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On p-Groups with Abelian Automorphism Group.

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Introduction.

In this paper we give an answer to the following question: «Which is the smallest order of a non cyclic p-group whose automorphism group is abelian?» (here p is a prime number). For $p = 2$ the answer is already well known; namely in 1913 G. Miller explicitly constructed a group of order 2^6 with the property stated above [5]. For $p \neq 2$ the problem was investigated mainly by B. Earnley who proved that no non-cyclic p-groups of order less or equal to p^5 have abelian automorphism groups ([1], p.30). In a previous paper Jonah and Konvisser had stated that there exist some groups of order p^8, $p \neq 2$, whose automorphism groups are abelian of order p^{16} [4] and afterwards B. Earnley generalized this result by constructing a family of groups of order p^{2+3n} with the given property, for each natural number $n \geq 2$ [1].

After these achievements, the unsolved problem was actually whether there existed a non-cyclic group G whose automorphism group is abelian and such that $p^6 \leq |G| \leq p^7$. In this paper the answer is obtained in two steps:

— in the first section we prove that there exist no groups of order p^6 whose automorphism groups are abelian,

— in the second section we give the example of a group of order p^7 whose automorphism group is abelian. This group is special, is generated by 4 elements and is the smallest of an infinite family of groups of order p^{n^2+3n+3}, where n is a natural number.

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Notation and preliminary results.

The notation used is standard. In the whole paper if G is a group $Z = Z(G)$ will denote its center, if no ambiguity can arise.

$\mathrm{Aut}_C G = \{\alpha \in \mathrm{Aut}\, G \mid \alpha$ induces the identity on $G/Z(G)\}$ is the group of central automorphisms of G.

$C_G(S)$ is the centralizer of S in G, if S is a subset of G.

$\Omega_1(G) = \langle y \in G \mid y^p = 1\rangle$, if G is a p-group.

A PN group is a group with no non-trivial abelian direct factors.

$\boldsymbol{Z}/p\boldsymbol{Z}$ is the field with p elements and if $r \in \boldsymbol{Z}/p\boldsymbol{Z}$, $r \neq 0$ then $1/r$ will denote its inverse.

In the whole paper, we shall often represent the automorphisms of an elementary abelian p-group by matrices. Infact such a group is a vector space over the field $\boldsymbol{Z}/p\boldsymbol{Z}$ so that, once we have fixed a basis $\{x_i \mid i = 1, \ldots, n\}$, we can associate to each $\alpha \in \mathrm{Aut}\, G$ the matrix $A = (a_{ij})_{i,j=1,\ldots,n}$ with entries in $\boldsymbol{Z}/p\boldsymbol{Z}$ satisfying $x_i^\alpha = \prod_{j=1}^{n} x^{a_{ij}}$.

We collect in the following lemmas some known results which will be used in the sequel.

LEMMA 0.1. *Let G be a group of class 2. For all $x, y, w \in G$, $m \in \boldsymbol{Z}$ and $n \in \boldsymbol{N}$ we have*:

(i) $[x, yw] = [x, y][x, w]$,

(ii) $[xy, w] = [x, w][y, w]$,

(iii) $[x, y^m] = [x^m, y] = [x, y]^m$,

(iv) $(xy)^n = x^n y^n [y, x]^{n(n-1)/2}$.

PROOF. See [3], p. 253.

LEMMA. 0.2. *If G is a PN group*

$$|\mathrm{Aut}_C G| = \prod_{i=1}^{k} |\Omega_i(Z)|^{r_i}$$

where p^k is the exponent of G/G' and r_i factors of order p^i occur in the decomposition of G/G' as direct product of cyclic groups.

PROOF. See [6].

LEMMA 0.3. *Let G be a finite non-abelian PN group such that $G' = Z(G)$. Then $\mathrm{Aut}_C G$ is abelian. Moreover if $\varphi \in \mathrm{Aut}\, G$ the function f given by: $g^f = g^{-1} g^\varphi$ is a homomorphism of G in Z and we have $g^{\varphi^k} = g(g^f)^k$.*

PROOF. See [1], 7-8.

LEMMA 0.4. *The group of central automorphisms of a p-group, when p is odd, is a p-group if and only if G is a PN group.*

PROOF. See [6].

