

PROPERTIES OF BÖRÖCZKY TILINGS IN HIGH DIMENSIONAL HYPERBOLIC SPACES

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ABSTRACT. In this paper we consider families of Böröczky tilings in hyperbolic space in arbitrary dimension, study some basic properties and classify all possible symmetries. In particular, it is shown that these tilings are non-crystallographic, and that there are uncountably many tilings with a fixed prototile.

1. Introduction

In 1975, K. Böröczky published some ingenious constructions of tilings in the hyperbolic plane \mathbb{H}^2 [3]. His aim was to show that there is not such a natural definition of density in the hyperbolic plane \mathbb{H}^2 as there is in the Euclidean plane \mathbb{E}^2 . A very similar tiling is mentioned also in [14], wherefore these tilings are often attributed to R. Penrose. In context of a local theorem for regular point sets ([6], see also [7]), M.I. Shtogrin realized that the Böröczky tilings are not crystallographic. V.S. Makarov considered analogues of these tilings in d -dimensional hyperbolic space and paid attention to the fact that for all $d \geq 2$, Böröczky-type prototiles never admit isohedral tilings of \mathbb{H}^d [12]. This is of interest in the context of Hilbert's 18th problem. Moreover, these d -dimensional Böröczky-type tilings provide an example for the construction of monohedral hyperbolic tilings in arbitrary high dimension. Following Makarov it is the only example of such kind.

Our motivation to study Böröczky tilings comes from the theory of aperiodic order. During the last decades it became clear that there is a large class of structures in between the realm of crystallographic structures on one side and the realm of completely disordered structures on the other side. A milestone was the discovery of quasicrystals, structures with high aperiodic order, but without any translational symmetry. This generated a need for reasonable definitions of aperiodic order. In several references, a tiling \mathcal{T} in \mathbb{E}^d is said to be nonperiodic if $\mathcal{T} = t + \mathcal{T}$ implies $t = 0$. According to this definition, there is a single tile in \mathbb{E}^3 which tiles only aperiodically ('Conway's biprism' or SCD tile for Schmitt-Conway-Danzer tile, see [5] or [2]). This is slightly unsatisfactory, since those SCD tilings can possess symmetries of infinite order, namely, screw motions. We propose that a precise definition of (strong) nonperiodicity should require the symmetry group of \mathcal{T} to be finite. Böröczki tilings are good examples to sharpen the definition of nonperiodicity. This becomes clear from our main results Theorem 6.1 and Corollary 6.2. Another interesting point is that any tiling in \mathbb{E}^d gives rise to a Böröczky type tiling in \mathbb{H}^{d+1} , by stacking orbits of nonperiodic substitution tilings in a similar way as we stack canonical cube tilings in the present paper [9]. This yields further examples of tilings in the range between (strongly) nonperiodic tilings and crystallographic tilings.

We should emphasize that we do not consider the problem of hyperbolic density here. But we should mention that recently Bowen and Radin introduced a measure theoretic approach to define 'optimally dense' packings in \mathbb{H}^d by considering invariant measures on the space S of all packings of \mathbb{H}^d by spheres with fixed radius [4]. This definition coincides with the usual one for crystallographic sphere packings, but it also allows assigning density to almost all nonperiodic sphere packings. In this framework, the 'evil' examples like Böröczky's can be shown to be of measure zero with respect to the invariant measures on S (and therefore negligible). It is also shown in [4] that optimal density and symmetry of sphere packings are strongly related: Almost all optimally dense sphere packings in \mathbb{H}^d are not crystallographic (with respect to the radius of the spheres).

In the next section, we give an explicit construction of Böröczky's prototile. In Section 3, we describe shortly the situation in the hyperbolic plane \mathbb{H}^2 . Some basic terms and tools are introduced. Since Section 3 is a special case of Section 5, some proofs are omitted to Section 5. In Section 4 we state a necessary and sufficient condition for a tiling to be crystallographic [7]. This statement can be applied to B-tilings in \mathbb{H}^2 . In Section 5 we consider Böröczky's construction in arbitrary dimension $d \geq 2$ and obtain some results on B -tilings in \mathbb{H}^d . Section 6 uses these results and gives a complete classification of the symmetry groups of these tilings.

Notation: We denote d -dimensional hyperbolic space by \mathbb{H}^d , d -dimensional Euclidean space by \mathbb{E}^d , and the set of positive integers by \mathbb{N} . Let \mathbb{X} be either a Euclidean space, or a hyperbolic space, or a spherical space. Consider compact subsets $T \subseteq \mathbb{X}$, such that T is the closure of its interior. A collection of such sets $\{T_1, T_2, \dots\}$ is called a *tiling*, if the union of the T_i is the whole space \mathbb{X} and the T_i do not overlap, i.e., the interiors of the tiles are pairwise disjoint. The T_i are called *tiles* of the tiling. A tiling is called *crystallographic*, if the symmetry group of the tiling has compact fundamental domain, see [13]¹.

2. Construction of Böröczky's prototile

Let \mathbb{X} be either a Euclidean space, or a hyperbolic space, or a spherical space. Consider compact subsets $T \subseteq \mathbb{X}$, such that T is the closure of its interior. A collection of such sets $\{T_1, T_2, \dots\}$ is called a *tiling*, if the union of the T_i is the whole space \mathbb{X} and the T_i do not overlap, i.e., the interiors of the tiles are pairwise disjoint. The T_i are called *tiles* of the tiling.

Let us give a simple description of one of Böröczky's constructions, which follows [10]. We assume familiarity with basic terms and facts of d -dimensional hyperbolic geometry, see for instance [1] (for $d = 2$, with emphasis of length and area in \mathbb{H}^2) or [15] (for $d \geq 2$).

Let ℓ be a line in the hyperbolic plane of curvature $\chi = -1$ (see Figure 2). Place points $\{X_i \mid i \in \mathbb{Z}\}$ on ℓ , such that the length of the line segment $X_i X_{i+1}$ is $\ln 2$ for all $i \in \mathbb{Z}$. Draw through every point X_i a horocycle E_i orthogonal to ℓ , such that all the horocycles E_i have a common ideal point \mathcal{O} at infinity. On each E_i , choose points X_i^j , such that $X_i^0 = X_i$ and the length of the arc $X_i^j X_i^{j+1}$ is the same for all $i, j \in \mathbb{Z}$. Denote by ℓ_j the line parallel to ℓ , which intersects E_0 at X_0^j , and intersects ℓ at the ideal point \mathcal{O} . (In particular: $\ell_0 = \ell$.) Due to the choice $|X_i X_{i+1}| = \ln 2$ and $\chi = -1$, the arc on E_1 between ℓ_0 and ℓ_1 is twice the length as the arc on E_0 between the same lines.

¹Sometimes, a group is called crystallographic if its fundamental domain has finite volume [16].

Let H_0 be a strip between horocycle E_0 and horocycle E_1 (including E_0 and E_1 themselves), and L_i a strip between two parallel lines ℓ_i and ℓ_{i+1} (including ℓ_i and ℓ_{i+1} themselves). All intersections $B_i := H_0 \cap L_i$, $i \in \mathbb{Z}$, are pairwise congruent shapes.

These shapes tile the plane [3],[10]. Indeed, they pave a horocyclic strip between horocycles E_0 and E_1 . It is clear that shape B_1 can be obtained from B_0 by means of a horocyclic turn τ about the ideal point \mathcal{O} that moves point $X_0 \in E_0$ to point $X_0^1 \in E_0$. Any shape B_i in the horocyclic strip H_0 is obtained as $\tau^i(B_0)$. Now, let λ be a shift along ℓ_0 moving the strip H_0 to the strip H_1 . This shift transfers the pavement of H_0 to a pavement of H_1 . Thus, a sequence of shifts λ^j ($j \in \mathbb{Z}$) along a line ℓ_0 extends the pavement of the horocyclic strip H_0 to the entire plane, resulting in one of several possible Böröczky tilings.

