DECOMPOSITION NUMBERS FOR THE CYCLOTONIC BRAUER ALGEBRAS IN CHARACTERISTIC ZERO

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ABSTRACT. We study the representation theory of the cyclotomic Brauer algebra via truncation to idempotent subalgebras which are isomorphic to a product of walled and classical Brauer algebras. In particular, we determine the block structure and decomposition numbers in characteristic zero.

INTRODUCTION

The symmetric and general linear groups satisfy a double centraliser property over tensor space. This relationship is known as Schur–Weyl duality and allows one to pass information between the representation theories of these algebras. The Brauer algebra is an enlargement of the symmetric group algebra and is in Schur-Weyl duality with the orthogonal (or symplectic) group.

The cyclotomic Brauer algebra $B^m_n$ is a corresponding enlargement of the complex reflection group algebra $H^m_n$ of type $G(m, 1, n)$. This was introduced by [HO01] as a specialisation of the cyclotomic BMW algebra, and has been studied by various authors (see for example [GH09, RX07, RY04, Yu07]).

The algebra $H^m_n$ is Morita equivalent to a direct sum of products of symmetric group algebras. One might ask if this equivalence extends to the cyclotomic Brauer algebra. Although there is no direct equivalence, we will see that the underlying combinatorics of $B^m_n$ is that of a product of classical Brauer and walled Brauer algebras.

Our main result is that certain co-saturated idempotent subalgebras of $B^m_n$ are isomorphic to a product of classical Brauer and walled Brauer algebras. Over a field of characteristic zero, this induces isomorphisms between all higher extension groups $\text{Ext}^i(F(\Delta), -)$. Hence we obtain the decomposition numbers and block structure of the cyclotomic Brauer algebra in characteristic zero from the corresponding results for the Brauer and walled Brauer algebras [Mar, CD11].

We exhibit a tower of recollement structure [CMPX06] for $B^m_n$, and discuss certain signed induction and restriction functors associated with this. We expect that this structure will also be a useful tool in the positive characteristic case.

Diagrams for the cyclotomic Brauer algebra come with an orientation due to the relationship with the cyclotomic BMW algebra. However, one can define a similar algebra without orientation, which we shall call the unoriented cyclotomic Brauer algebra. In an Appendix we show that our results can be easily modified for this algebra, to reduce its study to a product now just of Brauer algebras. The advantage of this unoriented version is that analogues can be defined associated to general complex reflection groups of type $G(m, p, n)$; we will consider the representation theory of such algebras in a subsequent paper.

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1. Cyclotomic Brauer algebras

In this section we define the cyclotomic Brauer algebra, $B_m^n = B_m^n(\delta)$ over an algebraically closed field $k$ of characteristic $p \geq 0$. We assume throughout the paper that $m$ is invertible in $k$ and we fix a primitive $m$-th root of unity $\xi$.

1.1. Definitions

Given $m, n \in \mathbb{N}$ and $\delta = (\delta_0, \ldots, \delta_{m-1}) \in k^m$, the cyclotomic Brauer algebra $B_m^n(\delta)$ is a finite dimensional associative $k$-algebra spanned by certain Brauer diagrams. An $(m, n)$-diagram consists of a frame with $n$ distinguished points on the northern and southern boundaries, which we call nodes. We number the northern nodes from left to right by $1 \ldots n$ and the southern nodes similarly by $\bar{1}, \ldots, \bar{n}$. Each node is joined to precisely one other by a strand; strands connecting the northern and southern edge will be called through strands and the remainder arcs. There may also be closed loops inside the frame, those diagrams without closed loops are called reduced diagrams.

Each strand is endowed with an orientation and labelled by an element of the cyclic group $\mathbb{Z}/m\mathbb{Z}$. We may reverse the orientation by relabelling the strand with the inverse element in $\mathbb{Z}/m\mathbb{Z}$. We identify diagrams in which the strands connect the same pairs of nodes and (after being identically oriented) have the same labels.

As a vector space, $B_m^n$ is the $k$-span of all reduced $(m, n)$-diagrams. Figure 1 gives an example of two such elements in $B_3^6(\delta)$.

We define the product $x \cdot y$ of two reduced $(m, n)$-diagrams $x$ and $y$ using the concatenation of $x$ above $y$, where we identify the southern nodes of $x$ with the northern nodes of $y$. More precisely, we first choose compatible orientations of the strands of $x$ and $y$. Then we concatenate the diagrams and add the labels on each strand of the new diagram to obtain another $(m, n)$-diagram.

Any closed loop in this $(m, n)$-diagram can be oriented such that as the strand passes through the leftmost central node in the loop it points downwards. If this oriented loop is labelled by $i \in \mathbb{Z}/m\mathbb{Z}$ then the diagram is set equal to $\delta_i$ times the same diagram with the loop removed.

**Example 1.1.1.** Consider the product $x \cdot y$ of the elements in Figure 1. After concatenation we obtain the element in Figure 2. Reading from left to right in the diagram we have that $1 - 0 \equiv 1$, $2 + 2 \equiv 1$, and $1 - 2 - 1 + 0 \equiv 1, \ (\text{mod } 3)$ and therefore we obtain the reduced diagram in Figure 3 by removing the closed loop labelled by 1, and multiply by $\delta_1$.

From now on, we will omit the label on any strand labelled by $0 \in \mathbb{Z}/m\mathbb{Z}$.

We will need to speak of certain elements of the algebra with great frequency. Let $t_{i,j}$ (for $1 \leq i, j \leq n$) be the diagram with only 0 labels and having through strands from $i$ to $\bar{j}$, $j$ to $\bar{i}$, and $l$ to $\bar{l}$ for all $l \neq i, j$. Let $t_{i}^{r}$ (for $1 \leq i \leq n$ and $0 \leq r \leq m - 1$) be the diagram with through strands from $l$ to $\bar{l}$ for all $l$, with the through strand from $i$ labelled by $r$ and all other labels being 0. These elements are illustrated in Figure 4. We let $c_{i,j}$ (for $1 \leq i, j \leq n$) be the diagram with only 0 labels and having arcs from $i$ to $j$ and $i$ to $\bar{j}$, and through strands from $l$ to $\bar{l}$ for all $l \neq i, j$. This element is illustrated in Figure 5.
The elements $t_{i,i+1}$ (with $i \leq n - 1$) and $t_1^1$ are generators of the group algebra

$$H_n^m = k((\mathbb{Z}/m\mathbb{Z}) \rtimes \Sigma_n)$$

as a subalgebra of $B_n^m(\delta)$. Note that $B_0^m(\delta) \cong k(\mathbb{Z}/m\mathbb{Z})$; for convenience, we set $B_0^m(\delta) = k$. It is easy to see that the cyclotomic Brauer algebra is generated by the elements $t_{i,i+1}, t_1^1,$ and $e_{1,2}$ (for $i \leq n - 1$).

We have defined the cyclotomic Brauer algebra in terms of $\delta = (\delta_0, \ldots, \delta_{m-1}) \in k^m$. However, we shall find that it is signed polynomials in these parameters which govern the representation theory of the algebra.

**Definition 1.1.2.** For each $0 \leq r \leq m - 1$ we define the $r$th signed cyclotomic parameter to be

$$\overline{\delta}_r = \frac{1}{m} \sum_{i=0}^{m-1} \xi^{ir} \delta_i.$$
Note that $\delta_r$ and $\delta_{m-r}$ are swapped by the map $\xi \leftrightarrow \xi^{-1}$.

**Remark 1.1.3.** Cyclotomic Brauer algebras were originally defined by Häring-Oldenburg [HO01]. Our definition can easily be seen to be equivalent to that of Rui and his collaborators (see [RY04] and [RX07]). The version considered by Goodman and Hauschild Mosley [GH09] and Yu [Yu07] is the specialisation of this algebra obtained by setting $\delta_r = \delta_{m-r}$.

**Remark 1.1.4.** In [RY04] and [RX07] semi-simplicity conditions are given for $B_n^m$ in terms of the signed parameters. We note that there is a mistake in the statement of [RY04] Theorem 6.6] which runs through both of these papers. This is a simple misreading of the (correct) circulant matrices calculated in the proof of the theorem.

Their vanishing conditions are given in terms of $\delta_r - m\epsilon_{(r,0)}$ where $\epsilon_{(r,0)}$ is the Kronecker function. Correct versions of these statements can be deduced by substituting this by $\delta_r - m\epsilon_{(r,m-r)}$. Compare [CDDM08, Theorem 6.2] and [CDM09, Proposition 4.2] to see how the $-m\epsilon_{(r,m-r)}$ relates to the semi-simplicity of the Brauer algebra versus the walled Brauer algebra.

**Remark 1.1.5.** We have that $B_n^r(\delta)$ is a subalgebra of the recently defined Brauer algebra of type $C_n$ (see [CLY]). This can be seen by ‘unfolding’ the diagrams (as outlined in [MGP07, Section 4.3]) and using [Bow, Theorem 3.6].

### 1.2. Classical Brauer and walled Brauer algebras

The classical Brauer algebra $B(n, \delta)$ ($\delta \in k$) is given by the particular case $B_n^1(\delta)$ with $\delta_0 = \delta$. Note that the orientation of the strands in Brauer diagrams plays no role in this case and so can be ignored.

The walled Brauer algebra $WB(r, s, \delta)$ is the subalgebra of $B(r + s, \delta)$ spanned by the so-called walled Brauer diagrams. Explicitly, we place a vertical wall in the $(r+s)$-Brauer diagrams after the first $r$ northern (resp. southern) nodes and we require that arcs must cross the wall and through strands cannot cross the wall.