LEMMA 0.5. *Consider the extension:* $1 \to Z \to G \to G/Z \to 1$ *where* G *is a p-group and* G/Z *is a direct product of* $n \geq 2$ *cyclic groups all of the same order* p^t. *Let* $T\colon G/Z \to Z/Z^{p^t}$ *be the homomorphism given by:* $\bar{x}^T = x^{p^t} Z^{p^t}$, *where* $xZ = \bar{x}$, *and let* $[\![\,,\,]\!]\colon G/Z \times G/Z \to Z$ *be defined by:* $[\![\bar{x}, \bar{y}]\!] = [x, y]$, *where* $xZ = \bar{x}$ *and* $yZ = \bar{y}$ *(note that neither map depend on the choice of representatives in* G*). Now let* $(\alpha, \beta) \in \mathrm{Aut}\, G/Z \times \mathrm{Aut}\, Z$. *Then there exists an automorphism of* G *which induces* α *on* G/Z *and* β *on* Z *if and only if the following two diagrams commute:*

$$\begin{array}{ccc} G/Z \times G/Z & \xrightarrow{[\![\,,\,]\!]} & Z \\ \downarrow{\scriptstyle \alpha \times \alpha} & & \downarrow{\scriptstyle \beta} \\ G/Z \times G/Z & \xrightarrow{[\![\,,\,]\!]} & Z \end{array} \qquad \begin{array}{ccc} G/Z & \xrightarrow{T} & Z/Z^{p^t} \\ \downarrow{\scriptstyle \alpha} & & \downarrow{\scriptstyle \bar{\beta}} \\ G/Z & \xrightarrow{T} & Z/Z^{p^t} \end{array}$$

where $(zZ^{p^t})^{\bar{\beta}} = z^{\beta} Z^{p^t}$.

PROOF. See [1], p. 19.

1. – We show that there exists no non-abelian group of order p^6 whose automorphism group is abelian. (Here, and in the whole paper, p is an odd prime.) The outline of the proof is the following: we first analyze the structure which such a group should have and then we come to a contradiction. We start with the following

OBSERVATION 1.0. *If* G *is a group such that* $\mathrm{Aut}\, G$ *is abelian then every automorphism of* G *is central; so in order to prove that the automorphism group of a given group* G *is not abelian it suffices to show that there exists a non-central automorphism.*

The proof follows immediately from the fact that the group of central automorphisms is the centralizer of $\mathrm{Inn}\, G$ in $\mathrm{Aut}\, G$.

We also need the following result, proved by B. Earnley.

LEMMA 1.1. *If* G *is a non-cyclic p-group such that* $\mathrm{Aut}\, G$ *is abelian then:*

(i) *$Z(G)$ and the Frattini subgroup $\Phi(G)$ of G cannot have cyclic intersection.*

(ii) *If $|G| = p^6$ then G/Z is elementary abelian of rank 4.*

PROOF. See [2], pp. 16 and 48.

PROPOSITION 1.2. *Let G be a non-abelian p-group of order p^6 such that* Aut G *is abelian. Then Z and G/Z are elementary abelian of rank 2 and 4 respectively and $Z = \Phi(G)$. Furthermore, a maximal abelian subgroup of G has order p^4.*

PROOF. By the Lemma above G/Z is elementary abelian of rank 4 and Z is not cyclic, so it must be elementary abelian of rank 2. Then we have: $\Phi(G) \leqslant Z$, as G/Z is elementary abelian, and it cannot be a proper inclusion because otherwise $\Phi(G) \cap Z$ would be cyclic, contradicting the Lemma above. Let A be a maximal abelian subgroup of G; Z is contained in A and the inclusion is proper because $\langle g, Z \rangle$ is abelian for all $g \in G \backslash Z$; hence $|A| \geqslant p^3$. Assume $|A| = p^3$ and take $a \in A \backslash Z$, so that $A = \langle a, Z \rangle$. Since $G' \leqslant Z$, we have $|[a, G]| \leqslant p^2$, $|G : C_G(a)| \leqslant p^2$ and there exists $x \in G \backslash A$ such that $[x, a] = 1$. Then $\langle a, x, Z \rangle$ is abelian and A is properly contained in it, contrary to the assumptions. Thus $|A| \geqslant p^4$. Assume $|A| = p^5$. Hence $G = A\langle y \rangle$ for some $y \in G \backslash A$ and as we have $|G : C_G(y)| \leqslant p^2$ it follows that $|A \cap C_G(y)| \geqslant p^3$ and there exists an element $x \in (A \cap C_G(y)) \backslash Z$. Anyway A is abelian and if $x \in A$ centralizes y it centralizes every element of G, hence $x \in Z$, contrary to the assumption. Since G is not abelian we have $|A| \neq p^6$; hence $|A| = p^4$, as we wanted to prove.

