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## ON SOME PROJECTIVE TRIPLY-EVEN BINARY CODES INVARIANT UNDER THE CONWAY GROUP $Co_1$

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**ABSTRACT.** A binary triply-even  $[98280, 25, 47104]_2$  code invariant under the sporadic simple group  $Co_1$  is constructed by adjoining the all-ones vector to the faithful and absolutely irreducible 24-dimensional code of length 98280. Using the action of  $Co_1$  on the code we give a description of the nature of the codewords of any non-zero weight relating these to vectors of types 2, 3 and 4, respectively of the Leech lattice. We show that the stabilizer of any non-zero weight codeword in the code is a maximal subgroup of  $Co_1$ . Moreover, we give a partial description of the nature of the codewords of minimum weight of the dual code.

### 1. Introduction

A triply-even binary code is a linear code in which the weight of every codeword is divisible by 8; such codes have previously been classified up to length 48 by Betsumiya and Munemasa [3]. Recent interest is growing in regards to the study of  $\Delta$ -divisible codes of large lengths, of which triply-even codes are a special case. A linear code  $C$  over  $\mathbb{F}_q$  is said to be  $\Delta$ -divisible if the Hamming weight  $w(c)$  of every codeword  $c \in C$  is divisible by  $\Delta > 1$ , and  $C$  is said to be a projective code if  $d(C^\perp) \geq 3$ . In particular, binary  $\Delta$ -divisible codes have been studied in [7] and applications of these have been given therein. More recently a study of the lengths for which triply-even binary codes are known to exist was done in [8]. The authors prove the non-existence of a projective triply-even binary linear code of length 59. In addition, the authors remark that the distinction between the existence of a projective/non-projective

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$q^r$ -divisible code of a certain length matters for the determination of upper bounds on the maximum possible cardinality of partial  $t$ -spreads. They also give references of an example of non-existence of a projective  $2^3$ -divisible code of length 52 while non-projective codes of this length exist. It follows from [8, Fact 1] that triply-even binary codes exist for length  $n \geq 60$ .

In the present note we answer a question posed by Wolfgang Knapp on the combinatorial properties of a 25-dimensional submodule of the permutation module of length 98280 invariant under  $\text{Co}_1$  which contains the unique irreducible faithful 24-dimensional code as a subcode of codimension 1. Given the relevance of the study of triply-even binary codes, we present the binary codes examined in this paper as examples of triply-even projective binary codes of large length admitting a sporadic simple group as a permutation group of automorphisms. We also examine the properties of some point- and block-primitive 1-designs obtained as support 1-designs of the non-zero codewords of this triply-even binary 25-dimensional code of length 98280.

In the theorem given below, we summarize our results; the specific results relating to the codes are given as propositions in the following sections.

**Theorem 1.1.** *Let  $G$  be the simple group  $\text{Co}_1$  of Conway. Let  $V$  be the Leech lattice modulo 2, and  $\Omega$  be the orbit of length 98280 obtained by the action of  $G$  on  $V$  and  $\mathbb{F}_2\Omega$  the corresponding permutation module over  $\mathbb{F}_2$  invariant under  $G$ . Then the following hold:*

- (a)  $\mathbb{F}_2\Omega$  contains a unique submodule of dimension 25. Let  $C_{25}$  denote this submodule. Then  $C_{25} = \langle C_{24}, \mathbf{1} \rangle$ , where  $C_{24}$  is the unique faithful and irreducible  $\text{Co}_1$ -invariant  $\mathbb{F}_2$ -module of dimension 24;
- (b)  $C_{25}$  is a projective triply-even code;
- (c)  $C_{25}$  is not spanned by its minimum-weight codewords;
- (d)  $\text{Aut}(C_{25}) \cong \text{Co}_1$ ;
- (e) the codewords of non-zero weight in  $C_{25}$  are stabilized by maximal subgroups of  $G$ .

The paper is organized as follows: in Section 2 we outline the background and notation and in Section 3 we give a brief overview on the  $\text{Co}_1$  group. In Section 4 we describe the construction method used, and give our results on the 25-dimensional binary code invariant under  $\text{Co}_1$  in the ensuing sections.

## 2. Terminology

In this section, we state some useful facts in coding theory, design theory and finite group theory. Our notation for designs and groups will be standard, and it is as in [2] and ATLAS [6].

Let  $\mathbb{F}$  be a finite field of order  $q = p^t$ , where  $p$  is a prime and  $t \in \mathbb{N}$ ; and  $G$  a finite group. Let  $\Omega$  be a finite  $G$ -set, i.e.  $\Omega$  is a finite set and there is a  $G$ -action on  $\Omega$ , namely, a map  $\cdot : G \times \Omega \rightarrow \Omega$  given by  $(g, \omega) \mapsto g \cdot \omega$ , satisfying  $(g \cdot h) \cdot \omega = g \cdot (h \cdot \omega)$  for all  $g, h \in G$  and all  $\omega \in \Omega$ , and that  $1 \cdot \omega = \omega$  for all  $\omega \in \Omega$ .

Then  $\mathbb{F}\Omega = \{ \sum_{\omega \in \Omega} g_\omega \omega \mid g_\omega \in \mathbb{F} \}$  is a vector space over  $\mathbb{F}$  with basis  $\Omega$ . Extending the  $G$ -action on  $\Omega$  linearly,  $\mathbb{F}\Omega$  becomes an  $\mathbb{F}G$ -module, called an  $\mathbb{F}G$ -permutation module with permutation basis  $\Omega$ , (we remark that the permutation module  $\mathbb{F}\Omega$  need not be semisimple in general). The  $\mathbb{F}$ -vector space  $\mathbb{F}\Omega$  is

equipped with a non-degenerate symmetric bilinear form

$$\left\langle \sum_{\omega \in \Omega} g_{\omega} \omega, \sum_{\omega \in \Omega} h_{\omega} \omega \right\rangle = \sum_{\omega \in \Omega} g_{\omega} h_{\omega}, \forall \mathbf{g} = \sum_{\omega \in \Omega} g_{\omega} \omega \text{ and } \mathbf{h} = \sum_{\omega \in \Omega} h_{\omega} \omega \in \mathbb{F}\Omega$$

