11.	$(D_{4mr}^*/C_{2m}, D_{4nr}^*/C_{2n})_s$	\mathbb{Z}_2	$\{1\}$	\mathbb{Z}_2
11'.	$(D_{2mr}^*/C_m, D_{2nr}^*/C_n)_s$	$\mathbb{Z}_2 \times \mathbb{Z}_2$	$\{1\}$	$\mathbb{Z}_2 \times \mathbb{Z}_2$
12.	$(D_{8m}^*/D_{4m}^*, D_{8n}^*/D_{4n}^*)$	\mathbb{Z}_2	$\{1\}$	\mathbb{Z}_2
13.	$(D_{8m}^*/D_{4m}^*, D_{4n}^*/C_{2n})$	$\mathbb{Z}_2 \times \mathbb{Z}_2$	$\{1\}$	$\mathbb{Z}_2 \times \mathbb{Z}_2$
14.	$(D_{4m}^*/D_{4m}^*, T^*/T^*)$	$\mathbb{Z}_2 \times \mathbb{Z}_2$	$\{1\}$	$\mathbb{Z}_2 \times \mathbb{Z}_2$
15.	$(D_{4m}^*/D_{4m}^*, O^*/O^*)$	\mathbb{Z}_2	$\{1\}$	\mathbb{Z}_2
16.	$(D_{4m}^*/C_{2m}, O^*/T^*)$	$\mathbb{Z}_2 \times \mathbb{Z}_2$	$\{1\}$	$\mathbb{Z}_2 \times \mathbb{Z}_2$
17.	$(D_{8m}^*/D_{4m}^*, O^*/T^*)$	\mathbb{Z}_2	$\{1\}$	\mathbb{Z}_2
18.	$(D_{12m}^*/C_{2m}, O^*/D_8^*)$	\mathbb{Z}_2	$\{1\}$	\mathbb{Z}_2
19.	$(D_{4m}^*/D_{4m}^*, I^*/I^*)$	\mathbb{Z}_2	$\{1\}$	\mathbb{Z}_2
20.	$(T^*/T^*, T^*/T^*)$	$\mathbb{Z}_2 \times \mathbb{Z}_2$	$\{1\}$	$\mathbb{Z}_2 \times \mathbb{Z}_2$
21.	$(T^*/C_2, T^*/C_2)$	\mathbb{Z}_2	$\{1\}$	\mathbb{Z}_2
21'.	$(T^*/C_1, T^*/C_1)$	$\mathbb{Z}_2 \times \mathbb{Z}_2$	$\{1\}$	$\mathbb{Z}_2 \times \mathbb{Z}_2$
22.	$(T^*/D_8^*, T^*/D_8^*)$	D_6	$\{1\}$	D_6
23.	$(T^*/T^*, O^*/O^*)$	\mathbb{Z}_2	$\{1\}$	\mathbb{Z}_2
24.	$(T^*/T^*, I^*/I^*)$	\mathbb{Z}_2	$\{1\}$	\mathbb{Z}_2
25.	$(O^*/O^*, O^*/O^*)$	$\{1\}$	$\{1\}$	$\{1\}$
26.	$(O^*/C_2, O^*/C_2)$	$\{1\}$	$\{1\}$	$\{1\}$
26'.	$(O^*/C_1, O^*/C_1)_{Id}$	\mathbb{Z}_2	$\{1\}$	\mathbb{Z}_2
26''.	$(O^*/C_1, O^*/C_1)_f$	\mathbb{Z}_2	$\{1\}$	\mathbb{Z}_2
27.	$(O^*/D_8^*, O^*/D_8^*)$	\mathbb{Z}_3	$\{1\}$	\mathbb{Z}_3
28.	$(O^*/T^*, O^*/T^*)$	\mathbb{Z}_2	$\{1\}$	\mathbb{Z}_2
29.	$(O^*/O^*, I^*/I^*)$	$\{1\}$	$\{1\}$	$\{1\}$
30.	$(I^*/I^*, I^*/I^*)$	$\{1\}$	$\{1\}$	$\{1\}$
31.	$(I^*/C_2, I^*/C_2)_{Id}$	$\{1\}$	$\{1\}$	$\{1\}$
31'.	$(I^*/C_1, I^*/C_1)_{Id}$	\mathbb{Z}_2	$\{1\}$	\mathbb{Z}_2
32.	$(I^*/C_2, I^*/C_2)_f$	$\{1\}$	$\{1\}$	$\{1\}$
32'.	$(I^*/C_1, I^*/C_1)_f$	\mathbb{Z}_2	$\{1\}$	\mathbb{Z}_2
33.	$(D_{8m}^*/C_{2m}, D_{8n}^*/C_{2n})_f$	$\{1\}$	$\{1\}$	$\{1\}$
33'.	$(D_{8m}^*/C_m, D_{8n}^*/C_n)_f$	\mathbb{Z}_2	$\{1\}$	\mathbb{Z}_2
34.	$(C_{4m}/C_m, D_{4n}^*/C_n)$	$O(2)$	S^1	\mathbb{Z}_2

TABLE 2. Table of orientation-preserving isometry groups for $C_{2m} \neq C_2$, $D_{4m}^* \neq D_4^*, D_8^*$, $r > 2$

Hence the orientation-preserving isometry group is trivial. Clearly any group in Family 33' is normalized by the corresponding group in Family 33, and thus the group of orientation-preserving isometries is \mathbb{Z}_2 .

Family 34, namely

$$\tilde{G} = (C_{4m}/C_m, D_{4n}^*/C_n),$$

is defined by means of the fact that the quotients L/L_K and R/R_K are both isomorphic to \mathbb{Z}_4 . The normalizer here is $(O(2)^*/S^1, D_{8n}^*/D_{4n}^*)$. The orientation-preserving isometry group is a dihedral extension of $(S^1 \times D_{4n}^*)/\tilde{G}$. The latter is a quotient of $S^1 \times D_4^* \cong S^1 \times \mathbb{Z}_4$ by a diagonal action of \mathbb{Z}_4 , and therefore still isomorphic to S^1 . In conclusion, the group of orientation-preserving isometries is isomorphic to $O(2)$.

Case 8. *Exceptional cases for small m or n .*

It is necessary to distinguish from the results obtained above some special cases for small values of the indices m and n . Indeed, as in the list (3), when $n = 2$ the subgroup C_2 of S^3 is normalized by the whole S^3 , whereas the normalizer of D_8^* is O^* . Therefore one obtains different isometry groups when $L, R = C_2$ or $L, R = D_8^*$. The results are collected in Table 3.

Excluding Families 1, 1', 11, 11' which are discussed below, to compute the isometry group in these special cases one uses the same approach as above. For Families 2, 5, 7, 9, 10, 14, 15, 19, which are products, one obtains straightforwardly the result.

For the other groups in which D_8^* may appear, one checks that there are no difference with the case $m > 1$ since O^* , which is the normalizer of D_8^* , does not normalize any subgroup of order 4 of D_8^* .

Case 9. *Families 1, 1', 11, 11'.*

We are left with the treatment of the groups for which L_K and R_K are both cyclic groups, while L and R are both of the same type, either cyclic or generalized dihedral. For Family 1,

$$\tilde{G} = (C_{2mr}/C_{2m}, C_{2nr}/C_{2n})_s,$$

where we recall that the index s denotes the isomorphism $\phi : \mathbb{Z}_r \rightarrow \mathbb{Z}_r$ given by $1 \mapsto s$, we have

$$\text{Norm}_{S^3}(L) = \text{Norm}_{S^3}(R) = O(2)^*.$$

Moreover $O(2)^*$ preserves the subgroups L_K and R_K . We need to check the commutativity of diagram (2). For this purpose, observe that the diagram commutes trivially when we choose elements of the form $(g, 1)$ or $(1, g)$, for $g \in S^1$. On the other hand, the induced action of elements of $O(2)^* \setminus S^1$ on \mathbb{Z}_r is dihedral, hence the normalizer is

$$\text{Norm}_{S^3 \times S^3}(\tilde{G}) = (O(2)^*/S^1, O(2)^*/S^1)$$

unless $r = 2$ (or $r = 1$). The isometry group $\text{Norm}_{S^3 \times S^3}(\tilde{G})/\tilde{G}$ is a dihedral extension of $(S^1 \times S^1)/\tilde{G}$, the latter being again isomorphic to $S^1 \times S^1$ (for an explicit isomorphism, see Equation(6) below). Hence we get $\text{Isom}^+(S^3/\tilde{G}) \cong \text{Dih}(S^1 \times S^1)$. The same result is recovered analogously for Family 1', unless $r = 2$.