PROPOSITION 1.3. *Let G be a group of order p^6 such that Z and G/Z are elementary abelian of rank 2 and 4 respectively and assume $Z = \Phi(G)$. If there exists an elementary abelian subgroup A of G of order p^4, then* Aut G *is not abelian.*

PROOF. By Proposition 1.2 G cannot have abelian subgroups of order p^5, thus $Z \leqslant A$. As $|G'| \leqslant p^2$ we have $|[A, g]| \leqslant p^2$ for all $g \in G$; moreover $[A, g] \neq 1$ for all $g \in G \backslash A$ because A is maximal abelian. There are two cases:

(i) There exists $b_1 \in G \backslash A$ such that $|[A, b_1]| = p$.

Hence $|[A : C_A(b_1)]| = p$ and there is $a_1 \in A \backslash Z$ such that $[a_1, b_1] = 1$.
Put $A = \langle a_1, a_2, Z \rangle$ and $G = \langle a_1, a_2, b_1, b_2 \rangle$.

Let α be the automorphism of G/Z associated to the matrix

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 1 \end{pmatrix}$$

referring to the basis $\{a_1 Z, a_2 Z, b_1 Z, b_2 Z\}$ and let β be the identity of Z. Then by Lemma 0.5 G has an automorphism γ which induces α on G/Z and β on Z; γ is not central and by the observation 1.0 $\operatorname{Aut} G$ is not abelian.

(ii) For all $b \in G \backslash A$ we have $[A, b] = Z$.

Consider $b_1 \in G \backslash A$; hence $C_G(b_1) \cap A = Z$ and $|G : C_G(b_1)| = p^2$.
Put $C_G(b_1) = \langle b_1, b_2, Z \rangle$; thus $G = \langle A, b_1, b_2 \rangle$ and $[A, b_1] = [A, b_2] = Z$. Consider $a_1 \in A \backslash Z$; as $[A, b_1] = Z$, there exists $a_2 \in A$ such that $[a_2, b_1] = [a_1, b_2]$.

We now prove that $a_2 \notin \langle a_1, Z \rangle$.

Deny this statement and assume $a_2 = a_1 z$, with $z \in Z$; by Lemma 0.1 we have $[a_2, b_1] = [a_1 z, b_1] = [a_1, b_1]$, hence $[a_1, b_1][a_1, b_2]^{-1} = 1$, that is $[a_1, b_1 b_2^{-1}] = 1$.

It follows that $|[A, b_1 b_2^{-1}]| \leqslant p$, contrary to the assumptions.

Hence $G = \langle a_1, a_2, b_1, b_2 \rangle$.

Let α be the automorphism of G/Z associated to the matrix

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \end{pmatrix}$$

referring to the basis $\{a_1 Z, a_2 Z, b_1 Z, b_2 Z\}$ and let β be the identity of Z. By the same argument as before the result follows.

PROPOSITION 1.4. *Let G be a group of order p^6 such that Z and G/Z are elementary abelian of rank* 2 *and* 4 *respectively and assume $Z = \Phi(G)$. If G has no elementary abelian subgroups of order p^4 then* $\operatorname{Aut} G$ *is non-abelian.*

PROOF. G^p is contained in Z, so it has order at most p^2 and we have $|\Omega_1(G)| \geqslant p^4$. From the assumptions it also follows that for all $x, y \in \Omega_1(G) \backslash Z$ such that $xZ \neq yZ$ we have $[x, y] \neq 1$. If $A = \langle x, y, Z \rangle$ we have $A = E \times \langle z \rangle$, where $z \in Z$ and $E = \langle a_1, a_2, u \mid [a_1, a_2] = u, [a_1, u] = [a_2, u] = 1, a_1^p = a_2^p = 1 \rangle$.

There are two cases:

(i) There exists $b_1 \in G\backslash A$ such that $[A, b_1] = 1$.

