<table>
<thead>
<tr>
<th>Title</th>
<th>COHOMOLOGY OF GROUPS HAVING 3-SYLOW SUBGROUPS ISOMORPHIC TO THE EXTRASPECIAL 3-GROUP (Cohomology Theory of Finite Groups and Related Topics)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Author(s)</td>
<td>Yagita, Nobuaki</td>
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Kyoto University
COHOMOLOGY OF GROUPS HAVING 3-SYLOW SUBGROUPS ISOMORPHIC TO THE EXTRASPECIAL 3-GROUP

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1. INTRODUCTION

Let us write by $E$ the extraspecial $p$-group $p_+^{1+2}$ of order $p$ and exponent $p$ for an odd prime $p$. Let $G$ be a finite group having $E$ as a Sylow $p$-group, and let $BG (= Bp^A)$ the $p$-completed classifying space of $G$. In papers [T-Y],[Y1,2], the cohomology and stable splitting for such groups are studied. Results show that there are not so many homotopy types of $BG$. This fact was first suggested by C.B.Thomas [Th] and D.Green [G].

Indeed, recently, Ruiz and Viruel [R-V] classified all $p$-local finite groups. Classifying spaces induced from finite groups are homotopic to what are studied in [T-Y]. (While description of $H^*(^{2}F_{4}(2)'(3)$ and $H^*(Fi'_{24})(7)$ contained some errors.)

2. $p$-LOCAL FINITE GROUPS ASSOCIATED TO THE EXTRASPECIAL $p$ GROUP $P_+^{1+3}$

Recall that the extraspecial $p$-group $p_+^{1+2}$ has a representation as

$$p_+^{1+2} =< a, b, c | a^p = b^p = c^p = 1, [a, b] = c, c \in Center >$$

and denote it simply by $E$ in this paper. We consider $p$-local finite groups associated to $E$, which are extensions of groups whose $p$-Sylow subgroups are isomorphic to $E$.

The concept of the $p$-local finite groups arose in the work of Broto-Levi-Oliver [B-L-O 1,2] as a classical concept of finite groups. The $p$-local finite group is stated as a triple $< S, F, L >$ where $S$ is a $p$-group, $F$ is a saturated fusion system over a centric linking system $L$ over $S$ (for details see [R-V],[B-L-O 1]). Given a $p$-local finite group, we can construct its classifying space $B < S, F, L >$ by the realization $[L]_p$. Of course if $< S, F, L >$ is induced from a finite group $G$ having $S$ as a $p$-Sylow subgroup, then $B < S, F, L > \cong BG$. However note that in general, there exist $p$-local finite groups which are not induced from finite groups (exotic cases).

A.Ruiz and A.Viruel recently determined $< p_+^{1+2}, F, L >$ for all odd primes by using the classification of finite simple groups. Indeed, we check the possibility of existence of finite groups only for simple groups and their extensions. Moreover they find new exotic 7-local finite groups.

The $p$-local finite groups $< E, F, L >$ are classified by $Out_F(E)$, number of $F^{ec}$-radical $p$-subgroup $V$ (for details of definitions, see [R-V]) and $Aut_F(V)$. When a $p$-local finite group are induced from finite group $G$, then we see easily that $Out_F(E) \cong W_G(E)(= N_G(E)/E.C_G(E))$ and $Aut_F(V) \cong W_G(V)$. Moreover $V$ is

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$F^{ec}$-radical if and only if $\text{Aut}_F(V) \subset \text{SL}_2(\mathbb{F}_p)$ by Lemma 4.1 in [R-V]. When $G$ is a sporadic simple group, $V$ is $F^{ec}$-radical follows p-pure.

**Theorem 2.1.** ([Ruiz and Viuel [R-V]]) If $p \neq 3, 7, 5, 13$, then p-local finite group $< E, F, L >$ is isomorphic to one of the following (1),(2)

1. $E : W$ for $W \subset \text{Out}(E)$ and $|W|, p = 1$

2. $p^2 : \text{SL}_2(\mathbb{F}_p) : r$ for $r | (p - 1)$, $\text{SL}_3(\mathbb{F}_p) : H$ for $H \cong \mathbb{Z}/2, \mathbb{Z}/3, S_3$.

When $p = 3, 5, 7$ or 13 there are other types

3. $2F_4(2)', J_4$ for $p = 3$, Th for $p = 5$, $M$ for $p = 13$

4. $He, He : 2, F_{24}', O'N, O'N : 2$ for $p = 7$

and there exist three exotic 7-local finite groups.

For cases (1), we know that $H^*(E : W) \cong H^*(E)^W$. Except for these extensions and exotic cases, all $H^{even}(G; \mathbb{Z})_{(p)}$ are studied in [T-Y]. It is studied in [Y1] the way to know $H^{odd}(G; \mathbb{Z})_{(p)}$ and $H^*(G; \mathbb{Z}/p)$ from $H^{even}(G; \mathbb{Z})_{(p)}$. The stable splittings for such $BG$ are studied in [Y2]. However there were some error in cohomology of $2F_4(2)'$, $F_{24}'$. In this paper, we study cohomology and stable splitting of $BG$ for $p = 3$ and 7 mainly.

