

# CLASSIFICATION OF INTEGRAL MODULAR DATA UP TO RANK 13

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**ABSTRACT.** This paper classifies all integral modular data up to rank 13 (all can be categorified). Furthermore, it also classifies all integral half-Frobenius fusion rings up to rank 12. We find that each perfect integral modular fusion category up to rank 13, as well as every perfect integral half-Frobenius fusion ring up to rank 12, is trivial. We have also refined the categorifiable non-pointed odd-dimensional modular data at ranks below 25 to three possible items, all of rank 17, FPdim 225, and type  $[[1,3],[3,8],[5,6]]$ , filling potential gaps in the literature. For rank 25, we have narrowed down the perfect case to 5 types.

Our initial key insight is that the Egyptian fractions, which are typically employed to list possible types, can be chosen with squared denominators. We then develop several type criteria as initial filters. In particular, we establish that the number of distinct basic FPdims in a non-trivial perfect fusion ring must be at least 4. To obtain the fusion rings, we solve the dimension and associativity equations using new features on Normaliz created specifically for this purpose. The S-matrices (if they exist) are obtained by self-transposing the character table, while the T-matrices are derived by solving the Anderson-Moore-Vafa equations. Finally, we verify the extended axioms of modular data.

From rank 13 onward, the types were further restricted by additional properties unique to the modular case, which involved the universal grading, congruence representations of the modular group and Galois action, leading to critical arithmetic constraints. In particular, we get that, up to rank 21, a prime divisor of the global FPdim does not exceed the rank, and more strongly up to rank 15 in the non-pointed case, does not exceed half the rank.

## 1. INTRODUCTION

In this paper, we assume that all fusion categories are defined over the complex field. The concept of an integral modular fusion category has been extensively studied, as detailed in the references at the beginning of [13]. In [5], they have been classified up to rank 6 (all pointed), with Egyptian fractions playing a crucial role. The approach that enables us to extend this classification up to rank 13 in our work hinges on the observation that it is sufficient to consider Egyptian fractions with squared denominators. This restriction significantly reduces the combinatorial complexity. To illustrate this point, consider that the number of Egyptian fractions (summing to 1) of length  $n = 1, 2, \dots, 8$  is 1, 1, 3, 14, 147, 3462, 294314, 159330691, respectively (as per [42]). In contrast, when limited to squared denominators, the counts are 1, 0, 0, 1, 0, 1, 1, 4, respectively (refer to [1]).

We begin by recalling the concept of a fusion ring and its fundamental results in §2.1, with reference to [17, Chapter 3]. As defined in [19], a fusion ring  $\mathcal{F}$  is termed *s-Frobenius* if for every basic element  $b$ , the ratio  $\text{FPdim}(\mathcal{F})^s / \text{FPdim}(b)$  is an algebraic integer. According to [17, Proposition 8.14.6], the Grothendieck ring of a modular fusion category is 1/2-Frobenius (denoted *half-Frobenius* in the rest of the paper). Consider  $\mathcal{F}$  to be an integral half-Frobenius fusion ring with a basis  $\{b_1, \dots, b_r\}$ , FPdim  $D$ , and type  $[d_1, \dots, d_r]$ , where  $1 = d_1 \leq d_2 \leq \dots \leq d_r$  and  $d_i = \text{FPdim}(b_i)$ . Thus  $d_i^2$  is a divisor of  $D$ , for all  $i$ . There exists a unique square-free integer  $q$  such that  $D = qs^2$ , implying that each  $d_i$  is a divisor of  $s$ . Let  $s_i$  denote the positive integer  $s/d_i$ . Given that  $D = \sum_{i=1}^r d_i^2$ , we arrive at the following representation of  $q$  as an Egyptian fraction with squared denominators:

$$q = \sum_{i=1}^r \frac{1}{s_i^2}.$$

We have classified all such Egyptian fractions up to  $r = 13$  using SageMath, as will be discussed in §4, where a method to constrain to  $q \leq r/4$  is also described. Since  $s_1 = s$ , we have  $d_i = s_1/s_i$ , and we may assume that  $s_i$  is a divisor of  $s_1$ , for all  $i$ . As detailed in §4, this leads us to consider only 9025 types up to rank 13.

The subsequent phase entails implementing new criteria for identifying a type that emerges from a fusion ring, as delineated in §5. Particularly, we establish that the minimum number of distinct basic FPdims in a non-trivial perfect fusion ring is four (Theorem 5.1). The proof of these criteria predominantly relies on modular arithmetic and serves to rule out approximately 62% of the types up to rank 13.

To address the remaining types, we classify all possible fusion data  $(N_{i,j}^k)$ , as defined in §2.1, for each type  $(d_i)$ , utilizing our fusion ring solver described in §6. We begin by reducing the number of variables, leveraging the Unit axiom of fusion data and the Frobenius reciprocity. The main challenge, denoted as "patching", involves integrating the associativity equations  $\sum_s N_{i,j}^s N_{s,k}^t = \sum_s N_{j,k}^s N_{i,s}^t$  (which are non-linear) as efficiently as possible into the (linear) solving process of the dimension equations  $d_i d_j = \sum_k N_{i,j}^k d_k$ , which are positive linear Diophantine equations. This

approach was implemented using Normaliz [9], on which we developed new features dedicated to the classification of fusion rings, as explained in §6.1, and for more details, see Appendix H of the manual [10].

This step culminates in a classification of all the half-Frobenius integral fusion rings up to rank 12, tallying exactly 10628 instances derived from 71 types, and proves the absence of any non-trivial perfect integral half-Frobenius fusion rings up to rank 12 (see §7). From rank 13 onward, the types were further restricted by additional properties coming from more advanced results on modular fusion categories §8. This adjustment was necessary because we encountered computational limits for classifying all half-Frobenius fusion rings. Consequently, the result became less general at the fusion ring level compared what we get up to rank 12. In the non-perfect case, we applied specific *universal grading* techniques, as discussed in §8.1 and based on [28, Proposition VI.2]. Additionally, we explored congruence representations of the modular group (see §8.2) and Galois actions (see §8.3). Notably, we provide two proofs of the following folklore result, the shorter one applies [16, Theorem II (iii)].

**Theorem 1.1.** *For any prime factor  $p$  of the dimension norm of a modular fusion category with rank  $r$ , it holds that  $p \leq 2r + 1$ .*

This inequality is optimal, and the examples for which the equality holds are classified in [31]. Regarding the integral case, discussions with Eric Rowell and Andrew Schopieray indicated that the rank  $r$  can be substituted with the multiplicity  $m$  of a certain basic FPdim, leading to the inequality  $p \leq 2m + 1$ , see Theorem 8.2, required to exclude some hard types at rank 13. An even stronger integral version introduced in Theorem 8.4, was crucial in demonstrating Proposition 11.8, and also the following theorem proved in §10.2:

**Theorem 1.2.** *For any prime factor  $p$  of the FPdim of an integral modular fusion category with rank  $r$ ,*

- $p \leq r$ , for all  $r \leq 21$ ,
- $p \leq r/2$ , for all  $r \leq 15$ , in the non-pointed case.

These inequalities are conjectured to hold without rank restriction in §10.2. These conjectures are proved for  $\mathcal{Z}(\text{Rep}(G))$ , across all finite groups  $G$ , in §10.1, among other results.

The next step is to classify all possible modular data related to the fusion rings found up to rank 13. The definition of modular data we employ (refer to §2.2) is informed by the key attributes of a modular fusion category, specifically a pseudo-unitary one, as our research is centered on the integral case (see [17, Proposition 9.6.5]). We can limit our attention to commutative fusion rings since a modular fusion category, being braided, possesses a commutative Grothendieck ring (although our classification encompasses 213 noncommutative fusion rings as well; see §7).

First, we examine the  $S$ -matrices: for a given commutative fusion ring, we take its eigentable (as defined in Definition 2.7) and consider it as a matrix, retaining only those with cyclotomic elements—such fusion rings are termed *cyclotomic*. If suitable renormalization and permutation yield a self-transpose matrix (detailed in §3.1), we call the fusion ring as *self-transposable*; if not, it is dismissed. From this, we infer that there are precisely 69 self-transposable, cyclotomic, half-Frobenius, integral fusion rings up to rank 12, originating from 27 types, which is fewer than 0.7% of the 10628 identified in the initial stage. At rank 13, we reduced to 6 types (more restricted) with such fusion rings.

Moving on to the  $T$ -matrices: for the fusion rings that remain, we solve the Anderson-Moore-Vafa equations (see §2.2) in the  $\mathbb{Z}$ -module  $\mathbb{Q}/\mathbb{Z}$ . We preserve only those  $S$ - and  $T$ -matrices that satisfy all the conditions of Definition 2.11. The use of our so-called *magic criterion* was pivotal for several big cases and could lead to an interesting theoretical reformulation, see Question 3.2. Ultimately, we arrive at  $19 + 64$  modular data, derived from  $5 + 18$  fusion rings and  $3 + 13$  types (non-pointed + pointed).

**Remark 1.3.** *Every pointed modular fusion category corresponds to a metric group  $(G, q)$ —a finite Abelian group  $G$  equipped with a non-degenerate quadratic form  $q : G \rightarrow \mathbb{C}^*$ , represented by the  $T$ -matrix, as described in [17, §8.4].*

The modular data (MD) mentioned in §12 encompass  $S$ - and  $T$ -matrices, central charge, fusion data, and second Frobenius-Schur indicators for the non-pointed case. For the pointed case, however, it includes only the  $T$ -matrices. The following theorem provides a concise overview:

**Theorem 1.4.** *There are 19 MD of non-pointed integral modular fusion categories up to rank 13, given by:*

- Rank 8, FPdim 36, type  $[1, 1, 2, 2, 2, 2, 3, 3]$ :
  - 6 MD with central charge  $c = 0$  from  $\mathcal{Z}(\text{Vec}_{S_3}^\omega)$ , see [21],
  - 2 MD with  $c = 4$  from  $(C_3^2 + 0)^{C_2}$ , see [20, point (b) on page 983].
- Rank 10, FPdim 36, type  $[1, 1, 1, 2, 2, 2, 2, 2, 3]$ :
  - 3 MD with  $c = 4$  from  $SU(3)_3$ , its complex conjugate and a zesting, see [15, §6.3.1].
- Rank 11, FPdim 32, type  $[1, 1, 1, 1, 2, 2, 2, 2, 2, 2]$ :
  - 8 MD with  $c = \pm 1$  from  $SO(8)_2$ , conjugates and zestings, see §3.3.

There are 64 MD of pointed modular fusion categories up to rank 13; here are their number per group  $G$ :

| $G$ | $C_1$ | $C_2$ | $C_3$ | $C_2^2$ | $C_4$ | $C_5$ | $C_6$ | $C_7$ | $C_2^3$ | $C_2 \times C_4$ | $C_8$ | $C_3^2$ | $C_9$ | $C_{10}$ | $C_{11}$ | $C_2 \times C_6$ | $C_{12}$ | $C_{13}$ |
|-----|-------|-------|-------|---------|-------|-------|-------|-------|---------|------------------|-------|---------|-------|----------|----------|------------------|----------|----------|
| #MD | 1     | 2     | 2     | 5       | 4     | 2     | 4     | 2     | 4       | 4                | 4     | 2       | 2     | 4        | 2        | 10               | 8        | 2        |

There is no other integral modular data up to rank 13 (i.e. all categorifiable as above).

**Question 1.5.** *Is there a modular data without categorification?*

It should be noted that [28] provides an interesting (non-integral) candidate of rank 11 (in its introduction) relevant to Question 1.5, and it also recovers Theorem 1.4 up to rank 12. This theorem yields the following consequence:

**Corollary 1.6.** *Every perfect integral modular fusion category up to rank 13 is trivial.*

In fact, we obtained the following more general result within the context of fusion rings up to rank 12:

**Theorem 1.7.** *Every perfect integral half-Frobenius fusion ring up to rank 12 is trivial.*

The proof of Theorem 1.7 for ranks up to 9 is straightforward, following the list provided in §4.1 combined with an extended version of the Nichols-Richmond theorem applied to fusion rings, as detailed in the proof of [32, Theorem 11]. This is due to the consistent presence of a non-trivial basic element with  $\text{FPdim} \leq 2$ . However, proving the theorem for ranks up to 12 necessitates the employment of type criteria, as discussed in §5, and the use of a fusion ring solver, elaborated in §6.

It should be noted that the Drinfeld center of the representation category of any non-Abelian finite simple group  $G$ —and, more broadly, any centerless perfect group—is a perfect (though not simple) integral modular fusion category denoted as  $\mathcal{Z}(\text{Rep}(G))$  with  $\text{FPdim} = |G|^2$ . For further information, see [11, §11.1]. Thus, the Grothendieck ring of  $\mathcal{Z}(\text{Rep}(A_5))$ , of rank 22 and type  $[[1, 1], [3, 2], [4, 1], [5, 1], [12, 10], [15, 4], [20, 3]]$ , constitutes a perfect integral half-Frobenius fusion ring. Consequently, Theorem 1.7 cannot be extended to all ranks; however, it remains an open question whether its simple version can be:

**Question 1.8.** *Is there a non-pointed simple integral half-Frobenius fusion ring?*

A negative response to Question 1.8 would imply a negative answer to the renowned [18, Question 2] in the simple case, due to a result in [24], which states that every simple integral fusion category is weakly group-theoretical if and only if every simple integral modular fusion category is pointed. With this in mind, we propose the following question:

**Question 1.9.** *Is there a non-pointed simple integral modular fusion category?*

For further insights into Question 1.9 at the fusion ring level, [33, Corollary 6.16] adds a constraint: the absence of any basic elements with a prime-power  $\text{FPdim}$ . It is worth noting that Theorem 1.7 cannot be generalized to all ranks, even with this added constraint. This is because the Grothendieck ring of  $\mathcal{Z}(\text{Rep}(A_7))$ , which is a perfect integral half-Frobenius fusion ring of rank 74 and type

$$[[1, 1], [6, 1], [10, 2], [14, 2], [15, 1], [21, 1], [35, 1], [70, 9], [105, 4], [210, 20], [280, 9], [360, 14], [504, 5], [630, 4]],$$

satisfies this constraint (but consider Question 9.2). If necessary, Question 1.8 could be refined to include this constraint and the property of commutativity, and even the more advanced constraints mentioned above.

Employing similar techniques, along with [13, Remark 4.3] and [33, Corollary 6.16], we are able to prove the following (see §11):

**Theorem 1.10.** *The possibly categorifiable non-pointed odd-dimensional modular data at ranks below 25 reduce to:*

- Rank 17,  $\text{FPdim}$  225, type  $[1, 1, 1, 3, 3, 3, 3, 3, 3, 3, 5, 5, 5, 5, 5]$ :  
– 3 MD with central charge  $c = 4$  (see §13 for the details) from 2 fusion rings.

**Remark 1.11.** *A categorification of a MD mentioned in Theorem 1.10 would not align with [3, Theorem 4.2, proof of Case (viii)  $\text{FPdim}(C_{pt}) = p$ ] as well as [13, Theorem 6.3 (b), proof of Case  $|\mathcal{G}(C)| = 3$ ]. But Remark 11.4 points out gaps in these proofs. Should these gaps be filled, these MD would affirmatively address Question 1.5. Otherwise, consider the candidates discussed in Remark 11.7.*

Finally, this paper narrows down the possible rank 25 odd-dimensional perfect types to 5 ones, see Proposition 11.8.

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## 2. FUSION DATA AND MODULAR DATA

In this section, we review the concepts of fusion data and modular data, along with the essential results. For further details, we refer the reader to [17].

**2.1. Fusion Data.** The concept of fusion data expands upon the idea of a finite group.

**Definition 2.1.** Fusion data consist of a finite set  $\{1, 2, \dots, r\}$  with an involution  $i \mapsto i^*$ , and nonnegative integers  $N_{i,j}^k$  satisfying the following conditions for all  $i, j, k, t$ :

- (Associativity)  $\sum_s N_{i,j}^s N_{s,k}^t = \sum_s N_{j,k}^s N_{i,s}^t$ ,
- (Unit)  $N_{1,i}^j = N_{i,1}^j = \delta_{i,j}$ ,
- (Dual)  $N_{i^*,j}^1 = N_{j,i^*}^1 = \delta_{i,j}$ ,
- (Anti-involution)  $N_{i,j}^k = N_{j^*,i^*}^{k^*}$ .

Note that  $1^* = 1$ . We may represent the fusion data simply as  $(N_{i,j}^k)$ .

**Proposition 2.2** (Frobenius Reciprocity). For all  $i, j, k$ ,  $N_{i,j}^k = N_{k,j^*}^i = N_{k^*,i}^{j^*} = N_{j^*,i^*}^{k^*} = N_{j,k^*}^i = N_{i^*,k}^j$ .

*Proof.* Starting with (Associativity) and setting  $t = 1$ , we have  $\sum_s N_{i,j}^s N_{s,k}^1 = \sum_s N_{j,k}^s N_{i,s}^1$ . Applying (Dual), we get  $\sum_s N_{i,j}^s \delta_{s,k^*} = \sum_s N_{j,k}^s \delta_{s,i^*}$ . Consequently,  $N_{i,j}^{k^*} = N_{j,k}^{i^*}$ . Substituting  $k^*$  with  $k$ , we obtain  $N_{i,j}^k = N_{j,k^*}^{i^*}$ , which equals  $N_{k,j^*}^i$  by (Anti-involution). The proposition follows by iterating the equality  $N_{i,j}^k = N_{k,j^*}^i$ .  $\square$

**Remark 2.3.** We can construct data that satisfy the first three axioms of Definition 2.1 but not the fourth, proving it is not superfluous. However, (Unit) is redundant when combined with the other axioms, as it is not utilized in the proof of Proposition 2.2. Taken together, (Dual) and (Frobenius Reciprocity) trivially imply (Unit).

A fusion ring  $\mathcal{R}$  is a free  $\mathbb{Z}$ -module equipped with a finite basis  $\mathcal{B} = \{b_1, \dots, b_r\}$  and a fusion product defined by

$$b_i b_j = \sum_k N_{i,j}^k b_k,$$

where  $(N_{i,j}^k)$  constitutes fusion data, and a  $*$ -structure given by  $b_i^* := b_{i^*}$ . The four axioms for fusion data translate to the following for all  $i, j, k$ :

- $(b_i b_j) b_k = b_i (b_j b_k)$ ,
- $b_1 b_i = b_i b_1 = b_i$ ,
- $\tau(b_i b_j^*) = \delta_{i,j}$ ,
- $(b_i b_j)^* = b_j^* b_i^*$ ,

where  $\tau(x)$  is the coefficient of  $b_1$  in the decomposition of  $x \in \mathcal{R}$ . Consequently,  $\mathcal{R}_{\mathbb{C}} := \mathcal{R} \otimes_{\mathbb{Z}} \mathbb{C}$  becomes a finite-dimensional unital  $*$ -algebra, with  $\tau$  extending linearly to a trace (i.e.,  $\tau(xy) = \tau(yx)$ ) and an inner product defined by  $\langle x, y \rangle := \tau(xy^*)$ . Here,  $\langle x, b_i \rangle$  is the coefficient of  $b_i$  in the decomposition of  $x$ .

**Theorem 2.4** (Frobenius-Perron Theorem). *Given a fusion ring  $\mathcal{R}$  with basis  $\mathcal{B}$  and the corresponding finite-dimensional unital  $*$ -algebra  $\mathcal{R}_{\mathbb{C}}$  as defined above, there exists a unique  $*$ -homomorphism  $d : \mathcal{R}_{\mathbb{C}} \rightarrow \mathbb{C}$  such that  $d(\mathcal{B}) \subset \mathbb{R}_{>0}$ .*

The value  $d(b_i)$  is termed the *Frobenius-Perron dimension* of  $b_i$ , denoted as  $\text{FPdim}(b_i)$  or simply  $d_i$ . The sum  $\sum_i d_i^2$  is referred to as the Frobenius-Perron dimension of  $\mathcal{R}$ , denoted  $\text{FPdim}(\mathcal{R})$ . The sequence  $[d_1, d_2, \dots, d_r]$  is called the *type* of  $\mathcal{R}$ . A fusion ring  $\mathcal{R}$  is described as:

- *Frobenius* (or 1-Frobenius, or of Frobenius type) if  $\frac{\text{FPdim}(\mathcal{R})}{\text{FPdim}(b_i)}$  is an algebraic integer for all  $i$ ,
- *integral* if  $\text{FPdim}(b_i)$  is an integer for all  $i$ ,
- *pointed* if  $\text{FPdim}(b_i) = 1$  for all  $i$ ,
- *commutative* if  $b_i b_j = b_j b_i$  for all  $i, j$ , meaning  $N_{i,j}^k = N_{j,i}^k$ .

The *multiplicity* of  $\mathcal{R}$  is the maximum value among  $N_{i,j}^k$ , and its *rank* is  $r$ , the size of the basis.

**Remark 2.5.** Fusion data enable a representation of its corresponding fusion ring. Consider the matrices  $M_i = (N_{i,j}^k)_{k,j}$ . By the Associativity axiom in Definition 2.1, we verify that  $M_i M_j = \sum_k N_{i,j}^k M_k$ . Additionally,  $M_1$  is the identity matrix, and Frobenius Reciprocity ensures that the adjoint matrix  $M_i^*$  is  $M_{i^*}$ . According to Frobenius-Perron Theorem, the operator norm  $\|M_i\|$  equals  $\text{FPdim}(b_i)$ .