called the standard inner product on  $\mathbb{F}\Omega$ . For any  $a \in G$  and any  $\mathbf{g} = \sum_{\omega \in \Omega} g_{\omega} \omega$  and  $\mathbf{h} = \sum_{\omega \in \Omega} h_{\omega} \omega \in \mathbb{F}\Omega$ , we have

$$\begin{aligned} \langle a(\mathbf{g}), a(\mathbf{h}) \rangle &= \left\langle a\left(\sum_{\omega \in \Omega} g_{\omega} \omega\right), a\left(\sum_{\omega \in \Omega} h_{\omega} \omega\right) \right\rangle \\ &= \left\langle \sum_{\omega \in \Omega} g_{\omega} a\omega, \sum_{\omega \in \Omega} h_{\omega} a\omega \right\rangle = \sum_{\omega \in \Omega} g_{\omega} h_{\omega} \\ &= \langle \mathbf{g}, \mathbf{h} \rangle. \end{aligned}$$

So, the standard inner product on the vector space  $\mathbb{F}\Omega$  is  $G$ -invariant in the following sense:

$$\langle a(\mathbf{g}), a(\mathbf{h}) \rangle = \langle \mathbf{g}, \mathbf{h} \rangle, \forall a \in G, \forall \mathbf{g}, \mathbf{h} \in \mathbb{F}\Omega.$$

Moreover, for any  $U \subseteq \mathbb{F}\Omega$  denote  $U^{\perp} = \{\mathbf{v} \in \mathbb{F}\Omega \mid \langle \mathbf{u}, \mathbf{v} \rangle = 0, \forall \mathbf{u} \in U\}$ . If  $C$  is an  $\mathbb{F}G$ -submodule of  $\mathbb{F}\Omega$ , then for any  $a \in G$  and  $\mathbf{c}' \in C^{\perp}$ , and for any  $\mathbf{c} \in C$ , by the  $G$ -invariance of the inner-product we have that

$$\langle a\mathbf{c}', \mathbf{c} \rangle = \langle a\mathbf{c}', aa^{-1}\mathbf{c} \rangle = \langle \mathbf{c}', a^{-1}\mathbf{c} \rangle = 0,$$

so  $a\mathbf{c}' \in C^{\perp}$ , i.e.,  $C^{\perp}$  is  $G$ -invariant. Hence,  $C^{\perp}$  is an  $\mathbb{F}G$ -submodule.

We say that  $C$  is an  $\mathbb{F}G$ -permutation code of  $\mathbb{F}\Omega$ , denoted by  $C \subseteq \mathbb{F}\Omega$ , if  $C$  is an  $\mathbb{F}G$ -submodule of the  $\mathbb{F}G$ -permutation module  $\mathbb{F}\Omega$ ; and a permutation code  $C$  is said to be irreducible if  $C$  is an irreducible  $\mathbb{F}G$ -submodule of  $\mathbb{F}\Omega$ . Two linear codes are *isomorphic* if they can be obtained from one another by permuting the coordinate positions. For a linear code  $C$  of length  $n$  over  $\mathbb{F}$ , a permutation of the components of a codeword of length  $n$  is said to be a permutation automorphism of  $C$  if the permutation maps codewords to codewords. By  $\text{Aut}(C)$  we denote the automorphism group of  $C$  consisting of all the permutation automorphisms of  $C$ . With this we have that  $G$  acts on  $C$  and thus  $G \leq \text{Aut}(C)$  so that the code  $C$  becomes a  $\mathbb{F}G$ -submodule of the permutation module  $\mathbb{F}\Omega$ . In this note we consider only binary linear codes, so we restrict our attention to permutation automorphisms. It is easy to see that  $C$  is an  $\mathbb{F}G$ -permutation code of a  $G$ -permutation set  $\Omega$  of cardinality  $n$  if and only if there is a group homomorphism of  $G$  to  $\text{Aut}(C)$ .

A code  $C$  is *self-orthogonal* if  $C \subseteq C^{\perp}$ . The *hull* of  $C$  is  $\text{Hull}(C) = C \cap C^{\perp}$ . The all-one vector will be denoted by  $\mathbf{1}$ , and is the constant vector of weight the length of the code, and whose coordinate entries consist entirely of 1's. A binary code  $C$  is *doubly-even* if all its non-zero codewords have weight divisible by four, and *triply-even* if all its non-zero codewords have weight divisible 8. Let  $C$  be a code of length  $n$ . The weight distribution of a code  $C$  is the sequence  $\{A_i \mid i = 0, 1, \dots, n\}$ , where  $A_i$  is the number of codewords of weight  $i$  and the homogeneous polynomial  $W_C(x, y) = \sum_{i=0}^n A_i x^i y^{n-i}$  of degree  $n$  is called the weight enumerator of  $C$ . The weight enumerator of a code  $C$  and its dual  $C^{\perp}$  are related via MacWilliams' identity.

An incidence structure  $\mathcal{D} = (\mathcal{P}, \mathcal{B}, \mathcal{I})$ , with point set  $\mathcal{P}$ , block set  $\mathcal{B}$  and incidence  $\mathcal{I}$  is a  $t$ -( $v, k, \lambda$ ) design, if  $|\mathcal{P}| = v$ , every block  $B \in \mathcal{B}$  is incident with precisely  $k$  points, and every  $t$  distinct points are together incident with precisely  $\lambda$  blocks. The complement of  $\mathcal{D}$  is the structure  $\tilde{\mathcal{D}} = (\mathcal{P}, \mathcal{B}, \tilde{\mathcal{I}})$ , where  $\tilde{\mathcal{I}} = \mathcal{P} \times \mathcal{B} - \mathcal{I}$ . The dual structure of  $\mathcal{D}$  is  $\mathcal{D}^t = (\mathcal{B}, \mathcal{P}, \mathcal{I}^t)$ , where  $(B, p) \in \mathcal{I}^t$  if and only if  $(P, B) \in \mathcal{I}$ . Thus, the transpose of an incidence matrix for  $\mathcal{D}$  is an incidence matrix for  $\mathcal{D}^t$ . We will say that the design is symmetric if it has the same number of points and blocks, and self dual if it is isomorphic to its dual.

