

TETRAVALENT HALF-ARC-TRANSITIVE GRAPHS OF ORDER p^2q^2

HAILIN LIU, Ganzhou, BENGONG LOU, BO LING, Kunming

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Abstract. We classify tetravalent G -half-arc-transitive graphs Γ of order p^2q^2 , where $G \leq \text{Aut } \Gamma$ and p, q are distinct odd primes. This result involves a subclass of tetravalent half-arc-transitive graphs of cube-free order.

Keywords: half-arc-transitive graph; normal Cayley graph; cube-free order

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1. INTRODUCTION

Throughout the paper, graphs considered are simple, connected and undirected. For a graph Γ , we denote by $V\Gamma$, $E\Gamma$, $A\Gamma$, $\text{Aut } \Gamma$ and $\text{val}(\Gamma)$ the vertex set, edge set, arc set, full automorphism group and the valency of Γ , respectively. A graph Γ is G -vertex-transitive, G -edge-transitive or G -arc-transitive if $G \leq \text{Aut } \Gamma$ is transitive on $V\Gamma$, $E\Gamma$ or $A\Gamma$, respectively, and Γ is G -half-arc-transitive if $G \leq \text{Aut } \Gamma$ acts transitively on $V\Gamma$ and $E\Gamma$, but not on $A\Gamma$; in particular, when $G = \text{Aut } \Gamma$ then Γ is said to be vertex-transitive, edge-transitive, arc-transitive or half-arc-transitive, respectively. A graph Γ is a Cayley graph if there exists a group G and a subset $S \subset G$ with $1 \notin S = S^{-1} := \{g^{-1} : g \in S\}$ such that the vertices of Γ may be identified with the elements of G in such a way that x is adjacent to y if and only if $yx^{-1} \in S$. The Cayley graph Γ is denoted by $\text{Cay}(G, S)$. A Cayley graph $\Gamma = \text{Cay}(G, S)$ is connected if and only if $G = \langle S \rangle$, that is, S generates G . Let $A = \text{Aut } \Gamma$ and $\text{Aut}(G, S) = \{\alpha \in \text{Aut}(G) : S^\alpha = S\}$. For each $g \in G$, let $R(g)$ denote the permutation on G defined by $x \mapsto xg$. Then A contains the right regular

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representation $R(G) := \{R(g) : g \in G\}$ of G , which is regular on $V\Gamma$, and the group $\text{Aut}(G, S)$ is a subgroup of the stabilizer of 1 in A . A Cayley graph $\text{Cay}(G, S)$ is said to be X -normal if $X \leq A$ contains $R(G)$ as a normal subgroup; in particular, when $G = \text{Aut } \Gamma$ then Γ is said to be *normal*.

Let G be a group, N a normal subgroup and H a subgroup of G . Then we use $\text{Aut}(G)$, $\text{Out}(G)$, $Z(G)$, G/N , $C_G(H)$ and $N_G(H)$ to denote the automorphism group, outer automorphism group, the center, quotient group of G , the centralizer and the normalizer of H in G , respectively. Let M and N be two groups. Then we use $M : N$, $M \times N$ and $M \cdot N$ to denote a semidirect product, direct product and an extension of M by N . For a positive integer n , we denote by \mathbb{Z}_n , D_{2n} , A_n and S_n the cyclic group of order n , the dihedral group of order $2n$, the alternating group and the symmetric group of degree n , respectively.

The investigation of half-arc-transitive graphs was initiated by Tutte, see [25], and he proved that a vertex- and edge-transitive graph with odd valency must be arc-transitive. In 1970, Bouwer constructed the first family of half-arc-transitive graphs in [2]. From then on, half-arc-transitive graphs have been extensively studied over decades and more such graphs were constructed, see for example [1], [7], [8], [9], [12], [13] [16], [19], [24] [26], [27], [28], [29], [30], [32]. In particular, it is proved that for a prime p there is no tetravalent half-arc-transitive graph of order p , p^2 , $2p$ and $2p^2$, see [4], [5], [28]. The half-arc-transitive graphs of order $3p$ and $4p$ are classified in [1], [16], respectively. The tetravalent half-arc-transitive graphs of order p^3 , p^4 and $2pq$ are classified in [8], [9], [32], respectively. Recently, Pan et al. in [21] classified tetravalent edge-transitive graphs of order p^2q . Wang et al. in [30] studied tetravalent half-arc-transitive graphs of order a product of three primes.

In this paper, we will study tetravalent half-arc-transitive graphs of order p^2q^2 with p, q distinct odd primes. The main result of the paper is the following theorem:

Theorem 1.1. *Let Γ be a tetravalent G -half-arc-transitive graph of order p^2q^2 , where $G \leq \text{Aut } \Gamma$ and p, q are distinct odd primes. Then one of the following statements holds:*

- (1) G is soluble, $\Gamma = \text{Cay}(H, S)$ is a G -normal Cayley graph, $G_1 \leq \mathbb{Z}_2^2$ and $S = \{a, a^\tau, a^{-1}, (a^{-1})^\tau\}$, where $a \in H$, and $\tau \in \text{Aut}(H)$ is an involution.
- (2) G is insoluble, and one of the following holds:
 - (i) $|V\Gamma| = 225$ or 441 , $G \cong F \times A_5 = \mathbb{Z}_{pq} \times A_5$ or $\mathbb{Z}_{pq} \times \text{PSL}(2, 7)$, and $|G_\alpha| = 4$ or 8 ;
 - (ii) $|V\Gamma| = 225$ or 441 , and $\text{soc}(G) \cong A_5^2$ or $\text{PSL}(2, 7)^2$, where $\text{soc}(G)$ is the socle of G .

