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Some new results on the self-dual $[120,60,24]$ code

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Abstract

The existence of an extremal self-dual binary linear code of length 120 is a long-standing open problem. We continue the investigation of its automorphism group, proving that automorphisms of order 30 and 57 cannot occur. Supposing the involutions acting fixed point freely, we show that also automorphisms of order 8 cannot occur and the automorphism group is of order at most 120, with further restrictions. Finally, we present some necessary conditions for the existence of the code, based on shadow and design theory.

Keywords: Self-dual code, extremal code, automorphism group

1. Introduction

In coding theory, binary self-dual codes play a central role: they are linear codes with a rich algebraic structure, good decoding properties and relations with other areas of mathematics, such as group theory, lattice theory and design theory. For example, this class includes the binary extended Golay code, whose automorphism group is the sporadic simple group M_{24} and which is related to the Leech lattice.

Gleason, Pierce and Turyn showed (see [3]) that if a natural number $r > 1$ divides the weight of all codewords of a binary self-dual code, then $r = 2$ (*even* code) or $r = 4$ (*doubly-even* code). Every binary self-dual code is even. If a binary self-dual code is even but not doubly-even (*singly-even* code), then it is called a *Type I* code, while if a binary self-dual code is doubly-even, then it is called a *Type II* code. Type II codes exist only for lengths which

are multiples of 8 [24] and Mallows and Sloane showed in [27] that they have minimum distance bounded by $4\lfloor n/24 \rfloor + 4$, where n is the length. A type II code attaining this bound is called *extremal* code. Among extremal codes, those of length a multiple of 24 are particularly interesting: Assmus-Mattson's theorem [2] guarantees that the supports of their codewords of a fixed nonzero weight form a 5-design. Moreover, they have relations, as mentioned above, with simple groups and extremal lattices. Zhang proved in [32] that their length is at most 3672.

Despite their theoretical importance, only two extremal codes of length a multiple of 24 are known, namely the famous binary extended Golay code, the unique up to equivalence of length 24, and the extended quadratic residue code of length 48, which is the unique up to equivalence of this length. In 1973 Sloane [30] posed explicitly the question: is there a self-dual $[72, 36, 16]$ code? Since then, multiple attempts to establish the non existence of such a code or to present a construction have been done, till now unsuccessfully. The problem is still open for all lengths from 72 to 3672 and many investigations have been also done for the cases of length 96 and 120.

This paper focuses on the last one, i.e. on the study of a self-dual $[120, 60, 24]$ code. In particular, in Section 2 we will collect, for the reader's convenience, all the definitions and the known results which will be used in the following. In Section 3 we prove new properties about the automorphism group of a self-dual $[120, 60, 24]$ code. In particular we exclude the existence of automorphisms of order 30 and 57 and we investigate the structure of the automorphism group, in the case that involutions act fixed point freely (see the introduction of Subsection 3.3 for a motivation of this choice), proving that it is either trivial or isomorphic to a group of order at most 120, with further restrictions. Finally, in Section 4 we give necessary conditions for the existence of the code, based on shadow and design theory.

2. Background

In this section we collect some classical results of coding theory which are useful in the rest of the paper.

2.1. Gleason's theorem and the shadow of a code

For the whole subsection, let C be a binary code of length n , i.e. a subspace of \mathbb{F}_2^n . We recall that a $[n, k, d]$ code is a code of length n , dimension k and minimum distance d .

Definition 1. The *weight distribution* of C is the sequence $(A_0(C), \dots, A_n(C))$, where $A_i(C)$ is the number of codewords of C of weight i , for every $i \in \{1, \dots, n\}$.

The polynomial $W_C(y) := \sum_{i=0}^n A_i y^i = \sum_{c \in C} y^{\text{wt}(c)} \in \mathbb{Z}[x]$ is called the *weight enumerator* of C and the polynomial $W_C(x, y) := x^n W(\frac{y}{x}) \in \mathbb{Z}[x, y]$, is the *homogeneous weight enumerator* of C .

Definition 2. The *dual* of C is $C^\perp := \{v \in \mathbb{F}_2^n \mid \langle v, c \rangle = 0, \forall c \in C\}$.

If $C = C^\perp$, we say that C is self-dual.

If C and C^\perp have the same weight enumerator, C is called a *formally self-dual* code.

Theorem 3 ([24]). Let $g_1(x, y) := y^2 + x^2$, $g_2(x, y) := x^2 y^2 (x^2 - y^2)^2$, and $g_3(x, y) := y^{24} + 759x^8 y^{16} + 2576x^{12} y^{12} + 759x^{16} y^8 + x^{24}$.

(a) If C is formally self-dual and even,

$$W_C(x, y) = \sum_{i=0}^{\lfloor n/8 \rfloor} a_i g_1(x, y)^{\frac{n}{2}-4i} g_2(x, y)^i.$$

(b) If C is formally self-dual and doubly-even,

$$W_C(x, y) = \sum_{i=0}^{\lfloor n/24 \rfloor} a_i g_2(x, y)^{\frac{n}{8}-3i} g_3(x, y)^i.$$

In all cases, every $a_i \in \mathbb{Q}$ and $\sum_i a_i = 1$.

Let C be a self-dual code and let C_0 be the subset consisting of all codewords in C whose weights are multiples of 4. If C is of type II then $C_0 = C$, while C_0 is a subcode of index 2 of C if C is of type I.

Definition 4. The *shadow* of C is the set

$$S := \begin{cases} C_0^\perp \setminus C, & \text{if } C \text{ is of type I} \\ C, & \text{if } C \text{ is of type II.} \end{cases}$$

Let C be a type I code. Since C_0 is of index 2, then $\#(C_0^\perp/C_0) = 4$. Hence there are three cosets C_1, C_2, C_3 of C_0 in C_0^\perp such that $C_0^\perp = C_0 \cup C_1 \cup C_2 \cup C_3$, where $C = C_0 \cup C_2$ and $S = C_1 \cup C_3 = C_0^\perp \setminus C$ is the shadow of C (see [17, Theorem 5]).

