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On the number of crossed homomorphisms from a finite cyclic $p$-group to a finite $p$-group

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For finite groups $H$ and $C$ such that $C$ acts on $H$, let $Z(C, H)$ denote the set consisting 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 bijectively corresponds to the set of all crossed homomorphisms from $C$ to $H$ ([5, Ch.2, §8]), and let $z(C, H) = \# Z(C, H)$. One of the famous result concerning this number is the theorem due to P. Hall ([4, Theorem 1.6]):

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

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

is a multiple of $\gcd(n, |H|)$. This result is a generalization of the theorem of Frobenius:

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

Let $p$ denotes a prime integer. We shall show some results about $z(C, H)$ where $C$ and $H$ are $p$-groups. For a finite group $G$, let $C_2(G) = [G, G]$, and define $C_i(G) = [C_{i-1}, G]$ for each integer $i$ such that $i \geq 3$. We use the following famous theorem due to P. Hall.

**Theorem 1** ([3, 6]) Let $x$ and $y$ be any elements of a finite group $G$. Then there exist elements $c_2, c_3, \ldots, c_n$ of $\langle x, y \rangle$ such that $c_i$ is an element of $C_i(\langle x, y \rangle)$ for each $i$ and that

$$x^n y^n = (xy)^n c_2^{e_2} c_3^{e_3} \cdots c_n^{e_n}$$

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

Using Theorem 1, we obtain the following.
Proposition 1 Let $G$ be a finite $p$-group, and let $c$ be an element of $G$. Assume that $\exp C_i(G) \leq p^{u-i+2}$ for each integer $i$ such that $i \geq 2$. If either $p > 2$ or $\exp C_2(G) \leq p^{u-1}$, then $(cx)^{p^u} = c^{p^u}$ for any element $x$ of $G$ such that $x^{p^u} = 1$.

Let $H$ be a finite $p$-group that is not $\{1\}$, and let $C$ be a finite cyclic group of order $p^u$ that acts on $H$. Let $C_1(CH) = H$. Clearly, $C_{i+1}(CH) \subset C_i(CH)$ for each positive integer $i$. By [6, p.43, Corollary 2], $C_2(CH) \neq C_1(CH)$. It follows that $C_{i+1}(CH) \neq C_i(CH)$ for each positive integer $i$, provided $C_i(CH) \neq \{1\}$ ([6]). Let $j$ be the least integer such that $|C_{j+1}(CH)| \leq p^{u-1}$, and let $Q(CH)$ be a normal subgroup of $CH$ defined by

$$Q(CH) = \Omega_u(C_j(CH)).$$

Then $|Q(CH)| \geq \gcd(p^u, |H|)$, and $|[Q(CH), CH]| \leq p^{u-1}$. Furthermore,

$$\exp Q(CH) \leq p^u$$

by Proposition 1. The following proposition is a consequence of Proposition 1.

Proposition 2 Let $H$ be a finite $p$-group, and let $C$ be a cyclic $p$-group that acts on $H$. Then $z(C, H) \equiv 0 \mod |Q(CH)|$.

Corollary 1 ([2, Proposition 3.3]) Let $H$ be a finite $p$-group, and let $C$ be a cyclic $p$-group that acts on $H$. Then $z(C, H) \equiv 0 \mod \gcd(|C|, |H|)$.

By using Propositions 1 and 2, we get the following.

Theorem 2 Let $H$ be a finite $p$-group, and let $C$ be a cyclic group of order $p^u$ that acts on $H$. Assume that $H$ contains no cyclic normal $C$-invariant subgroup of order $p^{u+1}$. If either $p > 2$ or $H$ contains no proper cyclic normal $C$-invariant subgroup of order $p^u$, then $z(C, H) \equiv 0 \mod \gcd(p^{u+1}, |H|)$.

Equivalently, the following theorem holds.