Put $G = \langle A, b_1, b_2 \rangle$; then there are $r_1, r_2, s_1, s_2 \in \boldsymbol{Z}/p\boldsymbol{Z}$ such that $a_1^{b_2} = a_1 u^{r_1} z^{s_1}$ and $a_2^{b_2} = a_2 u^{r_2} z^{s_2}$.

If $s_1 \neq 0$ we may assume that $s_2 = 0$ (take $k \in \boldsymbol{Z}/p\boldsymbol{Z}$ such that $s_2 = s_1 k$ and replace a_1, a_2, u with $a_1' = a_1$, $a_2' = a_1^{-k} a_2$ and $u' = [a_1', a_2']$).

Let α the automorphism of G/Z associated to the matrix

$$\begin{pmatrix} 1 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & -r_2 & 0 & 1 \end{pmatrix}$$

referring to he basis $\{a_1 Z, a_2 Z, b_1 Z, b_2 Z\}$ and let β be the identity of Z. Then by Lemma 0.5 there is a non-central automorphism γ of G which induces α on G/Z and β on Z and the result follows from the observation 1.0.

If $s_1 = 0$ we come to the same conclusions by replacing the preceding matrix with

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ r_1 & 0 & 0 & 1 \end{pmatrix}$$

(ii) For all $b \in G\backslash A$ we have $[A, b] \neq 1$, that is $C_G(A) = Z$.

We shall now show that in this case $\Omega_1(G) = A$. A is contained in $\Omega_1(G)$ by definition of A and assume that the inclusion is proper. Hence there is $b \in \Omega_1(G)\backslash A$ and by the same argument as in the preceding case there is $a \in A\backslash Z$ such that $a^b = au^r$, $r \in \boldsymbol{Z}/p\boldsymbol{Z}$. Take $c \in A$ such that $[a, c] = u^r$ and put $b' = bc^{-1}$; we have $[a, b'] = 1$, $b' \in G\backslash A$ and $(b')^p = (bc^{-1})^p = b^p = 1$ (Lemma 0.7), but this contradicts the fact that G has no elementary abelian subgroups of order p^4. Hence $A = \Omega_1(G)$ and A is characteristic in G.

Put $G = \langle A, b_1, b_2 \rangle$ and assume $b_1^p = b_2^{rp}$. By Lemma 0.1 we have $(b_1 b_2^{-r})^p = 1$ and so $b_1 b_2^{-r} \in (G\backslash A) \cap \Omega_1(G)$, which contradicts the fact that $A = \Omega_1(G)$. Hence $\langle b_1^p \rangle \neq \langle b_2^p \rangle$.

We claim that it is possible to choose the generators of G in order to have:

$$G = AB, \qquad A = (\langle a_1, a_2, u \,|\, [a_1, u] = [a_2, u] = 1,$$

$$a_1^p = a_2^p = 1, [a_1, a_2] = u\rangle) \times \langle z \rangle;$$

$$B = \langle b_1, b_2 \rangle; \qquad b_1^p = u^k; \qquad b_2^p = z; \qquad [a_1, b_1] = [a_2, b_2] = z;$$

$$[a_1, b_2] = [a_2, b_1] = 1; \qquad [b_1, b_2] = u^{\xi} z^{\eta}; \qquad \xi, \eta \in \boldsymbol{Z/pZ};$$

$$G/Z = \langle a_1 Z \rangle \times \langle a_2 Z \rangle \times \langle b_1 Z \rangle \times \langle b_2 Z \rangle; \qquad Z = \langle u \rangle \times \langle z \rangle.$$

Up to now the situation is the following:

$$A = \langle E \rangle \times \langle z \rangle \lhd G; \qquad A' = \langle u \rangle; \qquad G = \langle A, b_1, b_2 \rangle;$$

$$Z = \langle b_1^p \rangle \times \langle b_2^p \rangle; \qquad B = \langle b_1, b_2 \rangle; \qquad B \cap A = Z.$$

Take $b \in B$; b induces an automorphism of the elementary abelian group A/A' which in turn determines a matrix of the type:

$$\begin{bmatrix} 1 & 0 & s \\ 0 & 1 & r \\ 0 & 0 & 1 \end{bmatrix}$$

referring to the basis $\{a_1 A', a_2 A', zA'\}$. In this way we produce a homomorphism

$$\phi\colon B \to S = \left\{ \begin{bmatrix} 1 & 0 & s \\ 0 & 1 & r \\ 0 & 0 & 1 \end{bmatrix} \,|\, r, s \in \boldsymbol{Z/pZ} \right\}.$$