Theorem 5 ([17]). *Let S be the shadow of C , code of type I.*

(a) *If we write*

$$W_C(x, y) = \sum_{j=0}^{\lfloor n/8 \rfloor} a_j (x^2 + y^2)^{\frac{n}{2} - 4j} (x^2 y^2 (x^2 - y^2)^2)^j,$$

for suitable rationals a_j , then

$$W_S(x, y) = \sum_{j=0}^{\lfloor n/8 \rfloor} (-1)^j a_j 2^{\frac{n}{2} - 6j} (xy)^{\frac{n}{2} - 4j} (x^4 - y^4)^{2j}.$$

(b) *Writing $W_S(x, y) = \sum_{i=0}^n B_i x^{n-i} y^i$, we have*

- (i) $B_i = B_{n-i}$ for all i .
- (ii) $B_i = 0$, unless $i \equiv n/2 \pmod{4}$.
- (iii) $B_0 = 0$.
- (iv) $B_i \leq 1$, for $i < d/2$.
- (v) *at most one B_i is nonzero for $i < (d + 4)/2$.*

Definition 6. If C is a self-dual $[n, n/2, d]$ code with $d > 2$, pick two positions and consider the $(n/2 - 1)$ -dimensional subcode C' of C with either two 0s or two 1s in these positions. If we puncture C' on these positions, we obtain a self-dual code C'^* of length $n - 2$; C'^* is called a *child* of C and C is called a *parent* of C'^* .

Theorem 7 ([26]). *Let $m \geq 1$ be an integer. If C is a $[24m - 2, 12m - 1, 4m + 2]$ type I code whose shadow has minimum distance $4m + 3$, then C is a child of a $[24m, 12m, 4m + 4]$ type II code.*

Lemma 8 ([26]). *If C is a child of an extremal type II code with shadow $S = C_1 \cup C_3$, then $W_{C_1}(y) = W_{C_3}(y)$.*

Lemma 9 ([4]). *Let C be a type I code of length n with the shadow $S = C_1 \cup C_3$. Suppose that $n \equiv 2 \pmod{4}$. Let C^* be the code of length $n + 2$ obtained by extending C_0^\perp as follows:*

$$(0, 0, C_0), (1, 0, C_2), (0, 1, C_1), (1, 1, C_3).$$

If $W_{C_1}(y) = W_{C_3}(y)$, then C^ is a formally self-dual code with weight enumerator*

$$W_{C_0}(y) + y(W_{C_1}(y) + W_{C_2}(y)) + y^2 W_{C_3}(y).$$

Definition 10. Two self-dual codes of length n are *neighbors* if their intersection is a code of dimension $n/2 - 1$.

2.2. Automorphism group of binary codes

The symmetric group S_n acts on \mathbb{F}_2^n by the group action $v\sigma := (v_{\sigma^{-1}(1)}, \dots, v_{\sigma^{-1}(n)})$, where $v = (v_1, \dots, v_n) \in \mathbb{F}_2^n$ and $\sigma \in S_n$.

Definition 11. Let C and C' be two codes of the same length n . We say that C and C' are *equivalent* and denote $C \sim C'$ if only if $C\sigma = C'$ where $\sigma \in S_n$. If $v\sigma \in C$ for all $v \in C$, then σ is an *automorphism* of C . The set of all automorphisms of C is a group, denoted $\text{Aut}(C)$.

Definition 12. Let C be a binary code of length n and $\sigma \in \text{Aut}(C)$.

- (a) If σ is of prime order p , we say that σ is of *type* p -($c; f$) if it has c cycles of length p and f fixed points.
- (b) If σ is of order $p \cdot r$, where p, r are distinct primes, then we say that σ is of *type* $p \cdot r$ -($s_1, s_2, s_3; f$) if σ has s_1 p -cycles, s_2 r -cycles, s_3 pr -cycles and f fixed points.

Remark 13. In order to simplify the notation, if σ is an automorphism of composite order r and has c r -cycles and f fixed points with $n = c \cdot r + f$, then we say that the cycle structure of σ is r -($c; f$).

Let us first prove a result which is useful in the following sections.

Lemma 14. *Let C be a code of length n , such that all automorphisms of prime order p act fixed point freely. If $|\text{Aut}(C)| = p^a m$, with $(p, m) = 1$, then $a \leq \max\{ r \in \mathbb{Z} : p^r \mid n \}$.*

Proof. Suppose $a > \max\{ r \in \mathbb{Z} : p^r \mid n \}$. By Sylow's theorem, there exists a subgroup $H \leq \text{Aut}(C)$ with $|H| = p^a$. The group H acts on the set $\{1, \dots, n\}$. Since all automorphisms of order p act fixed point freely, then each orbit has p^a elements. Therefore $p^a \mid n$, a contradiction. \square

Definition 15. Let $\sigma \in \text{Aut}(C)$. The *fixed code* of σ is

$$F_\sigma(C) := \{v \in C \mid v\sigma = v\}.$$

Let $\Omega_1, \dots, \Omega_c$ be the cycle sets and let $\Omega_{c+1}, \dots, \Omega_{c+f}$ be the fixed points of σ . Clearly $v \in F_\sigma(C)$ if and only if $v \in C$ and v is constant on each cycle. Let $\pi_\sigma : F_\sigma(C) \rightarrow \mathbb{F}_2^{c+f}$ denotes the *projection map* defined by $\pi_\sigma(v|_{\Omega_i}) = v_j$ for some $j \in \Omega_i$ and $i \in \{1, \dots, c+f\}$.

A useful result, which is a reformulation of a very classical result about group actions, is the following.

Lemma 16. *If $\sigma \in \text{Aut}(C)$, $W_C(y) = \sum A_i y^i$ and $W_{F_\sigma(C)}(y) = \sum A_i^F y^i$, then $A_i \equiv A_i^F \pmod{p}$.*

Finally, let us introduce a classical decomposition of a code with an automorphism of prime order, which comes from Maschke's theorem. Let p be an odd prime and σ is an automorphism of type p - (c, f) . Let

$$E_\sigma(C) := \{v \in C \mid \text{wt}(v|_{\Omega_i}) \equiv 0 \pmod{2}, \quad i = 1, \dots, c+f\},$$

where $v|_{\Omega_i}$ is the restriction of v on Ω_i .