	\tilde{G}	$\text{Isom}^+(S^3/G)$	$\text{Isom}_0(S^3/G)$	$\pi_0 \text{Isom}^+(S^3/G)$
1.	$(C_{2m}/C_{2m}, C_{2n}/C_{2n})$	$O(2) \times O(2)$	$S^1 \times S^1$	$\mathbb{Z}_2 \times \mathbb{Z}_2$
	$(C_{4m}/C_{2m}, C_{4n}/C_{2n})$	$O(2) \tilde{\times} O(2)$	$S^1 \times S^1$	$\mathbb{Z}_2 \times \mathbb{Z}_2$
	$(C_2/C_2, C_{2n}/C_{2n})$	$SO(3) \times O(2)$	$SO(3) \times S^1$	\mathbb{Z}_2
	$(C_2/C_2, C_2/C_2)$	$PSO(4)$	$PSO(4)$	$\{1\}$
1'.	$(C_{2m}/C_m, C_{2n}/C_n)$	$O(2)^* \tilde{\times} O(2)^*$	$S^1 \times S^1$	$\mathbb{Z}_2 \times \mathbb{Z}_2$
	$(C_2/C_1, C_{2n}/C_n)$	$S^3 \tilde{\times} O(2)^*$	$S^3 \tilde{\times} S^1$	\mathbb{Z}_2
	$(C_2/C_1, C_2/C_1)$	$SO(4)$	$SO(4)$	$\{1\}$
2.	$(C_2/C_2, D_{4n}^*/D_{4n}^*)$	$SO(3) \times \mathbb{Z}_2$	$SO(3)$	\mathbb{Z}_2
	$(C_{2m}/C_{2m}, D_8^*/D_8^*)$	$O(2) \times D_6$	S^1	$\mathbb{Z}_2 \times D_6$
	$(C_2/C_2, D_8^*/D_8^*)$	$SO(3) \times D_6$	$SO(3)$	D_6
5.	$(C_2/C_2, T^*/T^*)$	$SO(3) \times \mathbb{Z}_2$	$SO(3)$	\mathbb{Z}_2
7.	$(C_2/C_2, O^*/O^*)$	$SO(3)$	$SO(3)$	$\{1\}$
9.	$(C_2/C_2, I^*/I^*)$	$SO(3)$	$SO(3)$	$\{1\}$
10.	$(D_8^*/D_8^*, D_{4n}^*/D_{4n}^*)$	$D_6 \times \mathbb{Z}_2$	$\{1\}$	$D_6 \times \mathbb{Z}_2$
	$(D_8^*/D_8^*, D_8^*/D_8^*)$	$D_6 \times D_6$	$\{1\}$	$D_6 \times D_6$
11.	$(D_{4m}^*/C_{2m}, D_{4n}^*/C_{2n})$	$\mathbb{Z}_2 \times \mathbb{Z}_2 \times \mathbb{Z}_2$	$\{1\}$	$\mathbb{Z}_2 \times \mathbb{Z}_2 \times \mathbb{Z}_2$
	$(D_{8m}^*/C_{2m}, D_{8n}^*/C_{2n})$	$\mathbb{Z}_2 \times \mathbb{Z}_2 \times \mathbb{Z}_2$	$\{1\}$	$\mathbb{Z}_2 \times \mathbb{Z}_2 \times \mathbb{Z}_2$
	$(D_8^*/C_2, D_8^*/C_2)$	O	$\{1\}$	O
11'.	$(D_8^*/C_1, D_8^*/C_1)$	$D_6 \times \mathbb{Z}_2$	$\{1\}$	$D_6 \times \mathbb{Z}_2$
14.	$(D_8^*/D_8^*, T^*/T^*)$	$D_6 \times \mathbb{Z}_2$	$\{1\}$	$D_6 \times \mathbb{Z}_2$
15.	$(D_8^*/D_8^*, O^*/O^*)$	D_6	$\{1\}$	D_6
19.	$(D_8^*/D_8^*, I^*/I^*)$	D_6	$\{1\}$	D_6

TABLE 3. Table of orientation-preserving isometry groups for small indices

For some special cases of Family 1, when $r = 2$ or $r = 1$, $\text{Norm}_{S^3 \times S^3}(\tilde{G}) = O(2)^* \times O(2)^*$. For $r = 1$, one has $\text{Isom}^+(S^3/\tilde{G}) \cong O(2) \times O(2)$. For $r = 2$, the orientation-preserving isometry group is $O(2) \times O(2)/(-1, -1) = O(2) \tilde{\times} O(2)$. When $r = 2$ the group of orientation-preserving isometries of Family 1' turns out to be instead $O(2)^* \times O(2)^*/(-1, -1) = O(2)^* \tilde{\times} O(2)^*$. The latter cases are collected in Table 3. Trivial cases are recovered for S^3 itself and for projective space $S^3/\{\pm 1\}$.

For Family 11, namely

$$\tilde{G} = (D_{4mr}^*/C_{2m}, D_{4nr}^*/C_{2n})_s,$$

it is not difficult to see that the normalizer is

$$(D_{8mr}^*/C_{2m}, D_{8nr}^*/C_{2n})_s$$

unless $r = 1$ or $r = 2$. Hence $\text{Isom}^+(S^3/G)$ is isomorphic to \mathbb{Z}_2 . When $r = 1$ the normalizer of $(D_{4m}^*/C_{2m}, D_{4n}^*/C_{2n})$ is $D_{8m}^* \times D_{8n}^*$ (also if m or n are equal to 2), and the computation of the orientation-preserving isometry group follows. When $r = 2$, the normalizer of $(D_{8m}^*/C_{2m}, D_{8n}^*/C_{2n})$ turns out to be $(D_{16m}^*/D_{8m}^*, D_{16n}^*/D_{8n}^*)$, also if $m = 1$ or $n = 1$. However, when $m = n = 1$, the normalizer is $(O^*/D_8^*, O^*/D_8^*)$ and the orientation-preserving isometry group is isomorphic to $O = O^*/C_2$.

A similar argument shows that for Family 11', $\text{Isom}^+(S^3/G)$ is isomorphic to $\mathbb{Z}_2 \times \mathbb{Z}_2$, also if $r = 4$ and one among m and n equals 1. Thus the only exception is for the group $(D_8^*/C_1, D_8^*/C_1)$.

3.2. Orientation-reversing isometries. We now compute the full isometry groups of spherical orbifolds S^3/G . We collect the results of this section in Table 4 where we list the groups such that $\text{Isom}(S^3/G) \neq \text{Isom}^+(S^3/G)$ and the full isometry groups of the corresponding orbifolds are described. If the spherical orbifold does not admit any orientation-reversing isometry then $\text{Isom}(S^3/G)$ can be deduced from Tables 2 and 3.

An orientation-reversing element of $O(4)$ is of the form $h \rightarrow p\bar{h}q^{-1}$ where p and q are elements of S^3 and \bar{h} is the conjugate element of h (see [DV64, p.58]). We will denote this isometry by $\bar{\Phi}_{p,q}$. Let us remark that

$$\bar{\Phi}_{p,q}\bar{\Phi}_{l,r}\bar{\Phi}_{p,q}^{-1} = \bar{\Phi}_{prp^{-1},qlq^{-1}}. \quad (4)$$

We state two lemmata whose proofs are straightforward.

Lemma 3. *Let $\tilde{G} = (L, L_K, R, R_K, \phi)$ be a finite subgroup of $S^3 \times S^3$ containing $\text{Ker}(\Phi)$. If $\bar{\Phi}_{p,q}$ normalizes $\Phi(\tilde{G})$ then the following conditions are satisfied:*

- (1) $p^{-1}Lp = R$ and $q^{-1}Rq = L$;
- (2) $pL_Kp^{-1} = R_K$ and $qR_Kq^{-1} = L_K$.

So if an orientation reversing isometry of S^3 normalizes G , then we can suppose up to conjugacy that $L = R$ and $L_K = R_K$.

Lemma 4. *Let $\tilde{G} = (R, R_K, R, R_K, \phi)$ be a finite subgroup of $S^3 \times S^3$ containing $\text{Ker}(\Phi)$. The isometry $\bar{\Phi}_{p,q}$ normalizes $\Phi(\tilde{G})$ if and only if the following two conditions are satisfied:*

- (1) $p, q \in N_{S^3}(R)$;
- (2) $p, q \in N_{S^3}(R_K)$;
- (3) *the following diagram commutes:*

$$\begin{array}{ccc} R/R_K & \xrightarrow{\phi} & R/R_K \\ \downarrow \beta & & \downarrow \alpha \\ R/R_K & \xrightarrow{\phi^{-1}} & R/R_K \end{array} \quad (5)$$

where $\alpha(xR_K) = p^{-1}xpR_K$ and $\beta(xR_K) = q^{-1}xqR_K$.

Now we want to analyze which groups in Table 1 admit an orientation-reversing isometry in their normalizer. The condition given in Lemma 3 excludes all the groups in the families 2, 3, 4, 5, 6, 7, 8, 9, 14, 15, 16, 17, 18, 19, 23, 24, 29, 34 and the groups with $n \neq m$ in the families 1, 1', 10, 11, 11', 12, 33, 33'. For the remaining groups, by Lemma 4 we obtain that if $\phi = \text{Id}$ then $\bar{\Phi}_{1,1}$ (i.e. the isometry given by the conjugation in \mathbb{H}) normalizes the group and the quotient orbifold admits an orientation-reversing isometry. In these cases the normalizer of G in $O(4)$ is generated by the normalizer of G in $SO(4)$ and $\bar{\Phi}_{1,1}$. The element $\bar{\Phi}_{1,1}$ has order two and $\bar{\Phi}_{1,1}\bar{\Phi}_{l,r}\bar{\Phi}_{1,1}^{-1} = \bar{\Phi}_{r,l}$, hence the full isometry group of S^3/G can be easily computed.

The behavior of families $26''$, 32 , $32'$, 33 , $33'$ is similar, as $\phi^2 = Id$ and hence $\overline{\Phi}_{1,1}$ normalizes again the group.

The situation for the four remaining families of groups 1 , $1'$, 10 , 11 , $11'$ is more complicated. We have already remarked that, if an orientation-reversing element is in the normalizer, then $n = m$. However, in these cases this necessary condition is not sufficient.

We explain in detail the situation for Family 1 with $r \geq 2$. In the other remaining cases the full isometry group can be computed in a very similar way.

Family 1. If $\overline{\Phi}_{p,q}$ normalizes $G = \Phi((C_{2mr}/C_{2m}, C_{2mr}/C_{2m})_s)$, then both p and q normalize C_{2mr} . The action by conjugation of p and q on C_{2mr} is either trivial or dihedral. When p and q act in the same way (both trivially or both dihedrally), by Lemma 4 we obtain that $\phi^2 = Id$ and $s^2 \equiv_r 1$ (i.e. s^2 is congruent to 1 mod r). In this case $\overline{\Phi}_{1,1}$ normalizes the group. If p and q act differently, then ϕ^2 sends an element of C_{2mr}/C_{2m} to its inverse and $s^2 \equiv_r -1$ (i.e. s^2 is congruent to -1 mod r). In this case $\overline{\Phi}_{j,1}$ normalizes the group; we remark that $\overline{\Phi}_{j,1}$ has order 4.

