The number of subgroups of a finite $p$-group (Cohomology theory of finite groups)

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The number of subgroups of a finite $p$-group

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1 The main result

For a finitely generated group $A$, $m_A(d)$ denotes the number of subgroups of index $d$ in $A$. Let $p$ be a prime. We say that a finitely generated group $A$ admits $\text{CP}(p^s)$, where $s$ is a positive integer, if the following conditions hold:

1. For any integer $i$ with $1 \leq i \leq [(s+1)/2]$, where $[(s+1)/2]$ is the greatest integer $\leq (s+1)/2$,
   \[ m_A(p^{i-1}) \equiv m_A(p^i) \mod p^i. \]
2. Moreover
   \[ m_A\left(p^{\frac{s+1}{2}}\right) \equiv m_A\left(p^{\frac{s+1}{2}+1}\right) \mod p^{\frac{s}{2}}. \]

For a finite group $A$, let $A'$ be the commutator subgroup of $A$, $|A|$ the order of $A$, and $\exp A$ the exponent of $A$. Hereafter, we will mainly treat the results for $p$-groups. Butler proved the following [3]:

**Proposition 1** Any finite abelian $p$-group $P$ admits $\text{CP}(|P|)$.

**Question 2** What $p$-groups $P$ admit $\text{CP}(|P : P'|)$?

A finite $p$-group $P$ admits $\text{CP}(p)$, because

\[ m_P(p) = m_{P/\Phi(P)}(p) \equiv 1 = m_P(1) \mod p, \]

where $\Phi(P)$ denotes the Frattini subgroup of $P$. Also, for any finite $p$-group $P$ such that $|P/\Phi(P)| = p^s$,

\[ m_P(p^i) \equiv m_{P/\Phi(P)}(p^i) \mod p^{s-i+1} \]

by [4, Theorem 1.61]. This result, together with Proposition 1, implies that any finite $p$-group $P$ admits $\text{CP}(|P : \Phi(P)|)$ [8, Theorem 1.1]. So if the factor group $P/P'$ of a finite $p$-group $P$ by $P'$ is elementary abelian, then $P$ admits $\text{CP}(|P : P'|)$. As a generalization of this fact, we have the following main result of this report.

**Theorem 3** If $P/P'$ is the direct product of a cyclic group and an elementary abelian group, then $P$ admits $\text{CP}(|P : P'|)$. 
2 Related results

For a finitely generated group $A$ and for a finite group $G$, Hom$(A, G)$ denotes the number of homomorphisms from $A$ to $G$. Let $S_n$ be the symmetric group of degree $n$. In [9] Wohlfahrt proved that for a finitely generated group $A$,

\[ 1 + \sum_{n=1}^{\infty} \frac{\#\text{Hom}(A, S_n)}{n!} X^n = \exp \left( \sum_{B \leq A} \frac{1}{|A:B|} X^{|A:B|} \right) \]

where the summation $\sum_{B \leq A}$ runs over all subgroups $B$ of $A$ with the factor groups $A/B$ are finite groups. Using this formula we can prove the following.

**Proposition 4** If a finite $p$-group $P$ admits $\text{CP}(p^s)$, then

\[ \#\text{Hom}(P, S_n) \equiv 0 \mod \gcd(p^s, n!). \]

This proposition is a special case of [7, Theorem 1.2]. Combining Proposition 4 with Proposition 1 and 3, we have the following.

**Corollary 5** Let $P$ be a finite $p$-group.

1. If $P$ is abelian, then $\#\text{Hom}(P, S_n) \equiv 0 \mod \gcd(|P|, n!)$.

2. If $P/P'$ is the direct product of a cyclic group and an elementary abelian group, then $\#\text{Hom}(P, S_n) \equiv 0 \gcd(|P : P'|, n!)$.

The assertions of Corollary 5 are special cases of these results.