2. PRELIMINARY RESULTS

In this section, we will give some necessary preliminary results. The next lemma deals with a basic group-theoretic result.

Lemma 2.1 ([14], Theorem 4.5). *Let H be a subgroup of a group G . Then $C_G(H)$ is a normal subgroup of $N_G(H)$, and the quotient $N_G(H)/C_G(H)$ is isomorphic to a subgroup of $\text{Aut}(H)$.*

For a graph Γ and a positive integer s , an s -arc of Γ is a sequence $(\alpha_0, \alpha_1, \dots, \alpha_s)$ of vertices such that α_{i-1}, α_i are adjacent for $1 \leq i \leq s$ and $\alpha_{i-1} \neq \alpha_{i+1}$ for $1 \leq i \leq s-1$. A graph Γ is said to be (G, s) -arc-transitive, where $G \leq \text{Aut } \Gamma$, if G is transitive on the set of s -arcs of Γ . If Γ is (G, s) -arc-transitive but not $(G, s+1)$ -arc-transitive, then Γ is called a (G, s) -transitive graph. In particular, when $(G, s) = (\text{Aut } \Gamma, s)$ then Γ is simply called an s -transitive graph. The following result characterizes the vertex stabilizers of tetravalent edge-transitive graphs of odd order.

Lemma 2.2. *Let Γ be a tetravalent G -edge-transitive graph of odd order, where $G \leq \text{Aut } \Gamma$. Let $\alpha \in V\Gamma$ and $\{\alpha, \beta\} \in E\Gamma$. Then either*

- (1) G_α is a 2-group, and Γ is G -half-arc-transitive; or
- (2) Γ is (G, s) -transitive with $1 \leq s \leq 3$. Furthermore, the pair (s, G_α) satisfies the following Table 1:

s	G_α
1	2-group
2	$A_4 \leq G_\alpha \leq S_4$
3	$A_4 \times \mathbb{Z}_3 \leq G_\alpha \leq S_4 \times S_3$

Table 1.

Proof. Assume that Γ is G -arc-transitive. Then the part (2) can be easily derived from [18], Lemma 2.5. Assume that Γ is not G -arc-transitive. Note that $|V\Gamma|$ is odd, so Γ is G -vertex-transitive. It follows that Γ is G -half-arc-transitive. By [17], Lemma 2.1, $G_\alpha^{\Gamma(\alpha)} \leq S_4$ is a $\{2, 3\}$ -group. If $3 \mid |G_\alpha^{\Gamma(\alpha)}|$, then $G_\alpha^{\Gamma(\alpha)} = A_4$ or S_4 . It follows that G_α is transitive on $\Gamma(\alpha)$, and so Γ is G -arc-transitive, a contradiction. Thus G_α is a 2-group. This completes the proof of this lemma. □

By [3], page 337, Table 8.1, we give the soluble maximal subgroups of $\text{GL}(2, p)$ in the following lemma.

Lemma 2.3. *Let M be a soluble maximal subgroup of $\text{GL}(2, p)$. Then M is isomorphic to one of the following groups:*

- (1) $\mathbb{Z}_{p-1} \times (\mathbb{Z}_p : \mathbb{Z}_{p-1})$;

- (2) $\mathbb{Z}_{p^2-1} : \mathbb{Z}_2$;
- (3) $\mathbb{Z}_{p-1} \wr \mathbb{Z}_2$;
- (4) $2 \cdot S_4$.

By [21], we have the following lemma regarding the tetravalent edge-transitive graph with odd but not a prime power order.

Lemma 2.4 ([21], Lemma 4.3). *Let Γ be a tetravalent G -edge-transitive graph with odd but not a prime power order, where $G \leq \text{Aut } \Gamma$. Suppose that N is a nilpotent normal subgroup of G . Then N is semiregular on $V\Gamma$.*

For a group G , the largest nilpotent normal subgroup of G is called the Fitting subgroup of G .

Lemma 2.5 ([23], page 30, Corollary). *Let F be the Fitting subgroup of a group G . If G is soluble, then $F \neq 1$ and the centralizer $C_G(F) \leq F$.*

The next two lemmas give a characterization and classification for the tetravalent edge-transitive graphs of order p^2q with p, q distinct odd primes.