**Remark 2.6.** The concept of fusion data is a combinatorial reformulation of the fusion ring notion, so any property applicable to a fusion ring is also applicable to its fusion data.

**Definition 2.7** (Eigentable). *Given commutative fusion data  $(N_{i,j}^k)$ , consider the corresponding fusion matrices  $M_i = (N_{i,j}^k)_{k,j}$ . The commutativity and the property that  $M_i^* = M_{i^*}$  render these matrices normal and thus simultaneously diagonalizable. Let  $(D_i)$  denote their simultaneous diagonalization, where  $D_i = \text{diag}(\lambda_{i,j})$ . We can select  $\lambda_{i,1} = \|M_i\| = d_i$ . The matrix  $(\lambda_{i,j})$  is termed the eigentable (or character table) of the fusion data, and the values  $c_j := \sum_i |\lambda_{i,j}|^2$  are called the formal codegrees.*

**Lemma 2.8.** *Let  $M \in M_n(\mathbb{Z}_{\geq 0})$ . The matrix  $M$  is a permutation matrix if and only if  $\|M\| = 1$ .*

*Proof.* Consider an orthonormal basis  $\{e_1, \dots, e_n\}$  for which the entries of  $M$  are non-negative integers. If  $M$  is not a permutation matrix, then one of the following cases must occur:

- (0) there exists  $i$  for which  $M e_i = 0$ ,
- (1) there exist  $i, j$  such that  $\langle M e_i, e_j \rangle > 1$ ,
- (2) there exist  $i, j, k$  with  $j \neq k$ , such that  $\langle M e_i, e_j \rangle = \langle M e_i, e_k \rangle = 1$ ,
- (3) there exist  $i, j, k$  with  $i \neq j$ , such that  $M e_i = M e_j = e_k$ .

However, case (0) implies  $\|M e_i\|/\|e_i\| = 0$ , while case (1) leads to  $\|M e_i\|/\|e_i\| > 1$ . In case (2), it follows that  $\|M e_i\|/\|e_i\| \geq \sqrt{2}$ . Likewise, case (3) implies  $\|M(e_i + e_j)\|/\|e_i + e_j\| = \sqrt{2}$ . Each of these cases indicates that  $\|M\| > 1$ . Conversely, if  $M$  is a permutation matrix, it trivially follows that  $\|M\| = 1$ .  $\square$

**Corollary 2.9.** *For two basic elements  $x, y$  of a fusion ring with  $\text{FPdim}(x) = 1$ , both  $xy$  and  $yx$  are basic elements, and  $\text{FPdim}(xy) = \text{FPdim}(yx) = \text{FPdim}(y)$ .*

*Proof.* This follows directly from Remark 2.5, Lemma 2.8, and the fact that  $\text{FPdim}$  is a ring homomorphism.  $\square$

**Corollary 2.10.** *A fusion ring is pointed if and only if its basis forms a finite group under the fusion product.*

**2.2. Modular Data.** Broadly speaking, modular data refers to a fusion data together with two matrices,  $S$  and  $T = (t_{i,j})$ , that generate a projective representation of the modular group  $\text{SL}(2, \mathbb{Z})$ . To provide a more detailed description, we draw upon [27, Theorem 2.1] and [17, §8.13, §8.18]. Let  $\mathbf{i}$  be the imaginary unit.

**Definition 2.11.** *Given a fusion ring  $\mathcal{R}$  of rank  $r$ , type  $[d_1, \dots, d_r]$ , and fusion data  $(N_{i,j}^k)$ , let  $\mathbf{d} := \text{FPdim}(\mathcal{R})$  and  $\zeta_n := \exp(2\pi\mathbf{i}/n)$ . A (pseudounitary) modular data for  $\mathcal{R}$  consists of two matrices  $S, T \in M_r(\mathbb{C})$  satisfying:*

- $S$  and  $T$  are symmetric,  $T$  is unitary and diagonal with  $T_{1,1} = 1$ ,  $S_{1,i} = d_i$  for all  $i$ , and  $SS^* = \mathbf{d}\mathbf{1}$ .
- Verlinde formula:  $N_{i,j}^k = \frac{1}{\mathbf{d}} \sum_l \frac{S_{il} S_{lj} \overline{S_{lk}}}{d_l}$ .
- Twist: let  $\theta_i$  be  $T_{i,i}$ , then  $\sum_k N_{i,j}^k \theta_k d_k = \theta_i \theta_j S_{i,j}$ .
- Ribbon structure:  $\theta_i = \theta_{i^*}$  (see Remark 2.13).
- Central charge:  $p_{\pm} := \sum_{i=1}^r d_i^2 (\theta_i)^{\pm 1}$ . The ratio  $p_+/p_-$  is a root of unity, and  $p_+ = \sqrt{\mathbf{d}} \zeta_8^c$  for some rational number  $c$ , referred to as the **central charge**, determined modulo 8.
- The matrices  $S$  and  $T$  afford a projective representation of  $\text{SL}(2, \mathbb{Z})$ : we have  $(ST)^3 = p_+ S^2$ ,  $\frac{S^2}{\mathbf{d}} = C$ ,  $C^2 = \mathbf{1}$ , where  $C$  is the permutation matrix associated with the involution  $i \rightarrow i^*$  and satisfies  $\text{Tr}(C) > 0$ .
- Cauchy theorem: the set of distinct prime factors of  $\text{ord}(T)$  is identical to the distinct prime factors of  $\text{norm}(\mathbf{d})$ , where  $\text{norm}(x)$  denotes the product of the distinct Galois conjugates of the algebraic number  $x$ .
- Cyclotomic integers: for all  $i, j$ , the elements  $S_{i,j}$ ,  $S_{i,j}/d_j$  and  $T_{i,i}$  are cyclotomic integers. The conductor of  $S_{i,j}$  divides  $\text{ord}(T)$ , which in turn divides  $\mathbf{d}^{5/2}$ , and there exists  $j$  such that  $S_{i,j}/d_j \in \mathbb{R}_{\geq 1}$ , for all  $i$ .
- Frobenius-Schur indicators: for every  $i$  and for all  $n \geq 1$ , the sum  $\nu_n(i) := \frac{1}{\mathbf{d}} \sum_{j,k} N_{j,k}^i (d_j \theta_j^n) \overline{(d_k \theta_k^n)}$  is a cyclotomic integer with a conductor that divides both  $n$  and  $\text{ord}(T)$ . Additionally,  $\nu_1(i) = \delta_{i,1}$  and  $\nu_2(i) = \pm \delta_{i,i^*}$ .
- Anderson-Moore-Vafa equations:  $T_{i,i} = e^{2\pi\mathbf{i}t_i}$ , and  $\forall i, j, k, l$ , the following equation holds in the  $\mathbb{Z}$ -module  $\mathbb{Q}/\mathbb{Z}$ :

$$\left( \sum_{p=1}^r N_{i,j}^p N_{p,k}^l \right) (t_i + t_j + t_k + t_l) = \sum_{p=1}^r \left( N_{i,j}^p N_{p,k}^l + N_{i,k}^p N_{j,p}^l + N_{j,k}^p N_{i,p}^l \right) t_p.$$

The **topological spin** of the  $i$ -th basic element is the representative  $s_i \in (-1/2, 1/2]$  of  $t_i \in \mathbb{Q}/\mathbb{Z}$ .

We could question the necessity of each component in Definition 2.11, particularly whether the Anderson-Moore-Vafa equations can be inferred from the other assumptions.

**Remark 2.12.** *The Verlinde formula, in conjunction with results from [24, §2], implies that the fusion ring  $\mathcal{R}$  is commutative. Together with  $S$  symmetric and the identity  $SS^* = \text{FPdim}(\mathcal{R})\mathbf{1}$ , it can be deduced that  $\mathcal{R}$  is self-transposable (as discussed in §3.1). Moreover, according to the proof presented in [17, Proposition 8.14.6],  $\mathcal{R}$  is also half-Frobenius.*

**Remark 2.13.** *A modular tensor category  $\mathcal{C}$  possesses a ribbon structure, which means that the twist  $\theta \in \text{Aut}(\text{id}_{\mathcal{C}})$  satisfies the condition  $(\theta_X)^* = \theta_{X^*}$  for every object  $X$  within  $\mathcal{C}$ . Let  $(X_i)$  represent the set of simple objects (up to isomorphism) within  $\mathcal{C}$ . Schur's lemma guarantees that  $\theta_{X_i} = \theta_i \text{id}_{X_i}$ , where the scalar  $\theta_i$  is consistent with the one described in Definition 2.11. Owing to the ribbon structure, we deduce the following:*

$$\theta_{i^*} \text{id}_{X_{i^*}} = \theta_{X_{i^*}} = (\theta_{X_i})^* = (\theta_i \text{id}_{X_i})^* = \theta_i (\text{id}_{X_i})^* = \theta_i \text{id}_{X_{i^*}}.$$

From this, it follows that  $\theta_{i^*} = \theta_i$  for all simple objects  $X_i$ .

This paper primarily addresses integral fusion categories, implying that  $\mathbf{d}$  is an integer and  $\text{norm}(\mathbf{d}) = \mathbf{d}$ . Such categories are pseudounitary and, consequently, spherical as well as pivotal (see [17]). In contexts that are not pseudounitary, Definition 2.11 would require modifications (as suggested in [27, Theorem 2.1]) because the equality  $S_{1,i} = \text{FPdim}(b_i)$  may not be valid.

It should be noted that the definition of modular data provided here is so stringent that, as of now, no instances exist that lack a categorification, leading to Question 1.5.

### 3. FROM FUSION DATA TO MODULAR DATA

This section elucidates the classification of all potential modular data associated with a given set of fusion data. Initially, we may consider the fusion data to be commutative and half-Frobenius (refer to Remark 2.12). For ranks up to 12, there are exactly 10628 half-Frobenius integral fusion rings (of which 213 are noncommutative), from 71 types (see §7 for details). At rank 13, under the additional constraints, there remain only 15 types to consider, see §9.

**3.1. S-matrix.** Consider a commutative fusion data  $(N_{i,j}^k)$  of rank  $r$ , eigentable  $(\lambda_{i,j})$ , and formal codegrees  $(c_j)$  as defined in Definition 2.7. The objective here is to identify all permutations  $q$  of the set  $\{1, \dots, r\}$  such that:

- $q(1) = 1$ ,
- $d_{q(i)} = d_i$  for all  $i$ ,
- The matrix  $S = (\sqrt{c_1/c_j} \lambda_{i,q(j)})$  is symmetric (i.e. self-transpose).

**Remark 3.1.** *The symmetric requirement implies that*

$$\sqrt{c_1/c_j} = \sqrt{c_1/c_j} \lambda_{1,q(j)} = \sqrt{c_1/c_1} \lambda_{1,q(1)} = d_j,$$

hence we can infer that  $c_1/c_j = d_j^2$  for all  $j$ , as shown in [35, Example 2.9].

If such a permutation  $q$  exists (Remark 3.1 can serve as an effective necessary condition), the fusion data are referred to as *self-transposable*. This property is exceedingly rare, rendering this step a potent sieve. Using the Verlinde formula, one can reconstruct the fusion data from  $S$ . It is important to note that we need only consider *cyclotomic* fusion data, i.e. whose eigentable entries are all cyclotomic. Incorporating the self-transposable and cyclotomic prerequisites allows us to exclude over 99.3% of the commutative half-Frobenius integral fusion rings up to rank 12 discovered in §7. This leaves 69 fusion rings from 27 types; their distribution by type and rank is as follows:

| Rank          | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---------------|---|---|---|---|---|---|---|---|---|----|----|----|
| #Types        | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 4  | 5  | 6  |
| #Fusion Rings | 1 | 1 | 1 | 2 | 1 | 1 | 3 | 7 | 4 | 11 | 13 | 24 |

The types mentioned above, restricted to the non-pointed ones, are listed below:

- Rank 7: [1,1,1,1,2,2,2],
- Rank 8: [1,1,2,2,2,2,3,3],
- Rank 9: [1,1,1,1,4,4,6,6,6],
- Rank 10: [1,1,1,1,2,2,2,4,4,4], [1,1,1,2,2,2,2,2,2,3], [1,1,2,3,3,4,4,4,6,6],
- Rank 11: [1,1,1,1,2,2,2,2,2,2,2], [1,1,1,1,2,6,6,8,12,12,12], [1,1,1,3,4,4,4,4,4,6], [1,1,1,1,4,4,12,12,18,18,18],
- Rank 12: [1,1,1,1,2,8,18,18,24,36,36,36], [1,1,1,3,6,8,8,8,8,8,12], [1,1,2,2,2,2,6,6,6,9,9], [1,1,2,3,3,6,6,8,8,12,12], [1,1,2,6,6,6,6,10,10,10,15,15].

The list of fusion rings referenced above can be found in [39]. They were classified utilizing the list from §7 in conjunction with the function `preSMatrix` contained within the file `ModularData.sage`, also available at [39]. At rank 13, there remain only 6 types with such fusion rings to consider (see the list in §9.4).

**3.2. T-matrix.** For the remaining fusion rings  $\mathcal{R}$  with fusion data  $(N_{i,j}^k)$ , we address the Anderson-Moore-Vafa equations:

$$\left( \sum_{p=1}^r N_{i,j}^p N_{p,k}^l \right) (t_i + t_j + t_k + t_l) = \sum_{p=1}^r \left( N_{i,j}^p N_{p,k}^l + N_{i,k}^p N_{j,p}^l + N_{j,k}^p N_{i,p}^l \right) t_p$$

within the  $\mathbb{Z}$ -module  $\mathbb{Q}/\mathbb{Z}$ . For each valid solution  $t = (t_i) \in (\mathbb{Q}/\mathbb{Z})^r$ , if any, the corresponding  $T$ -matrix is  $\text{diag}(e^{2\pi i t_i})$ .

The solutions to the aforementioned equations are determined using the following method: Initially, the matrix reformulation is represented as  $At = 0$ , where  $A$  is an  $m \times n$  matrix over  $\mathbb{Z}$  with  $m = r^4$  and  $n = r$ . Subsequently, the Smith normal form is employed, denoted as  $D = UAV$ , in which  $U$  and  $V$  are invertible matrices over  $\mathbb{Z}$  of sizes  $m \times m$  and  $n \times n$ , respectively, and  $D$  is a diagonal  $m \times n$  matrix  $(\alpha_i \delta_{i,j})$ , where the integer  $\alpha_i$  is divisible by  $\alpha_{i+1}$  for all  $i < r$ , and  $\delta_{i,j}$  is the Kronecker delta. The solutions to  $Dx = 0$  are precisely represented by the vectors  $(k_i/\alpha_i)$ , where  $0 \leq k_i < \alpha_i$ . Consequently, we have  $U^{-1}DV^{-1}t = 0$ , which simplifies to  $DV^{-1}t = 0$ . Therefore, the solutions can be expressed as  $t = Vx$ .

A complete listing of potential  $T$ -matrices requires considering all vectors  $(k_i/\alpha_i)$ , where  $0 \leq k_i < \alpha_i$ . As a result, there are  $p = \prod_i \alpha_i$  possible combinations. This task remains manageable up to rank 11. However, in certain rank 12 cases, the value of  $p$  becomes too large. But a miraculous circumstance arises (referred to as the **magic criterion**): for all such cases, if one abstractly considers the  $T$ -matrix with variables  $(k_i)$ , then for every determined  $S$ -matrix  $S$  in §3.1, the abstract product  $(ST)^3$  consistently exhibits a zero where it should not, specifically at an entry  $(i, i^*)$  for some  $i$ . This is because  $(ST)^3/p_+ = S^2 = dC$ , where  $C$  is the duality matrix (realizing the involution  $i \rightarrow i^*$ , and thus  $C_{i,i^*} = 1$ , non-zero), as defined in Definition 2.11. The function `MagicCriterion` (also covered by the function `STMatrix`) can verify this. Up to rank 12, it effectively excludes exactly 33 fusion rings (8 distinct types) out of the 52 non-pointed ones (15 distinct types) resulting from §3.1. The remaining 7 non-pointed types are [1,1,1,1,2,2,2], [1,1,2,2,2,2,3,3], [1,1,1,1,2,2,2,4,4,4], [1,1,1,2,2,2,2,2,2,3], [1,1,1,1,2,2,2,2,2,2,2], [1,1,2,2,2,2,6,6,6,9,9], [1,1,2,6,6,6,6,10,10,10,15,15]. For these types, some (but not all) of their possible  $S$ -matrices can still be excluded by this method. At rank 13, our magic criterion excludes all what remained non-pointed, see §9.4.

**Question 3.2.** *Can the aforementioned magic criterion be reformulated at the level of fusion data?*

In conclusion, we retain only those  $S$ - and  $T$ -matrices that meet all criteria outlined in Definition 2.11. This process results in  $19 + 64$  distinct modular data originating from  $5 + 18$  fusion rings of  $3 + 13$  types (non-pointed + pointed), up to rank 13, thereby substantiating Theorem 1.4. This classification was executed by applying the function `STmatrix` or `STmatrix2` to the list of fusion rings discussed in §3.1, all of which can be found at [39]. When considering isomorphism classes, it is appropriate to adopt a *normal form* by sorting the basic elements according to their  $\text{FPdim}$  and spin, and limit basis permutations to those preserving both.

**3.3. Model by Zesting.** This subsection seeks to model certain modular data indicated in Theorem 1.4, predominantly through the process of zesting as delineated in [15]. The ensuing proposition is attributed to Eric C. Rowell.

**Proposition 3.3.** *The eight modular data delineated in §12.1.5 are derived from  $SO(8)_2$ , its conjugates, and zestings.*

*Proof sketch.* Commencing with  $SO(8)_2$ , one identifies that it is graded by the group  $G = C_2 \times C_2$ . This enables to twist the braiding by a bicharacter: the braiding is altered to  $B(\deg(X), \deg(Y))c_{X,Y}$ , where  $B$  represents the bicharacter. Correspondingly, the twists must be adjusted. This action exemplifies a specialized instance of braided (or ribbon) zesting. The resultant effect is the multiplication of specific rows and columns of the  $S$ -matrix by a sign. Upon inspecting the  $S$ -matrices itemized in §12.1.5, the rationale behind these variations should become apparent. Complex conjugation preserves the  $S$ -matrix while altering the  $T$ -matrix, thus providing a comprehensive explanation (notably, complex conjugation modifies the underlying fusion category).  $\square$

#### 4. EGYPTIAN FRACTIONS WITH SQUARED DENOMINATORS

A  $(q, r)$ -Egyptian fraction with squared denominators is defined as a sum of the form:

$$q = \sum_{i=1}^r \frac{1}{s_i^2},$$

where  $q, r, s_i \in \mathbb{Z}_{\geq 1}$  and the sequence satisfies  $s_1 \geq s_2 \geq \dots \geq s_r \geq 1$ . Additionally, in the context of classifying potential types of Grothendieck rings for modular integral fusion categories (or more broadly, half-Frobenius integral fusion rings), we can assume that each  $s_i$  is a divisor of  $s_1$  for all  $i$ . By repeatedly subtracting 1 from both  $q$  and  $r$  as necessary, we can further assume that  $s_i \geq 2$  for all  $i$ . Subsequently, we can complete the list of  $(q, r)$ -Egyptian fractions with squared denominators by including the  $(q - k, r - k)$  ones, augmented by  $k$  times the number 1 in their sum. Using this technique, we can assume that  $q \leq r/4$ .

The following steps outline our methodology:

- Employ the function `ModularRep` provided in §4.2 for  $1 \leq r \leq 13$  and  $1 \leq q \leq r/4$ .
- Refine the classification by incorporating additional 1s as described previously.
- Construct all possible types using  $d_i = s_1/s_i$ . The resulting list is presented in §4.1.

**4.1. List of Types Up to Rank 13.** Below is the count of possible types up to rank 13, based solely on Egyptian fractions with squared denominators. It also includes the count of perfect types (refer to §5):

| Rank           | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9  | 10 | 11  | 12  | 13   |
|----------------|---|---|---|---|---|---|---|---|----|----|-----|-----|------|
| #Types         | 1 | 1 | 1 | 1 | 2 | 3 | 3 | 7 | 11 | 42 | 144 | 812 | 7997 |
| #Perfect Types | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 2 | 2  | 24 | 88  | 591 | 6517 |

The ratio of perfect types exhibits an increasing trend, e.g. 18% for rank 9, but 81% for rank 13. This leads us to question whether this ratio tends to 1 as the rank goes to infinity.