Lemma 17 ([25]). *If p is odd, then $C = F_\sigma(C) \oplus E_\sigma(C)$. Moreover, if C is self-dual, then*

- (a) *the code $\pi_\sigma(F_\sigma(C)) \leq \mathbb{F}_2^{c+f}$ is self-dual and, if C is doubly even and $p \equiv 1 \pmod{2}$, then $\pi_\sigma(F_\sigma(C))$ is doubly even.*
- (b) $\dim E_\sigma(C) = \frac{(p-1)c}{2}$.

2.3. Designs and codes

In this section we briefly recall the main definitions of design theory and its relationship with coding theory.

Definition 18. A t - (v, k, λ) design, or briefly a t -design, is a pair $\mathcal{D} = (\mathcal{P}, \mathcal{B})$ where \mathcal{P} is a set of v elements, called *points*, and \mathcal{B} is a collection of distinct subsets of \mathcal{P} of size k , called *blocks*, such that every subset of points of size t is contained in precisely λ blocks.

If \mathcal{D} is a t - (v, k, λ) design, it is also an i - (v, k, λ_i) design for all $i \in \{0, \dots, t\}$, where λ_i is given by $\lambda_i = \lambda \frac{\binom{v-i}{t-i}}{\binom{k-i}{t-i}}$.

Definition 19. Let $\mathcal{D} = (\mathcal{P}, \mathcal{B})$ be a design with $|\mathcal{P}| = v$ and $|\mathcal{B}| = b$.

- (a) If we list the points $\{p_1, p_2, \dots, p_v\}$ and the blocks $\{B_1, B_2, \dots, B_b\}$, then we define the incidence matrix of \mathcal{D} as a $b \times v$ matrix $A = (a_{ij})$, where

$$a_{ij} = \begin{cases} 1, & \text{if } p_j \in B_i \\ 0, & \text{if } p_j \notin B_i. \end{cases}$$

- (b) The code $C(\mathcal{D})$ over \mathbb{F}_2 which is generated by the rows of A is called *code of the design* $\mathcal{D} = (\mathcal{P}, \mathcal{B})$.

Although there are several incidence matrices, depending on the choice of the order of the points and of the blocks, for a given design the codes generated by these matrices are equivalent: changing the order of the points is equivalent to permute the coordinates, while a reordering of the blocks does not change the code (see [1, p.41]).

The following theorem, due to Assmus and Mattson, establishes a relationship between coding theory and design theory.

Theorem 20 ([2]). *Let C be a binary $[n, k, d]$ code. Suppose C^\perp has minimum weight d^\perp . Suppose that A_0, \dots, A_n and $A_0^\perp, \dots, A_n^\perp$ are the weight distributions of C and C^\perp , respectively. Fix a positive integer t with $t < d$, and let s be the number of i with $A_i^\perp \neq 0$ for $i \in \{0 \dots n - t\}$. Suppose $s \leq d - t$.*

- (a) *The vectors of weight i in C form a t -design provided $A_i \neq 0$ and $d \leq i \leq n$.*
- (b) *The vectors of weight i in C^\perp form a t -design provided $A_i^\perp \neq 0$ and $d^\perp \leq i \leq n - t$.*

3. The automorphism group of an extremal [120, 60, 24] code

For the whole section, let C be an extremal [120, 60, 24] code. By Theorem 3 (b), we can easily deduce (see [27]) that

$$W_C(1, y) = 1 + 39703755y^{24} + 6101289120y^{28} + 475644139425y^{32} + \dots \quad (1)$$

Knowledge of the existence of a non-trivial automorphism group G is very useful in constructing the code, since in this case the code has the structure of a \mathbb{F}_2G -module. For this reason, there is an intensive research on the automorphism group of extremal codes.

Remark 21. Concerning the code of length 120, the following results on the automorphism group G of C are known (see [7, 13, 14, 18, 19]):

- (a) The order of G divides $2^a \cdot 3 \cdot 5 \cdot 7 \cdot 19 \cdot 23$ for a non-negative integer a (which is at most 116, since $G \subseteq S_{120}$).

- (b) If σ is an automorphism of C of prime order p then its cycle structure is

p	number of p -cycles	number of fixed points
2	48, 60	24, 0
3	40	0
5	24	0
7	17	1
19	6	6
23	5	5

- (c) If σ is an automorphism of C of odd composite order r , then the cycle structure of σ is either 15-(8; 0), $3 \cdot 19$ -(2, 0, 2; 0) or $5 \cdot 23$ -(1, 0, 1; 0).

Moreover, if all involutions act fixed point freely, the following conditions hold:

- (d) If σ is an automorphism of C of even composite order not divisible by 8, then the cycle structure of σ is either 4-(30; 0), 6-(20; 0), 10-(12; 0), 12-(10; 0), 20-(6; 0), 30-(4; 0), 60-(2; 0).
- (e) The order of G is in $\{7, 19, 23, 38, 56, 57, 114, 115, 552, 2760\}$ or G is a $\{2, 3, 5\}$ -group of order dividing 120.

Remark 22. Condition (d) is not stated explicitly in any of the above references, but it is an easy consequence of the results in [7]. Furthermore, we give only the structure of the automorphisms of even order not divisible by 8 because we prove in the following that an automorphism of order 8 cannot exist under the hypothesis that involutions act fixed point freely.

Remark 23. Condition (e) corrects a mistake in Proposition 15 b) of [14], where “ $|G| = 2^3 \cdot 5^c \cdot 23$ ” should have been “ $|G| = 2^3 \cdot 3 \cdot 5^c \cdot 23$ ”. Moreover, it gives a preciser statement about $\{2, 3, 5\}$ -groups, based on Lemma 14.