We have $\text{Isom}^+(S^3/G) \cong \text{Dih}(S^1 \times S^1)$. Since $\text{Isom}^+(S^3/G) \cong \text{Norm}_{S^3 \times S^3}(\tilde{G})/\tilde{G}$, we represent each isometry as the corresponding coset of \tilde{G} in $\text{Norm}_{S^3 \times S^3}(\tilde{G}) = (\text{O}(2)^*/S^1, \text{O}(2)^*/S^1)$. The group $\text{Isom}^+(S^3/G)$ is generated by the involution $(j, j)\tilde{G}$ and by the abelian subgroup of index two $N = (S^1 \times S^1)/\tilde{G}$. Both $\overline{\Phi}_{1,1}$ and $\overline{\Phi}_{j,1}$ commute with the element $(j, j)G$. The group N is isomorphic to $S^1 \times S^1$, but the direct factors of the quotient do not correspond in general to the projections of the direct factors of the original group $S^1 \times S^1$. This fact makes the comprehension of the extension of N by $\overline{\Phi}_{1,1}$ and $\overline{\Phi}_{j,1}$ more complicated. To represent N as the direct product of two copies of S^1 we define an isomorphism $\gamma : S^1 \times S^1 \rightarrow N$ by means of the following construction. Let

$$\tilde{\gamma} : \mathbb{R} \times \mathbb{R} \rightarrow N = (S^1 \times S^1)/\tilde{G} \quad \tilde{\gamma}(\alpha, \beta) = \left(e^{i(\frac{\alpha}{2mr} + \frac{\beta}{2m})}, e^{i(\frac{s\alpha}{2mr} + \frac{(s+1)\beta}{2m})} \right) \tilde{G}.$$

It is easy to check that $\text{Ker}(\tilde{\gamma}) = 2\pi\mathbb{Z} \times 2\pi\mathbb{Z}$ and thus $\tilde{\gamma}$ descends to the isomorphism $\gamma : S^1 \times S^1 \rightarrow N$ which can be defined as

$$\gamma(e^{i\alpha}, e^{i\beta}) = \left(e^{i(\frac{\alpha}{2mr} + \frac{\beta}{2m})}, e^{i(\frac{s\alpha}{2mr} + \frac{(s+1)\beta}{2m})} \right) \tilde{G}. \quad (6)$$

Since here we have two subgroups isomorphic to $S^1 \times S^1$, we need to distinguish the notation in the two cases: an element of $S^1 \times S^1 < S^3 \times S^3$ is denoted by (e^{ia}, e^{ib}) while an element of N is denoted by $(e^{ia}, e^{ib})\tilde{G}$ if it is seen in the quotient $(S^1 \times S^1)/\tilde{G}$ or by $((e^{ia}, e^{i\beta})) = \gamma(e^{i\alpha}, e^{i\beta})$ if N is seen as the direct product of two copies of S^1 .

Suppose that $s^2 \equiv_r -1$. The isometry $\overline{\Phi}_{j,1}$ normalizes the group; moreover $\overline{\Phi}_{j,1}$ is of order 4 and $\overline{\Phi}_{j,1}^2 = \Phi_{j,j}$. By [OS15, Proposition 7.12] the automorphism group of $S^1 \times S^1$ contains only one conjugacy class of order four, so we have a unique semidirect product $\mathbb{Z}_4 \ltimes N$ corresponding to the automorphism which maps $((e^{i\alpha}, e^{i\beta}))$ to $((e^{-i\beta}, e^{i\alpha}))$.

Suppose that $s^2 \equiv_r 1$. Here the full isometry group is a semidirect product of $\text{Isom}^+(S^3/G)$ with \mathbb{Z}_2 . In the automorphism group of $(S^1 \times S^1)$ we have three classes of involutions which correspond to non-isomorphic semidirect products. In order to determine to which semidirect product $\text{Isom}(S^3/G)$ is isomorphic, we compute the action by conjugation of $\overline{\Phi}_{1,1}$ on N . The element $(e^{i\alpha}, e^{i\beta})\tilde{G}$ is conjugate by $\overline{\Phi}_{1,1}$ to $(e^{i\beta}, e^{i\alpha})\tilde{G}$. To understand which semidirect product we obtain we will use a procedure introduced in [OS15], and to apply this procedure

G	case	$\text{Isom}(S^3/G)$	G	$\text{Isom}(S^3/G)$
1	$m = n, r > 2, s^2 \equiv_r 1$ and r odd	$(\mathbb{Z}_2 \times \mathbb{Z}_2) \ltimes_{\alpha_1} (S^1 \times S^1)$	12	$\mathbb{Z}_2 \times \mathbb{Z}_2$
1	$m = n, r > 2, s^2 \equiv_r 1$ and r even	$(\mathbb{Z}_2 \times \mathbb{Z}_2) \ltimes_{\alpha_2} (S^1 \times S^1)$	20	D_8
1	$m = n, r > 2$ and $s^2 \equiv_r -1 \pmod{r}$	$\mathbb{Z}_4 \ltimes_{\alpha_3} (S^1 \times S^1)$	21	$\mathbb{Z}_2 \times \mathbb{Z}_2$
1	$m = n, r = 1$ and $m > 1$	$\mathbb{Z}_2 \ltimes_{\alpha_4} (\text{O}(2) \times \text{O}(2))$	21'	$(\mathbb{Z}_2)^3$
1	$m = n, r = 1$ and $m > 1$	$\mathbb{Z}_2 \ltimes_{\alpha_4} (\text{O}(2) \tilde{\times} \text{O}(2))$	22	$\mathbb{Z}_2 \times D_6$
1	$m = n = 2$ and $r = 1$	$\text{PO}(4)$	25	\mathbb{Z}_2
1'	$m = n, r > 2, s \equiv_r 1$ and r odd	$(\mathbb{Z}_2 \times \mathbb{Z}_2) \ltimes_{\alpha_1} (S^1 \times S^1)$	26	\mathbb{Z}_2
1'	$m = n, r > 2, s \equiv_r 1$ and r even	$(\mathbb{Z}_2 \times \mathbb{Z}_2) \ltimes_{\alpha_2} (S^1 \times S^1)$	26'	$\mathbb{Z}_2 \times \mathbb{Z}_2$
1'	$m = n, r > 2, s \equiv_r -1$	$\mathbb{Z}_4 \ltimes_{\alpha_3} (S^1 \times S^1)$	26''	$\mathbb{Z}_2 \times \mathbb{Z}_2$
1'	$m = n, r = 2$ and $m > 1$	$\mathbb{Z}_2 \ltimes_{\alpha_4} (\text{O}(2)^* \tilde{\times} \text{O}(2)^*)$	27	D_6
10	$m = n$ and $m > 2$	D_8	28	$\mathbb{Z}_2 \times \mathbb{Z}_2$
10	$m = n = 2$	$\mathbb{Z}_2 \ltimes_{\alpha_4} (D_6 \times D_6)$	30	\mathbb{Z}_2
11	$m = n, r > 2$ and $s^2 \equiv_r \pm 1$	$\mathbb{Z}_2 \times \mathbb{Z}_2$	31	\mathbb{Z}_2
11	$m = n, m > 1$ and $r = 1$	$\mathbb{Z}_2 \times D_8$	31'	$\mathbb{Z}_2 \times \mathbb{Z}_2$
11	$m = n, m > 1$ and $r = 2$	$(\mathbb{Z}_2)^4$	32	\mathbb{Z}_2
11	$m = n = 2$ and $r = 2$	$\mathbb{Z}_2 \times O$	32'	$\mathbb{Z}_2 \times \mathbb{Z}_2$
11'	$m = n, r > 2, s^2 \equiv_r 1$, and $(s^2 - 1)/r$ even	$\mathbb{Z}_2 \times \mathbb{Z}_2 \times \mathbb{Z}_2$	33	\mathbb{Z}_2
11'	$m = n, r > 2, s^2 \equiv_r 1$ and $(s^2 - 1)/r$ odd	D_8	33'	$\mathbb{Z}_2 \times \mathbb{Z}_2$
11'	$m = n, r > 2, s^2 \equiv_r -1$ and $(s^2 + 1)/r$ even	$\mathbb{Z}_2 \times \mathbb{Z}_2 \times \mathbb{Z}_2$		
11'	$m = n, r > 2, s^2 \equiv_r -1$ and $(s^2 + 1)/r$ odd	D_8		
11'	$m = n = 1$ and $r = 4$	$\mathbb{Z}_2 \times \mathbb{Z}_2 \times D_6$		

α_1 : the group $\mathbb{Z}_2 \times \mathbb{Z}_2$ is generated by f and g s.t. $\alpha_1(f)((e^{i\alpha}, e^{i\beta})) = ((e^{-i\alpha}, e^{-i\beta}))$ and $\alpha_1(g)((e^{i\alpha}, e^{i\beta})) = ((e^{i\beta}, e^{i\alpha}))$.
 α_2 : the group $\mathbb{Z}_2 \times \mathbb{Z}_2$ is generated by f and g s.t. $\alpha_2(f)((e^{i\alpha}, e^{i\beta})) = ((e^{-i\alpha}, e^{-i\beta}))$ and $\alpha_2(g)((e^{i\alpha}, e^{i\beta})) = ((e^{-i\alpha}, e^{i\beta}))$.
 α_3 : the group \mathbb{Z}_4 is generated by f s.t. $\alpha_3(f)((e^{i\alpha}, e^{i\beta})) = ((e^{-i\beta}, e^{i\alpha}))$.
 α_4 : \mathbb{Z}_2 acts on a product, direct or central, whose generic element can be represented by a couple (x, y) ; the non trivial element in \mathbb{Z}_2 maps (x, y) to (y, x) .