3. COHOMOLOGY

In this paper we mainly consider the cohomology $H^*(BG; \mathbb{Z})/(p, \sqrt{0})$ where $\sqrt{0}$ is the ideal generated by nilpotent elemet. So we write it simply

$$H^*(BG) = H^*(BG; \mathbb{Z})/(p, \sqrt{0}).$$

Hence it is written by

$$H^*(BG) \cong \mathbb{Z}/p[y], \quad H^*(B(\mathbb{Z}/p)^2) \cong \mathbb{Z}/p[y_1, y_2]$$

with $|y| = |y_i| = 2$.

Let us write $(\mathbb{Z}/p)^2$ by $V$ simply, and a $V$-subgroup of $G$ mean a subgroup isomorphic to $(\mathbb{Z}/p)^2$.

The cohomology of the extraspecial $p$ group $E = p^{1+2}$ is wellknown. In particular recall that

1. $H^*(BE) \cong (\mathbb{Z}/p[y_1, y_2]/(y_1^2y_2 - y_1y_2^2) \oplus \mathbb{Z}/p[C]) \otimes \mathbb{Z}/p[y]

where $|y_1| = 2, |y_2| = 2p, |C| = 2p - 2$ and $C_{y_i} = y_i^{2p-1}$, $C = y_1^{2p-2} + y_2^{2p-2} - y_1^{p-1}y_2^{p-1}$. The $E$ conjugacy classes of $V$-subgroups of $E$ are written by

$$A_i = < ab^i, c > \quad \text{for } 0 \leq i \leq p - 1, \quad A_\infty = < b, c >.$$

Letting $H^*(BA_i) \cong \mathbb{Z}/p[y, u]$ and writing $i^*_{A_i}(x) = x|A_i$ for the inclusion $i_{A_i} : A_i \subset E$, the restriction images are given by

2. $y_1|A_i = y$ for $i \in \mathbb{F}_p$, $y_1|A_\infty = 0$, $y_2|A_i = iy$ for $i \in \mathbb{F}_p$, $y_2|A_\infty = y$.

$$C|A_i = y^{p-1}, \quad u|A_i = u^p - y^{p-1}u \quad \text{for all } i.$$

In particular, we can take a $\mathbb{Z}/p$-base $b_i$ of $H^{2p-2}(BE)$ such that

$$b_i|A_j \delta_{ij}y^{p-1}, \quad \text{e.g. } b_i = (y_1 - i^{-1}y_2)^{p-1} - C.$$
For an element \( g = \left( \begin{array}{cc} a & b \\ c & d \end{array} \right) \in GL_2(\mathbb{F}_p) \cong Out(E) \), its actions are given ([Ly],[T-Y] p491)

\[
(3) \quad g^*C = C, \quad g^*y_1 = ay_1 + by_2, \quad g^*y_2 = cy_1 + dy_2, \quad g^*v = (det(g))v,
\]

Let us write as \( Y_i = y_i^{p-1} \) and \( V = v^{p-1} \). Then we get the following additive expression of \( H^*(BE) \), which is used in Section .

\[
(4) \quad H^*(BE) \cong (\oplus_{i=1}^2 \mathbb{Z}/p[Y_i])\{y_i, \ldots, y_i^{p-2}, Y_i\}
\]

\[\oplus \mathbb{Z}/p[C]\{y_i, y_j|1 \leq i, j \leq p-1\} \oplus \mathbb{Z}/p\{1, C\}) \otimes \mathbb{Z}/p[V]\{1, \ldots, v^{p-2}\}.
\]

**Theorem 3.1.** (Theorem 4.3 in [T-Y], [B-L-O]) Let \( G \) have the \( p \)-Sylow subgroup \( E \), Then we have the isomorphism

\[
H^*(BG) \cong H^*(BE)^{Out(G)} \cap_{A} F^{*-\text{radical}} i_A^{-1} H^*(BA)^{W_G(A)}.
\]

4. **STABLE SPLITTING**

Martino-Priddy prove the following theorem of complete stable splitting

**Theorem 4.1.** (Martino-Priddy [M-P]) Let \( G \) be a finite group with a \( p \)-Sylow subgroup \( P \). The complete splitting of \( BG \) is given by

\[
BG \sim \bigvee \text{rank}_p A(Q, M) X_M
\]

where indecomposable summands \( X_M \) range over isomorphic classes of simple \( \mathbb{F}_p[Out(Q)] \)-modules \( M \) and over isomorphism classes of subgroups \( Q \subset P \).

For the definition of \( A(Q, M) \), see [M-P]. In particular, when \( Q \) is not subretract (that is, not a proper retract of a subgroup) of \( P \) and when \( W_G(Q) \subset Out(Q) \cong GL_n(\mathbb{F}_p) \), the rank of \( A(Q, M) \) is compute by

\[
\text{rank}_p A(Q, M) = \sum \text{dim}(\tilde{W}_G(Q_i) M)
\]

where \( \tilde{W}_G(Q) = \sum_{x \in W_G(Q)} x \) in \( \mathbb{F}_p[GL_n(\mathbb{F}_p)] \) and \( Q_i \) ranges over representatives of \( G \)-conjugacy classes of subgroups isomorphic to \( Q \) (see [M-P] Corollary 4.4).