3.1. Fixed code of automorphism of prime order

In this subsection we present some preliminary results about the automorphisms of prime order. It is a hard problem to prove that the primes 3, 5, 7, 19 and 23 cannot occur as orders of an automorphism σ of C : even

if we can completely determine the fixed code $F_\sigma(C)$, there are too many possibilities to check for the complement $E_\sigma(C)$ defined in Section 2. Also the case of the prime 2 is computationally hard and we do not even know the fixed code.

Automorphism of order 2: Let $\sigma \in \text{Aut}(C)$ be of order 2. Then σ is either of type 2-(48; 24) or of type 2-(60; 0). In the second case, by Theorem 1.2 of [10], $\pi_\sigma(F_\sigma(C))$ is a self-dual [60, 30, 12] code. Although some self-dual codes with these parameters are known, a complete classification is still unknown.

Automorphism of order 3: Let $\sigma \in \text{Aut}(C)$ be of order 3. Then σ is of type 3-(40; 0) and $\pi_\sigma(F_\sigma(C))$ is a self-dual doubly-even [40, 20, 8] code. By [5], there are 16470 such codes up to equivalence.

Automorphism of order 5: Let $\sigma \in \text{Aut}(C)$ be of order 5. Then σ is of type 5-(24; 0) and $\pi_\sigma(F_\sigma(C))$ is a self-dual [24, 12, 8] code. This implies that $\pi_\sigma(F_\sigma(C))$ is equivalent to the binary extended Golay code G_{24} .

Automorphism of order 7: Let $\sigma \in \text{Aut}(C)$ be of order 7. Then σ is of type 7-(17; 1) and $\pi_\sigma(F_\sigma(C))$ is a self-dual [18, 9, 4] code. By [28], $\pi_\sigma(F_\sigma(C))$ is equivalent to H_{18} or I_{18} .

A vector of weight 4 in $\pi_\sigma(F_\sigma(C))$ has to be a vector of weight 28 in $F_\sigma(C)$, i.e. all nonzero coordinates of vectors of weight 4 correspond to cycles. By the study of clusters (see [25]) we can easily prove that H_{18} cannot occur. Moreover, with the same technique, we can prove that, up to equivalence,

$$\text{gen}(F_\sigma(C)) = \left(\begin{array}{cccccccccccccccccccc|c} 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{array} \right)$$

where $\mathbf{1}$ is the all-one vector and $\mathbf{0}$ the zero-vector of length 7.

Automorphism of order 19: Let $\sigma \in \text{Aut}(C)$ be of order 19. Then σ is of type 19-(6; 6) and $\pi_\sigma(F_\sigma(C))$ is a self-dual [12, 6, 4] code. By [28],

$\pi_\sigma(F_\sigma(C))$ is equivalent to B_{12} .

By Lemma 16 and by (1), $A_{24}^F \equiv 6 \pmod{19}$. Therefore there are 6 mod 19 vectors of $F_\sigma(C)$ of weight 24. If $v \in F_\sigma(C)$ has weight 24, then $\text{wt}(\pi_\sigma(v)) = 6$. Suppose that $v_1, v_2 \in F_\sigma(C)$ of weight 24 coincide in the coordinate corresponding to a cycle of length 19. Then $\text{wt}(v_1 + v_2) \leq 2$. Therefore $v_1 = v_2$ and there are exactly 6 vectors in $F_\sigma(C)$ of weight $\text{wt}(v) = 24$. These vectors are linearly independent and so, up to a permutation of the last six columns,

$$\text{gen}(F_\sigma(C)) = \left(\begin{array}{cccccc|cccccc} \mathbf{1} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & 0 & 1 & 1 & 1 & 1 & 1 \\ \mathbf{0} & \mathbf{1} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & 1 & 0 & 1 & 1 & 1 & 1 \\ \mathbf{0} & \mathbf{0} & \mathbf{1} & \mathbf{0} & \mathbf{0} & \mathbf{0} & 1 & 1 & 0 & 1 & 1 & 1 \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{1} & \mathbf{0} & \mathbf{0} & 1 & 1 & 1 & 0 & 1 & 1 \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{1} & \mathbf{0} & 1 & 1 & 1 & 1 & 0 & 1 \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{1} & 1 & 1 & 1 & 1 & 1 & 0 \end{array} \right),$$

where $\mathbf{1}$ is the all-one vector and $\mathbf{0}$ the zero-vector of length 19.

Automorphism of order 23: Let $\sigma \in \text{Aut}(C)$ be of order 23. Then σ is of type 23-(5; 5) and $\pi_\sigma(F_\sigma(C))$ is a self-dual $[10, 5, 2]$ code. So (see [31]), up to equivalence,

$$\text{gen}(F_\sigma(C)) = \left(\begin{array}{cccccc|cccc} \mathbf{1} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & 1 & 0 & 0 & 0 & 0 \\ \mathbf{0} & \mathbf{1} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & 0 & 1 & 0 & 0 & 0 \\ \mathbf{0} & \mathbf{0} & \mathbf{1} & \mathbf{0} & \mathbf{0} & \mathbf{0} & 0 & 0 & 1 & 0 & 0 \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{1} & \mathbf{0} & \mathbf{0} & 0 & 0 & 0 & 1 & 0 \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{1} & \mathbf{0} & 0 & 0 & 0 & 0 & 1 \end{array} \right).$$

3.2. Automorphisms of composite order

In this subsection we present some new results about automorphisms of composite order. The result for the automorphism of order 8 is a corollary of Theorem 1.2. in [10] while the main idea for the other orders is the following: if $\sigma \in \text{Aut}(C)$ is an automorphism of order $p \cdot q$, then, in some cases, we can classify the possible sums $F_{\sigma^q}(C) + F_{\sigma^p}(C)$. If no sum has minimum distance greater than or equal to 24, then an automorphism of this order cannot occur. Note that these methods are a simplified version of those in Section V of [6].