TABLE 4. Table of full isometry groups when $\text{Isom}(S^3/G) \neq \text{Isom}^+(S^3/G)$

we need to understand the action of $\bar{\Phi}(1, 1)$ on N represented as a direct product of two copies of S^1 . By using γ the action by conjugation of $\bar{\Phi}_{1,1}$ on $N \cong S^1 \times S^1$ is the following:

$$((e^{i\alpha}, e^{i\beta})) \longrightarrow ((e^{i(s^2+s-1)\alpha+i(2s+s^2)r\beta}, e^{i\frac{1-s^2}{r}\alpha+i(1-s-s^2)\beta})).$$

By applying the procedure presented in the proof of [OS15, Proposition 7.9], we obtain that if r is odd the automorphism induced by $\bar{\Phi}_{1,1}$ is conjugate to the following automorphism:

$$((e^{i\alpha}, e^{i\beta})) \longrightarrow ((e^{i\beta}, e^{i\alpha})),$$

while if r is even $\bar{\Phi}_{1,1}$ is conjugate to the following automorphism:

$$((e^{i\alpha}, e^{i\beta})) \longrightarrow ((e^{-i\alpha}, e^{i\beta})).$$

4. SEIFERT FIBRATIONS

In this section, we consider those spherical orbifolds $\mathcal{O} = S^3/\Gamma$ which admit a Seifert fibration, and study the action of subgroups of $\text{Isom}(\mathcal{O})$ which preserve the Seifert fibration.

4.1. Definition of Seifert fibrations for orbifolds. A Seifert fibration of a 3-orbifold \mathcal{O} is a projection map $\pi : \mathcal{O} \rightarrow \mathcal{B}$, where \mathcal{B} is a 2-dimensional orbifold, such that for every point $x \in \mathcal{B}$ there is an orbifold chart $x \in U \cong \tilde{U}/\Gamma$, an action of Γ on S^1 (inducing a diagonal action of Γ on $\tilde{U} \times S^1$) and a diffeomorphism $\psi : (\tilde{U} \times S^1)/\Gamma \rightarrow \pi^{-1}(U)$ which makes the following diagram commute:

$$\begin{array}{ccccc}
 \pi^{-1}(U) & \xleftarrow{\psi} & (\tilde{U} \times S^1)/\Gamma & \xleftarrow{\quad} & \tilde{U} \times S^1 \\
 \searrow \pi & & \swarrow & & \swarrow \text{pr}_1 \\
 U \cong \tilde{U}/\Gamma & \xleftarrow{\quad} & \tilde{U} & &
 \end{array}$$

If we restrict our attention to orientable 3-orbifolds \mathcal{O} , then the action of Γ on $\tilde{U} \times S^1$ needs to be orientation-preserving. In this case, we will consider a fixed orientation both on \tilde{U} and on S^1 . Every element of Γ may preserve both orientations, or reverse both.

The fibers $\pi^{-1}(x)$ are simple closed curves or intervals. If a fiber projects to a non-singular point of \mathcal{B} , it is called generic. Otherwise we will call it exceptional.

Let us define the local models for an oriented Seifert fibered orbifold. Locally the fibration is given by the curves induced on the quotient $(\tilde{U} \times S^1)/\Gamma$ by the standard fibration of $\tilde{U} \times S^1$ given by the curves $\{y\} \times S^1$.

If the fiber is generic, it has a tubular neighborhood with a trivial fibration. When $x \in \mathcal{B}$ is a cone point labelled by q , the local group Γ is a cyclic group of order q acting orientation preservingly on \tilde{U} and thus it can act on S^1 by rotations. Hence a fibered neighborhood of the fiber $\pi^{-1}(x)$ is a fibered solid torus. One can define the *local invariant* of the fiber $\pi^{-1}(x)$ as the ratio $p/q \in \mathbb{Q}/\mathbb{Z}$, where a generator of Γ acts on \tilde{U} by rotation of an angle $2\pi/q$ and on S^1 by rotation of $-2\pi p/q$ – however the study of local invariants is not one of the main purposes of this paper. The fiber $\pi^{-1}(x)$ may be singular (in the sense of orbifold singularities) and the index of singularity is $\gcd(p, q)$. If $\gcd(p, q) = 1$ the fiber is not singular. Forgetting the singularity of the fiber (if any), the local model coincides with the local model of a Seifert fibration for manifold.

If x is a corner reflector, namely Γ is a dihedral group, then the non-central involutions in Γ need to act on \tilde{U} and on S^1 by simultaneous reflections. Here the local model is the so-called solid pillow, which is a topological 3-ball with some singular set inside. There is an index two cyclic subgroup of Γ , acting as we have previously described. Again, the local invariant associated to x can be defined as the local invariant p/q of the cyclic index two subgroup, and the fiber $\pi^{-1}(x)$ has singularity index $\gcd(p, q)$. The fibers of $U \times S^1$ intersecting the axes of reflections of Γ in \tilde{U} project to segments that are exceptional fibers of the 3-orbifold; the other fibers of $\tilde{U} \times S^1$ project to simple closed curves.

Finally, over mirror reflectors (local group \mathbb{Z}_2), we have a special case of the dihedral case. The local model is topologically a 3-ball with two disjoint singular arcs of index 2. More details can be found in [BS85] or [Dun81].

There is a classification theorem for Seifert fibered 3-orbifolds up to orientation-preserving, fibration-preserving diffeomorphisms by means of some invariants. We won't use this theorem here, so we don't provide details. We only briefly remind that an oriented Seifert fibered orbifold is determined up to diffeomorphisms which preserve the orientation and the fibration by the data of the base orbifold, the local invariants associated to cone points and corner reflectors, an additional invariant $\xi \in \mathbb{Z}_2$ associated to each boundary component of the base orbifold and the Euler number. If we change the orientation of the orbifold, then the sign of local invariants and Euler number are inverted. For the formal definitions of Euler number and of invariants associated to boundary components, as well as the complete statement and proof of the classification theorem, we refer again to [BS85] or [Dun81].

4.2. Seifert fibrations of S^3 . Seifert fibrations of S^3 are well known: it is proved in [Sei80] that, up to an orientation-preserving diffeomorphism, they are given by the maps of the form $\pi : S^3 \rightarrow S^2 \cong \mathbb{C} \cup \{\infty\}$

$$\pi(z_1 + z_2 j) = \frac{z_1^u}{z_2^v} \quad \text{or} \quad \pi(z_1 + z_2 j) = \frac{\bar{z}_1^u}{z_2^v}$$

for u and v coprimes. We call *standard* the Seifert fibrations given by these maps; the classification of Seifert fibrations of S^3 can thus be rephrased in the following way: each Seifert fibration of S^3 can be mapped by an orientation-preserving diffeomorphism of S^3 to a standard one.

The base orbifold of a Seifert fibration of S^3 is S^2 with two possible cone points. When $u = v = 1$, $\pi(z_1 + z_2 j) = z_1/z_2$ is called the Hopf fibration. In this case the base orbifold is S^2 and all the fibers are generic. The projection $\pi : S^3 \rightarrow S^2$ of the Hopf fibration is also obtained as the quotient by the following S^1 -action on S^3 : an element $w = x + iy \in S^1$ acts on S^3 simply as left multiplication by w . That is, $w \cdot (z_1 + z_2 j) = (wz_1 + wz_2 j)$.

The only other Seifert fibration whose generic fibers are all generic is given by $\pi(z_1 + z_2 j) = \bar{z}_1/z_2$; we call *anti-Hopf* this fibration.

A Seifert fibration of S^3/G can be induced by a Seifert fibration of S^3 left invariant by G . Hence let us determine those elements of $S^3 \times S^3$ which act on S^3 preserving a standard Seifert fibration.

We consider first the Hopf fibration. Equivalently, we want to determine $\text{Norm}_{S^3 \times S^3}(S^1 \times \{1\})$, where here S^1 is thought as the subset of elements of the form $(w, 0)$. It is straightforward that all isometries corresponding to $(0, w_1 + w_2 j) \in S^3 \times S^3$ normalize S^1 and thus preserve the Hopf fibration, with induced action on the base S^2 given by

$$\lambda \mapsto \frac{\bar{w}_1 \lambda + \bar{w}_2}{-w_2 \lambda + w_1}. \quad (7)$$

For example, elements of the form $w_1 = \cos \theta + i \sin \theta$ act on S^2 by rotations of angle 2θ fixing the poles (which are 0 and ∞ in our identification with $\mathbb{C} \cup \{\infty\}$). A further useful example is the induced action of j , which is a rotation of order two exchanging 0 and ∞ . On the other hand, it can be checked that an isometry given by $(w_1 + w_2 j, 0)$ normalizes S^1 , and thus preserves the Hopf fibration, if and only if $w_1 = 0$ or $w_2 = 0$. Clearly the elements with $w_2 = 0$ fix the base S^2 pointwise, while a direct computation shows that the elements

with $w_1 = 0$ act by antipodal map on S^2 . In summary,

$$\text{Norm}_{S^3 \times S^3}(S^1 \times \{1\}) = \text{Norm}_{S^3}(S^1) \times S^3,$$

where

$$\text{Norm}_{S^3}(S^1 \times \{1\}) = \{w_1 + w_2 j \mid w_1 = 0 \text{ or } w_2 = 0\} = \text{O}(2)^*.$$

On the other hand, the general fibration $\pi(z_1 + z_2 j) = z_1^u / z_2^v$ is preserved by $(w_1 + w_2 j, u_1 + u_2 j)$ provided $w_2 = u_2 = 0$ or $w_1 = u_1 = 0$.

In Du Val's list, the subgroups of $\text{SO}(4)$ which preserve the Hopf fibration are those with $L = C_m$ or $L = D_{2m}^*$, for some m . The other fibrations of type $\pi(z_1 + z_2 j) = \bar{z}_1^u / z_2^v$ are left invariant only by groups in Family 1,1',11,11' and the spherical orbifolds obtained as quotients by these groups have an infinite number of nonisomorphic fibrations.

