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ON A RESULT OF KIYOTA, OKUYAMA AND WADA

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Abstract

M. Kiyota, T. Okuyama and T. Wada recently proved that each 2-block of a symmetric group Σ_n contains a unique irreducible Brauer character of height 0. We present a more conceptual proof of this result.

1. Background on bilinear forms

According to the main result in [6], every 2-block of the symmetric group Σ_n has a unique irreducible Brauer character of height 0. This is not true for an arbitrary 2-block of a finite group. For example, let B be a real non-principal 2-block which is Morita equivalent to the group algebra of A_4 and which has a Klein-four defect group and a dihedral *extended defect group* (in the sense of [1]). Then one can show that B has three real irreducible Brauer characters of height 0. The non-principal 2-block of $((C_2 \times C_2) : C_9) : C_2$ is of this type.

In this note we place the results of [6] in a more general context using the approach to bilinear forms developed by R. Gow and W. Willems [2]. We use results and notation from [7] for representation theory, from [5] for symmetric groups, and from [8] for bilinear forms in characteristic 2.

Let G be a finite group and let (K, R, F) be a 2-modular system for G . So R is a complete discrete valuation ring with field of fractions K of characteristic 0, and residue field $R/J = F$ of characteristic 2. Assume that K contains a primitive $|G|$ -th root of unity, and that F is perfect. Then K and F are splitting fields for each subgroup of G .

The anti-isomorphism $g \mapsto g^{-1}$ on G extends to an involutory F -algebra anti-automorphism $\sigma : FG \rightarrow FG$ called the *contragredient map*. Let V be a right FG -module. The linear dual $V^* := \text{Hom}_F(V, F)$ is considered as a right FG -module via $(f \cdot x)(v) := f(vx^\sigma)$, for $f \in V^*$, $x \in FG$ and all $v \in V$. The Frobenius automorphism $\lambda \mapsto \lambda^2$ of the field F induces an automorphism $(a_{ij}) \mapsto (a_{ij}^2)$ of the group $\text{GL}_F(V)$. Composing the module map $G \rightarrow \text{GL}_F(V)$ with this automorphism endows V with another FG -module structure. This module is called the *Frobenius twist* of V , and is denoted $V^{(2)}$.

Let $V^* \otimes V^*$ be the space of bilinear forms on V and let $\Lambda^2(V^*)$ be the subspace of *symplectic bilinear forms* on V ; a bilinear form $b: V \times V \rightarrow F$ is symplectic if and only if $b(v, v) = 0$, for all $v \in V$. The quotient space $V^* \otimes V^* / \Lambda^2(V^*)$ is called the *symmetric square* of V^* and is denoted $S^2(V^*)$.

A *quadratic form* on V is a map $Q: V \rightarrow F$ such that $Q(\lambda v) = \lambda^2 Q(v)$ and $(u, v) \mapsto Q(u + v) - Q(u) - Q(v)$ is a bilinear form on V , for all $u, v \in V$ and $\lambda \in F$. Now if b is a bilinear form, its *diagonal* $\delta(b): v \mapsto b(v, v)$ is a quadratic form. The assignment δ is linear with kernel $\Lambda^2(V^*)$. So there is a short exact sequence of vector spaces

$$(1) \quad 0 \rightarrow \Lambda^2(V^*) \rightarrow V^* \otimes V^* \xrightarrow{\delta} S^2(V^*) \rightarrow 0.$$

We may identify $S^2(V^*)$ with the space of quadratic forms on V . If Q is a quadratic form, its *polarization* is the associated bilinear form $\rho(Q): (u, v) \mapsto Q(u + v) - Q(u) - Q(v)$.

The dual $S^2(V)^*$ of the symmetric square $S^2(V)$ of V is the space of *symmetric bilinear forms* on V . As $\text{char}(F) = 2$, each symplectic form is symmetric. If b is a symmetric bilinear form, $\delta(b)$ is additive and hence can be identified with a linear map $V^{(2)} \rightarrow F$. Thus there is a short exact sequence:

$$(2) \quad 0 \rightarrow \Lambda^2(V^*) \rightarrow S^2(V)^* \xrightarrow{\delta} V^{(2)*} \rightarrow 0.$$

All of these F -spaces are FG -modules, and the maps are FG -module homomorphisms. It is a singular feature of the characteristic 2-theory that $S^2(V^*)$ and $S^2(V)^*$ need not be isomorphic as FG -modules.

