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京都大学
RELATIVE PROJECTIVITY OF CARLSON MODULES

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1. INTRODUCTION

The simple groups of 2-rank two were classified about 1970 by Alperin, Brauer, Gorenstein, Walter, and Lyons. See for example Alperin-Brauer-Gorenstein [3]. The 2-groups of rank two which can be Sylow 2-subgroups of finite simple groups are

1. dihedral 2-groups (including four-groups);
2. semidihedral 2-groups;
3. wreathed 2-groups;
4. special 2-group which is a Sylow 2-subgroup of $SU(3,4)$.

All finite groups with these Sylow 2-subgroups above were determined in those works.

The cohomology algebras of finite simple groups of 2-rank two have been known, depending on the classification theorems and on the fact that the cohomology algebras of some classical groups were calculated. A nice overview of these results is in the work by Adem-Milgram [1].

\begin{table}
\centering
\begin{tabular}{|c|c|c|}
\hline
Sylow 2-subgroup & Simple Groups & Cohomology Algebras \\
non-abelian & & \\
\hline
dihedral & $PSL(2,q)$, $q$ odd $A_7$ & $k[\varepsilon_2, \zeta_3, \theta_3]/(\zeta \theta)$ \\
 & $PSL(2,q)$, $q$ odd $A_7$ & \\
semidihedral & $PSL(3,q)$, $q \equiv 3 \pmod{4}$ $PSU(3,q)$, $q \equiv 1 \pmod{4}$ $M_{11}$ & $k[\beta_3, \gamma_4, \delta_5]/(\beta^2 \gamma - \delta^2)$ \\
 & $PSL(3,q)$, $q \equiv 1 \pmod{4}$ $PSU(3,q)$, $q \equiv 1 \pmod{4}$ $M_{11}$ & \\
\hline
wreathed & $PSL(3,q)$, $q \equiv 1 \pmod{4}$ $PSU(3,q)$, $q \equiv 3 \pmod{4}$ & $k[\theta_3, \rho_4, \theta_5, \sigma_6]/(\theta_3^2, \theta_5^2)$ \\
\hline
special of order 64 & $SU(3,4)$ & \\
\hline
\end{tabular}
\caption{Finite simple groups of 2-rank 2 and cohomology algebras}
\end{table}

Remark 1.1. In Table 1 the subscript of a cohomology class indicates the degree. For example $\rho_4$ is of degree 4, $\sigma_6$ is of degree 6, and so on.

From the late 1980's the mod 2 cohomology algebras of those finite groups with dihedral, semidihedral, and quaternion Sylow 2-subgroups have been calculated:
(1) dihedral and quaternion case by Martino-Priddy [21], 1991; by Asai-Sasaki [5], 1993;
(2) semidihedral case by Martino [20], 1988; by Sasaki [24], 1994.

The works by Martino and Priddy dealt with the classifying spaces, and, as a consequence, obtained the cohomology algebras. On the other hand, the works by Asai and Sasaki depend on the theory of cohomology varieties of modules and on the modular representation theory of finite groups. Especially the theory of relative projectivity of modules played a crucial role. The theory of projectivity of modules relative to subgroups is fundamental in the theory of modular representations of finite groups. In [17] R. Knörr introduced the notion of projective covers of modules relative to subgroups. In the works [4] and [5] an injective hull of the trivial module relative to subgroups gave almost all information of the cohomology algebras. In [23] T. Okuyama introduced the notion of projectivity of modules relative to "modules". In the work [24] an injective hull of the trivial module relative to modules was essentially important. (Carlson pointed out in his lecture note [11] that the definition of projectivity relative to modules is just a special case of the relative homological algebra that can be defined for a projective class of epimorphism.)

The purpose of this report is to show that our method can be applied to finite groups whose Sylow subgroups are

(1) extraspecial $p$-groups of order $p^3$ and of exponent $p$;
(2) wreathed 2-groups.

This work was done with Professor Tetsuro Okuyama.

For $H$ a subgroup of a finite group $G$ and an element $\zeta$ in $H^*(G, k)$ we shall often write $\zeta_H$ or $\zeta|_H$ for the restriction $\text{res}_H \zeta$.

## 2. Relative Projectivity of Modules

### 2.1. Projectivity Relative to Subgroups

First we state some results concerning projectivity of Carlson modules relative to subgroups. The following lemma is easy to prove and well known. This can be used to show divisibility by a homogeneous element.

**Lemma 2.1.** Let

$$E_\rho : 0 \rightarrow k \rightarrow \Omega^{-1}(L_\rho) \xrightarrow{f} \Omega^{r-1}(k) \rightarrow 0$$

be the extension corresponding to an element $\rho$ in $H^r(G, k)$. Suppose that the Carlson module $L_\rho$ is relatively $\mathcal{H}$-projective, where $\mathcal{H}$ is a set of subgroups of $G$. If an element $\xi$ in $H^{n+r}(G, k)$ satisfies

$$\text{res}_H f^*(\xi) = 0 \quad \text{for every } H \in \mathcal{H},$$

where $f^* : \text{Ext}_{kG}^{n+r}(k, k) \rightarrow \text{Ext}_{kG}^{n}(L_\rho, k)$, then there exists an element $\eta$ in $H^n(G, k)$ such that

$$\xi = \rho \eta.$$

The Green correspondence is one of the important tools for analyzing indecomposable modules. The theorem below is of fundamental importance in investigation of indecomposable direct summands of Carlson modules by Green correspondence.
Theorem 2.2. Let $\rho$ in $H^n(G, k)$ be a homogeneous element. Let $U$ be an indecomposable direct summand of the Carlson module $L_\rho$ of $\rho$ with vertex $D$. Let $H$ be a subgroup of $G$ containing the normalizer $N_G(D)$ and let $V$ be a Green correspondent of $U$ with respect to $(G, D, H)$. Then the Green correspondent $V$ is a direct summand of the Carlson module $L_{(\rho_H)}$ of the restriction $\rho_H = \text{res}_H \rho$ to the subgroup $H$; moreover the multiplicity of the direct summand $U$ in $L_\rho$ is the same as the multiplicity of $V$ in $L_{(\rho_H)}$.