It is not necessary to repeat the computations for the remaining fibrations; it suffices to note that the orientation-reversing isometry $\bar{\Phi}_{1,1}$ maps the fibration $\pi(z_1 + z_2 j) = \bar{z}_1^u / z_2^v$ to $\pi(z_1 + z_2 j) = z_1^u / z_2^v$. The isometry $\Phi_{l,r}$ preserves a fibration $\pi(z_1 + z_2 j) = \bar{z}_1^u / z_2^v$ if and only if $\bar{\Phi}_{1,1}^{-1} \Phi_{l,r} \bar{\Phi}_{1,1} = \Phi_{r,l}$ preserves $\pi(z_1 + z_2 j) = z_1^u / z_2^v$.

4.3. Seifert fibrations of spherical orbifolds. In the previous sections we discussed which standard Seifert fibrations of S^3 are left invariant by the groups in Du Val's list. We remark that finite subgroups in Du Val's list can leave invariant also fibrations that are not standard, thus obtaining different fibrations on the same spherical orbifold. In this section we explore this phenomenon; the following Lemma shows that it can occur only in some specific cases.

Lemma 5. *Let G be a finite subgroup of $\text{SO}(4)$ leaving invariant a Seifert fibration π of S^3 , then one of the two following conditions is satisfied:*

- (1) G is conjugate in $\text{SO}(4)$ to a subgroup in Families 1, 1', 11 or 11';
- (2) there exists an orientation-preserving diffeomorphism $f : S^3 \rightarrow S^3$ such that $\pi \circ f$ is the Hopf or the anti-Hopf fibration and $f^{-1} G f$ is a subgroup of $\text{SO}(4)$.

Proof. The fibration π is mapped by an orientation-preserving diffeomorphism to a standard Seifert fibration of S^3 . We recall that the fibrations $\pi(z_1 + z_2 j) = z_1^u / z_2^v$ and $\pi(z_1 + z_2 j) = \bar{z}_1^u / z_2^v$ with $(u, v) \neq (1, 1)$ have exactly two exceptional fibers which have different invariants. If π is mapped to one of these Seifert fibrations, the group G must leave invariant both exceptional fibers. A finite group of isometries leaving invariant a simple closed curve is isomorphic to a subgroup of $\text{Dih}(\mathbb{Z}_n \times \mathbb{Z}_m)$, a dihedral 2-extension of an abelian group of rank at most two (see for example [MZ06, Lemma 1]). The only groups in Du Val's list with this property are in Families 1, 1', 11 or 11' and thus case 1 occurs.

Now we can suppose that π is mapped by an orientation-preserving diffeomorphism g either to the Hopf fibration or to the anti-Hopf fibration. Let us first consider the case of the Hopf fibration. In this case G is conjugate by g to G' , a finite group of diffeomorphisms of S^3 leaving invariant the Hopf fibration. By the proof of [DM84, Theorem 5.1] we can conjugate G' to a group of isometries by using a diffeomorphism h which leaves invariant the Hopf fibration. The diffeomorphism $h \circ g$ is the f we are looking for. We can reduce the anti-Hopf case to the previous one by conjugating by $\bar{\Phi}_{1,1}$. \square

This Lemma implies that, if L and R are both isomorphic to T^* , O^* or I^* , then no fibration of S^3 is preserved by the action of the group $G = \Phi(L, L_K, R, R_K, \phi)$.

From this point on, we will focus on the case of groups of isometries which leave invariant the Hopf fibration. The case of anti-Hopf fibration can then be deduced by conjugation. If G leaves invariant the Hopf fibration, then G is a subgroup of $\text{Norm}_{S^3 \times S^3}(S^1 \times \{1\})$. Moreover, conjugation of G by elements of $\text{Norm}_{S^3 \times S^3}(S^1 \times \{1\})$ respects the Hopf fibration, and therefore induces in the quotient orbifold S^3/G a fibration-preserving isometry. We remark that some of the conjugations used in the Du Val's list do not have this property, hence in order to get an algebraic classification of Seifert fibered spherical 3-orbifolds, we need to classify finite subgroups of $\text{Norm}_{S^3 \times S^3}(S^1 \times \{1\})$, up to conjugation in $\text{Norm}_{S^3 \times S^3}(S^1 \times \{1\})$.

There are three classes of phenomena which can occur, marking the difference with Du Val's list:

- If $\tilde{G} = (L, L_K, R, R_K, \phi)$ has $R = C_n$ or $R = D_{2n}^*$, the fibration given by \bar{z}_1/z_2 is left invariant and the group can be conjugated by $\Phi_{1,1}$ to the group $(R, R_K, L, L_K, \phi^{-1})$ which preserves the Hopf fibration. Thus with respect to the list of Du Val, two groups (L, L_K, R, R_K, ϕ) and $(R, R_K, L, L_K, \phi^{-1})$, that are not of the same form, must not be considered equivalent, and will provide nonequivalent fibrations of the same orbifold.
- In S^3 the subgroups generated by i and by j are conjugated, but they are not conjugated in $O(2)^*$. In Table 1, the subgroup $D_4^* = \{\pm 1, \pm j\} < O(2)^*$ is not considered since it gives the same group as when replaced with $C_4 = \{\pm 1, \pm i\}$. To classify the groups in $\text{Norm}_{S^3 \times S^3}(S^1 \times \{1\})$ it is necessary to distinguish the two cases.
- When $L = D_8^*$ and $L_K = C_1$ or C_2 , the groups of Family 33 with $m = 1$, namely $\tilde{G} = (D_8^*/C_2, D_{8n}^*/C_{2n})_f$ (recalling that the isomorphism f is defined in Subsection 2.1) is conjugate in S^3 to the case $r = 2, m = 1$ of Family 11, namely $\tilde{G} = (D_8^*/C_2, D_{8n}^*/C_{2n})$ (where the automorphism between L/L_K and R/R_K is the identity). But they are not conjugate in $\text{Norm}_{S^3 \times S^3}(S^1 \times \{1\})$. The same occurs for Family 33'. Thus we will consider the case $m = 1$ as independent.

The list of finite subgroups of $\text{Norm}_{S^3 \times S^3}(S^1 \times \{1\})$ up to conjugation in $\text{Norm}_{S^3 \times S^3}(S^1 \times \{1\})$ is thus shown in Table 5, together with the action on the base orbifold which is explained below. This is essentially the same list of Table 1, as in Du Val, having added the groups with the roles of L and R switched when they preserve the Hopf fibration, and with the caveat that the indices vary with no restrictions on $m \geq 1$, and with the usual restrictions on n .

In [MS15] the base orbifold and the Seifert invariants of the fibrations induced by the Hopf fibration on S^3/G , for the groups G in the Du Val's list, were computed. Those formulae hold unchanged also for all groups in Table 5, allowing that the indices vary with no restrictions on $m \geq 1$. In Table 5, we only included the base orbifolds of the fibrations.

If two groups G and G' , both leaving invariant the Hopf fibration, are conjugate in $\text{SO}(4)$ but not in $\text{Norm}_{S^3 \times S^3}(S^1 \times \{1\})$, then the quotient orbifold S^3/G has two inequivalent Seifert fibrations both induced by an isometric copy of the Hopf fibration. This remark allows us to make a list of the orbifolds admitting several inequivalent fibrations.

By the above discussion, groups G in Families 1, 1', 11, 11' are the families with an infinite number of fibrations, which are induced by all the fibrations of S^3 of the form z_1^u/z_2^v

and \bar{z}_1^u/z_2^v . There are some special cases for which an orbifold of the form S^3/G , with G in Families 1, 1', 11, 11', has some additional Seifert fibration induced by an nonstandard isometric copy of the Hopf fibration. Indeed:

- In Family 1 of Du Val's list, if $r = 1$ and $m = 1$, the group $\Phi(C_4/C_4, C_{2n}, C_{2n})$ is the same group as $\Phi(D_4^*/D_4^*, C_{2n}, C_{2n})$, which belongs to Family 2bis ($m = 2$) in Table 5, and thus has one more fibration obtained from an isometric copy of the Hopf fibration;
- In Family 1, if $r = 2$ and $m = 1$, $\Phi(C_4/C_2, C_{4n}/C_{2n})$ is conjugate in $SO(4)$ to $\Phi(D_4^*/C_2, C_{4n}/C_{2n})$, of Family 3bis ($m = 1$), and thus has two more fibrations, described in Table 5 by Families 3 and 3bis;
- The case Family 3 of Du Val, $(C_4/C_2, D_{4n}^*/C_{2n})$, is conjugate to the case $m = r = 1$ of Family 11 of Table 5, namely $(D_4^*/C_2, D_{4n}^*/C_{2n})$, thus having one more fibration;
- The case $(D_8^*/C_4, D_{4n}^*/C_{2n})$ of Family 11 also falls within Family 13 in Table 5, thus having one more fibration;
- In Family 1', if $r = 4$ and $m = 1$, $\Phi(C_4/C_1, C_{4n}/C_n)$ is conjugate in $SO(4)$ to $\Phi(D_4^*/C_1, C_{4n}/C_n)$, which is a case of Family 34bis ($m = 1$), and thus has one more fibration obtained from an isometric copy of the Hopf fibration;
- Family 34 of Table 1 with $m = 1$ coincides with Family 11' in the case $(D_4^*/C_1, D_{4n}^*/C_n)$;
- In Family 11, if $m = 1$ then $(D_8^*/C_2, D_{8n}^*/C_{2n})$ has the additional nonequivalent fibration from the case $m = 1$ in Family 33, and the same for the cases $m = 1$ in Families 11' and 33'.