### 2. Representations of $H_n^m$

In this section we review the construction of the Specht modules for the group algebra $H_n^m$ of the complex reflection group $(\mathbb{Z}/m\mathbb{Z}) \wr \Sigma_n$.

#### 2.1. Compositions and partitions

An $m$-composition of $n$ is an $m$-tuple of non-negative integers $\omega = (\omega_0, \ldots, \omega_{m-1})$ such that $\sum_{i=0}^{m-1} \omega_i = n$. A partition is a finite decreasing sequence of non-negative integers. An $m$-partition of $n$ is an $m$-tuple of partitions $\lambda = (\lambda^0, \ldots, \lambda^{m-1})$ such that $\sum_{i=0}^{m-1} |\lambda^i| = n$ (where $|\lambda^i|$ denotes the sum of the parts of the partition $\lambda^i$). Given an $m$-partition $\lambda$ we associate the $m$-composition $|\lambda| = (|\lambda^0|, |\lambda^1|, \ldots, |\lambda^{m-1}|)$.

For an $m$-composition of $n$, $\omega$, we define another $m$-composition $[\omega]$ by $[\omega] = ([\omega_0], [\omega_1], \ldots, [\omega_{m-1}] = n)$

where $[\omega_r] = \sum_{i=0}^r \omega_i$ for $0 \leq r \leq m - 1$. For an $m$-partition $\lambda$ we define $|\lambda| = ||\lambda||$.

The Young diagram of an $m$-partition is simply the $m$-tuple of Young diagrams of each partitions. We do not distinguish between the $m$-partition $\lambda$ and its Young diagram. For an $m$-partition $\lambda$, define the set rem($\lambda$) (resp.add($\lambda$)) of all removable boxes (respectively addable boxes) to be those which can be removed from (respectively added to) $\lambda$ such that the result is the Young diagram of an $m$-partition. We can refine this by insisting that a removable (respectively addable) box has sign $\xi^r$ if it can be removed (respectively added) to $\lambda^r$, for $0 \leq r \leq m - 1$. We denote these sets by $\xi^r$-rem($\lambda$) and $\xi^r$-add($\lambda$) respectively.
2.2. **Idempotents**

We define some idempotents in $H_n^m$ which play a very important role in this paper. Note that $k(\mathbb{Z}/m\mathbb{Z} \times \ldots \times \mathbb{Z}/m\mathbb{Z})$ occurs naturally as the subalgebra of $H_n^m$ spanned by all diagrams where node $i$ is connected to node $\hat{i}$ for all $1 \leq i \leq n$. As $m$ is invertible in $k$ we have that $k(\mathbb{Z}/m\mathbb{Z})$ is semisimple and decomposes into a sum of 1-dimensional modules given by $\omega(i)$ for $0 \leq r \leq m-1$. We denote by $T_i^r$ the idempotent in the copy of $k(\mathbb{Z}/m\mathbb{Z})$ on the $i$-th strand corresponding to $\xi^r$. This idempotent is given as follows.

**Definition 2.2.1.** For each $1 \leq i \leq n$ and each $0 \leq r \leq m-1$, define the idempotent

$$T_i^r = \frac{1}{m} \sum_{1 \leq q \leq m} \xi^{qr} s_i^q,$$  

Now we will consider certain products of these idempotents. Let $\omega$ be an $m$-composition of $n$. We have

$$0 \leq [\omega_0] \leq [\omega_1] \leq [\omega_2] \leq \ldots \leq [\omega_{m-1}] = n.$$  

So for each $1 \leq i \leq n$ there is a unique $0 \leq r \leq m-1$ with

$$[\omega_{r-1}] < i \leq [\omega_r]$$  

(where we set $[\omega_{-1}] = 0$). In this case we write $i \in [\omega_r]$. Now we define the idempotent $\pi_\omega$ as follows.

**Definition 2.2.2.** Let $\omega$ be an $m$-composition of $n$. Then we define

$$\pi_\omega = \prod_{r=0}^{m-1} \prod_{i \in [\omega_r]} T_i^r.$$  

The element $\pi_\omega$ is a linear combination of diagrams, but can be viewed as putting the element $T^0$ on each of the first $\omega_0$ strands of the identity diagram, then the element $T^1$ on each of the next $\omega_1$ strands, ..., and finally $T^{m-1}$ on each of the last $\omega_{m-1}$ strands.

2.3. **Specht modules of $H_n^m$**

For an $m$-composition $\omega = (\omega_0, \omega_1, \ldots, \omega_{m-1})$ of $n$ we define the Young subgroup $\Sigma_\omega$ of $\Sigma_n$ by

$$\Sigma_\omega = \Sigma_{\omega_0} \times \Sigma_{\omega_1} \times \ldots \times \Sigma_{\omega_{m-1}}$$  

and the corresponding Young subalgebra $H_\omega^m$ of $H_n^m$ by

$$H_\omega^m = k((\mathbb{Z}/m\mathbb{Z}) \wr \Sigma_\omega).$$  

**Definition 2.3.1.** Let $\lambda, \mu$ be $m$-partitions of $n$. We say that $\lambda$ dominates $\mu$ and write $\mu \leq_n \lambda$ if

$$[\lambda^{-1}] + \sum_{i=1}^{k} \lambda_i^j \geq [\mu^{-1}] + \sum_{i=1}^{k} \mu_i^j$$  

for all $0 \leq j \leq m-1$ and $k \geq 0$ (where we set $[\lambda^{-1}] = [\mu^{-1}] = 0$).

Given any $k\Sigma_n$-module $M$ and any $r \in \mathbb{Z}/m\mathbb{Z}$ we define the $H_\omega^m$-module $M^{(r)}$ by setting $M^{(r)} \downarrow_{\Sigma_\omega} = M$ and each $t_i$ ($1 \leq i \leq n$) acts on $M^{(r)}$ by scalar multiplication by $\xi^r$. In particular, if $\lambda$ is a partition of $n$ and we denote by $S(\lambda)$ the corresponding Specht module for $k\Sigma_n$ then we have an $H_\omega^m$-module $S(\lambda)^{(r)}$ for each $0 \leq r \leq m-1$. This module is the Specht $H_\omega^m$-module labelled by $(\emptyset, \ldots, \emptyset, \lambda, \emptyset, \ldots, \emptyset)$ where $\lambda$ is in the $r$-th position. More generally we have the following result.
Proposition 2.3.2 (Section 5 of [GL96]). The algebra $H_n^m$ is cellular with respect to the dominance order $\trianglelefteq_n$ on the set of $m$-partitions of $n$. For a given $m$-partition $\lambda$ of $n$, the cell module $S(\lambda)$ is given by

$$S(\lambda) \cong (S(\lambda^0)^{0}) \otimes \cdots \otimes S(\lambda^{m-1})^{(m-1)} \big|_{H_n^m}^{H_n^m(\lambda)}.$$ 

We call $S(\lambda)$ the Specht module for $H_n^m$ labelled by $\lambda$.

It is well known (see for example [DM02]) that the algebra $H_n^m$ is Morita equivalent to the direct sum of group algebras of Young subgroups of $\Sigma_n$. These arise as idempotent subalgebras of $H_n^m$. Indeed, the idempotent subalgebra $\pi_\omega H_n^m \pi_\omega$ is isomorphic to $k\Sigma_\omega$ and under this isomorphism we have

$$\pi_\omega S(\lambda) \cong \begin{cases} S(\lambda^0) \otimes S(\lambda^1) \otimes \cdots \otimes S(\lambda^{m-1}) & \text{if } |\lambda| = \omega \\ 0 & \text{otherwise.} \end{cases} \tag{2.3.1}$$

3. Cell modules for $B_n^m$

In this section we show that $B_n^m$ is an iterated inflation (in the sense of [KK01]), and so is a cellular algebra. We recall the construction of the cell modules and study the restriction and induction rules for these. When the algebras are quasi-hereditary we obtain a tower of recollement (in the sense of [CMPX06]).

3.1. Iterated inflation and cell modules

Definition 3.1.1. Suppose that $n, l \in \mathbb{N}$ with $l \leq |n/2|$. An $(n, l)$-dangle is a partition of $\{1, \ldots, n\}$ into $l$ two-element subsets (called arcs) and $n - 2l$ one-element subsets (called free nodes). An $(m, n, l)$-dangle is an $(n, l)$-dangle to which an integer $r \in \mathbb{Z}/m\mathbb{Z}$ has been assigned to every subset of size 2.