Lemma 2.6 ([30], Lemma 3.3). *Let p, q be distinct odd primes and Γ a tetravalent half-arc-transitive graph of order p^2q . Then Γ is a normal Cayley graph.*

Lemma 2.7 ([21], Theorem 5.3). *Let Γ be a tetravalent G -edge-transitive graph of order p^2q , where $G \leq \text{Aut } \Gamma$ and p, q are distinct odd primes. Then one of the following statements holds:*

- (1) Γ is of order 45, 63, 75 or 147, given in [31]. In particular, there are exactly 17 pairwise nonisomorphic graphs in this case;
- (2) $\Gamma \cong \mathcal{G}_{153}$ is a tetravalent arc-transitive graph of order 153 with $\text{Aut } \Gamma \cong \text{PSL}(2, 17)$;
- (3) $\Gamma = \text{Cay}(H, S)$ is a G -normal edge-transitive Cayley graph, and either
 - (i) Γ is $(G, 1)$ -transitive, and $S = \{a, a^\sigma, a^{\sigma^2}, a^{\sigma^3}\}$, where $\sigma \in \text{Aut}(H)$ is of order 4; or
 - (ii) $G_1 \leq \mathbb{Z}_2^2$ and $S = \{a, a^\tau, a^{-1}, (a^{-1})^\tau\}$, where $\tau \in \text{Aut}(H)$ is an involution.

Remark on Lemma 2.7. For the cases (1) and (2), G is insoluble; and for the case (3), G is soluble.

For a tetravalent G -edge-transitive graph Γ of odd order, where $G \leq \text{Aut } \Gamma$ is an insoluble group, we have the following lemma.

Lemma 2.8 ([21], Corollary 2.4). *Let Γ be a tetravalent G -edge-transitive graph of odd order, where $G \leq \text{Aut } \Gamma$. If G is insoluble, then Γ is not a G -normal edge-transitive Cayley graph.*

Let G be a finite group and let $\pi(G) = \{p : p \text{ is a prime divisor of } |G|\}$. Herzog in [11] and Huppert et al. in [15] classified nonabelian finite simple groups G for $|\pi(G)| = 3$, from which we may deduce the following lemma.

Lemma 2.9. *Let G be a nonabelian simple group, if $|\pi(G)| = 3$. Then $(G, |G|, \text{Out}(G))$ lies in Table 2:*

G	$ G $	$\text{Out}(G)$	G	$ G $	$\text{Out}(G)$
A_5	$2^2 \cdot 3 \cdot 5$	\mathbb{Z}_2	A_6	$2^3 \cdot 3^2 \cdot 5$	\mathbb{Z}_2^2
$\text{PSp}(4, 3)$	$2^6 \cdot 3^4 \cdot 5$	\mathbb{Z}_2	$\text{PSL}(2, 7)$	$2^3 \cdot 3 \cdot 7$	\mathbb{Z}_2
$\text{PSL}(2, 8)$	$2^3 \cdot 3^2 \cdot 7$	\mathbb{Z}_3	$\text{PSL}(2, 17)$	$2^4 \cdot 3^2 \cdot 17$	\mathbb{Z}_2
$\text{PSL}(3, 3)$	$2^4 \cdot 3^3 \cdot 13$	\mathbb{Z}_2	$\text{PSU}(3, 3)$	$2^5 \cdot 3^3 \cdot 7$	\mathbb{Z}_2

Table 2. Nonabelian simple $\{2, q, p\}$ -groups

Regarding the Cayley graph $\Gamma = \text{Cay}(G, S)$, we have the following basic result.

Lemma 2.10 ([10], Lemma 2.1). *Let $\Gamma = \text{Cay}(G, S)$ be a Cayley graph. Then the normalizer $N_{\text{Aut } \Gamma}(G) = G : \text{Aut}(G, S)$.*

Lemma 2.11 ([21], Lemma 2.10). *Let $G \leq \text{Sym}(\Omega)$ be a transitive permutation group on Ω , and let p^m be a divisor of $|\alpha^G|$, where $\alpha \in \Omega$ and p is a prime. If G has a subgroup H such that $(p, |G : H|) = 1$, then p^m divides $|\alpha^H|$. In particular, if $(|\Omega|, |G : H|) = 1$, then H is transitive on Ω .*

Let Γ be a vertex-transitive graph, and let N be a subgroup of $\text{Aut } \Gamma$. Denote by Γ_N the quotient graph corresponding to the orbits of N , that is, the graph having the orbits of N as vertices with two orbits adjacent in Γ_N if there is an edge in Γ between those orbits. Let \mathcal{B} be the set of N -orbits on $V\Gamma$. If for any adjacent orbits B, C of N , the induced subgraph $[B, C]$ of Γ is regular, then Γ is called a multi-cover of Γ_N . If in addition $[B, C]$ is of valency 1, then Γ is called a normal cover of Γ_N .

Lemma 2.12. *Let Γ be a connected G -half-arc-transitive graph, where $G \leq \text{Aut } \Gamma$. Let $N \trianglelefteq G$ and let N have more than two orbits on $V\Gamma$. Then Γ is a multi-cover of Γ_N , and $G/K \leq \text{Aut } \Gamma_N$, where K is the kernel of the action of the set of N -orbits on $V\Gamma$. If $|\Gamma(\alpha) \cap B| = 0$ or 1 for any N -orbit B and $\alpha \in V\Gamma \setminus B$, then the following statements hold:*

- (1) $G/N \leq \text{Aut } \Gamma_N$;
- (2) Γ is a normal cover of Γ_N ;
- (3) Γ_N is a G/N -half-arc-transitive graph.