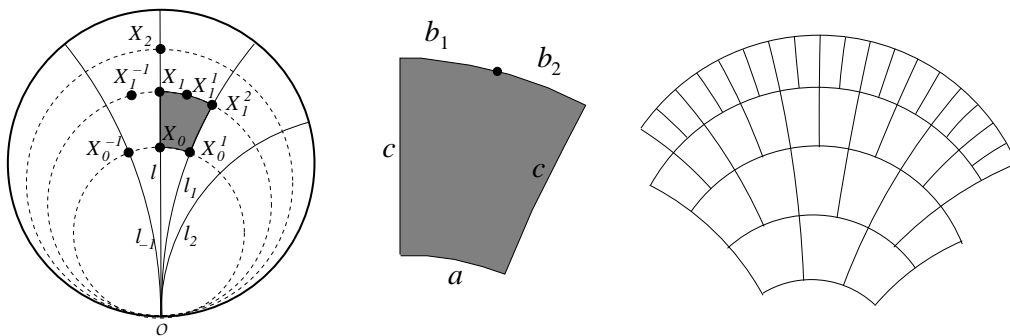


FIGURE 1. The construction of the prototile in the Poincaré-disc model (left), a Böröczky pentagon B with the types of the five edges indicated (centre), and a small part of a Böröczky tiling (right).

Let $B := B_0 = L \cap H_0$. The boundary of B consists of two straight line edges, labelled c in Figure 2 (centre), and two arcs, a shorter one labelled a , and a longer arc labelled b_1, b_2 . The arcs are parts of horocycles. The longer arc is subdivided in two halves b_1 and b_2 . For brevity, we will say that B has three (horocyclic) edges a, b_1, b_2 and two straight line edges c . Thus we regard B as a pentagon. Indeed, though the Böröczky pentagon B is neither bounded by straight line segments, nor it is a convex polygon, it suffices to replace all three horocyclic arcs by straight line edges in order to get a convex polygonal tile. But there is no need to use this modification here.

On the c -edges, we introduce an orientation from edge a to edge b_1 or b_2 respectively. An edge-to-edge tiling is a tiling in which any non-empty intersection of tiles is either their common edge or a vertex. An edge-to-edge tiling of the hyperbolic plane by Böröczky pentagons, respecting the orientations of c -edges, is called a *Böröczky tiling*, or, for the sake of brevity, *B-tiling*. As we have already mentioned, all B-tilings are not crystallographic. In the next sections we will examine the symmetry group of B-tilings in detail.

3. The Böröczky Tilings in \mathbb{H}^2

In a Böröczky tiling every tile is surrounded by adjacent tiles in essentially the same way: A c -edge meets always a c -edge of an adjacent tile. A b_1 -edge (b_2 -edge resp.) meets an a -edge of an adjacent tile. The a -edge of a tile always touches either the b_1 -edge or the b_2 -edge of an adjacent tile.

Therefore we consider in the following definitions two kinds of subsets of tiles in a B-tiling, which are connected in two different ways: either we move from tile to an adjacent tile only across c -edges, or only across a -, b_1 -, or b_2 -edges.

Definition 3.1. *A ring in a B-tiling is a set $(T_i)_{i \in \mathbb{Z}}$ of tiles ($T_i \neq T_j$ for $i \neq j$), such that T_i and T_{i+1} share c -edges for all $i \in \mathbb{Z}$ (see Figure 2).*

Definition 3.2. *Let $I \subset \mathbb{Z}$ be a set of consecutive numbers. A horocyclic path is a sequence $(T_i)_{i \in I}$ of tiles ($T_i \neq T_j$ for $i \neq j$), such that, for all $i \in \mathbb{Z}$, T_i and T_{i+1} share an edge which is not a c -edge (see Figure 2).*

We always require rings and horocyclic paths to contain no loops, i.e., all tiles in the sequence are pairwise different. A ring is a sequence of tiles which is infinite in both directions, shortly *biinfinite*. A ring forms a pavement of a horocyclic strip bounded by two consecutive horocycles E_i and E_{i+1} . A horocyclic path is either finite, or infinite in one direction, or biinfinite.

If, in the case of horocyclic paths, an a -edge of T_i touches a b_1 - or b_2 -edge of T_{i+1} , we say shortly: At this position the horocyclic path goes *down*, otherwise we say it goes *up*.

Proposition 3.3. *Any horocyclic path in a B-tiling contains either only ups, or only downs, or is of the form down-down- \dots -down-up-up- \dots -up.*

Proof. There is only one way to pass from a tile through its a -edge to an adjacent tile. So there is only one way to go down from a given tile. If we have in a horocyclic path the situation 'up to T_{i+1} , down to T_{i+2} ', it follows $T_i = T_{i+2}$. This situation is ruled out by the requirement, that all tiles in a horocyclic path are different. So 'up-down' cannot happen, which leaves only the possibilities mentioned in Proposition 3.3. \square

There are always two possibilities to go up from some tile T in a B-tiling. That means, there are 2^k different paths starting in T and containing exactly k ups (and no downs). Since there is only one possibility to go down from any tile, there is only one infinite horocyclic path of the form down-down-down- \dots starting in T .

Definition 3.4. *The unique infinite path of the form down-down- \dots starting at a tile T is called the tail (of T).*

If tiles T and T' and also tiles T' and T'' are linked by horocyclic paths w and w' respectively, then the tiles T and T'' are also linked by a horocyclic path. Therefore, the property of tiles to be linked by a horocyclic path is an equivalence relation. Hence a set of tiles is partitioned into a number of non-overlapping classes $\mathcal{P}_1, \mathcal{P}_2, \dots$ called pools.

Definition 3.5. *The set of all tiles which can be linked with some given tile by a horocyclic path forms a pool.*

It is clear that if $T \in \mathcal{P}$ then $t(T) \subset \mathcal{P}$.

Definition 3.6. *Two tails $t(T) = (T = T_0, T_2, \dots)$, $t(T') = (T' = T'_0, T'_2, \dots)$ in a B-tiling are called cofinally equivalent, written $t(T) \sim t(T')$, if there are $m, n \in \mathbb{N}$ such that $T_{m+i} = T'_{n+i}$ for all $i \in \mathbb{N}$.*

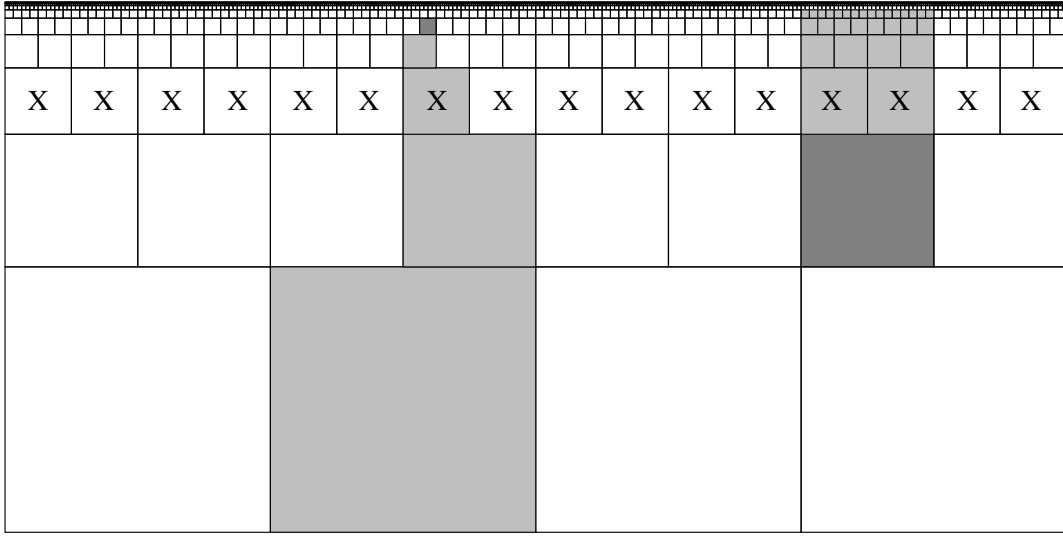


FIGURE 2. A patch of the Böröczky tiling in the half-plane model. The tiles marked by an X show (a part of) a ring. The grey shaded tiles show: a horocyclic path of length five (left, it is also the beginning of the tail of the dark tile on top); the tower on the dark tile (right, for the definition of a tower, cf. Section 5).

If $t(T) \sim t(T')$ then T and T' are linked by a horocyclic path

$$T = T_0, T_1, \dots, T_m, T'_{n-1}, \dots, T'_1, T'_0 = T',$$

hence T and T' belong to one pool. The inverse statement is also obviously true. Thus, the following is true.