2.2. Projectivity relative to modules. In the rest of this section we deal with the theory of projectivity relative to modules. See Okuyama [23] or Carlson [11] for details.

Definition 2.1. For $V$ a $kG$-module let

$$\mathcal{P}(V) = \{ X \mid X \text{ is a direct summand of } V \otimes A \text{ for some } kG\text{-module } A \}.$$

A module in $\mathcal{P}(V)$ is said to be $\mathcal{P}(V)$-projective or projective relative to $\mathcal{P}(V)$. It is also said to be $V$-projective or projective relative to $V$ for short. A module is said to be $\mathcal{P}(V)$-injective, injective relative to $\mathcal{P}(V)$, $V$-injective or injective relative to $V$ if it is $\mathcal{P}(V)$-projective.

Definition 2.2. An exact sequence $E : 0 \rightarrow A \overset{f}{\rightarrow} B \overset{g}{\rightarrow} C \rightarrow 0$ of $kG$-modules is said to be $\mathcal{P}(V)$-split (or $V$-split for short) if $V \otimes E : 0 \rightarrow V \otimes A \overset{1\otimes f}{\rightarrow} V \otimes B \overset{1\otimes g}{\rightarrow} V \otimes C \rightarrow 0$ splits.

Definition 2.3. Let $M$ be a $kG$-module. A short exact sequence $E : 0 \rightarrow X \rightarrow R \rightarrow M \rightarrow 0$ is called a $\mathcal{P}(V)$-projective cover of $M$ if

1. $R$ is $\mathcal{P}(V)$-projective;
2. $E$ is $\mathcal{P}(V)$-split;
3. the kernel $X$ has no $\mathcal{P}(V)$-projective direct summand.

If the exact sequence $E$ above is a $\mathcal{P}(V)$-projective cover of $M$, then the kernel $X$ is denoted by $\Omega_{\mathcal{P}(V)}(M)$. A $\mathcal{P}(V)$-projective cover is also called a $V$-projective cover and the kernel is also denoted by $\Omega_{V}(M)$. Similarly the notion of a $\mathcal{P}(V)$-injective hull is defined. If $F : 0 \rightarrow M \rightarrow S \rightarrow Y \rightarrow 0$ is a $\mathcal{P}(V)$-injective hull of $M$, then the cokernel $Y$ is denoted by $\Omega_{\mathcal{P}(V)}^{-1}(M)$.

Theorem 2.3. Every $kG$-module has a $\mathcal{P}(V)$-projective cover, which is uniquely determined up to isomorphism of sequences.

The following lemma is of fundamental importance in investigation of the projectivity relative to modules by Green correspondence.

Lemma 2.4. Let $X$ be a $kG$-module. Let

$$0 \rightarrow \Omega_{\mathcal{P}(X)}(M) \rightarrow R \rightarrow M \rightarrow 0$$

be a $\mathcal{P}(X)$-projective cover of a $kG$-module $M$ and let $U$ be an indecomposable direct summand of $R$ with vertex $D$. Let $H$ be a subgroup of $G$ containing the normalizer $N_G(D)$ and let $V$ be a Green correspondent of $U$ with respect to $(G, D, H)$. We let moreover

$$0 \rightarrow \Omega_{\mathcal{P}(X_H)}(M_H) \rightarrow S \rightarrow M_H \rightarrow 0.$$
be a \( \mathcal{P}(X_H) \)-projective cover of the restriction \( M_H \). Then the Green correspondent \( V \) is a direct summand of \( S \); moreover the multiplicity of \( V \) in \( S \) is the same as the multiplicity of \( U \) in \( R \).

**Definition 2.4 (Carlson [11]).** An element \( \zeta \) in \( H^n(G,k) - \{0\} \) is said to be productive if the exact sequence

\[
E_\zeta : 0 \to k \to \Omega^{-1}(L_\zeta) \to \Omega^{n-1}(k) \to 0
\]

is a \( \mathcal{P}(L_\zeta) \)-injective hull of the trivial module \( k \), or equivalently the extension \( E_\zeta \) is a \( \mathcal{P}(L_\zeta) \)-projective cover of the syzygy \( \Omega^{n-1}(k) \). This condition is equivalent to the condition that \( \zeta \operatorname{Ext}^*_k(L_\zeta, L_\zeta) = 0 \).

It is known that any homogeneous element of odd degree is productive when the prime \( p \) is odd (See for example Benson [6] Proposition 5.9.6 (ii)). However, for \( p = 2 \) no such general facts are known.

For a homogeneous element \( \zeta \) in \( H^*(G,k) \) and a subgroup \( H \) of \( G \) we see that \( L_{\rho|H} = L_{(\rho_H)} \oplus (\text{projective}) \). The lemma below is a kind of converse of this fact and is useful to show a productive element in the cohomology algebra of a subgroup of a finite group \( G \) containing a Sylow normalizer to be stable under \( G \).