The list of all such (non-pointed) types up to rank 10 is provided (those up to rank 13 can be found online at [39]):

- Rank 5:  $[[1, 1, 1, 1, 2]]$ .
- Rank 6:  $[[1, 1, 1, 1, 2, 2], [1, 2, 2, 3, 3, 3]]$ .
- Rank 7:  $[[1, 1, 1, 1, 2, 2, 2], [1, 2, 2, 3, 3, 3, 6]]$ .
- Rank 8:  $[[1, 1, 1, 1, 2, 2, 2, 2], [1, 1, 1, 1, 2, 2, 2, 4], [1, 1, 2, 2, 2, 2, 3, 3], [1, 1, 3, 3, 4, 6, 6, 6], [1, 2, 2, 3, 3, 3, 6, 6], [1, 2, 2, 6, 6, 9, 9, 9]]$ .
- Rank 9:  $[[1, 1, 1, 1, 1, 1, 1, 2], [1, 1, 1, 1, 1, 2, 3, 3, 3], [1, 1, 1, 1, 2, 2, 2, 2, 2], [1, 1, 1, 1, 2, 2, 2, 4, 4], [1, 1, 1, 1, 4, 4, 6, 6, 6], [1, 1, 2, 2, 2, 3, 3, 6], [1, 1, 3, 3, 4, 6, 6, 6, 12], [1, 1, 4, 9, 9, 12, 18, 18, 18], [1, 2, 2, 3, 3, 3, 6, 6, 6], [1, 2, 2, 6, 6, 9, 9, 9, 18]]$ .
- Rank 10:  $[[1, 1, 1, 1, 1, 1, 1, 1, 3], [1, 1, 1, 1, 1, 1, 1, 2, 2], [1, 1, 1, 1, 1, 2, 3, 3, 3, 6], [1, 1, 1, 1, 2, 2, 2, 2, 2, 2], [1, 1, 1, 1, 2, 2, 2, 4, 4], [1, 1, 1, 1, 4, 4, 6, 6, 6, 12], [1, 1, 1, 1, 2, 2, 2, 2, 2, 3], [1, 1, 1, 1, 2, 2, 3, 4, 6, 6, 6], [1, 1, 1, 2, 3, 8, 8, 12, 12, 12], [1, 1, 1, 7, 12, 28, 28, 42, 42, 42], [1, 1, 2, 2, 2, 2, 3, 3, 6, 6], [1, 1, 2, 3, 3, 4, 4, 4, 6, 6], [1, 1, 3, 3, 4, 6, 6, 6, 12, 12], [1, 1, 3, 3, 4, 12, 12, 18, 18, 18], [1, 1, 4, 4, 4, 5, 5, 10, 10, 10], [1, 1, 4, 9, 9, 12, 18, 18, 18, 36], [1, 1, 4, 12, 27, 27, 36, 54, 54, 54], [1, 2, 2, 2, 2, 2, 5, 5, 5], [1, 2, 2, 2, 6, 14, 14, 21, 21, 21], [1, 2, 2, 3, 3, 3, 3, 3, 3, 3], [1, 2, 2, 3, 3, 3, 6, 6, 6, 6], [1, 2, 2, 3, 3, 3, 6, 6, 6, 12], [1, 2, 2, 3, 6, 6, 6, 6, 9, 9], [1, 2, 2, 3, 9, 9, 12, 18, 18, 18], [1, 2, 2, 4, 5, 5, 5, 10, 10, 10], [1, 2, 2, 6, 6, 9, 9, 9, 18, 18], [1, 2, 2, 6, 6, 18, 18, 27, 27, 27], [1, 2, 3, 6, 10, 10, 10, 15, 15], [1, 2, 3, 6, 15, 15, 20, 30, 30, 30], [1, 3, 3, 3, 4, 4, 4, 4, 4, 6], [1, 3, 3, 3, 4, 6, 8, 12, 12, 12], [1, 3, 3, 3, 6, 16, 16, 24, 24, 24], [1, 4, 4, 4, 7, 7, 7, 14, 14, 14], [1, 4, 9, 28, 63, 63, 84, 126, 126, 126], [1, 5, 7, 35, 60, 140, 140, 210, 210, 210], [1, 5, 10, 18, 30, 30, 30, 45, 45], [1, 5, 10, 18, 45, 45, 60, 90, 90], [1, 6, 18, 38, 38, 114, 114, 171, 171, 171], [1, 12, 12, 17, 51, 51, 68, 102, 102, 102], [1, 18, 30, 70, 70, 210, 210, 315, 315, 315], [1, 70, 130, 182, 390, 910, 910, 1365, 1365, 1365]]$ .



## 4.2. SageMath Code.

```

def ModularRep(q,r):
    L=all_rep(q, r)
    P=[]
    for l in L:
        if l[0]!=1: # those starting with 1 should be considered with q-1.
            k=0
            for ll in l:
                if l[-1]%ll!=0:
                    k=1
                    break
            if k==0:
                lll=[l[-1]/ll for ll in l]
                lll.sort()
                Di=sum([i^2 for i in lll])
                P.append(lll+[[sqrt(Di)]])
    return P

def res_rep(s, N):
    def succ(t):
        s0, m = t
        if s0==0 or len(m)>=N:
            return []
        p = numerator(s0)
        q = denominator(s0)
        if len(m)==N-1:
            if p==1 and is_square(q):
                r = q.isqrt()
                if r>=m[-1]:
                    return [(0,m+(r,))]
            return []
        L = max(m[-1], ((q-1)//p).isqrt()+1)
        U = floor((N-len(m))/s0).isqrt()
        if len(m)==N-2:
            S = []
            try:
                two_squares(p)
                two_squares(q)
            except:
                return S
            q2 = q^2
            for r in (L..U):
                d = p*r^2-q
                if d>0 and q2%d==0:
                    r2 = (q2//d + q)//p
                    if is_square(r2):
                        S.append( (0,m+(r,r2.isqrt())) )
            return S
        if len(m)==N-3:
            t = p*q
            a = valuation(t,2)
            if a%2==0 and (t>>a)%8==7:
                return []
            return ( (s0-1/r^2, m+(r,)) for r in (L..U) )
    return RecursivelyEnumeratedSet(seeds=[(s-1/r^2,(r,)) for r in range(1,floor(N/s).isqrt()+1)], \
    successors=succ, structure='forest')

```

```

def all_rep(s, N):
    return res_rep(s,N).map_reduce(lambda t: {t[1]} if t[0]==0 and len(t[1])==N else set(), set.union, \
    set() )

def count_rep(s, N):
    return res_rep(s,N).map_reduce(lambda t: int(t[0]==0 and len(t[1])==N))

```

## 5. TYPE CRITERIA

In this section, we delineate criteria that were employed to exclude certain candidates from being the type of a fusion ring. A *type* refers to a list denoted by  $t = [[d_1, m_1], [d_2, m_2], \dots, [d_s, m_s]]$ , where the conditions  $1 = d_1 < d_2 < \dots < d_s$  and  $m_i \geq 1$  for all indices  $i$  are satisfied. Such a type is characterized as:

- *trivial* if  $t = [[1, 1]]$ ,
- *pointed* if  $t = [[1, m]]$  for some  $m$ ,
- *perfect* if  $m_1 = 1$ ,
- *integral* if each  $d_i$  is an integer.

A type  $t = [[d_1, m_1], [d_2, m_2], \dots, [d_s, m_s]]$  may sometimes be represented simply as

$$[d_1, \dots, d_1, d_2, \dots, d_2, \dots, d_s, \dots, d_s],$$

where each  $d_i$  appears  $m_i$  times. Thus, we can rephrase the notation for a type of rank  $r$  as  $[d_1, \dots, d_r]$  with the condition  $1 = d_1 \leq d_2 \leq \dots \leq d_r$ .

The criteria described herein are proved using modular arithmetic, and arranged in order of increasing computational complexity. They permit to exclude about 62% of the types presented in §4. Here is their counting:

| Rank             | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9  | 10 | 11  | 12  | 13   |
|------------------|---|---|---|---|---|---|---|---|----|----|-----|-----|------|
| # Types          | 1 | 1 | 1 | 1 | 2 | 3 | 3 | 7 | 11 | 42 | 144 | 812 | 7997 |
| # Excluded Types | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 3 | 5  | 26 | 85  | 520 | 4970 |

For the remaining types, we will utilize the fusion ring solver, as elaborated in §6.

### 5.1. Small Perfect Type.

**Theorem 5.1.** *A perfect integral fusion ring of the type  $[[d_1, m_1], [d_2, m_2], \dots, [d_s, m_s]]$ , with  $s \leq 3$ , is trivial.*

*Proof.* If  $s = 1$ , then the type  $t = [[1, 1]]$  is trivial. If  $s = 2$ , then we have a type  $t = [[1, 1], [d, n]]$  with  $d > 1$  and  $n \geq 1$ . However, should a fusion ring of type  $t$  exist, let  $b$  be a basic element with  $\text{FPdim}(b) = d$ . When applying  $\text{FPdim}$  to the decomposition of  $bb^*$ , we obtain that  $d^2 = 1 + kd$  for some integer  $k \geq 1$ . Reducing this equation modulo  $d$  yields  $0 = 1 \pmod{d}$ , which is contradictory to  $d > 1$ . Lastly, if  $s = 3$ , then the type is  $t = [[1, 1], [a, m], [b, n]]$ , with  $1 < a < b$  and  $m, n \geq 1$ . Suppose  $\mathcal{R}$  is a fusion ring of this type, with basic elements  $1, a_1, \dots, a_m, b_1, \dots, b_n$ .

**Claim 5.2.** *The greatest common divisor of  $a$  and  $b$ , denoted  $a \wedge b$ , is 1.*

*Proof.* Let  $d = a \wedge b$ . Then  $\text{FPdim}(a_i a_i^*) = a^2 = 1 + \alpha a + \beta b$ , but since  $d$  divides both  $a$  and  $b$ , we have  $0 = 1 \pmod{d}$ , which implies  $d = 1$ .  $\square$

**Claim 5.3.** *For every  $i$ , there exists  $j$  such that  $\langle a_i a_i^*, b_j \rangle \neq 0$ .*

*Proof.* If this were not the case, then  $a^2 = 1 + \alpha a$ , leading to  $1 = 0 \pmod{a}$ , which contradicts the fact that  $a > 1$ .  $\square$

**Claim 5.4.** *If  $k \neq i^*$ , then  $\langle a_i a_k, b_j \rangle = 0$ .*

*Proof.* If the claim were false, then  $a^2 = \alpha a + \beta b$  with  $\beta \neq 0$ , which would mean that  $\beta b = 0 \pmod{a}$ . However, since  $a \wedge b = 1$  (indicating that  $b$  is invertible modulo  $a$ ), we get  $\beta = b^{-1} \times 0 = 0 \pmod{a}$ . Therefore,  $\beta = ka$  for some  $k \geq 1$ . Now, since  $a^2 = \alpha a + \beta b \geq \beta b = kab \geq ab$ , we would have  $a^2 \geq ab$ , which contradicts the fact that  $b > a$ .  $\square$

**Claim 5.5.**  $a_i^* b_j = b a_{i^*}$ .

*Proof.* By Frobenius reciprocity and Claim 5.4, if  $k \neq i^*$  then  $\langle a_i^* b_j, a_k \rangle = 0$ . Claim 5.3 ensures that  $\langle a_i^* b_j, a_{i^*} \rangle \neq 0$ . We know  $\text{FPdim}(a_i^* b_j) = ab = \alpha a + \beta b$ , with  $\alpha \geq 1$ , leading to the conclusion that  $\beta = 0 \pmod{a}$ . Hence,  $\beta = ka$  for some  $k \geq 0$ . As a result,  $ab = \alpha a + kab$ , which simplifies to  $(1 - k)ab = \alpha a > 0$ . This implies  $(1 - k) > 0$  and thus  $k < 1$ . Therefore,  $k = 0$  and  $\beta = 0$ . Combining the initial part of this proof with  $\beta = 0$  indicates that  $a_i^* b_j = \alpha a_{i^*}$ , where  $\alpha$  must equal  $b$  (determined by applying  $\text{FPdim}$ ).  $\square$

Claim 5.5, together with Frobenius reciprocity, leads us to deduce that  $\langle a_i a_{i^*}, b_j \rangle = b$ , which means that  $a^2 \geq b^2$ . This is in contradiction with  $a < b$ .  $\square$

**Remark 5.6.** Theorem 5.1 is not extendable to  $s = 4$  because the representation category of the alternating group  $A_5$ , denoted  $\text{Rep}(A_5)$ , is of type  $[[1, 1], [3, 2], [4, 1], [5, 1]]$ .

By applying Theorem 5.1 to the list presented in §4, we can exclude the following four types (up to rank 13):  $[[1, 1], [2, 2], [3, 3]]$ ,  $[[1, 1], [2, 6], [5, 3]]$ ,  $[[1, 1], [2, 2], [3, 7]]$ ,  $[[1, 1], [3, 7], [4, 5]]$ .

**Corollary 5.7.** A non-trivial perfect integral fusion ring has a rank of at least 4.

*Proof.* Suppose there is a perfect integral fusion ring with a rank less than 4. Then its type would be  $[[d_1, m_1], \dots, [d_s, m_s]]$  with  $s \leq r = \sum_i m_i \leq 3$ , which contradicts Theorem 5.1.  $\square$

## 5.2. Gcd Criterion.

**Lemma 5.8.** Consider a non-pointed fusion ring of type  $[d_1, d_2, \dots, d_r]$ . For all  $i$  such that  $d_i > 1$ , let  $Z_i$  be the set of indices  $j \neq 1$  for which  $N_{i,i^*}^j$  is nonzero, and let  $g_i$  be  $\gcd(d_j \mid j \in Z_i)$ . Then it holds that  $d_i^2 \equiv 1 \pmod{g_i}$  and  $\gcd(d_i, g_i) = 1$ .

*Proof.* First, note that  $Z_i$  is non-empty, which implies that  $g_i \neq 0$ . According to the Frobenius-Perron theorem, the dimension equation, and the Dual axiom, we have

$$d_i^2 = d_i d_{i^*} = \sum_k d_k N_{i,i^*}^k = 1 + \sum_{j \in Z_i} d_j N_{i,i^*}^j = 1 + K g_i,$$

where  $K$  is some integer. Consequently,  $d_i^2 \equiv 1 \pmod{g_i}$ , and  $0 \equiv 1 \pmod{\gcd(d_i, g_i)}$ . The lemma follows.  $\square$

**Proposition 5.9.** Consider a non-trivial perfect fusion ring of type  $[d_1, d_2, \dots, d_r]$ . Take  $i > 1$ , let  $Z'_i$  be the set of indices  $j \neq 1$  for which  $d_j < d_i^2$ , and let  $g'_i$  be  $\gcd(d_j \mid j \in Z'_i)$ . Then  $g'_i = 1$ . In particular,  $\gcd(d_2, \dots, d_r) = 1$ .

*Proof.* Note that if  $N_{i,i^*}^j$  is nonzero, then  $d_i^2 \geq d_j$ . Hence, following the notation in Lemma 5.8,  $Z_i$  is included in  $Z'_i$ , and as a result,  $g'_i$  divides  $g_i$ . Due to perfectness, we have  $d_i > 1$ , implying  $d_i^2 > d_i$  and therefore  $i$  belongs to  $Z'_i$ . Consequently,  $g'_i$  divides  $d_i$ . However, according to Lemma 5.8,  $g'_i = 1$ . For the final assertion, note that  $\gcd(d_2, \dots, d_r)$  is a divisor of  $g'_2 = 1$ .  $\square$

The SageMath code implementing the criterion from Proposition 5.9 can be found in the function `GcdCriterion` within the file `TypeCriteria.sage`, available at [39]. This criterion excludes more than 37% of the perfect types listed in §4, for example,  $[1, 2, 2, 6, 6, 9, 9, 9]$ . Here is the count per rank:

| Rank                     | 8 | 9 | 10 | 11 | 12  | 13   |
|--------------------------|---|---|----|----|-----|------|
| # Excluded Perfect Types | 1 | 1 | 7  | 19 | 212 | 2474 |

**5.3. Type Test.** Let's consider a type  $t = [d_1, \dots, d_r]$  with  $1 = d_1 \leq \dots \leq d_r$  and  $d_2 > 1$  (signifying that it is perfect). If there is an index  $i$  and  $g_i > 1$  such that  $g_i$  divides every  $d_j$  not equal to 1 or  $d_i$ , and  $d_i$  is coprime with  $g_i$ , then assume a fusion ring of this type exists with a basis  $\{b_1, \dots, b_r\}$  where  $d_k = \text{FPdim}(b_k)$ .

**Lemma 5.10.** For every  $j$  with  $d_j \neq 1$  and  $d_j \neq d_i$ , the following equation holds:

$$\sum_{k; d_k = d_i} N_{j,j^*}^k \equiv -1/d_i \pmod{g_i}.$$

*Proof.* For each  $j$  with  $d_j \neq 1$  and  $d_j \neq d_i$ , we have:

$$b_j b_{j^*} = b_1 + \sum_{k; d_k = d_i} N_{j,j^*}^k b_k + \sum_{k; d_k \neq 1, d_i} N_{j,j^*}^k b_k.$$

By applying  $\text{FPdim}$  and reducing modulo  $g_i$ , we obtain:

$$0 = 1 + x d_i \pmod{g_i},$$

where  $d_i$  has a multiplicative inverse modulo  $g_i$ . Therefore,  $x \equiv -1/d_i \pmod{g_i}$ .  $\square$

Given an integer  $a_{d_i}$  such that  $0 \leq a_{d_i} < g_i$  and  $a_{d_i} \equiv -1/d_i \pmod{g_i}$ , let  $S$  be the set containing all such  $d_i$ . From Lemma 5.10, for every  $j \neq 1$ , the inequality below must hold:

$$d_j^2 \geq 1 + \sum_{d \in S \setminus \{d_j\}} a_d d,$$

thus if the inequality does not hold,  $t$  cannot be a type of a fusion ring. Furthermore, if the set  $\{k \mid d_k = d_j\}$  is a singleton, we can use a stronger inequality:

$$d_j^2 \geq 1 + b_j d_j + \sum_{d \in S \setminus \{d_j\}} a_d d,$$

with  $0 \leq b_j < g_j^2$  and  $b_j \equiv d_j - \frac{1}{d_j} \pmod{g_j^2}$ .

The SageMath code implementing this criterion can be found in the function `TypeTest` within the file `TypeCriteria.sage`, available at [39]. This criterion helped to exclude a certain number of perfect types per rank in the list from §4, as shown in the table below:

| Rank                    | 8 | 9 | 10 | 11 | 12  | 13   |
|-------------------------|---|---|----|----|-----|------|
| #Excluded Perfect Types | 1 | 1 | 12 | 37 | 249 | 2380 |

**5.4. Local Criterion.** Consider a type  $t = [[d_1, m_1], [d_2, m_2], \dots, [d_s, m_s]]$ . Assume the existence of  $g, i_0 > 1$  such that  $g$  divides each  $d_i$  for all indices  $i$  not in the set  $\{1, i_0\}$ , and  $d_{i_0}$  is coprime with  $g$ . Let  $(d, m) := (d_{i_0}, m_{i_0})$ . If it corresponds to a fusion ring with a basis  $\{b_{1-m_1}, \dots, b_0, b_1, \dots, b_{r-1}\}$ , where  $b_0$  is the unit,  $\text{FPdim}(b_i) = 1$  for  $i \leq 0$ , and  $\text{FPdim}(b_j) = d$  for  $j \in \{1, \dots, m\}$ , then the following lemma applies:

**Lemma 5.11.** *For each  $i \in \{1, \dots, m\}$ , the equation below is valid:*

$$\sum_{j,k=1}^m N_{i,j}^k \equiv md - \frac{m_1}{d} \pmod{g^2},$$

and for all  $j > m$ , the integer  $g$  divides  $\sum_{k=1}^m N_{i,j}^k$ .

*Proof.* For any  $i \in \{1, \dots, m\}$  and  $j > m$ , since  $\text{FPdim}(b_i) \neq \text{FPdim}(b_j)$ , by Corollary 2.9 and Frobenius reciprocity, we have:

$$b_i b_j = \sum_{k \geq 1} N_{i,j}^k b_k = \sum_{k=1}^m N_{i,j}^k b_k + \dots,$$

Applying  $\text{FPdim}$  and reducing modulo  $g$ , we conclude that:

$$d \sum_{k=1}^m N_{i,j}^k \equiv 0 \pmod{g},$$

which implies that  $g$  divides  $\sum_{k=1}^m N_{i,j}^k$ . For each  $i \in \{1, \dots, m\}$ , the sum over the basis elements yields:

$$b_{i*} \sum_{k=1}^m b_k = \sum_{s \leq 0} b_s + \sum_{j=1}^m \left( \sum_{k=1}^m N_{i,j}^k \right) b_j + \sum_{j>m} \left( \sum_{k=1}^m N_{i,j}^k \right) b_j.$$

After applying  $\text{FPdim}$ , we obtain  $md^2 = m_1 + xd + yg^2$ , hence  $x \equiv md - \frac{m_1}{d} \pmod{g^2}$ .  $\square$

For a type  $t$ , we can analyze the partitions of  $md^2 - xd - m_1$  in the form  $\sum_{i \notin \{1, i_0\}} a_i d_i$ , with  $x \equiv md - \frac{1}{d} \pmod{g^2}$  and  $a_i \equiv 0 \pmod{g}$ . The SageMath code performing this analysis can be found in the function `LocalCriterion` within the file specified earlier, also available at [39]. This criterion, which can rule out types when no suitable partitions are found, is further detailed in the following example.