There are also some groups $G < SO(4)$ such that S^3/G has a finite number (> 1) of nonequivalent Seifert fibrations for orbifolds. This can happen in the already treated cases of Families 2, 3, 4, 13 and 34, which preserve both the Hopf fibration and the anti-Hopf fibration, thus giving rise to two nonequivalent fibrations in S^3/G ; the latter is equivalent (up to orientation-reversing diffeomorphisms) to the fibrations of Families 2bis, 3bis, 4bis, 13bis and 34bis described in Table 5. And also Families 10 and 12 leave invariant both the Hopf and the anti-Hopf fibration, and the two induced fibrations in the quotient are nonequivalent if $m \neq n$. Moreover, there are some other special cases in which a group G leaves invariant the Hopf fibration and some other isometric copy of the Hopf fibration:

- In Table 5, Family 3bis with $m = 2$ coincides with Family 4bis with $m = 1$. More precisely $(D_8^*/C_4, C_{4n}/C_{2n})$ is conjugate to $(D_8^*/D_4^*, C_{4n}/C_{2n})$. This group also preserves the anti-Hopf fibration and therefore the quotient has a fibration which comes from Family 3 in Table 5 (which would be equivalent to the case $n = 1$ of Family 4, and therefore the latter was not considered in the list). Thus S^3/G has 3 nonequivalent Seifert fibrations;
- Family 2 with $m = 2$ is the conjugate in $S^3 \times S^3$ to Family 10 with $m = 1$, i.e. $(C_4/C_4, D_{4n}^*/D_{4n}^*)$ and $(D_4^*/D_4^*, D_{4n}^*/D_{4n}^*)$. Considering also the fibration coming from Family 2bis, these groups have 3 fibrations as well;
- The case $(C_4/C_2, D_{8n}^*/D_{4n}^*)$ of Family 4 coincides with Family 13bis, thus also having 3 fibrations;
- The case $(D_8^*/D_4^*, D_{8n}^*/D_{4n}^*)$ of Family 12 is also a group in Family 13 and 13bis;
- Finally, there are correspondences of Family 5 ($m = 2$) and 14 ($m = 1$), Family 7 ($m = 2$) and 15 ($m = 1$), Family 8 and 16 ($m = 1$), Family 9 ($m = 2$) and

19 ($m = 1$), Family 16 ($m = 2$) and 17 ($m = 1$). All these groups thus have 2 nonequivalent fibrations.

4.4. The action on Seifert fibrations. In this section we want to understand the action of the isometry group of a Seifert fibered spherical 3-orbifold \mathcal{O} . We will focus the attention on the induced action on the base orbifold \mathcal{B} . In particular, we will first determine the subgroup $\text{Isom}_p(\mathcal{O})$ of $\text{Isom}(\mathcal{O})$ which preserves the Seifert fibration of \mathcal{O} . By an Euler number argument, an isometry which preserves a Seifert fibration must necessarily be orientation-preserving. It will thus suffice to study elements in $\text{Isom}^+(\mathcal{O})$. Subsequently, we will understand the subgroup $\text{Isom}_f(\mathcal{O})$ of $\text{Isom}(\mathcal{O})$ which acts trivially on the base orbifold \mathcal{B} ; equivalently, it leaves invariant every fiber (although in general it does not fix the fiber pointwise). Finally, we will describe the action of $\text{Isom}_p(\mathcal{O})/\text{Isom}_f(\mathcal{O})$ on the base orbifold \mathcal{B} .

As discussed above, we will consider the groups of Table 5 and their fibrations induced by the Hopf fibration. Equivalently, we consider Seifert fibrations for spherical orbifolds with good base orbifold. Some of these groups are conjugated in $\text{SO}(4)$ and thus there will be several inequivalent fibrations in the same orbifold S^3/G . Let us fix a group G in the list of Table 5, and consider the fibration p induced on S^3/G by the Hopf fibration. Recalling that $\text{Norm}_{S^3 \times S^3}(S^1) = \text{O}(2)^* \times S^3$, the subgroup

$$\text{Isom}_p(S^3/G) = \{\varphi \in \text{Isom}(S^3/G) : \varphi \text{ preserves the fibration } p\}$$

is isomorphic to

$$\text{Norm}_{\text{O}(2)^* \times S^3}(G)/G.$$

On the other hand, the subgroup fixing the fibration:

$$\text{Isom}_f(S^3/G) = \{\varphi \in \text{Isom}(S^3/G) : \varphi \text{ fixes every fiber of } p\},$$

is determined as the quotient of the subgroup of $\text{Norm}_{\text{O}(2)^* \times S^3}(G)$ generated by G and by $S^1 \times \{1\}$, quotiented by G . Up to composing with an element of G , it is not difficult to show that every isometry φ of S^3/G which is in $\text{Isom}_f(S^3/G)$ has a lift to S^3 which is in $\text{SO}(4)$ and fixes the Hopf fibration, and therefore is in $S^1 \times \{1\}$. Hence $\text{Isom}_f(S^3/G)$ is also the image of $\text{Norm}_{\text{O}(2)^* \times S^3}(G) \cap (S^1 \times \{1\})$ in $\text{Isom}(S^3/G)$, by means of the usual projection $\text{Norm}_{S^3 \times S^3}(G) \rightarrow \text{Isom}(S^3/G) \cong \text{Norm}_{S^3 \times S^3}(G)/G$.

To understand the induced action on the fibration, one has first to find the base orbifold \mathcal{B} of the Seifert fibration (this had already been done in [MS15]), and then determine the action of $\text{Isom}_p(S^3/G)/\text{Isom}_f(S^3/G)$ on such base orbifold. This is done case-by-case, and we will treat in detail the cases of Families 1, 3 and 4, which are quite illustrating.

Family 3. Let us start by Family 3, namely $\tilde{G} = (C_{4m}/C_{2m}, D_{4n}^*/C_{2n})$. The normalizer of \tilde{G} is $\text{Norm}_{S^3 \times S^3}(\tilde{G}) = \text{O}(2)^* \times D_{8n}^*$ and is entirely contained in $\text{Norm}_{S^3 \times S^3}(S^1)$, thus $\text{Isom}_p(S^3/G) = \text{Isom}^+(S^3/G)$. On the other hand, the S^1 component in $\text{Isom}^+(S^3/G) \cong \text{O}(2) \times \mathbb{Z}_2$ fixes all the fibers, and thus the group acting on \mathcal{B} is $\mathbb{Z}_2 \times \mathbb{Z}_2$. To find \mathcal{B} , it suffices to understand the action of $R = D_{4n}^*$: recalling Formula (7) and the following example, the subgroup C_{2n} acts by rotations as a cyclic group of order n , and the elements of $D_{4n}^* \setminus C_{2n}$ by rotations of order two which switch the fixed points of the cyclic action. Thus \mathcal{B} is the orbifold $S^2(2, 2, n)$. The group $\mathbb{Z}_2 \times \mathbb{Z}_2$ then acts on \mathcal{B} in such a way that one generator produces a rotation of order 2, fixing the cone point of order n and switching the cone points