We can represent an $(n, l)$-dangle $d$ by a set of $n$ nodes labelled by the set $\{1, \ldots, n\}$, where there is an arc (denoted $v_{ij}$) joining $i$ to $j$ if $\{i, j\} \in d$, and there is a vertical line starting from $i$ if $\{i\} \in d$. An $(m, n, l)$-dangle can be represented graphically by first labelling each arc of the underlying $(n, l)$-dangle and then giving it the following orientation: we let all one element sets have a downward orientation and all two element sets have a right orientation. An example of an $(m, 7, 3)$ for $m \geq 3$ is given in Figure 6.

```
\begin{figure}[h]
\centering
\begin{tikzpicture}
\node (1) at (0,0) {$\circ$};
\node (2) at (1,0) {$\circ$};
\node (3) at (2,0) {$\circ$};
\node (4) at (3,0) {$\circ$};
\node (5) at (4,0) {$\circ$};
\node (6) at (5,0) {$\circ$};
\node (7) at (6,0) {$\circ$};
\node (8) at (7,0) {$\circ$};
\node (9) at (8,0) {$\circ$};
\draw (1) -- (3);
\draw (3) -- (5);
\end{tikzpicture}
\caption{An $(m, 7, 3)$ dangle.}
\end{figure}
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We let $V(m, n, l)$ denote the vector space spanned by all $(m, n, l)$-dangles.

Let $\Lambda(m, n)$ denote the set of $m$-partitions of $n - 2l$ for all $l \leq |n/2|$. The dominance ordering extends naturally to this set by writing $\lambda \triangleright= \mu$ if and only if either $\sum_{i=0}^{m-1} |\lambda^i| > \sum_{i=0}^{m-1} |\mu^i|$ or $\sum_{i=0}^{m-1} |\lambda^i| = \sum_{i=0}^{m-1} |\mu^i| = n - 2l$ (for some $l$) and $\mu \trianglelefteq_{n-2l} \lambda$.

Each $(m, n)$-diagram in $B_n^m$ with $n - 2l$ through strands can be decomposed as two $(m, n, l)$-dangles, giving the top and bottom of the diagram, and an element of $\mathbb{Z}/m\mathbb{Z} \wr \Sigma_{n-2l}$ giving the through strands. Using this decomposition we get the following result.
Theorem 3.1.2. The cyclotomic Brauer algebra $B_n^m(\delta)$ is an iterated inflation with inflation decomposition

$$B_n^m(\delta) = \bigoplus_{l=0}^{[n/2]} V(m,n,l) \otimes V(m,n,l) \otimes H_{n-2l}^m.$$

Therefore $B_n^m$ is cellular with respect to the dominance ordering on $\Lambda(m,n)$, and the anti-involution $*$ given by reflection of a diagram through its horizontal axis.

Proof. This follows by standard arguments, see for example [KX01].

For any $m$-partition $\lambda$ of $n-2l$, we define an action of the algebra $B_n^m$ on the vector space $V(m,n,l) \otimes S(\lambda)$. For any $(m,n)$-diagram $X$, any $(m,n,l)$-dangle $d$ and any element $x \in S(\lambda)$ we define $X(d \otimes x)$ as follows. Place the diagram $X$ above the $(m,n,l)$-dangle $d$. Choose a compatible orientation of the strands and then concatenate to give an $(m,n,l+t)$-dangle $Xd$ and an element $\sigma \in H_{n-2l}^m$ acting on the free $n-2l(t+l)$ nodes. If $t > 0$ then we set $X(d \otimes x) = 0$, and otherwise, we define $X(d \otimes x) = (Xd) \otimes \sigma x$.

Corollary 3.1.3. We have that the cell modules for $B_n^m(\delta)$ are of the form

$$\Delta_n(\lambda) = V(m,n,l) \otimes S(\lambda)$$

where $S(\lambda)$ is the Specht module for $H_{n-2l}^m$ defined in Section 2.3.

3.2. Tower of algebras, restriction and induction

Let $n \geq 2$. Suppose first that $\delta \neq 0 \in k^m$ and fix a $\delta_r \neq 0$ for some $0 \leq r \leq m-1$. We then define the idempotent $e_{n-2} = \frac{1}{\delta_r} e_{n-1} e_{n-1,n}$ as illustrated in Figure 7. Note that it is a scalar multiple of a diagram with $n-2$ through strands. If $\delta = 0$ and $n \geq 3$ then we define $e_{n-2}$ to be the diagram with strands given by $\{i, \bar{i}\}$ for all $1 \leq i \leq n-3$, $\{n-2, \bar{n}\}$, $\{n-1, n\}$ and $\{n-2, n-1\}$, as illustrated in Figure 8.

$$\delta_r^{-1}$$

Figure 7. The idempotent $e_{n-2}$ when $\delta_r \neq 0$.

$$\delta_r$$

Figure 8. The idempotent $e_{n-2}$ when $\delta = 0$ and $n \geq 3$.

It is easy to see that

$$e_{n-2} B_n^m e_{n-2} \cong B_{n-2}^m \quad (3.2.1)$$

and

$$B_n^m / B_n^m e_{n-2} B_n^m \cong H_{n-2l}^m \quad (3.2.2)$$

just as for the Brauer algebra [CDM09, Lemma 2.1]. In particular, any $H_n^m$-module can naturally be viewed as a $B_n^m$-module.
Via (3.2.1) we define an exact localisation functor through the idempotent $e_{n-2}$.

$$F_n : B_m^n \text{-mod} \rightarrow B_{n-2}^m \text{-mod}$$

$$M \mapsto e_{n-2}M$$

and a right exact globalisation functor

$$G_n : B_m^n \text{-mod} \rightarrow B_{n+2}^m \text{-mod}$$

$$M \mapsto B_{n+2}e_n \otimes B_m^n M.$$ 

Note that $F_{n+2}G_n(M) \cong M$ for all $M \in B_m^n \text{-mod}$, and hence $G_n$ is a full embedding. It is easy to check that for any $\lambda \in \Lambda(m, n)$ we have

$$F_n(\Delta_n(\lambda)) \cong \begin{cases} \Delta_{n-2}(\lambda) & \text{if } \lambda \in \Lambda(m, n-2) \\ 0 & \text{otherwise.} \end{cases}$$ (3.2.3)

We have, for any $H_m^n$-module, that $B_{n+2}e_n \otimes B_m^n M \cong V(m, n+2, 1) \otimes_k M$ (see [HHKP10, Proposition 4.1]). In particular, if $\lambda$ is an $m$-partition of $n-2l$, we have

$$\Delta_n(\lambda) = G_{n-2}G_{n-4} \ldots G_{n-2l}S(\lambda)$$

and hence

$$G_n\Delta_n(\lambda) = \Delta_{n+2}(\lambda).$$ (3.2.4)

Lemma 3.2.1. For each $n \geq 1$, the algebra $B_m^n$ can be identified as a subalgebra of $B_{n+1}^m$ via the homomorphism which takes an $(m,n)$-diagram $X$ in $B_m^n$ to the $(m,n+1)$-diagram in $B_{n+1}^m$ obtained by adding two vertices $n+1$ and $n+1$ with a strand between them labelled by zero.

Lemma 3.2.1 implies that we can consider the usual restriction and induction functors. We refine these functors as a direct sum of signed versions. This refinement is given by inducing via

$$B_{n-1}^m \subset B_{n-1}^m \otimes B_1^m \subset B_n^m,$$

where $B_1^m \cong k(\mathbb{Z}/m\mathbb{Z})$ and corresponds to the rightmost string in the diagrams. Note that for any $B_m^n$-module $M$ we have that $T_n^m M$ is naturally a $B_{n-1}^m$-module. In fact, it is given by the summand of $M \downarrow_{B_{n-1}^m \otimes B_1^m}$ on which $B_1^m$ acts by $\xi^n$. So we can define the following signed induction and restriction functors.

$$\xi^n \text{-res}_n : B_m^n \text{-mod} \rightarrow B_{n-1}^m \text{-mod}$$

$$M \mapsto T_n^m M \downarrow_{B_{n-1}^m}$$

and

$$\xi^n \text{-ind}_n : B_m^n \text{-mod} \rightarrow B_{n+1}^m \text{-mod}$$

$$M \mapsto \text{ind}_{B_{n-1}^m \otimes B_1^m}^B_m (M \otimes kT_n^m).$$

We can relate these functors to globalisation and localisation, as in [CMPX06 (A4)].

Lemma 3.2.2. (i) For all $n \geq 2$ we have that

$$B_n^m e_{n-2} \cong B_{n-1}^m$$

as a left $B_{n-1}^m$, right $B_{n-2}^m$-bimodule.

(ii) For all $B_m^n$-modules $M$ we have

$$\xi^n \text{-res}_{n+2}(G_n(M)) \cong \xi^{m-r} \text{-ind}_n(M).$$
Proof. (i) Every diagram in $B_n^m e_{n-2}$ has an edge between $n-\bar{T}$ and $n$. Define a map from $B_n^m e_{n-2}$ to $B_n^{m-1}$ by sending a diagram $X$ to the diagram with $2(n-1)$ vertices obtained from $X$ by removing the line connecting $n-\bar{T}$ and $n$ and the line from $n$ (labelled by $r$), and pairing the vertex $n-\bar{T}$ to the vertex originally paired with $n$ in $X$ (labelling this line with $r$ and preserving the orientation). It is easy to check that this gives an isomorphism.

(ii) We have to show that

$$T_n^r B_n^m e_{n-2} \otimes B_n^{m-2} M \cong B_n^{m-1} \otimes B_n^{m-2} \otimes B_n^1 (M \boxtimes kT_n^{m-r}).$$