**Example 5.12.** *Consider the type  $t = [[1, 1], [1295, 2], [3990, 1], [4218, 1], [24605, 1], [42180, 1], [98420, 2], [147630, 3]]$ . We can apply Lemma 5.11 to the triples  $(d, m, g) = (1295, 2, 19), (3990, 1, 37), (4218, 1, 5)$ . Subsequently, we obtain  $md - \frac{1}{d} \equiv 126, 1135, 11 \pmod{g^2}$  for each respective triple. The application of the function `LocalCriterion` to the triple  $(d, m, g) = (1295, 2, 19)$  enables us to eliminate the type  $t$  in less than one second.*

```
sage: %time LocalCriterion(T, 1295, 2, 19)
CPU times: user 640 ms, sys: 0 ns, total: 640 ms
Wall time: 982 ms
[]
```

*However, we cannot employ the triple  $(d, m, g) = (3990, 1, 37)$ , as it yields 55 solutions.*

```
sage: L = LocalCriterion(T, 3990, 1, 37)
sage: len(L)
55
```

The application of `LocalCriterion` to the list in §4 led to the exclusion of several types per rank, as summarized in the following table:

| Rank                     | 6 | 7 | 8 | 9 | 10 | 11 | 12  | 13   |
|--------------------------|---|---|---|---|----|----|-----|------|
| # Excluded Types         | 1 | 1 | 3 | 5 | 21 | 63 | 344 | 2852 |
| # Excluded Perfect Types | 1 | 1 | 2 | 2 | 14 | 37 | 238 | 2173 |

It is noteworthy that this criterion alone suffices to eliminate all perfect types up to rank 9. Therefore, it can be stated conclusively that no non-trivial perfect integral half-Frobenius fusion rings, and thus no non-trivial perfect

## 6. ENHANCED FUSION RING SOLVER USING NORMALIZ

```
amb_space auto
fusion_type_for_partition
[1,1,2,3,3,6,6,8,8,8,12,12]
```

Here, the default computation goal is `SingleLatticePoint`, focusing on the solvability of the system.

For additional information and further options, refer to Appendix H of the Normaliz manual (`Normaliz.pdf`), available in the `doc` directory of the Normaliz distribution or online at [10]. This includes details on restricting computations to fusion rings that meet certain criteria for modular categorification.

**6.2. Normaliz and its approach to fusion rings.** Normaliz [9] is an open source software for discrete convex geometry and its algebraic aspects. Readers are referred to Bruns and Gubeladze [7] for detailed terminology and a comprehensive discussion. Normaliz is designed to solve Diophantine systems of linear inequalities, equations, and congruences with integer coefficients. Additionally, it calculates enumerative information such as multiplicities (which correspond to geometric volumes) and Hilbert series. Objects in Normaliz can be defined either by generators, such as the extreme rays of cones, bases of lattices, and vertices of polytopes, or by constraints like inequalities, equations, and congruences. For systems with coefficients in real algebraic number fields, Normaliz can execute fundamental operations like convex hull computation and its dual, vertex enumeration. Moreover, it is capable of computing lattice points within (bounded) polytopes over real algebraic number fields, facilitating applications to non-integral fusion rings. In the context of fusion rings, it is crucial that lattice points within polytopes can be subjected to constraints imposed by polynomial equations and inequalities. Each release of Normaliz includes source code, comprehensive documentation, sample examples, a testing suite, and pre-compiled binaries for Linux, Mac OS, and MS Windows systems.

For lattice points in generic polytopes denoted by  $P$ , Normaliz employs the project-and-lift algorithm. It sequentially projects  $P$  onto coordinate hyperplanes until reaching zero dimensions and then lifts the lattice points back up. If  $P'$  is a projection of  $P$  onto a coordinate hyperplane, then the lattice points of  $P$  are projected to lattice points in  $P'$ , and if  $x \in P'$  is a lattice point within  $P'$ , its preimages are the lattice points in a line segment. Polynomial constraints can be introduced as soon as the lifting process reaches the highest coordinate present in the constraint.

In its standard form, the project-and-lift method is suitable for only minor cases of fusion rings. For satisfactory performance, the algorithm has been tailored to the special linear and polynomial constraint structure specific to fusion rings. Each linear equation is inhomogeneous with nonnegative coefficients and a positive right-hand side. We can refer to the set of coordinates that appear in the equation with positive coefficients as a "patch". These patches encompass the entire set of coordinates, and thus the linear equations, when restricted to the nonnegative orthant, delineate a polytope  $P$ . Solutions to a linear equation, confined to its patch, are ascertained using the project-and-lift technique previously outlined, and the lattice points in  $P$  are derived by combining these local solutions along matching components. In essence, we begin with the solutions of one of the equations and progressively extend them patch by patch. The sequence in which patches are integrated into the extension process is pivotal. Normaliz includes options that allow alteration of the sequence, as detailed later on.

In the partition version (§6.4), the input file is only made of simplified dimension (linear) equations. Particularly for this case, it is critical to recognize a secondary, implicit constraint type: congruences extracted from the linear equations by taking successive residue classes modulo their coefficients. By default, each congruence involves only the coordinates pertaining to the patch of its originating equation. Nonetheless, since congruences only involve a subset of these coordinates, they frequently pertain to other patches or combinations thereof, potentially significantly limiting their number of solutions. Our current classification up to rank 13 would not have been achievable without meticulous utilization of the congruences.

When polynomial equations of degree two or higher are in play, Normaliz endeavors to determine an optimal patch extension order that allows these equations to be applied as early as feasible. Users can influence this order by either insisting on the "linear" input order or by directing Normaliz to employ "weights" that gauge the anticipated solution count for each patch and prioritize those with lower weight. Regardless of whether polynomial equations are present, users can request an order based on the applicability of congruences. This order can also be weight-dependent.

Some computations for simple rank 13 were executed on the high-performance cluster (HPC) at Osnabrück by early splitting of partial solutions into parts, which were then processed separately. Despite the rather basic approach of using a static subdivision without intercommunication between running instances of Normaliz, the HPC proved to be advantageous.

### 6.3. Full Version.

**Remark 6.1.** *All the processes outlined in this subsection have been fully automated in the recently released Normaliz 3.10.2 [9], see §6.1. Appendix H of its manual [10] specifically addresses the computation of the fusion rings for a specified type.*

Consider a fusion ring with the basis  $\{b_1, \dots, b_r\}$ . As described in §2.1, for all indices  $i, j$ :

$$b_i b_j = \sum_k N_{i,j}^k b_k,$$

$$d_i d_j = \sum_k N_{i,j}^k d_k.$$

A critical factor in accelerating computation is the strategic use of associativity equations (non-linear)

$$\sum_s N_{i,j}^s N_{s,k}^t = \sum_s N_{j,k}^s N_{i,s}^t$$

In practice, for a given type  $L = [d_1, d_2, \dots, d_r]$ , utilize the function `TypeToNormaliz`, the SageMath code for which can be found at [39]. This function generates input files (.in), one for each potential duality map  $i \rightarrow i^*$ . Place these files in a directory alongside the `normaliz.exe` and `run_normaliz.bat` files available at [39], and execute `run_normaliz` (note the existence of a more recent and faster Linux version used for our latest computations). This process yields output files (.out) containing all potential solutions (if any exist). The remaining task is to convert these solutions into fusion data, considering isomorphism. We demonstrate how this can be done with the following example. Take the type  $L = [1, 1, 2]$  of the character ring of  $S_3$ . When `TypeToNormaliz` is applied, it generates the file `[1,1,2][0,1,2].in` with the content as follows:

|   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 1 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 2 | 0 | 3 | 1 | 2 | 1 |   |   |
| 1 | 0 | 1 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 2 | 1 | 2 | 2 | 1 | 1 |
| 1 | 0 | 1 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 2 | 2 | 1 | 3 | 0 | 1 |   |





## 7. HALF-FROBENIUS INTEGRAL FUSION RINGS UP TO RANK 12

Here is the count of half-Frobenius integral fusion rings and noncommutative ones up to rank 12.

| Rank            | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8  | 9   | 10  | 11   | 12   |
|-----------------|---|---|---|---|---|---|---|----|-----|-----|------|------|
| #Fusion Rings   | 1 | 1 | 1 | 2 | 3 | 6 | 9 | 23 | 105 | 158 | 1218 | 9101 |
| #Noncommutative | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 4  | 5   | 7   | 38   | 158  |

The comprehensive list of these fusion rings has been compiled and made accessible online as indicated in [39]. These rings were identified by implementing the type criteria detailed in §5 and utilizing the fusion ring solver discussed in §6 on the list of types referenced in §4. The count of types for each rank is relatively modest when contrasted with the table in §4.1.

| Rank   | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|--------|---|---|---|---|---|---|---|---|---|----|----|----|
| #Types | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 4 | 5 | 9  | 15 | 28 |

Below is the list of (non-pointed) types for each rank, arranged in lexicographic order:

- Rank 5:  $[[1, 1, 1, 1, 2]]$ ,
- Rank 6:  $[[1, 1, 1, 1, 2, 2]]$ ,
- Rank 7:  $[[1, 1, 1, 1, 2, 2, 2]]$ ,
- Rank 8:  $[[1, 1, 1, 1, 2, 2, 2, 2], [1, 1, 1, 1, 2, 2, 2, 4], [1, 1, 2, 2, 2, 2, 3, 3]]$ ,
- Rank 9:  $[[1, 1, 1, 1, 2, 2, 2, 2, 2], [1, 1, 1, 1, 2, 2, 2, 4, 4], [1, 1, 1, 1, 4, 4, 6, 6, 6], [1, 1, 2, 2, 2, 2, 3, 3, 6]]$ ,
- Rank 10:  $[[1, 1, 1, 1, 1, 1, 1, 1, 1, 3], [1, 1, 1, 1, 1, 1, 1, 2, 2], [1, 1, 1, 1, 2, 2, 2, 2, 2], [1, 1, 1, 1, 2, 2, 2, 4, 4, 4], [1, 1, 1, 1, 4, 4, 6, 6, 6, 12], [1, 1, 1, 2, 2, 2, 2, 2, 2, 3], [1, 1, 2, 2, 2, 2, 3, 3, 6, 6], [1, 1, 2, 3, 3, 4, 4, 4, 6, 6]]$ ,
- Rank 11:  $[[1, 1, 1, 1, 1, 1, 1, 1, 1, 3, 3], [1, 1, 1, 1, 2, 2, 2, 2, 2, 2, 2], [1, 1, 1, 1, 1, 1, 1, 2, 2, 4], [1, 1, 1, 1, 1, 1, 2, 2, 2, 3, 3], [1, 1, 1, 2, 2, 2, 2, 2, 3, 6], [1, 1, 1, 1, 2, 2, 2, 4, 4, 4, 4], [1, 1, 1, 1, 2, 2, 2, 4, 4, 8], [1, 1, 1, 1, 2, 4, 4, 4, 4, 6, 6], [1, 1, 2, 2, 2, 2, 3, 3, 6, 6], [1, 1, 2, 3, 3, 4, 4, 4, 6, 6, 12], [1, 1, 1, 1, 2, 6, 6, 8, 12, 12, 12], [1, 1, 1, 1, 4, 4, 6, 6, 6, 12, 12], [1, 1, 1, 3, 4, 4, 4, 4, 4, 6], [1, 1, 1, 1, 4, 4, 12, 12, 18, 18, 18]]$ ,
- Rank 12:  $[[1, 1, 1, 1, 1, 1, 1, 1, 1, 3, 3, 3], [1, 1, 1, 1, 1, 1, 1, 1, 2, 2, 2, 2], [1, 1, 1, 1, 1, 1, 1, 1, 2, 2, 4, 4], [1, 1, 1, 1, 1, 1, 1, 2, 2, 2, 3, 3, 6], [1, 1, 1, 1, 2, 2, 2, 2, 2, 2, 2, 2], [1, 1, 1, 1, 2, 2, 2, 2, 2, 2, 4], [1, 1, 1, 1, 2, 2, 2, 2, 4, 6, 6, 6], [1, 1, 1, 1, 2, 2, 2, 4, 4, 4, 4, 4, 4], [1, 1, 1, 1, 2, 2, 2, 4, 4, 4, 8, 8], [1, 1, 1, 1, 2, 2, 8, 8, 12, 12, 12], [1, 1, 1, 1, 2, 4, 4, 4, 4, 6, 6, 12], [1, 1, 1, 1, 2, 6, 6, 8, 12, 12, 12, 24], [1, 1, 1, 1, 2, 8, 18, 18, 24, 36, 36, 36], [1, 1, 1, 1, 3, 3, 3, 3, 4, 4, 6, 6], [1, 1, 1, 1, 4, 4, 6, 6, 6, 12, 12, 12], [1, 1, 1, 1, 4, 4, 12, 12, 18, 18, 36], [1, 1, 1, 2, 2, 2, 2, 2, 3, 6, 6], [1, 1, 1, 2, 2, 2, 3, 4, 4, 4, 6, 6], [1, 1, 1, 3, 4, 4, 4, 4, 4, 6, 12], [1, 1, 1, 3, 6, 8, 8, 8, 8, 8, 12], [1, 1, 2, 2, 2, 2, 3, 3, 3, 3, 3, 3], [1, 1, 2, 2, 2, 3, 3, 6, 6, 6, 6], [1, 1, 2, 2, 2, 3, 3, 6, 6, 6, 12], [1, 1, 2, 2, 2, 6, 6, 6, 6, 9, 9], [1, 1, 2, 3, 3, 4, 4, 4, 6, 6, 12, 12], [1, 1, 2, 3, 3, 6, 6, 8, 8, 8, 12, 12], [1, 1, 2, 6, 6, 6, 6, 10, 10, 10, 15, 15]]$ .

Observe that the list above contains no non-trivial perfect types, which proves Theorem 1.7. It is noteworthy that the perfect integral modular fusion category (and therefore half-Frobenius)  $\mathcal{Z}(\text{Rep}(A_5))$  has an  $\text{FPdim}$  of  $60^2 = 3600$ , a rank of 22, and a type of  $[[1, 1], [3, 2], [4, 1], [5, 1], [12, 10], [15, 4], [20, 3]]$ . This type was calculated using [26, Section 3] and GAP.

**Question 7.1.** *Is there a perfect integral half-Frobenius fusion ring/category with a rank less than 22?*

## 8. ADVANCED RESULTS ON MODULAR FUSION CATEGORIES

From rank 13 onward, the types were further restricted by additional properties coming from more advanced results on modular fusion categories §8, which involved the universal grading §8.1, congruence representations of the modular group §8.2 and Galois action §8.3.

**8.1. Universal Grading.** Let  $G$  be a finite group. A  $G$ -grading of a fusion ring  $R$  is given by a partition of its basis  $B = \sqcup_{g \in G} B_g$  such that:

- For any  $x \in B_g$  and any  $y \in B_{g'}$ , the basic components of  $xy$  belong to  $B_{gg'}$ .
- For any  $x \in B_g$ ,  $x^*$  is in  $B_{g^{-1}}$ .

A  $G$ -grading is called *faithful* if  $B_g$  is non-empty for all  $g \in G$ . Consequently, by [17, Theorem 3.5.2],  $\text{FPdim}(B_g) := \sum_{x \in B_g} \text{FPdim}(x)^2$  is constant in  $g$ . The faithful grading with the largest group is called the *universal grading*. By [17, Lemma 8.22.9], the universal grading group of the Grothendieck ring of modular fusion category is  $G = B_{pt}$ , the group of basic element with  $\text{FPdim} = 1$  (see Corollary 2.10). The classification of fusion rings constrained to such a grading is a coming Normaliz feature, already available for the  $C_2$ -grading, see §6.

**Theorem 8.1.** *Let  $\mathcal{C}$  be an integral modular fusion category. Let  $R$  be its Grothendieck ring with basis  $B$ . Let  $G = B_{pt}$  be the universal grading group. Let  $T_g := (\text{FPdim}(x))_{x \in B_g}$ . Let  $\mathcal{C}_e$  be the fusion subcategory corresponding to  $B_e$ . Then:*

- (0) *If  $\mathcal{C}_e$  is perfect then it is modular,*
- (1) *If  $B_{pt} \subset B_e$  and  $T_e$  has an entry with odd multiplicity, then  $\forall g \neq e$ , every entry of  $T_g$  has multiplicity  $\geq 2$ ,*
- (2) *If (1) holds, if  $p := |B_{pt}|$  is prime, and if an entry  $d$  appears with multiplicity one in  $T_e$ , then  $p$  divides  $d$ .*

*Proof.* Immediate from [28, Proposition VI.2] as a group of prime order must be cyclic.  $\square$

Here are three examples of exclusion using each point of Theorem 8.1 (fully automated in §9.4):

- (0) In the partitioned type  $[[1, 2, 2, 3, 3, 3, 3], [1, 2, 2, 3, 6]]$ , the neutral component is perfect, but we already know that there is no perfect integral modular fusion category of rank 8,
- (1) In the partitioned type  $[[1, 1, 1, 1, 2, 2, 2, 3, 10, 10], [15], [15], [15]]$ , the pointed part is in the neutral component  $T_e$ , and the entry 2 has multiplicity three (odd) in  $T_e$ , but 15 appears with multiplicity one in some non-neutral components.
- (2) In the partitioned type  $[[1, 1, 2, 2, 3, 3, 5, 6, 6, 10, 15], [15, 15]]$ , the pointed part is in the neutral component  $T_e$ , and the entry 5 has multiplicity one (odd) in  $T_e$ , but 5 is not divisible by the prime  $2 = |B_{pt}|$ .

**8.2. Congruence Representation.** This subsection reviews some applications of congruence representations of the modular group to modular fusion categories, leading to a proof of the folklore Theorem 1.1. Although a more concise proof is presented later in §8.3, the current exposition is meant to be informative and to serve for future research.

As discussed in [27, Section 3], a modular fusion category  $\mathcal{C}$  is associated with modular data  $(S, T)$ , which gives a projective representation of

$$\mathrm{SL}(2, \mathbb{Z}) = \langle s, t \mid (st)^3 = s^2, s^4 = e \rangle.$$

This representation can be lifted to a usual (linear) representation  $\rho$  by utilizing the linear characters (i.e. one-dimensional representations), forming a cyclic group of order 12. This representation is  $r$ -dimensional—where  $r$  represents the rank of  $\mathcal{C}$ —and is *congruence*. This means it factors through  $\mathrm{SL}(2, \mathbb{Z}/n\mathbb{Z})$ , for some  $n$  whose smallest one is called the *level*. The level is determined as  $\mathrm{ord}(\rho(t))$  and satisfies

$$\mathrm{ord}(T) \mid \mathrm{ord}(\rho(t)) \mid 12\mathrm{ord}(T).$$

A finite-dimensional congruence representation  $\rho$  of level  $n$  is completely reducible, hence it can be broken down into a direct sum of irreducible representations of  $\mathrm{SL}(2, \mathbb{Z}/n\mathbb{Z})$ . It's important to note that this includes only those irreducible representations that do not further factor through  $\mathrm{SL}(2, \mathbb{Z}/d\mathbb{Z})$  for any proper divisor  $d$  of  $n$ . Nevertheless, if  $n = \prod_i p_i^{n_i}$  represents the prime factorization of  $n$ , then  $\rho = \bigotimes_i \rho_i$  with each  $\rho_i$  being a congruence representation of level  $p_i^{n_i}$ .

For deeper applications, note that [29] proves that the finite-dimensional congruence representations are equivalent to *symmetric* ones, which are classified in [30].

The dimensions  $d$  of the irreducible finite-dimensional congruence representations at level  $n = p^a$  are provided in the table at the end of [34]. Observe that  $d \geq (n - 1)/2$  [with equality only if  $a = 1$ ], leading to  $p \leq p^a = n \leq 2d + 1$ . Given that the rank  $r$  of the modular fusion category is the sum of dimensions  $d$  of such irreducible representations, it follows that  $d \leq r$  and therefore  $p \leq 2r + 1$ .

According to the Cauchy theorem in [4], the set  $S$  of prime factors of  $\mathrm{ord}(T)$  coincides with the prime factors of the global dimension norm  $N$  of the modular fusion category (of rank  $r$ ). The prime numbers  $p$  lastly mentioned (satisfying  $p \leq 2r + 1$ ) constitute the set  $S'$  of prime factors of the level  $n$  of the congruence representation. Thus,  $S \subseteq S' \subseteq S \cup \{2, 3\}$ , since  $\mathrm{ord}(T) \mid n \mid 12\mathrm{ord}(T)$  and  $12 = 2^2 \cdot 3$ . Hence, for all prime factors  $p \neq 2, 3$  of  $N$ , it follows that  $p \leq 2r + 1$ . The inequality trivially holds for  $p = 2, 3$ . This ends the proof of Theorem 1.1.

**8.3. Galois Action.** Let  $(s, t)$  be a *normalized* modular data. A Galois automorphism  $\sigma$  induces a permutation  $X \rightarrow \sigma(X)$  on the simple objects, and acts as follows on  $\dim$ ,  $s$  and  $t$ :

- (1)  $\sigma(\dim(X)^2) = \frac{\sigma(\dim(\mathcal{C}))}{\dim(\mathcal{C})} \dim(\sigma(X))^2$ , see [17],
- (2)  $\sigma(s_{X,Y}^2) = s_{X,\sigma(Y)}^2$ , see [17],
- (3)  $\sigma^2(t_X) = t_{\sigma(X)}$ , see [16, Theorem II (iii)].

See for example [40, Section 2] for an explicit normalization of the modular data.