Automorphism of order 8: Let $\sigma \in \text{Aut}(C)$ be a fixed point free automorphism of order 8. Then σ is of type 8-(15; 0). By Theorem 1.2. in

[10], C is a free $\mathbb{F}_2\langle\sigma^4\rangle$ -module, so, by Chouinard's Theorem [16], C is a free $\mathbb{F}_2\langle\sigma\rangle$ -module. This is impossible, since 8 does not divide 60.

Theorem 24. *The automorphism group of a self-dual [120, 60, 24] code does not contain fixed point free elements of order 8.*

Automorphism of order 30: Let $\sigma \in \text{Aut}(C)$ be of order 30. Then σ is of type 30-(4; 0). We can suppose, up to equivalence, that

$$\sigma = (1, \dots, 30)(31, \dots, 60)(61, \dots, 90)(91, \dots, 120).$$

Let $\sigma_3 := \sigma^{10}$ and $\sigma_5 := \sigma^6$. Then σ_3 is of type 3-(40; 0) and σ_5 is of type 5-(24; 0). Since σ is in the centralizer of both σ_3 and σ_5 in S_{120} , it acts on $\pi_{\sigma_3}(F_{\sigma_3}(C))$ as an automorphism, say $\pi_{\sigma_3}(\sigma)$, of type 10-(4; 0) and on $\pi_{\sigma_5}(F_{\sigma_5}(C))$ as an automorphism, say $\pi_{\sigma_5}(\sigma)$, of type 6-(4; 0). Among the 16470 self-dual [40, 20, 8] codes, only 28, say D_1, \dots, D_{28} , have an automorphism of this type, for a total of 69 conjugacy classes. So, up to a permutation in $C_{S_{40}}(\pi_{\sigma_3}(\sigma))$, $\pi_{\sigma_3}(C)$ belong to a set, say \mathcal{D} , of 69 elements. On the other hand, the extended binary Golay code has only one conjugacy class of elements of type 6-(4; 0). If E_0 is an extended binary Golay code with automorphism $\pi_{\sigma_5}(\sigma)$, then the orbit, say \mathcal{E} , of E_0 under the action of $C_{S_{24}}(\pi_{\sigma_5}(\sigma))$ has 1296 elements. The code $\pi_{\sigma_5}(F_{\sigma_5}(C))$ belongs to \mathcal{E} . With MAGMA [12] we check that all the codes in $\mathcal{C} := \{\pi_{\sigma_3}^{-1}(D) + \pi_{\sigma_5}^{-1}(E) \mid D \in \mathcal{D}, E \in \mathcal{E}\}$ have minimum distance less than 24. Since $F_{\sigma_3}(C) + F_{\sigma_5}(C) \subseteq C$ would have to belong to \mathcal{C} , this implies the following result.

Theorem 25. *The automorphism group of a self-dual [120, 60, 24] code does not contain elements of order 30.*

This theorem implies that also automorphism of order 60 cannot occur in $\text{Aut}(C)$.

Automorphism of order 57: Let $\sigma \in \text{Aut}(C)$ be of order 57. Then σ is of type 3 · 19-(2, 0, 2; 0). We can suppose, up to equivalence, that

$$\sigma = (1, \dots, 57)(58, \dots, 114)(115, 116, 117)(118, 119, 120).$$

Let $\sigma_3 := \sigma^{19}$ and $\sigma_{19} := \sigma^3$. Then σ_3 is of type 3-(40; 0) and σ_{19} is of type 19-(6; 6). Since σ is in the centralizer of both σ_3 and σ_{19} in S_{120} , it acts on $\pi_{\sigma_3}(F_{\sigma_3}(C))$ as an automorphism, say $\pi_{\sigma_3}(\sigma)$, of type 19-(2; 2) and

on $\pi_{\sigma_{19}}(F_{\sigma_{19}}(C))$ as an automorphism, say $\pi_{\sigma_{19}}(\sigma)$, of type 3-(4; 0). Among the 16470 self-dual $[40, 20, 8]$ codes, only 3, say D_1, D_2 and D_3 , have an automorphism of this type, for a total of 396 conjugacy classes. So, up to a permutation in $C_{S_{40}}(\pi_{\sigma_3}(\sigma))$, $\pi_{\sigma_3}(C)$ belong to a set, say \mathcal{D} , of 396 elements. On the other hand, the code B_{12} has only one conjugacy class of elements of type 3-(4; 0). If E_0 is a B_{12} code with automorphism $\pi_{\sigma_{19}}(\sigma)$, then the orbit, say \mathcal{E} , of E_0 under the action of $C_{S_{12}}(\pi_{\sigma_{19}}(\sigma))$ has 27 elements. The code $\pi_{\sigma_{19}}(F_{\sigma_{19}}(C))$ belongs to \mathcal{E} . With MAGMA [12] we check that all the codes in $\mathcal{C} := \{\pi_{\sigma_3}^{-1}(D) + \pi_{\sigma_{19}}^{-1}(E) \mid D \in \mathcal{D}, E \in \mathcal{E}\}$ have minimum distance less than 24. Since $F_{\sigma_3}(C) + F_{\sigma_{19}}(C) \subseteq C$ would have to belong to \mathcal{C} , this implies the following result.

Theorem 26. *The automorphism group of a self-dual $[120, 60, 24]$ code does not contain elements of order 57.*

Other orders: in the case of automorphisms of order 12 (fixed point free), 15, 20 (fixed point free) and 115 we do not get a contradiction on the minimum distance, while in the case of the automorphism of order $2 \cdot p$, with p prime, we cannot use the method above, since we do not have a classification of the fixed code by the automorphism of order 2.

3.3. Structure of the automorphism group in the fixed point free case

In this subsection we present a theorem on the structure of the automorphism group of a self-dual $[120, 60, 24]$ code as in Section 6 of [11] for the self-dual $[72, 36, 16]$. Note that in [13] it is proved that involutions acting on extremal codes of length $24m$ with $m > 1$ are always fixed point free, except for $m = 5$, i.e. our case. It seems to be very difficult, although very interesting, to exclude this exceptional case. Allowing fixed points increases enormously the number of possible automorphism groups and we cannot get nice results. Therefore we decided, as in [14], to restrict our attention to the fixed point free case in order to get, at least under this hypothesis, a stronger result.