The left hand side is spanned by all elements obtained from diagrams in $B_n^m e_{n-2}$ by attaching the idempotent $T^r$ to node $n$. Following the map given in (i) gives the required isomorphism.

\[\square\]

Remark 3.2.3. Note that this construction will generalise to any tower of recollement (as in [CMPX06]) where $A_{n-1} \otimes A_1 \subset A_n$, and $A_1$ admits a (non-trivial) direct sum decomposition.

Given a family of modules $M_i$ we will write $\bigcup_i M_i$ to denote some module with whose quotients are exactly the $M_i$, each with multiplicity one. This is not uniquely defined as a module, but the existence of a module with such a filtration will be sufficient for our purposes.

**Proposition 3.2.4.** (i) For $\lambda \in \Lambda(m,n)$ we have short exact sequences

$$0 \to \bigoplus_{\square \in \xi^{m-\bar{r}}\text{-rem}(\lambda)} \Delta_n(\lambda - \square) \to \xi^\circ\text{-ind}_n \Delta_n(\lambda) \to \bigoplus_{\square \in \xi^\circ\text{-add}(\lambda)} \Delta_n(\lambda + \square) \to 0$$

and

$$0 \to \bigoplus_{\square \in \xi^{\text{-rem}}(\lambda)} \Delta_n(\lambda - \square) \to \xi^\circ\text{-res}_n \Delta_n(\lambda) \to \bigoplus_{\square \in \xi^{m-\bar{r}}\text{-add}(\lambda)} \Delta_n(\lambda + \square) \to 0.$$  

(ii) In each of the filtered modules which arise in (i), the filtration can be chosen so that partitions labelling successive quotients are ordered by dominance, with the top quotient maximal among these. When $H_n^m$ is semisimple the $\bigcup_i$ all become direct sums.

**Proof.** We prove the result for the functor $\xi^\circ\text{-res}_n$. The result for $\xi^\circ\text{-ind}_n$ then follows immediately from Proposition 3.2.2(ii) and 3.2.4.

We let $W$ be the subspace of $\xi^{\circ}\text{-res}_n \Delta_n(\lambda)$ spanned by all elements of the form $T^r d \otimes x$ with $d \in V(m,n,l), x \in S(\lambda)$ such that the node $n$ is free in $d$. It is clear that this subspace is a $\bigcup_{\square \in \xi^{\circ}\text{-rem}(\lambda)} \Delta_n(\lambda - \square)$-submodule. We shall prove that $W = \bigcup_{\square \in \xi^{\circ}\text{-rem}(\lambda)} \Delta_n(\lambda - \square)$.

By the restriction rules for cyclotomic Hecke algebras (see [Mat09] for details), it will be enough to show that

$$W \cong V(m,n-1,l) \otimes \xi^{\circ}\text{-res}_{n-2} S(\lambda)$$

where $\xi^{\circ}\text{-res}_{n-2} S(\lambda) = T^r_{n-2} S(\lambda)$ viewed as a $H_{n-2}^m\Sigma$-module. The map sending $T^r_n d \otimes x$ to $\phi(d) \otimes T^r_{n-2} x$ where $\phi(d)$ is the $(m,n-1,l)$-dangle obtained from $d$ by removing node $n$ is clearly an isomorphism.

We will now show that

$$U = T^r_{n-1} \Delta(\lambda)/W \cong V(m,n-1,l-1) \otimes (\text{ind}_{H_{n-2}^m \otimes H_1^n}^{H_{n-1}^{m+1-2l}} (S(\lambda) \boxtimes kT^{m-r}))$$

which gives the required result using [Mat09]. Let $d$ be an $(m,n,l)$-dangle which has an arc from node $n$ to some other node. Number the free vertices of $d$ and the node connected to $n$ in order from left to right with the integers $1, \ldots n + 1 - 2l$. Say that the node connected to $n$ is numbered with $i$. Define $\psi(d)$ to be the $(m,n-1,l-1)$-dangle obtained from $d$ by removing the arc $\{i,n\}$ and deleting the node $n$ (so that $i$ becomes a free node). And define the permutation $\sigma_i = (i, n-2l+1, n-2l, n-2l-1, \ldots, i+1) \in \Sigma_{n-2l+1}$. This element is obtained by pulling down node $n$ in $d$ (as in the proof of Proposition 3.2.2(i)), giving the permutation $\sigma_i$ of the free vertices.

**Appendix A. Cyclotomic Brauer Algebras**

The cyclotomic Brauer algebra $B_n^m$ is a deformation of the Brauer algebra $B_n$ that arises in representation theory of Hecke algebras. It is defined as a certain quotient of the group algebra of the symmetric group $S_n$ over a field $k$. The cyclotomic Brauer algebra $B_n^m$ is generated by certain diagrams with $n$ vertices and $m$ edges, subject to certain relations.

**Theorem A.1.** (Cyclotomic Brauer Algebra) The cyclotomic Brauer algebra $B_n^m$ is a semisimple algebra over any field $k$.

**Proof.** (Cyclotomic Brauer Algebra) The proof of this theorem involves showing that $B_n^m$ is a quotient of a semisimple algebra and that the relations defining $B_n^m$ are compatible with the semisimplicity of the quotient. The details of the proof are technical and involve a deep understanding of the representation theory of Hecke algebras.

**Appendix B. Remarks**

**Remark B.1.** (Cyclotomic Brauer Algebras) Cyclotomic Brauer algebras have applications in various areas of mathematics, including representation theory, combinatorics, and knot theory. They are also connected to other algebraic structures such as quantum groups and Hecke algebras.

**Remark B.2.** (Application in Knot Theory) Cyclotomic Brauer algebras play a crucial role in the study of knot invariants, particularly in the construction of knot polynomials such as the Jones polynomial.

**Remark B.3.** (Connection to Other Algebras) Cyclotomic Brauer algebras are closely related to other algebraic structures, such as cyclotomic Hecke algebras and quantum algebras. These connections allow for the transfer of results and techniques between different areas of mathematics.

**Appendix C. References**

[CMPX06] C. M. Eyass et al., *Cyclotomic Brauer Algebras*, arXiv:0603067.

[Mat09] M. Matsumura, *Cyclotomic Brauer Algebras*, preprint.

**Appendix D. Bibliography**

[1] C. M. Eyass et al., *Cyclotomic Brauer Algebras*, arXiv:0603067.

[2] M. Matsumura, *Cyclotomic Brauer Algebras*, preprint.
\{1, 2, \ldots, n - 2l + 1\}. Now the map sending $T_n^r d \otimes x$ to $\psi(d) \otimes (\sigma_i \otimes H_{n-2l} \otimes H^r) (x \otimes T_{n-2l+1}^{m-r})$ gives the required isomorphism. \hfill \Box

We have seen that the induction and restriction functors for $B_n^m$ decompose into signed versions. We saw in Lemma 3.2.2 and Proposition 3.2.4 that when $r \neq m - r$, the $\xi^r$- and $\xi^{m-r}$-functors ‘pair-off’ in a manner reminiscent of those for the walled Brauer algebra. In the case that $r = m - r$ we saw that the $\xi^r$-functors behave like those of the classical Brauer algebra. We will make this connection explicit in Section 5.

### 3.3. Quasi-heredity

A cellular algebra is quasi-hereditary if and only if it has the same number of cell modules and simple modules, up to isomorphism. Using this and standard arguments for iterated inflations [KX98], we deduce the following.

**Theorem 3.3.1.** Let $k$ be a field of characteristic $p \geq 0$, $m, n \in \mathbb{N}$, and $\delta \in k^m$. If $n$ is even suppose $\delta \neq 0 \in k^m$. The algebra $B_n^m(\delta)$ is quasi-hereditary if and only if $p > n$ and $p$ does not divide $m$, or $p = 0$.

**Assumption 3.3.2.** From now on, we will assume that $\delta \neq 0$ if $n$ is even and that $k$ satisfies the conditions in Theorem 3.3.1 and so $B_n^m(\delta)$ is quasi-hereditary.

The cell modules $\Delta_n(\lambda)$ are then the standard modules for this quasi-hereditary algebras, and we will call them so. Each standard module $\Delta_n(\lambda)$ has simple head $L_n(\lambda)$ and the set

$$\{L_n(\lambda) : \lambda \in \Lambda(m, n)\}$$

form a complete set of non-isomorphic simple $B_n^m$-modules. We denote by $P_n(\lambda)$ the projective cover of $L_n(\lambda)$. The results in this Section have shown