Proof. Let \mathcal{B} be the set of N -orbits on $V\Gamma$ and let K be the kernel of the action of G on \mathcal{B} . Obviously, $N \leq K$. Since $N \trianglelefteq G$, it is easy to show that the induced subgraph $[B, C]$ of Γ is regular for any adjacent orbits B, C . Hence Γ is a multi-cover or a normal cover of Γ_N and $G/K \leq \text{Aut } \Gamma_N$.

Suppose that $|\Gamma(\alpha) \cap B'| = 1$, where B' is an N -orbit on $V\Gamma$. Since N is transitive on B and B' , it follows that the subgraph $[B, B']$ is a perfect matching and so Γ and Γ_N have the same valency. It then follows that Γ is a normal cover of Γ_N . For $\alpha \in V\Gamma$, the stabilizer K_α fixes each member of \mathcal{B} setwise, and since distinct vertices of $\Gamma(\alpha)$ lie in distinct N -orbits, we have that K_α acts trivially on $\Gamma(\alpha)$. Since Γ is connected it follows that K_α fixes all the vertices of Γ , and hence $K_\alpha = 1$. Since this is true for all α , K acts semiregularly on $V\Gamma$, and hence so does N . Furthermore, as $N \leq K$ and acts transitively on the orbits of K , we see that $K = N$. Thus $G^{V\Gamma_N} \cong G/N$ and so $G/N \leq \text{Aut } \Gamma_N$.

For any $(\alpha, \beta), (\gamma, \delta) \in A\Gamma$, we have $(\alpha^N, \beta^N), (\gamma^N, \delta^N) \in A\Gamma_N$, where $\alpha, \beta, \gamma, \delta \in V\Gamma$. If Γ_N is G/N -arc-transitive, then we have $g \in G$ such that $(\alpha^N)^g = \alpha^{gN} = \gamma^N$ and $(\beta^N)^g = \beta^{gN} = \delta^N$. It then follows that $(\alpha, \beta)^g = (\gamma^{n_1}, \delta^{n_2})$ for some $n_1, n_2 \in N$. And for $(\gamma^{n_1}, \delta^{n_2}), (\gamma, \delta) \in A\Gamma$, we have $n \in N$ such that $(\gamma^{n_1}, \delta^{n_2})^n = (\gamma, \delta)$. Hence $(\alpha, \beta)^{gn} = (\gamma, \delta)$. Thus Γ is G -arc-transitive, a contradiction. So Γ_N is G/N -half-arc-transitive. \square

For the tetravalent normal half-arc-transitive Cayley graphs, the following proposition gives a general construction.

Proposition 2.13. *Let $\Gamma = \text{Cay}(H, S)$ be a tetravalent G -half-arc-transitive Cayley graph of order p^2q^2 , where p, q are distinct odd primes. Let 1 denote the vertex of Γ corresponding to the identity element of H . Assume that $H \triangleleft G$. Then $G_1 \leq \mathbb{Z}_2^2$ and $S = \{a, a^\tau, a^{-1}, (a^{-1})^\tau\}$, where $\tau \in \text{Aut}(H)$ is an involution.*

Proof. By Lemma 2.10, $G_1 \leq \text{Aut}(H, S)$. Since Γ is connected, $H = \langle S \rangle$ and then G_1 acts faithfully on $\Gamma(1) = S$, which implies $G_1 \leq S_4$. Since G_1 is a 2-group, $G_1 \leq D_8$. Let $a \in S$. If $G_1 \geq \langle \sigma \rangle \cong \mathbb{Z}_4$, then $\langle \sigma \rangle$ is regular on S . Hence Γ is G -arc-transitive, a contradiction. Thus $G_1 \leq \mathbb{Z}_2^2$. Since Γ is a G -normal half-arc-transitive Cayley graph, $S = T^{-1} \cup T$ by [22], Proposition 1, where T is an orbit of the action of G_1 on S . So there exists an involution $\tau \in G_1$ such that $a^\tau \neq a$ or a^{-1} ; it follows that $S = \{a, a^\tau, a^{-1}, (a^{-1})^\tau\}$. \square

By Proposition 2.13, more specific constructions of the graph $\Gamma = \text{Cay}(H, S)$ depend on the automorphism group of the group H .

3. PROOF OF THEOREM 1.1

Let Γ be a tetravalent G -half-arc-transitive graph of order p^2q^2 , where $G \leq \text{Aut } \Gamma$ and p, q are distinct odd primes. Let $\alpha \in V\Gamma$. By Lemma 2.2, G_α is a 2-group, and hence G is a $\{2, p, q\}$ -group. Obviously, G has no nontrivial normal 2-subgroup.

Now we first consider the case when G is soluble.

Lemma 3.1. *If G is soluble, then Γ is a G -normal Cayley graph.*

Proof. Since G_α is a 2-group, $|G| = 2^i p^2 q^2$ for some positive integer i . Let F be the Fitting subgroup of G . By Lemma 2.5, $F \neq 1$, $C_G(F) \leq F$. In particular, $F = \vee_p(G) \times \vee_q(G)$, where $\vee_p(G)$ and $\vee_q(G)$ are the largest normal p -subgroup and q -subgroup of G , respectively. Therefore, F is abelian and $C_G(F) = F$. Now F is semiregular on $V\Gamma$ and hence $|F| \mid p^2 q^2$.