Recall that \( Out(E) \cong Out(V = (\mathbb{Z}/p)^2) \cong GL_2(\mathbb{F}_p) \). The simple modules of \( G = GL_2(\mathbb{F}_p) \) is wellknown. Let us think \( V \) be the natural two-dimensional representation, and \( det \) the determinant representation of \( G \). Then there are \( p(p-1) \) simple \( \mathbb{F}_p[G] \)-modules given by \( M_{q,k} = S(V)^q \otimes (det)^k \) for \( 0 \leq q \leq p-1, 0 \leq k \leq p - 2 \). Harris-Kuhn determined the stable splitting of abelian \( p \)-groups. In particular, they showed

**Theorem 4.2.** (Harris-Kuhn) Let \( \tilde{X}_{q,k} = X_{M_{q,k}} \) (resp. \( L(1, k) \)) identifying \( M_{q,k} \in \mathbb{F}_p[V] \) (resp \( M_{0,k} \in \mathbb{F}_p[\mathbb{Z}/p] \)). There is the complete stable splitting

\[
BV \sim \bigvee \text{rank}_q L(1, k) \tilde{X}_{q,k} \forall q \neq 0 (q + 1)L(1, q)
\]

where \( 0 \leq q \leq p - 1, 0 \leq k \leq p - 2 \).

The summand \( L(1, p - 1) \) is usually written by \( L(1, 0) \).

It is also known \( H^+(L(1, k)) \cong \mathbb{Z}/p[y^{p-1}]\{y^k\} \). Since we have the isomorphism

\[
H^{2k}(BV) \cong (\mathbb{Z}/p)^{k+1} \cong H^{2k}((k + 1)L(1, k)),
\]

we also know if \( * \leq 2(p - 1) \), then \( H^*(\tilde{X}_{q,k}) \cong 0 \).
Lemma 4.3. Let $H \subset GL_2(\mathbb{F}_p)$ with $|H,p) = 1$ and let $G = V : H$. Let us write by $BG \sim V_{q,k} \tilde{n}(H)_{q,k} \tilde{X}_{q,k} \ V_{q'} \tilde{m}(H)_{q} L(1,q')$. Then
\[ \tilde{n}(H)_{q,k} = \text{rank}_p H^0(H; M_{q,k}), \quad \tilde{m}(H)_{q'} = \text{rank}_p H^{2q'}(BG). \]
In particular $\tilde{n}(H)_{q,0} = \text{rank}_p H^{2q}(BG)$.

Proof. Since $H^*(\tilde{X}_{q,k}) \cong 0$ for $* \leq 2(p-1)$, it is immediate that $\tilde{m}(H)_{q'} = \text{rank}_p H^{2q'}(G)$. To prove the first equation, assume that $H = \langle x \rangle \cong \mathbb{Z}/s$. Then for $v \in M_{q,k}$,
\[ \tilde{W}_G(V)v = (1 + (detx)^kx + \ldots + (detx)^{(s-1)}x^{s-1})v. \]
Since $(1 - (detx)^kx)^* = 0$, we get $\text{Ker}(1 - (detx)^kx) \subset \text{Image}(\tilde{W}_G(V))$. Since $M_{q,k}$ is a $\mathbb{Z}/p$-module and $|H,p) = 1$, we know $H^*(H; M_{q,k}) = 0$ for $* > 0$. Hence we get $\text{Ker}(1 - (detx)^kx)/\text{Image}(1 + (detx)^kx + \ldots + (detx)^{(s-1)}x^{s-1}) \cong H^1(H, M_{q,k}) \cong 0$.

Thus we have
\[ \tilde{m}_{q,k}(H) = \text{rank}_p M^{H}_{q,k} = \text{rank}_p H^0(H, M_{q,k}). \]

Next let $1 \to H' \to H \to \mathbb{Z}/s \to 0$. By induction, we assume $\text{Image}(\tilde{H}') = H^0(H'; M_{q,k})$. Then we can see
\[ \text{Image}(\tilde{H}) = H^0(\mathbb{Z}/s; H^0(H'; M_{q,k})) \cong M^{H}_{q,k} \cong H^0(H, M_{q,k}). \]

□

Next consider the stable splitting for the extraspecial $p$-group $E$.

Diez-Priddy prove the following theorem.

Theorem 4.4. (Diez-Priddy [D-P]) Let $X_{q,k} = X_{M_{q,k}}$ (resp. $L(2,k)$, $L(1,k)$) identifying $M_{q,k}$ (resp. $M_{p-1,k}$, $\in \mathbb{F}_p[V]$, $\mathbb{F}_p[\mathbb{Z}/p]$). There is the complete stable splitting
\[ BE \sim V_{q,k} (q+1)X_{q,k} \lor_k (p+1)L(2,k) \lor_{q \neq 0} (q+1)L(1,q) \lor L(1,p-1) \]
where $0 \leq q \leq p-1$, $0 \leq k \leq p-2$.

Remark. Of course $\tilde{X}_{q,k}$ is different from $X_{q,k}$ but $\tilde{X}_{p-1,k} = L(2,k)$.