**Lemma 2.5.** Let \( S \) be a Sylow \( p \)-subgroup of a finite group \( G \) and let \( H \) be a subgroup of \( G \) containing the normalizer \( N_G(S) \). Suppose that an element \( \rho \) in \( H^r(H,k) \) is productive, namely, the extension

\[
0 \to k_H \to \Omega^{-1}(L_\rho) \to \Omega^{r-1}(k_H) \to 0
\]

is a \( \mathcal{P}(L_\rho) \)-projective cover of the syzygy \( \Omega^{r-1}(k_H) \). Assume that there exists a \( kG \)-module \( X \) such that

\[
X_H \simeq L_\rho \oplus (\text{projective}).
\]

Then there exists a productive element \( \tilde{\rho} \) in \( H^r(G,k) \) such that

\[
\operatorname{res}_H \tilde{\rho} = \rho.
\]

3. **System of Parameters of Cohomology Algebras**

We first state a theorem of Carlson on system of parameters of cohomology algebras and a corollary, which is a key fact for investigation of the projectivity relative to subgroups of Carlson modules.

Let \( G \) be a finite group of \( p \)-rank \( r \) and let \( S \) be a Sylow \( p \)-subgroup of \( G \), where \( p \) is a prime number. For \( i = 1, \ldots, r \) let

\[
\mathcal{H}_i(G) = \{ C_G(E) \mid S \supseteq E \text{ is elementary abelian of rank } i \}.
\]

Let \( k \) be a field of characteristic \( p \).

**Theorem 3.1 (Carlson [10] Proposition 2.4).** The cohomology algebra \( H^*(G,k) \) has a homogeneous system \( \{ \zeta_1, \ldots, \zeta_r \} \) of parameters with the property that for every \( i = 1, \ldots, r \)

\[
\zeta_i \in \sum_{H \in \mathcal{H}_i(G)} \operatorname{tr}_k^H H^*(H,k).
\]
Corollary 3.2 (Okuyama). If a homogeneous system \(\{\zeta_1, \ldots, \zeta_r\}\) of parameters is taken as in the theorem above, then the tensor product \(L_{\zeta_1} \otimes \cdots \otimes L_{\zeta_{r-1}}\) is \(H_r(G)\)-projective.

In particular, if \(r = 2\), then \(L_{\zeta_1}\) is \(H_2(G)\)-projective and the element \(\zeta_1\) is regular in \(H^*(G, k)\).

The following theorem shows that a system of parameters can be obtained from a productive cohomology element when the \(p\)-rank is two.

Theorem 3.3. Let \(G\) be a finite group of \(p\)-rank two. Let \(\rho\) in \(H^r(G, k)\) be a regular element in \(H^*(G, k)\). Assume that the element \(\rho\) is productive, that is, the extension

\[
E_\rho : 0 \rightarrow k_G \rightarrow \Omega^{-1}(L_\rho) \xrightarrow{f} \Omega^{-r-1}(k_G) \rightarrow 0
\]

is a \(P(L_\rho)\)-injective hull of the trivial \(kG\)-module \(k_G\) and that for a number \(s\) with \(s \geq r + 1\)

\[
\Omega^s(L_\rho) \simeq L_\rho.
\]

Then there exists an inverse image \(\sigma\) in \(\text{Ext}_k^{s+1}(k, k)\) of \(\Omega^{-r+1}f : \Omega^{-r+1}(L_\rho) \rightarrow k\) by the induced homomorphism \(f^{*} : \text{Ext}_k^s(k, k) \rightarrow \text{Ext}_k^s(L_\rho, k)\). The elements \(\sigma\) and \(\rho\) form a system of parameters for the cohomology algebra \(H^*(G, k)\).

4. Extraspecial \(p\)-groups

Let \(p\) be an odd prime. In this section we consider the cohomology algebra of an extraspecial \(p\)-group

\[
P = \langle a, b \mid a^p = b^p = [a, b]^p = 1, [[a, b], a] = [[a, b], b] = 1 \rangle
\]

of order \(p^3\) of exponent \(p\); especially we shall choose a system of parameters whose members are universally stable. The mod \(p\) cohomology algebra of \(P\) was calculated by Leary [18]. Tezuka-Yagita [26] investigated the \(p\)-parts of integral cohomology algebras of finite groups \(G\) having \(P\) as Sylow \(p\)-subgroups. Tezuka-Yagita [25] studied the mod \(p\) cohomology algebra of the general linear group \(\text{GL}(3, \mathbb{F}_p)\), whose Sylow \(p\)-subgroup is our \(P\) above. We apply our results on relative projectivity of modules stated in Sections 2 and 3 to the \(p\)-group \(P\) and finite groups with \(P\) as Sylow \(p\)-subgroups.

4.1. System of parameters.

Definition 4.1. Let

\[
c = [a, b].
\]

Then \(Z(P) = \langle c \rangle\). For \(i, 0 \leq i \leq p - 1\), let

\[
E_i = \langle ab^i, c \rangle; \quad a_i = ab^i, \quad b_i = b.
\]

Let

\[
E_\infty = \langle b, c \rangle; \quad a_\infty = b, \quad b_\infty = a.
\]

We put

\[
\Omega = \{0, 1, \ldots, p - 1, \infty\}; \quad \mathcal{E} = \{E_i \mid i \in \Omega\}.
\]

The set \(\mathcal{E}\) is the collection of elementary abelian subgroups of \(P\) of rank two. We note that \(C_P(E) = E\) for \(E\) in \(\mathcal{E}\); hence \(H_2(P) = \mathcal{E}\).
Theorem 3.1 and Corollary 3.2 say that there exists a system \( \{ \xi_1, \xi_2 \} \) of parameters such that

1. \( \xi_2 \in \sum_{E \in \mathcal{E}} \text{tr}^P H^*(E, k) \);
2. \( L_{\xi_1} \) is \( \mathcal{E} \)-projective;
3. \( \xi_1 \) is regular in \( H^*(P, k) \).

Of course there are many choices of system of parameters as above. The cohomology classes which we define below are good ones because of Lemma 4.1, Theorems 4.2 and 4.3. We have to mention that they and their properties would be seen or verified by similar arguments to those in the papers [18], [25], or [26].