If $b \in \operatorname{Ker} \phi$ we have $a_1^b = a_1 u^s$, $a_2^b = a_2 u^r$ for some $r, s \in \boldsymbol{Z/pZ}$, hence $a^{a_1^{-r} a_2^s} = a_i^b$ with $i = 1, 2$; $a_1^{-r} a_2^s b^{-1} \in C_G(A) = Z$ and $b \in A \cap B = Z$. Since $Z \leqslant \operatorname{Ker} \phi$ trivially, we have $\operatorname{Ker} \phi = Z$, $|B^{\phi}| = |B/\operatorname{Ker} \phi| = p^2 = |S| =$ and ϕ is surjective.

So we can assume $b_1 \in \phi^{\leftarrow} \begin{bmatrix} 1 & 0 & 1 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$ and $b_2 \in \phi^{\leftarrow} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 0 & 1 \end{bmatrix}$.

We have $a_1^{b_1} = a_1 z u^{r_1}$; $a_2^{b_1} = a_2 u^{r_2}$; $a_1^{b_2} = a_1 u^{r_3}$; $a_2^{b_2} = a_2 z u^{r_4}$, with $r_i \in \boldsymbol{Z/pZ}$ for $i = 1, \ldots, 4$. Multiplying b_1 and b_2 for suitable elements of A we can arrange things in order to have $[a_1, b_1] = [a_2, b_2] = z$ and $[a_i, b_j] = 1$ if $i \neq j$. Hence $[A, B] = \langle z \rangle$. Since $Z = \langle u \rangle \times \langle z \rangle = B^p$ there are $c_1, c_2 \in B$ such that $c_1^p = u$; $c_2^p = z$ and $B = \langle c_1, c_2 \rangle$.

Consider $R = \{\alpha \in \operatorname{Aut} B \mid b^\alpha b^{-1} \in \langle z \rangle \, \forall\, b \in B\}$ and let $\psi: A \to R$ be the homomorphism which associates to each $a \in A$ the inner automorphism induced by a on B. $\operatorname{Ker} \psi = C_A(B) = Z$, hence $|A^\psi| = |A/Z| = p^2$.

There is also a bijection $R \to \operatorname{Hom}(B, \langle z \rangle)$ which associates to each $\alpha \in R$ the homomorphism f defined by $x^f = x^\alpha x^{-1}$.

Thus $|R| = |\operatorname{Hom}(B, \langle z \rangle)| = p^2$ and ψ is surjective, that is the automorphisms of B which induce the identity on $B/\langle z \rangle$ are the restrictions to B of the inner automorphisms induced by the elements of A.

It is easy to check that the functions α_1, α_2 defined by: $c_1^{\alpha_1} = c_1 z^{-1}$, $c_2^{\alpha_1} = c_2$, $c_1^{\alpha_2} = c_1$, $c_2^{\alpha_2} = c_2 z^{-1}$ extend by linearity to automorphisms of B which belong to R; hence there are $a_1', a_2' \in A$ such that $c_1^{a_1'} = c_1 z^{-1}$; $c_2^{a_2'} = c_2 z^{-1}$; $c_j^{a_i'} = c_i$ if $i \neq j$; $i, j = 1, 2$. Moreover $A = \langle a_1', a_2', Z \rangle$. Putting $u' = [a_1', a_2']$ we obtain $c_1^p = (u')^k$ with $k \in \boldsymbol{Z}/p\boldsymbol{Z}$, $k \neq 0$; $c_2^p = z$, $[a_1', c_1] = [a_2', c_2] = z$ and $[a_i', c_j] = 1$ if $i \neq j$; $i, j = 1, 2$. This establishes our claim.

Consider the matrices

$$M = \begin{bmatrix} -1 & \eta/k & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & \eta & -1 & 0 \\ \eta & -\eta^2/k & \eta/k & 1 \end{bmatrix}, \qquad N = \begin{bmatrix} -1 & 0 \\ \eta & 1 \end{bmatrix}$$

and let α and β be the automorphisms of G/Z and Z respectively associated to M and N, referring to the basis $\{a_1 Z, a_2 Z, b_1 Z, b_2 Z\}$ and $\{u, v\}$. (We remind that η and k are defined by the relations written before.)