Recall that
\[ H^{2q}(BE) \cong \begin{cases} \left( \mathbb{Z}/p \right)^{q+1} \cong H^{2q}((q+1)L(1,q)) & \text{for } 0 \leq k \leq p-1 \\ \left( \mathbb{Z}/p \right)^{q+2} \cong H^{2p-2}((p+1)L(1,0)) & \text{for } q = p-1 \end{cases} \]
This shows $H^*(X_{q,k}) \cong 0$ for $* \leq 2p-2$ since so is $L(2,k)$. The number $n(G)_{q,k}$ is only depend on $\text{Out}(G) = H$. Hence we have the following corollary.

Corollary 4.5. let $G$ have the $p$-Sylow subgroup $E$ and $\text{Out}(G) = H$. Let
\[ BG \sim Vn(G)_{q,k} X_{q,k} \lor m(G,2)_k L(2,k) \lor m(G,1)_k L(1,k). \]
Then $n(G)_{q,k} = \tilde{n}(H)_{q,k}$ and $m(G,1)_k = \text{rank}_p H^{2k}(G)$.

Hence next problem is to seek $m(G,2)$. The number $p+1$ for the summand $L(2,k)$ in $BE$ is given as follows. Let $u = \begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix}$ in $GL_2(\mathbb{F}_p)$ and $U = < u >$ : the maximal unipotent subgroup. Then for each $E$-conjugacy class of $V$-subgroup
$A_i = <ab^i,c>, i \in \mathbb{F}_p \cup \infty,$ we see $W_E(A_i) \cong U$. For $y_1^i y_2^j \in M_{q,k}$ (identifying $H^*(BV) \cong S^*(V) = \mathbb{Z}/p[y_1, y_2]$), we can compute

$$\bar{W}_G(A)y_1^iy_2^j = (1 + u + \ldots + u^{p-1})y_1^iy_2^j = \sum_i (y_1 + iy_2)^iy_2^j$$

$$= \sum_{s,t} (s,t)i^s y_1^{s-t}y_2^t = \sum_{s,t} i^s y_1^{s-t}y_2^{t+i}.$$  

Here $\sum_{i=0}^{p-1} i^t = 0$ for $1 \leq t \leq p-2$, and $= -1$ for $t = p - 1$. Hence we know

$$\dim_p \bar{W}_G(A_i) = 0 \text{ for } 1 \leq q \leq p - 2, \quad = 1 \text{ for } q = p - 1.$$  

Thus we know that $BE$ has just one $L(2, k)$ for each $E$-conjugacy $V$-subgroup $A_i$.

**Lemma 4.6.** Let $A$ be a $F^{ec}$-radical subgroup, i.e., $W_G(A) \supset SL_2(\mathbb{F}_p)$. Then $\bar{W}_G(A)(M_{q,k}) = 0$ for all $k$ and $1 \leq q \leq p - 1$.

**Proof.** The group $SL_2(\mathbb{F}_p)$ is generated by $u = \begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix}$ and $u' = \begin{pmatrix} 1 & 0 \\ 1 & 1 \end{pmatrix}$.

We know

$$Ker(1-u) \cong \mathbb{Z}/p[y_1^p - y_1^{p-1}, y_2] \quad \text{and} \quad Ker(1-u') \cong \mathbb{Z}/p[y_2^p - y_1^{p-1}, y_1].$$

identifying $S(V)^* \cong \mathbb{Z}/p[y_1, y_2]$. Hence we get $(Ker(1-u) \cap Ker(1-u'))^* \cong 0$ for $0 < * \leq p - 1$. □

**Proposition 4.7.** Let $G$ has the $p$-Sylow subgroup $E$. The number of $L(2, 0)$ in $BG$ is given by

$$m(G, 2)_0 = \#_G(V) - \#_G(F^{ec}V)$$

where $\#_G(V)$ (resp. $\#_G(F^{ec}V)$) is the number of $G$-conjugacy class of $V$-subgroups (resp. $F^{ec}$-radical subgroups).

**Proof.** We recall

$$H^*(BG) \cong H^*(BE)^{Out(G)} \cap A:F^{ec}-radical A^{-1}H^*(BA)^{Out(A)}.$$  

Let us write $K = E : Out(G)$ and $H^*(BE)^{Out(G)} = H^*(BK)$. From the above lemma, we only need to show

$$m(K, 2)_0 = \#_K(V) = \#_G(V).$$

Let $A$ be a $V$-subgroup of $K$ and $x \in W_K(A)$. Recall $A = <ab^i,c>$ for some $i$. Identifying $x$ as an element in $Aut(E)$, we see $x < c > = <c>$ since $<c>$ is the center of $E$. Hence

$$W_K(A) \subset B = U : (\mathbb{F}_p)^2 \text{; the Borel subgroup}.$$  

So we easily see that $\bar{W}_K(y_1^{p-1}) = \lambda y_2^{p-1}$ for some $\lambda \neq 0$ because $b^*y_2^{p-1} = y_2^{p-1}$ for $b = \text{diagonal} \in (\mathbb{F}_p)^* \times \mathbb{Z}/p\times$. That means $m(G, 2)_0 = \#_K(V) - \#_G(F^{ec}V)$.