Theorem 27. *If all the involutions act fixed point freely, the automorphism group G of a self-dual $[120, 60, 24]$ code is trivial or isomorphic to one of the following 64 groups:*

Order	Groups	Order	Groups
2	C_2	23	C_{23}
3	C_3	24	$Dic_{24}, S_3 \times C_4, D_{12}, Dic_{12} \times C_2, C_3 \rtimes D_4, C_6 \times C_4, D_4 \times C_3, S_4, A_4 \times C_2, D_6 \times C_2, C_2 \times C_2 \times C_2 \times C_3$
4	$C_4, C_2 \times C_2$	30	$D_{15}, C_5 \times S_3, C_3 \times D_5$
5	C_5	38	D_{19}
6	C_6, S_3	40	$C_{20} \times C_2, D_5 \times C_4, C_5 \times (C_4 \times C_2), D_{20}, C_5 \rtimes D_4, D_4 \times C_5, GA(1, 5) \times C_2, D_5 \times C_2 \times C_2, C_2 \times C_2 \times C_2 \times C_5$
7	C_7	56	$(C_2 \times C_2 \times C_2) \rtimes C_7$
8	$C_4 \times C_2, C_2 \times C_2 \times C_2, D_4$	57	$C_{19} \rtimes C_3$
10	C_{10}, D_5	60	$A_5, D_5 \times C_6, C_{15} \rtimes C_4, D_{15} \times C_2, A_4 \times C_5$
12	$C_{12}, C_6 \times C_2, D_6, A_4, Dic_{12}$	114	$C_{19} \rtimes C_6$
15	C_{15}	115	C_{115}
19	C_{19}	120	$S_5, A_5 \times C_2, S_4 \times C_5, A_4 \rtimes D_5, A_4 \times D_5$
20	$C_{20}, C_{10} \times C_2, D_{10}, Dic_{20}, GA(1, 5)$		

Proof. All assertions about groups of order less than or equal to 552 make use of the library SmallGroups of MAGMA [12]. Condition (e) of Remark 21 implies that the order of G is in $\{1, 2, 3, 4, 5, 6, 7, 8, 10, 12, 15, 19, 20, 23, 24, 30, 38, 40, 56, 57, 60, 114, 115, 120, 552, 2760\}$.

Moreover, by Remark 21 and by the previous results, the order of every element in G is in $O := \{1, 2, 3, 4, 5, 6, 7, 10, 12, 15, 19, 20, 23, 115\}$.

If $|G| = 2760$, then there exists either one 23-Sylow or 24 23-Sylow subgroups. In the first case, the 23-Sylow is normal and its product with a 2-Sylow subgroup is a subgroup of order 184. All groups of order 184 contain an element of order 46. In the second case, G acts on the 24 23-Sylow subgroups and G_H is of order 115 for every 23-Sylow subgroup H . Therefore G_H is cyclic. Let K be the only subgroup of G_H of order 23. This acts on 23 groups (all except H) and so it has 23 fixed points. Then K is contained in G_H for every H and it should be the unique group of order 23 which is

contained in G_H for all H . This is not possible, since every H is contained in G_H , so we have a contradiction.

The quaternion group Q_8 cannot occur, again by Chouinard's Theorem (see the proof above for the element of order 8).

The group $C_5 \times (S_3 \times C_4)$, of order 120, is not possible, since if σ is the element of order 5, then in the automorphism group of $\pi_\sigma(F_\sigma(C))$ (which is an extended binary Golay code) there should be a subgroup isomorphic to $S_3 \times C_4$ acting fixed point freely, and this is not the case.

Finally, all the other groups are excluded by verifying that they have elements of order which is not in O , or a subgroup isomorphic to Q_8 or to $C_5 \times (S_3 \times C_4)$. \square

Remark 28. It would be interesting to exclude other non-abelian groups, using methods similar to those in [8], or elementary abelian groups, using methods similar to those in [9]. However, for a lack of classification of smaller codes, this seems to be still computationally impossible. It would be also interesting to get similar results without the hypothesis of the fixed point free action, but this seems to make the number of possibilities grow enormously. Finally, another direction of further research can be to get a similar result for the extremal code of length 96, which is studied in [15, 20, 22], but this is beyond the aim of this paper.

4. Some necessary conditions for the existence of a self-dual extremal [120, 60, 24] code

In this section we establish some necessary conditions for the existence of an extremal [120, 60, 24] code. Similar conditions are given in [23] and [4] for an extremal [72, 36, 16] and [96, 48, 20] code.

Let C be a [118, 59, 22] type I code. By Theorem 3 (a) we have

$$\begin{aligned} W_C(y) &= \sum_{j=0}^{14} a_j (1+y^2)^{59-4j} (y^2(1-y^2)^2)^j = \\ &= a_0 + (59a_0 + a_1)y^2 + (1711a_0 + 53a_1 + a_2)y^4 + (32509a_0 + 1376a_1 + \\ &\quad 47a_2 + a_3)y^6 + (455126a_0 + 23320a_1 + 1077a_2 + 41a_3 + a_4)y^8 + \dots \end{aligned}$$

with $a_j \in \mathbb{Q}$ for $j = 0, \dots, 14$. Since the minimum distance of C is 22, we get $a_0 = 1$, $a_1 = -59$, $a_2 = 1416$, $a_3 = -17877$, $a_4 = 128679$, $a_5 = -538375$,