Assume $F \cong \mathbb{Z}_p$. Then by Lemma 2.1 $G/F \leq \text{Aut}(F) \cong \mathbb{Z}_{p-1}$, it follows that $p^2 \nmid |G|$, which is not possible. Similarly, we can exclude the cases $F \cong \mathbb{Z}_q$ and \mathbb{Z}_{pq} .

Assume $|F| = p^2$. Then we consider the quotient graph Γ_F , induced by F . Let K be the kernel of G acting on $V\Gamma_F$. By Lemma 2.12, $G/K \leq \text{Aut } \Gamma_F$ and $K = F : K_\alpha$. Suppose that $\text{val}(\Gamma_F) = 4$. Again by Lemma 2.12, we obtain that $K = F$ and Γ is a normal cover of Γ_F . So Γ_F is a G/F -half-arc-transitive graph of order q^2 . If $F = \mathbb{Z}_{p^2}$, then $G/F \leq \text{Aut}(F)$ is abelian. Thus G/F is regular on $V\Gamma_F$, which is not possible. So $F \cong \mathbb{Z}_p^2$, and $G/F \leq \text{Aut}(F) \cong \text{GL}(2, p)$. Note that G/F is soluble, G/F is one of subgroups listed in Lemma 2.3. We consider the candidates one by one.

(1) Suppose that $G/F \leq \mathbb{Z}_{p-1} \times (\mathbb{Z}_p : \mathbb{Z}_{p-1})$. Since $p \nmid |G/F|$, hence $G/F = \mathbb{Z}_l \times \mathbb{Z}_m$ for some $l, m \mid p-1$, which is not possible.

(2) Suppose that $G/F \leq \mathbb{Z}_{p^2-1} : \mathbb{Z}_2$. Then $G/F = \mathbb{Z}_k : \mathbb{Z}_2$ for some $k \mid p-1$ and $q^2 \mid k$. Let Q be a Sylow q -subgroup of G/F . Then $|Q| = q^2$ and $Q \triangleleft G/F$. Therefore, G has a normal subgroup isomorphic to $F \cdot Q$ which is regular on $V\Gamma$. That is to say Γ is a G -normal Cayley graph in this case.

(3) Suppose that $G/F \leq \mathbb{Z}_p \wr \mathbb{Z}_2$. Then $G/F = (\mathbb{Z}_t \times \mathbb{Z}_t) : \mathbb{Z}_2$ for some $t \mid p-1$ and $q \mid t$. Similarly, the Sylow q -subgroup Q of G/F is normal, and G has a normal subgroup isomorphic to $F \cdot Q$ which is regular on $V\Gamma$. Therefore Γ is also a G -normal Cayley graph.

(4) Suppose that $G/F \leq 2 \cdot S_4$. Obviously, this is not possible since $q^2 \nmid |G/F|$. Now we consider the case $\text{val}(\Gamma_F) = 2$. Then $\Gamma_F := \{B_1, B_2, \dots, B_{q^2}\}$ is a cycle of length q^2 , where B_i is adjacent to B_{i+1} in Γ_F for $1 \leq i \leq q^2 - 1$, so the induced subgraph $[B_i, B_{i+1}]$ is a cycle of length $2p^2$. This implies that $K_\alpha \leq \mathbb{Z}_2$, $K = F$ or $F : \mathbb{Z}_2$, and $G \leq K \cdot \text{Aut } \Gamma_F = K \cdot D_{2q^2}$. It follows that G has a normal Hall $\{p, q\}$ -subgroup which is regular on Γ , hence Γ is a G -normal Cayley graph. Similarly, Γ is also a G -normal Cayley graph when $|F| = q^2$.

Assume $|F| = p^2q$. Then $G/K \leq \text{Aut } \Gamma_F$, where K is the kernel of G acting on $V\Gamma_F$. If $\text{val}(\Gamma_F) = 4$, then $K = F$ and Γ_F is G/F half-arc-transitive of order q . Note that G/F is soluble. It follows that $G/F \leq \mathbb{Z}_q : \mathbb{Z}_{q-1}$ from [6], Corollary 3.5B. Thus G has a normal subgroup isomorphic to $F \cdot \mathbb{Z}_q$ which is regular on $V\Gamma$. So Γ is a G -normal half-arc-transitive Cayley graph. For $\text{val}(\Gamma_F) = 2$, $K_\alpha \leq \mathbb{Z}_2$, $K = F$ or $F : \mathbb{Z}_2$, and $G \leq K \cdot \text{Aut } \Gamma_F = K \cdot D_{2q}$. It follows that G has a normal Hall- $\{p, q\}$ -subgroup which is regular on Γ , hence Γ is a G -normal Cayley graph. Similarly, Γ is also a G -normal Cayley graph when $|F| = pq^2$.

Finally, assume $|F| = p^2q^2$. Then F is regular on $V\Gamma$, and so Γ is a G -normal Cayley graph on F . □

Next we consider the case when G is insoluble.

Lemma 3.2. *Let M be the radical of G , and let F be the Fitting subgroup of M . If G is insoluble, then one of the following statements holds:*

- (1) $M \neq 1$, $F \cong \mathbb{Z}_{pq}$, $|V\Gamma| = 225$ or 441 , $G \cong F \times A_5 = \mathbb{Z}_{pq} \times A_5$ or $\mathbb{Z}_{pq} \times \text{PSL}(2, 7)$, and $|G_\alpha| = 4$ or 8 ;
- (2) $M = 1$ and $\text{soc}(G) \cong A_5, A_6, \text{PSL}(2, 7), \text{PSL}(2, 8), \text{PSL}(2, 17), A_5^2$ or $\text{PSL}(2, 7)^2$.