The support of a nonzero vector  $x := (x_1, \dots, x_n), x_i \in \mathbb{F}_q$  is the set of indices of its nonzero coordinates:  $\text{supp}(x) = \{i | x_i \neq 0\}$ . The support design of a code of length  $n$  for a given nonzero weight  $w$  is the design with  $n$  points of coordinate indices and blocks the supports of all codewords of weight  $w$ .

### 3. The Conway group $\text{Co}_1$

The Leech lattice is a certain 24-dimensional  $\mathbb{Z}$ -submodule of the 24-dimensional Euclidean space  $\mathbb{R}^{24}$  discovered by John Leech. John Conway showed that the automorphism group of the Leech lattice is a quasisimple group. Its central factor group is the Conway group  $\text{Co}_1$ . The Conway groups  $\text{Co}_2$  and  $\text{Co}_3$  are stabilizers of sublattices of the Leech lattice. We give a brief description of the construction of these groups, omitting detail. The content of this section is mostly drawn from [1]. A more recent and comprehensive account is given in [13], see also [5, 11, 12].

Let  $H = M_{24}$  and  $(\Omega, \mathcal{C})$  be the Steiner system  $S(24, 8, 5)$  for  $H$ . Let  $V$  be the permutation module over  $\mathbb{F}_2$  of  $H$  with basis  $\Omega$  and  $V_{\mathcal{C}}$  the Golay code submodule. Let  $\mathbb{R}^{24}$  be the permutation module over the reals for  $H$  with basis  $\Omega$  and let  $\langle \cdot, \cdot \rangle$  be the symmetric bilinear form on  $\mathbb{R}^{24}$  for which  $\Omega$  is an orthogonal basis. Then  $\mathbb{R}^{24}$  together with  $\langle \cdot, \cdot \rangle$  is simply the 24-dimensional Euclidean space admitting the action of  $H$ , and for  $\sum_{\omega} \alpha_{\omega} \omega$  and  $\sum_{\omega} \beta_{\omega} \omega$  in  $\mathbb{R}^{24}$ ,

$$\left\langle \sum_{\omega} \alpha_{\omega} \omega, \sum_{\omega} \beta_{\omega} \omega \right\rangle = \sum_{\omega} \alpha_{\omega} \beta_{\omega}.$$

For  $v \in \mathbb{R}^{24}$  define  $q(v) = \langle v, v \rangle / 16$ . Thus  $q$  is a positive definite quadratic form on  $\mathbb{R}^{24}$ . Given  $Y \subseteq \Omega$ , define  $e_Y = \sum_{y \in Y} y \in \mathbb{R}^{24}$ . For  $\omega \in \Omega$  let  $\lambda_{\omega} = e_{\Omega} - 4\omega$ .

The Leech lattice is the set  $\Lambda$  of vectors  $v = \sum_{\omega} \alpha_{\omega} \omega \in \mathbb{R}^{24}$  such that:

- : (A1)  $\alpha_{\omega} \in \mathbb{Z}$  for all  $\omega \in \Omega$ .
- : (A2)  $m(v) = (\sum_{\omega} \alpha_{\omega}) / 4 \in \mathbb{Z}$ .
- : (A3)  $\alpha_{\omega} \equiv m(v) \pmod{2}$  for all  $\omega \in \Omega$ .
- : (A4)  $\mathcal{C}(v) = \{\omega \in \Omega \mid \alpha_{\omega} \not\equiv m(v) \pmod{4}\} \in V_{\mathcal{C}}$ .

The Leech lattice  $\Lambda$  is a  $\mathbb{Z}$ -submodule of  $\mathbb{R}^{24}$ . Let  $\Lambda_0$  denote the set of vectors  $v \in \Lambda$  such that  $m(v) \equiv 0 \pmod{4}$ . Then  $\Lambda_0$  is a  $\mathbb{Z}$ -submodule spanned by the set  $\{2e_B \mid B \subset \mathcal{C}\}$ . Further,  $\Lambda$  as a  $\mathbb{Z}$ -submodule is generated by  $\Lambda_0$  and  $\lambda_{\omega_0}$ , for  $\omega_0 \in \Omega$ . Write  $O(\mathbb{R}^{24})$  for the subgroup of  $\text{GL}(\mathbb{R}^{24})$  preserving the bilinear form  $\langle \cdot, \cdot \rangle$ , or equivalently preserving the quadratic form  $q$ . Let  $G$  be the subgroup of  $O(\mathbb{R}^{24})$  acting on  $\Lambda$ . The group  $G$  is the automorphism group of the Leech lattice. For  $Y \subset \Omega$ , write  $e_Y$  for the

element of  $GL(\mathbb{R}^{24})$  such that

$$\epsilon_Y(\omega) = \begin{cases} -\omega & , \text{if } \omega \in Y, \\ \omega & , \text{if } \omega \notin Y. \end{cases}$$

Let  $Q = \{\epsilon_Y \mid Y \in V_G\}$ . Then  $K = H \cdot Q \leq G$ . Given any positive integer  $l$ , write  $\Lambda_l$  for the set of all vectors  $v$  in  $\Lambda$  with  $q(v) = l$ . Then  $\Lambda = \cup_l \Lambda_l$ . For  $v = \sum_{\omega} \alpha_{\omega} \omega \in \Lambda$  and  $i$  a non-negative integer, let