Proposition 3.7. *Tiles T and T' belong to a pool if and only if their tails are cofinally equivalent.*

A tail (T_0, T_1, T_2, \dots) gives rise to a sequence $s(T) = (s_1, s_2, \dots) \in \{-1, 1\}^{\mathbb{N}}$ in the following way: If the a -edge a of T_{i-1} coincides with the b_1 -edge of T_i , then set $s_i := 1$, otherwise (if it coincides with the b_2 -edge) set $s_i := -1$.

Definition 3.8. Let $s = (s_1, s_2, \dots), s' = (s'_1, s'_2, \dots) \in \{-1, 1\}^{\mathbb{N}}$.

- s and s' are cofinally equivalent, denoted by $s \sim s'$, if there exist $m, n \in \mathbb{N}$, such that $s_{m+i} = s'_{n+i}$ for all $i \in \mathbb{N}$.
- s is periodic (with period k), if there exists $k \geq 2$ such that $s = (s_k, s_{k+1}, \dots)$.
- s is cofinally periodic, if s is cofinally equivalent to a periodic sequence.

Proposition 3.9. *Every pool contains infinitely many tiles. Moreover, every intersection of any ring with any pool contains infinitely many tiles.*

Proof. The tail of any tile T contains infinitely many tiles, all belonging to the same pool. Moreover, from any tile there are starting 2^k horocyclic paths of length k going upwards. The final tiles of these paths are all in the same ring.

So, by going down from T by k steps and after that going up k steps gives us horocyclic paths to 2^k different tiles in the same ring as T and in the same pool as T . Since k can be chosen arbitrary large, the claim follows. \square

Proposition 3.10. *In a B-tiling in \mathbb{H}^2 there is either one pool or two pools.*

Proof. First of all, note the following. Let x be an interior point of some pool, and let ℓ' be a line such that $x \in \ell'$, and such that ℓ' contains the ideal point \mathcal{O} at infinity (compare Section 1). Then ℓ' is contained entirely in the interior of the pool. Therefore, if a point x is on the boundary of two pools then the line ℓ' entirely belongs to the boundary of two pools.

Assume there is more than one pool. Consider some ring R . Each of the pools has infinite intersection with R . Let T and $T' \in R$ be adjacent tiles from different pools, say, \mathcal{P}_1 and \mathcal{P}_2 . Then a line ℓ' containing the common c -edge of \mathcal{P}_1 and \mathcal{P}_2 separates these pools. Moreover, since a pool is a linearly connected set, these pools lie on opposite sides each of the line ℓ' . Assume there is a third pool \mathcal{P}_3 . Let it lie on the same side of ℓ' as \mathcal{P}_2 . Since $\mathcal{P}_3 \cap R \neq \emptyset$, there is some tile $T_3 \in \mathcal{P}_3 \cap R$. There exists a line ℓ'' which separates \mathcal{P}_2 and \mathcal{P}_3 . The pool has to lie between two parallel lines ℓ' and ℓ'' . But this impossible because in this case the intersection $\mathcal{P} \cap R$ is finite what contradicts Proposition 3.9. \square

In particular, there are two pools if and only if there are tiles $T, T' \in \mathcal{T}$, whose tails have sequences $s(T) = (1, 1, 1, \dots)$ and $s(T') = (-1, -1, -1, \dots)$.

Proposition 3.11. *In any B-tiling holds: $t(T) \sim t(T') \Leftrightarrow s(T) \sim s(T')$*

Proof. One direction (\Rightarrow) is clear from the construction of $s(T)$ out of $t(T)$.

The other direction: If there is only one pool, all tiles are cofinally equivalent, and we are done. If there are two pools $\mathcal{P}_1 \neq \mathcal{P}_2$, we know that these pools corresponds to sequences $(-1, -1, -1, \dots)$ and $(1, 1, 1, \dots)$. Therefore, if $s(T) \sim s(T')$, then T and T' belong to the same pool: $t(T) \sim t(T')$. \square

Let $\text{Sym}(\mathcal{T})$ be the symmetry group of \mathcal{T} , i.e., the set of all isometries φ where $\varphi(\mathcal{T}) = \mathcal{T}$. The group of order two is denoted by \mathcal{C}_2 .

Theorem 3.12. *The symmetry group $\text{Sym}(\mathcal{T})$ of any B-tiling in \mathbb{H}^2 is*

- isomorphic to $\mathbb{Z} \times \mathcal{C}_2$ in the case of two pools,
- isomorphic to \mathbb{Z} in the case of one pool and $s(T)$ periodic for some T ,
- trivial else.

Proof. (in Section 5) \square

If there is one pool and $s(T)$ is periodic for some T , it can happen, that $\text{Sym}(\mathcal{T})$ contains shifts along a line, and also 'glide-reflections', i.e. a reflection followed by a shift along a line. The latter is the case, if $s = (s_1, s_2, \dots)$ has a period k as in Definition 3.8, where k is an even number, and if holds:

$$(1) \quad s = (-s_{k/2+1}, -s_{k/2+2}, \dots).$$

In the following, we mean by *essential period* $\frac{k}{2}$, if (1) holds, otherwise k .

Example: A tiling \mathcal{T} with a periodic sequence

$$s(T) = (1, 1, -1, -1, 1, 1, -1, -1, \dots)$$

has period 4, and essential period 2. \mathcal{T} has a symmetry φ , where φ is a glide-reflection. The action of the reflection on $s(T)$ gives $(-1, -1, 1, 1, -1, -1, 1, 1, \dots)$. This is followed by a shift along an edge of type C along two tiles which gives

$$(1, 1, -1, -1, 1, 1, -1, -1, \dots) = s(T).$$

Corollary 3.13. *The fundamental domain of $\text{Sym}(\mathcal{T})$ is*

- one half ring in the case of two pools,
- the union of k rings in the case of one pool and $s(T)$ for some T periodic, where k is the essential period of $s(T)$,
- \mathbb{H}^2 else.

4. Böröczky tilings are non-crystallographic

Let \mathcal{T} be a face-to-face tiling in \mathbb{E}^d or \mathbb{H}^d .

Definition 4.1. *The 0-corona $C_0(T)$ of a tile T is T itself. The k -corona $C_k(T)$ of T is the complex of all tiles of \mathcal{T} which have a common $(d-1)$ -face with some $T' \in C_{k-1}(T)$.*

Figure 4 shows a tile T in a B-tiling together with its first and second coronae. Note that, for $T \neq T'$, the coronae $C_k(T)$ and $C_k(T')$ can coincide as complexes. Nevertheless, the corona denoted by $C_k(T)$ is considered as a corona about the centre T , whereas corona $C_k(T')$ considered as a corona about T' .

Definition 4.2. *Coronae $C_k(T)$ and $C_k(T')$ are considered as congruent if there is an isometry that moves T to T' and $C_k(T)$ to $C_k(T')$.*

Given a tiling \mathcal{T} , denote by N_k the number of congruence classes of k -coronae.

Proposition 4.3. *The number N_k of different k -coronae ($k \geq 1$) in a B-tiling is 2^{k-1} , up to isometries.*

Proof. Let us enumerate all rings in a biinfinite way. Given a tile T , we denote the ring containing T by \mathcal{R}_0 . All the rings lying upward from \mathcal{R}_0 are enumerated as $\mathcal{R}_{-1}, \mathcal{R}_{-2}, \mathcal{R}_{-3}, \dots$. All rings going downward from \mathcal{R}_0 are enumerated by positive integers $\mathcal{R}_1, \mathcal{R}_2, \mathcal{R}_3, \dots$

It is easy to see that $C_k(T) \cap \mathcal{R}_i \neq \emptyset$ if and only if $-k \leq i \leq k$. It is also easy to check that for any tiles T and $T' \in \mathcal{R}_0$ the following complexes in \mathcal{T}

$$C_k^-(T) := C_k(T) \cap \left(\bigcup_{i=-k}^0 \mathcal{R}_i \right) \quad \text{and} \quad C_k^-(T') := C_k(T') \cap \left(\bigcup_{i=-k}^0 \mathcal{R}_i \right)$$

are pairwise congruent. In other words: All k -coronae look the same, if we only look at the rings $\mathcal{R}_0, \mathcal{R}_{-1}, \mathcal{R}_{-2}, \dots$ (i.e., the tiles 'above' T). Moreover, since T and $C_k^-(T)$ are both mirror symmetric, this congruence can be realized by two isometries both moving T into T' . In addition, the same is true also for any two tiles from a B-tiling.