Proof. Let N be the socle of G , that is, the product of all minimal normal subgroups of G . Let M be the radical of G , that is, the largest normal soluble subgroup of G . And let $|G| = 2^i p^2 q^2$ for some integer i .

Case 1. Assume $M \neq 1$. Let F be the Fitting subgroup of M . Then $F \leq G$ and $F \neq 1$ by Lemma 2.5. We consider Γ_F . Let K be the kernel of G acting on $V\Gamma_F$. Then $K = FK_\alpha$, and hence K is soluble as K_α is soluble by Lemma 2.2. If $\text{val}(\Gamma_F) = 2$, then Γ_F is a cycle and $G/K \leq \text{Aut } \Gamma_F = D_{2m}$, where $m = |V\Gamma_F|$. So G is soluble, which is a contradiction. Thus, $\text{val}(\Gamma_F) = 4$. Then $K = F$ and $G/F \leq \text{Aut } \Gamma_F$. Further, by Lemma 2.4, F is semiregular on $V\Gamma$ and hence $|F|$ divides p^2q^2 . Suppose $|F| = p^2q^2$, then Γ is a G -normal half-arc-transitive Cayley graph of F , which is not possible by Lemma 2.8.

Suppose $|F| = p^2$. Then Γ_F is a tetravalent G/F -half-arc-transitive graph of order q^2 . If $q \geq 5$, then we obtain a contradiction by [21], Lemma 4.2. If $q = 3$ then Γ_F is an edge-transitive graph of order 9. By [20], $\Gamma_F = DW(3, 3)$ is a deleted wreath graph, and $\text{Aut } \Gamma_F \cong \mathbb{Z}_3^2 \cdot D_8$. It follows that G is soluble, a contradiction. Similarly, we can exclude the case $|F| = q^2$.

Suppose $|F| = pq^2$. Then Γ_F is a tetravalent G/F -half-arc-transitive graph of order p . Since $|V\Gamma_F| = p$, G/F is almost simple and 2-transitive on $V\Gamma_F$ by [6], page 99. It follows that $\Gamma_F = K_p$. Since $\text{val}(\Gamma_F) = 4$, $p = 5$. As $G/F \leq \text{Aut } K_5 = S_5$ is insoluble, we have $G = F \cdot A_5$ or $F \cdot S_5$, and so $3 \mid |G_\alpha|$, which is a contradiction by Lemma 2.2. Similarly, we can exclude the case $|F| = p^2q$.

Suppose $|F| = pq$. Then Γ_F is a tetravalent G/F -half-arc-transitive graph of order pq . But by [1], [26], there is no tetravalent edge-transitive graph of order pq which is half-arc-transitive, so Γ_F is arc-transitive. It follows that $(pq, \Gamma_F, \text{Aut } \Gamma_F, (\text{Aut } \Gamma_F)_{\bar{\alpha}})$ satisfies Table 1 in [21], Lemma 2.6, where $\bar{\alpha} \in V\Gamma_F$. We first consider rows 1–2 of Table 1. If $pq = 15$ or 21 , then $|V\Gamma| = 225$ or 441 , $G \cong F \times A_5 = \mathbb{Z}_{pq} \times A_5$ or $\mathbb{Z}_{pq} \times \text{PSL}(2, 7)$, and $|G_\alpha| = 4$ or 8 , respectively. For rows 3–5 of Table 1. If $pq = 35$ as in row 3, then $G/F < \text{Aut } \Gamma_F = S_7$. Note that G/F is insoluble, and since G/F is edge-transitive on $V\Gamma_F$, $70 \mid |G/F|$, we conclude that $G/F \cong A_7$. It follows that $|G| \geq |F||A_7|$, and so $3 \mid |G_\alpha|$, which is a contradiction by Lemma 2.2. Similarly, we can also exclude the cases where $pq = 55$ or 253 , as in rows 4 or 5, respectively.

Finally, suppose $|F| = p$. Then Γ_F is a tetravalent G/F -half-arc-transitive Cayley graph of order pq^2 . It follows that $\text{Aut } \Gamma_F$ is half arc-transitive or arc-transitive on Γ_F . For convenience, we say $\Gamma_F = \text{Cay}(R, S)$, where $|R| = pq^2$. If $\text{Aut } \Gamma_F$ is half arc-transitive on Γ_F ; then $R \triangleleft \text{Aut } \Gamma_F$ by Lemma 2.6. That is, $\Gamma_F = \text{Cay}(R, S)$ is a normal edge transitive Cayley graph. Noting that G is insoluble, Γ_F is not normal edge transitive by Lemma 2.8. A contradiction occurs. If $\text{Aut } \Gamma_F$ is arc-transitive on Γ_F , by checking the tetravalent edge-transitive graphs of order pq^2 in Lemma 2.7, then $\Gamma_F = \mathcal{G}_{153}$ and $\text{Aut } \Gamma_F = \text{PSL}(2, 17)$. It follows that $G = F \cdot \text{PSL}(2, 17) = F \times \text{PSL}(2, 17)$. But there exists no tetravalent half arc-transitive graph of order $3^2 \cdot 17^2$ admitting G as a graph automorphism group by simple computing.