**Theorem 6 ([10])** For a finite abelian group $A$ and for a finite group $G$,

\[ \#\text{Hom}(A, G) \equiv 0 \mod \gcd(|A|, |G|). \]

**Theorem 7 ([1, 2])** For a finite groups $A$ and $G$, if a Sylow $p$-subgroup of $A/A'$ is either a cyclic group or the direct product of a cyclic group and an elementary abelian group for each prime $p$ dividing $|A/A'|$, then

\[ \#\text{Hom}(A, G) \equiv 0 \mod \gcd(|A/A'|, |G|). \]

The above Theorem 6 due to Yoshida is a generalization of the following Frobenius' theorem:

**Theorem 8** The number of solutions of $x^n = 1$ in a finite group $H$ is a multiple of $\gcd(n, |H|)$. 
3 Key results

For a finite group $H$ and for a finite group $C$ that acts on $H$, let $z(C, H)$ denote the number of all complements of $H$ in the semidirect product $CH$ with respect to a fixed action of $C$ on $H$, i.e.,

$$z(C, H) = \#\{D \leq CH | D \cap H = \{1\}, DH = CH\},$$

which is equal to the number of all crossed homomorphisms from $C$ to $H$. The following proposition is due to Asai and Yoshida [2, Proposition 3.3]:

**Proposition 9** Let $H$ be a finite $p$-group and $C$ a cyclic $p$-group that acts on $H$. Then $z(C, H) \equiv 0 \mod \gcd(|C|, |H|)$.

This result is a special case of the following theorem due to P. Hall [5, Theorem 1.6]:

**Theorem 10** For a finite group $H$ and for an automorphism $\theta$ of $H$ with $\theta^n = 1$, the number of elements $x$ of $H$ that satisfy the equation

$$x \cdot x^\theta \cdot x^{\theta^2} \cdots x^{\theta^{n-1}} = 1$$

is a multiple of $\gcd(n, |H|)$.

This theorem is also a generalization of Theorem 8. Proposition 9 played an important role in the proof of Theorem 7. For the proof of Theorem 3, we need another type of result concerning $z(C, H)$. The following theorem is due to P.Hall [4, 6]:

**Theorem 11** Let $x$ and $y$ be any elements of a finite group $G$. Then there exist elements $c_2, c_3, \ldots, c_n$ of $(x, y)$ such that $c_i$ is an element of $C_i((x, y))$ for each $i$ and

$$x^n y^n = (xy)^n c_2 c_3 \cdots c_n$$

where $e_i = n(n - 1) \cdots (n - i + 1)/i!$ for each $i$.

Using Theorem 11, we obtain the following.

**Proposition 12** Let $H$ be a finite $p$-group and $C$ a cyclic $p$-group that acts on $H$. If $\exp H \leq |C|$ and $|[CH, H]| < |C|$, then $z(C, H) = |H|$.

To prove Theorem 3, we use this fact and the following result [8, Proposition 2.2]:

**Proposition 13** Let $L$ be a finite group and $H$ a normal subgroup of $L$ such that $L/H$ is a cyclic $p$-group. Let $C$ be a cyclic $p$-subgroup of $L$ with $C \cap H = \{1\}$. If $L \neq CH$ and $z(C, H) = |H|$, then $\{\tilde{C} \leq L | \tilde{C} \cap H = \{1\}, |\tilde{C}| = p|C|\}$ is not empty.
4 Further results

The following proposition is a special case of [8, Theorem 1.2].

**Theorem 14** Let $P$ be a finite $p$-group such that $\exp P/P' = p^{\lambda_1}$. Then

$$m_P(p^{i-1}) \equiv m_P(p^i) \mod p^i$$

for any integer $i$ with $1 \leq i \leq \lambda_1$.

**Corollary 15** Under the hypothesis of Theorem 14, $P$ admits $\mathrm{CP}(p^s)$ if $2\lambda_1 \geq s + 2$.

A sequence $\lambda = (\lambda_1, \lambda_2, \ldots, \lambda_r, 0, \ldots)$ of nonnegative integers in weekly decreasing order is called the type of a finite abelian $p$-group isomorphic to

$$\mathbb{Z}/p^{\lambda_1}\mathbb{Z} \oplus \mathbb{Z}/p^{\lambda_2}\mathbb{Z} \oplus \cdots \oplus \mathbb{Z}/p^{\lambda_r}\mathbb{Z}.$$

**Question 16** Does a finite $p$-group $P$ such that the type $\lambda = (\lambda_1, \lambda_2, \ldots)$ of $P/P'$ satisfies $\lambda_1 \geq \lambda_2 + \lambda_3 + \cdots$ admit $\mathrm{CP}(|P : P'|)$?

As an answer of the Question 16, we have the following.

**Theorem 17** Let $P$ be a finite $p$-group, and let $\lambda = (\lambda_1, \lambda_2, \ldots)$ be the type of $P/P'$. If $\lambda_2 \leq 2$, $\lambda_3 \leq 1$ and $\lambda_1 \geq \lambda_2 + \lambda_3 + \cdots$, then $P$ admits $\mathrm{CP}(|P : P'|)$.

**References**