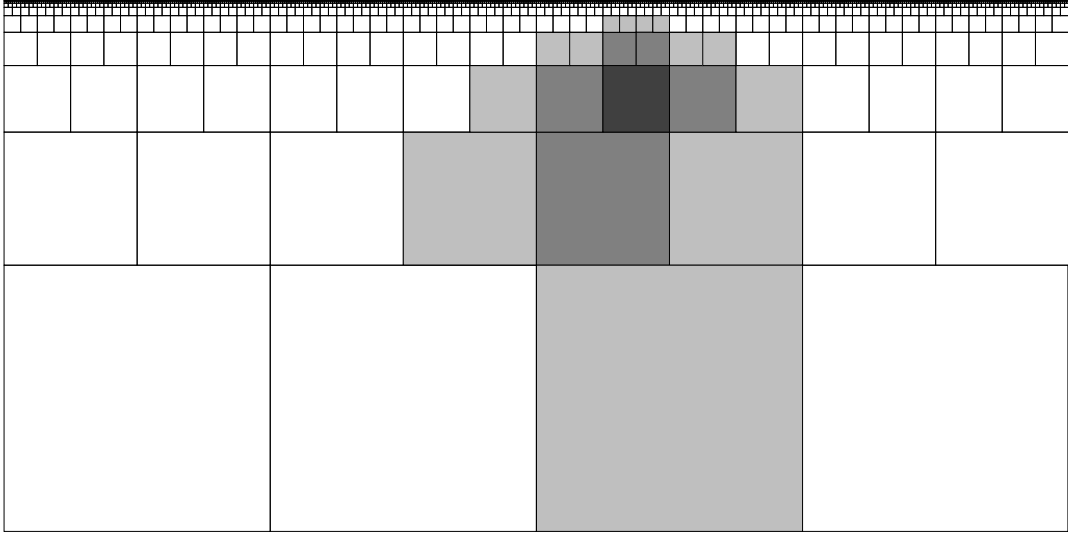


FIGURE 3. The first corona (medium grey) and the second corona (all grey tiles) of the dark tile.

The upper part of any corona is on one convex side of a horocycle. This part obviously contains a half plane cut of by a line perpendicular to ℓ . Thus, all the tiles in \mathcal{T} for any $k \in \mathbb{N}$ have k -coronae whose larger parts are pairwise congruent.

So, the upper part $C_k^-(T)$ of some k -corona $C_k(T)$ around T is uniquely determined independently of T . The entire corona $C_k(T)$ is determined completely (up to orientation) by the first k members of the tail $t(T)$, or, what is equivalent, by the first numbers s_1, s_2, \dots, s_k in the sequence $s(T)$. Our next task is to show that in a given tiling for any finite sequence of $k \pm 1$'s there is a tile T whose tail is encoded exactly by this sequence.

Let us enumerate the tiles in ring \mathcal{R}_0 (the ring containing T) by upper indices. Let $T^0 := T$ and let other tiles on one side of T^0 be enumerated by positive i 's and on the other side by negative i 's in a consecutive manner.

Let $s_k(T^0) = (s_1, s_2, \dots, s_k)$. Then (see Figure 2) all tiles T^{2^n} from ring \mathcal{R}_0 have the same first number s_1 in $s(T^{2^n})$. And, in general, it is easy to see that every $T^i \in \mathcal{R}_0$, where $i \equiv 0 \pmod{2^k}$, has the same first k numbers in $s(T^i)$. It follows that in a biinfinite sequence $(T_i) \in \mathcal{R}_0$ each 2^k -th tile has the same coronae encoded by $s_k(T^0)$.

Consider in ring \mathcal{R}_0 a segment $T^0, T^1, T^2, \dots, T^{2^k-1}$. Recall that $s_k(T^0) = (s_1, s_2, \dots, s_k)$. Now, one can easily check that either $s_k(T^1) = (-s_1, s_2, s_3, \dots, s_k)$, or $s_k(T^2) = (s_1, -s_2, s_3, \dots, s_k)$, compare for instance Figure 2.

And, in general, take $0 \leq i \leq 2^k - 1$. The number i can be represented in a unique way as

$$i = \sum_{j=0}^{k-1} \delta_j 2^j,$$

where $\delta_j = 0$ or 1 . Then, as one can easily see,

$$s_k(T^i) = \{(-1)^{\delta_j} s_j \mid 0 \leq j \leq k\}.$$

Thus, any B-tiling contains 2^k different k -coronae, up to orientation. \square

Now we should emphasise that the number N_k of coronae in a B-tiling is unbounded, as k tends to infinity. But in any crystallographic tiling (independently on how it is defined, as with either compact or cocompact fundamental domain), the number of coronae classes is always bounded: $N_k \leq m < \infty$, where m is some fixed number independent of k . Therefore we have obtained the following result.

Theorem 4.4. *All B-tilings are non-crystallographic.*

On the other side, this last theorem (in the context of Proposition 4.3 and a local theory on crystallographic structures) can be considered as a consequence of the following theorem, which appears in [7]. This theorem is a generalization of the Local Theorem, see [6].

Theorem 4.5. *Let \mathbb{X}^d be a Euclidean or hyperbolic space. A tiling \mathcal{T} in \mathbb{X}^d is crystallographic if and only if the following two conditions hold for some $k \geq 0$:*

- (1) *For the numbers N_k of k -coronae in \mathcal{T} holds: $N_{k+1} = N_k$, and N_k is finite.*
- (2) *$S_{k+1}(i) = S_k(i)$ for $1 \leq i \leq N_k$,*

where $S_k(i)$ denotes the symmetry group of the i -th k -corona.

Note that Condition (2) in the theorem makes sense only when Condition (1) is fulfilled. In a B-tiling, condition (2) is violated for $k = 0$, and condition (1) is violated for all $k \geq 1$. Thus Theorem 4.4 is a particular case of the Local Theorem.

But in fact, the necessity part of the Local Theorem is trivial in contrast to a valuable sufficiency part. Indeed, if for any $k \in \mathbb{N}$ at least one condition does not hold, this means that $N_k \rightarrow \infty$ as $k \rightarrow \infty$. The latter one implies that the tiling under consideration is non-crystallographic.

5. Böröczky Tilings in \mathbb{H}^{d+1}

Let us give the construction of a $d + 1$ -dimensional prototile. The construction in Section 1 is a special case of this one, with $d = 1$. Throughout this section, we will make strong use of the fact that any d -dimensional horosphere E in \mathbb{H}^{d+1} is isometric to the Euclidean space \mathbb{E}^d , see for instance [15, §4.7]. Whenever we consider a subset A of a horosphere E , we will freely switch between regarding A as a subset of \mathbb{E}^d and a subset of E .