**Definition 4.2.** For \( i \) with \( 0 \leq i \leq p-1 \), regarding \( H^1(E_i, k) \) as \( \text{Hom}(E_i, k) \), let
\[
\lambda_i = a_i^*, \quad \mu_i = b_i^*.
\]
We also let
\[
\lambda_{\infty} = -a_{\infty}^*, \quad \mu_{\infty} = b_{\infty}^*.
\]
For \( i \) in \( \Omega \) we let
\[
\alpha_i = \Delta(\lambda_i), \quad \gamma_i = \Delta(\mu_i),
\]
where \( \Delta : H^1(E_i, k) \to H^2(E_i, k) \) is the Bockstein homomorphism. Then the element \( b_i \) acts on these elements as follows:
\[
\alpha_i^{b_i} = \alpha_i, \quad \gamma_i^{b_i} = -\alpha_i + \gamma_i.
\]

**Definition 4.3.** Let
\[
\nu = \text{norm}^P_{E_{\infty}}(\gamma_{\infty}) \in H^{2p}(P, k).
\]
For \( i \) in \( \Omega \) let
\[
\zeta_i = \text{tr}^P_{E_i}(\gamma_i^{p-1}) \in H^{2(p-1)}(P, k)
\]
and define
\[
\zeta = \sum_{i \in \Omega} \zeta_i.
\]
We define moreover
\[
\rho = \nu^{p-1} - \zeta^p \in H^{2p(p-1)}(P, k),
\]
\[
\sigma = \nu^{p-1} \zeta \in H^{2(p^2-1)}(P, k).
\]
Note that
\[
\sigma \in \sum_{E \in \mathcal{E}} \text{tr}^P_E H^{2(p^2-1)}(E, k).
\]

For \( E = E_i \) in \( \mathcal{E} \) we shall often omit subscript \( i \) of the cohomologies \( \gamma_i \) and \( \alpha_i \).

**Lemma 4.1.** For \( E \) in \( \mathcal{E} \) one has
\[
\text{res}_E \rho = \prod_{\eta \in \mathbb{F}_{p^2} \setminus \mathbb{F}_p} (\gamma - \eta \alpha), \quad \text{res}_E \sigma = -\left( \alpha \prod_{i \in \mathbb{F}_p} (\gamma - i \alpha) \right)^{p-1}.
\]
For $E_i$ in $\mathcal{E}$ the factor group $P/E_i = \langle \overline{b}_i \rangle$, where $\overline{b}_i = E_ib_i$, acts on the set

$$\{ L_{\gamma - \eta\alpha} \mid \eta \in \mathbb{F}_p^2 \setminus \mathbb{F}_p \}$$

by conjugation as follows

$$L_{\gamma - \eta\alpha}^{b_i} = L_{\gamma - (\eta+1)\alpha}.$$

This action induces the action of $P/E_i = \langle \overline{b}_i \rangle$ on the set $\mathbb{F}_p^2 \setminus \mathbb{F}_p$ such that $\eta^{h_i} = 1 + \eta$ for $\eta$ in $\mathbb{F}_p^2 \setminus \mathbb{F}_p$. Thus, if we write $(\mathbb{F}_p^2 \setminus \mathbb{F}_p)/P$ for the quotient set of $\mathbb{F}_p^2 \setminus \mathbb{F}_p$ under this action, then a complete set of representatives of the conjugation on $\{ L_{\gamma - \eta\alpha} \mid \eta \in \mathbb{F}_p^2 \setminus \mathbb{F}_p \}$ can be written as

$$\{ L_{\gamma - \eta\alpha} \mid \eta \in (\mathbb{F}_p^2 \setminus \mathbb{F}_p)/P \}.$$

Using Lemma 4.1 and Corollary 3.2, we can show the following.

**Theorem 4.2.** (1) The set $\{ \rho, \sigma \}$ is a system of parameters of the cohomology algebra $H^*(P, k)$.

(2) The Carlson module $L_\rho$ is $\mathcal{E}$-projective. In fact the module $L_\rho$ decomposes as follows:

$$L_\rho = \bigoplus_{E \in \mathcal{E}} \bigoplus_{\eta \in (\mathbb{F}_p^2 \setminus \mathbb{F}_p)/P} L_{\gamma - \eta\alpha}^P.$$

(3) The element $\rho$ is regular in $H^*(P, k)$.

### 4.2. Finite group with $P$ as a Sylow $p$-subgroup.

In the rest of this section we let $G$ be a finite group with $P$ as a Sylow $p$-subgroup. We can show that the elements $\rho$ and $\sigma$ are the restrictions from any such $G$. Namely

**Theorem 4.3.** The cohomologies $\rho$ and $\sigma$ are universally stable.

**Definition 4.4.** Since the cohomologies $\rho$ and $\sigma$ are universally stable, there exits an element $\tilde{\rho}$ in $H^{2p(p-1)}(G, k)$ such that

$$\text{res}_P(\tilde{\rho}) = \rho$$

and an element $\tilde{\sigma}$ in $H^{2(p^2-1)}(G, k)$ such that

$$\text{res}_P(\tilde{\sigma}) = \sigma.$$

**Definition 4.5.** The Carlson module $L_{\tilde{\rho}}$ of the element $\tilde{\rho}$ is projective relative to $\mathcal{H}_2(G) = \{ C_G(E) \mid E \in \mathcal{E} \}$ by Corollary 3.2. The centralizer $C_G(E)$ of $E$ in $\mathcal{E}$ has a normal $p$-complement; hence $L_{\tilde{\rho}}$ is $\mathcal{E}$-projective. Theorem 4.2 implies an indecomposable direct summand of $L_{\tilde{\rho}}$ has vertex some $E$ in $\mathcal{E}$ and source some $L_{\gamma - \eta\alpha}$, $\eta$ in $\mathbb{F}_p^2 \setminus \mathbb{F}_p$. For $E$ in $\mathcal{E}/G$ we write

$$\{ X_i^{(E)} \mid i \in I^{(E)} \}$$

for the set of indecomposable direct summands of $L_{\tilde{\rho}}$ whose vertices are $E$; we denote by $X^{(E)}$ their direct sum. Then we have

$$L_{\tilde{\rho}} = \bigoplus_{E \in \mathcal{E}/G} X^{(E)}.$$
Theorem 4.4. The Carlson module $L_{\overline{\rho}}$ decomposes as follows:

$$L_{\overline{\rho}} = \bigoplus_{E \in \mathcal{E}/G} \bigoplus_{i \in I(E)} X_{i}^{(E)},$$

where if $i \neq j$, then $X_{i}^{(E)}$ and $X_{j}^{(E)}$ have different sources.