**Second proof of Theorem 1.1 (shorter).** If  $p = 2, 3$  then  $p \leq 2r + 1$  trivially as  $r \geq 1$ . Let  $p \neq 2, 3$  be a prime factor of the global dimension norm. By Cauchy theorem in [4],  $p$  divides  $\mathrm{ord}(t)$ . So there must be a simple object  $X$  such that  $p$  divides the conductor of  $t_X$ , thus the orbit of  $(\sigma^2(t_X))$  has at least  $(p - 1)/2$  distinct elements, because the group of units in  $\mathbb{Z}/p\mathbb{Z}$  is cyclic of order  $p - 1$ , so it has an element  $g$  with  $\mathrm{ord}(g^2) = (p - 1)/2$ . So by (3),  $r \geq (p - 1)/2$ , i.e.,  $p \leq 2r + 1$ .  $\square$

Here is an example of type of rank  $r = 13$  and  $\mathrm{FPdim} = 2^4 3^2 5^2 7^2 19^2 37^2$  excluded Theorem 1.1:

$$[1, 777, 1036, 1295, 3990, 4218, 24605, 42180, 98420, 98420, 147630, 147630, 147630],$$

because  $p = 37 > 2r + 1 = 27$ .

Here is a stronger version in the integer case (shared by Eric Rowell and Andrew Schopieray):

**Theorem 8.2.** *For an integral modular fusion category, for every prime  $p$  dividing the global  $\mathrm{FPdim}$ , there is a basic  $\mathrm{FPdim}$  of multiplicity  $m$  such that  $p \leq 2m + 1$ .*

*Proof.* Consider the orbit  $(\sigma^2(t_X))$  with at least  $(p-1)/2$  distinct elements from above proof of Theorem 1.1. By (3), the orbit  $(\sigma(X))$  has also at least  $(p-1)/2$  distinct elements. By applying (1) on the (weakly) integral case, we get that  $\sigma(\text{FPdim}(X)) = \text{FPdim}(X)$ . Thus all simple objects in the orbit  $(\sigma(X))$  has the same FPdim, so the multiplicity  $m$  of this basic FPdim satisfies  $m \geq (p-1)/2$ , i.e.,  $p \leq 2m+1$ .  $\square$

Here is an example of type of rank 13 and  $\text{FPdim} = 2^4 3^6 5^2 7^2 17^2$  excluded by Theorem 8.2 (but not Theorem 1.1):

$$[1, 238, 459, 540, 595, 918, 5355, 9180, 21420, 21420, 32130, 32130, 32130],$$

because  $p = 17 > 2m+1 = 7$ , where  $m = 3$  is the largest multiplicity of a basic FPdim.

**Remark 8.3.** *The assertion of Theorem 8.2 can be generalized beyond the integral assumption, albeit with the necessity to substitute the usual multiplicity with the Galois-multiplicity, that is, the count of Galois-conjugate basic dim of the given basic dim.*

Here is an even stronger version of Theorem 8.2:

**Theorem 8.4.** *For an integral modular fusion category, let  $S$  be the set of odd prime factors of the global FPdim. There is a partition  $(S_i)$  of  $S$ , and multiplicities  $(m_i)$  of some distinct basic FPdims such that*

$$m_i \geq \frac{1}{2} \text{lcm}_{p \in S_i} (p-1).$$

*Proof.* Let  $S_X$  be the set of odd prime divisors of  $t_X$ . By Cauchy theorem in [4], the union of the sets  $S_X$  over all the simple objects  $X$  is exactly  $S$ . Let  $\lambda$  be the *Carmichael function*, i.e. the exponent of the multiplicative group of integers modulo  $n$ . It is well-known that if  $n = \prod_i p_i^{n_i}$  is the prime factorization of  $n$ , then  $\lambda(n) = \text{lcm}_i \lambda(p_i^{n_i})$ , whereas for  $p_i$  odd then  $\lambda(p_i^{n_i}) = \varphi(\lambda(p_i^{n_i})) = (p_i-1)p_i^{n_i-1}$ , where  $\varphi$  is the Euler totient function. The orbit  $(\sigma(X))$  has at least  $\frac{1}{2} \lambda(\prod_{p \in S_X} p)$  distinct elements. Therefore, by above and the proof of Theorem 8.2, the multiplicity of  $\text{FPdim}(X)$  is at least  $\frac{1}{2} \text{lcm}_{p \in S_X} (p-1)$ . The result follows.  $\square$

Here is an example of type of rank 25 and  $\text{FPdim} = 3^4 5^2 7^2 11^2 13^2$  excluded by Theorem 8.4 (but not Theorem 8.2):

$$[[1, 1], [39, 2], [231, 2], [273, 2], [1001, 2], [1287, 2], [3465, 2], [4095, 2], [9009, 2], [15015, 8]],$$

because the largest prime factor,  $p = 13$ , is insufficient for the largest multiplicity of 8 since  $(13-1)/2 = 6$ , which is less than 8. Therefore, the subset  $S_i$  that includes 13 must also include another prime to increase  $\text{lcm}_{p \in S_i} (p-1)$ . Primes 3, 5, and 7 do not contribute to an increase; although they could be part of  $S_i$ , another prime is needed. Thus, 11 must be included in  $S_i$ . Now,  $\text{lcm}(13-1, 11-1)/2 = 60$ , which is greater than 8, presenting a contradiction.

The checking of Theorems 8.2 and 8.4 are automated by the function `Theorem3Check` and `Theorem4Check` in `Equipartition.sage` in [39].

## 9. RANK 13

From rank 13 onwards, it becomes impractical to classify all half-Frobenius integral fusion rings using our current technology. Therefore, when necessary, we will either assume the commutativity or apply more advanced modular criteria mentioned in §8. This approach yields results that are less general at the fusion ring level but still sufficiently comprehensive for general modular data.

**9.1. General.** The process commenced, as previously, with 7997 half-Frobenius types derived from Egyptian fractions with squared denominators, as described in §4. Initially, more than 60% were dismissed based on type criteria outlined in §5. Subsequently, over 90% were eliminated using the partition version in §6.4, restricted to a quick use, leaving only 212 types for further consideration. Next, the application of Theorems 8.1 and 8.2, via the functions `AllCriteria` and `Theorem3Check` in `Equipartition.sage` in [39], reduces to 56 types. Among them, 11 are identified as perfect without any prime-power entries (see §9.2 for further examination), 22 are perfect but include a prime-power entry (see §9.3), and the remaining 23 are non-perfect (see §9.4); see `Rank13ReducedList` in [39].

**9.2. Simple.** We turn our attention to the study of simple integral modular fusion categories of rank 13. The following theorem provides a significant constraint on the types occurring in such categories.

**Theorem 9.1** (Corollary 6.16 in [33]). *Let  $\mathcal{C}$  be an integral modular fusion category. If  $\mathcal{C}$  contains a simple object whose FPdim is a prime-power, then it must have a nontrivial symmetric subcategory.*

Consequently, our analysis is narrowed down to perfect integral half-Frobenius types that lack any prime-power entries. From §4 and the list in [39], precisely 2044 such types have been classified, but we can quickly reduce to 11 types only, as explained in §9.1. A more extensive use (involving HPC) of §6.4, and then §6.3 assuming the commutativity, excluded all these 11 types.

Note that the perfect integral modular fusion category  $\mathcal{Z}(\text{Rep}(A_7))$ , with  $\text{FPdim } (7!/2)^2$ , rank 74, and type:

$$[[1, 1], [6, 1], [10, 2], [14, 2], [15, 1], [21, 1], [35, 1], [70, 9], [105, 4], [210, 20], [280, 9], [360, 14], [504, 5], [630, 4]],$$

notably lacks any basic elements whose  $\text{FPdim}$  is a prime-power.

**Question 9.2.** *Is there a perfect integral half-Frobenius fusion ring/category, without any basic elements of prime-power  $\text{FPdim}$ , that has a rank lower than 74?*

**9.3. Perfect Non-Simple.** According to §9.2, a perfect type that includes a prime-power entry cannot characterize a simple integral modular fusion category. From §4 and the list in [39], exactly 4473 such types have been identified. However, as explained in §9.1, we can quickly reduce to 22 types. Subsequently, all of these types can be ruled out, by §6.3, using relatively short computations. The exception is the type  $[1, 20, 20, 27, 27, 30, 45, 54, 180, 180, 270, 270, 270]$ , which requires a longer, yet still reasonable, computation time.

**9.4. Non-Perfect.** From §4 and the list in [39], precisely 1480 non-perfect types have been classified, but as explained in §9.1, we can quickly reduce to 23 types only. A more extensive use of §6.3 further narrows the count down to 15 types having fusion rings, where only 6 ones below have cyclotomic self-transposable fusion rings (see §3.1):

1.  $[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]$ ,
2.  $[1, 1, 1, 1, 4, 4, 4, 4, 4, 4, 10, 10, 10]$ ,
3.  $[1, 1, 1, 1, 4, 4, 12, 12, 36, 36, 54, 54, 54]$ ,
4.  $[1, 1, 1, 3, 6, 12, 16, 16, 16, 16, 16, 16, 24]$ ,
5.  $[1, 1, 1, 3, 12, 12, 20, 20, 20, 20, 20, 20, 30]$ ,
6.  $[1, 1, 2, 3, 3, 24, 30, 30, 40, 40, 40, 60, 60]$ .

Finally, all non-pointed ones are quickly excluded by the magic criterion (see §3.2), which completes the proof of Theorem 1.4 at rank 13.

Note that 4. and 5. admits the following alternative exclusion: their modular partition (i.e., as in §8.1) would be

$$[[1, 1, 1, 3, 6, 12, 24], [16, 16, 16], [16, 16, 16]] \text{ and } [[1, 1, 1, 3, 12, 12, 30], [20, 20, 20], [20, 20, 20]].$$

By [28, Proposition VI.2 (e)] citing [6], the *modularization* of their neutral component would be of type

$$[1, 1, 1, 1, 2, 2, 2, 4, 4, 4, 8, 8, 8] \text{ and } [1, 1, 1, 1, 4, 4, 4, 4, 4, 10, 10, 10],$$

both of rank 13, where the first admits no modular partition, and the second is 2. (excluded).

## 10. STRONGER ARITHMETIC CONSTRAINTS

In this section, we will first prove some arithmetic constraints on the rank of the Drinfeld center of  $\text{Rep}(G)$ , for any finite group  $G$ . Then, we will discuss how far they can be generalized to any integral modular fusion categories.

**10.1. Rank of  $\mathcal{Z}(\text{Rep}(G))$ .** This subsection is inspired from discussions with Geoff Robinson and Dave Benson in [36, 37]. The goal is to simplify the group theoretic way to express the rank of  $\mathcal{Z}(\text{Rep}(G))$ , for any finite group  $G$ , and to provide some bounds involving the prime divisors of  $|G|$ . Consequently, this class of integral modular fusion categories satisfies Conjectures 10.8 and 10.11. We will adopt the following notations throughout our discussion:

- $Z(G)$  denotes the center of  $G$ ,
- $\Gamma_G$  represents a complete set of conjugacy class representatives,
- $c_G$  is the rank of  $\text{Rep}(G)$ , corresponding to the total number of conjugacy classes, so  $|\Gamma_G|$ ,
- $r_G$  refers to the rank of  $\mathcal{Z}(\text{Rep}(G))$ .

**Lemma 10.1.** *Let  $G$  be a finite group. Then*

$$(1) \quad r_G = \sum_{a \in \Gamma_G} c_{C_G(a)}.$$

*Proof.* According to [12] or [26, Section 3], the rank  $r_G$  is determined by the number of irreducible characters within the centralizers of class representatives of  $G$ , which is precisely the equality (1).  $\square$

Let us simplify how to express the rank  $r_G$ .

**Lemma 10.2.** *The rank  $r_G$  is the number of conjugacy classes of pairs of commuting elements of  $G$ , i.e. the cardinality of the set*

$$A_G := \{c(a_1, a_2) \mid a_1, a_2 \in G \text{ with } a_1 a_2 = a_2 a_1\},$$

where

$$c(a_1, a_2) := \{(ga_1 g^{-1}, ga_2 g^{-1}) \mid g \in G\}.$$

*Proof.* By the equality in Lemma 10.4, it suffices to establish a bijection between the set  $A_G$  and the set

$$B_G := \{(a, \beta) \mid a \in \Gamma_G \text{ and } \beta \text{ is a conjugacy class within } C_G(a)\}.$$

Given  $c(a_1, a_2) \in A_G$ , we associate the element  $(a_1, \{ha_2h^{-1} \mid h \in C_G(a_1)\}) \in B_G$ . We merely need to confirm that if  $a_1 = ga_1g^{-1}$ , then  $a_2$  and  $ga_2g^{-1}$  are conjugates in  $C_G(a_1)$ , which is apparent since  $a_1 = ga_1g^{-1}$  means that  $g \in C_G(a_1)$ . Given  $(a, \beta) \in B_G$ , we associate the element  $c(a, b) \in A_G$ , where  $b \in \beta$ . We only need to verify that if  $b' \in \beta$ , then  $c(a, b') = c(a, b)$ . Note that  $b' = h b h^{-1}$ , where  $h \in C_G(a)$ . Therefore,  $c(a, b) = c(h a h^{-1}, h b h^{-1}) = c(a, b')$  because  $h a h^{-1} = a$ , given that  $h \in C_G(a)$ .  $\square$

Recall that a prime  $p$  divides  $\text{FPdim}(\mathcal{Z}(\text{Rep}(G))) = |G|^2$  if and only if it divides  $|G|$ .

**Proposition 10.3.** *Let  $G$  be a finite group. For every prime  $p$  dividing  $|G|$ , then  $r_G \geq p$ .*

*Proof.* This proof is due to Dave Benson. The pair of commuting elements  $(g, g^i)$  for  $1 \leq i \leq \text{ord}(g)$  are all in distinct conjugacy classes, so by Lemma 10.2,  $r_G \geq \text{ord}(g)$  for all  $g$  in  $G$ . By Cauchy's theorem, there is an element of order  $p$  dividing  $|G|$ . Thus,  $r_G \geq p$ .  $\square$

The number of conjugacy classes of pairs of commuting elements in the alternating group  $A_n$  is 1, 1, 9, 14, 22, 44, 74 for  $n = 1, \dots, 7$ , respectively, see [38].

**Lemma 10.4.** *Let  $G$  be a finite group. Then*

$$(2) \quad r_G \geq |Z(G)|c_G + \sum_{g \in \Gamma_G \setminus Z(G)} \text{ord}(g),$$

$$(3) \quad r_G \geq \sum_{g \in \Gamma_G} \text{ord}(g).$$

*Proof.* In general, we have

$$(4) \quad c_{C_G(a)} \geq |Z(C_G(a))| \geq \text{ord}(a)$$

but if  $a \in Z(G)$  then  $C_G(a) = G$  and so  $c_{C_G(a)} = c_G$ . The inequalities (2) and (3) follow from (1).  $\square$

**Theorem 10.5.** *Let  $G$  be a finite group. For every prime  $p$  dividing  $|G|$ , then  $r_G \geq 2p$ .*

*Proof.* By Cauchy's theorem, there is an element  $g$  of order  $p$ . If  $p = 2$  then  $r_G \geq 3$  by (3). So if  $r_G \leq 3$ , then  $r_G = 3$  and  $|\Gamma_G| = 2$  by (3), thus  $G = C_2$ , contradiction. So  $r_G \geq 4 = 2p$ .

Therefore, we can assume that  $p$  is odd. If  $g^2$  is not in the conjugacy class of  $g$  then, by (1) and (4),

$$r_G \geq c_{C_G(g)} + c_{C_G(g^2)} \geq |Z(C_G(g))| + |Z(C_G(g^2))| \geq 2p,$$

because  $x \in Z(C_G(x))$  and  $\text{ord}(g^2) = p$ , as  $p$  is odd. Thus, we can assume the existence of  $h$  in  $G$  such that  $hgh^{-1} = g^2$ , but then  $h^ngh^{-n} = g^{2^n}$ . Fermat's little theorem states that  $2^{p-1} \equiv 1 \pmod{p}$ , and the multiplicative group  $(\mathbb{Z}/p\mathbb{Z})^\times$  is cyclic of order  $p-1$ . So  $h^ngh^{-n} = g$  for  $n = p-1$ , and  $\{h^ngh^{-n} \mid n = 1, \dots, p-1\} = \langle g \rangle \setminus \{e\}$ . Thus  $p-1$  divides  $\text{ord}(h)$ . But  $g$  and  $h$  have different order, so cannot be in the same conjugacy class, so by (3),  $r_G \geq \text{ord}(e) + \text{ord}(g) + \text{ord}(h) \geq 1 + p + p-1 = 2p$ .  $\square$

The equality  $r_G = 2p$  is realized by  $(G, p) = (C_2, 2)$ . Out of this example, we can get even better:

**Theorem 10.6.** *Let  $G$  be a finite group. For every prime  $p$  dividing  $|G|$ , then  $r_G \geq 3p-1 - \delta_{G, C_2}$ .*

*Proof.* If  $G$  is Abelian then  $r_G = |G|^2$  by (2), so  $r_G < 3p-1$  implies  $G = C_2$ , and  $r_G = 4 = 3p-2$ . The non-Abelian case (by far harder) is due to Geoff Robinson in its answer in [37].  $\square$

The equality  $r_G = 3p-1$  is realized by  $(G, p) = (S_3, 3)$ . We can expect even better in the non-solvable case:

**Conjecture 10.7.** *For every non-solvable finite group  $G$ , and for every prime  $p$  dividing the order of  $G$ , the inequality  $r_G \geq 5p-3$  holds.*

This has been verified for all non-solvable groups of order less than 1920 and for all non-Abelian finite simple groups of order less than  $10^8$ . The equality is achieved for  $G = A_5$  and  $\text{PSL}(2, 7)$ . Geoff has shown that  $r \geq 5p-1$  for any non-solvable groups without a self-centralizing Sylow  $p$ -subgroup of order  $p$ , where  $p$  the largest prime factor of  $|G|$ .

**10.2. Integral modular fusion categories.** Referring to the notations used previously, recall that Theorem 1.1 asserts that  $p \leq 2r + 1$ , which is enhanced for the integral case by Theorem 8.2 to  $p \leq 2m + 1$ , and also consult Theorem 8.4 for a more robust version. Now, let's explore the extent to which the arithmetic constraints discussed in §10.1 can be applied to integral modular fusion categories. The subsequent conjecture aims to expand upon Proposition 10.3.

**Conjecture 10.8.** *For any prime number  $p$  that divides the global dimension of a integral modular fusion category with rank  $r$ , then  $p \leq r$ .*

**Proposition 10.9.** *The statement of Conjecture 10.8 is true up to rank 21.*

*Proof.* The proof largely relies on computer assistance. The script detailed in §4.2 can be adapted to focus on types that comply with Theorem 8.4 yet contradict Conjecture 10.8, see in [2]. Consequently, we identified exactly 187 potential types up to rank 21, as listed in `ListUpToRank21SomePrimeAboveRank.txt` in [39]. Specifically, we found none up to rank 13, and then 1, 4, 22, 2, 28, 0, 8, 122 types at ranks 14 through 21, respectively. Of these, only 81 types pass `GcdCriterion` from §5.2. Following this, 75 types pass `TypeTest` from §5.3, and then 40 types pass `LocalCriterion` from §5.4, with a time limit of one second per type. This leaves 12 non-perfect types and 28 perfect types. Among these, only two non-perfect types pass `AllCriterion` from §8.1. The remaining  $2 + 28$  types are ultimately excluded by our fusion ring solver's partition version in §6.4, limited to one second per type, except one that required ten seconds. The detailed computational data is accessible in `InvestigationUpToRank21SomePrimeAboveRank.txt` in [39].  $\square$

**Remark 10.10.** *The extension of Proposition 10.9 to rank 22 is in progress. About the rank 23, we can reduce to the following type of  $\text{FPdim} = 2^{43}3^85^429^2$  which requires deeper examination:*

$$[[1, 1], [540, 1], [725, 1], [1450, 1], [2610, 1], [3132, 1], [8100, 1], [26100, 1], [58725, 14], [78300, 1]].$$

If Conjecture 10.8 is true then it is optimal as demonstrated by the pointed examples of prime rank. Thus, we could expect better for the non-pointed case. The following conjecture generalizes Theorem 10.5.

**Conjecture 10.11.** *For any prime number  $p$  that divides the global dimension of a non-pointed integral modular fusion category with rank  $r$ , then  $p \leq r/2$ .*

**Proposition 10.12.** *The statement of Conjecture 10.11 is true up to rank 15.*

*Proof.* As for Proposition 10.9, the proof is mainly computer-assisted, but computationally a bit harder, and the last remaining type is excluded by hand. We started from 3094 non-pointed types up to rank 15 satisfying Theorem 8.4 but contradicting Conjecture 10.11, via Egyptian fraction (with squared denominators) classification, available in `ListUpToRank15SomePrimeAboveHalfRank.txt`. We found none up to rank 8, and then 6, 36, 250, 2266, 45, 491 types at ranks 9 through 15, respectively. The irregularity between rank 13 and rank 14 comes the fact that if  $p > 14/2 = 7$ , then  $p \geq 11$  because 9 is not prime. Of these, only 2336 types pass `GcdCriterion` from §5.2. Following this, 1688 types pass `TypeTest` from §5.3, and then 1256 types pass `LocalCriterion` from §5.4, with a time limit of one second per type. This leaves 362 non-perfect types and 894 perfect types. Among these, only 33 non-perfect types pass `AllCriterion` from §8.1. The use of our fusion ring solver's partition version from §6.4, limited to one second per type, reduced these  $894 + 33$  remaining types to just 20 types, then 17 ones with 10 seconds per types, then 10 ones with 100 seconds per type, and finally 8 ones with 1000 seconds per type. Next, we applied our full fusion ring solver's partition version from §6.3, requiring to specified the duality, so our 8 types becomes 120 cases, we simplified with the commutativity option. After the first round limited to 10 seconds per case, there remain 23 cases from 5 types, then with 100 seconds per case, 15 cases from the following 3 types:

- $[1, 1, 2, 12, 12, 14, 14, 14, 21, 21, 42, 42, 42]$ ,
- $[1, 70, 75, 150, 168, 175, 350, 525, 1400, 1400, 2100, 2100, 2100]$ ,
- $[1, 105, 175, 182, 300, 390, 3900, 6825, 9100, 9100, 9100, 9100, 9100, 13650]$ .