Let ℓ be a line in \mathbb{H}^{d+1} . Choose a horosphere E_0 orthogonal to ℓ . Let \square' be a d -dimensional cube in E_0 , centred at $E_0 \cap \ell$. Let H_1, \dots, H_{2d} be hyperbolic hyperplanes, orthogonal to E_0 , such that each H_i contains one of the $2d$ distinct $(d - 1)$ -faces of the cube \square' . Denote by H_i^+ the halfspace defined by H_i which contains the cube \square' , and let $C_{d+1} := \bigcap_{i=1}^{2d} H_i^+$. Note that the intersection $C_{d+1} \cap E_0 = \square'$. Let E_1 be another horosphere, such that E_1 is concentric with E_0 , E_1 is not contained in the convex hull of E_0 , and the distance of E_0 and E_1 is $\ln 2$. Then, $C_{d+1} \cap E_1$ is a d -dimensional cube of edge-length 2. Without loss of generality, let this cube in E_1 be $\square := \{x = (x_1, \dots, x_d) \in E_1 \mid -1 \leq x_i \leq 1\}$. Divide \square into 2^d cubes

$$\square_{(\sigma_1, \sigma_2, \dots, \sigma_d)} = \{x \in \square \mid x_i \sigma_i \geq 0\}, \quad \sigma_i \in \{-1, 1\}.$$

Let L_0 be the layer between E_0 and E_1 . A *Böröczky prototile* in \mathbb{H}^{d+1} is defined as

$$B := C_{d+1} \cap L_0.$$

By construction, the prototile B has $2^d + 2d + 1$ facets: one 'lower' facet (a unit Euclidean cube in E_0 , denoted as a -facet), 2^d 'upper' facets (unit Euclidean cubes in E_1 , denoted as b -facets), and $2d$ aside facets, denoted as c -facets. One should mention that the Böröczky prototile is not a convex polyhedron. Moreover, it is not a polyhedron at all. Though we call them facets, the lower and upper facets are Euclidean d -cubes isometrically embedded into hyperbolic space and they do not lie in hyperbolic hyperplanes. The c -facets lie in hyperbolic hyperplanes, but for $d \geq 2$ they are also not d -dimensional polyhedra, because their boundaries do not consist of hyperbolic polyhedra of dimension $d - 1$. A c -facet of a $d + 1$ -dimensional Böröczky prototile is a point set which lies in a hyperbolic hyperplane H and is contained between the intersections $E_0 \cap H$ and $E_1 \cap H$. Since the intersections are also horocycles of dimension $d - 1$, the c -facets are Böröczky prototiles of dimension $d - 1$.

Proposition 5.1. *Prototile B admits a face-to-face tiling T by its copies.*

Proof. Take a horosphere E_0 and a unit cube $\square' \subset E_0$. There are parabolic turns g_i ($i = 1, 2, \dots, d$) of \mathbb{H}^{d+1} such that their restrictions $g_i|_{E_0}$ on E_0 are translations of E_0 along edges of \square' . The g_i ($i = 1, 2, \dots, d$) span an Abelian group G isomorphic to \mathbb{Z}^d . The orbit of the Böröczky prototile under G is a pavement of the layer between E_0 and E_1 by copies of B .

Let τ be a shift of \mathbb{H}^{d+1} along the line ℓ moving E_0 to E_1 . Then, the shifts τ^k , $k \in \mathbb{Z}$, move the pavement of the mentioned layer into all other layers, resulting in a tiling of the whole space. \square

We call any face-to-face tiling of \mathbb{H}^{d+1} with prototile B a *Böröczky tiling*, or shortly *B-tiling*. Analogously to \mathbb{H}^2 , we call a - and b -facets of B *horospheric facets*. We should emphasise that if some horosphere E_0 is fixed, then a unique sequence $(E_i)_{i \in \mathbb{Z}}$ of horospheres orthogonal to ℓ is induced, provided the distance along ℓ between any two consecutive horospheres E_i and E_{i+1} is $\ln 2$. By construction of a B-tiling, all a - and b -facets induce a tiling of each horosphere by pairwise parallel unit cubes.

Let us state the definition of an analogue of a two-dimensional ring.

Definition 5.2. *Let \mathcal{T} be a B-tiling in \mathbb{H}^{d+1} , and let L_i be a layer of space between horospheres E_i and E_{i+1} . The set \mathcal{R}_i of all tiles from \mathcal{T} lying in L_i is called a layer (of the tiling).*

It is obvious that two tiles belong to one layer if and only if there is some path T_i , $i \in I$, such that for any $i, i + 1 \in I$, the tiles T_i and T_{i+1} have a c -facet in common.

Let I be a segment of \mathbb{Z} of consecutive numbers. In analogy to Section 3, a sequence $(T_i)_{i \in I}$ of tiles is called a *horospheric path*, if for all $i, i + 1 \in I$ the tiles T_i and T_{i+1} share a horospheric facet, and $T_i \neq T_j$ if $i \neq j$. By construction, the single a -facet of any tile in some Böröczky tiling in \mathbb{H}^{d+1} coincides with one of 2^d b -facets of an adjacent tile. To describe horospheric paths by sequences, we use the alphabet

$$\mathcal{A} = \{\sigma \mid \sigma = (\sigma_1, \sigma_2, \dots, \sigma_d), \sigma_i = \pm 1\}, |\mathcal{A}| = 2^d$$

First of all, we emphasise that for any tile B' from a B-tiling, a natural bijection between its 2^d b -facets and the elements of \mathcal{A} is uniquely determined, provided such a bijection (between

b -facets and elements of \mathcal{A}) is already established for some tile B . Indeed, assume that a tile B' lies in the i -th layer \mathcal{R}_i . Then the bijection for B is canonically carried by a single shift τ^i of the tile B along ℓ into \mathcal{R}_i , followed by an appropriate translation inside the layer \mathcal{R}_i .

Analogous to the two-dimensional case, any horospheric path $(T_i)_{i \in I}$ of the form down-down- \dots gives rise to a word $s(T) = (\sigma^{(i)})_{i \in I}$ over \mathcal{A} in the following way: If an a -facet of T_i lies on a b -facet of T_{i+1} , which corresponds to the cube $\square_{(\sigma_1, \dots, \sigma_d)}$, we set $\sigma^{(i)} := (\sigma_1, \dots, \sigma_d)$.

As in Section 3, the tail $t(T)$ of a tile T is the unique infinite horospheric path $(T = T_0, T_1, \dots)$ beginning in T of the form down-down-down- \dots .

The definition of a pool and of the equivalence of tails goes exactly as in Definition 3.5 and Definition 3.6 (replace 'horocyclic' by 'horospheric'). Moreover, the proofs of Propositions 3.3 and 3.9 work in any dimension, so both propositions are valid here.

Definition 5.3. For a tile $T \in \mathcal{T}$, let $W(T)$ be the set of all tiles T' , such that T can be linked with T' by a horospheric path T, \dots, T' of the form up-up- \dots . We call $W(T)$ a tower, or the tower on T .

For an example of a tower in \mathbb{H}^2 , see Figure 2.

Proposition 5.4. Let $\mathcal{P} \subset \mathcal{T}$ be a pool, $T \in \mathcal{P}$ and $t(T) = (T = T_0, T_1, T_2, \dots)$. Then

$$(2) \quad W(T_i) \subset W(T_{i+1}) \quad \text{and} \\ \mathcal{P} = \bigcup_{T' \in t(T)} W(T') = W(T_0) \cup W(T_1) \cup W(T_2) \cup \dots .$$

Proof. Since a horospheric path T_{i+1}, T_i is of the form 'up', any tile $T' \in W(T_i)$ can be linked with T_{i+1} by a path of the form up-up- \dots , namely T_{i+1}, \dots, T' . This implies $W(T_i) \subset W(T_{i+1})$.

Of course, all tiles $T' \in t(T)$ are in the same pool as T because they are connected by a horospheric patch in $t(T)$. All tiles in $W(T')$ are in the same pool as T' , therefore in the same pool as T . This shows $\mathcal{P} \supseteq \bigcup_{T' \in t(T)} W(T')$.

Let $T'' \in \mathcal{P}$. Then, by definition of a pool, exists a horospheric path connecting T and T'' . By Proposition 3.3, this path is either of the form up-up- \dots , or down-down- \dots , or down-down- \dots -down-up- \dots -up.

If this path (T, \dots, T'') is up-up- \dots , then $T'' \in W(T_i)$ for any $T_i \in t(T)$, thus T'' is contained in the right hand side of (2).

If the path (T, \dots, T'') is down-down- \dots , then $T'' \in t(T)$, thus T'' is contained in the right hand side of (2).