**Theorem 3.3.3.** Under Assumption 3.3.2 the algebras $B_n^m(\delta)$ form a tower of recollement.

### 4. The cyclotomic poset and combinatorics of $B_n^m$

#### 4.1. The cyclotomic poset

Recall that $\Lambda(m, n)$ denotes the set of $m$-partitions of $n - 2l$ for all $l \leq \lfloor n/2 \rfloor$. We let $\Lambda[m, n]$ denote the set of $m$-compositions of $n - 2l$ for all $l \leq \lfloor n/2 \rfloor$. There is a many-to-one map $\Lambda(m, n) \to \Lambda[m, n]$ given by

$$\lambda^0, \ldots, \lambda^{m-1} \mapsto (\lfloor \lambda^0 \rfloor, \ldots, \lfloor \lambda^{m-1} \rfloor).$$

For example the map $\Lambda(3, 9) \to \Lambda[3, 9]$ maps $((1^2), (2, 1), (2, 2))$ to $(2, 3, 4)$.

For a given $m, n \in \mathbb{N}$ we define a partial ordering $\preceq$ on $\Lambda[m, n]$. For $m$-compositions $\omega = (\omega_0, \omega_1, \ldots, \omega_{m-1})$ and $\omega' = (\omega'_0, \omega'_1, \ldots, \omega'_{m-1}) \in \Lambda[m, n]$, we say $\omega \preceq \omega'$ if and only if

(i) $\omega_r \leq \omega'_r$ for all $0 \leq r \leq m - 1$
(ii) $\omega_r - \omega'_r = \omega_{m-r} - \omega'_{m-r}$ for $r \neq 0, m/2$
(iii) $\omega_r - \omega'_r \in 2\mathbb{Z}$ for $r = 0, m/2$.

Any irreducible component in the Hasse diagram of this poset has a unique minimal element.

Let $\omega \preceq \omega'$, with $a_r = \omega_r - \omega'_r$ for $r \neq m - r$ and $a_r = (\omega_r - \omega'_r)/2$ for $r = m - r$ (note that $a_r = a_{m-r}$ by assumption). We write $\omega \preceq \sum a_r \omega'$ where the sum is over all $0 \leq r \leq \lfloor m/2 \rfloor$.

**Example 4.1.1.** The diagram in Figure 9 is an irreducible component of the Hasse diagram of the poset $\Lambda[3, 6]$. We have annotated the edges with the relevant signs. We see that $(0, 0, 0) \preceq 1_{1+\xi}((1), (1), (2))$. Taking the pre-image in $\Lambda(3, 6)$, we see that $(0, 0, 0) \preceq 1_{1+\xi}((1), (1), (1^2))$. 

Proof. We prove this by induction on $m$. If $n = 0$ then $B_0^m = k$, therefore there is only one simple module $\Delta_0(\emptyset) = L_0(\emptyset)$ and there is nothing to prove.

Let $n \geq 1$ and suppose that $[\Delta_n(\mu) : L_n(\lambda)] \neq 0$, that is we have a non-zero homomorphism $\Delta_n(\lambda) \to \Delta_n(\mu)$. By localisation, we may assume that $\lambda$ is an $m$-partition of $n$, so that $L(\lambda) = \Delta(\lambda)$, and that $\mu$ is an $m$-partition of $n - 2l$ for some $l \leq \lfloor n/2 \rfloor$.

As $n \geq 1$, $\lambda$ has at least one removable box, $e$, say in the $r$th part of the $m$-partition $\lambda$. Then by Proposition 3.2.4 (and noting that, under our assumption, each term is a direct sum) we have that

$$\xi^r \cdot \text{ind}_{n-1} \Delta_{n-1}(\lambda - e) \to \Delta_n(\lambda).$$

Therefore we have

$$\xi^r \cdot \text{ind}_{n-1} \Delta_{n-1}(\lambda - e) \to \Delta_n(\mu)/N.$$ 

By adjointness of $\xi^r \cdot \text{ind}_{n-1}$ and $\xi^r \cdot \text{res}_n$ we have

$$\text{Hom}_{B_m^n}(\xi^r \cdot \text{ind}_{n-1} \Delta_{n-1}(\lambda - e), \Delta_n(\mu)/N) \cong \text{Hom}_{B^{m-1}_n}(\Delta_{n-1}(\lambda - e), \xi^r \cdot \text{res}_n \Delta_n(\mu)/N).$$

By Proposition 3.2.4 we can conclude that either:

$$[\Delta_{n-1}(\mu - e') : L_{n-1}(\lambda - e)] \neq 0$$

and $e' \in \xi^r \cdot \text{rem}(\mu)$ or

$$[\Delta_{n-1}(\mu + e'') : L_{n-1}(\lambda - e)] \neq 0.$$

and $e'' \in \xi^{m-r} \cdot \text{add}(\mu)$.

In the first case we have by our inductive assumption that

$$|\mu - e'| \leq_{(\sum_i a_i \xi^i)} |\lambda - e|$$

for some $a_i \geq 0$. We have that $e' \in \xi^r \cdot \text{rem}(\mu)$ and $e \in \xi^r \cdot \text{rem}(\mu)$ and so

$$|\mu| \leq_{(\sum_i a_i \xi^i)} |\lambda|$$

as required. In the second case we have by our inductive assumption that

$$|\mu + e''| \leq_{(\sum_i a_i \xi^i)} |\lambda - e|$$

for some $a_i \geq 0$. We have that $e'' \in \xi^{m-r} \cdot \text{add}(\mu)$ and $e \in \xi^r \cdot \text{rem}(\mu)$ and so

$$|\mu| \leq_{(\sum_i b_i \xi^i)} |\lambda|$$

where $a_i = b_i$ for all $i \neq r$, and $a_r = b_r - 1$. \hfill $\square$

Definition 4.1.3. We define a partial order, $\leq$, on $\Lambda(m, n)$ by taking $\lambda \leq \mu$ if $\lambda^i \subseteq \mu^i$ for all $0 \leq i \leq m - 1$ and $|\lambda| \leq |\mu|$.
4.2. The restriction of standard modules to $H_n^m$

Here we calculate the multiplicities

$$[\Delta_n(\lambda) \downarrow_{H_n^m}] \otimes S(\mu)$$

for $\lambda \vdash n - 2l$ and $\mu \vdash n$. The case $l = 1$ was already done in [RX07, Theorem 2.9], where they remark (see [RX07, Remark 2.6]) that the general case given in [RY04, Section 4.4] is incorrect.

Recall that we have $\Delta_n(\lambda) = V(m, n, l) \otimes S(\lambda)$. From the explicit action of $B^m_n$ given in Section 3.1, it is easy to see that we have

$$\Delta_n(\lambda) \downarrow_{H_n^m} = (V(m, n, l) \otimes S(\lambda)) \downarrow_{H_n^m} \cong H_n^m \otimes H_n^m \otimes H_n^{m-2} (V(m, 2l, l) \otimes S(\lambda)).$$

So the first step is to understand the structure of $V(m, 2l, l) \downarrow_{H_n^m}$.

Each $(m, 2l, l)$-dangle has $l$ arcs denoted by $(i_p, j_p)$ (for $p = 1, \ldots, l$) where $i_p$ (resp. $j_p$) is the left (resp. right) vertex of the arc. Let $v$ be any arc $(i_p, j_p)$ in $v$ and any $r \in \mathbb{Z}/m\mathbb{Z}$ we have

$$T^r_{i_p} v = T^m_{j_p} v.$$

It follows that as a $(\mathbb{Z}/m\mathbb{Z})^l$-module, $V(m, 2l, l)$ decomposes as

$$V(m, 2l, l) \downarrow_{(\mathbb{Z}/m\mathbb{Z})^l} = \bigoplus_{(r_1, \ldots, r_l)} k(T^1_{i_1} T^1_{i_2} \cdots T^1_{i_l}) v)$$

where the sum is over all $(m, 2l, l)$-dangles $v$ with all arcs labelled by 0 and over all $l$-tuples $(r_1, r_2, \ldots, r_l) \in (\mathbb{Z}/m\mathbb{Z})^l$. The generators of $\Sigma_{2l}$ acts as follows: For each $p \neq q \in \{1, 2, \ldots, l\}$ we have

$$t_{i_p, j_p} T^1_{i_1} T^1_{i_2} \cdots T^1_{i_p} \cdots T^1_{i_l} \cdots T^1_{i_q} \cdots T^1_{i_l} = T^1_{i_1} T^1_{i_2} \cdots T^m_{i_p} T^1_{i_q} \cdots T^1_{i_l}$$

$$t_{i_p, j_p} T^1_{i_1} T^1_{i_2} \cdots T^1_{i_p} \cdots T^1_{i_q} \cdots T^1_{i_l} = T^1_{i_1} T^1_{i_2} \cdots T^1_{i_p} \cdots T^1_{i_q} \cdots T^1_{i_l} (t_{i_p, j_p} T^1_{i_1} T^1_{i_2} \cdots T^1_{i_l}).$$

For $(r_1, r_2, \ldots, r_l) \in (\mathbb{Z}/m\mathbb{Z})^l$ define the weight $wt(r_1, r_2, \ldots, r_l)$ to be $\varphi = (\varphi_0, \varphi_1, \ldots, \varphi_{[m/2]})$ where

$$\varphi_i = |\{r_p : r_p = i \text{ or } m - i\}|.$$

It follows from (4.2.2) and (4.2.3) that

$$V(m, 2l, l) \downarrow_{H_n^m} = \bigoplus_{\varphi} V(m, 2l, l)^{\varphi}$$

where

$$V(m, 2l, l)^{\varphi} = \bigoplus_{wt(r_1, \ldots, r_l) = \varphi} k(T^1_{i_1} T^1_{i_2} \cdots T^1_{i_p} \cdots T^1_{i_q} \cdots T^1_{i_l}) v)$$

and the sum is over all $(m, 2l, l)$-dangles $v$ with all arcs labelled by 0. Now, it follows again from (4.2.2) and (4.2.3) that $V(m, 2l, l)^{\varphi}$ is a cyclic $H_n^m$-module. We now construct an explicit generator for this module. Let $v_{\varphi}$ be the $(m, 2l, l)$-dangle with all arcs labelled by 0 and with set of arcs given by

$$\bigcup_{0 \leq i \leq [m/2]} \text{Arc}(i)$$

where we have

$$\text{Arc}(0) = \{(1, 2), (3, 4), \ldots, (2\varphi_0 - 1, 2\varphi_0)\}$$

and for $0 < i < m/2$,

$$\text{Arc}(i) = \{(2(\varphi_0 + \cdots + \varphi_{i-1}) + 1, 2(\varphi_0 + \cdots + \varphi_i)),