Definition 4.6. Let $Y_{i}^{(E)}$ be a Green correspondent of $X_{i}^{(E)}$ with respect to $(G, E, N_{G}(E))$. By Theorem 2.2 the $kN_{G}(E)$-module $Y_{i}^{(E)}$ is an indecomposable direct summand of the Carlson module $L_{\rho'}$ of the restriction $\rho' = \text{res}_{N(G)}(\overline{\rho})$ with multiplicity one. Let us denote by $Y^{(E)}$ the direct sum of these modules:

$$Y^{(E)} = \bigoplus_{i \in I^{(E)}} Y_{i}^{(E)}.$$

Proposition 4.5. One has

$$(Y^{(E)})^{G} = X^{(E)} \oplus \text{(projective)}.$$

Corollary 4.6. One has

$$\text{Ext}^{*}_{kG}(L_{\overline{\rho}}, k) \simeq \bigoplus_{E \in \mathcal{E}/G} \text{Ext}^{*}_{kN_{G}(E)}(Y^{(E)}, k).$$

In particular

$$\dim H^{n+2p(p-1)}(G, k) = \dim H^{n}(G, k) + \sum_{E \in \mathcal{E}/G} \dim \text{Ext}^{*}_{kN_{G}(E)}(Y^{(E)}, k).$$

Therefore we have to investigate the module $Y^{(E)}$, which is a direct summand of the Carlson module $L_{\rho'}$ of $\rho' = \text{res}_{N(G)}(\overline{\rho})$.

Definition 4.7. We write $\{ L_{\gamma - \eta \alpha} | i \in I^{(E)} \}$ for a set of complete set of representatives of the action of the factor group $N_{G}(E)/C_{G}(E)$ on the set $\{ L_{\gamma - \eta \alpha} | \eta \in F_{p^{2}} \setminus F_{p} \}$.

For $i$ in $I^{(E)}$ the module $Y_{i}^{(E)}$ would be investigated in the following way. We omit the superscript $(E)$ and subscript $i$ in what follows, namely, we write $Y$ for an indecomposable direct summand of $L_{\rho'}$ with vertex $E$ and source $L_{\gamma - \eta \alpha}$.

1. First investigate

$$H_{\eta} = \{ g \in N_{G}(E) | L_{\gamma - \eta \alpha}^{g} \simeq L_{\gamma - \eta \alpha} \}.$$

2. Denote by $L_{C}$ the extension of $L_{\gamma - \eta \alpha}$ to $C_{G}(E)$ in a natural way. Let

$$L_{C}^{H_{\eta}} = \bigoplus_{j} M_{j}$$

be an indecomposable decomposition of the induced module $L_{C}^{H_{\eta}}$. The module $Y$ is the induced module $M_{j}^{N_{G}(E)}$ of some indecomposable $M_{j}$.

3. Determine $M_{j}$.
Let $S = \langle a, b, t | a^{2^n} = b^{2^n} = t^2 = 1, ab = ba, tat = b \rangle, \ n \geq 2$
be a wreathed 2-group.

Let $k$ be a field of characteristic 2 containing a cubic root of unity. We shall consider the cohomology algebras $H^*(G, k)$ of finite groups $G$ having $S$ above as Sylow 2-subgroups.

5.1. System of Parameters.

**Definition 5.1.** Let
\[
c = ab, \ x = a^{2^{n-1}}, \ y = b^{2^{n-1}}, \ z = xy = c^{2^{n-1}}
\]
and let
\[
E = \langle x, y \rangle, \ F = \langle z, t \rangle.
\]
Then $\{ E, F \}$ is a complete set of representatives of the conjugacy classes of four-groups in $S$. Their centralizers are
\[
C_S(E) = \langle a \rangle \times \langle b \rangle, \ C_S(F) = \langle c \rangle \times \langle t \rangle.
\]

We set
\[
\langle a \rangle \times \langle b \rangle = U, \ \langle c \rangle \times \langle t \rangle = V.
\]
Then we have
\[
\mathcal{H}_2(S) = \{ U, V \}.
\]

By Theorem 3.1 and Corollary 3.2, the cohomology algebra $H^*(S, k)$ has a homogeneous system $\{ \xi_1, \xi_2 \}$ of parameters such that
\begin{enumerate}
  \item $\xi_2 \in \text{tr}_U^S H^*(U, k) + \text{tr}_V^S H^*(V, k)$;
  \item $L_{\xi_1}$ is $\{ U, V \}$-projective;
  \item $\xi_1$ is regular in $H^*(S, k)$.
\end{enumerate}

In the rest of this report the subscript of a cohomology class indicates the degree. For example $\alpha_2$ is of degree 2, $\nu_4$ is of degree 4, and so on.