By Lemma 0.5 there is a non-central automorphism γ of G which induces α on G/Z and β on Z and we can conclude that $\operatorname{Aut} G$ is not abelian.

PROPOSITION 1.4. *There is no group G of order p^6 whose automorphism group is an abelian p-group.*

PROOF. Deny the statement and assume that there is a group G with the given properties. Then by Lemma 0.4 G is a *PN* group and the result follows from Propositions 1.2, 1.3 and 1.4.

From the proofs of Propositions 1.3 and 1.4 and from [3] we can also obtain the following

PROPOSITION 1.5. *Every non abelian group of order p^6 has a non central automorphism.*

2. – In this section we describe a family of p-groups whose automorphism groups are abelian. Among them, the one with smallest order has p^7 elements and it is the smallest non abelian p-group with the property stated above.

PROPOSITION 2.1. *For each natural number n there exists a group $G(n)$ of order p^{n^2+3n+3} whose automorphism group is an elementary abelian p-group of order $p^{(n^2+n+1)(2n+2)}$.*

PROOF. Let n be a natural number and let $G = G(n)$ be the group of class two generated by the set $\{a_1, a_2, b_1, \ldots, b_{2n}\}$ and satysfying the following further relations:

$$[a_1, b_{2i+1}] = [a_2, b_{2i+2}] = [b_{2i+1}, b_{2i+2}] =$$

$$= [b_{2i+2}, b_{2j+2}] = [b_{2i+1}, b_{2j+1}] = 1; \qquad \text{for } i, j = 0, \ldots, n-1;$$

$$a_1^p = a_2^p = 1;$$

$$[a_1, a_2]^p = [a_1, b_{2i+2}]^p = [a_2, b_{2i+1}]^p = [b_{2i+1}, b_{2j+2}]^p = 1;$$

$$\text{for } i, j = 0, \ldots, n-1; \; i \neq j;$$

b_1^p is the product of the elements of the set

$$X = \{[a_1, a_2], [a_1, b_{2i+2}], [a_2, b_{2i+1}], [b_{2i+1}, b_{2j+2}];$$

$$i, j = 0, \ldots, n-1; \; i \neq j\};$$

$$b_2^p = b_1^p [a_1, b_2]^{-1}, \quad b_{2i+1}^p = b_{2i}^p [a_2, b_{2i+1}]^{-1}, \quad b_{2i+2}^p = b_{2i+1}^p [a_1, b_{2i+2}]^{-1},$$

$$i = 1, \ldots, n-1.$$

By a standard construction we can see that G is a group of order p^{n^2+3n+3}; G' is elementary abelian of rank n^2+n+1 and basis X, and $\Omega_1(G) = \langle a_1, a_2, G' \rangle$.

We now determine $C_G(a)$, where a is any element of $\Omega_1(G) \backslash G'$.

If $a = a_1^{x_1} a_2^{x_2} z$, $g = a_1^{y_1} a_2^{y_2} b_1^{w_1} \ldots b_{2n}^{w_{2n}} u$, with $z, u \in G'$; $x_i, y_i, w_i \in \mathbf{Z}$; $i = 1, 2$; $j = 1, \ldots, n$; we have:

$$[a, g] = [a_1, a_2]^{x_1 y_2 - x_2 y_1} \prod_{i=0}^{n-1} ([a_1, b_{2i+2}]^{x_1 w_{2i+2}} [a_2, b_{2i+1}]^{x_2 w_{2i+1}}).$$

If $x_1 \equiv 0 \pmod p$, we have $[a, g] = 1$ if and only if $w_{2j+1} \equiv 0 \pmod p$ for all $j = 0, \ldots, n-1$ and $y_1 \equiv 0 \pmod p$.

If $x_2 \equiv 0 \pmod p$, we have $[a, g] = 1$ if and only if $w_{2j+2} \equiv 0 \pmod p$ for all $j = 0, \ldots, n-1$ and $y_2 \equiv 0 \pmod p$.

If $x_1 \not\equiv 0 \not\equiv x_2 \pmod p$ we have $[a, g] = 1$ if and only if $w_{2i+1} \equiv w_{2j+2} \equiv 0 \pmod p$ for all $i, j = 1, \ldots, n$ and $y_1 \equiv kx_1$, $y_2 \equiv kx_2 \pmod p$ with $k \in \boldsymbol{Z}$.