If the path (T, \dots, T'') is down-down- \dots -down-up- \dots -up, then this path contains a tile \tilde{T} , such that the path (T, \dots, T'') consists of two paths: a down-down- \dots -down path (T, \dots, \tilde{T}) , and an up-up- \dots path (\tilde{T}, \dots, T'') . From here it follows that $\tilde{T} \in t(T)$ and $T'' \in W(\tilde{T})$, thus T'' is contained in the right hand side of (2). \square

Let us now investigate the structure of a tower and a pool, respectively. Consider a pool $\mathcal{P} \subseteq \mathcal{T}$. Fix some horosphere E_0 and let a tile $T \in \mathcal{P}$ have its b -facets in E_0 . Obviously, the

intersection

$$u_0(T) := \text{supp}(W(T)) \cap E_0$$

is exactly the union of b -facets (which are unit cubes) of T . (Here, $\text{supp}(W(T))$ denotes the support of $W(T)$, that is, the union of all tiles in $W(T)$). This union is a d -dimensional cube C_2 of edge length 2. We introduce in E_0 , as in Euclidean d -space, a Cartesian coordinate system with axes parallel to the edges of C_2 . Therefore, there are $a_i^{(0)}, b_i^{(0)} \in \mathbb{R}$, such that

$$u_0(T) = \{x \in E_0 \mid a_i^{(0)} \leq x_i \leq b_i^{(0)}\}$$

where $b_i^{(0)} - a_i^{(0)} = 2$. Consider the tail $t(T) = (T = T_0, T_1, T_2, \dots)$ and let

$$u_0(T_j) := \text{supp}(W(T_j)) \cap E_0, \quad (T_j \in t(T_0))$$

Let us calculate a representation of $u_0(T_{j+1})$ in terms of $u_0(T_j)$ and the biinfinite word $(\sigma_i)_{i \in I}$ encoding $t(T)$. The intersection $u_0(T_j) = \text{supp}(W(T_j)) \cap E_0$ is a d -cube

$$u_0(T_j) = \{x \in E_0 \mid a_i^{(j)} \leq x_i \leq b_i^{(j)}\}$$

of edge-length 2^{j+1} : $b_i^{(j)} - a_i^{(j)} = 2^{j+1}$. Now we calculate coordinates of the section $u_0(T_{j+1})$. Since $W(T_j) \subseteq W(T_{j+1})$, we have $a_i^{(j+1)} \leq a_i^{(j)}$ and $b_i^{(j)} \leq b_i^{(j+1)}$. Moreover, if in an infinite word $s(T) = (\sigma^{(1)}, \sigma^{(2)}, \dots)$ holds $\sigma_i^{(j+1)} = -1$, then $a_i^{(j+1)} = a_i^{(j)} - 2^{j+1}$, $b_i^{(j+1)} = b_i^{(j)}$. If $\sigma_i^{(j+1)} = 1$, then $a_i^{(j+1)} = a_i^{(j)}$ and $b_i^{(j+1)} = b_i^{(j)} + 2^{j+1}$. Altogether we obtain

$$(3) \quad a_i^{(j+1)} = a_i^{(j)} + \frac{\sigma_i^{(j+1)} - 1}{2} (b_i^{(j)} - a_i^{(j)}),$$

$$(4) \quad b_i^{(j+1)} = b_i^{(j)} + \frac{\sigma_i^{(j+1)} + 1}{2} (b_i^{(j)} - a_i^{(j)}).$$

Note again, that from (3) and (4), in particular, it follows that the intersection of the tower $W(T_j)$ with the horosphere E_0 is a d -cube of edge length 2^{j+1} .

Theorem 5.5. *In a B-tiling in \mathbb{H}^{d+1} the following properties hold:*

- (1) *The number of pools is 2^k for some $0 \leq k \leq d$.*
- (2) *For any d and any $0 \leq k \leq d$, there are B-tilings in \mathbb{H}^{d+1} with 2^k pools.*
- (3) *Given $0 \leq k \leq d$, in all B-tilings in \mathbb{H}^{d+1} with 2^k pools the supports of all pools are pairwise congruent to each other.*
- (4) *Given a B-tiling T , all pools are pairwise congruent to each other with respect to tiles.*
- (5) *All 2^k pools in a B-tiling share a common $(d - k + 1)$ -plane.*

Proof. Let \mathcal{P} be a pool in a B-tiling \mathcal{T} . By Proposition 5.4, \mathcal{P} is the union of towers $(W(T_j))_{j \in \mathbb{N}}$, where $W(T_j) \subset W(T_{j+1})$. Let E_0 be a horosphere that contains some b -facet $b \subset T \in \mathcal{P}$. Since the intersection of a tower and E_0 is a d -cube, the intersection of \mathcal{P} and E_0 is the union of countably many d -cubes $\{\square_j\}_{j \geq 0}$, where $\square_j \subset \square_{j+1}$.

Let $a_i^{(j)}, b_i^{(j)}$ as in (3),(4) correspond to $\mathcal{P} = \bigcup_{j \geq 0} W(T_j)$. From (3) and (4) we read off: if there are only finitely many k , such that $\sigma_i^{(j)} = -1$, then there is a sharp lower bound a for $a_i^{(j)}$. Therefore, in this case the union $\bigcup_{j \geq 0} \square_j$ (where $\square_j = W(T_j) \cap E_0$) is contained in the half-space $H_i^+ = \{x = (x_1, \dots, x_d) \in E_0 = \mathbb{E}^d \mid x_i \geq a\}$.

Analogously, if there are only finitely many j , such that $\sigma_i^{(j)} = 1$, then there is an upper bound b for $b_i^{(j)}$. In this case $\bigcup_{j \geq 0} \square_j$ is contained in the half-space $\tilde{H}_i^- = \{x = (x_1, \dots, x_d) \in \mathbb{E}^d \mid x_i \leq b\}$. We obtain:

(A) For any fixed coordinate i , $\bigcup_{j \geq 0} \square_j$ is either unbounded in one direction or unbounded in both directions.

Assume a hyperplane \bar{h} is the boundary (at least partly) of a pool \mathcal{P} in \mathcal{T} . Consider a tile with a c -facet on \bar{h} . All tiles $T_j \in t(T)$ have c -facets in the hyperplane \bar{h} . Now, since \mathcal{T} is face-to-face, the reflection τ in the hyperplane \bar{h} moves T to some tile T' which shares with T a common c -facet. Note that, by assumption, T' belongs to another pool \mathcal{P}' . The tail $t(T)$ moves under τ into $t(T')$. Therefore, the pool \mathcal{P} moves under τ into pool \mathcal{P}' too. And, in particular, the tail of T' — determining $\mathcal{T} \cap \mathcal{P}'$ uniquely — is obtained from $t(T)$ by a reflection. Thus $s(T)$ differs from $s(T')$ only by exchanging the sign in one coordinate.

Now, since \mathcal{T} is face-to-face, the hyperplane \bar{h} , which separates two pools, is a totally separating hyperplane. Indeed, if \bar{h} contains a common facet of two tiles in a horospheric layer, it cannot dissect any other tile in the same layer. Since, for being (part of) a boundary of two pools, \bar{h} separates some adjacent tiles in any layer, it cannot dissect a tile in tiling \mathcal{T} at all. Therefore, for two tiles T and T' lying on different sides of \bar{h} , their tails have no tiles in common.

Now, by **(A)**, and since any hyperplane in the boundary of some pool is parallel to some c -facet, the hyperplanes in $\partial\mathcal{P}$ are pairwise orthogonal to each other. Thus they partition \mathbb{H}^{d+1} into 2^k pools, proving the first point of the theorem. It is a simple exercise to construct B-tilings with 2^k pools for all $0 \leq k \leq d$. In fact, one can use sequences $s(T)$, where the numbers of 1s in exactly k coordinates is finite. This proves the second point of the theorem. Being pairwise orthogonal to each other, all the k hyperplanes share a common $d - k + 1$ -dimensional plane which is also orthogonal to the horospheres, proving the fifth point of the theorem.

Now we know the structure of the intersection of the pool \mathcal{P} with the horosphere E :

$$\mathcal{P} \cap E = \mathbb{E}^m \oplus E^{+(d-m)},$$

where $E^{+(d-m)}$ denotes a $d - m$ -dimensional 'octant', i.e, the sum $\mathbb{R}^+ \oplus \dots \oplus \mathbb{R}^+$ of $d - m$ half-lines. Therefore, in all B-tilings with 2^k pools, all supports of the pools are the same, which proves the third point of the theorem. Note that, up to here, two pools may have congruent supports, but can be pairwise different as tilings.

Now we prove that all 2^k in some given B-tiling \mathcal{T} are pairwise congruent with respect to tiles. We did prove it already for two pools having some c -facet in common. But any two pools can be linked by a chain of pools in which all sequel pools have d -dimensional boundary in common. Therefore, the fourth point of the theorem is proved. □

Let us emphasise that point (4) of Theorem 5.5 implies that all tails in a given B-tiling are cofinally equivalent, up to multiplying entire coordinates (that is, entire sequences $(\sigma_i^{(j)})_{j \in \mathbb{N}}$) by -1 . This is stated precisely in the following corollary.