**Definition 5.2.** Let
\[
\alpha_2 \in \inf^U H^2(U/\langle b \rangle, k), \ \beta_2 \in \inf^U H^2(U/\langle a \rangle, k),
\]
\[
\chi_2 \in \inf^V H^2(V/\langle t \rangle, k), \ \psi_2 \in \inf^V H^2(V/\langle c \rangle, k).
\]
Let
\[
\tau_1 \in \inf^S H^1(S/U, k), \ \zeta_2 = \text{tr}_U^S \alpha_2 \in H^2(S, k), \ \nu_4 = \text{norm}_U^S \alpha_2 \in H^4(S, k)
\]
and let
\[
\rho_4 = \tau_1^4 + \zeta_2^2 + \nu_4, \ \sigma_6 = (\tau_1^3 + \zeta_2)\nu_4.
\]
Then we have

**Theorem 5.1.** (1) The set \( \{ \rho_4, \sigma_6 \} \) is a homogeneous system of parameters of \( H^*(S, k) \).
(2) \( \sigma_6 \in \text{tr}_U^S H^6(U, k) + \text{tr}_V^S H^6(V, k) \);
(3) The Carlson module \( L_{\rho_4} \) is \{ \( U, V \) \} -projective. In fact
\[
L_{\rho_4} = L_{\alpha_2 + \omega \beta_2}^S \oplus L_{\chi_2 + \omega \psi_2}^S,
\]
where \( \omega = \sqrt[3]{1} \in k \).
(4) The element \( \rho_4 \) is regular in \( H^*(S, k) \).

The element \( \rho_4 \) is universally stable. To show this, we use the theory of projectivity of modules relative to “modules”. First we see

**Theorem 5.2.** The element \( \rho_4 \) is productive. Namely, the extension
\[
0 \to k \to \Omega^{-1}L_\rho \to \Omega^3k \to 0
\]
induced by the element \( \rho_4 \) in \( H^4(S, k) \) is a \( P(L_\rho) \)-injective hull of the trivial module \( k \).

### 5.2. Finite group with \( S \) with a Sylow 2-subgroup.
Let \( G \) be a finite group which has \( S \) as a Sylow 2-subgroup. Structure of these groups had been deeply investigated in Brauer-Wong [9], Brauer [8], and Alperin-Brauer-Gorenstein [2].

The fusion of 2-elements can be described by behavior of several involutions and subgroups. Among them we use four-groups and their normalizers. The reason is of course Theorem 3.1 by Carlson and Corollary 3.2.

The fusion of 2-elements in \( G \) is indicated in Table 2.

<table>
<thead>
<tr>
<th></th>
<th>a: ( N_G(E)/C_G(E) \simeq \mathbb{Z}/2\mathbb{Z} )</th>
<th>b: ( N_G(E)/C_G(E) \simeq S_3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:</td>
<td>( E \sim F ) ( (x \sim z) ) ( S \cap G' = S' = \langle ab^{-1} \rangle )</td>
<td>( S \cap G' = \langle a, b \rangle )</td>
</tr>
<tr>
<td>2:</td>
<td>( E \sim F ) ( (x \sim t) ) ( S \cap G' = \langle ab^{-1}, xt \rangle )</td>
<td>( S \cap G' = S )</td>
</tr>
</tbody>
</table>

Following Alperin-Brauer-Gorenstein [2], we call a group of type 1b a “\( D \)-group”; a group of type 2a a “\( Q \)-group”; a group of type 2b a “\( QD \)-group”.

The cohomology algebra of the wreathed 2-group is calculated by Nakaoka’s theorem. The cohomology algebras of finite groups with wreathed Sylow 2-subgroups are obtained below. In the following the cohomology algebras of other types of groups are stated as subalgebras of that of the wreathed Sylow 2-subgroup \( S \).

**Theorem 5.3.** Let \( G \) be a finite group with \( S \) as a Sylow 2-subgroup.
(1) If $G$ is of type 1a, then
\[ H^*(G, k) \simeq H^*(S, k) \]
\[ = k[\zeta_1, \tau_1, \zeta_2, \nu_2, \zeta_3, \nu_3, \tau_1 \zeta_2, \tau \zeta_3, \nu_2 \zeta_1, \nu_2 \zeta_3, \zeta_1 \zeta_3 - \zeta_2 \nu_2]. \]

(2) If $G$ is a $D$-group, then
\[ H^*(G, k) = k[\tau_1, \nu_2, \theta_3, \rho_4, \theta_5, \sigma_6], \]
where
\[ \theta_3 = \tau_1 \nu_2 + \zeta_1 \zeta_2 + \zeta_3, \]
\[ \rho_4 = \tau_1^4 + \zeta_2^2 + \nu_4, \]
\[ \theta_5 = \tau^3 \nu_2 + \zeta_1 \rho_4 + \zeta_2 \zeta_3, \]
\[ \sigma_6 = (\tau_1^2 + \zeta_2) \nu_4. \]

(3) If $G$ is a $Q$-group, then
\[ H^*(G, k) = k[\zeta_1, \sigma_2, \theta_3, \rho_4], \]
where
\[ \sigma_2 = \tau_1^2 + \zeta_2. \]

(4) If $G$ is a $QD$-group, then
\[ H^*(G, k) = k[\theta_3, \rho_4, \theta_5, \sigma_6]. \]

Remark 5.1. The elements $\zeta_1$, $\nu_2$, and $\zeta_3$ above will be stated in subsection 5.5.