Thus:

$$C_G(a_1) = \langle a_1, b_{2i+1}, G' \mid i = 0, \ldots, n-1 \rangle,$$

$$C_G(a_2) = \langle a_2, b_{2i+2}, G' \mid i = 0, \ldots, n-1 \rangle,$$

$$C_G(a) = \langle a, G' \rangle \qquad \text{if } a \in \Omega_1(G) \setminus (G'\langle a_1 \rangle \cup G'\langle a_2 \rangle).$$

$C_G(a_i)/G'$ is elementary abelian of rank $n+1$, for $i = 1, 2$, and $C_G(a)/G'$ is cyclic of order p for all $a \in \Omega_1(G) \setminus (G'\langle a_1 \rangle \cup \cup G'\langle a_2 \rangle)$.

This also shows that $Z(G) = G'$.

Let $\varphi \in \operatorname{Aut} G$; hence $C_G(a_i)^\varphi = C_G(a_i^\varphi)$ and we have $a_1^\varphi \in \langle a_1, G' \rangle$ or $a_1^\varphi \in \langle a_2, G' \rangle$.

We shall say that φ is of type 1 if it fixes $C_G(a_1)$ and $C_G(a_2)$, of type 2 if it interchanges them.

Assume that φ is of type 1 and consider $r \in \{0, \ldots, n-1\}$.

It must be $b_{2r+1}^\varphi \in C_G(a_1)$; $b_{2r+2}^\varphi \in C_G(a_2)$ and $[b_{2r+1}^\varphi, b_{2r+2}^\varphi] = 1$.

If $b_{2r+1}^\varphi = a_1^{x_1} b_1^{y_1} \ldots b_{2n-1}^{y_{2n-1}}$ and $b_{2r+2}^\varphi = a_2^{x_2} b_2^{y_2} \ldots b_{2n}^{y_{2n}}$; with $x_i, y_j \in \boldsymbol{Z}$; $i = 1, 2$; $j = 1, \ldots, n$ we have:

$$[b_{2r+1}^\varphi, b_{2r+2}^\varphi] = [a_1, a_2]^{x_1 x_2} \prod_{i,j=0}^{n-1} \cdot$$

$$\cdot ([a_1, b_{2i+2}]^{x_1 y_{2i+2}} [a_2, b_{2i+1}]^{-x_2 y_{2i+1}} [b_{2i+1}, b_{2j+2}]^{y_{2i+1} y_{2j+2}}).$$

Since $b_{2r+1}^\varphi, b_{2r+2}^\varphi \notin \Omega_1(G)$ there exist $\tilde{i}$ and $\tilde{j}$ such that $y_{2\tilde{i}+1} \not\equiv 0 \not\equiv y_{2\tilde{j}+2} \pmod p$.

Hence we have $x_2 \equiv 0$, $y_{2j+2} \equiv 0 \pmod p$ for all $j \neq \tilde{i}$ and then $\tilde{j} = \tilde{i}$, $x_1 \equiv 0$ and $y_{2i+1} \equiv 0 \pmod p$ for all $i \neq \tilde{i}$; that is $b_{2r+1}^\varphi \in \langle b_{2\tilde{i}+1}, G' \rangle$ and $b_{2r+2}^\varphi \in \langle b_{2\tilde{i}+2}, G' \rangle$.

Consider the permutation $\sigma \in S_n$ such that $b_{2i+1}^\varphi \in \langle b_{2\sigma(i)+1}, G' \rangle$.

We have $b_{2i+2}^\varphi \in \langle b_{2\sigma(i)+2}, G' \rangle$ and furthermore:

$$[a_1, a_2]^\varphi = [a_1, a_2]^r, \qquad [a_1, b_{2i+2}]^\varphi = [a_1, b_{2\sigma(i)+2}]^{s_i},$$

$$[a_2, b_{2i+1}]^\varphi = [a_2, b_{2\sigma(i)+1}]^{v_i},$$

$$[b_{2i+1}, b_{2j+2}]^\varphi = [b_{2\sigma(i)+1}, b_{2\sigma(j)+2}]^{w_{ij}},$$

with $0 \leqslant i \neq j \leqslant n-1$; $r, s_i, v_i, w_{ij} \neq 0$. Hence we can see that σ permutes the cyclic groups generated by the elements of the set X.