Corollary 5.6. *Let \mathcal{T} be a B-tiling, and let $T, \tilde{T} \in \mathcal{T}$. Denote their sequences by $s(T) = (\sigma_1^{(j)}, \dots, \sigma_d^{(j)})_{j \in \mathbb{N}}$, $s(\tilde{T}) = (\tilde{\sigma}_1^{(j)}, \dots, \tilde{\sigma}_d^{(j)})_{j \in \mathbb{N}}$. Then there are $m, n \in \mathbb{N}$ such that for each*

$i \leq d$ holds

$$\forall j \in \mathbb{N} : \sigma_i^{(j+m)} = \tilde{\sigma}_i^{(j+n)} \quad \text{or} \quad \forall j \in \mathbb{N} : \sigma_i^{(j+m)} = -\tilde{\sigma}_i^{(j+n)}.$$

If T and \tilde{T} are contained in the same layer, then there is $m \in \mathbb{N}$ such that

$$\forall j \geq m : \sigma_i^{(j)} = \tilde{\sigma}_i^{(j)} \quad \text{or} \quad \forall j \geq m : \sigma_i^{(j)} = -\tilde{\sigma}_i^{(j)}.$$

Proof. By Theorem 5.5, all pools in \mathcal{T} are congruent with respect to tiles. This was proven by the fact, that any two pools are mapped to each other by reflections τ_i in hyperplanes supporting the boundary of the pools. This means that all tails are cofinally equivalent after applying some of the reflections τ_i . These reflections act as multiplication by -1 in the i -th coordinate, and the first claim follows. The second claim covers the special case where the tiles are contained in the same layer. Then the tails coincide from some common position m on, up to reflections τ_i . \square

6. Symmetries of Böröczky Tilings in \mathbb{H}^{d+1}

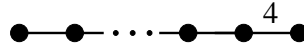
In the last section we strongly used the fact that horospheres in \mathbb{H}^{d+1} are isometric to \mathbb{E}^d , compare for instance [15, §4.7]. This will also be useful in the sequel, where we apply the results of the last section to determine all possible symmetries of a B-tiling.

Theorem 6.1. *Let \mathcal{T} be a Böröczky tiling in \mathbb{H}^{d+1} with 2^k pools, let $0 \leq k \leq d$, and denote by $\text{Sym}(\mathcal{T})$ its symmetry group. Then $\text{Sym}(\mathcal{T})$ is isomorphic to*

- $\mathbb{Z} \times B_k$ if there is a periodic sequence in \mathcal{T} , or
- B_k else;

where B_k is the symmetry group of a k -cube.

The notation B_k follows Coxeter, see [11]. B_k is the group with Coxeter diagram



Proof. Let S be the union of all k hyperplanes bounding the 2^k pools in \mathcal{T} . In the following, φ denotes always a symmetry of \mathcal{T} , i.e., an isometry of \mathbb{H}^{d+1} with the property $\varphi(\mathcal{T}) = \mathcal{T}$. Then, in particular, $\varphi(S) = S$.

The proof is organised as follows: First we prove that a group isomorphic to B_k is contained in $\text{Sym}(\mathcal{T})$. Then we show that there is $\varphi \in \text{Sym}(\mathcal{T})$ which maps some horosphere E_0 to some horosphere $E_j \neq E_0$ if and only if there is a tail which is cofinally periodic (Claims 1,2,3). Finally it is shown that any $\varphi \in \text{Sym}(\mathcal{T})$ fixing some horosphere E_0 is element of B_k (Claims 4,5,6).

By Theorem 5.5, the intersection of the k hyperplanes in S is a plane H^{d-k+1} which is orthogonal to the horospheres E_j in \mathbb{H}^{d+1} . The intersection of $S \cap E_j$ for any j consists of k pairwise orthogonal hyperplanes $h_1 \dots, h_k$ in $E_j = \mathbb{E}^d$. They share a common $d - k$ -dimensional Euclidean plane.

Since a reflection τ_i in any of these k hyperplanes, as we have seen, keeps the tiling \mathcal{T} invariant, the group generated by the reflections $\langle \tau_i \rangle \subseteq \text{Sym}(\mathcal{T})$.

The restrictions ν_i of the hyperbolic reflections τ_i onto the E are Euclidean reflections of E in hyperplanes h_i . Besides these reflections there are reflections ν_{ij} in bisectors of all dihedral angles between hyperplanes h_i and h_j , which also keep the set S invariant. A Coxeter group generated by all ν_i and ν_{ij} , $1 \leq i, j \leq k$, is exactly a group B_k of the k -dimensional cube. Denote by \bar{B}_k a Coxeter group $\langle \tau_i, \tau_{ij} \rangle$ generated by corresponding reflections of \mathbb{H}^{d+1} and show that $\bar{B}_k \subseteq \text{Sym}(\mathcal{T})$.

Let $\mathcal{P} \subseteq \bar{h}_i^+ \cap \bar{h}_j^+$ and \bar{h}_{ij} the bisector of the dihedral angle $\angle \bar{h}_i \bar{h}_j$. Let us consider a tile $T \in \mathcal{P}$ which is 'inscribed' into the $\angle \bar{h}_i \bar{h}_j$, that is, two c -facets of T lie on the boundary hyperplanes \bar{h}_i and \bar{h}_j . The bisector \bar{h}_{ij} dissects horospheric a - and b -facets of T , which are d -dimensional Euclidean cubes, into two parts. It is clear that the reflection τ_{ij} moves T into itself. So, $\tau_{ij}(T) = T$ and, consequently, $\tau_{ij}(t(T)) = t(T)$ and $\tau_{ij}(\mathcal{P}) = \mathcal{P}$. By the face-to-face property, this implies that $\tau_{ij}(\mathcal{T}) = \mathcal{T}$. Therefore, $\bar{B}_k \subseteq \text{Sym}(\mathcal{T})$.

We proceed by showing that there are no other symmetries, except possibly the ones arising from shifts along some line orthogonal to the horospheres E_i (possibly followed by some $\nu \in \bar{B}_k$). These symmetries correspond to the occurrence of the infinite cyclic group.

Claim 1: $\varphi(t(T)) = t(\varphi(T))$.

The set $\varphi(t(T)) = \{\varphi(T), \varphi(T_1), \varphi(T_2), \dots\}$ is clearly a tail. Since, for each fixed B-tiling \mathcal{T} , each tail is uniquely determined by its first element, the claim follows.

Claim 2: If T and $\varphi(T)$ are in different layers, then $s(T)$ is cofinally periodic.

Let T and $\tilde{T} = \varphi(T)$ be in different layers. Then, by Corollary 5.6, there are $m, n \in \mathbb{N}$ such that for their sequences holds:

$$(5) \quad \forall j \in \mathbb{N} : \sigma_i^{(j+m)} = \tilde{\sigma}_i^{(j+n)} \quad \text{or} \quad \forall j \in \mathbb{N} : \sigma_i^{(j+m)} = -\tilde{\sigma}_i^{(j+n)} \quad (1 \leq i \leq d).$$

Since T and \tilde{T} are in different layers, we have $m \neq n$. Without loss of generality, let $m > n$. By Claim 1, $t(T)$ and $t(\tilde{T})$ are congruent. Therefore $s(T)$ and $s(\varphi(T))$ are identical, up to multiplication of entire sequences $(\sigma_i^{(j)})_{j \in \mathbb{N}}$ by -1 . Thus, for each $1 \leq i \leq d$,

$$(6) \quad \forall j \in \mathbb{N} : \sigma_i^{(j)} = \tilde{\sigma}_i^{(j)} \quad \text{or} \quad \sigma_i^{(j)} = -\tilde{\sigma}_i^{(j)}$$

Let $k = m - n$. From (5) and (6) follows for each $1 \leq i \leq d$:

$$\forall j \in \mathbb{N} : \sigma_i^{(j+k)} = \pm \tilde{\sigma}_i^{(j)} = \begin{cases} \pm \sigma_i^{(j)} \\ \mp \sigma_i^{(j)} \end{cases}$$

We obtain either $\sigma_i^{(j+k)} = \sigma_i^{(j)}$, or $\sigma_i^{(j+k)} = -\sigma_i^{(j)}$. In the second case holds for $j \geq k$: $\sigma_i^{(j+k)} = \sigma_i^{(j-k)}$. In each case, $p_i = 2k$ is a period of σ_i . Then, the lowest common multiple of all the p_i is a period of $s(T)$. So we can already conclude: If the sequence of one pool is not periodic, any possible symmetry of \mathcal{T} maps tiles onto tiles in the same layer.