On the other hand $m(G, 2)_k \leq \#_G(V) - \#_G(F^{ec}V)$ from the above lemma. Since $\#_K(V) \geq \#_G(V)$, we see that $\#_K(V) = \#_G(V)$ and the proposition. □

**Lemma 4.8.** Let $\xi \in \mathbb{F}_p^*$ and $(3k, p-1) \neq 1$. If $G \supset E : <\text{diag}(\xi, \xi)>$, then $BG$ does not contain the summand $L(2, k)$, i.e., $m(G, 2)_k = 0$. 

Proof. It is sufficient to prove the case \( G = E : < \text{diag}(\xi, \xi) > \). Let \( G = E : < \text{diag}(\xi, \xi) > \). Recal \( A_i = < ab^i, c > \) and

\[
\text{diag}(\xi, \xi) : ab^i \mapsto (ab^i)^\xi, \quad c \mapsto c^2.
\]

So the Weyle group is \( W_G(A_i) = U : < \text{diag}(\xi, \xi^2) > \). For \( v \in M_{q, k} \), we have

\[
\tilde{W}_G(A_i)v = \sum_{i=0}^{p-2} (\xi^{3i})^k \text{diag}(\xi^i, \xi^{2i})(1 + \ldots + u^{p-1})v.
\]

Thus we get the lemma from \( \sum_{i=0}^{p-2} \xi^{2ik} = 0 \) for \( 3k \neq 0 \ mod(p - 1) \) and \( = -1 \) otherwise.

\[\square\]

5. COHOMOLOGY AND SPLITTING OF \( B(\mathbb{Z}/3)^2 \)

In this section, we study the cohomology and stable splitting of \( BG \) for \( G \) having a 3-Sylow subgroup \( (\mathbb{Z}/3)^2 = V \). In this and next sections, \( p \) always means 3. Recall \( \text{Out}(V) \cong GL_2(\mathbb{F}_3) \) and \( \text{Out}(V)' \) consists the semidihedral group

\[
SD_{16} = < x, y | x^8 = y^2 = 1, xyx^{-1} = x^3 > .
\]

Each group \( G \) having 3-Sylow subgroup \( V \) is isomorphic to \( E : W, W \subset SD_{16} \). There is the \( SD_{16} \)-conjucacy classes of subgroups(here \( A \leftrightarrow B \) means \( A \supset B \))

\[
SD_{16} = \begin{cases} Q_8 \leftrightarrow \mathbb{Z}/4 \\ \mathbb{Z}/8 \leftrightarrow \mathbb{Z}/4 \leftrightarrow b\mathbb{Z}/2 \leftrightarrow 0 \\ D_8 \leftrightarrow \mathbb{Z}/2 \oplus \mathbb{Z}/2 \leftrightarrow \mathbb{Z}/2 \\
\end{cases}
\]

We can take generators of subgroups in \( GL = 2(\mathbb{F}_3) \) by the matrices

\[
\text{Z}/8 = < l >, \quad Q_8 = < w, k >, \quad D_8 = < w', k >, \quad \text{Z}/4 = < w >
\]

\[
\text{Z}/4 = < k >, \quad \text{Z}/2 \oplus \text{Z}/2 = < w', c >, \quad \text{Z}/2 = < c >, \quad \text{Z}/2 = < w' >
\]

where \( l = \begin{pmatrix} 0 & 1 \\ 1 & -1 \end{pmatrix}, \quad w = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}, \quad k = l^2 = \begin{pmatrix} 1 & -1 \\ -1 & -1 \end{pmatrix}, \quad w' = \quad w = \begin{pmatrix} 1 & -1 \\ 0 & -1 \end{pmatrix}, \quad c = t^4 = \begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix} \).

Here we note that \( k \) and \( w \) is \( GL_2(\mathbb{F}_3) \)-conjugate, in fact \( uku^{-1} = w \).

The cohomology of \( V \) is given \( H^*(BV) \cong \mathbb{Z}/3[y_1, y_2] \), and the following are immediately

\[
H^*(BV)^{<e>} \cong \mathbb{Z}/3[y_1^2, y_2^2]\{1, y_1y_2\} \quad H^*(BV)^{<w>} \cong \mathbb{Z}/3[y_1 + y_2, y_2^2] .
\]

Let us write \( Y_1 = y_1^2 \) and \( t = y_1y_2 \). The \( k \)-action is given

\[
k : Y_1 \mapsto Y_1 + Y_2 + t, \quad Y_2 \mapsto Y_1 + Y_2 - t, \quad t \mapsto -Y_1 + Y_2.
\]

So the following are invariant

\[
a = -Y_1 + Y_2 + t, \quad a_1 = Y_1(Y_1 + Y_2 + t), \quad a_2 = Y_2(Y_1 + Y_2 - t), \quad b = t(Y_1 - Y_2).
\]

here we note that \( a^2 = a_1 + a_2, \quad b^2 = a_1a_2 \). We can prove the invariant ring is

\[
H^*(BV)^{<e>} \cong \mathbb{Z}/3[a_1, a_2, b, ab].
\]
Next consider the invariant under $Q_8 = < w, k >$. The action for $w$ is $a \mapsto -a$, $a_1 \leftrightarrow a_2$, $b \mapsto b$. Hence we get