We must have

$$(\star) \qquad (b_{2i+1}^{\varphi})^p = (b_{2i+1}^{p})^{\varphi}$$

hence $b_{2\sigma(i)+1}^{p} \in \langle (b_{2i+1}^{p})^{\varphi} \rangle$ and as in the representation of b_{2i+1}^{p} there are exactly $n^2 + n - 1 - 2i$ elements of X with non-zero exponent we must have $n^2 + n - 1 - 2i = n^2 + n - 1 - 2\sigma(i)$, that is σ must be the identity. In the same way, if $\varphi \in \operatorname{Aut} G$ is of type 2, we have $b_{2i+1}^{\varphi} \in \langle b_{2\tau(i)+2}, G' \rangle$ and $b_{2i+2}^{\varphi} \in \langle b_{2\tau(i)+1}, G' \rangle$, with $\tau \in S_n$; and the condition $(\star)$ leads to a contradiction.

Hence every $\varphi \in \operatorname{Aut} G$ is of type 1 and induces on G/G' an automorphism associated to a diagonal matrix M with entries in $\boldsymbol{Z}/p\boldsymbol{Z}$ of the type

$$M = \begin{pmatrix} \alpha_1 & & & & & \\ & \alpha_2 & & & & \\ & & \beta_1 & & & \\ & & & \beta_2 & & \\ & & & & \ddots & \\ & & & & & \beta_{2n} \end{pmatrix}$$

where the basis of G/G' is $\{a_1 G', a_2 G', b_1 G', \ldots, b_{2n} G'\}$. We have:

$$[a_1, a_2]^{\varphi} = [a_1, a_2]^{\alpha_1\alpha_2}, \qquad [a_1, b_{2i+2}]^{\varphi} = [a_1, b_{2i+2}]^{\alpha_1\beta_{2i+2}},$$

$$[a_2, b_{2i+1}]^{\varphi} = [a_2, b_{2i+1}]^{\alpha_2\beta_{2i+1}},$$

$$[b_{2i+1}, b_{2j+2}]^{\varphi} = [b_{2i+1}, b_{2j+2}]^{\beta_{2i+1}\beta_{2j+2}},$$

with $0 \leq i \neq j \leq n - 1$.

From the conditions $(b_1^{\varphi})^p = (b_1^p)^{\varphi}$ and $(b_2^{\varphi})^p = (b_2^p)^{\varphi}$ we obtain:

$$\alpha_1\alpha_2 = \beta_1 = \alpha_2\beta_{2i+1} = \alpha_1\beta_{2i+2} \text{ for all } i = 0, \ldots, n-1 \text{ and } \beta_2 = \alpha_1\alpha_2;$$

and it follows that M is the identity.

Hence we have proved that every automorphism of G is central and by Lemma 0.2 we have $|\operatorname{Aut} G| = |\operatorname{Aut}_C G| = p^{(n^2+n+1)(2n+2)}$. From the fact that Z has exponent p it follows that $(g^f)^p = 1$ for all $f \in \operatorname{Hom}(G, Z(G))$ and for all $g \in G$, thus $\varphi^p = 1$ for all $\varphi \in \operatorname{Aut} G$. Moreover $Z(G) = G'$, so by Lemma 0.3 $\operatorname{Aut} G$ is an elementary abelian p-group, as we wanted to prove.

OBSERVATION. For $n = 1$ we obtain that $G = G(1)$ has order p^7, it is generated by 4 elements $\{a_1, a_2, b_1, b_2\}$, it has class 2, it satisfies the relations

$$a_1^p = a_2^p = 1 ; \qquad [a_1, b_1] = [a_2, b_2] = [b_1, b_2]^p = 1 ;$$

$$[a_1, a_2]^p = [a_1, b_2]^p = [a_2, b_1]^p = 1 ;$$

$$b_1^p = [a_1, a_2][a_1, b_2][a_2, b_1] ; \qquad b_2^p = [a_1, a_2][a_2, b_1]$$

and its automorphism group is elementary abelian of order p^{12}.

From this facts and Proposition 1.5 we obtain the following

PROPOSITION 2.2. *Let p be an odd prime. The smallest order of a p-group whose automorphism group is abelian is* p^7.

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