All the cases from the two perfect types were excluded by a round with 30 minutes per case. The non-perfect one is excluded theoretically as follows: its modular partition must be

$$[[1, 1, 2, 12, 12, 14, 14, 14, 21, 21, 42], [42, 42]]$$

and the neutral part has  $\text{FPdim} = 2^33^27^2$ , the modularization of the neutral part must have a pointed part of size 3, and to keep it half-Frobenius, it should split every multiple of 4, so we get the types:  $[1, 1, 1, 6, 6, 6, 6, 7, 7, 14, 21, 21, 21]$  or  $[1, 1, 1, 6, 6, 6, 6, 7, 7, 7, 7, 7, 21, 21, 21]$ . The first has no modular partition, and the second, only

$$[[1, 1, 1, 6, 6, 6, 6, 21], [7, 7, 7, 21], [7, 7, 7, 21]].$$

The neutral component has  $\text{FPdim} = 2^23^17^2$ , so the modularisation should split the multiple of 3, and we get the type  $[[1, 1], [2, 12], [7, 3]]$  of  $\text{FPdim} = 2^27^2$ , so non-trivial perfect and solvable, contradiction with [18, Proposition 4.5 (iv)].

The detailed computational data is accessible in `InvestigationUpToRank15SomePrimeAboveHalfRank.txt` in [39].  $\square$

With our current knowledge, it would not be reasonable to conjecture a generalization of Theorem 10.6 suggesting that  $p \leq (r+1)/3$  in the non-pointed case, or of Conjecture 10.7 suggesting that  $p \leq (r+3)/5$  in the non-solvable case. But it makes sense to explore in this direction.

**Question 10.13.** *Is it true that for any prime number  $p$  dividing the global dimension of a non-solvable integral modular fusion category with rank  $r$ , the inequality  $p \leq (r+3)/5$  holds?*

The following proposition is related to Question 7.1.

**Proposition 10.14.** *An affirmative response to Question 10.13 would indicate that the minimum rank required for a non-trivial perfect integral modular fusion category is 22.*

*Proof.* By [18, Proposition 4.5 (iv)], a non-trivial perfect integral fusion category  $\mathcal{C}$  is non-solvable. Thus by [18, Theorem 1.6],  $\text{FPdim}(\mathcal{C})$  must have at least three distinct prime factors, so there must be a prime factor  $p \geq 5$ . Assume that  $\mathcal{C}$  is modular of rank  $r$ , then an affirmative response to Question 10.13 implies that  $r \geq 5p - 3 \geq 22$ . Finally, the bound is realized by  $\mathcal{Z}(\text{Rep}(A_5))$  having rank 22.  $\square$

Here is what we can deduce in the perfect integral case:

**Corollary 10.15.** *For any prime number  $p$  that divides the global dimension of a non-trivial perfect integral modular fusion category with rank  $r$ , then  $p \leq 2r - 5$ .*

*Proof.* By Theorem 5.1, the number of distinct basic FPdims is at least 4. Let  $p$  be the biggest prime divisor of the global dimension, then by Theorem 8.2, there is a basic FPdim of multiplicity  $m \geq (p-1)/2$ . Thus  $r \geq m+3 = (p+5)/2$ . The result follows.  $\square$

**10.3. Simple Rank 14.** There remain 46 open types for the simple rank 14 case. The set of prime divisors of their FPdim is always  $\{2, 3, 5, 7\}$ , i.e. their FPdim is always of the form  $2^a 3^b 5^c 7^d$  with  $abcd$  nonzero.

## 11. THE ODD-DIMENSIONAL CASE

For an overview of the current state of knowledge on odd-dimensional modular fusion categories, we refer the reader to [13, 14]. A foundational result in this area establishes that an odd-dimensional modular fusion category  $\mathcal{C}$  is equivalent to being maximally non self-dual (MNSD), meaning that its only self-dual simple object is the unit object. Let  $(d_i)_{i \in I}$  represent the FPdim of the simple objects in  $\mathcal{C}$ , considered up to isomorphism. Since  $d_i^2$  is a divisor of the odd  $\text{FPdim}(\mathcal{C})$ , each  $d_i$  must be odd. Furthermore, the equation  $\sum_{i \in I} d_i^2 = \text{FPdim}(\mathcal{C})$  implies that the rank  $r = |I|$  must also be odd. This reduces our investigation to Egyptian fractions of the form  $q = \sum_{i=1}^r \frac{1}{s_i^2}$ , where  $q, r, s_i \in \mathbb{Z}_{\geq 1}$ ,  $s_1 \geq \dots \geq s_r \geq 1$ , and both  $r$  and  $s_i$  are odd. Additionally,  $s_i$  divides  $s_1$  for all  $i$ , and  $s_{2k} = s_{2k+1}$ . This yields the expression

$$q = \frac{1}{s_1^2} + \sum_{k=1}^{(r-1)/2} \frac{2}{s_{2k}^2}.$$

Since each  $s_i$  is odd, we have  $s_i^2 \equiv 1 \pmod{8}$ , which implies  $q \equiv r \pmod{8}$  and that  $q$  is odd as well. Utilizing a similar technique as in §4, we can assume  $s_i > 1$  (hence  $s_i \geq 3$ ), by completing the classification with additional 1s if necessary. Consequently, we can assume  $q \leq r/9$ . For  $r < 27$ , this allows us to deduce that  $q = 1$ , and therefore  $r \equiv 1 \pmod{8}$ , which narrows the possibilities for  $r$  to 1, 9, 17, 25 (up to completing by 1s).

**Remark 11.1.** *This strategy can be extended. For instance, by adding eighteen 3s to complete the classification, we may assume that  $s_i = 5$  for  $i + 16 \leq r$ , which leads to  $q \leq 16/9 + (r-16)/25$ . If  $r < 47$  (which becomes 51 because  $q \equiv r \pmod{8}$ ), we can assume that  $q = 1$ . However, this extended strategy will not be applied in this paper.*

Consequently, for all  $r < 25$ , we have compiled the following list of all possible non-pointed types (as for §4):

- $[[1, 9], [3, 8], [9, 2a]],$
- $[[1, 7], [3, 2], [5, 8], [15, 2a]],$
- $[[1, 3], [3, 8], [5, 6], [15, 2a]],$
- $[[1, 1], [3, 2], [7, 2], [9, 4], [21, 8], [63, 2a]],$
- $[[1, 1], [9, 4], [25, 2], [45, 2], [75, 8], [225, 2a]],$

where  $a \geq 0$  represents the number of 1s added for completion. It is noteworthy that these ranks are  $17 + 2a$ , which corroborates a result from [13] stating that any odd-dimensional modular fusion category with rank less than 17 is pointed. Further, [13, Remark 4.3] states that any perfect odd-dimensional modular fusion category is a Deligne product of simple ones. From the preceding analysis, a non-pointed one must have a rank of at least 17, meaning a perfect non-simple one must have a rank of at least 289 ( $= 17^2$ ). Therefore, a perfect one with a rank less than 289 must be simple and cannot have non-trivial simple objects of prime-power FPdim, as shown in [33, Corollary 6.16]. Consequently, the previously mentioned perfect types are excluded. It follows that:

**Theorem 11.2.** *Every perfect odd-dimensional modular fusion category of rank less than 25 is trivial, and so everyone of rank less than 625 ( $= 25^2$ ) is simple.*

### Proof of Theorem 1.10

*Proof.* By Theorem 11.2, there remain to address the non-perfect types above. Their rank is always  $17 + 2a < 25$ , which implies  $a < 4$ . As outlined in §8.1, the modular grading results in a partition indexed by the pointed part, with each component having the same FPdim, in particular the FPdim of the pointed part divides the global FPdim.

- First, let's examine the type  $[[1, 9], [3, 8], [9, 2a]]$ . The FPdim for this type is  $81(1 + 2a)$ . Consequently, each partition component must have FPdim  $= 9(1 + 2a)$ . If  $a > 0$ , a component with 9 must have FPdim  $\geq 81$ . This leads to  $81 \leq 9(1 + 2a)$ , resulting in  $a \geq 4$ , contradiction. Thus,  $a = 0$ . The modular partition must be

$$[[1, 1, 1, 1, 1, 1, 1, 1, 1], [3], [3], [3], [3], [3], [3], [3], [3]],$$

which contradicts Theorem 8.1 (1).

- Regarding the second type  $[[1, 7], [3, 2], [5, 8], [15, 2a]]$ , the FPdim of the pointed part equaling 7 is not a divisor of the global FPdim  $= 225(1 + 2a)$ , for  $0 \leq a < 4$ , except  $a = 3$ . Therefore, each partition component must have FPdim  $= 225(1 + 2 \times 3)/7 = 225 = 15^2$ , so the modular partition must be

$$[[1, 1, 1, 1, 1, 1, 1, 3, 3, 5, 5, 5, 5, 5, 5, 5], [15], [15], [15], [15], [15], [15]],$$

which contradicts Theorem 8.1 (1).

- Lastly, consider the third type  $[[1, 3], [3, 8], [5, 6], [15, 2a]]$ . If  $a = 1$  then the modular partition must be

$$[[1, 1, 1, 3, 3, 3, 3, 3, 3, 3, 3, 5, 5, 5, 5, 5], [15], [15]],$$

which contradicts Theorem 8.1 (1). If  $a = 2$ , then there is no modular partition. If  $a = 3$ , then the global FPdim  $= 3^2 5^2 7$ , but its powerless prime factor  $p = 7$  does not divide  $\text{FPdim}(\mathcal{C}_{pt}) = 3$ , contradicting [11, Theorem 1.17]. Alternatively, see Remark 11.3. Hence,  $a = 0$ . Following this, applying the fusion ring solver outlined in §6.3 to the type  $[[1, 3], [3, 8], [5, 6]]$  yields two fusion rings. Applying `STmatrix2` to these fusion rings provides 3 modular data, detailed in §13.  $\square$

**Remark 11.3.** *Here is an alternative proof for the case  $a = 3$  in the last item above. The neutral component  $\mathcal{C}_e$  must be of type  $[[1, 3], [3, 8], [15, 2]]$  and  $\text{FPdim} = 3^{15} 5^2 7$ , so its modularization  $\mathcal{M}$  would have  $\text{FPdim} = 5^2 7$ , hence cannot have basic FPdim  $= 3$ , thus must be of type  $[[1, 25], [5, 6]]$ , but each component of the modular partition (for  $\mathcal{M}$ ) would have FPdim  $= 7$ , and so  $5^2 \leq 7$ , contradiction.*

**Remark 11.4.** *As highlighted in Remark 1.11, potential gaps have been identified in the literature:*

- (1) In [3, Theorem 4.2, proof of Case (viii)  $\text{FPdim}(\mathcal{C}_{pt}) = p$ ], on page 727, the assertion that the anomaly-freeness (as defined in their reference [16], see Definition 11.5) necessarily leads to  $p_+ = pq$  is incorrect, see Lemma 11.6, it may also be  $-pq$ , as for the MD described in §13, thus also allowing  $p|(q + 1)$ .
- (2) In [13, Theorem 6.3 (b), proof of Case  $|\mathcal{G}(\mathcal{C})| = 3$ ], on page 1936, the deduction “Hence  $l \leq 24$ ” in the seventh last line is accurate, except when  $c_{X_1} = 1$ , which permits  $l = 5$ , thereby accommodating the type  $[[1, 3], [3, 8], [5, 6]]$ .

**Definition 11.5.** *A modular data is called anomaly-free if its Gauss sums are equal ( $p_+ = p_-$ ), see Definition 2.11.*

**Lemma 11.6.** *A modular data is anomaly-free if and only if  $p_+ = \pm\sqrt{\dim}$ , if and only if the central charge  $c \in \{0, 4\}$ .*

*Proof.* Recall from Definition 2.11 that  $p_{\pm} := \sum_{i=1}^r d_i^2(\theta_i)^{\pm 1}$ . Thus  $p_+$  and  $p_-$  are complex-conjugate. So anomaly-free is equivalent to  $p_+$  real. Now,  $p_+ = \sqrt{\dim} \zeta_8^c$ , thus it is real if and only if  $\zeta_8^c = \pm 1$ , if and only if  $c = 0$  or 4.  $\square$

**Remark 11.7.** *Regarding the categorification of a MD in §13, as a modular fusion category  $\mathcal{C}$ , a discussion with Sebastian Burciu revealed that the adjoint fusion subring, which is of rank 11, FPdim 75, type  $[[1, 3], [3, 8]]$ , and basis  $\{b_g\}_{g \in C_3} \cup \{x_i, x_i^*\}_{i \in \{1, 2, 3, 4\}}$ , is isomorphic to  $\text{ch}(G)$ , where  $G = C_5^2 \rtimes C_3$  is the unique non-Abelian finite group of order 75. In fact, the application §6.3 shows a unique MNSD cyclotomic fusion ring of this type. Furthermore, the braided adjoint fusion subcategory  $\mathcal{D} = \mathcal{C}_{ad}$  would not be symmetric, as indicated by the  $S$ -matrix mentioned in §13. In*



- $$\begin{bmatrix} 1 & 1 & 2 & 2 & 2 & 2 & 3 & 3 \\ 1 & 1 & 2 & 2 & 2 & 2 & -3 & -3 \\ 2 & 2 & 2\zeta_9^4 + 2\zeta_9^5 & 2\zeta_9^2 + 2\zeta_9^7 & -2 & 2\zeta_9 + 2\zeta_9^8 & 0 & 0 \\ 2 & 2 & 2\zeta_9^2 + 2\zeta_9^7 & 2\zeta_9 + 2\zeta_9^8 & -2 & 2\zeta_9^4 + 2\zeta_9^5 & 0 & 0 \\ 2 & 2 & -2 & -2 & 4 & -2 & 0 & 0 \\ 2 & 2 & 2\zeta_9 + 2\zeta_9^8 & 2\zeta_9^4 + 2\zeta_9^5 & -2 & 2\zeta_9^2 + 2\zeta_9^7 & 0 & 0 \\ 3 & -3 & 0 & 0 & 0 & 0 & 3 & -3 \\ 3 & -3 & 0 & 0 & 0 & 0 & -3 & 3 \end{bmatrix},$$

- $$\begin{bmatrix} 1 & 1 & 2 & 2 & 2 & 2 & 3 & 3 \\ 1 & 1 & 2 & 2 & 2 & 2 & -3 & -3 \\ 2 & 2 & 2\zeta_9 + 2\zeta_9^8 & 2\zeta_9^4 + 2\zeta_9^5 & -2 & 2\zeta_9^2 + 2\zeta_9^7 & 0 & 0 \\ 2 & 2 & 2\zeta_9^4 + 2\zeta_9^5 & 2\zeta_9^2 + 2\zeta_9^7 & -2 & 2\zeta_9 + 2\zeta_9^8 & 0 & 0 \\ 2 & 2 & -2 & -2 & 4 & -2 & 0 & 0 \\ 2 & 2 & 2\zeta_9^2 + 2\zeta_9^7 & 2\zeta_9 + 2\zeta_9^8 & -2 & 2\zeta_9^4 + 2\zeta_9^5 & 0 & 0 \\ 3 & -3 & 0 & 0 & 0 & 0 & 3 & -3 \\ 3 & -3 & 0 & 0 & 0 & 0 & -3 & 3 \end{bmatrix},$$

- $$\begin{bmatrix} 1 & 1 & 2 & 2 & 2 & 2 & 3 & 3 \\ 1 & 1 & 2 & 2 & 2 & 2 & -3 & -3 \\ 2 & 2 & 2\zeta_9^4 + 2\zeta_9^5 & 2\zeta_9^2 + 2\zeta_9^7 & -2 & 2\zeta_9 + 2\zeta_9^8 & 0 & 0 \\ 2 & 2 & 2\zeta_9^2 + 2\zeta_9^7 & 2\zeta_9 + 2\zeta_9^8 & -2 & 2\zeta_9^4 + 2\zeta_9^5 & 0 & 0 \\ 2 & 2 & -2 & -2 & 4 & -2 & 0 & 0 \\ 2 & 2 & 2\zeta_9 + 2\zeta_9^8 & 2\zeta_9^4 + 2\zeta_9^5 & -2 & 2\zeta_9^2 + 2\zeta_9^7 & 0 & 0 \\ 3 & -3 & 0 & 0 & 0 & 0 & -3 & 3 \\ 3 & -3 & 0 & 0 & 0 & 0 & 3 & -3 \end{bmatrix},$$

- $$\begin{bmatrix} 1 & 1 & 2 & 2 & 2 & 2 & 3 & 3 \\ 1 & 1 & 2 & 2 & 2 & 2 & -3 & -3 \\ 2 & 2 & 2\zeta_9 + 2\zeta_9^8 & 2\zeta_9^4 + 2\zeta_9^5 & -2 & 2\zeta_9^2 + 2\zeta_9^7 & 0 & 0 \\ 2 & 2 & 2\zeta_9^4 + 2\zeta_9^5 & 2\zeta_9^2 + 2\zeta_9^7 & -2 & 2\zeta_9 + 2\zeta_9^8 & 0 & 0 \\ 2 & 2 & -2 & -2 & 4 & -2 & 0 & 0 \\ 2 & 2 & 2\zeta_9^2 + 2\zeta_9^7 & 2\zeta_9 + 2\zeta_9^8 & -2 & 2\zeta_9^4 + 2\zeta_9^5 & 0 & 0 \\ 3 & -3 & 0 & 0 & 0 & 0 & -3 & 3 \\ 3 & -3 & 0 & 0 & 0 & 0 & 3 & -3 \end{bmatrix}$$

[illegible]

- $$\begin{bmatrix} 1 & 1 & 2 & 2 & 2 & 2 & 3 & 3 \\ 1 & 1 & 2 & 2 & 2 & 2 & -3 & -3 \\ 2 & 2 & -2 & 4 & -2 & -2 & 0 & 0 \\ 2 & 2 & 4 & -2 & -2 & -2 & 0 & 0 \\ 2 & 2 & -2 & -2 & 4 & -2 & 0 & 0 \\ 2 & 2 & -2 & -2 & -2 & 4 & 0 & 0 \\ 3 & -3 & 0 & 0 & 0 & 0 & 3 & -3 \\ 3 & -3 & 0 & 0 & 0 & 0 & -3 & 3 \end{bmatrix}$$

- $$\begin{bmatrix} 1 & 1 & 2 & 2 & 2 & 2 & 3 & 3 \\ 1 & 1 & 2 & 2 & 2 & 2 & -3 & -3 \\ 2 & 2 & -2 & 4 & -2 & -2 & 0 & 0 \\ 2 & 2 & 4 & -2 & -2 & -2 & 0 & 0 \\ 2 & 2 & -2 & -2 & -2 & 4 & 0 & 0 \\ 2 & 2 & -2 & -2 & 4 & -2 & 0 & 0 \\ 3 & -3 & 0 & 0 & 0 & 0 & -3 & 3 \\ 3 & -3 & 0 & 0 & 0 & 0 & 3 & -3 \end{bmatrix}$$

- $[0, 0, -1/3, 1/3, 0, 0, -1/4, 1/4], 1, 12, 0, [1, 1, 1, 1, 1, 1, -1, -1].$

$$\begin{bmatrix} 1 & 1 & 2 & 2 & 2 & 2 & 3 & 3 \\ 1 & 1 & 2 & 2 & 2 & 2 & -3 & -3 \\ 2 & 2 & -2 & 4 & -2 & -2 & 0 & 0 \\ 2 & 2 & 4 & -2 & -2 & -2 & 0 & 0 \\ 2 & 2 & -2 & -2 & 4 & -2 & 0 & 0 \\ 2 & 2 & -2 & -2 & -2 & 4 & 0 & 0 \\ 3 & -3 & 0 & 0 & 0 & 0 & -3 & 3 \\ 3 & -3 & 0 & 0 & 0 & 0 & 3 & -3 \end{bmatrix}$$

- $[0, 0, -1/3, -1/3, 1/3, 1/3, -1/4, 1/4], 1, 12, 4, [1, 1, 1, 1, 1, 1, 1, 1],$

$$\begin{bmatrix} 1 & 1 & 2 & 2 & 2 & 2 & 3 & 3 \\ 1 & 1 & 2 & 2 & 2 & 2 & -3 & -3 \\ 2 & 2 & -2 & 4 & -2 & -2 & 0 & 0 \\ 2 & 2 & 4 & -2 & -2 & -2 & 0 & 0 \\ 2 & 2 & -2 & -2 & -2 & 4 & 0 & 0 \\ 2 & 2 & -2 & -2 & 4 & -2 & 0 & 0 \\ 3 & -3 & 0 & 0 & 0 & 0 & 3 & -3 \\ 3 & -3 & 0 & 0 & 0 & 0 & -3 & 3 \end{bmatrix}$$