Now let b be a bilinear form on V . We say that b is *G-invariant* if the associated map $v \mapsto b(v, \cdot)$ for $v \in V$, is an FG -module map $V \rightarrow V^*$. We say that b is *nondegenerate* if this map is an F -isomorphism. Taking G -fixed points in (2) we get a long exact sequence of the form

$$0 \rightarrow \Lambda^2(V^*)^G \rightarrow S^2(V)^{*G} \xrightarrow{\delta} V^{(2)*G} \rightarrow H^1(G, \Lambda^2(V^*)) \rightarrow \dots$$

In particular, if $V^{(2)*G} = 0$, then each G -invariant symmetric bilinear form on V is symplectic. Now the trivial FG -module equals its Frobenius twist. A simple argument then shows:

Lemma 1. *If $V \cong V^*$, and V has no trivial G -submodules, then each G -invariant symmetric bilinear form on V is symplectic.*

We will make use of Fong's lemma:

Lemma 2. *Let V be an absolutely irreducible non-trivial FG -module. Then $V \cong V^*$ if and only if V affords a nondegenerate G -invariant symplectic bilinear form. In particular $\dim(V)$ is even.*

For $h \in G$ define a quadratic form Q_h on FG by setting, for $u = \sum_{g \in G} u_g g \in FG$

$$(3) \quad Q_h(u) = \begin{cases} \sum_{\{g, hg\} \subseteq G} u_g u_{hg}, & \text{if } h^2 = 1, \\ \sum_{g \in G} u_g u_{hg}, & \text{if } h^2 \neq 1. \end{cases}$$

Then $Q_h = Q_{h^{-1}}$ and $\{Q_h \mid \{h, h^{-1}\} \subseteq G\}$ is a basis for the space of G -invariant quadratic form on FG .

2. Real 2-blocks of defect zero

Assume that G has even order, and that B is a real 2-block of G which has a trivial defect group. Equivalently B is a simple F -algebra which is a σ -invariant $FG \times G$ -direct summand of FG . Moreover, B has a unique irreducible K -character χ and a unique simple module S .

Let e_B be the identity element (or block idempotent) of B . Then

$$e_B = e_1 + e_2 + \cdots + e_d,$$

where $d = \dim_F(S)$ and the e_i are pairwise orthogonal primitive idempotents in FG . Each $e_i FG$ is isomorphic to S . In particular S is a projective FG -module.

Let M be an RG -lattice whose character is χ . Then $M/J(R)M \cong S$, as FG -modules. Now M has a quadratic geometry because χ has Frobenius-Schur indicator $+1$. Thus S has a quadratic geometry.

By [2] there exists an involution t in G such that the restriction of the form Q_t of (3) to $e_1 FG$ is non-degenerate. It follows that e_1 can be chosen so that $e_1 = e_1^{t\sigma}$ (where $e_1^{t\sigma} = (te_1 t)^\sigma = te_1^\sigma t$). We note that it can be shown that $\langle t \rangle$ is an extended defect group of B and S is a direct summand of the induced module $F_{C_G(t)} \uparrow^G$.

As $e_B = e_B^{t\sigma}$, we have $e_B = e_1 + e_2^{t\sigma} + \cdots + e_d^{t\sigma}$, and each $e_i^{t\sigma}$ is primitive in FG and $e_1 e_i^{t\sigma} = 0 = e_i^{t\sigma} e_1$, for $i > 1$.

Suppose next that V is a B -module, equipped with a (possibly degenerate) G -invariant symmetric bilinear form $\langle \cdot, \cdot \rangle$. The G -invariance is equivalent to $\langle ux, v \rangle = \langle u, vx^\sigma \rangle$, for all $u, v \in V$ and $x \in FG$. Now $e_1 e_i = 0$, for $i > 1$. So

$$\langle Ve_1, Ve_i^\sigma \rangle = 0, \quad \text{for } i > 1.$$

Following [6], we define a bilinear form b on the F -space Ve_1 by

$$b(ue_1, ve_1) := \langle ue_1, ve_1 t \rangle, \quad \text{for all } ue_1, ve_1 \in Ve_1.$$

Then b is symmetric, as

$$b(ue_1, ve_1) = \langle ue_1 t, ve_1 \rangle = \langle ve_1, ue_1 t \rangle = b(ve_1, ue_1).$$

Now consider the radicals of the forms

$$\begin{aligned}\text{rad}(V) &:= \{u \in V \mid \langle u, v \rangle = 0, \forall v \in V\}, \\ \text{rad}(Ve_1) &:= \{ue_1 \in Ve_1 \mid b(ue_1, ve_1) = 0, \forall ve_1 \in Ve_1\}.\end{aligned}$$

We include a proof of Lemma 4.5 of [6] for the benefit of the reader:

Lemma 3. $\text{rad}(Ve_1) = \text{rad}(V)e_1$ and $Ve_1/\text{rad}(Ve_1) \cong (V/\text{rad}(V))e_1$.