Case 2. Assume $M = 1$. Then each nontrivial normal subgroup of G is insoluble. Let $\text{soc}(G) = M_1 \times \dots \times M_s$, where M_i ($1 \leq i \leq s$) are all minimal normal subgroups of G . Suppose that $M_k = T_k^{d_k}$, where T_k is a nonabelian simple group and $1 \leq k \leq s$. Since G_α is a 2-group, N is a $\{2, p, q\}$ -group. By Lemma 2.9, $\text{soc}(G) \cong A_5, A_6, \text{PSL}(2, 7), \text{PSL}(2, 8), \text{PSL}(2, 17), A_5^2$ or $\text{PSL}(2, 7)^2$. \square

Proof of Theorem 1.1. Let Γ be G -half-arc-transitive. If G is soluble, then, by Lemma 3.1, Γ is a G -normal half-arc-transitive Cayley graph. Combining Proposition 2.13, we complete the proof of part (1) in Theorem 1.1.

Suppose that G is insoluble. Let $\text{soc}(G) \cong A_5, A_6, \text{PSL}(2, 7), \text{PSL}(2, 8), \text{PSL}(2, 17), A_5^2$ or $\text{PSL}(2, 7)^2$. Let $\alpha \in V\Gamma$. Then $|G| = |G_\alpha| \cdot p^2q^2$. If $N := \text{soc}(G) \cong A_5$, then $G = A_5$ or S_5 . Since $|A_5| = 2^2 \cdot 3 \cdot 5$ and $|S_5| = 2^3 \cdot 3 \cdot 5$, $p^2q^2 \nmid |G|$. Similarly, we can exclude the cases $N \cong A_6, \text{PSL}(2, 7), \text{PSL}(2, 8)$ and $\text{PSL}(2, 17)$.

If $N \cong A_5^2$, then $|N| = 2^4 \cdot 3^2 \cdot 5^2$. Since $|N| \mid |G_\alpha| \cdot p^2q^2$ and G_α is a 2-group, $(p^2q^2, |G : N|) = 1$. By Lemma 2.11, N is transitive on $V\Gamma$. So $|N : N_\alpha| = 3^2 \cdot 5^2$, that is, $|V\Gamma| = 225$. Similarly, we can obtain that $|V\Gamma| = 441$ when $N \cong \text{PSL}(2, 7)^2$. Apply Lemma 3.2 (1), we complete the proof of part (2) in Theorem 1.1. \square