To show that the element $\rho_4$ in $H^4(S, k)$ is universally stable, we show the following

**Theorem 5.4.** There exists a $kG$-module $\bar{X}$ such that
\[ \bar{X}_S = L_\rho \oplus \text{(projective)}. \]

Using Theorem 5.4, Lemma 2.5, and lemma 2.4, we can show

**Theorem 5.5.** There exists a productive element $\bar{\rho}$ in $H^4(G, k)$ such that

\[ \text{res}_S \bar{\rho} = \rho, \quad L_{\bar{\rho}} = \bar{X}. \]

5.3. **$QD$-groups.** Our proof of Theorem 5.4 is slightly complicated. So we sketch our argument only for $QD$-groups $G$; namely suppose, in this subsection, that the four-groups $E$ and $F$ are conjugate in $G$ and the quotient group $N_G(E)/C_G(E)$ is isomorphic with $S_3$. Let $H$ be the subgroup of $N_G(E)$ of index two containing the centralizer $C_G(E)$. We may assume that there exists an element $h$ in $H$ such that
\[ a^h = b, \quad b^h = ab. \]

Suppose for the moment that there exits an element $\bar{\rho}$ in $H^4(G, k)$ such that
\[ \text{res}_S \bar{\rho} = \rho. \]

Then an indecomposable direct summand $\bar{X}$ of the Carlson module $L_{\bar{\rho}}$ would have vertex $U$ and a source $L_{\alpha_2+\omega_\beta_2}$ so that $\bar{X}$ would be the Green correspondent of an indecomposable direct summand $X'$ of the Carlson module $L_{\rho'}$ of the restriction $\rho' = \text{res}_{N_G(E)} \bar{\rho}$ with vertex $U$ and a source $L_{\alpha_2+\omega_\beta_2}$. We write $N = N_G(E)$ and $C = C_G(E)$. We know that the centralizer $C_G(E)$ has a normal 2-complement:
\[ C_G(E) = U \ltimes O(C_G(E)). \]
Let 

\[ \epsilon = \alpha_2 + \omega \beta_2. \]

Since \( C_G(E) = U \ltimes O(C_G(E)) \), the Carlson module \( L_\epsilon \) can be extended to \( C = C_G(E) \).

We denote by \( L_C \) the extension of \( L_\epsilon \) to \( C_G(E) \):

\[ L_{C|U} \simeq L_\epsilon, \quad L_{C|O(C_G(E))} = \text{trivial module}. \]

Because the module \( X' \) belongs to the principal \( kN \)-block, the module \( X' \) is a direct summand of the induced module \( L_C^N \). The induced module \( L_C^N \) can be analyzed by Clifford theory. First we have

\[ H = \{ x \in N \mid L_x^\epsilon \simeq L_\epsilon \}. \]

Thus if \( L_C^H = \sum M_j \) is an indecomposable decomposition, then the induced modules \( M_j^N \) are indecomposable and \( L_C^N = \sum M_j^N \). Indeed the induced module \( L_C^H \) decomposes as follows.

**Lemma 5.6.** For \( i = 0, 1, 2 \), let \( k_i \) be the one-dimensional \( kH \)-module on which \( U \) acts trivially and the element \( h \) acts as multiplication by \( \omega^i \). Then the induced module \( L_C^H \) has a decomposition

\[ L_C^H = M_0 \oplus M_1 \oplus M_2 \]

of indecomposable \( kH \)-modules \( M_0, M_1, M_2 \) such that

1. \( M_j|U \simeq L_\epsilon, \quad i = 0, 1, 2; \)
2. \( M_j \)s are periodic of period six;
3. \( M_i \simeq M_0 \otimes k_i, \quad i = 0, 1, 2; \)
4. \( M_0/\text{rad} M_0 = k_2 \oplus k_0, \quad \text{soc} M_0 = k_1 \oplus k_2; \)
5. \( \Omega(M_0)/\text{rad} \Omega(M_0) = k_0 \oplus k_1, \quad \text{soc} \Omega(M_0) = k_2 \oplus k_0; \)
6. \( \Omega^2(M_0) = M_2, \quad \Omega^2(M_1) = M_0, \quad \Omega^2(M_2) = M_1. \)

The indecomposable \( kN \)-module \( X' \) would be one of \( M_i^N \); we put, say,

\[ X' = M_i^N. \]

Since the module \( M_i^N \) would be a direct summand of \( L_{\rho'} \), the module \( M_i \) would be a direct summand of the Carlson module \( L_{\rho''} \) of the restriction \( \rho'' = \text{res}_H \rho' \).

Now let us return to construction of the \( kG \)-module \( \bar{X} \).

**Lemma 5.7.** The cohomology \( \rho_4 \) is \( N_G(E) \)-stable.

**Definition 5.3.** Let us take \( \rho' \) in \( H^4(N_G(E), k) \) such that

\[ \text{res}_S \rho' = \rho. \]

Then we have

\[ \rho' = \text{tr}_S^N \rho. \]

We also let

\[ \rho'' = \text{res}_H \rho'. \]

Then we have
Proposition 5.8. The Carlson module $L_{\rho''}$ has a decomposition

$$L_{\rho''} = M \oplus M^t$$

of indecomposable $kH$-modules $M$ and $M^t$ such that

1. $M_U \simeq L_\varepsilon$
2. $M_{N_U}s_\varepsilon \simeq L_\epsilon$
3. $M$ is periodic of period six;
4. $M/\text{rad } M = k_1 \oplus k_2$, $\text{soc } M = k_0 \oplus k_1$;
5. $\Omega^3(M)/\text{rad } \Omega^3(M) \simeq \Omega^2(M)/\text{rad } \Omega^2(M)$;
   $\text{soc } \Omega^3(M) \simeq \text{soc } \Omega^2(M)$.

Definition 5.4. Let $X' = M^N$.

The indecomposable $kN$-module $X'$ has vertex $U$ and source $L_\varepsilon$.

By our definition of the indecomposable $kN$-module $X'$ we have

Proposition 5.9. (1) The indecomposable $kN$-module $X'$ is periodic of period six.
(2) $X'_S = L_\epsilon^S$.
(3) The indecomposable $kN$-module $X'$ is a direct summand of $L_{\rho'}$.