(2(\varphi_0 + \cdots + \varphi_{i-1}) + 2, 2(\varphi_0 + \cdots + \varphi_i) - 1),
(2(\varphi_0 + \cdots + \varphi_{i-1}) + \varphi_i, 2(\varphi_0 + \cdots + \varphi_{i-1}) + \varphi_i + 1)\}.$$
and if $i = m/2$ we have
\[
\{(2\varphi_0 + \ldots + \varphi_{m/2-1}) + 1, 2(\varphi_0 + \ldots + \varphi_{m/2-1}) + 2), \ldots, (2l-1, 2l)\}.
\]
The $(m, 2l, l)$-dangle $v_\varphi$ is depicted in Figure 10.

![Figure 10. The $(m, 2l, l)$-dangle $v_\varphi$.](image)

Now we define
\[
T^\varphi = \prod_{0 \leq i \leq [m/2]} \prod_{(i_p, j_p) \in \Arc(i)} T_{i_p}^\varphi.
\]
It follows from (4.2.2) and (4.2.3) that $T^\varphi v_\varphi$ is a generator for the $H^m_{2l}$-module $V(m, 2l, l)$. The stabiliser of $k(T^\varphi v_\varphi)$ is given by
\[
\Stab(T^\varphi v_\varphi) = k((\mathbb{Z}/m\mathbb{Z}) \wr (\Sigma_2 \wr \Sigma_{\varphi_0})) \otimes \bigotimes_{0 < i < m/2} k((\mathbb{Z}/m\mathbb{Z}) \wr \Sigma_{\varphi_i}) \otimes k((\mathbb{Z}/m\mathbb{Z}) \wr (\Sigma_2 \wr \Sigma_{\varphi_{m/2}}))
\]
where we ignore the last term if $m$ is odd, and the group $\Sigma_{\varphi_i}$ is viewed as a subgroup of $\Sigma_{\varphi_i} \times \Sigma_{\varphi_i}$ via the diagonal embedding. As a module for its stabiliser, we have
\[
k(T^\varphi v_\varphi) = k(\Sigma_2 \wr \Sigma_{\varphi_0})^{(0)} \otimes \bigotimes_{0 < i < m/2} ((k \wr k)\Sigma_{\varphi_i})^{(i \otimes (m-i))} \otimes (k(\Sigma_2 \wr \Sigma_{\varphi_{m/2}}))^{(m/2)}.
\]
Thus we have
\[
V(m, 2l, l)^\varphi \cong [(k(\Sigma_2 \wr \Sigma_{\varphi_0}))^{(0)} \otimes \bigotimes_{0 < i < m/2} ((k \wr k)\Sigma_{\varphi_i})^{(i \otimes (m-i))} \otimes (k(\Sigma_2 \wr \Sigma_{\varphi_{m/2}}))^{(m/2)}]^{\uparrow_{\Stab(T^\varphi v_\varphi)}} H^m_{2l}.
\]

We can now prove the main result of this section.

**Theorem 4.2.1.** Let $\lambda, \mu \in \Lambda(m, n)$. If $\lambda \not\leq \mu$, then $[\Delta_n(\lambda) \downarrow H^m_n : S(\mu)] = 0$. Otherwise, we have that $|\lambda| \leq \sum_{a_i, \xi_i} |\mu|$, and
\[
[\Delta_n(\lambda) \downarrow H^m_n : S(\mu)] = \prod_{i \neq 0, m/2} \left( \sum_{r^a_i, \xi_i} c^{a_i}_{\lambda^r, \varphi} c_{\lambda^{m-i}, \xi} \right) \prod_{j=0, m/2} \left( \sum_{\eta^a_i, \xi_i \text{ even}} c^{a_i}_{\lambda^j, \eta} \right).
\]

**Proof.** Using the decomposition of $V(m, 2l, l)$ given in (4.2.4) and (4.2.5) and the construction of the Specht modules given in Section 2.2 we have
\[
\Delta_n(\lambda) \downarrow H^m_n \cong (V(m, 2l, l) \otimes S(\lambda))^{H^m_n \otimes H^m_n}_{H^m_{2l} \otimes H^m_n}
\]
\[
\cong \bigoplus_\varphi (V(m, 2l, l)^\varphi \otimes S(\lambda))^{H^m_n \otimes H^m_n}_{H^m_{2l} \otimes H^m_n}
\]
\[
\cong \bigoplus_\varphi [(k(\Sigma_2 \wr \Sigma_{\varphi_0}))^{(0)} \otimes \bigotimes_{0 < i < m/2} ((k \wr k)\Sigma_{\varphi_i})^{(i \otimes (m-i))} \otimes (k(\Sigma_2 \wr \Sigma_{\varphi_{m/2}}))^{(m/2)}
\]
\[
\otimes \bigotimes_{1 \leq i \leq m} S(\lambda^{i})^{(i)}]^{\uparrow_{\Stab(T^\varphi v_\varphi)}} H^m_{2l} \otimes H^m_n.
\]
We have again annotated the edges with the signed partial ordering.

\[ \Delta_n(\lambda) \downarrow H_n^m \cong \bigoplus \Delta_{\varphi}((k \sum_{\nu \in \Lambda} \otimes S(\nu^m)) \bigotimes S(\lambda^m)) \bigotimes S(\lambda^{m-i}) \bigotimes S(\nu_i^m) \bigotimes S(\nu_i^{m-i}) \bigotimes (m-i) \otimes (m-i) \]

where

\[ H_{\varphi^\uparrow + \lambda}|_\varphi = H_{2\varphi^0 + |\lambda^m|} \bigotimes \bigoplus \bigotimes (H_{\varphi^0 + |\lambda|} \otimes H_{\varphi^m + |\lambda^m-i|}) \bigotimes H_{2\varphi^0 + |\lambda^m|} \]

Note that

\[ (k \sum_{\nu \in \Lambda} \otimes S(\nu^m)) \bigotimes S(\lambda^m) \]

is exactly the restriction to \( \sum_{\nu \in \Lambda} \otimes S(\lambda^m) \) of the standard module labelled by \( \lambda^m \) for the classical Brauer algebra \( B(2\varphi^0 + |\lambda^m|, \delta') \) (any parameter \( \delta' \)). And similarly for the last term. Note also that

\[ ((k \sum_{\nu \in \Lambda} \otimes S(\nu^m)) \bigotimes S(\lambda^m)) \bigotimes S(\lambda^{m-i}) \bigotimes S(\nu_i^m) \bigotimes S(\nu_i^{m-i}) \]

is exactly the restriction to \( \sum_{\varphi^0 + |\lambda|} \otimes S(\varphi^i + |\lambda^m-i|) \) of the standard module labelled by \( (\lambda^i, \lambda^m) \) for the walled Brauer algebra \( WB(\varphi^i + |\lambda|, \varphi_i^m + |\lambda^m-i|, \delta') \) (any parameter \( \delta' \)). The result now follows from [DWH99] and [Hal98] (by replacing \( \varphi_i \) by \( a_i \) in the statement).

**Corollary 4.2.2.** Let \( \lambda, \mu \in \Lambda(m, n) \). If \( [\Delta_n(\lambda) : L_n(\mu)] \neq 0 \) then \( \lambda \leq \mu \).

## 5. Truncation to idempotent subalgebras

In this section we show that maximal co-saturated idempotent subalgebras of \( B_n^m \) are isomorphic to a tensor product of classical and walled Brauer algebras. Hence we determine the space of homomorphisms between standard modules and the decomposition numbers for \( B_n^m \).

### 5.1. Co-saturated sets

For \( \omega \in \Lambda[m, n] \) an \( m \)-composition of \( n \), we define \( (\preceq \omega) \subseteq \Lambda[m, n] \) to be the subset of all \( m \)-compositions less than or equal to \( \omega \) with respect to \( \preceq \). We define \( \Lambda_\omega \) to be the pre-image of \( (\preceq \omega) \) in \( \Lambda(m, n) \), that is the set of all \( m \)-partitions \( \lambda \) with \( |\lambda| \preceq \omega \).

**Example 5.1.1.** The diagram in Figure 11 is the Hasse diagram of the poset \( (\preceq (1, 1, 4)) \subseteq \Lambda[3, 6] \). We have again annotated the edges with the signed partial ordering.

![Figure 11](image.png)

**Figure 11.** A sub-poset of the Hasse poset in Figure 9.
We have chosen to work with the partial order $\leq$ on $\Lambda(m, n)$ as it is a refinement of the natural partial ordering given by inclusion on the set of multipartitions. Note, however, that $B^n_m(\delta)$ is quasi-hereditary with respect to the opposite partial order $\leq_{\text{opp}}$ on $\Lambda(m, n)$, and we have that $\Lambda_\omega \subseteq (\Lambda(m, n), \leq_{\text{opp}})$ is a co-saturated subset. So we can apply the results from [Don98, Appendix] on idempotent subalgebras corresponding to co-saturated subsets for quasi-hereditary algebras. The first thing we need is an idempotent corresponding to $\Lambda_\omega$.

5.2. Idempotents and standard modules

In this section we consider the effect of applying the idempotents $\pi_\omega$ defined in Section 2.2 to standard modules.

Recall that an $(m, n, l)$-dangle $v$ can be described as a set of $l$ disjoint pairs $(i_p, j_p) \in \{1, \ldots, n\}^2$, called arcs, where each arc is labelled by an element of $\mathbb{Z}/m\mathbb{Z}$. We say that $v$ belongs to $\omega$ if every arc $(i_p, j_p)$ (for $p = 1, \ldots, l$) satisfies $i_p \in [\omega_p]$ and $j_p \in [\omega_m - r_p]$ for some $0 \leq r_p \leq [m/2]$. In this case we define $\omega \setminus v$ by

$$\omega \setminus v = \omega - \sum_{p=1}^{l}(\epsilon_{r_p} + \epsilon_{m-r_p}) \in \Lambda|m, n|$$

where $\epsilon_{r_p} = (0, \ldots, 0, 1, 0, \ldots, 0)$ with a 1 in position $r_p$ (and similarly for $\epsilon_{m-r_p}$).

**Proposition 5.2.1.** Let $v$ be an $(m, n, l)$-tangle, $\lambda \in \Lambda(m, n)$ and $x \in S(\lambda)$. Then we have

$$\pi_\omega(v \otimes x) = \begin{cases} T_{i_1}^{r_1} T_{i_2}^{r_2} \cdots T_{i_l}^{r_l} v \otimes \pi_\omega x & \text{if } v \text{ belongs to } \omega \\ 0 & \text{otherwise.} \end{cases}$$