12.1.3. *Rank 10, type  $[1, 1, 1, 2, 2, 2, 2, 2, 2, 3]$ , first fusion ring.*

[illegible]

- $[0, 0, 0, 1/9, 4/9, -2/9, -2/9, 4/9, 1/9, 1/2], 9, 18, 4, [1, 0, 0, 0, 0, 0, 0, 0, 0, 1].$

|   |              |              |                           |                           |                           |                           |                           |                           |    |
|---|--------------|--------------|---------------------------|---------------------------|---------------------------|---------------------------|---------------------------|---------------------------|----|
| 1 | 1            | 1            | 2                         | 2                         | 2                         | 2                         | 2                         | 2                         | 3  |
| 1 | 1            | 1            | $2\zeta_3^2$              | $2\zeta_3$                | $2\zeta_3$                | $2\zeta_3^2$              | $2\zeta_3^2$              | $2\zeta_3$                | 3  |
| 1 | 1            | 1            | $2\zeta_3$                | $2\zeta_3^2$              | $2\zeta_3^2$              | $2\zeta_3$                | $2\zeta_3$                | $2\zeta_3^2$              | 3  |
| 2 | $2\zeta_3^2$ | $2\zeta_3$   | $-2\zeta_9^7$             | $-2\zeta_9^5$             | $2\zeta_9^2 + 2\zeta_9^5$ | $2\zeta_9^4 + 2\zeta_9^7$ | $-2\zeta_9^4$             | $-2\zeta_9^2$             | 0  |
| 2 | $2\zeta_3$   | $2\zeta_3^2$ | $-2\zeta_9^5$             | $2\zeta_9^4 + 2\zeta_9^7$ | $-2\zeta_9^7$             | $-2\zeta_9^2$             | $2\zeta_9^2 + 2\zeta_9^5$ | $-2\zeta_9^4$             | 0  |
| 2 | $2\zeta_3$   | $2\zeta_3^2$ | $2\zeta_9^2 + 2\zeta_9^5$ | $-2\zeta_9^7$             | $-2\zeta_9^4$             | $-2\zeta_9^5$             | $-2\zeta_9^2$             | $2\zeta_9^4 + 2\zeta_9^7$ | 0  |
| 2 | $2\zeta_3^2$ | $2\zeta_3$   | $2\zeta_9^4 + 2\zeta_9^7$ | $-2\zeta_9^2$             | $-2\zeta_9^5$             | $-2\zeta_9^4$             | $-2\zeta_9^7$             | $2\zeta_9^2 + 2\zeta_9^5$ | 0  |
| 2 | $2\zeta_3^2$ | $2\zeta_3$   | $-2\zeta_9^4$             | $2\zeta_9^2 + 2\zeta_9^5$ | $-2\zeta_9^2$             | $-2\zeta_9^7$             | $2\zeta_9^4 + 2\zeta_9^7$ | $-2\zeta_9^5$             | 0  |
| 2 | $2\zeta_3$   | $2\zeta_3^2$ | $-2\zeta_9^2$             | $-2\zeta_9^4$             | $2\zeta_9^4 + 2\zeta_9^7$ | $2\zeta_9^2 + 2\zeta_9^5$ | $-2\zeta_9^5$             | $-2\zeta_9^7$             | 0  |
| 3 | 3            | 3            | 0                         | 0                         | 0                         | 0                         | 0                         | 0                         | -3 |

- $[0, 0, 0, 2/9, -1/9, -4/9, -4/9, -1/9, 2/9, 1/2], 9, 18, 4, [1, 0, 0, 0, 0, 0, 0, 0, 0, 1],$

|   |              |              |                           |                           |                           |                           |                           |                           |    |
|---|--------------|--------------|---------------------------|---------------------------|---------------------------|---------------------------|---------------------------|---------------------------|----|
| 1 | 1            | 1            | 2                         | 2                         | 2                         | 2                         | 2                         | 2                         | 3  |
| 1 | 1            | 1            | $2\zeta_3$                | $2\zeta_3^2$              | $2\zeta_3^2$              | $2\zeta_3$                | $2\zeta_3$                | $2\zeta_3^2$              | 3  |
| 1 | 1            | 1            | $2\zeta_3^2$              | $2\zeta_3$                | $2\zeta_3$                | $2\zeta_3^2$              | $2\zeta_3^2$              | $2\zeta_3$                | 3  |
| 2 | $2\zeta_3$   | $2\zeta_3^2$ | $-2\zeta_9^5$             | $2\zeta_9^4 + 2\zeta_9^7$ | $-2\zeta_9^7$             | $-2\zeta_9^2$             | $2\zeta_9^2 + 2\zeta_9^5$ | $-2\zeta_9^4$             | 0  |
| 2 | $2\zeta_3^2$ | $2\zeta_3$   | $2\zeta_9^4 + 2\zeta_9^7$ | $-2\zeta_9^2$             | $-2\zeta_9^5$             | $-2\zeta_9^4$             | $-2\zeta_9^7$             | $2\zeta_9^2 + 2\zeta_9^5$ | 0  |
| 2 | $2\zeta_3^2$ | $2\zeta_3$   | $-2\zeta_9^7$             | $-2\zeta_9^5$             | $2\zeta_9^2 + 2\zeta_9^5$ | $2\zeta_9^4 + 2\zeta_9^7$ | $-2\zeta_9^4$             | $-2\zeta_9^2$             | 0  |
| 2 | $2\zeta_3$   | $2\zeta_3^2$ | $-2\zeta_9^2$             | $-2\zeta_9^4$             | $2\zeta_9^4 + 2\zeta_9^7$ | $2\zeta_9^2 + 2\zeta_9^5$ | $-2\zeta_9^5$             | $-2\zeta_9^7$             | 0  |
| 2 | $2\zeta_3$   | $2\zeta_3^2$ | $2\zeta_9^2 + 2\zeta_9^5$ | $-2\zeta_9^7$             | $-2\zeta_9^4$             | $-2\zeta_9^5$             | $-2\zeta_9^2$             | $2\zeta_9^4 + 2\zeta_9^7$ | 0  |
| 2 | $2\zeta_3^2$ | $2\zeta_3$   | $-2\zeta_9^4$             | $2\zeta_9^2 + 2\zeta_9^5$ | $-2\zeta_9^2$             | $-2\zeta_9^7$             | $2\zeta_9^4 + 2\zeta_9^7$ | $-2\zeta_9^5$             | 0  |
| 3 | 3            | 3            | 0                         | 0                         | 0                         | 0                         | 0                         | 0                         | -3 |





- $[0, 0, 0, 0, -5/16, 7/16, -5/16, -1/4, 3/16, -1/16, 3/16], 8, 16, -1, [1, 1, 1, 1, -1, 1, -1, 1, -1, 1, -1],$

$$\begin{bmatrix} 1 & 1 & 1 & 1 & 2 & 2 & 2 & 2 & 2 & 2 & 2 & 2 \\ 1 & 1 & 1 & 1 & -2 & -2 & 2 & 2 & 2 & -2 & -2 \\ 1 & 1 & 1 & 1 & -2 & 2 & -2 & 2 & -2 & 2 & -2 \\ 1 & 1 & 1 & 1 & 2 & -2 & -2 & 2 & -2 & -2 & 2 \\ 2 & -2 & -2 & 2 & -2\zeta_8 + 2\zeta_8^3 & 0 & 0 & 0 & 0 & 0 & 2\zeta_8 - 2\zeta_8^3 \\ 2 & -2 & 2 & -2 & 0 & 2\zeta_8 - 2\zeta_8^3 & 0 & 0 & 0 & -2\zeta_8 + 2\zeta_8^3 & 0 \\ 2 & 2 & -2 & -2 & 0 & 0 & -2\zeta_8 + 2\zeta_8^3 & 0 & 2\zeta_8 - 2\zeta_8^3 & 0 & 0 \\ 2 & 2 & 2 & 2 & 0 & 0 & 0 & -4 & 0 & 0 & 0 \\ 2 & 2 & -2 & -2 & 0 & 0 & 2\zeta_8 - 2\zeta_8^3 & 0 & -2\zeta_8 + 2\zeta_8^3 & 0 & 0 \\ 2 & -2 & 2 & -2 & 0 & -2\zeta_8 + 2\zeta_8^3 & 0 & 0 & 0 & 2\zeta_8 - 2\zeta_8^3 & 0 \\ 2 & -2 & -2 & 2 & 2\zeta_8 - 2\zeta_8^3 & 0 & 0 & 0 & 0 & 0 & -2\zeta_8 + 2\zeta_8^3 \end{bmatrix}$$

- $[0, 0, 0, 0, -5/16, -5/16, -5/16, -1/4, 3/16, 3/16, 3/16], 8, 16, -1, [1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1],$

$$\begin{bmatrix} 1 & 1 & 1 & 1 & 2 & 2 & 2 & 2 & 2 & 2 & 2 \\ 1 & 1 & 1 & 1 & -2 & -2 & 2 & 2 & 2 & -2 & -2 \\ 1 & 1 & 1 & 1 & -2 & 2 & -2 & 2 & -2 & 2 & -2 \\ 1 & 1 & 1 & 1 & 2 & -2 & -2 & 2 & -2 & -2 & 2 \\ 2 & -2 & -2 & 2 & -2\zeta_8 + 2\zeta_8^3 & 0 & 0 & 0 & 0 & 0 & 2\zeta_8 - 2\zeta_8^3 \\ 2 & -2 & 2 & -2 & 0 & -2\zeta_8 + 2\zeta_8^3 & 0 & 0 & 0 & 2\zeta_8 - 2\zeta_8^3 & 0 \\ 2 & 2 & -2 & -2 & 0 & 0 & -2\zeta_8 + 2\zeta_8^3 & 0 & 2\zeta_8 - 2\zeta_8^3 & 0 & 0 \\ 2 & 2 & 2 & 2 & 0 & 0 & 0 & -4 & 0 & 0 & 0 \\ 2 & 2 & -2 & -2 & 0 & 0 & 2\zeta_8 - 2\zeta_8^3 & 0 & -2\zeta_8 + 2\zeta_8^3 & 0 & 0 \\ 2 & -2 & 2 & -2 & 0 & 2\zeta_8 - 2\zeta_8^3 & 0 & 0 & 0 & -2\zeta_8 + 2\zeta_8^3 & 0 \\ 2 & -2 & -2 & 2 & 2\zeta_8 - 2\zeta_8^3 & 0 & 0 & 0 & 0 & 0 & -2\zeta_8 + 2\zeta_8^3 \end{bmatrix}$$

- $[0, 0, 0, 0, -1/16, -1/16, -1/16, -1/4, 7/16, 7/16, 7/16], 8, 16, -1, [1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1],$

$$\begin{bmatrix} 1 & 1 & 1 & 1 & 2 & 2 & 2 & 2 & 2 & 2 & 2 \\ 1 & 1 & 1 & 1 & -2 & -2 & 2 & 2 & 2 & -2 & -2 \\ 1 & 1 & 1 & 1 & -2 & 2 & -2 & 2 & -2 & 2 & -2 \\ 1 & 1 & 1 & 1 & 2 & -2 & -2 & 2 & -2 & -2 & 2 \\ 2 & -2 & -2 & 2 & 2\zeta_8 - 2\zeta_8^3 & 0 & 0 & 0 & 0 & 0 & -2\zeta_8 + 2\zeta_8^3 \\ 2 & -2 & 2 & -2 & 0 & 2\zeta_8 - 2\zeta_8^3 & 0 & 0 & 0 & -2\zeta_8 + 2\zeta_8^3 & 0 \\ 2 & 2 & -2 & -2 & 0 & 0 & 2\zeta_8 - 2\zeta_8^3 & 0 & -2\zeta_8 + 2\zeta_8^3 & 0 & 0 \\ 2 & 2 & 2 & 2 & 0 & 0 & 0 & -4 & 0 & 0 & 0 \\ 2 & 2 & -2 & -2 & 0 & 0 & -2\zeta_8 + 2\zeta_8^3 & 0 & 2\zeta_8 - 2\zeta_8^3 & 0 & 0 \\ 2 & -2 & 2 & -2 & 0 & -2\zeta_8 + 2\zeta_8^3 & 0 & 0 & 0 & 2\zeta_8 - 2\zeta_8^3 & 0 \\ 2 & -2 & -2 & 2 & -2\zeta_8 + 2\zeta_8^3 & 0 & 0 & 0 & 0 & 0 & 2\zeta_8 - 2\zeta_8^3 \end{bmatrix}$$

**12.2. Pointed Modular Data Up To Rank 13.** In light of Remark 1.3, it suffices to specify only the Abelian groups and their corresponding T-matrices, which encapsulate the topological spins in this context. Let us denote by  $C_n$  the cyclic group of order  $n$ . The complete data set, akin to the format presented in §12.1, is available at [39].

- $C_1: [0],$
- $C_2: [0, 1/4], [0, -1/4],$
- $C_3: [0, 1/3, 1/3], [0, -1/3, -1/3],$
- $C_2^2: [0, 1/2, 0, 0], [0, -1/4, 1/4, 0], [0, 1/2, 1/4, 1/4], [0, 1/2, 1/2, 1/2], [0, -1/4, -1/4, 1/2],$
- $C_4: [0, 1/2, 1/8, 1/8], [0, 1/2, 3/8, 3/8], [0, 1/2, -3/8, -3/8], [0, 1/2, -1/8, -1/8],$
- $C_5: [0, 1/5, -1/5, -1/5, 1/5], [0, 2/5, -2/5, -2/5, 2/5],$
- $C_6: [0, -1/4, 1/12, 1/3, 1/3, 1/12], [0, -1/4, 5/12, -1/3, -1/3, 5/12], [0, 1/4, -5/12, 1/3, 1/3, -5/12], [0, 1/4, -1/12, -1/3, -1/3, -1/12],$
- $C_7: [0, 1/7, -3/7, 2/7, 2/7, -3/7, 1/7], [0, 3/7, -2/7, -1/7, -1/7, -2/7, 3/7],$
- $C_2^3: [0, -1/4, 1/4, 1/4, 1/4, 1/2, 0, 0], [0, -1/4, -1/4, -1/4, 1/4, 1/2, 0, 0], [0, -1/4, 1/2, 1/2, 1/4, 1/2, 1/4, 1/4], [0, -1/4, 1/2, -1/4, 1/2, -1/4, 1/2, 1/4],$
- $C_2 \times C_4: [0, 1/2, -1/4, 1/4, 1/8, 3/8, 3/8, 1/8], [0, 1/2, 1/4, -1/4, 1/8, -1/8, -1/8, 1/8], [0, 1/2, -1/4, 1/4, 3/8, -3/8, -3/8, 3/8], [0, 1/2, -1/4, 1/4, -3/8, -1/8, -1/8, -3/8],$
- $C_8: [0, 0, 1/4, -7/16, 1/16, 1/16, -7/16, 1/4], [0, 0, 1/4, -3/16, 5/16, 5/16, -3/16, 1/4], [0, 0, -1/4, -5/16, 3/16, 3/16, -5/16, -1/4], [0, 0, -1/4, -1/16, 7/16, 7/16, -1/16, -1/4],$
- $C_2^4: [0, 0, 0, 1/3, -1/3, -1/3, 1/3, 0, 0], [0, 1/3, 1/3, -1/3, -1/3, -1/3, 1/3, 1/3],$
- $C_9: [0, 0, 1/9, -2/9, 4/9, 4/9, -2/9, 0], [0, 0, 2/9, -4/9, -1/9, -4/9, 2/9, 0],$
- $C_{10}: [0, 1/4, 1/20, -1/5, 1/5, 9/20, 9/20, 1/5, -1/5, 1/20], [0, -1/4, 3/20, 2/5, -2/5, 7/20, 7/20, -2/5, 2/5, 3/20], [0, -1/4, -9/20, -1/5, 1/5, -1/20, -1/20, 1/5, -1/5, -9/20], [0, 1/4, -7/20, 2/5, -2/5, -3/20, -3/20, -2/5, 2/5, -7/20],$

- $C_{11}$ :  $[0, 1/11, 4/11, -2/11, 5/11, 3/11, 3/11, 5/11, -2/11, 4/11, 1/11], [0, 2/11, -3/11, -4/11, -1/11, -5/11, -5/11, -1/11, -4/11, -3/11, 2/11]$ ,
- $C_2 \times C_6$ :  $[0, -1/4, 0, 1/4, -1/3, 5/12, -1/3, -1/12, -1/12, -1/3, 5/12, -1/3], [0, 1/2, -1/4, -1/4, -1/3, 1/6, 5/12, 5/12, 5/12, 5/12, -1/6, -1/3], [0, 1/2, 1/2, 1/2, -1/3, 1/6, 1/6, 1/6, 1/6, 1/6, 1/6, -1/3], [0, 1/2, 1/4, 1/4, -1/3, 1/6, -1/12, -1/12, -1/12, -1/12, 1/6, -1/3], [0, 1/2, 0, 0, -1/3, 1/6, -1/3, -1/3, -1/3, -1/3, 1/6, -1/3], [0, 1/2, 1/2, 1/2, 1/3, -1/6, -1/6, -1/6, -1/6, -1/6, 1/3], [0, 1/4, 1/2, 1/4, 1/3, -5/12, -1/6, -5/12, -5/12, -1/6, -5/12, 1/3], [0, 0, 1/2, 0, 1/3, 1/3, -1/6, 1/3, 1/3, -1/6, 1/3, 1/3], [0, -1/4, 0, 1/4, 1/3, 1/12, 1/3, -5/12, -5/12, 1/3, 1/12, 1/3], [0, -1/4, 1/2, -1/4, 1/3, 1/12, -1/6, 1/12, 1/12, -1/6, 1/12, 1/3]$ ,
- $C_{12}$ :  $[0, 1/2, -1/8, -1/3, 1/6, -11/24, -11/24, -11/24, -11/24, 1/6, -1/3, -1/8], [0, 1/2, -1/8, 1/3, -1/6, 5/24, 5/24, 5/24, -1/6, 1/3, -1/8], [0, 1/2, -3/8, -1/3, 1/6, 7/24, 7/24, 7/24, 7/24, 1/6, -1/3, -3/8], [0, 1/2, -3/8, 1/3, -1/6, -1/24, -1/24, -1/24, -1/24, -1/6, 1/3, -3/8], [0, 1/2, 3/8, -1/3, 1/6, 1/24, 1/24, 1/24, 1/24, 1/6, -1/3, 3/8], [0, 1/2, 3/8, 1/3, -1/6, -7/24, -7/24, -7/24, -7/24, -1/6, 1/3, 3/8], [0, 1/2, 1/8, -1/3, 1/6, -5/24, -5/24, -5/24, -5/24, 1/6, -1/3, 1/8], [0, 1/2, 1/8, 1/3, -1/6, 11/24, 11/24, 11/24, 11/24, -1/6, 1/3, 1/8]$ ,
- $C_{13}$ :  $[0, 1/13, 4/13, -4/13, 3/13, -1/13, -3/13, -3/13, -1/13, 3/13, -4/13, 4/13, 1/13], [0, 2/13, -5/13, 5/13, 6/13, -2/13, -6/13, -6/13, -2/13, 6/13, 5/13, -5/13, 2/13]$ .

### 13. NON-POINTED ODD-DIMENSIONAL MODULAR DATA OF RANK 17

The data are organized as in §12.1. Additionally, it is accessible in a format compatible with computers within the file `Rank17MNSD.txt` in [39]. About their categorification, see Remark 1.11, 11.4 and 11.7.