	\bar{G}	$\bar{\mathcal{B}}$	Isom_p	Isom_f	action on $\bar{\mathcal{B}}$
1.	$(C_{2mr}/C_{2m}, C_{2nr}/C_{2n})_s$	$S^2(nr, nr)$	$\text{Dih}(S^1 \times S^1)$	S^1	$\text{O}(2)$
	$(C_{2m}/C_{2m}, C_{2n}/C_{2n})$	$S^2(n, n)$	$\text{O}(2) \times \text{O}(2)$	S^1	$\text{O}(2) \times \mathbb{Z}_2$
	$(C_{4m}/C_{2m}, C_{4n}/C_{2n})$	$S^2(2n, 2n)$	$\text{O}(2) \tilde{\times} \text{O}(2)$	S^1	$\text{O}(2) \times \mathbb{Z}_2$
	$(C_{2m}/C_{2m}, C_2/C_2)$	S^2	$\text{O}(2) \times \text{SO}(3)$	S^1	$\text{O}(3)$
1'.	$(C_{mr}/C_m, C_{nr}/C_n)_s$	$S^2(nr/2, nr/2)$	$\text{Dih}(S^1 \times S^1)$	S^1	$\text{O}(2)$
	$(C_{2m}/C_m, C_{2n}/C_n)$	$S^2(n, n)$	$\text{O}(2)^* \tilde{\times} \text{O}(2)^*$	S^1	$\text{O}(2) \times \mathbb{Z}_2$
	$(C_{2m}/C_m, C_2/C_1)$	S^2	$\text{O}(2)^* \tilde{\times} S^3$	S^1	$\text{O}(3)$
2.	$(C_{2m}/C_{2m}, D_{4n}^*/D_{4n}^*)$	$S^2(2, 2, n)$	$\text{O}(2) \times \mathbb{Z}_2$	S^1	$\mathbb{Z}_2 \times \mathbb{Z}_2$
	$(C_{2m}/C_{2m}, D_8^*/D_8^*)$	$S^2(2, 2, 2)$	$\text{O}(2) \times D_6$	S^1	$D_6 \times \mathbb{Z}_2$
2.bis	$(D_{4m}^*/D_{4m}^*, C_{2n}/C_{2n})$	$\begin{cases} D^2(n;) & n \text{ even} \\ \mathbb{R}P^2(n) & n \text{ odd} \end{cases}$	$\text{O}(2) \times \mathbb{Z}_2$	\mathbb{Z}_2	$\text{O}(2)$
	$(D_{4m}^*/D_{4m}^*, C_2/C_2)$	$\mathbb{R}P^2$	$\text{SO}(3) \times \mathbb{Z}_2$	$\mathbb{Z}_2 \times \mathbb{Z}_2$	$\text{PSO}(3)$
3.	$(C_{4m}/C_{2m}, D_{4n}^*/C_{2n})$	$S^2(2, 2, n)$	$\text{O}(2) \times \mathbb{Z}_2$	S^1	$\mathbb{Z}_2 \times \mathbb{Z}_2$
3.bis	$(D_{4m}^*/C_{2m}, C_{4n}/C_{2n})$	$\begin{cases} D^2(n;) & n \text{ odd} \\ \mathbb{R}P^2(n) & n \text{ even} \end{cases}$	$\text{O}(2) \times \mathbb{Z}_2$	\mathbb{Z}_2	$\text{O}(2)$
4.	$(C_{4m}/C_{2m}, D_{8n}^*/D_{4n}^*)$	$S^2(2, 2, 2n)$	$\text{O}(2)$	S^1	\mathbb{Z}_2 reflection
	$(C_{4m}/C_{2m}, D_8^*/C_4)$	$S^2(2, 2, 2)$	$\text{O}(2) \times \mathbb{Z}_2$	S^1	$\mathbb{Z}_2 \times \mathbb{Z}_2$
4.bis	$(D_{8m}^*/D_{4m}^*, C_{4n}/C_{2n})$	$D^2(2n;)$	$\text{O}(2)$	\mathbb{Z}_2	$\text{O}(2)$
5.	$(C_{2m}/C_{2m}, T^*/T^*)$	$S^2(2, 3, 3)$	$\text{O}(2) \times \mathbb{Z}_2$	S^1	$\mathbb{Z}_2 \times \mathbb{Z}_2$
6.	$(C_{6m}/C_{2m}, T^*/D_8^*)$	$S^2(2, 3, 3)$	$\text{O}(2)$	S^1	\mathbb{Z}_2 reflection
7.	$(C_{2m}/C_{2m}, O^*/O^*)$	$S^2(2, 3, 4)$	$\text{O}(2)$	S^1	\mathbb{Z}_2
8.	$(C_{4m}/C_{2m}, O^*/T^*)$	$S^2(2, 3, 4)$	$\text{O}(2)$	S^1	\mathbb{Z}_2
9.	$(C_{2m}/C_{2m}, I^*/I^*)$	$S^2(2, 3, 5)$	$\text{O}(2)$	S^1	\mathbb{Z}_2
10.	$(D_{4m}^*/D_{4m}^*, D_{4n}^*/D_{4n}^*)$	$\begin{cases} D^2(; 2, 2, n) & n \text{ even} \\ D^2(2; n) & n \text{ odd} \end{cases}$	$\mathbb{Z}_2 \times \mathbb{Z}_2$	\mathbb{Z}_2	\mathbb{Z}_2
	$(D_{4m}^*/D_{4m}^*, D_8^*/D_8^*)$	$D^2(; 2, 2, 2)$	$D_6 \times \mathbb{Z}_2$	\mathbb{Z}_2	D_6
11.	$(D_{4mr}^*/C_{2m}, D_{4nr}^*/C_{2n})_s$	$D^2(; nr, nr)$	\mathbb{Z}_2	$\{1\}$	\mathbb{Z}_2
	$(D_{4m}^*/C_{2m}, D_{4n}^*/C_{2n})$	$D^2(; n, n)$	$\mathbb{Z}_2 \times \mathbb{Z}_2 \times \mathbb{Z}_2$	\mathbb{Z}_2	$\mathbb{Z}_2 \times \mathbb{Z}_2$
	$(D_{8m}^*/C_{2m}, D_{8n}^*/C_{2n})$	$D^2(; 2n, 2n)$	$\mathbb{Z}_2 \times \mathbb{Z}_2 \times \mathbb{Z}_2$	\mathbb{Z}_2	$\mathbb{Z}_2 \times \mathbb{Z}_2$
11'.	$(D_{2mr}^*/C_m, D_{2nr}^*/C_n)_s$	$D^2(; nr/2, nr/2)$	$\mathbb{Z}_2 \times \mathbb{Z}_2$	\mathbb{Z}_2	\mathbb{Z}_2
12.	$(D_{8m}^*/D_{4m}^*, D_{8n}^*/D_{4n}^*)$	$D^2(; 2, 2, 2n)$	\mathbb{Z}_2	\mathbb{Z}_2	$\{1\}$
	$(D_{8m}^*/D_{4m}^*, D_8^*/C_4)$	$D^2(; 2, 2, 2)$	$\mathbb{Z}_2 \times \mathbb{Z}_2$	\mathbb{Z}_2	\mathbb{Z}_2
13.	$(D_{8m}^*/D_{4m}^*, D_{4n}^*/C_{2n})$	$\begin{cases} D^2(; 2, 2, n) & n \text{ even} \\ D^2(2; n) & n \text{ odd} \end{cases}$	$\mathbb{Z}_2 \times \mathbb{Z}_2$	\mathbb{Z}_2	\mathbb{Z}_2
13.bis	$(D_{4m}^*/C_{2m}, D_{8n}^*/D_{4n}^*)$	$\begin{cases} D^2(; 2, 2, n) & n \text{ odd} \\ D^2(2; n) & n \text{ even} \end{cases}$	$\mathbb{Z}_2 \times \mathbb{Z}_2$	\mathbb{Z}_2	\mathbb{Z}_2
	$(D_{8m}^*/D_{4m}^*, D_8^*/C_4)$	$D^2(; 2, 2)$	$\mathbb{Z}_2 \times \mathbb{Z}_2 \times \mathbb{Z}_2$	$\mathbb{Z}_2 \times \mathbb{Z}_2$	$\mathbb{Z}_2 \times \mathbb{Z}_2$
14.	$(D_{4m}^*/D_{4m}^*, T^*/T^*)$	$D^2(3; 2)$	$\mathbb{Z}_2 \times \mathbb{Z}_2$	\mathbb{Z}_2	\mathbb{Z}_2
15.	$(D_{4m}^*/D_{4m}^*, O^*/O^*)$	$D^2(; 2, 3, 4)$	\mathbb{Z}_2	\mathbb{Z}_2	$\{1\}$
16.	$(D_{4m}^*/C_{2m}, O^*/T^*)$	$D^2(; 2, 3, 3)$	$\mathbb{Z}_2 \times \mathbb{Z}_2$	\mathbb{Z}_2	\mathbb{Z}_2
17.	$(D_{8m}^*/D_{4m}^*, O^*/T^*)$	$D^2(; 2, 3, 4)$	\mathbb{Z}_2	\mathbb{Z}_2	$\{1\}$
18.	$(D_{12m}^*/C_{2m}, O^*/D_8^*)$	$D^2(; 2, 3, 3)$	\mathbb{Z}_2	\mathbb{Z}_2	$\{1\}$
19.	$(D_{4m}^*/D_{4m}^*, I^*/I^*)$	$D^2(; 2, 3, 5)$	\mathbb{Z}_2	\mathbb{Z}_2	$\{1\}$
33.	$(D_{8m}^*/C_{2m}, D_{8n}^*/C_{2n})_f$	$D^2(; 2, 2, n)$	$\{1\}$	$\{1\}$	$\{1\}$
33'.	$(D_{8m}^*/C_m, D_{8n}^*/C_n)_f$	$D^2(; 2, 2, n)$	\mathbb{Z}_2	$\{1\}$	\mathbb{Z}_2
34.	$(C_{4m}/C_m, D_{4n}^*/C_n)$	$S^2(2, 2, n)$	$\text{O}(2)$	S^1	\mathbb{Z}_2 rotation
34.bis	$(D_{4m}^*/C_m, C_{4n}/C_n)$	$D^2(n;)$	$\text{O}(2)$	$\{1\}$	$\text{O}(2)$

TABLE 5. The action on the fibrations with good base orbifold

of order 2. The other generator comes from the action of $j \in \mathrm{O}(2)^*$ on the left, and gives a reflection in a plane which fix all the three cone points of $S^2(2, 2, n)$. This is actually the only way in which $\mathbb{Z}_2 \times \mathbb{Z}_2$ can act effectively on $S^2(2, 2, n)$. In Table 5, we report the group which acts effectively on \mathcal{B} , without giving further details when the action is obvious.

Family 4. Group $\tilde{G} = (C_{4m}/C_{2m}, D_{8n}^*/D_{4n}^*)$ is a normal extension of the corresponding group in Family 3, the whole orientation-preserving isometry group $\mathrm{O}(2)$ preserves the fibration, and the base orbifold \mathcal{B} is $S^2(2, 2, 2n)$. The effective action on \mathcal{B} is a \mathbb{Z}_2 action. Here the action is not obvious, and is an action by reflection, as indicated in Table 5. However, when $n = 1$ in Family 4, we find $\tilde{G} = (C_{4m}/C_{2m}, D_8^*/D_4^*)$, which is conjugate to $\tilde{G} = (C_{4m}/C_{2m}, D_8^*/C_4)$ by an element which preserves the Hopf fibration (as it acts on the right). Hence this case falls in the already considered case of Family 3, having base orbifold $S^2(2, 2, 2)$ and action $\mathbb{Z}_2 \times \mathbb{Z}_2$ generated by a rotation and a reflection, as one can check. For this reason, the case $n = 1$ is not considered in the list.

Families 3bis and 4bis. It is also quite illuminating to consider the case of Families 3 bis and 4 bis, namely $(D_{4m}^*/C_{2m}, C_{4n}/C_{2n})$ and $(D_{4m}^*/D_{2m}^*, C_{4n}/C_{2n})$. In the first case, to understand the base orbifold, notice that the subgroup $\{1\} \times R_K = \{1\} \times C_{2n}$ acts as a group of rotations of order n , while the elements of $R = C_{4n}$ are paired to the antipodal map due to the action of $L = D_{4m}^*$ on the left (recall again the discussion in Subsection 4.2). Hence, depending whether n is odd or even, the quotient can be seen to be $D^2(n)$ or $\mathbb{R}P^2(n)$. Now, the action of the normalizer $D_{8n}^* \times \mathrm{O}(2)^*$ gives an $\mathrm{O}(2)$ action on \mathcal{B} , where the S^1 component acts by rotations and the other elements by reflections. Finally, observe that the groups in Family 3 having $m = 2$, namely $(D_8^*/C_4, C_{4n}/C_{2n})$, are conjugate in $S^3 \times S^3$ to groups of Family 4 with $m = 1$, of the form $(D_8^*/D_4^*, C_{4n}/C_{2n})$. However, the conjugating element does not preserve the Hopf fibration, and indeed the fibrations of the quotient orbifolds are different.