$$S_i(v) = \{\omega \in \Omega : |\alpha_{\omega}| = i\},$$

and define the shape of  $v$  to be  $(0^{l_0}, 1^{l_1}, \dots)$ , where  $l_i = |S_i(v)|$ . Let  $\Lambda_2^2$  be the set of all vectors in  $\Lambda$  of shape  $(2^8, 0^{16})$ ,  $\Lambda_2^3$  the vectors in  $\Lambda$  of shape  $(3, 1^{23})$ , and  $\Lambda_2^4$  the vectors in  $\Lambda$  of shape  $(4^2, 0^{22})$ . Then  $\Lambda_2^i$ ,  $2 \leq i \leq 4$ , are the orbits of  $K$  on  $\Lambda_2$ , with  $|\Lambda_2^2| = 2^7 \cdot 759$ ,  $|\Lambda_2^3| = 2^{12} \cdot 24$  and  $|\Lambda_2^4| = 2^2 \cdot \binom{24}{2}$ . Moreover,  $|\Lambda_2| = 2^4 \cdot 3^3 \cdot 5 \cdot 7 \cdot 13$  and  $K = N_G(\Lambda_2^4)$ . Using this information it can be shown that  $G$  acts transitively on  $\Lambda_2$ ,  $\Lambda_3$ , and  $\Lambda_4$ . Also  $K$  is a maximal subgroup of  $G$  and  $|G| = 2^{22} \cdot 3^9 \cdot 5^4 \cdot 7^2 \cdot 11 \cdot 13 \cdot 23$ . Notice that  $\epsilon_{\Omega}$  is the scalar map on  $\mathbb{R}^{24}$  determined by  $-1$ , and hence is in the center of  $G$ . Denote by  $Co_1$  the factor group  $G/\langle \epsilon_{\Omega} \rangle$ . Denote by  $Co_2$  the stabilizer of a vector in  $\Lambda_2$  and denote by  $Co_3$  the stabilizer of a vector in  $\Lambda_3$ . The groups  $Co_1$ ,  $Co_2$  and  $Co_3$  are the *Conway groups*, with  $|Co_1| = 2^{21} \cdot 3^9 \cdot 5^4 \cdot 7^2 \cdot 11 \cdot 13 \cdot 23$ ,  $|Co_2| = 2^{18} \cdot 3^6 \cdot 5^3 \cdot 7 \cdot 11 \cdot 23$  and  $|Co_3| = 2^{10} \cdot 3^7 \cdot 5^3 \cdot 7 \cdot 11 \cdot 23$ . Recall that  $Co_1$ ,  $Co_2$  and  $Co_3$  are finite simple groups.

In Table 1 we give the primitive representations of  $Co_1$  of degree  $\leq 8386560$ . The first column gives the ordering of the primitive representations as given by the ATLAS [6] and as used in our computations; the second gives the degrees (the number of cosets of the point stabilizer), the third the number of orbits, and the remaining columns give the size of the non-trivial orbits of the respective point stabilizers.

No.	Max. sub.	Deg.	#	length					
1	$Co_2$	98280	4	4600	46575	47104			
2	$3 \text{Suz}:2$	1545600	5	5346	22880	405405	11119682		
3	$2^{11} \text{M}_{24}$	8292375	6	3542	48576	1457280	2637824	4145152	
4	$Co_3$	8386560	7	11178	37950	257600	1536975	2608200	3934656

TABLE 1. Maximal subgroups of  $Co_1$  of degree  $\leq 8386560$

#### 4. The construction of codes

Our approach is representation theoretic and based on Theorem 4.1.

**Theorem 4.1.** *Let  $G$  be a finite group and let  $V$  be an  $\mathbb{F}G$ -module over a finite field  $\mathbb{F}$  and let  $\Omega$  be a  $G$ -invariant subset of  $V$ . Let  $\mathbb{F}\Omega$  be the (formal) permutation module with basis  $\bar{\Omega} = \{\bar{\alpha} \mid \alpha \in \Omega\}$  where*

$\bar{\alpha} = (\delta_{\beta\alpha})_{\beta \in \Omega}$  where  $\delta_{\beta\alpha}$  denotes the Kronecker  $\delta$  function.

Then

$$\rho: \sum_{\alpha \in \Omega} r_{\alpha} \bar{\alpha} \mapsto \sum_{\alpha \in \Omega} r_{\alpha} \alpha$$

is an  $\mathbb{F}G$ -homomorphism of  $\mathbb{F}\Omega$  into  $V$  with kernel of  $\rho = M = \{\sum_{\alpha \in \Omega} r_{\alpha} \bar{\alpha} \mid \sum_{\alpha \in \Omega} r_{\alpha} \alpha = 0 \text{ in } V\}$  and image  $U$  where  $U$  is the submodule of  $V$  generated by  $\Omega$ . Hence, we have

$$\mathbb{F}\Omega/M \cong U \text{ (by the homomorphism theorem) and}$$

$$M^{\perp} \cong U^* \text{ (by orthogonality)}$$

where  $M^{\perp}$  denotes the submodule of  $\mathbb{F}\Omega$  orthogonal to  $M$  with respect to the canonical bilinear form on  $\mathbb{F}\Omega$  and  $U^* = \text{Hom}(U, \mathbb{F})$  denotes the  $\mathbb{F}G$ -module dual to  $U$  in the sense of representation theory.

*Proof.* The action of  $G$  on  $\Omega$  is given by restricting the action of  $G(\subseteq \mathbb{F}G)$  on  $V$ . So the theorem is basically just a restatement of the universal property of the permutation module as a free structure over  $\Omega$  using in addition some elementary facts of representation theory and linear algebra. We leave to the reader to complete the details of the proof.  $\square$

**Remark 4.2.** Usually  $\alpha$  is identified with  $\bar{\alpha}$  and  $\Omega$  is identified with  $\bar{\Omega}$ , but for the purposes of Theorem 4.1 we keep them distinct.

**Corollary 4.3.** With the same assumptions of Theorem 4.1 the following hold:

- (i) Let  $V$  be irreducible. Then  $\mathbb{F}\Omega$  has an irreducible submodule  $W$  isomorphic to  $V^*$ , if  $\Omega \neq \emptyset$ .
- (ii) Let  $V \cong V^*$  be irreducible and self-dual (in the sense of representation theory). Then  $\mathbb{F}\Omega$  has an irreducible submodule  $W$  isomorphic to  $V$ .

**Remark 4.4.** Theorem 4.1 is useful in other situations, for instance if  $V$  has a unique maximal submodule  $V_0$  and  $\emptyset \neq \Omega \subseteq V \setminus V_0$ . Then necessarily  $U = V$ .

Theorem 4.1, Corollary 4.3 and Remark 4.4 above have been suggested by Wolfgang Knapp [9] as means of construction of codes.