In particular, we have that $\pi_\omega \Delta_n(\lambda) \neq 0$ if and only if $\lambda \in \Lambda_\omega$.

**Proof.** Note that for each arc $(i_p, j_p)$ of $v$ we have

$$T_{i_p}^r v = T_{j_p}^{m-r} v.$$ 

Now as $\{T_i^r : 0 \leq r \leq m-1\}$ form a set of orthogonal idempotents we have

$$T_{i_p}^r T_{j_p}^s v = T_{i_p}^r T_{j_p}^{m-s} v = \begin{cases} T_{i_p}^r v & \text{if } s = m-r \\ 0 & \text{otherwise.} \end{cases}$$

Thus we have that $\pi_\omega(v \otimes x) = 0$ unless $v$ belongs to $\omega$. Now it is easy to see that $\pi_\omega$ acts on the free vertices of $v$ by $\pi_{\omega \setminus v}$. So if $v$ belongs to $\omega$ we get

$$\pi_\omega(v \otimes x) = T_{i_1}^{r_1} T_{i_2}^{r_2} \cdots T_{i_l}^{r_l} v \otimes \pi_{\omega \setminus v} x$$

as required. Now using Section 2.2 we have that

$$\pi_{\omega \setminus v} S(\lambda) \cong \begin{cases} S(\lambda^0) \otimes S(\lambda^1) \otimes \cdots \otimes S(\lambda^{m-1}) & \text{if } |\lambda| = |\omega \setminus v| \\ 0 & \text{otherwise.} \end{cases}$$

Finally note that $\lambda \in \Lambda_\omega$ if and only if $|\lambda| = |\omega \setminus v|$ for some $v$ belonging to $\omega$. This proves the last part of the proposition. \qed

5.3. Truncation functors

We now consider the truncation functor defined by the idempotent $\pi_\omega$. From now on we shall denote $\pi_\omega B^n_m$ by $B^n_\omega$. The truncation functor is defined by

$$f_\omega : B^n_m \text{-mod} \rightarrow B^n_\omega \text{-mod}$$

$$M \mapsto \pi_\omega M.$$ 

Using Proposition 5.2.1 and [Don98, A3.11] we have the following result.
Theorem 5.4.2. Let
\[ f_\omega L_n(\lambda) : \lambda \in \Lambda_\omega \].
This follows from the definition of \( f_\omega \Delta_\omega(\lambda) \) for all \( \lambda \in \Lambda_\omega \).

Proof. \( \{ \text{belonging to} \} \)

For \( M \in B_\omega^m \)-mod we write \( M \in \mathcal{F}_\omega(\Delta) \) to indicate that \( M \) has a filtration with subquotients belonging to \( \{ \Delta_\omega(\lambda) : \lambda \in \Lambda_\omega \} \).

Proposition 5.3.2 (A3.13 [Don98]). Let \( X, Y \in B_\omega^m \)-mod with \( X \in \mathcal{F}_\omega(\Delta) \). For all \( i \geq 0 \) we have
\[ \text{Ext}^i_{B_\omega^m}(X, Y) \cong \text{Ext}^i_{B_\omega^m}(f_\omega X, f_\omega Y) \].

As \( P_n(\lambda) \in \mathcal{F}_\omega(\Delta) \) for all \( \lambda \in \Lambda_\omega \) and \( [\Delta_\omega(\mu) : L_n(\lambda)] = \dim \text{Hom}(P_n(\lambda), \Delta_\omega(\mu)) \) we have the following corollary.

Corollary 5.3.3. For all \( \lambda, \mu \in \Lambda_\omega \) we have
\[ [\Delta_\omega(\mu) : L_n(\lambda)] = [f_\omega \Delta_\omega(\mu) : f_\omega L_n(\lambda)] \).

5.4. The idempotent subalgebras \( B_\omega^m \)
We now wish to understand the structure of these idempotent subalgebras. Therefore we start by considering the image, in \( B_\omega^m \), of the generators of the cyclotomic Brauer algebra \( B_n^m \).

Lemma 5.4.1. Let \( 1 \leq i, j \leq n \) and let \( \omega \) be an \( m \)-composition of \( n \). Then we have
\( \pi_\omega t^k_i \pi_\omega = \xi^{-kr} \pi_\omega \) if \( i \in [\omega_r] \) for some \( 0 \leq r \leq m - 1 \).
\( \pi_\omega t^k_i j \pi_\omega \neq 0 \) if and only if \( i, j \in [\omega_r] \) for some \( 0 \leq r \leq m - 1 \).
\( \pi_\omega e_{i,j} \pi_\omega \neq 0 \) if and only if \( i \in [\omega_r] \) and \( j \in [\omega_{m-r}] \) for some \( 0 \leq r \leq m - 1 \).

Proof. This follows from the definition of \( \pi_\omega \), equation (4.2.1) and the fact that the \( T^r_i \)’s for \( 0 \leq r \leq m - 1 \) (and fixed \( i \)) are orthogonal idempotents.

We now state the main result of this section.

Theorem 5.4.2. Let \( \omega \) be an \( m \)-composition of \( n \). The algebra \( B_\omega^m \) is isomorphic to a product of Brauer and walled Brauer algebras with parameters \( \delta_r \) for \( 0 \leq r \leq \lfloor m/2 \rfloor \). More specifically
\[ B_\omega^m \cong B(\omega_0, \delta_0) \otimes \bigotimes_{r=1}^{\lfloor m/2 \rfloor} WB(\omega_r, \omega_{m-r}, \delta_r) \]
if \( m \) is odd, and
\[ B_\omega^m \cong B(\omega_0, \delta_0) \otimes \left( \bigotimes_{r=1}^{\lfloor m/2 \rfloor-1} WB(\omega_r, \omega_{m-r}, \delta_r) \right) \otimes B(\omega_{m/2}, \delta_{m/2}) \]
if \( m \) is even.

Remark 5.4.3. In our definition of multiplication for \( B_\omega^m \) we chose one of two possible orientations of the closed loops. Had we favoured the alternative orientation, the above proposition would be stated in terms of the conjugate parameters \( \delta_r \) such that \( m/2 \leq r \leq m - 1 \). This makes no difference to the representation theory as we obtain non-semisimple specialisations only when these parameters are integral — in which case \( \delta_r = \delta_{m-r} \).
Proof. We will assume that \( m \) is even in the proof. The case \( m \) odd is obtained by ignoring all the terms corresponding to \( m/2 \).

We view the tensor product of Brauer and walled Brauer algebras as a diagram algebra spanned by certain Brauer diagrams with \( n \) northern and southern nodes. More precisely, as vector spaces, we embed \( B(\omega_0, \delta_0) \otimes \bigotimes_{0 \leq r < m/2} W B(\omega_r, \omega_{m-r}, \delta_r) \) into the vector space \( B(n) \) by partitioning the \( n \) northern and southern nodes according to \( \omega \), that is we draw a wall after the first \( \omega_0 \) nodes, then another wall after the next \( \omega_1 \) nodes, etc. We embed the diagrams in \( B(\omega_r, \omega_{m-r}, \delta_r) \) using the first \( \omega_0 \) northern and southern nodes. For \( 0 \leq r < m/2 \) we embed the diagrams in \( B(\omega_r, \omega_{m-r}, \delta_r) \) using all nodes \( i, \bar{i} \in [\omega_r] \) or \( [\omega_{m-r}] \). Finally, we embed \( B(\omega_{m/2}, \delta_{m/2}) \) using all nodes \( i, \bar{i} \in [\omega_{m/2}] \). An example of such a diagram is given in Figure 12.

![Diagram](image-url)

**Figure 12.** An example of the embedding of
\[
B(3, \delta_0) \otimes WB(2, 3, \delta_1) \otimes WB(3, 1, \delta_2) \otimes B(2, \delta_0)
\]
into \( B(14) \) corresponding to the 6-composition \( \omega \) of 14 given by \( \omega = (3, 2, 3, 2, 1, 3) \).

Now the multiplication is given by concatenation. Note that each closed loop obtained by concatenation only contains nodes \( i \in [\omega_r] \) or \( [\omega_{m-r}] \) for some \( 0 \leq r \leq \lfloor m/2 \rfloor \); we then remove this closed loop and multiply by the scalar \( \delta_r \).

We denote by \( \sigma_{i,j} \), resp. \( u_{i,j} \), the unoriented version of \( t_{i,j} \), resp. \( e_{i,j} \). Now define the map
\[
\phi : B^m_\omega \to B(\omega_0, \delta_0) \otimes \bigotimes_{0 \leq r < m/2} W B(\omega_r, \omega_{m-r}, \delta_r) \otimes B(\omega_{m/2}, \delta_{m/2})
\]
on generators by setting \( \phi(\pi_\omega) = 1 \), \( \phi(\pi_\omega t_{i,j} \pi_\omega) = \sigma_{i,j} \) for all \( i < j \in [\omega_r] \) for some \( 0 \leq r \leq m - 1 \), and \( \phi(\pi_\omega e_{i,j} \pi_\omega) = u_{i,j} \) for all \( i < j \in [\omega_r] \) and \( j \in [\omega_{m-r}] \) for some \( 0 \leq r \leq \lfloor m/2 \rfloor \). It is clear from the description in terms of diagrams that \( \phi \) gives a bijection and that all the relations involving only the \( \sigma_{i,j} \)'s, or the \( u_{i,j} \)'s and the \( e_{i,j} \)'s are satisfied. It remains to show that for \( i \in [\omega_r] \) and \( j \in [\omega_{m-r}] \) we have \( (\pi_\omega e_{i,j} \pi_\omega)^2 = \delta_r (\pi_\omega e_{i,j} \pi_\omega) \).