Family 1. Another case when the action of $\mathrm{Isom}_p(S^3/G)/\mathrm{Isom}_f(S^3/G)$ on \mathcal{B} is not obvious is Family 1. In fact, the normalizer of the groups of Family 1 is $(\mathrm{O}(2)^*/S^1, \mathrm{O}(2)^*/S^1)$ unless $r = 1$ or $r = 2$. The left S^1 acts by fixing all fibers pointwise. Hence the action on the base orbifold $S^2(nr, nr)$ is an $\mathrm{O}(2)$ action, where the S^1 subgroup clearly fix the two singular points, while the involutions act by reflections. Essentially what happens is that the local invariants associated to the two cone points of order nr are different, hence there are no fibration-preserving isometries which switch the two singular fibers. However, when $r = 1$ or $r = 2$, the isometry group is larger and the action on \mathcal{B} turns out to be an $(\mathrm{O}(2) \times \mathbb{Z}_2)$ -action, where the action of $\mathrm{O}(2)$ is the same as before, and the nontrivial element in the \mathbb{Z}_2 factor acts by the antipodal map of the “football” \mathcal{B} . For the same reason, the groups in Family 11, i.e. $(D_{4mr}^*/C_{2m}, D_{4nr}^*/C_{2n})_s$, have isometry group \mathbb{Z}_2 if $r > 2$, acting on $\mathcal{B} = D^2(; nr, nr)$ by a reflection which fixes the two corner points. When $r = 1$ or $r = 2$, extra isometries appear, which induce on \mathcal{B} reflections switching the two corner points.

5. GENERALIZED SMALE CONJECTURE

The purpose of this section is to provide a proof of the π_0 -part of the Generalized Smale Conjecture for spherical compact 3-orbifolds.

Theorem 1 (π_0 -part of the Generalized Smale Conjecture for spherical 3-orbifolds). *Let \mathcal{O} be any compact three-dimensional spherical orbifold. The inclusion $\mathrm{Isom}(\mathcal{O}) \rightarrow \mathrm{Diff}(\mathcal{O})$*

induces a group isomorphism

$$\pi_0 \text{Isom}(\mathcal{O}) \cong \pi_0 \text{Diff}(\mathcal{O}).$$

Let $\mathcal{O} = S^3/G$ be a spherical 3-orbifold, where G is a finite subgroup of $\text{SO}(4)$. We denote by Σ the singular set of \mathcal{O} and by M the complement of $\mathring{N}(\Sigma)$ in \mathcal{O} , where $\mathring{N}(\Sigma)$ is the interior of a regular neighbourhood of Σ .

Lemma 6. *If M is a Seifert fibered manifold, then G is conjugate to one of the groups in Families from 1 to 9 (including 1') or in Family 34.*

Proof. Since M has a Seifert fibration for manifolds, then Σ is a link.

Lift the fibration of M to $S^3 \setminus \mathring{N}(\tilde{\Sigma})$ where $\tilde{\Sigma}$ is the preimage in S^3 of Σ under the projection $S^3 \rightarrow S^3/G$ and $\mathring{N}(\tilde{\Sigma})$ is the interior of a regular neighbourhood of $\tilde{\Sigma}$; we note that $\tilde{\Sigma}$ is the set of points in S^3 that are fixed by a non-trivial element of G . The fibration of $S^3 \setminus \mathring{N}(\tilde{\Sigma})$ extends to a fibration of S^3 invariant under the action of G unless $\tilde{\Sigma}$ is the link in Figure 3 (see the proof of [BM70, Theorem 1]).

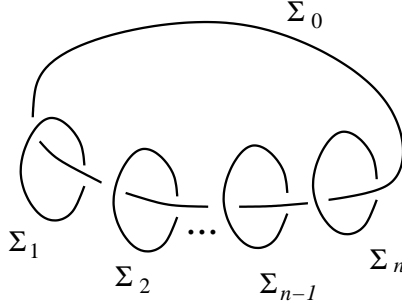


FIGURE 3.

Case 1: the fibration of $S^3 \setminus \mathring{N}(\tilde{\Sigma})$ extends. In this case the Seifert fibration of M is induced by a Seifert fibration of S^3 invariant under the action on G and extends to \mathcal{O} . We remark that the fibration on M is a classical Seifert fibration for manifold, while the fibration on \mathcal{O} is a Seifert fibration in an orbifold sense. The base orbifold of \mathcal{O} contains mirror reflector or corner reflector if and only if the fibration of \mathcal{O} contains infinite fibers that are not closed curves (they are arcs). Hence the fibration of \mathcal{O} induces a Seifert fibration on the manifold M when the singularities of the base orbifold are only cone points.

Table 5 gives the base orbifolds for all fibrations induced by an isometric copy of the Hopf fibration (including the anti-Hopf fibration). Lemma 5 ensures that the spherical orbifolds only have such fibrations except for groups which belong to Families 1, 1', 11, 11' up to conjugation. We recall that the fibrations of S^3 of the form z_1^u/z_2^v or \bar{z}_1^u/z_2^v , with $(u, v) \neq (1, 1)$ have two exceptional fibers, each left invariant by the group. For groups in Families 11, 11', there must be an involution which acts as a reflection on the exceptional fibers, and therefore the base orbifold of the quotient contains corner reflectors. Finally, by analyzing Table 5, one sees that if a spherical orbifold S^3/G has (at least) one Seifert

fibration with only cone singular points in the base orbifold, then it is conjugate to a group in Families 1 to 9 (including 1') or in Family 34.

Case 2: $\tilde{\Sigma}$ is the link in Figure 3. In this case Σ_0 is the fixed point set of a non trivial element of G . Since Σ admits no singular point with dihedral local group, the subgroup of G leaving invariant Σ_0 is cyclic or the direct product of two cyclic groups (see for instance [MZ06, Lemma 1]) and can be conjugated to a group in Family 1 or 1'. If $n \neq 1$, the whole group G leaves invariant Σ_0 and we are done. In the case of $n = 1$, G contains a subgroup G_0 of index at most two leaving invariant Σ_0 . If $G = G_0$, then the group can be conjugated to a group in Family 1 or 1'. Otherwise the elements in $G \setminus G_0$ exchange Σ_0 with Σ_1 . The groups having these properties are in Families 2, 3, 4 and 34. \square

Proof of Theorem 1. We denote by $\iota : \pi_0 \text{Isom}(\mathcal{O}) \rightarrow \pi_0 \text{Diff}(\mathcal{O})$ the homomorphism induced by the inclusion $\text{Isom}(\mathcal{O}) \rightarrow \text{Diff}(\mathcal{O})$.

For spherical manifolds the theorem was proved in [McC02]. Therefore we can suppose that Σ is not empty and we can apply the results in [CZ92] where the authors proved the existence of a finite subgroup of diffeomorphisms H such that the standard projection $\text{Diff}(\mathcal{O}) \rightarrow \pi_0 \text{Diff}(\mathcal{O})$ restricted to H is surjective. As a consequence of the Thurston Orbifold Geometrization Theorem (see [BLP05] and [DL09]), we can suppose that H is a group of isometries of \mathcal{O} , and we can conclude that also ι is surjective.

If Σ is a link, then [GL84, Theorem 2] implies directly that $M = \mathcal{O} \setminus \overset{\circ}{N}(\Sigma)$ is irreducible and atoroidal (i.e. each incompressible torus is boundary parallel). Indeed the argument used in the proof of [GL84, Theorem 2] works also if Σ is not a link, so we have that in any case M is irreducible and atoroidal. By the geometrization of 3-manifolds with non-empty boundary (see for example [Sha84, Proposition 3]) we obtain that M is either hyperbolic or Seifert fibered.

If M is hyperbolic, then by [CZ92, Theorem 1] the homomorphism ι is also injective and we are done. We can suppose that M is Seifert fibered and by Lemma 6 the group G is in one of the Families from 1 to 9 (including 1') or in Family 34.

An orientation-reversing isomorphism cannot be homotopic to the identity, hence to prove that ι is injective we can reduce to the orientation preserving case. We denote by $\text{Diff}^+(\mathcal{O})$ the group of orientation-preserving diffeomorphism of \mathcal{O} .

From now on we will identify the orbifold fundamental group $\pi_1(\mathcal{O})$ with G . We denote by $\text{Out}(G)$ the outer automorphism group, namely the quotient of the group of automorphisms of G by the normal subgroup of inner automorphisms. By using the properties of the universal covering orbifolds (see for example [Cho12, Sections 4.6 and 4.7]), we will define a homomorphism $\beta : \text{Diff}^+(\mathcal{O}) \rightarrow \text{Out}(G)$. If $f \in \text{Diff}^+(\mathcal{O})$, then f can be lifted to a diffeomorphism \tilde{f} of S^3 that normalizes G and by conjugation induces an automorphism of G . Different choices of the lifting can give different automorphisms, but they coincide up to the composition with an inner automorphism. Thus we can define $\beta(f)$ as the outer automorphism induced by a lift of f . Since an element of $\text{Diff}^+(\mathcal{O})$ isotopic to the identity lifts to a diffeomorphism of S^3 isotopic to the identity, an element of $\text{Diff}_0^+(\mathcal{O})$ induces a trivial automorphism on G . Thus $\text{Diff}_0^+(\mathcal{O})$ is contained in the kernel of β and we obtain an induced homomorphism $\pi_0 \text{Diff}(\mathcal{O}) \rightarrow \text{Out}(G)$ that we denote by α .

Therefore we have the following composition of group homomorphisms

$$\pi_0 \text{Isom}^+(\mathcal{O}) \xrightarrow{\iota} \pi_0 \text{Diff}^+(\mathcal{O}) \xrightarrow{\alpha} \text{Out}(G).$$

Analyzing the isometry group of \mathcal{O} when G is in Families 1-9 and 34 (see Tables 2 and 3), we can conclude that, if an element of $\text{Isom}^+(\mathcal{O})$ induces a trivial outer automorphism on G , we can find an isotopy from this element to the identity such that each level of the isotopy is an isometry. We obtain that $\alpha \circ \iota$ is injective, and consequently ι is injective. \square

We remark that the restriction to Families 1-9 and 34 is essential, in fact in some other cases $\alpha \circ \iota$ is not injective, even in the orientation preserving case (e.g. for groups in Family 31').

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