Using the proposition above and the assumption that the four-groups $E$ and $F$ are conjugate, we obtain

Proposition 5.10. It follows that

$$X'^G_S \equiv L_\rho \pmod{\text{projective}}.$$ 

We can now define the $kG$-module $\tilde{X}$.

Definition 5.5. Let

$\tilde{X}$ be a Green correspondent of $X'$ with respect to $(G, U, N_G(E))$.

By means of Propositions 5.9, 5.10 and the properties of the Green correspondence we see that the $kG$-module $\tilde{X}$ is the desired one.

Theorem 5.11. We have

1. the $kG$-module $\tilde{X}$ is periodic of period six;
2. $X'^G = \tilde{X} \oplus (\text{projective})$;
3. $\tilde{X}_S = L_\rho \oplus (\text{projective})$. 
Remark 5.2. When the four-groups $E$ and $F$ are not conjugate in $G$, the $kG$-module $\bar{X}$ in Theorem 5.4 is not indecomposable.

5.4. Relative injective hull of the trivial module. We resume our situation that $G$ is a finite group with wreathed Sylow 2-subgroup $S$. The element $\rho_4$ is productive by Theorem 5.5. The $L_{\bar{\rho}}$-injective hull

$$0 \to k_G \to \Omega^{-1}(L_{\bar{\rho}}) \to \Omega^3(k_G) \to 0$$

gives us much information about the cohomology algebra. First we can deduce the following theorem from Theorem 3.3.

**Theorem 5.12.** The element $\sigma_6$ is universally stable. Namely there exists an element $\tilde{\sigma}_6 \in H^6(G, k)$ such that

$$\text{res}_S \tilde{\sigma}_6 = \sigma_6.$$  

Consequently the set

$$\{ \rho_4, \sigma_6 \}$$

is a homogeneous system of parameters for $H^*(G, k)$ for every $G$.

Second we can obtain dimension formulae for the cohomology groups $H^*(G, k)$. Applying the cohomology functor $\text{Ext}_{kG}(-, k)$ to the extension

$$0 \to k_G \to \Omega^{-1}L_{\bar{\rho}} \to \Omega^3k_G \to 0,$$

we obtain the short exact sequences

$$0 \to \text{Hom}_{kG}(\Omega^3k, k) \to \text{Hom}_{kG}(\Omega^{-1}L_{\bar{\rho}_4}, k) \to 0,$$

$$0 \to \text{Ext}_{kG}^n(k, k) \to \text{Ext}_{kG}^{n+1}(\Omega^3k, k) \to \text{Ext}_{kG}^{n+1}(\Omega^{-1}L_{\bar{\rho}_4}, k) \to 0, \quad n \geq 0.$$  

In particular we have a formula

$$\dim \text{Ext}_{kG}^{n+4}(k, k) = \dim \text{Ext}_{kG}^n(k, k) + \dim \text{Ext}_{kG}^n(L_{\bar{\rho}_4}, k).$$
and we can compute \( \dim \text{Ext}_{kG}^{n}(L_{\tilde{\rho}_4}, k) \) by our construction of the module \( \tilde{X} = L_{\tilde{\rho}} \). For example, if \( G \) is a \( QD \)-group, then

\[
\dim \text{Ext}_{kG}^{n}(L_{\tilde{\rho}_4}, k) = \begin{cases} 
0 & \text{if } n \equiv 0 \pmod{3} \\
1 & \text{if } n \equiv 1 \pmod{3} \\
1 & \text{if } n \equiv 2 \pmod{3}
\end{cases}
\]

We can also calculate \( \dim \text{Ext}_{kG}^{n}(k, k) \), \( n = 1, 2, 3 \), so that we obtain dimension formulae for \( H^{*}(G, k) \).

We have obtained a system of parameters \( \{ \tilde{\rho}_4, \tilde{\sigma}_6 \} \) and established dimension formulae for the cohomology groups \( H^{*}(G, k) \). We have to get generators of the cohomology algebras over the subalgebra \( k[\tilde{\rho}_4, \tilde{\sigma}_6] \).

### 5.5. Generators of Cohomology Algebras

First let us state generators of the cohomology algebra of the wreathed 2-group \( S \). The cohomology algebra \( H^{*}(S, k) \) has \( \{ \sigma_2 (= \tau_1^2 + \zeta_2), \rho_4 \} \) as a system of parameters. Hence we can take generators of degree up to 4. In fact, \( H^{*}(S, k) \) is generated over the subalgebra \( k[\sigma_2, \rho_4] \) by \( \tau_1 \), which was defined in Section 2, and the elements \( \zeta_1, \nu_2, \zeta_3 \in H^{*}(S, k) \). To state these elements, let \( \alpha_1 \in \inf^U H^1(U/\langle b \rangle, k) \); and let us define

\[
\zeta_1 = \text{tr}_{U}^{S} \alpha_1 \in H^1(S, k),
\nu_2 = \text{norm}_{U}^{S} \alpha_1 \in H^2(S, k),
\zeta_3 = \text{tr}_{U}^{S} (\alpha_1 \alpha_2) \in H^3(S, k).
\]

When the four-groups \( E \) and \( F \) are not conjugate in \( G \), the cohomology algebras \( H^{*}(G, k) \) and \( H^{*}(N_G(E), k) \) are isomorphic. This can be seen by comparing the dimensions of the cohomology groups. On the other hand, when \( E \) and \( F \) are conjugate, one can take an element \( g_0 \in C_G(c) \) such that \( E^{g_0} = F \) and \( U^{g_0} \cap S = V \). Then we can determine the stable elements by considering the subspaces

\[
\{ \xi \in H^n(S, k) \mid \xi^{g_0} V = \xi_V \}, \quad n \leq 4.
\]

Of course the element \( g_0 \) above plays an important role throughout in our investigation for those groups in which \( E \) and \( F \) are conjugate.

### References