$$H^*(BV)^{Q_8} \cong \mathbb{Z}/3[a_1 + a_2, a_1a_2, 1, b]{1, (a_1 - a_2)a}.$$ 

Let us write $S = \mathbb{Z}/3[a_1 + a_2, a_1a_2]$ and $a' = (a_1 - a_2)a$. The action for $l$ is given $l : Y_1 \mapsto Y_2 \mapsto Y_1 + Y_2 + t \mapsto Y_1 + Y_2 - t \mapsto Y_1$. Hence $l : a \mapsto -a$, $a_1 \leftrightarrow a_2$, $b \mapsto -b$. Therefore we get

$$H^*(BV)^{<l>} \cong S{1, a', ab, (a_1 - a_2)b}.$$ 

The action for $w' : Y_1 \mapsto Y_1 + Y_2 + t$, $Y_2 \mapsto Y_2$, implies that $w' : a \mapsto a$, $a_1 \mapsto a_i$, $b \mapsto -b$. Then we can see

$$H^*(BV)^{D_8} = H^*(BV)^{<k, w'>} \cong \mathbb{Z}/3[a_1, a_2]{1, a} \cong S{1, a, a_1, a'}.$$ 

Hence we also have

$$H^*(BV)^{SD_{16}} \cong S{1, a'}.$$ 

Recall the Dickson algebra $DA = \mathbb{Z}/3[\tilde{D}_1, \tilde{D}_2] \cong H^*(BV)^{GL_2(\mathbb{F}_3)}$ where

$$\tilde{D}_1 = Y_1^3 + Y_2Y_4 + Y_2Y_2^2 + Y_2^3 = (a_2 - a_1)a = a', \quad \tilde{D}_2 = (y_3^2 - y_1y_2^2)^2 = a_1a_2.$$ 

Using $a^2 = (a_1 + a_2)$ and $\tilde{D}_1 = a^6 - a_1a_2a^2$, we can write

$$H^*(BV)^{SD_{16}} \cong \mathbb{Z}/3[a^2, \tilde{D}_2]{1, \tilde{D}_1} \cong DA{1, a^2, a^4}.$$ 

**Theorem 5.1.** Let $G = (\mathbb{Z}/3)^2 : H$ for $H \subset SD_{16}$. Then $BG$ has the following stable splitting

$$H^0(BG) \cong \mathbb{Z}/3, \quad H^2(BG) \cong 0, \quad H^4(BG) \cong \mathbb{Z}/3$$

implies that $BG$ contains just one $\tilde{X}_{0,0}$, $\tilde{X}_{2,0}$, $L(1,0)$ but does not $\tilde{X}_{1,0}$, $L(1,1)$. Since $det(k) = 1$, we also know that $\tilde{X}_{0,1}$ and $\tilde{X}_{2,1}$ are contained. So we can see

$$B(V : \mathbb{Z}/4) \sim \tilde{X}_{0,0} \vee \tilde{X}_{0,1} \vee \tilde{X}_{2,0} \vee \tilde{X}_{2,1} \vee L(1,0).$$

Main parts of the above splittings are given in (6) in [Y2] by direct computations of $\tilde{W}_G(V)$ (see p149 in [Y2]). However we get the theorem more easily by using cohomology here. For example, let us consider the case $G = V : < k >$. The cohomology

$$H^0(BG) \cong \mathbb{Z}/3, \quad H^2(BG) \cong 0, \quad H^4(BG) \cong \mathbb{Z}/3$$

implies that $BG$ contains just one $\tilde{X}_{0,0}$, $\tilde{X}_{2,0}$, $L(1,0)$ but does not $\tilde{X}_{1,0}$, $L(1,1)$. Since $det(k) = 1$, we also know that $\tilde{X}_{0,1}$ and $\tilde{X}_{2,1}$ are contained. So we can see

$$B(V : \mathbb{Z}/4) \sim \tilde{X}_{0,0} \vee \tilde{X}_{0,1} \vee \tilde{X}_{2,0} \vee \tilde{X}_{2,1} \vee L(1,0).$$

Next consider the case $G' = V : < l >$. The fact $H^4(G) \cong 0$ implies that $BG'$ does not contain $\tilde{X}_{2,0}$, $L(1,0)$. The determinant $det(l) = -1$, and $l : a \mapsto -a$ shows that $BG'$ contains $X_{2,1}$ but does not $\tilde{X}_{0,1}$. Hence we know $BG' \sim \tilde{X}_{0,0} \vee \tilde{X}_{2,1}$. Moreover we know $BV : SD_{16} \sim \tilde{X}_{0,0}$ since $w : a \mapsto -a$ but $det(w) = 1$. Thus we have the graph

$$\tilde{X}_{0,0} \leftarrow SD_{16} \tilde{X}_{2,1} \mathbb{Z}/8 \tilde{X}_{2,0} \vee \tilde{X}_{0,1} L(1,0) \mathbb{Z}/4$$
Similarly we get the other parts of the above graph.