13.1. **Type  $[[1,3],[3,8],[5,6]]$ , First Fusion Ring.** The whole fusion data would be too big to be entirely displayed here. So here is a compressed version. Consider its basis

$$B = \{b_g\}_{g \in C_3} \cup \{x_i, x_i^*\}_{i \in \{1,2,3,4\}} \cup \{y_g, y_g^*\}_{g \in C_3},$$

where  $\text{FPdim}(b_g) = 1$ ,  $\text{FPdim}(x_i) = 3$  and  $\text{FPdim}(y_g) = 5$ . Here are the fusion rules:

- $b_{g_1} b_{g_2} = b_{g_1 g_2}$ ,  $b_g^* = b_{g^{-1}}$ ,
- $b_g x_i = x_i$ ,
- $b_{g_1} y_{g_2} = y_{g_1 g_2}$ ,
- $x_i x_j$  and  $x_i x_j^* - \delta_{i,j} \sum_{q \in C_3} b_q$  are sum of  $x_k$  or  $x_k^*$ , with multiplicities written below (see also Remark 11.7):

[illegible]

- $x_i y_g = x_i^* y_g = \sum_{g \in C_3} y_g$ ,
- $y_{g_1} y_{g_2} = y_{(g_1 g_2)}^{-1} + 2 \sum_{g_1 g_2 g \neq e} y_g^*$ ,
- $y_{g_1} y_{g_2}^* = b_{g_1 g_2}^{-1} + \sum_i (x_i + x_i^*)$ ,

the other rules follows by commutativity and duality. Now we write the rest of the modular data as in §12.1:

- $[0, 0, 0, -2/5, -2/5, -1/5, -1/5, 1/5, 1/5, 2/5, 2/5, -1/3, -1/3, 0, 0, 1/3, 1/3], 15, 15, 4, [1, 0, \dots, 0],$

|   |              |              |                            |                            |                            |                            |                            |                            |                            |                            |               |               |               |               |               |               |
|---|--------------|--------------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|---------------|---------------|---------------|---------------|---------------|---------------|
| 1 | 1            | 1            | 3                          | 3                          | 3                          | 3                          | 3                          | 3                          | 3                          | 3                          | 5             | 5             | 5             | 5             | 5             | 5             |
| 1 | 1            | 1            | 3                          | 3                          | 3                          | 3                          | 3                          | 3                          | 3                          | 3                          | $5\zeta_3^2$  | $5\zeta_3$    | $5\zeta_3^2$  | $5\zeta_3$    | $5\zeta_3^2$  | $5\zeta_3$    |
| 1 | 1            | 1            | 3                          | 3                          | 3                          | 3                          | 3                          | 3                          | 3                          | 3                          | $5\zeta_3^2$  | $5\zeta_3^2$  | $5\zeta_3$    | $5\zeta_3^2$  | $5\zeta_3$    | $5\zeta_3^2$  |
| 3 | 3            | 3            | $6\zeta_5^3 + 3\zeta_5^4$  | $3\zeta_5 + 6\zeta_5^2$    | $-3\zeta_5^2 - 3\zeta_5^3$ | $-3\zeta_5^2 - 3\zeta_5^3$ | $-3\zeta_5 - 3\zeta_5^4$   | $-3\zeta_5 - 3\zeta_5^4$   | $3\zeta_5^2 + 6\zeta_5^4$  | $6\zeta_5 + 3\zeta_5^3$    | 0             | 0             | 0             | 0             | 0             | 0             |
| 3 | 3            | 3            | $3\zeta_5 + 6\zeta_5^2$    | $6\zeta_5^3 + 3\zeta_5^4$  | $-3\zeta_5^2 - 3\zeta_5^3$ | $-3\zeta_5^2 - 3\zeta_5^3$ | $-3\zeta_5 - 3\zeta_5^4$   | $-3\zeta_5 - 3\zeta_5^4$   | $6\zeta_5 + 3\zeta_5^3$    | $3\zeta_5^3 + 6\zeta_5^4$  | 0             | 0             | 0             | 0             | 0             | 0             |
| 3 | 3            | 3            | $-3\zeta_5^2 - 3\zeta_5^3$ | $-3\zeta_5^2 - 3\zeta_5^3$ | $3\zeta_5^3 + 6\zeta_5^4$  | $6\zeta_5 + 3\zeta_5^3$    | $6\zeta_5^3 + 3\zeta_5^4$  | $3\zeta_5 + 6\zeta_5^2$    | $3\zeta_5 + 6\zeta_5^2$    | $-3\zeta_5 - 3\zeta_5^4$   | 0             | 0             | 0             | 0             | 0             | 0             |
| 3 | 3            | 3            | $-3\zeta_5^2 - 3\zeta_5^3$ | $-3\zeta_5^2 - 3\zeta_5^3$ | $6\zeta_5 + 3\zeta_5^3$    | $3\zeta_5^3 + 6\zeta_5^4$  | $3\zeta_5 + 6\zeta_5^2$    | $6\zeta_5^3 + 3\zeta_5^4$  | $-3\zeta_5 - 3\zeta_5^4$   | $-3\zeta_5 - 3\zeta_5^4$   | 0             | 0             | 0             | 0             | 0             | 0             |
| 3 | 3            | 3            | $-3\zeta_5 - 3\zeta_5^4$   | $-3\zeta_5 - 3\zeta_5^4$   | $6\zeta_5^3 + 3\zeta_5^4$  | $3\zeta_5 + 6\zeta_5^2$    | $6\zeta_5 + 3\zeta_5^3$    | $3\zeta_5^2 + 6\zeta_5^3$  | $-3\zeta_5^2 - 3\zeta_5^3$ | $-3\zeta_5^2 - 3\zeta_5^3$ | 0             | 0             | 0             | 0             | 0             | 0             |
| 3 | 3            | 3            | $-3\zeta_5 - 3\zeta_5^4$   | $-3\zeta_5 - 3\zeta_5^4$   | $3\zeta_5 + 6\zeta_5^2$    | $6\zeta_5^3 + 3\zeta_5^4$  | $3\zeta_5 + 6\zeta_5^2$    | $6\zeta_5^3 + 3\zeta_5^4$  | $-3\zeta_5^2 - 3\zeta_5^3$ | $-3\zeta_5^2 - 3\zeta_5^3$ | 0             | 0             | 0             | 0             | 0             | 0             |
| 3 | 3            | 3            | $3\zeta_5^3 + 6\zeta_5^4$  | $6\zeta_5 + 3\zeta_5^3$    | $-3\zeta_5 - 3\zeta_5^4$   | $-3\zeta_5 - 3\zeta_5^4$   | $-3\zeta_5^2 - 3\zeta_5^3$ | $-3\zeta_5^2 - 3\zeta_5^3$ | $3\zeta_5 + 6\zeta_5^2$    | $6\zeta_5^3 + 3\zeta_5^4$  | 0             | 0             | 0             | 0             | 0             | 0             |
| 3 | 3            | 3            | $6\zeta_5 + 3\zeta_5^3$    | $3\zeta_5^3 + 6\zeta_5^4$  | $-3\zeta_5 - 3\zeta_5^4$   | $-3\zeta_5 - 3\zeta_5^4$   | $-3\zeta_5^2 - 3\zeta_5^3$ | $-3\zeta_5^2 - 3\zeta_5^3$ | $6\zeta_5^3 + 3\zeta_5^4$  | $3\zeta_5 + 6\zeta_5^2$    | 0             | 0             | 0             | 0             | 0             | 0             |
| 5 | $5\zeta_3^2$ | $5\zeta_3$   | 0                          | 0                          | 0                          | 0                          | 0                          | 0                          | 0                          | 0                          | $-5\zeta_3^2$ | $-5\zeta_3$   | $-5\zeta_3$   | $-5\zeta_3^2$ | -5            | -5            |
| 5 | $5\zeta_3$   | $5\zeta_3^2$ | 0                          | 0                          | 0                          | 0                          | 0                          | 0                          | 0                          | 0                          | $-5\zeta_3$   | $-5\zeta_3^2$ | $-5\zeta_3^2$ | $-5\zeta_3$   | -5            | -5            |
| 5 | $5\zeta_3^2$ | $5\zeta_3$   | 0                          | 0                          | 0                          | 0                          | 0                          | 0                          | 0                          | 0                          | $-5\zeta_3$   | $-5\zeta_3^2$ | -5            | -5            | $-5\zeta_3^2$ | $-5\zeta_3$   |
| 5 | $5\zeta_3$   | $5\zeta_3^2$ | 0                          | 0                          | 0                          | 0                          | 0                          | 0                          | 0                          | 0                          | $-5\zeta_3^2$ | $-5\zeta_3$   | -5            | -5            | $-5\zeta_3$   | $-5\zeta_3^2$ |
| 5 | $5\zeta_3^2$ | $5\zeta_3$   | 0                          | 0                          | 0                          | 0                          | 0                          | 0                          | 0                          | 0                          | -5            | -5            | $-5\zeta_3^2$ | $-5\zeta_3$   | $-5\zeta_3$   | $-5\zeta_3^2$ |
| 5 | $5\zeta_3$   | $5\zeta_3^2$ | 0                          | 0                          | 0                          | 0                          | 0                          | 0                          | 0                          | 0                          | -5            | -5            | $-5\zeta_3$   | $-5\zeta_3^2$ | $-5\zeta_3^2$ | $-5\zeta_3$   |

**13.2. Type  $[[1,3],[3,8],[5,6]]$ , Second Fusion Ring.** The basis and fusion rules are the same as in §13.1, except that there is  $h \in C_3 \setminus \{e\}$  such that

- $y_{g_1} y_{g_2} = b_h(y_{(q_1 q_2)}^*)^{-1} + 2 \sum_{q_1 q_2 q \neq e} y_q^*$ ,

which sounds like a zesting. The element  $b_h$  can equivalently be the second or the third basic element (here we chose the second one).

- $[0, 0, 0, -2/5, -2/5, -1/5, -1/5, 1/5, 1/5, 2/5, 2/5, -2/9, -2/9, 1/9, 1/9, 4/9, 4/9], 45, 45, 4, [1, 0, \dots, 0]$ .

$$\begin{bmatrix}
1 & 1 & 1 & 3 & 3 & 3 & 3 & 3 & 3 & 3 & 3 & 5 & 5 & 5 & 5 & 5 & 5 \\
1 & 1 & 1 & 3 & 3 & 3 & 3 & 3 & 3 & 3 & 3 & 5\zeta_3 & 5\zeta_3^2 & 5\zeta_3 & 5\zeta_3^2 & 5\zeta_3 & 5\zeta_3^2 \\
1 & 1 & 1 & 3 & 3 & 3 & 3 & 3 & 3 & 3 & 3 & 5\zeta_3^2 & 5\zeta_3 & 5\zeta_3^2 & 5\zeta_3 & 5\zeta_3^2 & 5\zeta_3 \\
3 & 3 & 3 & 6\zeta_3^2 + 3\zeta_3^4 & 3\zeta_3 + 6\zeta_3^2 & -3\zeta_3^2 - 3\zeta_3^3 & -3\zeta_3^2 - 3\zeta_3^3 & -3\zeta_3 - 3\zeta_3^4 & -3\zeta_3 - 3\zeta_3^4 & 3\zeta_3^2 + 6\zeta_3^4 & 6\zeta_3 + 3\zeta_3^3 & 0 & 0 & 0 & 0 & 0 & 0 \\
3 & 3 & 3 & 3\zeta_3 + 6\zeta_3^2 & 6\zeta_3^2 + 3\zeta_3^4 & -3\zeta_3^2 - 3\zeta_3^3 & -3\zeta_3^2 - 3\zeta_3^3 & -3\zeta_3 - 3\zeta_3^4 & -3\zeta_3 - 3\zeta_3^4 & 6\zeta_3 + 3\zeta_3^3 & 3\zeta_3^2 + 6\zeta_3^4 & 0 & 0 & 0 & 0 & 0 & 0 \\
3 & 3 & 3 & -3\zeta_3^2 - 3\zeta_3^3 & -3\zeta_3^2 - 3\zeta_3^3 & 3\zeta_3^2 + 6\zeta_3^4 & 6\zeta_3 + 3\zeta_3^3 & 6\zeta_3^2 + 3\zeta_3^4 & 3\zeta_3 + 6\zeta_3^2 & -3\zeta_3 - 3\zeta_3^4 & -3\zeta_3 - 3\zeta_3^4 & 0 & 0 & 0 & 0 & 0 & 0 \\
3 & 3 & 3 & -3\zeta_3^2 - 3\zeta_3^3 & -3\zeta_3^2 - 3\zeta_3^3 & 6\zeta_3 + 3\zeta_3^3 & 3\zeta_3^2 + 6\zeta_3^4 & 3\zeta_3 + 6\zeta_3^2 & 6\zeta_3^2 + 3\zeta_3^4 & -3\zeta_3 - 3\zeta_3^4 & -3\zeta_3 - 3\zeta_3^4 & 0 & 0 & 0 & 0 & 0 & 0 \\
3 & 3 & 3 & -3\zeta_3 - 3\zeta_3^4 & -3\zeta_3 - 3\zeta_3^4 & 6\zeta_3^2 + 3\zeta_3^4 & 3\zeta_3 + 6\zeta_3^2 & 6\zeta_3 + 3\zeta_3^3 & 3\zeta_3^2 + 6\zeta_3^4 & -3\zeta_3^2 - 3\zeta_3^3 & -3\zeta_3^2 - 3\zeta_3^3 & 0 & 0 & 0 & 0 & 0 & 0 \\
3 & 3 & 3 & -3\zeta_3 - 3\zeta_3^4 & -3\zeta_3 - 3\zeta_3^4 & 3\zeta_3 + 6\zeta_3^2 & 6\zeta_3^2 + 3\zeta_3^4 & 3\zeta_3 + 6\zeta_3^2 & 6\zeta_3 + 3\zeta_3^3 & -3\zeta_3^2 - 3\zeta_3^3 & -3\zeta_3^2 - 3\zeta_3^3 & 0 & 0 & 0 & 0 & 0 & 0 \\
3 & 3 & 3 & 3\zeta_3^2 + 6\zeta_3^4 & 6\zeta_3 + 3\zeta_3^3 & -3\zeta_3 - 3\zeta_3^4 & -3\zeta_3 - 3\zeta_3^4 & -3\zeta_3^2 - 3\zeta_3^3 & -3\zeta_3^2 - 3\zeta_3^3 & 3\zeta_3 + 6\zeta_3^2 & 6\zeta_3^2 + 3\zeta_3^4 & 0 & 0 & 0 & 0 & 0 & 0 \\
3 & 3 & 3 & 6\zeta_3 + 3\zeta_3^3 & 3\zeta_3^2 + 6\zeta_3^4 & -3\zeta_3 - 3\zeta_3^4 & -3\zeta_3 - 3\zeta_3^4 & -3\zeta_3^2 - 3\zeta_3^3 & -3\zeta_3^2 - 3\zeta_3^3 & 3\zeta_3 + 6\zeta_3^2 & 6\zeta_3^2 + 3\zeta_3^4 & 0 & 0 & 0 & 0 & 0 & 0 \\
5 & 5\zeta_3 & 5\zeta_3^2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -5\zeta_3^4 & -5\zeta_3^5 & 5\zeta_3^4 + 5\zeta_3^7 & 5\zeta_3^2 + 5\zeta_3^5 & -5\zeta_3^7 & -5\zeta_3^2 \\
5 & 5\zeta_3^2 & 5\zeta_3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -5\zeta_3^5 & -5\zeta_3^4 &/>$$

$$\bullet [0, 0, 0, -2/5, -2/5, -1/5, -1/5, 1/5, 1/5, 2/5, 2/5, -4/9, -4/9, -1/9, -1/9, 2/9, 2/9], 45, 45, 4, [1, 0, \dots, 0],$$

$$\begin{bmatrix}
1 & 1 & 1 & 3 & 3 & 3 & 3 & 3 & 3 & 3 & 3 & 5 & 5 & 5 & 5 & 5 & 5 \\
1 & 1 & 1 & 3 & 3 & 3 & 3 & 3 & 3 & 3 & 3 & 5\zeta_3^2 & 5\zeta_3 & 5\zeta_3^2 & 5\zeta_3 & 5\zeta_3^2 & 5\zeta_3 \\
1 & 1 & 1 & 3 & 3 & 3 & 3 & 3 & 3 & 3 & 3 & 5\zeta_3 & 5\zeta_3^2 & 5\zeta_3 & 5\zeta_3^2 & 5\zeta_3 & 5\zeta_3^2 \\
3 & 3 & 3 & 6\zeta_3^2 + 3\zeta_3^4 & 3\zeta_3 + 6\zeta_3^2 & -3\zeta_3^2 - 3\zeta_3^3 & -3\zeta_3^2 - 3\zeta_3^3 & -3\zeta_3 - 3\zeta_3^4 & -3\zeta_3 - 3\zeta_3^4 & 3\zeta_3^2 + 6\zeta_3^4 & 6\zeta_3 + 3\zeta_3^3 & 0 & 0 & 0 & 0 & 0 & 0 \\
3 & 3 & 3 & 3\zeta_3 + 6\zeta_3^2 & 6\zeta_3^2 + 3\zeta_3^4 & -3\zeta_3^2 - 3\zeta_3^3 & -3\zeta_3^2 - 3\zeta_3^3 & -3\zeta_3 - 3\zeta_3^4 & -3\zeta_3 - 3\zeta_3^4 & 6\zeta_3 + 3\zeta_3^3 & 3\zeta_3^2 + 6\zeta_3^4 & 0 & 0 & 0 & 0 & 0 & 0 \\
3 & 3 & 3 & -3\zeta_3^2 - 3\zeta_3^3 & -3\zeta_3^2 - 3\zeta_3^3 & 3\zeta_3^2 + 6\zeta_3^4 & 6\zeta_3 + 3\zeta_3^3 & 6\zeta_3^2 + 3\zeta_3^4 & 3\zeta_3 + 6\zeta_3^2 & -3\zeta_3 - 3\zeta_3^4 & -3\zeta_3 - 3\zeta_3^4 & 0 & 0 & 0 & 0 & 0 & 0 \\
3 & 3 & 3 & -3\zeta_3^2 - 3\zeta_3^3 & -3\zeta_3^2 - 3\zeta_3^3 & 6\zeta_3 + 3\zeta_3^3 & 3\zeta_3^2 + 6\zeta_3^4 & 3\zeta_3 + 6\zeta_3^2 & 6\zeta_3^2 + 3\zeta_3^4 & -3\zeta_3 - 3\zeta_3^4 & -3\zeta_3 - 3\zeta_3^4 & 0 & 0 & 0 & 0 & 0 & 0 \\
3 & 3 & 3 & -3\zeta_3 - 3\zeta_3^4 & -3\zeta_3 - 3\zeta_3^4 & 6\zeta_3^2 + 3\zeta_3^4 & 3\zeta_3 + 6\zeta_3^2 & 6\zeta_3 + 3\zeta_3^3 & 3\zeta_3^2 + 6\zeta_3^4 & -3\zeta_3^2 - 3\zeta_3^3 & -3\zeta_3^2 - 3\zeta_3^3 & 0 & 0 & 0 & 0 & 0 & 0 \\
3 & 3 & 3 & -3\zeta_3 - 3\zeta_3^4 & -3\zeta_3 - 3\zeta_3^4 & 3\zeta_3 + 6\zeta_3^2 & 6\zeta_3^2 + 3\zeta_3^4 & 3\zeta_3 + 6\zeta_3^2 & 6\zeta_3 + 3\zeta_3^3 & -3\zeta_3^2 - 3\zeta_3^3 & -3\zeta_3^2 - 3\zeta_3^3 & 0 & 0 & 0 & 0 & 0 & 0 \\
3 & 3 & 3 & 3\zeta_3^2 + 6\zeta_3^4 & 6\zeta_3 + 3\zeta_3^3 & -3\zeta_3 - 3\zeta_3^4 & -3\zeta_3 - 3\zeta_3^4 & -3\zeta_3^2 - 3\zeta_3^3 & -3\zeta_3^2 - 3\zeta_3^3 & 3\zeta_3 + 6\zeta_3^2 & 6\zeta_3^2 + 3\zeta_3^4 & 0 & 0 & 0 & 0 & 0 & 0 \\
3 & 3 & 3 & 6\zeta_3 + 3\zeta_3^3 & 3\zeta_3^2 + 6\zeta_3^4 & -3\zeta_3 - 3\zeta_3^4 & -3\zeta_3 - 3\zeta_3^4 & -3\zeta_3^2 - 3\zeta_3^3 & -3\zeta_3^2 - 3\zeta_3^3 & 3\zeta_3 + 6\zeta_3^2 & 6\zeta_3^2 + 3\zeta_3^4 & 0 & 0 & 0 & 0 & 0 & 0 \\
5 & 5\zeta_3^2 & 5\zeta_3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 5\zeta_3^4 + 5\zeta_3^7 & 5\zeta_3^2 + 5\zeta_3^5 & -5\zeta_3^7 & -5\zeta_3^2 & -5\zeta_3^7 & -5\zeta_3^2 \\
5 & 5\zeta_3 & 5\zeta_3^2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 5\zeta_3^5 + 5\zeta_3^4 & 5\zeta_3^5 + 5\zeta_3^7 & -5\zeta_3^7 & -5\zeta_3^4 & -5\zeta_3^7 & -5\zeta_3^4 \\
5 & 5\zeta_3^2 & 5\zeta_3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -5\zeta_3^5 & -5\zeta_3^4 & -5\zeta_3^7 & -5\zeta_3^2 & 5\zeta_3^2 + 5\zeta_3^5 & 5\zeta_3^4 + 5\zeta_3^7 \\
5 & 5\zeta_3 & 5\zeta_3^2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -5\zeta_3^4 & -5\zeta_3^5 & -5\zeta_3^7 & -5\zeta_3^2 & 5\zeta_3^2 + 5\zeta_3^5 & 5\zeta_3^4 + 5\zeta_3^7 \\
5 & 5\zeta_3^2 & 5\zeta_3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -5\zeta_3^7 & -5\zeta_3^2 & 5\zeta_3^2 + 5\zeta_3^5 & 5\zeta_3^4 + 5\zeta_3^7 & -5\zeta_3^5 & -5\zeta_3^4 \\
5 & 5\zeta_3 & 5\zeta_3^2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -5\zeta_3^7 & -5\zeta_3^2 & 5\zeta_3^2 + 5\zeta_3^5 & 5\zeta_3^4 + 5\zeta_3^7 & -5\zeta_3^5 & -5\zeta_3^4
\end{bmatrix}$$

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**Availability of data and materials.** Data for the computations in this paper are available on reasonable request from the authors. The softwares used for the computations can be downloaded from the URLs listed in the references.

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