Proof. Let $u \in \text{rad}(V)$ and $ve_1 \in Ve_1$. Then

$$b(ue_1, ve_1) = \langle ue_1, ve_1t \rangle = \langle u, ve_1te_1^\sigma \rangle = 0.$$

So $\text{rad}(Ve_1) \supseteq \text{rad}(V)e_1$. Now let $ue_1 \in \text{rad}(Ve_1)$ and $v \in V$. Writing $v = \sum_{i=1}^d ve_i^\sigma$, we have

$$\langle ue_1, v \rangle = \sum_{i=1}^d \langle ue_1, ve_i^\sigma \rangle = \langle ue_1, ve_1^\sigma \rangle = b(ue_1, ve_1) = 0.$$

So $\text{rad}(Ve_1) \subseteq \text{rad}(V)e_1$. The stated equality follows.

We have an F -vector space map $\phi: Ve_1 \rightarrow (V/\text{rad}(V))e_1$ such that $\phi(ve_1) = ve_1 + \text{rad}(V)$. Now $(v + \text{rad}(V))e_1 = ve_1 + \text{rad}(V)$ as $\text{rad}(V)e_1 \subseteq \text{rad}(V)$. So ϕ is onto. Moreover, $\ker(\phi) = \text{rad}(V)e_1$. The stated isomorphism follows from this. \square

3. Brauer characters of symmetric groups

Let n be a positive integer. Corresponding to each partition λ of n , there is a Young subgroup Σ_λ of Σ_n and a permutation $R\Sigma_n$ -module $M^\lambda := \text{Ind}_{\Sigma_\lambda}^{\Sigma_n}(R\Sigma_\lambda)$. This module has a Σ_n -invariant symmetric bilinear form with respect to which the permutation basis is orthonormal. The *Specht lattice* S^λ is a uniquely determined R -free $R\Sigma_n$ -submodule of M^λ cf. [5, 4.3]. Then $S^\lambda \otimes_R K$ is an irreducible $K\Sigma_n$ -module and all irreducible $K\Sigma_n$ -modules arise in this way.

Now S^λ is usually not a self-dual $R\Sigma_n$ -module; the dual module $S_\lambda := S^{\lambda*}$ is naturally isomorphic to $S^{[1^n]} \otimes_R S_R^{\lambda^t}$ where λ^t is the transpose partition to λ . Note that $S^{[1^n]}$ is the 1-dimensional *sign module*.

Set $\overline{S^\lambda} := S^\lambda / JS^\lambda$. Then $\overline{S^\lambda}$ is a Specht module for $F\Sigma_n$. It inherits an Σ_n -invariant symmetric bilinear form $\langle \cdot, \cdot \rangle$ from S^λ . This form is nonzero if and only if λ is 2-regular (i.e. if λ has different parts).

Suppose that λ is 2-regular. Then $D^\lambda := \overline{S^\lambda} / \text{rad}(\overline{S^\lambda})$ is a simple $F\Sigma_n$ -module, and all simple $F\Sigma_n$ -modules arise uniquely in this way. The D^λ are evidently self-dual. Indeed, $\langle \cdot, \cdot \rangle$ induces a nondegenerate form on D^λ , which by Fong's lemma is symplectic if D^λ is non-trivial. Note that $\overline{S^{[1^n]}}$ is the trivial $F\Sigma_n$ -module, as $\text{char}(F) = 2$.

It follows that the dual of a Specht module in characteristic 2 is a Specht module:

$$\overline{S_\lambda} \cong \overline{S^{\lambda'}}.$$

Let B be a 2-block of Σ_n . Then B is determined by an integer *weight* w such that $n - 2w$ is a nonnegative triangular number $k(k + 1)/2$. The partition $\delta := [k, k - 1, \dots, 2, 1]$ is called the *2-core* of B . Each defect group of B is Σ_n -conjugate to a Sylow 2-subgroup of Σ_{2w} .