Claim 3: If there is a cofinally periodic sequence $s(T)$ for some $T \in \mathcal{T}$, then there exists a symmetry φ such that $\varphi^k(\mathcal{T}) = \mathcal{T}$ for all $j \in \mathbb{Z}$.

Let $s(T)$ be a periodic sequence in \mathcal{T} . Then there is a tile T with a tail $t(T)$ which belongs to this sequence. This tail is infinite in one direction. In the other direction we can extend it in any way we want (since by passing from T through a b -facet to another tile, we can choose each of the 2^d tiles which are lying there). In particular, we can extend $t(T)$ to a biinfinite horospheric path $t_b = (\dots, T_{-2}, T_{-1}, T_0 = T, T_1, T_2, \dots)$, which belongs to a biinfinite periodic

sequence $s_b = (\dots, \sigma^{(-2)}, \sigma^{(-1)}, \sigma^{(0)}, \sigma^{(1)}, \sigma^{(2)}, \dots)$. Let k be the period of s_b , then it holds

$$\dots = \sigma^{(i-2k)} = \sigma^{(i-k)} = \sigma^{(i)} = \sigma^{(i+k)} = \sigma^{(i+2k)} = \dots$$

for every $i \in \mathbb{Z}$. So for every $i \in \mathbb{Z}$, the set $t^{(i)} = \{T_i, T_{i+1}, T_{i+2}, \dots\}$ is congruent to $t^{(i+k)} = \{T_{i+k}, T_{i+k+1}, T_{i+k+2}, \dots\}$. In other words, there is an isometry φ such that $\varphi(t^{(i)}) = t^{(i+k)}$. Consequently, $\varphi(t_b) = t_b$, and therefore $\varphi^j(t_b) = t_b$ for every $j \in \mathbb{Z}$. From Proposition 5.4 follows that t_b determines its pool uniquely. By Theorem 5.5, this pool determines the whole tiling. It follows $\varphi^j(\mathcal{T}) = \mathcal{T}$ for $j \in \mathbb{Z}$.

The deduced symmetry φ is obviously a shift along some line ℓ . If the period k is not prime, it is possible that there is an essential period (see the end of Section 3) smaller than k . However, some power of some symmetry ψ corresponding to such an essential period is a shift along a line: $\psi^m = \varphi$, with φ as above.

By considering the action of φ on tails $t(T)$, it follows that φ maps the horospheres E_i to E_{i+k} . Hence $\varphi^m \neq \varphi^j$ for $m \neq j$. This gives rise to the occurrence of an infinite cyclic group in the symmetry group of \mathcal{T} .

It remains to consider symmetries which fix some (and thus each) horosphere E_i in the sequel. This is the same as requiring φ to fix some layer \mathcal{R} : φ then fixes also the boundary $\partial\mathcal{R} = E_i \cup E_{i+1}$. Since φ maps a -facets to a -facets and b -facets to b -facets, it fixes E_i as well as E_{i+1} .

Claim 4: Let $T \in \mathcal{T}$. Every symmetry φ , where $\varphi(T)$ and T are in the same layer \mathcal{R} and in the same pool, has a fixed point in \mathcal{R} .

By Claim 1, φ maps $t(T)$ to $\varphi(t(T)) = t(\varphi(T))$. Since T and $\varphi(T)$ are in the same pool and in the same layer, these tails coincide from some position k on. In particular, there is $T_k \in t(T)$ such that $\varphi(T_k) = T_k$. Thus, by Brouwer's fixed point theorem, φ fixes some point in T_k . Moreover, by the symmetry of T_k , φ fixes some point x_a in the a -facet of T_k , as well as some point x_b in some b -facet of T_k . Being an isometry, φ fixes the line ℓ' through x_a and x_b pointwise. Therefore, the intersection $\ell' \cap \mathcal{R}$ consists of fixed points of φ .

In fact, these symmetries are those arising from the reflections τ_{ij} .

Claim 5: Let $T \in \mathcal{T}$. Every symmetry φ , where $\varphi(T)$ and T are in the same layer \mathcal{R} but in different pools $\mathcal{P}, \mathcal{P}'$, has a fixed point in this layer.

This can be shown in analogy to the proof of the last claim. By Theorem 5.5, $\mathcal{P} \cap \mathcal{P}'$ intersect in a common $(d-k+1)$ -plane. Thus there are tiles $\tilde{T} \in \mathcal{P}$, $\tilde{T}' \in \mathcal{P}'$ having $d-k+1$ -dimensional intersection. By the face-to-face property, this intersection is a $(d-k+1)$ -face F . By the proof of Theorem 5.5, this is also true for any pair of tiles $\tilde{T}_k \in t(\tilde{T})$, $\tilde{T}'_k \in t(\tilde{T}')$, where $k \in \mathbb{N}$. By Proposition 5.4, there is k such that also holds: $\tilde{T}_k \in t(T)$, $\tilde{T}'_k \in t(\varphi(T))$. Now, similar as in the proof of the last claim, φ fixes a $(d-k+1)$ -face $F' = \tilde{T}_k \cap \tilde{T}'_k$. Moreover, φ fixes some point $x_a \in F$ ($x_b \in F$), contained in the intersection of F with the a -facets (b -facets) of \tilde{T}_k and \tilde{T}'_k . As above, φ fixes the line ℓ' through x_a and x_b pointwise. Therefore, the intersection $\ell' \cap \mathcal{R}$ consists of fixed points of φ .

In fact, these symmetries are the ones corresponding to the reflections τ_i .

Claim 6: Let $\varphi \in \text{Sym}(\mathcal{T})$ fix some (and thus each) horosphere E_i . Then $\varphi \in \bar{B}_k$.

By the construction of a B-tiling, \mathcal{T} induces a cube tiling of E_i by a -facets. For any symmetry φ which fixes both \mathcal{T} and E_i , the restriction $\nu := \varphi|_{E_i}$ fixes this cube tiling. By the last two

claims, each such ν has a fixed point in E_i . In particular, ν is not a translation. But, fixing a cube tiling in $E_i = \mathbb{E}^d$, the set of all these ν form a crystallographic group. The crystallographic groups which fix some cube tiling and which contain no translations are well known, see for instance [11]. These are exactly the subgroups of B_k , which proves Claim 6.

Altogether, we found two kinds of possible symmetries: Symmetries in \bar{B}_k , and shifts along a line orthogonal to each E_i , possibly followed by some map $\tau \in \bar{B}_k$. \square

A consequence of Theorem 6.1 is that all Böröczky-type tilings are non-crystallographic. This can also be shown by Theorem 4.5, along the same lines as in Section 4 for the 2-dimensional tiling: It is not hard to convince oneself that the number of k -coronae in a Böröczky-type tiling in \mathbb{H}^{d+1} for $d > 2$ is strictly larger than 2^{k-1} for $k \geq 2$, but a proper proof may be lengthy, and yields no new result.

As another consequence of Theorem 6.1 we obtain:

Corollary 6.2. *Almost every Böröczky-type tiling has finite symmetry group.*

Proof. Theorem 6.1 shows, that $\text{Sym}(\mathcal{T})$ is infinite, if and only if there is a tail $t(T)$ with a periodic sequence $s(T)$. Since there are only countably many of these, there are only countably many congruence classes of Böröczky-type tilings in \mathbb{H}^{d+1} with an infinite symmetry group. Since the Böröczky-type tilings are non-crystallographic, it follows from [8] that there are uncountably many congruence classes of them, which proves the claim. \square

ACKNOWLEDGEMENTS

This work was started 2003 during the workshop 'Mathematics of Aperiodic Order' at the Krupp-Kolleg in Greifswald and supported, in part, by RFBR grants 06-01-72551 and 08-01-91202. The second author acknowledges support from the CRC 701 of the German Science Foundation (DFG).

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