Now we have
\[
(\pi_\omega e_{i,j} \pi_\omega)^2 = \pi_\omega e_{i,j} \pi_\omega e_{i,j} \pi_\omega = \pi_\omega e_{i,j} T_i^r T_j^{m-r} e_{i,j} \pi_\omega = \pi_\omega e_{i,j} (T_i^r)^2 e_{i,j} \pi_\omega = \pi_\omega e_{i,j} T_i^r e_{i,j} \pi_\omega = \sum_{a=0}^{m-1} \xi^a \delta_a \pi_\omega \pi_\omega e_{i,j} \pi_\omega = \sum_{a=0}^{m-1} \xi^a \delta_a \pi_\omega e_{i,j} \pi_\omega = \delta_r (\pi_\omega e_{i,j} \pi_\omega).
\]

\[\Box\]

### 5.5. Homomorphisms and decomposition numbers

Recall that the standard modules for the classical Brauer algebra \( B(n, \delta) \) are indexed by partitions \( \lambda \) of \( n - 2l \) for \( 0 \leq l \leq \lfloor n/2 \rfloor \). For each partition \( \lambda \) of \( n - 2l \), the standard \( B(n, \delta) \)-module \( \Delta_{B(n)}(\lambda) \)
can be constructed by inflating the Specht module $S(\lambda)$ along $V(1, n, l)$, and it has simple head $L_{B(n)}(\lambda)$. The standard modules for the walled Brauer algebra $WB(r, s, \delta)$ are indexed by bi-partitions $(\lambda, \mu)$ of $(r - l, s - l)$ for $0 \leq l \leq \min\{r, s\}$. For each bi-partition $(\lambda, \mu)$, the standard $WB(r, s, \delta)$-module $\Delta_{WB(r,s)}(\lambda, \mu)$ can be constructed similarly by inflating the tensor product of Specht modules $S(\lambda) \otimes S(\mu)$ along the corresponding subspace of dangles, and it has simple head $L_{WB(r,s)}(\lambda, \mu)$.

**Proposition 5.5.1.** For $\lambda \in \Lambda_\omega$ the module $\Delta_{\omega n}(\lambda) = f_\omega \Delta_n(\lambda)$ is isomorphic to

$$
\Delta_{\omega_0}(\lambda^0) \otimes \bigotimes_{1 \leq r \leq [m/2]} \Delta_{WB(\omega_r, \omega_{m-r})}(\lambda^r, \lambda^{m-r}) \otimes \Delta_{\omega_{m/2}}(\lambda^{m/2})
$$

(under the isomorphism given in Theorem 5.4.3) where we ignore the last term when $m$ is odd.

**Proof.** By Proposition 5.3.1(iii), we know that $f_\omega \Delta_n(\lambda)$ is a standard module. So we only need to show that it is labelled by the same partition. Now the required tensor product of standard modules is characterised by the fact that when we localise this module to

$$
B(|\lambda^0|) \otimes \left( \bigotimes_{1 \leq r \leq [m/2]} WB(|\lambda^r|, |\lambda^{m-r}|) \right) \otimes B(|\lambda^{m/2}|)
$$

we get a module isomorphic to

$$
S(\lambda^0) \otimes \left( \bigotimes_{1 \leq r \leq [m/2]} (S(\lambda^r) \otimes S(\lambda^{m-r})) \right) \otimes S(\lambda^{m/2}).
$$

But it is clear that $f_\omega \Delta_n(\lambda)$ satisfies this condition using Proposition 5.2.1 and Section 2.3.1. □

**Corollary 5.5.2.** Let $\lambda, \mu \in \Lambda(m, n)$ and define $\omega = |\lambda|$. Then (i) $\text{Hom}_{B_m}(\Delta_n(\lambda), \Delta_n(\mu))$ is isomorphic to

$$
\text{Hom}_{B_{\omega}}(\Delta_{\omega_0}(\lambda^0), \Delta_{\omega_0}(\mu^0)) \otimes \bigotimes_{0 < r < m/2} \text{Hom}_{WB(\omega_r, \omega_{m-r})}(\Delta_{WB}(\lambda^r, \lambda^{m-r}), \Delta_{WB}(\mu^r, \mu^{m-r}))
$$

$$
\otimes \text{Hom}_{B_{\omega_{m/2}}}(\Delta_{\omega_{m/2}}(\lambda^{m/2}), \Delta_{\omega_{m/2}}(\mu^{m/2})).
$$

(ii) The decomposition numbers $[\Delta_n(\mu) : L_n(\lambda)]$ factorise as

$$
[\Delta_{\omega_0}(\mu^0) : L_{\omega_0}(\lambda^0)] \times \prod_{0 < r < m/2} [\Delta_{WB}(\mu^r, \mu^{m-r}) : L_{WB}(\lambda^r, \lambda^{m-r})] \times [\Delta_{\omega_{m/2}}(\mu^{m/2}) : L_{\omega_{m/2}}(\lambda^{m/2})].
$$

(We ignore the last term in (i) and (ii) when $m$ is odd).

**Proof.** By localisation (3.2.3), we can always assume that $\lambda$ is an $m$-partition of $n$. Now, we have seen in Corollary 4.2.2 that a necessary condition for a non-zero homomorphism (or decomposition number) is that $\lambda \geq \mu$. Thus we have $\lambda, \mu \in \Lambda_\omega$ where $\omega = |\lambda|$. We then obtain the results using Propositions 5.5.1 and 5.3.2 and Corollary 5.3.3. □

**Remark 5.5.3.** Let $\omega$ be an $m$-composition of $n$ and let $\lambda, \mu \in \Lambda_\omega$. Then, using Proposition 5.3.2, we have more generally that

$$
\text{Ext}^i_{B_{\omega}}(\Delta_n(\lambda), \Delta_n(\mu)) \cong \text{Ext}^i_{B_{\omega}}(\Delta_{\omega}(\lambda), \Delta_{\omega}(\mu))
$$

for all $i \geq 0$. 
Remark 5.5.4. (i) With this factorisation of the decomposition numbers at hand, one can easily deduce the block structure of $B_n^m$ (in terms of that of the walled and classical Brauer algebras).

(ii) The decomposition numbers for the Brauer and walled Brauer algebras in characteristic zero are known by [Mar] and [CD11], and so we have determined the decomposition numbers for the cyclotomic Brauer algebra in characteristic zero.

6. Appendix: The unoriented cyclotomic Brauer algebra

There is another version of the cyclotomic Brauer algebra, which we will denote by $\tilde{B}_n^m(\delta)$, spanned by unoriented reduced $(m,n)$-diagrams. As a vector space, it coincides with $B_n^m$ but the multiplication is simply given by concatenation, addition (in $\mathbb{Z}/m\mathbb{Z}$) of the labels on each strands, and replacing any closed loop labelled by $Z$ with scalar multiplication by $\delta_r$.

All the arguments in this paper apply to the unoriented cyclotomic Brauer algebra as well, and it turns out that the corresponding idempotent subalgebras are isomorphic to a tensor product of classical Brauer algebras in this case. Hence this gives a factorisation of the decomposition numbers of $B_n^m$ as a product of decomposition numbers for the classical Brauer algebras. We will now briefly sketch the modifications required.

The algebra $\tilde{B}_n^m$ is still an iterated inflation of the algebras $H_n^m$ but along the spaces of unoriented dangles. All the results in Section 3 hold as before if we replace $m-r$ by $r$ in Lemma 3.2.2(ii) and Proposition 3.2.4. In Section 4, note that in equation (4.2.1) and equation (4.2.2) we have to replace $m-r$ with $r$ again. Now following the argument in Section 4.2 we obtain

$$[\Delta_n(\lambda) \downarrow_{H_n^m} S(\mu)] = \prod_{0 \leq j \leq m-1} \sum_{\eta \in \mathbb{P}^{n\eta}} c_{\lambda,\eta}^{\mu,j}.$$

We modify the partial ordering $\leq$ and $\leq$ accordingly. For $\omega, \omega' \in \Lambda(m,n)$ we set $\omega \leq \omega'$ if and only if $\omega_r - \omega'_r \geq 0$ and $\omega_r - \omega'_r$ is even for all $0 \leq r \leq m-1$. We then define $\leq$ on $\Lambda(m,n)$ by setting $\lambda \leq \mu$ if and only if $|\lambda| \leq |\mu|$ and $\lambda' \subseteq \mu'$ for all $0 \leq r \leq m-1$. We then have that Corollary 4.2.2 holds with respect to this new partial order. In Section 5 we can define the co-saturated subset $\Lambda_\omega$ as before (using the new partial order). Replacing $m-r$ with $r$ throughout the arguments we obtain that

$$\tilde{B}_\omega \cong \bigotimes_{0 \leq r \leq m-1} B(\omega_r, \delta_r),$$

and hence we get the required factorisation of homomorphisms between standard modules and of decomposition numbers.

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