## 5. Binary codes of small dimension invariant under $\text{Co}_1$ of degree 98280

With the notation established in Section 3, for  $v \in \Lambda$  let  $\Lambda_l(v, i)$  denote the set of  $u \in \Lambda_l$  for which  $\langle v, u \rangle = 8i$ . Let  $2\Lambda = \{2v : v \in \Lambda\}$ . Then  $2\Lambda$  is a  $2\text{Co}_1$ -invariant  $\mathbb{Z}$ -module, and  $2\text{Co}_1$  acts on the quotient module  $\tilde{\Lambda} = \Lambda/2\Lambda$ . The module  $\tilde{\Lambda}$  is the reduction modulo 2 of the Leech lattice. For  $v \in \Lambda$ , let  $\tilde{v} = v + 2\Lambda$  and for  $S \subseteq \Lambda$  let  $\tilde{S} = \{\tilde{s} : s \in S\}$ . Then  $2\tilde{v} = 0$  for all  $v \in \Lambda$ , and  $\tilde{\Lambda}$  is an elementary abelian 2-group which may be viewed as a  $\mathbb{F}_2 2\text{Co}_1$ -module. Recall from Section 3 that  $\text{Co}_1 \cong 2\text{Co}_1/\langle \epsilon_{\Omega} \rangle$ . Since  $\langle \epsilon_{\Omega} \rangle$  acts trivially on  $\tilde{\Lambda}$  it follows that  $\tilde{\Lambda}$  is a  $\mathbb{F}_2 \text{Co}_1$ -module. In [1, Lemma 23.2 (4), Lemma 23.3] Aschbacher showed that  $\tilde{\Lambda}$  is a 24-dimensional, faithful and irreducible  $\mathbb{F}_2 \text{Co}_1$ -submodule. Using these and other properties of  $\tilde{\Lambda} \cong \mathbb{F}_2^{24}$  in [10] we denoted this module  $\text{C}_{24}$  and examined its combinatorial properties. We state the pertinent result below

**Result 5.1.** Let  $G$  be the simple Conway group  $Co_1$  in its rank 5 primitive permutation action of degree 98280 and let  $C_{24}$  denote a submodule of dimension 24 of the permutation module of degree 98280 over  $\mathbb{F}_2$ . Then

- (i)  $C_{24}$  is a self-orthogonal doubly-even projective two-weight  $[98280, 24, 47104]_2$  code with weight enumerator  $x^0y^{98280} + 98280x^{47104}y^{51176} + 16678935x^{49152}y^{49128}$ ;
- (ii) The dual code  $C_{24}^\perp$  of  $C_{24}$  is a  $[98280, 98256, 3]_2$  uniformly packed code with 75348000 codewords of weight 3;
- (iii)  $\mathbf{1} \in C_{24}^\perp$  and  $C_{24}$  is the unique submodule of its dimension on which  $Co_1$  acts absolutely irreducibly;
- (iv)  $\text{Aut}(C_{24}) \cong Co_1$ .

**Remark 5.2.** (i) The code  $C_{24}$  can be constructed as an application of Theorem 4.1.

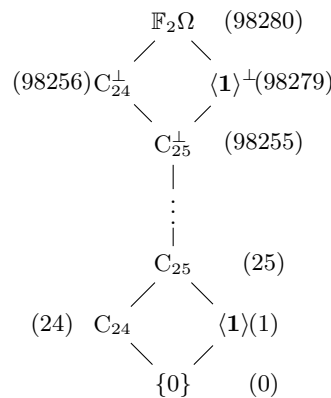
(ii) Observe that  $C_{24}$  is a  $\Delta$ -divisible code with  $\Delta = 2^{12}$ : for every  $c \neq \mathbf{0}$  in  $C_{24}$ , where  $\mathbf{0}$  represents the zero vector in  $C_{24}$  we have  $\text{wt}(c) \mid 2048$ .

As stated in Remark 5.2 (ii) one can apply Theorem 4.1 to the situation given in Result 5.1 by identifying  $V = \tilde{\Lambda}$  and  $\Omega = \bar{\Lambda}_2 = \Lambda_2 + \Lambda/2\Lambda$  with  $\mathbb{F} = \mathbb{F}_2$ , i.e., the reduction image of  $\Lambda_2$  modulo  $2\Lambda$ , and  $G = Co_1$ . Notice that  $V \cong V^*$  follows since  $G$  acts as an orthogonal group on  $V$  and  $C_{24}$  can be identified with the submodule  $U$  of  $\mathbb{F}_2\Omega$  given by Theorem 4.1. Notice also that  $C_{24}^\perp$  is the module denoted  $M$  in Theorem 4.1.

**5.1. The  $[98280, 25, 47104]_2$  code.** Observe that  $C_{24}$  does not contain the all-ones vector  $\mathbf{1}$ . Below, we construct a binary linear code of dimension 25, denoted  $C_{25}$  which results by adjoining the all ones vector to  $C_{24}$ . In fact,  $C_{25} \setminus C_{24}$  consists of the codewords complementary to those of  $C_{24}$ .

In Figure 1 below we give a partial description of the submodule structure (the composition factors can be derived from this) of the permutation module  $\mathbb{F}_2\Omega$  of degree 98280. The vector space dimension is given in parentheses.

FIGURE 1. Partial submodule lattice for  $\mathbb{F}_2\Omega$



Naturally, one can ask: what are the combinatorial properties of the code  $C_{25}$



In Proposition 5.3 we examine the combinatorial properties of  $C_{25}$  and give its main parameters. In addition, in Proposition 6.1 we determine the orbits of the action of  $Co_1$  on the non-zero codewords of  $C_{25}$  and describe the corresponding geometric subgroups, i.e., stabilizers of points or blocks, and finally in Remark 6.3 we give a geometric significance of the nature of the complementary pairs of non-zero codewords, in particular those of minimum weight. Notice that the notation  $\langle \cdot, \cdot \rangle$  used in Proposition 5.3 parts (i) and (v) and their proofs differs from that used for the bilinear form. Here we mean subspace generation.