References

- [1] *B. Alspach, M. Y. Xu*: 1/2-transitive graphs of order $3p$. *J. Algebr. Comb.* *3* (1994), 347–355. [zbl](#) [MR](#) [doi](#)
- [2] *I. Z. Bouwer*: Vertex and edge transitive, but not 1-transitive, graphs. *Can. Math. Bull.* *13* (1970), 231–237. [zbl](#) [MR](#) [doi](#)
- [3] *J. N. Bray, D. F. Holt, C. M. Roney-Dougak*: The Maximal Subgroups of the Low-Dimensional Finite Classical Groups. London Mathematical Society Lecture Note Series 407, Cambridge University Press, Cambridge, 2013. [zbl](#) [MR](#) [doi](#)
- [4] *C. Y. Chao*: On the classification of symmetric graphs with a prime number of vertices. *Trans. Amer. Math. Soc.* *158* (1971), 247–256. [zbl](#) [MR](#) [doi](#)
- [5] *Y. Cheng, J. Oxley*: On weakly symmetric graphs of order twice a prime. *J. Combin. Theory Ser. B* *42* (1987), 196–211. [zbl](#) [MR](#) [doi](#)
- [6] *J. D. Dixon, B. Mortimer*: Permutation Groups. Graduate Texts in Mathematics 163, Springer, New York, 1996. [zbl](#) [MR](#) [doi](#)
- [7] *S. F. Du, M. Y. Xu*: Vertex-primitive 1/2-arc-transitive graphs of smallest order. *Commun. Algebra* *27* (1999), 163–171. [zbl](#) [MR](#) [doi](#)
- [8] *Y. Q. Feng, J. H. Kwak, X. Wang, J. X. Zhou*: Tetravalent half-arc-transitive graphs of order $2pq$. *J. Algebr. Comb.* *33* (2011), 543–553. [zbl](#) [MR](#) [doi](#)
- [9] *Y. Q. Feng, J. H. Kwak, M. Y. Xu, J. X. Zhou*: Tetravalent half-arc-transitive graphs of order p^4 . *Eur. J. Comb.* *29* (2008), 555–567. [zbl](#) [MR](#) [doi](#)
- [10] *C. D. Godsil*: On the full automorphism group of a graph. *Combinatorica* *1* (1981), 243–256. [zbl](#) [MR](#) [doi](#)
- [11] *M. Herzog*: On finite simple groups of order divisible by three primes only. *J. Algebra* *10* (1968), 383–388. [zbl](#) [MR](#) [doi](#)
- [12] *D. F. Holt*: A graph which is edge transitive but not arc transitive. *J. Graph Theory* *5* (1981), 201–204. [zbl](#) [MR](#) [doi](#)
- [13] *A. Hujdurović, K. Kutnar, D. Marušič*: Half-arc-transitive group actions with a small number of alternets. *J. Comb. Theory, Ser. A* *124* (2014), 114–129. [zbl](#) [MR](#) [doi](#)
- [14] *B. Huppert*: Endliche Gruppen. I. Die Grundlehren der mathematischen Wissenschaften 134, Springer, Berlin, 1967. (In German.) [zbl](#) [MR](#) [doi](#)
- [15] *B. Huppert, W. Lempken*: Simple groups of order divisible by at most four primes. *Izv. Gomel. Gos. Univ. Im. F. Skoriny* *16* (2000), 64–75. [zbl](#)
- [16] *K. Kutnar, D. Marušič, P. Šparl, R. J. Wang, M. Y. Xu*: Classification of half-arc-transitive graphs of order $4p$. *Eur. J. Comb.* *34* (2013), 1158–1176. [zbl](#) [MR](#) [doi](#)
- [17] *C. H. Li*: Semiregular automorphisms of cubic vertex transitive graphs. *Proc. Am. Math. Soc.* *136* (2008), 1905–1910. [zbl](#) [MR](#) [doi](#)
- [18] *C. H. Li, Z. P. Lu, H. Zhang*: Tetravalent edge-transitive Cayley graphs with odd number of vertices. *J. Comb. Theory. Ser. B* *96* (2006), 164–181. [zbl](#) [MR](#) [doi](#)
- [19] *C. H. Li, H. S. Sim*: On half-transitive metacirculant graphs of prime-power order. *J. Comb. Theory Ser. B* *81* (2001), 45–57. [zbl](#) [MR](#) [doi](#)
- [20] *B. D. McKay*: Transitive graphs with fewer than twenty vertices. *Math. Comput.* *33* (1979), 1101–1121. [zbl](#) [MR](#) [doi](#)
- [21] *J. Pan, Y. Liu, Z. Huang, C. Liu*: Tetravalent edge-transitive graphs of order p^2q . *Sci. China Math.* *57* (2014), 293–302. [zbl](#) [MR](#) [doi](#)
- [22] *C. E. Praeger*: Finite normal edge-transitive Cayley graphs. *Bull. Aust. Math. Soc.* *60* (1999), 207–220. [zbl](#) [MR](#) [doi](#)
- [23] *M. Suzuki*: Group Theory II. Grundlehren der mathematischen Wissenschaften 248, Springer, New York, 1986. [zbl](#) [MR](#)
- [24] *D. E. Taylor, M. Y. Xu*: Vertex-primitive half-transitive graphs. *J. Aust. Math. Soc. Ser. A* *57* (1994), 113–124. [zbl](#) [MR](#) [doi](#)

- [25] *W. T. Tutte*: Connectivity in Graphs. Mathematical Expositions 15, University of Toronto Press, Toronto; Oxford University Press, London, 1966. [zbl](#) [MR](#)
- [26] *R. J. Wang*: Half-transitive graphs of order a product of two distinct primes. Commun. Algebra 22 (1994), 915–927. [zbl](#) [MR](#) [doi](#)
- [27] *X. Wang, Y. Q. Feng*: Half-arc-transitive graphs of order $4p$ of valency twice a prime. Ars Math. Contemp. 3 (2010), 151–163. [zbl](#) [MR](#) [doi](#)
- [28] *X. Wang, Y. Q. Feng*: There exists no tetravalent half-arc-transitive graph of order $2p^2$. Discrete Math. 310 (2010), 1721–1724. [zbl](#) [MR](#) [doi](#)
- [29] *Y. Wang, Y. Q. Feng*: Half-arc-transitive graphs of prime-cube order of small valencies. Ars Math. Contemp. 13 (2017), 343–353. [zbl](#) [MR](#) [doi](#)
- [30] *X. Wang, Y. Feng, J. Zhou, J. Wang, Q. Ma*: Tetravalent half-arc-transitive graphs of order a product of three primes. Discrete Math. 339 (2016), 1566–1573. [zbl](#) [MR](#) [doi](#)
- [31] *S. Wilson, P. Potočnik*: A census of edge-transitive tetravalent graphs, Mini-Census. Available at <https://www.fmf.uni-lj.si/~potocnik/work.htm>.
- [32] *M. Y. Xu*: Half-transitive graphs of prime-cube order. J. Algebr. Comb. 1 (1992), 275–282. [zbl](#) [MR](#) [doi](#)

Authors' addresses: Hailin Liu, School of Science, Jiangxi University of Science and Technology, No. 86, Hongqi Ave, Ganzhou, Jiangxi 341000, P. R. China, e-mail: hailinliuqp@163.com; Hailin Liu, Bengong Lou (corresponding author), School of Mathematics and Statistics, Yunnan University, No. 2, Cuihubei Rd, Kunming 650091 P. R. China, e-mail: bengong188@163.com; Bo Ling, School of Mathematics and Computer Science, Yunnan Minzu University, No. 2929, Yuehua Ave, Kunming 650504, P. R. China, e-mail: bolinggxu@163.com.