$a_6 = 1291628$, $a_7 = -1713124$, $a_8 = 1187434$, $a_9 = -400374$ and $a_{10} = 0$.
Let S be the shadow of C . Then by Theorem 5 (a) we have

$$\begin{aligned} W_S(y) = & \frac{1}{33554432}a_{14}y^3 + \left(-\frac{1}{524288}a_{13} - \frac{7}{8388608}a_{14}\right)y^7 + \left(\frac{189}{16777216}a_{14} + \right. \\ & \left. \frac{1}{8192}a_{12} + \frac{13}{262144}a_{13}\right)y^{11} + \left(-\frac{819}{8388608}a_{14} - \frac{1}{128}a_{11} - \frac{325}{524288}a_{13} \right. \\ & \left. - \frac{3}{1024}a_{12}\right)y^{15} + \left(\frac{325}{65536}a_{13} + \frac{69}{2048}a_{12} + \frac{11}{64}a_{11} + \frac{20475}{33554432}a_{14}\right)y^{19} + \\ & \left(\frac{231}{128}a_{11} - \frac{7475}{262144}a_{13} - \frac{12285}{4194304}a_{14} - \frac{253}{1024}a_{12} + 12811968\right)y^{23} + \dots \end{aligned}$$

Let $W_S(y) = \sum_{i=0}^{118} B_i y^i$. By Theorem 5 (b) we have $B_i \in \{0, 1\}$ for $i = 3, 7$ and at most one B_i is nonzero for $i \leq 11$. Therefore there are four possibilities:

- If $B_3 = 1$, $B_7 = 0$, $B_{11} = 0$, then $a_{14} = 33554432$, $a_{13} = -14680064$, $a_{12} = 2867200$. Since $B_{15} = -2576 - \frac{1}{128}a_{11} \geq 0$, we have $B_{19} = 44275 + \frac{11}{164}a_{11} < 0$, a contradiction.
- If $B_3 = 0$, $B_7 = 1$, $B_{11} = 0$, then $a_{14} = 0$, $a_{13} = -524288$, $a_{12} = 212992$. Since $B_{15} = -299 - \frac{1}{128}a_{11} \geq 0$, we have $B_{19} = 4576 + \frac{11}{164}a_{11} < 0$. It is again a contradiction.
- If $B_3 = 0$, $B_7 = 0$, $B_{11} \neq 0$, then $a_{14} = a_{13} = 0$ and $a_{12} > 0$. Therefore the system of inequalities $B_{15} = -\frac{1}{128}a_{11} - \frac{3}{1024}a_{12} \geq 0$ and $B_{19} = \frac{69}{2048}a_{12} + \frac{11}{64}a_{11} \geq 0$ has no solutions, a contradiction.

Hence $B_3 = 0$, $B_7 = 0$, $B_{11} = 0$ and we obtain $a_{14} = a_{13} = a_{12} = a_{11} = 0$. In conclusion the shadow has minimal distance 23 and we can calculate the weight enumerators $W_C(y)$ and $W_S(y)$ (see Table 1 and Table 2).

Lemma 29. *Let C_0 be the subcode of C containing all codewords whose weights are multiples of 4. Then the supports of all vectors of a given weight in C_0 and in C_0^\perp form a 3-design.*

Proof. Since C_0 is a $[118, 58, 24]$ code and $C_0^\perp = C \cup S$, then C_0^\perp is a $[118, 60, 22]$ code. If $W_{C_0}(x, y) = \sum_{i=0}^{118} A_i x^{118-i} y^i$, then we have $|\{i \mid A_i \neq 0, 0 < i \leq 115\}| = 19 \leq d(C_0^\perp) - 3$. Therefore by Theorem 20 the supports of the vectors of weight i in C_0^\perp and in C_0 form a 3-design. \square

Table 1: The weight enumerator of a self-dual $[118, 59, 22]$ code

i	A_i
22 96	1534767
24 94	25357020
26 92	323009424
28 90	3577030288
30 88	33041945820
32 86	255009210885
34 84	1660986238080
36 82	9190790517376
38 80	43420813336368
40 78	175902467952336
42 76	613510461769920
44 74	1848313759032000
46 72	4823479510074576
48 70	10929799315381752
50 68	21547310072116608
52 66	37017173713636224
54 64	55486969304739115
56 62	72637487089840296
58 60	83095867738716768

Question 30. By Assmus-Mattson theorem the supports of the codewords of minimal weight 22 in a self-dual $[118, 59, 22]$ code build a 3- $(118, 22, 8885)$ design \mathcal{D} . Similarly the supports of the codewords of minimal weight 24 in a self-dual $[120, 60, 24]$ code build a 5- $(120, 24, 8855)$ design. In [21] the authors showed that if \mathcal{D} is a self-orthogonal 5- $(120, 24, 8855)$ design, then $C(\mathcal{D})$ is a self-dual $[120, 60, d]$ code with $d = 20$ or $d = 24$. Unfortunately it was not possible to exclude the case $d = 20$ and show that the code is extremal. A natural question, although very difficult, is: if \mathcal{D} is a self-orthogonal 3- $(118, 22, 8885)$ design, then is $C(\mathcal{D})$ a self-dual extremal $[118, 59, 22]$ code?

Remark 31. Since the shadow of a self-dual $[118, 59, 22]$ code has minimal distance 23, the existence of a self-dual $[120, 60, 24]$ code is equivalent to the existence of a self-dual $[118, 59, 22]$ code C (In general by [29] the existence of an extremal code of length $24m$ is equivalent to the existence of a self-dual

Table 2: The weight enumerator of the shadow of a self-dual $[118, 59, 22]$ code

i	B_i
23 95	12811968
27 91	2201249408
31 87	187592982720
35 83	7972733942784
39 79	178129081470720
43 75	2168688143930880
47 71	14778320201079552
51 67	57459493525644288
55 63	129133310381938304
59	169008544553322240

$[24m - 2, 12m - 1, 4m + 2]$ code). By Lemma 29 the supports of the vectors of weight k in the shadow S of C form a 3 - $(118, k, \lambda)$ design. Therefore if there exists a $[118, 59, 22]$ code and its shadow has enumerator weight $W_S(y) = \sum_{k=0}^{118} B_k y^k$, then the coefficients of the shadow must satisfy the following condition of divisibility $\frac{(k-i)!}{k!} \frac{118!}{(118-i)!} \mid B_k$, since the terms $\lambda_i = B_k \frac{k!}{(k-i)!} \frac{(118-i)!}{118!} \in \mathbb{N}_0$. Actually, all the coefficients B_k satisfy this condition (see Table 3).