**Proposition 5.3.** *Let  $G$  be the simple group  $Co_1$  of Conway and let  $\mathbb{F}_2\Omega$  denote the permutation module of degree 98280 over  $\mathbb{F}_2$  obtained by the action of  $G$  on the Leech lattice modulo 2. Then the following occur:*

- (i) *There exists a unique submodule of  $\mathbb{F}_2\Omega$  of dimension 25 invariant under  $Co_1$ . Let  $C_{25}$  denote this submodule. Then  $C_{25} = \langle C_{24}, \mathbf{1} \rangle$ , where  $C_{24}$  is the smallest non-trivial faithful  $Co_1$ -invariant irreducible  $\mathbb{F}_2$ -module of dimension 24 of Result 5.1;*
- (ii)  *$C_{25}$  is a triply-even projective  $[98280, 25, 47104]_2$  code,  $\mathbf{1} \in C_{25}^\perp$  and in  $C_{25}$ ;*
- (iii)  *$C_{25}$  is not spanned by its minimum-weight codewords;*
- (iv) *The dual code  $C_{25}^\perp$  of  $C_{25}$  is a  $[98280, 98255, 4]_2$  code with 297601053750 codewords of weight 4;*
- (v)  *$\text{Aut}(C_{25}) \cong Co_1$ .*

*Proof.* (i) By construction  $C_{25} = \langle C_{24}, \mathbf{1} \rangle$ . Since  $C_{24}$  and  $\langle \mathbf{1} \rangle$  are  $Co_1$ -invariant subspaces, we deduce that  $C_{25}$  is a decomposable 25-dimensional  $\mathbb{F}_2$ -module of  $Co_1$  containing the 24-dimensional  $\mathbb{F}_2$ -module  $C_{24}$ . Thus  $C_{25} = C_{24} + \langle \mathbf{1} \rangle$ . Moreover, the uniqueness of  $C_{25}$  follows from Result 5.1(iii). See also, [1, Lemma 23.2 (4), Lemma 23.3].

(ii) Since  $C_{25} \subseteq C_{25}^\perp$ , if  $w \in C_{25}$  it follows that  $w \in C_{25}^\perp$  and so  $(w, w) = 0$ . Write  $w = w_1w_2 \dots w_{98280}$ . Then  $\sum_{i=1}^{98280} w_i^2 = 0$ . Furthermore, since  $w_i^2 = w_i$  for all  $w_i \in \mathbb{F}_2$  then  $\sum_{i=1}^{98280} w_i = w_i \mathbf{1}$ . Hence  $\mathbf{1} \in C_{25}^\perp$ . That  $\mathbf{1} \in C_{25}$  follows by construction. Now, we have  $A_{98280-i}(C_{25}) = |\{w_i + \mathbf{1} : w_i \in C_{25}\}| = |\{w_i : w_i \in C_{25}\}| = A_i$ . From the latter and Result 5.1(ii) we deduce the weight enumerator  $x^0y^{98280} + 98280x^{47104}y^{51176} + 98280x^{51176}y^{47104} + 16678935x^{49128}y^{49152} + 16678935x^{49152}y^{49128} + x^{98280}y^0$  for  $C_{25}$ , from which we deduce that  $C_{25}$  is triply-even and hence self-orthogonal.

(iii) By Result 5.1(i) we deduce that the codewords of weight 47104 generate the code  $C_{24}$ . We verified through computations with Magma that the codewords of weight 49128 span  $C_{25}$ . Hence the result.

(iv) Using MacWilliams' identities and Pless' power moment identities the weight distribution of the dual can be obtained. In fact, we used computations with Magma [4] to confirm the full weight distribution. From this we deduce that  $C_{25}$  is projective since  $d(C_{25}^\perp) = 4$ , i.e.,  $C_{25}^\perp$  satisfies  $d(C_{25}^\perp) \geq 3$ .<sup>1</sup>

(v) We show here that  $\text{Aut}(C_{25}) \cong Co_1$ . Obviously,  $Co_1 \subseteq \text{Aut}(C_{24})$ . Now, suppose that  $\alpha \in \text{Aut}(C_{24})$ . Since  $\alpha(\mathbf{1}) = \mathbf{1}$  and  $C_{25} = \langle C_{24}, \mathbf{1} \rangle$ , we have  $\alpha \in \text{Aut}(C_{25})$ . So that  $\text{Aut}(C_{24}) \subseteq \text{Aut}(C_{25})$ . Since by Result 5.1(iv) we have  $\text{Aut}(C_{24}) \cong Co_1$ , order considerations show  $\text{Aut}(C_{25}) \cong Co_1$ .  $\square$

<sup>1</sup>The entire weight distribution can be obtained on request from the author.



**Remark 5.4.** In Remark 5.2(iii) we observed that  $C_{24}$  is a  $2^{12}$ -divisible code. However, in Proposition 5.3 we show that  $C_{25}$  is  $\Delta = 2^3$ -divisible. This gives an example of a smaller  $\Delta$ -divisible code containing a larger  $\Delta$ -divisible subcode. Thus, in general, if  $C$  is a  $\Delta$ -divisible code and  $C'$  is a  $\Delta'$ -divisible with  $C' \supset C$  then  $C'$  need not be a  $\Delta$ -divisible code where  $\Delta = \Delta'$ .