**Corollary 5.2.** Let \( S = \mathbb{Z}/3[a_1 + a_2, a_1a_2] \), We have the isomorphisms

\[
H^*(\tilde{X}_{0,0}) \cong S\{1, \tilde{D}_1\}, \quad H^*(\tilde{X}_{0,1}) \cong S\{b, \tilde{D}_1b\},
\]

\[
H^*(\tilde{X}_{2,1}) \cong S\{ab, (a_1 - a_2)b\}, \quad H^*(\tilde{X}_{2,0} \vee L(1,0)) \cong S\{a, a_1 - a_2\} \cong DA\{a, a^2, a^3\}.
\]

Here we write down the decomposition of cohomology for most typical case

\[
H^*(BV)^{<k>} \cong S\{1, a_1 - a_2\}\{1\}a\{1, b\}
\]

\[
\cong S\{1, a(a_1 - a_2), b, b(a_1 - a_2), ab, (a_1 - a_2)b, a, (a_1 - a_2)\}
\]

\[
\cong H^*(\tilde{X}_{0,0}) \oplus H^*(\tilde{X}_{0,1}) \oplus H^*(\tilde{X}_{2,1}) \oplus H^*(\tilde{X}_{2,0} \vee L(1,0)).
\]

6. COHOMOLOGY AND SPLITTING OF \( B3^1_{+2} \).

In this section we study the cohomology and stable splitting of \( BG \) for \( G \) having a 3-Sylow subgroup \( E = 3^1_{+2} \). In the splitting for \( BE \), the summands \( X_{q,k} \) are called dominant summands. Moreover the summands \( L(2,0) \vee L(1,0) \) is usually written by \( M(2) \). The following lemma is almost immediately from Proposition 4.7 and Lemma 4.8.

**Lemma 6.1.** If \( G \supset E : < \text{diag}(-1, -1) > \) defining \( Out(E) \cong GL_2(\mathbb{F}_3) \) and \( G \) has \( E \) as a 3-Sylow subgroup, then

\( BG \sim (\text{dominant summand}) \vee (\#_G(V) - \#_G(F^{\text{st}}V)(L(2,0) \vee L(1,0)). \)

**Theorem 6.2.** If \( G \) has a 3-Sylow subgroup \( E \), then \( BG \) is homotopic to the classifying space of one of the following groups. Moreover the stable splitting is given by the graph so that \( \tilde{X}_1 \rightarrow \ldots \tilde{X}_i \rightarrow G \) means \( BG \sim X_1 \vee \ldots \vee X_i \) and \( EH = E : H \) for \( H \subset SD_{16} \).

![Graph diagram](image)

**Proof.** All groups except for \( E \) and \( E : < w' > \) contain \( E : < \text{diag}(-1, -1) > \). Hence we get the theorem from Corollary 4.5, Theorem 5.1 and Lemma 6.1, except for the place for \( H^*(BE : < w' >) \). Let \( G = E : < w' > \). Note \( w' : y_1 \mapsto y_1 - y_2, y_2 \mapsto -y_2, v \mapsto -v \). Hence \( H^2(G) \cong \mathbb{Z}/3[y_1 + y_2] \}. \) So \( BG \) contains one \( L(1,1) \). Next consider the number of \( L(2,0), L(2,1) \). The \( G \)-conjugacy classes of \( V \)-subgroups are \( A_0 \sim A_2, A_1, A_{\infty} \). The weyle groups are

\( W_G(A_0) \cong U, \quad W_G(A_1) \cong U : < \text{diag}(1, -1) >, \quad W_G(A_{\infty}) \cong U : < \text{diag}(-1, -1) >. \)
By the arguments similar to the proof of Lemma 4.8, we have that
\[
\begin{align*}
\dim(\overline{W}_G(A_i)M_{2,0}) &= 1 \quad \text{for all } i \\
\dim(\overline{W}_G(A_i)M_{2,0}) &= 1, 0, 1 \quad \text{for } i = 0, 1, \infty.
\end{align*}
\]
Thus we know $BG \supset 3L(2,0) \vee 2L(2,1)$.

We write down the cohomologies explicitly (see also [T-Y],[Y2]). First we compute $H^*(BE:H)$. The following cohomologies are easily computed
\[
\begin{align*}
H^*(BE)^{<c>} &\cong \mathbb{Z}/3[Y_1] \oplus \mathbb{Z}/3[Y_2]^+ \oplus \mathbb{Z}/3[C] \{1, y_1y_2\} \otimes \mathbb{Z}/3[v] \\
H^*(BE)^{<w>} &\cong \mathbb{Z}/3[Y_1 + Y_2]^+ \oplus \mathbb{Z}/3[C] \otimes \mathbb{Z}/3[v] \\
H^*(BE)^{<k>} &\cong (\mathbb{Z}/3[C] \{1, a\}) \otimes \mathbb{Z}/3[v]
\end{align*}
\] where $a = -Y + Y_2 + y_1y_2$.

\[
\begin{align*}
H^*(BE)^{w'} &\cong (\mathbb{Z}/3[Y_2]^+ \oplus \mathbb{Z}/3[C]) \otimes \mathbb{Z}/3[v]
\end{align*}
\]

Let $D_1 = C^3 + V$, $D_2 = CV$. Then it is known that
\[
\begin{align*}
D_1|A_i &= \tilde{D}_1, \quad D_2|A_i = \tilde{D}_2 \quad \text{for all } i \in \mathbb{F}_3 \cup \infty.
\end{align*}
\]