Theorem 3 Let $H$ be a finite $p$-group, and let $\theta$ be an automorphism of $H$ such that $\theta^{p^u} = 1$. Assume that $H$ contains no cyclic normal subgroup $Q$ of order $p^{u+1}$ such that $Q^\theta = Q$. If either $p > 2$ or $H$ contains no proper cyclic normal subgroup $Q$ of order $p^u$ such that $Q^\theta = Q$, then the number of elements $x$ of $H$ that satisfy the equation

$$(x\theta^{-1})^{p^u} = x \cdot x^\theta \cdot x^{\theta^2} \cdots x^{\theta^{p^u-1}} = 1$$

is a multiple of $\gcd(p^{u+1}, |H|)$.

Corollary 2 Let $H$ be a finite $p$-group that contains no normal cyclic subgroup of order $p^{u+1}$. If either $p > 2$ or $H$ contains no proper cyclic normal subgroup of order $p^u$, then the number of solutions of $x^{p^u} = 1$ in $H$ is a multiple of $\gcd(p^{u+1}, |H|)$. 
We also have some results in the case where $C$ is an abelian $p$-group that acts on a $p$-group $H$. The following theorem is a result concerning to the number of cocycles.

**Theorem 4 ([1])** Let $H$ and $C$ be finite abelian $p$-groups such that $C$ acts on $H$. Then $z(C,H) \equiv 0 \mod \gcd(|C|,|H|)$.

*Sketch of proof.* Suppose that $C = C_1 \times C_2 \times \cdots \times C_r$, where $C_1, C_2, \ldots, C_r$ are cyclic $p$-groups. Let $x_j$ be a generator of $C_j$ for each $j$. Let $G_i$ denote the set of all elements $h$ of $H$ such that $[h, x_j] = 1$ for any $j$ except $i$. Assume that $|G_i| \geq |C_i|$ for any $i$. Let $G = Q(C_1G_1) \times \cdots \times Q(C_rG_r)$. Then $|G| \geq |C|$. For each $i$, if the order of element $y$ of $C_iH$ is $|C_i|$, then the order of $yh$ is also $|C_i|$ for any element $h$ of $Q(C_iG_i)$ by Proposition 1. Thereby, $G$ acts on $Z(C,H)$, and the action is semiregular. Hence, $z(C,H) \equiv 0 \mod |C|$. Next, assume that $|G_{i_0}| < |C_{i_0}|$ for some $i_0$. By Corollary 1, $G_{i_0}$ acts on $Z(C_{i_0}, H)$. Moreover, $H/C_{i_0}(C)$ acts on $Z(C,H)$ by conjugation. So, the action of $H/C_{i_0}(C) \times G_{i_0}$ on $Z(C,H)$ is naturally defined. We have that the order of the stabilizer of an element of $Z(C,H)$ is $|G_{i_0} : C_{i_0}(C)|$. Hence, $z(C,H) \equiv 0 \mod |H|$. Thus, the theorem holds. □

It follows from [2, Proposition 3.2] that if an elementary abelian $p$-group $C$ acts on a finite $p$-group $H$, $z(C,H) \equiv 0 \mod |C|$. The following proposition is a generalization of Corollary 1.

**Proposition 3 ([1])** Let $H$ be a finite $p$-group, and let $C$ be a finite abelian $p$-group that acts on $H$. Assume that $C$ is the direct product of a cyclic $p$-group and an elementary abelian $p$-group. Then $z(C,H) \equiv 0 \mod \gcd(|C|,|H|)$.

This results yields the following.

**Theorem 5 ([1, 2])** Let $A$ be a finite group such that a Sylow $p$-group of $A/A'$ is the direct product of a cyclic $p$-group and an elementary abelian $p$-group. For any finite group $G$, the number of homomorphisms from $A$ to $G$ is a multiple of $\gcd(|A/A'|_p,|G|)$, where $|A/A'|_p$ is the highest power of $p$ dividing $|A/A'|$.

**References**