### 6. Geometric subgroups of $Co_1$ as stabilizers of vectors of the codes

By [12, Theorem A1], we know that there are just three orbits of  $Co_1$  on 1-dimensional spaces in  $\Lambda/2\Lambda$  and these orbits have lengths 98280, 8292375 and 8386560, respectively. In Proposition 6.1, we use these facts and the fact that  $\mathbf{1} \in C_{25}$  by part (ii) of Proposition 5.3 to show how  $Co_1$  acts on the non-zero codewords of  $C_{25}$ . The reader will notice that since  $\mathbf{1} \in C_{25}$  the weight distribution of  $C_{25}$  is symmetric and the codewords of  $C_{25}$  occur in complementary pairs. Thus we determine the structure of  $(Co_1)_{w_i}$  where  $i$  is in  $W$  with  $W = \{47104, 49152\}$  and the structure of  $(Co_1)_{\bar{w}_i}$  where  $i$  is in  $\bar{W}$ , the complement of  $W$ , i.e.,  $\bar{W} = \{51176, 49128\}$ . For  $i \in W$  (respectively for  $i \in \bar{W}$ ) we define  $W_i$  (respectively  $\bar{W}_i$ ) to be  $W_i = \{w_i \in C_{25} \mid wt(w_i) = i\}$  (respectively  $\bar{W}_i = \{\bar{w}_i \in C_{25} \mid wt(\bar{w}_i) = i\}$ ). We show in Proposition 6.1 that  $(Co_1)_{w_i}$  (respectively  $(Co_1)_{\bar{w}_i}$ ) is a maximal subgroup of  $Co_1$ , for all  $i$ . Taking the support of  $w_i$  (respectively  $\bar{w}_i$ ) and orbiting that under  $Co_1$  we form the blocks of the 1-(98280,  $i, k_i$ ) support designs  $\mathcal{D} = \mathcal{D}_{w_i}$  (respectively  $\mathcal{D} = \mathcal{D}_{\bar{w}_i}$ ) where  $k_i = |(w_i)^{Co_1}| \times \frac{i}{98280}$  (respectively  $k_i = |(\bar{w}_i)^{Co_1}| \times \frac{i}{98280}$ ). We show that  $Co_1$  acts point primitively on  $\mathcal{D}$ . For economy we prove the result for the codewords in  $W$ . The proof for the codewords in  $\bar{W}$  follows by replacing the relevant complementary pairs.

**Proposition 6.1.** *Let  $i \in W$  and  $w_i \in W_i$ . Then  $(Co_1)_{w_i}$  is a maximal subgroup of  $Co_1$ . Furthermore  $Co_1$  is primitive on  $\mathcal{D}_{w_i}$ .*

*Proof.* The proof follows from the two cases discussed below.

**Case 1.** Consider  $W_{47104} = \{w_i \in W \mid wt(w_i) = 47104\}$ . Since  $W_{47104}$  is invariant under the action of  $Aut(C_{25})$  for all  $w_i \in W_{47104}$ , it follows from the weight enumerator of  $C_{25}$  above, that  $w_i^{Co_1} = W_{47104}$ . Therefore  $W_{47104}$  forms an orbit under the action of  $Co_1$  and thus  $Co_1$  is transitive on  $W_{47104}$ . Now let  $x = w_{(47104)}$ . Then  $(Co_1)_x$  is a subgroup of order  $2^{18} \cdot 3^6 \cdot 5^3 \cdot 7 \cdot 11 \cdot 23$  we deduce that thus maximal in  $Co_1$ . Using the weight enumerator of  $C_{25}$  once again, and the orbit stabilizer theorem we deduce that  $[Co_1 : (Co_1)_x] = 98280$  and by order considerations and Table 1 we have  $(Co_1)_x \cong Co_2$ .

**Case 2.** Let  $W_{49152} = \{w_i \in W \mid wt(w_i) = 49152\}$ . It can be deduced from [12, Theorem A1] that under the action of  $Co_1$  the set  $W_{49152}$  splits into two orbits of lengths 8292375 and 8386560, say  $W_{(49152)_1}$  and  $W_{(49152)_2}$ . Let  $y = w_{(49152)_1} \in W_{(49152)_1}$  and  $z = w_{(49152)_2} \in W_{(49152)_2}$ . Then  $(Co_1)_y$  is a subgroup of order 501397585920 and thus maximal in  $Co_1$ . Moreover,  $(Co_1)_y \cong 2^{11} : M_{24}$ . (Note that there is a misprint in [6, p. 183] for the index  $[Co_1 : (2^{11} : M_{24})]$ .) Similarly,  $|(Co_1)_z| = 2^{10} \cdot 3^7 \cdot 5^3 \cdot 7 \cdot 11 \cdot 23$ , so that  $(Co_1)_z \cong Co_3$ .

By the transitivity of  $Co_1$  on the code coordinate positions, the codewords of  $W_i$  form a 1-design  $\mathcal{D}_{w_i}$  with  $A_i$  blocks. This implies that  $Co_1$  is transitive on the blocks of  $\mathcal{D}_{w_i}$  for each  $w_i$  and since  $(Co_1)_{w_i}$  is a maximal subgroup of  $Co_1$ , we deduce that  $Co_1$  acts primitively on  $\mathcal{D}_{w_i}$  for each  $i$ . This still holds if we replace  $w_i$  with  $\bar{w}_i$  in each case discussed.

In Table 2 we depict the structure of the vector stabilizer for all the codewords of  $C_{25}$ .

$i$	$(Co_1)_w$	Maximality	$i$	$(Co_1)_w$	Maximality
0	$Co_1$	No	98280	$Co_1$	No
47104	$Co_2$	Yes	51176	$Co_2$	Yes
$(49152)_1$	$Co_3$	Yes	$(49128)_1$	$Co_3$	Yes
$(49152)_2$	$2^{11}:M_{24}$	Yes	$(49128)_2$	$2^{11}:M_{24}$	Yes

TABLE 2. Stabilizer in  $Co_1$  of a codeword  $w$  ( $=w_i$  or  $\bar{w}_i$ )

In Table 3 the first column represents the codewords of weight  $i$  and the second column gives the parameters of the designs  $\mathcal{D}_w$ , where  $w = w_i$ ( or  $\bar{w}_i$ ) accordingly. In the third column we list the number of blocks of  $\mathcal{D}_w$ . We test the primitivity for the action of  $Co_1$  on  $\mathcal{D}_w$  in the final column.  $\square$

$i$	$\mathcal{D}_w$	No. of blocks	Primitivity
47104	1-(98280, 47104, 47104)	98280	Yes
51176	1-(98280, 51176, 51176)	98280	Yes
$(49152)_1$	1-(98280, 49152, 4194304)	8386560	Yes
$(49152)_2$	1-(98280, 49152, 4147200)	8292375	Yes
$(49128)_1$	1-(98280, 49128, 4192256)	8386560	Yes
$(49128)_2$	1-(98280, 49128, 4145175)	8292375	Yes

TABLE 3. Non-trivial point- and block-primitive 1-designs  $\mathcal{D}_w$  on 98280 points invariant under  $Co_1$

In what follows our main interest is in determining the orbits of  $Co_1$  on the set of codewords of minimum weight in the dual code  $C_{25}^\perp$ . While this is of independent interest our investigation was motivated by a question of Wolfgang Knapp [9] since it would be of help in the classification of these types of codewords. We are able to trace some of these codewords to vectors of the Leech lattice and provide a partial description of the geometric nature of this class of codewords.