Now we have the following necessary condition on the existence of an extremal type II code of length 120.

Theorem 32. *If no linear $[120, 60, 23]$ code with weight enumerator given in Table 4 exists, then there exists no self-dual $[120, 60, 24]$ code.*

Proof. A self-dual $[120, 60, 24]$ code has a child C , which is a self-dual $[112, 59, 22]$ code. By Lemma 8, $W_{C_1}(y) = W_{C_3}(y)$. Therefore the code C^* defined as in Lemma 9 is formally self-dual, and the theorem follows (the weight enumerator of the code C^* is given in Table 4. It is calculated thanks to Lemma 9, knowing the weight enumerator of the $[118, 59, 22]$ type I code and of its shadow, which are given in Table 1 and Table 2 respectively). \square

Theorem 33. *If no self-dual doubly-even $[120, 60, 4]$ code with weight enumerator given in Table 5 exists, then there exists no self-dual $[120, 60, 24]$ code.*

Table 3: Parameters of the 3-designs

k	$\lambda_0 = B_k$	λ_1	λ_2	$\lambda_3 = \lambda$
23	12811968	2497248	469568	85008
27	2201249408	503675712	9327328	24122400
31	187592982720	49282902240	12636641600	3159160400
35	7972733942784	2364793966080	687205084160	195497998080
39	178129081470720	58873170994560	19121200835840	6099003714880
43	2168688143930880	790284662618880	283691930170880	100270423594880
47	14778320201079552	5886280080091008	2314263963112704	897774813276480
51	57459493525644288	24834187879727616	10612900803302400	4483035684153600
55	129133310381938304	60189254839039040	27779656079556480	12692429070831840
59	169008544553322240	84504272276661120	41891006769626880	20584374016109760
63	129133310381938304	68944055542899264	36534456783416704	19212085032658784
67	57459493525644288	32625305645916672	18404018569491456	10312596612215040
71	14778320201079552	8892040120988544	5320024004010240	3164497036868160
75	2168688143930880	1378403481312000	871810748864000	548639522992000
79	178129081470720	119255910476160	79503940317440	52774167279680
83	7972733942784	5607939976704	3930351094784	2744469298944
87	187592982720	138310080480	101663819840	74495040400
91	2201249408	1697573696	1305825920	1001883680
95	12811968	10314720	8287040	6643920

Proof. Let C be a self-dual $[120, 60, 24]$ code, $u \in \mathbb{F}_2^{120}$ of weight $\text{wt}(u) = 4$ and $D := C \cap \langle u \rangle^\perp$. Since $D^\perp = C^\perp + (\langle u \rangle^\perp)^\perp = C \oplus \langle u \rangle$, then $D \leq D^\perp$ and $\dim D^\perp = \dim(C + \langle u \rangle) = 61$ i.e. D is a self-orthogonal $[120, 59]$ code. If $N := \langle D, u \rangle$, then $N = D \oplus \langle u \rangle$ and $\dim N = 60$. Since $(d_1 + u) \cdot (d_2 + u) = 0$, for all $d_1, d_2 \in D$, we have that N is self-orthogonal and therefore it is self-dual. On the other hand, $\text{wt}(d + u) \equiv 0 \pmod{4}$, because $d \cdot u = 0$ for all $d \in D$. Therefore N is a self-dual doubly-even $[120, 60, 4]$ code. Since $\dim(N \cap C) = 59$, we have N is neighbor of C . The code N has only a vector of weight 4. To determine the number of vectors of weight 20 it is sufficient to calculate the number of vectors $w \in C$ of weight 24 with $|\text{supp}(w) \cap \text{supp}(u)| = 4$. Since the vectors of weight 24 in C form a 5-design, then this number is equal to $\lambda_4 = 51359$ where λ_4 is the number of blocks incident with 4 different points. If $\sum A_i y^i$ is the weight enumerator of N , then $A_0 = 1$, $A_4 = 1$, $A_8 = 0$, $A_{12} = 0$, $A_{16} = 0$ and $A_{20} = 51359$. Therefore by Theorem 3 we obtain the weight enumerator of the code N , which is given in Table 5. This concludes the proof. \square

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Table 4: The weight enumerator of a formally self-dual $[120, 60, 23]$ code

Weight	Weight distribution	Weight	Weight distribution
0	1	61	84504272276661120
23	1534767	63	72637487089840296
24	31763004	64	120053624495708267
25	6405984	65	64566655190969152
27	323009424	67	37017173713636224
28	4677654992	68	50277056834938752
29	1100624704	69	28729746762822144
31	33041945820	71	10929799315381752
32	348805702245	72	12212639610614352
33	93796491360	73	7389160100539776
35	1660986238080	75	1848313759032000
36	13177157488768	76	1697854533735360
37	3986366971392	77	1084344071965440
39	43420813336368	79	175902467952336
40	264967008687696	80	132485354071728
41	89064540735360	81	89064540735360
43	613510461769920	83	9190790517376
44	2932657830997440	84	5647353209472
45	1084344071965440	85	3986366971392
47	4823479510074576	87	255009210885
48	18318959415921528	88	126838437180
49	7389160100539776	89	93796491360
51	21547310072116608	91	3577030288
52	65746920476458368	92	1423634128
53	28729746762822144	93	1100624704
55	55486969304739115	95	25357020
56	137204142280809448	96	7940751
57	64566655190969152	97	6405984
59	83095867738716768		
60	167600140015377888		

Table 5: The weight enumerator of a $[120, 60, 4]$ neighbor of an extremal $[120, 60, 24]$ code

i	A_i
0 120	1
4 116	1
20 100	51359
24 96	43481179
28 92	6539254776
32 88	494044041905
36 84	19178964940125
40 80	400399951557816
44 76	4639015235035296
48 72	30526043817770504
52 68	115980280893408771
56 64	257259077150523955
60	335272511326715600