Recall that the *2-core* of a partition λ is obtained by successively stripping removable domino shapes from λ . We attach to B all partitions of n which have 2-core δ .

Set $m := n - 2w$ and identify $\Sigma_{2w} \times \Sigma_m$ with a Young subgroup of Σ_n . Now Σ_m has a 2-block B_δ of weight 0 and 2-core δ . This block is real and has a trivial defect group. Moreover, $S^\delta \otimes_R K$ is the unique irreducible $K\Sigma_m$ -module in B_δ and $D^\delta = \overline{S^\delta}$ is the unique simple B_δ -module. It is important to note that D^δ is a projective $F\Sigma_m$ -module and every $F\Sigma_m$ -module in B_δ is semi-simple.

Let e_δ be the block idempotent of B_δ . Following Section 2, choose an involution $t \in \Sigma_m$ and a primitive idempotent e_1 in $F\Sigma_m$ such that $e_1 = e_1 e_\delta$ and $e_1^{t\sigma} = e_1$. Note that $\dim_F(D^\delta e_1) = 1$.

Let μ be a 2-regular partition in B . Regard $V := \overline{S^\mu} e_\delta$ as an $F\Sigma_{2w} \times \Sigma_m$ -module by restriction. Then $V e_1$ is an $F\Sigma_{2w}$ -module, as the elements of Σ_{2w} commute with e_1 . Indeed

$$V \cong V e_1 \otimes_F D^\delta \quad \text{as } F\Sigma_{2w} \times \Sigma_m\text{-modules.}$$

Now $\overline{S^\mu}$ and hence V affords a $\Sigma_{2w} \times \Sigma_m$ -invariant symmetric bilinear form $\langle \cdot, \cdot \rangle$ such that $V/\text{rad}(V) = D^\mu e_\delta$. It then follows from Lemma 3 that we may use the identity $e_1^{t\sigma} = e_1$ to construct a symmetric bilinear form b on $V e_1$. Moreover, $V e_1/\text{rad}(V e_1) \cong D^\mu e_1$. So the $F\Sigma_{2w}$ -module $D^\mu e_1$ inherits a nondegenerate symmetric bilinear form b . Reviewing the construction of b from $\langle \cdot, \cdot \rangle$, we see that b is Σ_{2w} -invariant (as $t \in \Sigma_m$ commutes with all elements of Σ_{2w} , and $\langle \cdot, \cdot \rangle$ is Σ_n -invariant).

Lemma 4. *Suppose that $\mu \neq [k + 2w, k - 1, \dots, 2, 1]$. Then $D^\mu e_1$ affords a non-degenerate Σ_{2w} -invariant symplectic bilinear form.*

Proof. In view of Lemma 1 and the discussion above, it is enough to show that $D^\mu e_1$ has no trivial $F\Sigma_{2w}$ -submodules. Suppose otherwise. Then $F\Sigma_{2w} \otimes_F D^\delta$ is a submodule of the restriction of D^μ to $\Sigma_{2w} \times \Sigma_m$. But D^μ is a submodule of $\overline{S_\mu}$. So D^δ is a submodule of $\text{Hom}_{F\Sigma_{2w}}(F\Sigma_{2w}, \overline{S_\mu})$ as $F\Sigma_m$ -modules.

We have F -isomorphisms

$$\begin{aligned} \text{Hom}_{F\Sigma_{2w}}(F\Sigma_{2w}, \overline{S_\mu}) &\cong \text{Hom}_{F\Sigma_n}(M^{[2w, 1^m]}, \overline{S_\mu}), \quad \text{by Eckmann-Shapiro} \\ &\cong \text{Hom}_{F\Sigma_n}(\overline{S^\mu}, M^{[2w, 1^m]}), \quad \text{as } M^{[2w, 1^m]} \text{ is self-dual.} \end{aligned}$$

As μ is 2-regular, it follows from [5, 13.13] that $\text{Hom}_{F\Sigma_m}(\overline{S^\mu}, M^{[2w, 1^m]})$ has a basis of semistandard homomorphisms. The argument of Theorem 4.5 of [4] now applies, and shows that

$$\text{Hom}_{F\Sigma_{2w}}(F\Sigma_{2w}, \overline{S_\mu}) \cong \overline{S^{\mu^t \setminus [1^{2w}]}} \quad \text{as } F\Sigma_m\text{-modules.}$$