**Proposition 6.2.**  $Co_1$  has 3 orbits on the set of minimum weight codewords of  $C_{25}^\perp$ , the orbit lengths being 88114776750, 159134976000 and 50351301000, respectively.

*Proof.* Let  $W_4(C_{25}^\perp) = \{w \in C_{25}^\perp \mid \text{wt}(w) = 4\}$  denote the set of weight 4 vectors in  $C_{25}^\perp$ . Then by Proposition 5.3 (iv), we have  $|W_4(C_{25}^\perp)| = 297601053750$  and thus  $Co_1$  acts intransitively on  $W_4(C_{25}^\perp)$ . Under the action of  $Co_1$  we have that  $W_4(C_{25}^\perp)$  splits into the orbits  $W_4(C_{25}^\perp)_i$  with  $1 \leq i \leq 3$ . In particular,  $|W_4(C_{25}^\perp)_1| = 88114776750$ ,  $|W_4(C_{25}^\perp)_2| = 159134976000$  and  $|W_4(C_{25}^\perp)_3| = 50351301000$ , respectively. Let  $a \in W_4(C_{25}^\perp)_1, b \in W_4(C_{25}^\perp)_2$  and  $c \in W_4(C_{25}^\perp)_3$ . Then  $(Co_1)_a$  is a subgroup of order 47185920 and follows from the list of maximal subgroups of  $Co_1$ , see ATLAS [6, p. 183], that  $(Co_1)_a$  is not maximal in  $Co_1$ . Notice that  $|(Co_1)_b| = 26127360$  and  $|(Co_1)_c| = 82575360$ , and as in the preceding case, these groups are not maximal in  $Co_1$ .

By order considerations and examining the structure of the maximal subgroups of  $Co_1$  we notice that  $(Co_1)_a$  is possibly a maximal subgroup of  $2^{1+12}:(A_8 \times S_3)$  or  $2^{4+12}:(S_3 \times 3S_6)$  with index 42 and 18, respectively. By computations with Magma [4] we obtained the maximal subgroups of  $2^{1+12}:(A_8 \times S_3)$  and  $2^{4+12}:(S_3 \times 3S_6)$ , and since neither of these subgroups possesses a maximal subgroup of the given index we conclude that  $(Co_1)_a$  is not a second maximal subgroup. We determine the chief factors and deduce that  $(Co_1)_a \cong (3 \times 2^{17}):S_5$ , since the soluble radical quotient  $3 \times 2^{17}$  has degree 6.

Next we consider the group  $(Co_1)_b$ . Inspecting the list of maximal subgroups of  $Co_2$  we deduce that  $(Co_1)_b$  is a maximal subgroup of  $Co_2$  isomorphic to  $U_4(3) \cdot D_8$ . Furthermore,  $(Co_1)_b$  is the setwise stabilizer in  $\Lambda$  of an  $S$ -lattice of type  $2^{1+4}:3^2$ , and point stabilizer isomorphic to  $U_4(3)$ , see ATLAS [6, pp. 52].

Arguing as above we note that  $(Co_1)_c$  is possibly a maximal subgroup of  $2^{1+12}:(A_8 \times S_3)$  of index 24. However, it can be proven by inspecting the list of maximal subgroups of this group computed using Magma that this possibility does not occur. Now, direct calculations of the chief factors shows that  $(Co_1)_c \cong 2^{11}:L_3(4) \cdot 2$ , since the soluble radical quotient  $2^{11}$  has degree 280. □

The preceding propositions and theorems give the proof of Theorem 1.1 stated in Section 1.

**Remark 6.3.** The geometric significance and the nature of the codewords of  $C_{25}$  can be described using the Leech lattice as it was the case for the codewords of  $C_{24}$ , see [10]. The description that is presented below follows directly by using [12, Theorem A1] and [12, Theorem A2].

(1). The minimum words of  $C_{25}$  are the 98280 pairs consisting of a type 2 vector and its negative in the Leech lattice [11, p. 156]. The stabilizer of such a pair has just three non-trivial orbits on the other pairs, where the orbit in which a particular vector lies depends only on the angles its vectors form with the fixed vector. The permutation character of this action is  $\chi_1 + \chi_3 + \chi_6 + \chi_{10}$ , of degrees 1, 299, 17250, 80730 respectively, see [6, p. 183].

(2). Observe (from Table 2) that the codewords of weight 49152 in  $C_{25}$  split into two classes, namely a class of codewords whose stabilizer is isomorphic to  $2^{11}:M_{24}$ , and another with stabilizer of a codeword isomorphic to  $Co_3$ . The class of codewords with stabilizer isomorphic to  $2^{11}:M_{24}$  consists of the type 4 base (or  $A_1^{24}$ -hole) vectors, while those vectors with stabilizer  $Co_3$  are known to be type 3 vectors in the Leech lattice, see [6, p. 183] or [11, p. 156].

- (3). A result along the lines of [10, Proposition 5.2] can be obtained for the 1-(98280, 51176, 51176) design  $\mathcal{D}$  invariant under  $\text{Co}_1$ .
- (4). Observe that in Proposition 6.2 we show that the set  $W_4(\text{C}_{25}^\perp)$  of minimum weight codewords of  $\text{C}_{25}^\perp$  is not an orbit of  $\text{Co}_1$ . In particular, we give a geometric description of the nature of  $W_4(\text{C}_{25}^\perp)_2$ , tracing it to the Leech lattice, and showed that the stabilizer of a codeword in  $W_4(\text{C}_{25}^\perp)_2$  is a second maximal subgroup of  $\text{Co}_1$ . It would be of interest to give a geometric description of the nature of the codewords of  $W_4(\text{C}_{25}^\perp)_1$  and  $W_4(\text{C}_{25}^\perp)_3$ , respectively.

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