So we also write $DA \cong \mathbb{Z}/3[D_1, D_2]$. We have
\[
\begin{align*}
H^*(BE)^{Q*} &\cong H^*(BE)^{<k>} \cap H^*(BE)^{<w>} \cong (\mathbb{Z}/3[C]) \otimes \mathbb{Z}/3[v] \\
H^*(BE)^{D} &\cong H^*(BE)^{<k>} \cap H^*(BE)^{<w>} \cong \mathbb{Z}/3[C] \{1, a\} \otimes \mathbb{Z}/3[D_1] \\
H^*(BE)^{D_e} &\cong (\mathbb{Z}/3[C]) \{1, a\} \otimes \mathbb{Z}/3[D_1]
\end{align*}
\]
Hence we have
\[
H^*(BE)^{SD_{16}} \cong \mathbb{Z}/3[C, D_1]
\]

Proposition 6.3. There is isomorphisms for $|a''| = 4$,
\[
H^*(2F_4(2)') \cong DA\{1, (D_1 - C^3)a''\}
\]
\[
H^*(M_{24}) \cong (\mathbb{Z}/3[D_2] \oplus \mathbb{Z}/3[C]\{a''\}) \otimes \mathbb{Z}/3[D_1]
\]

Proof. Let $G = M_{24}$. Then $G$ has just two $G$-conjugacy classes of $V$-subgroups
\[
A_0 \sim A_1 \quad A_2 \sim A_{\infty}
\]
It is known that one is $F^{ec}$-radical on the other is not. Suppose that $A_0$ is $F^{ec}$-radical. Then $W_G(A_0) \cong GL_2(\mathbb{F}_3)$. Let $a'' = a + C$. Then
\[
a''|A_0 = (-Y_1 + Y_2 + y_1y_2 + C)|A_0 = 0, \quad a''|A_{\infty} = -Y.
\]
By the Theorem 3.1
\[
H^*(BM_{24}) \cong H^*(BE)^{D_e} \cap i_{A_0}^{-1} H^*(BA_0)^{W_G(A_0)}
\]
we get the isomorphism for $M_{24}$. For $G = 2F_4()'$, the both conjugacy classes are $F^{ec}$-subgroups and $W_G(A_2) \cong GL_2(\mathbb{F}_3)$. Hence
\[
H^*(2^2F_4(2)') \cong H^*(BM_{24}) \cap i_{A_2}^{-1} H^*(BA_2)^{GL_2(\mathbb{F}_3)}
\]
We know
\[
(D_1 - C^3)a''|A_0 = 0 \quad (D_1 - C^3)a''|A_{\infty} = -VY = \tilde{D}_1.
\]
Thus we get the cohomology of $2^2F_4(2)'$. 

\[\square\]
**Remark.** In \([T-Y],[Y2]\), we take

\[
(Z/2)^2 \cong \langle \text{diag}(\pm 1, \mp 1) \rangle, \quad D_8 \cong \langle \text{diag}(\pm 1, \mp 1) \rangle.
\]

For this case, the \(M_{24}\)-conjugacy classes of \(V\)-subgroups are \(A_0 \sim A_\infty, A_1 \sim A_2\), and we can take \(a'' = B = C - Y_1 - Y_2\). This case the expressions of \(H^*(M_{1,2}), H^*(V : GL_2(\mathbb{F}_3))\) are more simple (see \([T-Y],[Y2]\)).

**Remark.** Corollary 6.3 in \([T-Y]\) and Corollary 3.7 in \([Y2]\) are not correct. This came from Theorem 6.1. This theorem is only correct with adding the assumption that there are exactly two \(G\) c.c. of \(\mathbb{F}_p^2\) subgroups such that one is \(p\)-pure and the other in not, which is always satisfied for sporadic simple groups but not for \(2F_4(2)'\).

**Corollary 6.4.** We also have the isomorphisms.

\[
H^*(X_{2,0}) \cong DA\{D_2\}, \quad H^*(X_{2,1}) \cong \mathbb{Z}/3[C, D_1]\{c'\} \text{ where } (c')^2 = CD_2, c' = (av)
\]

\[
H^*(X_{0,1}) \cong \mathbb{Z}/3[C, D_1]\{v\}, \quad H^*(M(2)) \cong DA\{C, C^2, C^3\} \text{ where } C^4 = CD_1 - D_2.
\]

Here we write the typical examples. First note that \(C^4 = CD_1 - D_2\) implies

\[
\mathbb{Z}/3[C, D_1] \cong DA\{1, C, C^2, C^3\} \cong H^*(X_{0,0}) \oplus H^*(M(2)),
\]

\[
\mathbb{Z}/3[C, D_1]\{C\} \cong DA\{C, C^2, C^3, D_2\} \cong H^*(M(2)) \oplus H^*(X_{2,0}).
\]

The decomposition for \(H^*(BE)^{D_s}\) is isomorphic to

\[
\mathbb{Z}/3[C, D_1]\{1, a^v, a''\} \cong DA\{1, C, C^2, C^3, (D_1 - C^3) a'', a'', a'^2, a'^3\}
\]

\[
\cong H^*(X_{0,0}) \oplus H^*(M(2)) \oplus H^*(X_{2,0}) \oplus H^*(M(2)).
\]

The decomposition for \(H^*(BE)^{<k>}\) is

\[
\mathbb{Z}/3[C, D_1]\{1, a, v, av\} \cong H^*(BE)^{D_s} \oplus H^*(X_{0,1}) \oplus H^*(X_{2,1}).
\]

**References**


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