Here $\mu^t \setminus [1^{2w}]$ is a skew-partition of m ; it is empty if $\mu_1 < 2w$ (in which case $\text{Hom}_{F\Sigma_{2w}}(F\Sigma_{2w}, \overline{S_\mu}) = 0$). Otherwise its diagram is the set of nodes in the Young diagram of μ^t not in the top $2w$ rows of the first column. Now $\overline{S^{\mu^t \setminus [1^{2w}]}}$ has an $F\Sigma_m$ -submodule isomorphic to D^δ if and only if $S_K^{\mu^t \setminus [1^{2w}]}$ has a $K\Sigma_m$ -submodule isomorphic to S_K^δ , as $D^\delta = \overline{S^\delta}$, and using the projectivity of D^δ .

The multiplicity of S_K^δ in $S_K^{\mu^t \setminus [1^{2w}]}$ is the number of $\mu \setminus [2w]$ -tableau of type $\delta^t = \delta$ which are strictly increasing along rows and nondecreasing down columns. Suppose for the sake of contradiction that such a tableau T exists.

We claim that $\mu_i \leq k - i + 2$ for $i = 2, \dots, k$, and $\mu_i = 0$ for $i > k + 1$. This is true for $i = 2$, as the entries in the second row of T are different. Suppose that $i \geq 2$ and $\mu_{i-1} \leq k - i + 3$. But $\mu_i < \mu_{i-1}$, as μ is 2-regular. So $\mu_i \leq k - i + 2$, proving our claim.

On the other hand, $\mu_i \geq \delta_i = k - i + 1$, for $i = 1, \dots, k$, as μ has 2-core δ . It follows that $\mu \setminus \delta$ consists of the last $\mu_1 - k$ nodes in the first row of μ , and a subset of the nodes $(2, k), (3, k - 1), \dots, (k, 2), (k + 1, 1)$. On the other hand, μ has 2-core δ . So $\mu \setminus \delta$ is a union of domino shapes. It follows that T does not exist if $\mu \neq [k + 2w, k - 1, \dots, 2, 1]$. This contradiction completes the proof of the lemma. \square

Suppose that G is a finite group and that B is a 2-block of G with defect group $P \leq G$. Then it is known that $[G : P]_2$ divides the degree of every irreducible Brauer character in B . Recall that a Brauer character in B has *height zero* if the 2-part of its degree is $[G : P]_2$. We now prove the main result of [6].

Theorem 5. *Let B be a 2-block of Σ_n . Then B contains a unique irreducible Brauer character of height 0.*

Proof. Suppose as above that B has weight w and 2-core δ , and let θ be a height zero irreducible Brauer character in B . Then θ is the Brauer character of D^μ for some 2-regular partition μ of n belonging to B .

Let P be a vertex of D^μ . Then P is a defect group of B . We may assume that P is a Sylow 2-subgroup of Σ_{2w} . It is easy to show that $N_{\Sigma_n}(P) = P \times \Sigma_m$, a subgroup of $\Sigma_{2w} \times \Sigma_m$.

Let B_0 denote the principal 2-block of Σ_{2w} . Then $B_0 \otimes B_\delta$ is the Brauer correspondent of B with respect to $(\Sigma_n, P, \Sigma_{2w} \times \Sigma_m)$. So the Green correspondent of D^μ with respect to $(\Sigma_n, P, \Sigma_{2w} \times \Sigma_m)$ has the form $U^\mu \otimes D^\delta$, where U^μ is an indecomposable

Σ_{2w} -direct summand of $D^\mu e_1$ which belongs to B_0 . Moreover, U^μ is the unique component of $D^\mu e_1$ that has vertex P .

If $\mu = [k + 2w, k - 1, \dots, 2, 1]$ it can be shown that U^μ is the trivial $F\Sigma_{2w}$ -module. Suppose that $\mu \neq [k + 2w, k - 1, \dots, 2, 1]$. Lemma 4 implies that $D^\mu e_1$ has a symplectic geometry. It then follows from the first proposition in [3] that U^μ has a symplectic geometry. In particular $\dim(U^\mu)$ is even.

Now the 2-part of $\dim(U^\mu \otimes D^\delta)$ divides $2|\Sigma_m|_2 = 2[\Sigma_n : P]_2$. A standard result on the Green correspondence implies that the 2-part of $\dim(D^\mu)$ divides $2[\Sigma_n : P]_2$. This contradicts the assumption that θ has height zero, and completes the proof. \square

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